Assessing Wood Biomass Residue Availability for UNC-Chapel Hill's Cogeneration Facility

by
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ABSTRACT

As part of its Climate Action Plan, UNC has pledged to become coal-free by 2020 and carbon-neutral by 2050. As UNC's combined heat and power (CHP) plant is the largest source of greenhouse gas (GHG) emissions, the University has aggressively initiated an effort to identify a cleaner fuel to substitute for coal. Due to technical specifications of the CHP plant, biomass has been identified as the best option, although until now no local sources are currently available.

This project identifies specific wood biomass sources within a 50-mile radius of the University campus and locates potential fuel supply sources that could be used for firing or co-firing the boiler. The National Land Cover Database, ReferenceUSA platform and the NC Division of Solid Waste Management Permitted Facility List were used to identify 157 potential locations of biomass supply that were subdivided into 7 classes: Logging Residue, Construction and Demolition (C&D) Waste, Land Clearing and Inert Debris (LCID), Yard Waste (YW), Furniture Manufacturing, Mill Residue and Other Wood Waste. ArcGIS Network Analysis was used to model optimal routes and calculate transportation distances to the CHP plant from each potential supply location. A simple cost model was created that specified per unit transportation and fuel costs, including collection and harvesting, processing and on-site purchase expenses. Results from network analysis and cost modeling were combined in a linear programming model that was set to identify optimal monthly supply sources such that the fuel delivery cost is minimized.

The results of the study show that there potentially exists a diverse and extensive fuel basket on a monthly basis. Of the seven classes of biomass fuel, C&D and Furniture Manufacturing were identified as the most optimal sources. Mill Residue and Other Wood Waste were optimal only during the peak demand or winter months. The remaining biomass fuel types were not optimal for use irrespective of demand fluctuations.

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1. Introduction

This thesis attempts to determine wood biomass availability for the Cogeneration Facility at the University of North Carolina at Chapel Hill (UNC) to co-fire or replace coal. It also attempts to identify the most optimal sources based on modeled fuel, transportation and plant parameters. This section provides historical background explaining the motivation behind this research. The Cogeneration Facility at UNC has investigated various biomass options for over five years, but has been unable to find reliable suppliers to begin cofiring coal with biomass. Seven different wood biomass options are considered as alternative fuel categories to the pelletized and torrefied wood previously considered. These biomass options include logging residue, mill residue, construction and demolition (C&D) waste, yard waste (YW), land clearing and inert debris (LCID), furniture manufacturing and other wood waste[1]. The next section explains the methodology to quantify and assess the financial viability of purchasing each of the seven biomass options. The following steps were employed in this assessment:

a) Identification of fuel sources and quantities;

b) Design of optimal routes from each supply source to UNC campus;

c) Establishment of the probable cost of delivered fuel for each source;

d) Optimization of fuel selection to minimize cost.

The Results section includes an evaluation of the main findings based on the Transportation Network analysis in ArcGIS, biomass fuel delivered cost estimations and the optimization model solution. The Discussion section evaluates the advantages of using Network Analysis and GIS for quantifying the optimal distance and provides the analysis of the optimization model. The Discussion also elaborates on several limitations of the modeling approach, including limitations of the datasets and employee conversion factors. Finally, the Discussion provides recommendations for the

[1] Definitions of these fuel classes taken from NCDENR and EPA websites and relevant biomass logging case studies are provided in Appendix F

Cogeneration Facility on the optimal fuel choice based on the model results and considers future work to make the model more complex and provide more accurate results. The Conclusion section summarizes the main findings of this study.

2. UNC and Wood Biomass Initiatives

In January of 2007 UNC-Chapel Hill signed the American College and University President's Climate Commitment (ACUPCC) and joined 650[2] other universities in pursuing a pledge to attain climate neutrality and sustainability. This was the beginning of UNC's official commitment to reduce greenhouse gas (GHG) emissions on campus by becoming carbon-neutral by 2050 and coal-free by 2020[3]. Two years later UNC published its 2009 Climate Plan addressing the University's carbon footprint and the distribution of carbon emissions arising from transportation, electricity purchases, and campus operations[4]. According to the 2010-2011 Climate Action Plan Update and based on results from the 2011 GHG inventory update[5], UNC-Chapel Hill emitted approximately 523,000 metric tons of carbon dioxide equivalent (MTCDE) in that year. Of those annual emissions, about 251,000 metric tons, or roughly 48% of total GHG's, came from a single source – coal combustion at the UNC-Chapel Hill combined heat and power (CHP) plant on Cameron Avenue.

The plant currently operates two circulating fluidized bed (CFB) boilers that utilize coal for fuel and produce 250,000 pounds/hour of steam. It is one of the most efficient coal burning plants in the country, with almost 70% efficiency, as compared to electricity-only generating plants that operate at an average of 33% efficiency.[6] This high efficiency is attributed to the utilization of steam byproduct for campus services, such as sterilization of medical equipment at UNC Hospitals, providing steam to research laboratories and dining operations, as well as heating campus buildings. Ultimately, the steam condenses into water, which is then used for equipment cooling and campus air conditioning.

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[2] *UNC submits Climate Action Plan as part of commitment to carbon neutrality*. (2009). Retrieved from http://uncnews.unc.edu/content/view/2865/68/
[3] Waste Reduction and Recycling. (n.d.). *UNC Climate Action Plan*. Retrieved from http://www.wastereduction.unc.edu/WhyRecycle/UNCsClimateActionPlan
[4] Climate Action Program. (2009). *2009 Climate Action Plan*. Retrieved from http://www.climate.unc.edu/ClimateActionProgram/ClimateActionPlan
[5] *University of North Carolina at Chapel Hill Climate Action Plan Update 2010*. (2010). Retrieved from http://sustainability.unc.edu/Portals/Sustainability2009/2010-2011%20Climate%20Action%20Plan%20Update.pdf
[6] Environmental Protection Agency. (n.d.). *Combined Heat and Power Partnership*. Retrieved from http://www.epa.gov/chp/basic/efficiency.html

Source	CO_2 (MTCDE)
Individual Building Boilers	6,260
Cameron Cogeneration Plant	250,968
Emergency Generators	127
Manning Steam Plant	12,984
Other (mainly includes Purchased Power and Transportation)	265,750
Grand Total	**523,104**

Figure 1. GHG Emissions by source (Adapted from 2011 GHG Inventory Update and Baseline Analysis).

The Cameron Avenue Power Plant is highly efficient and essential for campus operations, but through coal combustion, which is the primary source of GHG emissions from power generation in the U.S.[7], it contributes the most CO_2 emissions on campus (Figure 1). Thus in its goal of pursuing climate neutrality, the University needs to develop a strategy to reduce the emissions of Cameron Plant. Before suggesting various alternative fuel options for the Plant, there are two aspects to consider about the Plant's technical and financial operations need to be considered. The technical aspect is that the CFB boiler in the Cogeneration Plant requires 50% solid fuel to operate[8] and the financial aspect is that Cameron Plant is relatively new and its mortgage represents 34% of the Plant's total budget. The mortgage balance was $94 million in 2010, and is projected to be fully paid in 2022[9]. These two conditions would determine the alternative fuel type to use and more importantly, the mortgage obligation would imply that the Plant couldn't fully switch to burning

[7] U.S. Environmental Protection Agency. (n.d.). *Sources of Greenhouse Gas Emissions*. Retrieved from http://www.epa.gov/climatechange/ghgemissions/sources/electricity.html
[8] Pers.comm. with UNC Energy Services director Philip Barner
[9] Orange County Board of County Commissioners. (2010).*UNC-Chapel Hill Energy Task Force: Interim Report*. Retrieved from http://www.co.orange.nc.us/occlerks/1006157d.pdf

natural gas (NG) until at least 2030, at the end of its useful life, even though prices for NG have been gradually decreasing since 2008[10].

A fuel alternative that satisfies the two criteria mentioned above is wood biomass, which has large potential for power generation in North Carolina (NC). According to The North Carolina Forestry Association, approximately 2.8 million dry tons of forest residue is potentially available in NC,[11] and based on data from Antares Group, Inc., NC has more than 500MW of potential capacity for power generation fueled by forest residues[12]. There are many air quality benefits of burning biomass instead of coal, as unlike coal, wood biomass is low in sulfur, chlorine and nitrogen[13]. Additionally, clean, untreated wood has lower concentrations of trace metals as compared to coal including arsenic, beryllium, cadmium, mercury, and lead[14].

As part of a comprehensive study of renewable energy opportunities, engineers at the Cogeneration Facility have identified three potential biomass fuel types for the eventual replacement of coal: torrefied wood, wood pellets, and dry wood chips to substitute for coal in UNC's CFB boilers. Torrefied wood was particularly interesting to the University, as its energy density is comparable with coal. This is due to the torrefaction process, which removes moisture from the wood and alters its hydrophilic properties.[15]. Torrefaction is a relatively new technology and is not been commercially viable in the U.S. at a commercial scale. The University has been unable to find reliable suppliers since 2009 because large quantities of the product must be available to perform tests

[10] U.S. Energy Information Administration. (2013). *Natural Gas Prices*. Retrieved from http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_SNC_a.htm
[11] Cooper Fielding , D. (2011). *Perceptions of Biomass Harvesting Guidelines in North Carolina: A Qualitative Analysis of Forest Managers, Loggers and Landowners* . Retrieved from http://repository.lib.ncsu.edu/ir/bitstream/1840.16/7139/1/etd.pdf
[12] Energy and Environmental Analysis, Inc. (2007). *Biomass Combined Heat and Power Catalog of Technologies.* U.S. Environmental Protection Agency, v.1.1.
[13] Speight, J. (2008). Fuels from Biomass. *Synthetic Fuels Handbook: Properties, Process and Performance* (p. 221). New York: McGraw-Hill Education.
[14] Mann, M. K., & Spath, P. L. (2003). The Environmental Benefits of Cofiring Biomass and Coal. *National Renewable Energy Laboratory*, p.8.
[15] Koppejan, Sokhansanj, Melin, & Madrali. (2012). Status overview of torrefaction technologies. *IEA Bioenergy Task 32 report* . Retrieved from http://www.ieabcc.nl/publications/IEA_Bioenergy_T32_Torrefaction_review.pdf

to ensure compatibility with the Cogeneration boilers[16]. The CHP was able, however, to conduct test burns co-firing coal with wood pellets, which are wood chips that underwent a densification process.

In September 2010 and March 2011, two test burns of wood pellets were successfully completed in one of the boilers at the Cameron Plant. In the initial test burn, 20 tons of dry wood pellets were used to demonstrate the ability to feed dried wood pellets through the existing coal handling and fuel-feeding systems into the boiler[17]. In the subsequent test burn, 390 tons of wood pellets were combusted, during which operators tested varying ratios of coal to wood pellets while monitoring boiler operation and emissions[17]. It was concluded that the boiler operated well during the test and that no significant adverse effects or instabilities were observed while the tests were conducted[17]. More recently, in March 2012, approximately 20 tons of dry wood chips were burned. Dry wood chips required less processing than the wood pellets burned in 2010 and 2011, but they have a lower heating value[16] and are hydrophilic.

The Cogeneration facility could consider wood pellets as an alternative to the preferred torrefied wood until torrefaction technology becomes commercially feasible. However, the biggest issue is current market dynamics, where the majority of wood pellet supply is produced for foreign markets. Enviva LP, the largest wood pellet manufacturer in the world, produces 865,000 tons of pellets per year at its two North Carolina mills in Ahoskie and Northampton mills. The pellets Enviva produces are not being used domestically; instead they are shipped from Chesapeake, VA to the European Union. The company is planning to build another pellet-exporting facility in Wilmington, NC for the shipment of an additional one million tons of pellets a year by 2015[18]. As it apparently is economically advantageous for Enviva to ship pellets abroad, UNC would have to offer a competitive price should it decide to use pellets to offset some of its use of coal.,

[16] Pers.comm. with UNC Energy Services director Philip Barner
[17] Sega Inc. (Sega), University of North Carolina, Affiliated Engineers Inc., and Foster Wheeler. (2011). Sustained Biomass Co-Firing Test - Final Report, pp. 3.2–3.5.
[18] Campbell, N., & Stasio, F. (2013). *State of Things: Wood Pellets Industry Booming In Eastern Carolina*. Retrieved from http://wunc.org/post/wood-pellets-industry-booming-eastern-carolina

Another concern with wood pellets, specifically with wood pellets produced by Enviva, is their potentially negative environmental impact on forest ecosystems. A recent report by The Natural Resources Defense Council (NRDC) and The Dogwood Alliance used Geographical Information Systems (GIS) data to demonstrate that Enviva's Ahoskie mill plant is sourcing wood from the bottomland hardwood wetland forest, containing some of the most valuable ecosystem remaining on the NC coastal plain. The report adds that Enviva's pellet mill, which uses wetland tree species, practices clear-cutting in these wetland forests. These forests are critical not only for wildlife habitat, but also for natural water filtration, estuaries and flood control.[19]

Ultimately, torrefied wood is locally unavailable and wood pellets, though available, have both supply-side and environmental concerns. Therefore, this paper attempts to identify fuel sources for the Cogeneration Facility that are commercially and financially and sustainably feasible to aid in meeting UNC's climate commitment of being coal-free by 2020 and carbon neutral by 2050. This study therefore considers various waste wood streams, including, logging residue, construction and demolition waste (C&D), yard waste (YW), land clearing and inert debris (LCID), mill residue, furniture manufacturing residue, and other wood waste. Subsequent sections explain the methods to quantify and estimate the delivered cost of these fuel classes.

[19] Natural Resources Defense Council, & Dogwood Alliance. (2013). Enviva's Wood Pellet Mill in Ahoskie, North Carolina Threatens Endangered Ecosystems and Wildlife. Retrieved from http://www.nrdc.org/energy/forestnotfuel/files/enviva-wood-pellets-FS.pdf

3. Methodology

Wood biomass was considered from the perspective of three categories of upstream (logging residue) and downstream (wood manufacturing and urban wood waste) wood waste. Within these categories several wood biomass classes were considered (Figure 2). The methodology to obtain each of the classes is explained in subsequent sections.

Category	Class
Logging Residue	
Wood Manufacturing	Furniture Manufacturing
	Mill Residue
	Other Wood Waste
Urban Wood Waste	Construction and Demolition (C&D) Waste
	Land Clearing and Inert Debris (LCID)
	Yard Waste (YW)

Figure 2. Wood biomass classes and categories.

3.1 Locating and Quantifying Fuel Supply

3.1.1 Wood Manufacturing

Wood Manufacturing residue was identified by Standard Industry Classification codes (SIC) using the ReferenceUSA database. Seven relevant SIC codes, identified from a literature search[20,21,22], were entered into ReferenceUSA. For each SIC code specified, the database provided addresses, geographic coordinates, total sales, and total employees of wood manufacturing companies in North Carolina. The result was exported to ArcMap and geocoded by supply locations. A 50-mile radius zone was then constructed around the UNC Cogeneration facility to restrict the analysis to local sites.

The ReferenceUSA database does not include production information at individual locations which could be used to estimate wood residue quantities; it specifies the number of employees at each site, which could be used as a proxy for wood waste. Previous studies on wood waste generation

[20] Crowley, R. M. (2010). *A Biomass Fuel Assessment for Duke University's Chilled Water Plant #2*. Retrieved from http://dukespace.lib.duke.edu/dspace/bitstream/handle/10161/2200/Crowley_Rich_MP.pdf?sequence=1
[21] Bogart, F. (2004). *Evaluations of Industrial Wood Waste in Tennessee*. Retrieved from http://www.cisdb.tennessee.edu/library/pdf/Final_Report_Non_Eng_Wood_Waste_Only.doc.
[22] Buggeln, R., & Young, T. (2001). *Wood Waste Generation by Secondary Wood Products Manufacturers*.

derived comparative factors that could be used to calculate wood waste produced based on number of employees[21,22](Figure 3); these factors were used in this study to obtain monthly estimate of wood waste generated in each site[23].

Comparative Factors (Ton/Year) per Employee (Bogart[210])	Comparative Factors (Ton/Year) per Employee (Buggeln & Young[21])	SIC Description	Assigned biomass class
101		2421: Sawmills and planning mills	Other Wood Waste
	45.8	2426: Furniture Frames; include dimension hardwood, hardwood flooring and furniture components	Furniture Manufacturing
	54.9	2431: Millwork	Mill Residue
	22.3	2434: Cabinets Manufacturers	Furniture Manufacturing
75		2435: Plywood and Veneer Manufacturers	Other Wood Waste
	120.6	2448: Wood pallets and skids	Other Wood Waste
	50.7	2511: Wood household furniture	Furniture Manufacturing

Figure 3. Standard Industry Classification Codes taken from the ReferenceUSA database with assigned comparative factors based on literature review.

3.1.2 Urban Wood Waste

Urban Wood Waste locations were obtained from a solid waste permitted facility list compiled by the N.C. Department of Environment and Natural Resources, Division of Waste Management. Construction and Demolition (C&D), Land Clearing and Inert Debris (LCID) and Yard Waste (YW) facilities were chosen out of a total of 14 active waste facility types, as they were stated to receive naturally occurring vegetative material such as trees, limbs, brush, untreated wood, leaves and grass[24]. As with wood manufacturing facilities, urban wood waste sites were geocoded using their addresses and restricted to a 50-mile radius zone from the cogeneration facility at UNC. Wood waste

[23] Monthly wood waste at each wood manufacturing site was calculated as follows: (employee number*comparative factor/12 months)

[24] *Solid Waste Management General Provisions. 15A NCAC 13B .0101*. (2008). Retrieved from http://portal.ncdenr.org/web/wm/sw/rules/rulelist

quantities were determined in three ways: a) Facility Annual Reports[25] b) Personal Communication c) Annual Waste Disposal reports[26]. Facility annual reports are required by the State to be completed by all permitted waste facilities and some provide information on recycled wood quantity. For those facilities that included such information, monthly averages were calculated. Facilities that did not specify their wood recycle rate were contacted to determine the amount of boiler fuel and/or mulch the facility had produced within the last year and the unit prices for which is was sold. Finally, if neither of these methods worked, a proportion of annual waste disposal was taken as a proxy for amount of wood waste available[27].

3.1.3 Logging Residue

Unlike wood manufacturing and urban wood waste locations, individual logging residue sites are impossible to identify due to privacy laws regarding locations and ownership of forest plots[28]. Therefore, the U.S. Forest Service, an agency that administers national forests, provides data for a sample of private inventory plots (approximately 6,000 permanent plots across N.C.) through its EVALIDator database, available through the Forest Inventory and Analysis National Program (FIA). Approximately 1/7th of these plots are visited and measured each year by the field crews, so the information given in the dataset is a running average that spans across 7 years[29,30]. Due to the nature of FIA dataset, it does not provide estimates for all locations of interest, only to around 60 inventory points per county[29]. Thus it was decided to select few centralized consolidation areas from where the logging residue would be drawn. These areas were chosen by analyzing the distribution of hardwoods

[25] Facility Reports for the period of July 1, 2012-June 30 30, 2013 were retrieved from NCDENR website: https://edm.nc.gov/DENR-Portal/

[26] Solid Waste Management Annual Reports publish waste disposal information predominantly for C&D landfills. Reports for Fiscal Year 2011-2012 are available on NCDENR website: http://portal.ncdenr.org/c/document_library/get_file?p_l_id=4649434&folderId=9377383&name=DLFE-58181.pdf

[27] According to published data, the amount of clean wood in C&D landfill is around 15% of total disposal. Thus, monthly wood waste at each site was found in the following manner: ((annual waste disposed*.15)/12 months)

[28] Pers. comm. with FIA SDS/GIS Forester Samuel Lambert

[29] Pers. comm. with specialists at NC State University Extension Forestry Dr. Dennis Hazel and James Jeuck

[30] Dataset could be downloaded from http://apps.fs.fed.us/Evalidator/evalidator.jsp

(HW) and softwoods (SW) from the National Land Cover Database (NLCD)[31]. The resulting raster dataset was vectorized and the largest three polygons of HW and SW were chosen; the polygons were later converted into points by polygon centroids, each representing a potential consolidation areas (Figure 4). The geographic coordinates of these points were then entered into EVALIDator to estimate the average annual growth and average annual removal for each colsolidated timberland. The estimates were obtained for a radius of 30 mile surrounding the entered points to ensure a large enough sample size and to reduce sampling error. EVALIDator data does not directly calculate the amount of logging residue, therefore, the following formulas, derived from the literature[32], were used to calculate monthly logging residue amounts for both average annual growth and average annual removal on timberland:

a) Logging Residue for Softwoods (in Gtons/month)

Softwood volumes in 30-mile radius area [(cubic feet) / 0.85[32] (to convert to 100%)] * 0.15 (to get 15% in topwood) * 0.6 (to estimate 60% recovery efficiency of logging residue[34]) *68.593 (lbs/cubic feet)[33] / 2000 (lbs/Gton) /12 (months)

b) Logging Residue for Hardwoods (in Gtons/month)

Hardwood volumes in 30-mile radius area [(cubic feet) / 0.77[32] (to convert to 100%)] * 0.15 (to get 15% in topwood) * 0.6 (to estimate 60% recovery efficiency of logging residue[34]) *74.7811 (lbs/cubic feet) / 2000 (lbs/Gton) /12 (months)

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[31] NCLD raster dataset is available from http://www.mrlc.gov/nlcd06_data.php. Hardwoods were created from NCLD 'deciduous' and 'woody wetlands' and softwoods were created from 'conifers' and 'mixed forest'.

[32] Bentley , J. W., & Johnson, T. G. (2010). *North Carolina harvest and utilization study, 2007*. Retrieved from http://treesearch.fs.fed.us/pubs/37157

[33] Conversion factors for sawtimber from cubic foot to pounds for HW and SW are state specific. The latest conversion factors were obtained from Timber Product Output (TPO) website: http://srsfia2.fs.fed.us/php/tpo_2009/tpo_rpa_int2.php

[34] Roger C. Conner and Tony G. Johnson. (2011). Estimates of Biomass in Logging Residue and Standing Residual Inventory Following Tree-Harvest Activity on Timberland Acres in the Southern Region. *U.S. Forest Service, Southern Research Station*, p.2.

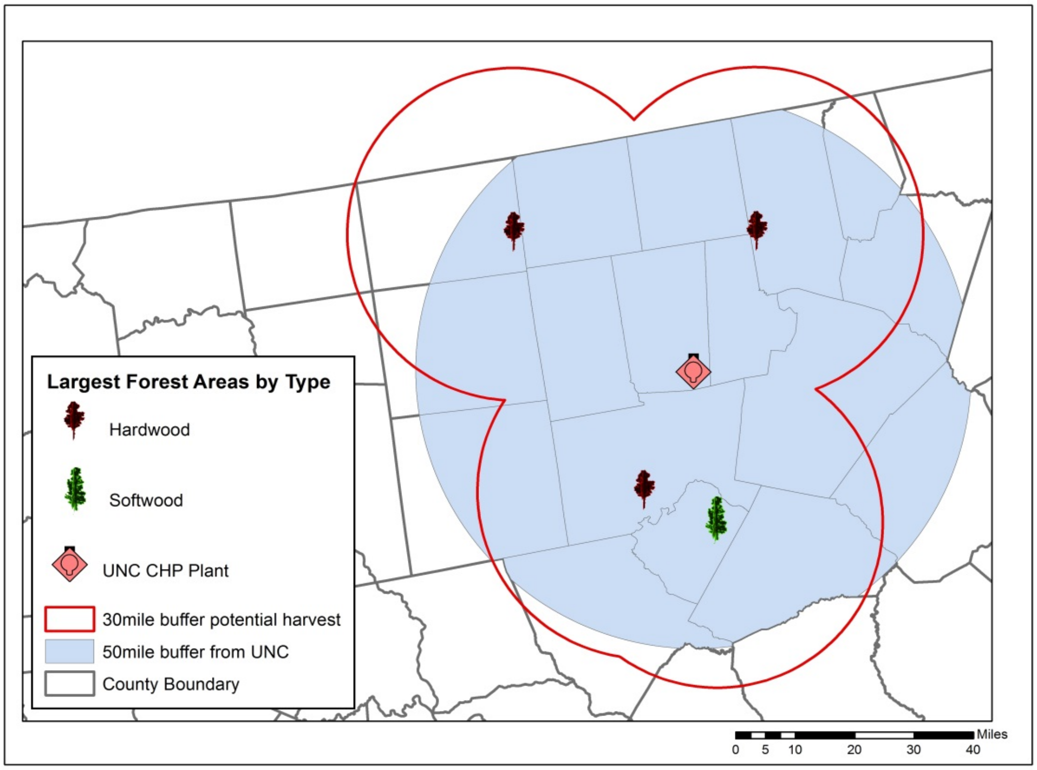

Figure 4. Potential consolidation areas based on NLCD data.

Logging residue quantities derived from annual average removal on timberlands were summed for HW and SW, and used as an estimate of potential monthly supply of logging residue for chosen locations (Appendix C). Logging residue quantities derived from annual average growth were compared to annual average removal to provide an estimate of sustainability at each location: if annual rate of growth was larger than removal, the location was considered to be sustainable.

3.2 Building Optimal Route

UNC's cogeneration facility is located on a rail line that connects to the major lines.It is this infrastructure that is used to provide coal to the facility. If the cogeneration plant were to switch from burning coal to utilizing some biomass, it would want to continue utilizing rail service. Most of the selected wood biomass supply locations were not serviced by a railway line to their site. Thus, when modeling optimal routes from supply locations to the cogeneration facility, it was determined to include two modes of transportation: trucks, to deliver woody biomass from supply locations to the nearest freight stations, and railway cars to deliver woody biomass from freight stations to the cogeneration facility. ArcGIS Network Analysis Closest Facility solver was used in two steps: first, to obtain optimal trucking routes, then to obtain the optimal railway.

Initially, all supply locations within the wood biomass categories were imported into ArcMap and geocoded using the address locator from StreetMap Premium 10.1 GIS Data[35]. Next freight station locations were manually recreated from Federal Railroad Administration (FRA) GIS web application[36]. Finally, the Esri StreetMap North America for ArcGIS 10.1 was used to provide the road network layer. ArcGIS Network Analyst Closest Facility solver was used to obtain the routes from supply locations to freight stations using the road network. The solver was programmed to avoid one-way road, limited access roads and parking lots. After the optimal trucking routes were determined, a new Closest Facility solver was started, utilizing railways as a network layer. ArcGIS Network Analyst toolbox was used to build a railroad network with distance attributes based on length accumulation[37]. This time, railway optimized routes were found from freight stations to the cogeneration facility. The method was replicated three times for each wood biomass category (Figure 5).

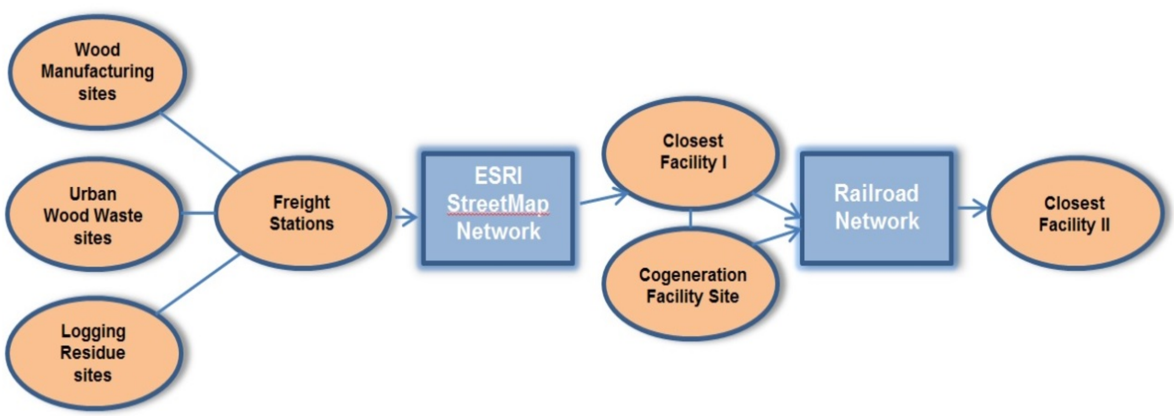

Figure 5. Flowchart of ArcGIS Network Analyst Closest facility solver used to model optimal routes

[35] The address locator is a stand-alone index of addresses within the StreetMap Premium for ArcGIS for Windows Mobile NAVTEQ North America and Europe
[36] Freight stations had to be manually redrawn from FRA GIS website since publicly accessible dataset of freight station locations was not available for a download. Graphic markers were drawn in ArcGIS within a 50-mile radius from UNC closely following freight station locations from the website.
[37] Railway polyline data was downloaded from U.S. Department of Transportation National Transportation Atlas Database 2013: http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_atlas_database/2013/polyline.html

3.3 Estimating Cost of Delivered Fuel

Cost of delivered fuel was assumed to be a combination of transportation cost and fuel cost[12,20,38]. Unit transportation cost for each supply location was based on optimal route analysis from ArcGIS coupled with hauling cost per ton-mile specific to a mode of transport. Hauling cost estimates were taken to be the average revenue per ton-mile, available from the National Transportation Statistics by the U.S. Department of Transportation[39] and Class I Railroad Statistics by the Association of American Railroads[40]. Per unit fuel cost was modeled as a sum of components in Figure 6. Per unit transportation and fuel costs were added to obtain total cost of delivered fuel for each supply site. The costs generalized to the seven biomass classes are provided in Appendix A.

Transportation cost ($/ton-mile)	Fuel cost ($/ton)
Truck freight	Collection/Harvest (Labor)
Railroad freight	Fuel Premium (Landowner)
Additional transit cost ($/mile)	Fuel Processing (Machinery)
	Fuel Purchase

Figure 6. Components of per unit total delivered fuel cost derived from literature search[10,19,37]

3.4 Optimizing Fuel Supply

A linear programming approach[20,41,42] was used to model the optimal sources for the cogeneration facility considering cost and distance constraints. The model was solved using

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[38] Zhang, F., Johnson, D. M., Johnson , M. A., & Sutherland , J. W. (2011). Development of a Biomass Supply Chain for Biofuel Production, p. 4.
[39] Bureau of Transportation Statistics. (2007). *National Transportation Statistics*. Retrieved from http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_03_21.html
[40] Association of American Railroads. (2013). *Class I Railroad Statistics*. Retrieved from https://www.aar.org/StatisticsAndPublications/Documents/AAR-Stats-2013-07-09.pdf
[41] Nienow, S., McNamara, K. T., & Gillespie, A. R. (2000). Assessing plantation biomass for co-firing with coal in northern Indiana: A linear programming approach. *Biomass and Bioenergy*, *18*(2), 125–135.
[42] Nienow, S., McNamara, K. T., Gillespie, A. R., & Preckel, P. V. (1999). A Model for the Economic Evaluation of Plantation Biomass Production for Co-firing with Coal in Electricity Production. *Agricultural and Resource Economics Review*,*28*(1), 106–118.

MATLAB Optimization Software[43]. The objective of the model was to identify sources of wood biomass at minimum cost subject to Btu constraints.

The minimized cost is the monthly total cost of delivering the wood biomass fuel to cogeneration facility explained in section 3.3. The model outcome, optimal fuel sources, serves as a guide for purchasing fuels under varying monthly demand requirements.

The objective function of the model is to minimize the total cost of delivered fuel:

$$\text{Min} \sum_i c_i x_i$$

Subject to:

The first constraint requires the sum of all fuel locations to generate a specified Btu level.

$$\sum_i H_i E_i x_i \geq D_j E, \qquad \forall i, j$$

The next constraint requires that the amount of fuel purchased is less than the amount supplied at each site.

$$x_i \leq S_i, \qquad \forall i$$

The final restriction specifies that the amount of fuel purchased is limited to non-negative numbers.

$$x_i \geq 0, \qquad \forall i$$

where

i Supply sources 1…157

j Months 1…12

c_i Unit cost of biomass at each location i (\$/ton); includes transportation cost and fuel cost listed in in section 3.3

x_i Amount of biomass fuel to be purchased each month (ton/month)

[43] MathWorks Documentation Center. (n.d.). *Minimization: Linear Programming*. Retrieved from http://www.mathworks.com/help/optim/linear-programming-and-binary-integer-programming.html

H_i Heat content of fuel at each location i (Btu/ton)

E_i Boiler efficiency adjusted to account for moisture level of each biomass class

D_j Monthly heat demand derived from the Tons of coal burned each month in the fiscal year 2012 (Btu)[44]

S_i Supply of biomass fuel available each month at location i

[44] The chart of fuel burned in the fiscal year 2012 was provided by the Cogeneration Facility and is based on the monthly demand for coal (tons) by the Facility (Appendix E).

4. Results

The analysis demonstrates that with the 50-mile radius zone there are diverse sources with sufficient supply of wood biomass to satisfy monthly demand of the Cogeneration Facility (Appendix B). The network distance varies both among the biomass categories and within biomass classes, ranging from 1 mile to as high as 125 miles. The distributions overall were close to normal, which could be inferred by comparing their mean and median (Figure 7). The distributions of supply, except for the logging residue, were, on the other hand, highly skewed to the right. All categories within the wood manufacturing class, less so in urban wood waste class, had their mean significantly higher than the median (Figure 7, 8). This means that both of the biomass categories generally have smaller sources and thus, in case the Cogeneration Facility decides to buy wood biomass from those sources, it would have to draw from multiple locations.

	Wood Manufacturing 113 locations		**Urban Wood Waste 41 locations**		**Logging Residue 3 locations**	
	Supply (Ton/Month)	Network Distance (mile)	Supply (Ton/Month)	Network Distance (mile)	Supply (Ton/Month)	Network Distance (mile)
Minimum	4	1	1	6	12,000	70
Maximum	3,000	112	2,600	125	21,000	110
Mean	200	60	372	58	17,000	90
Median	46	60	180	56	19,000	93
Total	22,500	7,000	15,000	2,400	52,000	270

Figure 7. Summary statistics of supply and network distance by biomass category

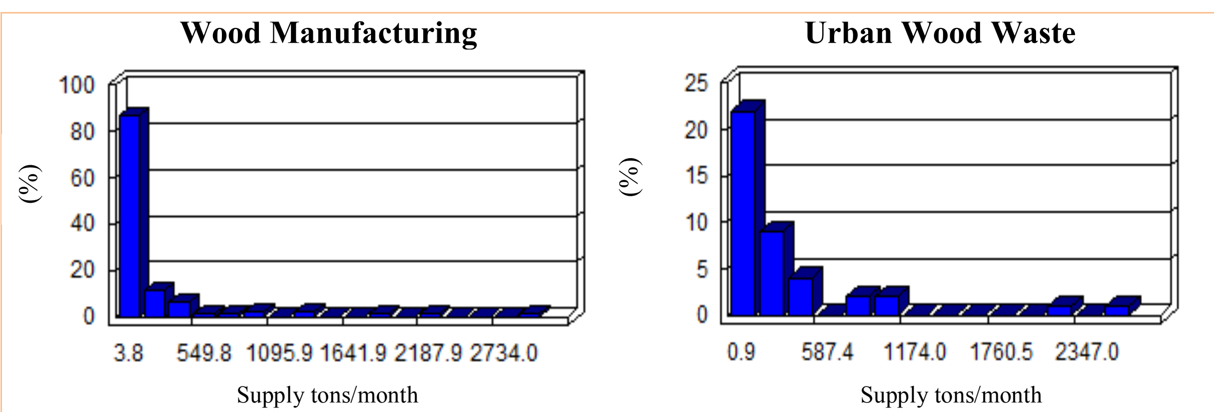

Figure 8. Fuel supply distributions

The logging residue category has the largest total monthly supply as well as one of the most concentrated supply. The value for the network distance was expected, as the result is not for individual plot locations, but rather from the centers of 30-mile buffers. Mills have the second largest amount of potential supply with 57 potential sites and a total of 12,000 tons per month of wood biomass. However, mill residue sites were spread out the most within the specified 50-mile radius and thus have the largest total network distance. It is important to note that none of the sources, with the exception of logging residue, is able to satisfy the CHP's monthly demand individually (Figure 9). This implies that unless the Cogeneration Facility chooses to buy logging residue, it would have to buy wood biomass not only from multiple sites within the same biomass class, but also to mix different biomass classes.

Fuel Type	# Sources	Total Supply (Tons/Month)	Total Network Distance (Mile)	Average Total Demand (Tons/Month) (if only 1 fuel type is chosen)
Log. Residue	3	52,000	270	19,200
C&D	17	7,000	1,010	14,800
YW	6	4,600	260	16,900
LCID	18	3,600	1,090	18,100
Furniture	34	5,700	2,300	14,800
Mill Residue	57	12,000	3,140	15,500
Other Wood	22	4,800	1,360	14,800

Figure 9. Summary statistics of supply and network distance by biomass class

Because Figures 7-9 imply that logging residue is the preferable fuel to purchase due to its large quantity and more central supply, the next step is to consider logging residue's sustainability. Sustainability is a broad term with a variety of explanations; therefore we selected two aspects of logging practices as indicators of sustainability: annual growth of timber and annual removals of timber (Appendix C). If annual growth exceeds annual removals, the timber, and hence logging residue, is growing sustainably in the region. Figure 10 shows that the growth is greater than the removals at two of the three chosen locations for both HW and SW (Locations 1 and 2). Location 3 is considered sustainable for HW, but not for SW; the growth (tons) to removal (tons) ratio there is 0.67[45].

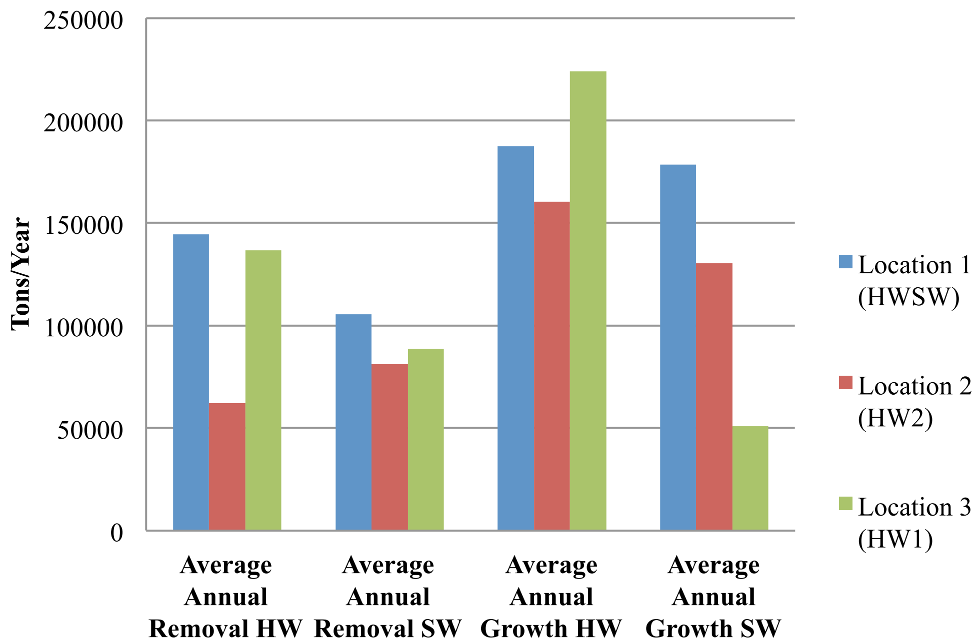

Figure 10. Comparison of hardwoods and softwoods annual growth and annual removal by location

Analysis of delivered fuel cost explained in section 3.3 and summarized in Appendix A indicates that all but two wood biomass classes are competitive with the natural gas (NG) on a MMBtu basis (Figure 11). The fuel costs for coal, NG, #2 Oil and Dried Wood Pellets (DWP) are based on the fuel comparison chart in Appendix D.

[45] Pers. Comm. with NC State University Extension Forestry specialist James Jeuck: "Any ratio >1.0 means that growth exceeds removals (it is preferable to find it 1.25 or greater), a ratio <1.0 means removals are outstripping growth. This, of course, happens periodically locally but regionally it should not be lower than, say 0.9"

Supply Source	Average Delivered Cost ($/MMBtu)
Logging Residue	5.53
C&D	2.12
YW	4.62
LCID	5.45
Furniture	2.23
Mill Residue	2.67
Other Wood Waste	2.38
Coal	5.6
Natural Gas	4.7
#2 Oil	22.5
DWP	11.2

Figure 11. Delivered biomass fuel prices per MMBtu based on the created network of sources

The fact that logging residue had the highest average delivered cost of wood biomass sources had an impact on the optimization model results: this fuel class was chosen for purchase zero times throughout the year (Figure 12). Yard Waste and Land Clearing Debris also were not optimal for purchase. The model's "all-season favorite" fuel, C&D material, was chosen across all months. Another fuel class, furniture manufacturing, was among the top choice as well; 91% of its supply was chosen as a full-time option for the year. Less than half of locations of the mill residue and other wood wastes were chosen for year-round purchase. The majority of those sites were identified to be optimal for purchase only from November to February. Therefore, these fuel classes were classified as winter fuel options.

Fuel Type	Locations Chosen (%)	Conclusion
C&D	100	**all season fuel**
YW	0	**not optimal**
LCID	0	**not optimal**
Furniture	91	**all season fuel**
Mill Residue	47	**winter fuel**
Other Wood	41	**winter fuel**
Logging Residue	0	**not optimal**

Figure 12. Optimization model results.

5. Discussion

This analysis is the first systematic attempt to locate and quantify wood biomass alternatives for the cogeneration facility at UNC Chapel Hill. It was found that a diverse source of biomass exists that could satisfy monthly energy requirements of the cogeneration facility (Appendix A,B, Figure 9). ArcGIS Network Analysis tools were used to model the transportation routes and provide distance estimates. These estimates calculated were accurate for all biomass classes, except for the logging residue. Inaccuracies and uncertainties in logging residue distances were not caused by the model approach, but by the origin of the dataset that was used to provide the logging residue quantities. As the available dataset gave meaningful estimates only for larger areas, it was impossible to identify the point sources. This inaccuracy further impacted the delivered cost calculation and the optimization results. This is one of the reasons why the logging residue with its relatively uniform supply and shortest distance was not chosen in any of the months as the optimal fuel type. Because logging residue locations were modeled as consolidation areas of 30 miles, we assumed that roughly 20 miles of that area would be driven by trucks to deliver logging residue to a freight station for further transportation via railway. Due to this, in the distance calculation, logging residue had cost due to the higher price of truck freight, which increased the overall per ton cost of delivered fuel. Higher truck freight weights are not the sole reason for not choosing the logging residue – the fuel also had higher fuel cost from the additional costs of collection & harvest and landowner premium expenses. Finally, logging residue was shown as not optimal due to its high moisture content and low heating value, which didn't satisfy one of the optimization constraints stated in the model. Hence, although inaccurate estimates of distances for logging residue could have contributed to the optimization results, this was outweighed by high fuel costs and high moisture content that characterized logging residue.

Construction and demolition (C&D) material along with furniture manufacturing residue were identified as the most optimal fuel sources for the cogeneration facility to use throughout the year.

The advantages of using these biomass fuel classes are their low cost and lower moisture content. The price for the C&D is lower than other sources, and as identified through contacting C&D landfills, is sometimes zero. C&D landfills are willing to provide the fuel for free because untreated lumber can pose a significant fire risk at the landfill [46]. Unlike logging residue, yard waste and land clearing and inert debris, C&D and furniture manufacturing residue fuels have a lower moisture content, generally in the range of 12% to 15% contrasted with 30% to 50% moisture.[47]

The main issues with using C&D material are human perception and regulatory compliance. Many reports[48,49,50,51] indicate that public perception on biomass combustion in general is negative. One survey in the city of Raleigh[48] found that public has a greater preference for composting the urban wood waste rather than burning it for electricity. More research needs to be done to uncover the perceptions of UNC students, faculty and staff and Chapel Hill residents on firing or cofiring C&D material at the Cameron Power Plant.

C&D material is classified as "solid waste" by Non-Hazardous Secondary Materials That Are Solid Wastes Rule and as such is subject to the Commercial and Industrial Solid Waste Incineration Units (CISWI) standard under Section 129 of the Clean Air Act (CAA)[52]. UNC's Cameron Plant is currently classified as a Major Source Boiler that is regulated under section 112 of CAA[53]. If the Cogeneration Facility switched from coal to C&D burning, it would face more stringent regulations: "the limits imposed on burning the same material are far less onerous" under Major Source Boiler

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[46] TriData Corporation. (2002). Landfill Fires: their magnitude, characteristics, and mitigation, 7.
[47] Energy and Environmental Analysis Inc., Biomass Combined Heat and Power Catalog of Technologies, in Combined Heat and Power Partnership. 2007, U.S. Environmental Protection Agency: Washington, DC.,113.
[48] NESCAUM. (2006). Emissions from Burning Wood Fuels Derived from Construction and Demolition Debris, 2.
[49] Megan E. Lawler. (n.d.). Assessing Potential of Municipal Biomass Residue for Renewable Energy, (2001), 3. Retrieved from http://repository.lib.ncsu.edu/ir/bitstream/1840.16/7125/1/etd.pdf
[50] Biomass Themal Energy Council. (2011). *Biomass Thermal Public Perception Identifying Sentiment, Overcoming Challenges*. Retrieved from http://www.biomassthermal.org/pdf/WERC_Webinar_8_final.pdf
[51] Combs, S. (n.d.). *Municipal Waste Combustion*. Retrieved from http://www.window.state.tx.us/specialrpt/energy/renewable/municipal.php
[52] Environmental Protection Agency. (1990). *The Clean Air Act: Section 129*. Retrieved from http://www.epa.gov/ttnatw01/129/sec129.pdf
[53] Environmental Protection Agency. (2011). *Emissions Standards for Boilers and Process Heaters and Commercial / Industrial Solid Waste Incinerators*. Retrieved from http://www.epa.gov/airquality/combustion/index.html

regulations than under CISWI rules[54]. Qualifying cogeneration facilities that burn homogeneous waste for the production of electricity or those that burn homogeneous waste for the production of electricity and steam or forms of useful energy which are used for industrial, commercial, heating or cooling purposes are exempted from the CISWI rule,[55] but this must be shown through a case-by-case petition to the US EPA[56]. Again, as with the case of public perception, more policy analysis needs to be done to determine the opportunity costs of CISWI regulations and if those costs are too high, to investigate the opportunity of justifying C&D material as boiler fuel.

Furniture manufacturing residue, second after C&D material as an optimal fuel type, might be in decline as the furniture-manufacturing sector of the economy has suffered from rising international competition and has been impacted by the recent economic downturn[57,58]. Those manufacturing facilities that were able to withstand the crisis already use the wood waste on-site for their own purposes. One research paper concludes that in NC large percentage of wood manufacturing industry's wood waste is already being used[59]. Thus, the estimates of wood manufacturing waste quantities calculated in the model have a chance of being overestimated and may not be as realistic.

Realistic estimates for the wood manufacturing waste biomass classes, may not just suffer from overestimation of source points, but also a more complex issue with the methodology used that could have contributed to unrealistic estimates. The ReferenceUSA database, the source used to identify source points based on company SIC code, despite being a reliable, high quality database, has a major limitation. This limitation results from the fact that the database assumes that companies correctly report their SIC codes[19]. If the company incorrectly classifies itself, there is a chance of choosing an

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[54] Bell, B. (2013). Why Aren't Construction and Demolition Wastes Considered Biomass Fuel? *Power*, *157*(3), 37–38. Retrieved from http://www.kbr.com/Newsroom/Publications/Articles/Bell_Power-Mag_March-2013.pdf

[55] Bob J.E., Mike K., Roy L., Eric R.S. (2010). *The 4 Rules: Summaries, Impacts, and Recommended Action*. Retrieved from http://www.all4inc.com/the-4-rules-summaries-impacts-and-recommended-action

[56] Holman, S. C. (2013). *CISWI NHSM Determinations*. Retrieved from http://daq.state.nc.us/permits/memos/CISWI-NHSM_Determinations.pdf

[57] Pirc, A., & Vlosky, R. (2010). A Brief Overview of the U.S. Furniture Industry. *Louisiana Forest Products Development Center*. Retrieved from http://www.lfpdc.lsu.edu/publications/working_papers/wp89.pdf

[58] Grushecky, S., Buehlmann, U., Schuler, A., & Luppold, W. (2006). Decline in the U.S. Furniture Industry: A Case Study of the Impacts to the Hardwood Lumber Supply Chain. *Wood and Fiber Science*, *38*(2), 365–376.

[59] Hazel , D., & Bardon, R. (2008). Evaluating wood energy users in North Carolina and the potential for using logging chips to expand wood fuel use.*Forest Producst Journal*, *58*(5), 34–39.

incorrect company and missing the right one when selecting companies based on their SIC codes. Although SIC code-based company identification method has been and relied on used historically[60], these limitation demonstrate that more accurate method need to be identified.

Another limitation come from methodology of the model rather than the inaccuracies within the ReferenceUSA database; this limitation stems from using comparative factors of wood waste per employee to calculate the monthly wood manufacturing residue supply. These comparative factors were derived from a study in Tennessee and not in NC, and although it might be the case that the wood manufacturing facilities produce comparable amounts of wood residue based on the number of employees, this is not necessarily true. Additionally, the report estimates were based on 2001, and in the last 12 years labor intensities and productivity and technology of wood manufacturing facilities may have affected factor estimates. However, we were unable to verify the accuracy of comparative factors used within the scope of this analysis.

Considering the limitations above, our main recommendation to the Cogeneration Facility would be to investigate the potential of C&D fuel and stakeholder perceptions (i.e. UNC students, faculty and staff and Chapel Hill residents) as well as to examine the policy implications of burning C&D material. Analysis of stakeholder perceptions could be conducted by the student body in the form of surveys/interviews as part of the Environmental Capstone course (ENST 698).

It is important to note that this work does not propose C&D material specifically and wood residue products generally to be a long-term solution to UNC's coal-free goals, but it lays a foundation upon which the facility can consider various options of wood residue sources that could help UNC reach its goal of becoming coal free by 2020.

Future work considered is threefold as it involves refining: a) Optimization model - adding air quality constraints and making the objective function more complex; b) Delivery cost - taking into

[60] Alderman, D. (1998). Assessing the Availability of Wood Residues And Residue Markets in Virginia (pp. 20–21). Retrieved from http://scholar.lib.vt.edu/theses/available/etd-51898-10750/unrestricted/Deledt.PDF

account biomass drying cost and storing logistics; c) Supply: taking into account competition and internal demand for the biomass fuel classes.

6. Conclusion

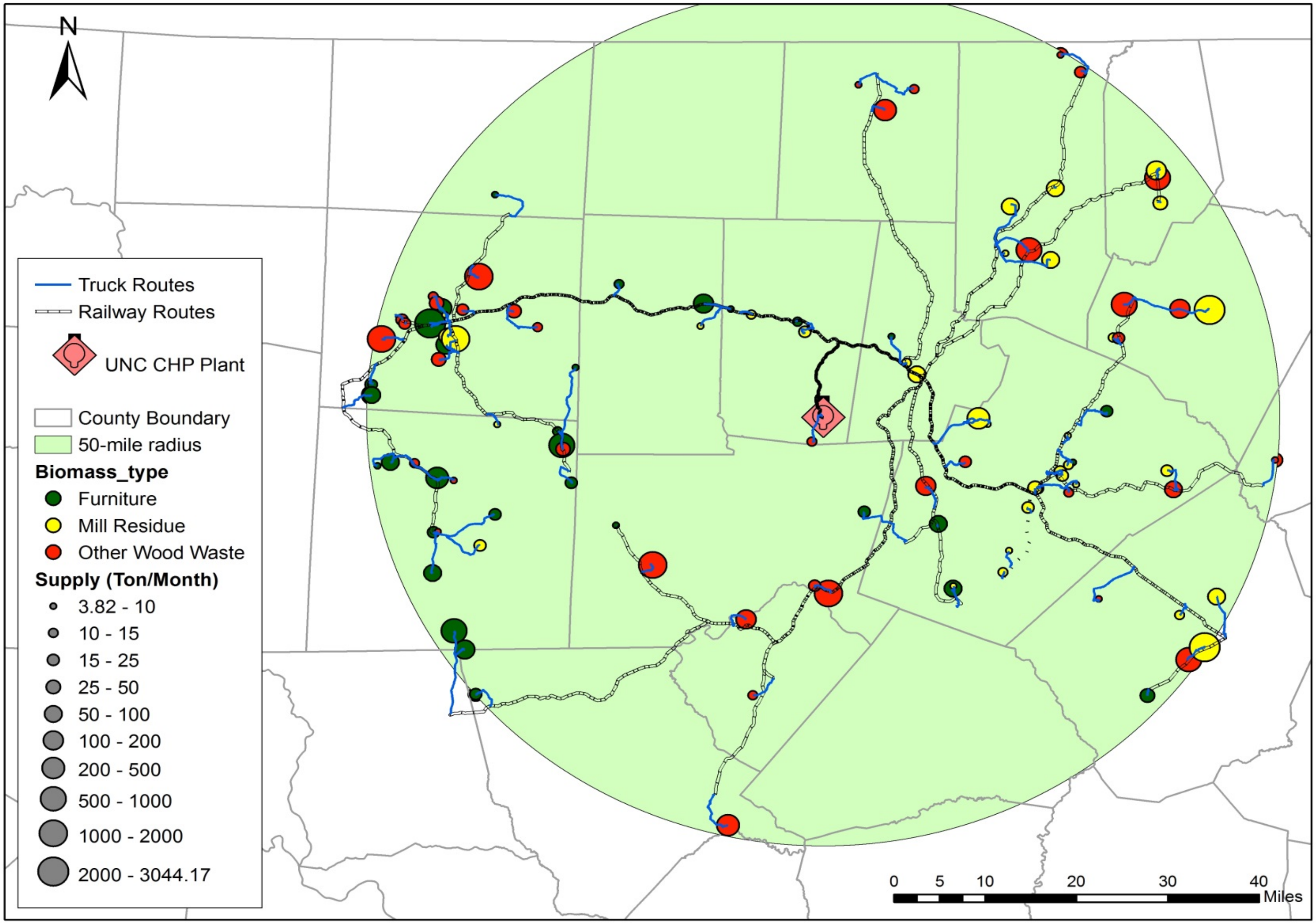
This thesis provides an initial assessment of biomass residue availability for the Cameron Avenue Cogeneration Facility by identifying the residue locations, monthly supply estimates and utilizing these data to calculate the delivered cost of fuel for each location as well as to identify optimal biomass classes. One hundred fifty seven locations of seven biomass classes within fifty-mile radius were located. Of these 7 classes, C&D material and Furniture Manufacturing residue were identified as the sources with the greatest potential.. Between these two classes C&D material requires further consideration, as unlike Furniture Manufacturing residue that is already being used by the furniture-manufacturing facilities on-site, there is a potential for an additional supply for C&D material. The main recommendations to the Cogeneration Facility are to investigate stakeholder perceptions on burning C&D material and to assess the regulatory implications related to burning solid waste. Through petitions the Cogeneration Facility could demonstrate that the C&D material under consideration is not a waste product and thus could be exempt from CISWI rules. This proposition, though, needs further investigation and analysis.

7. Appendices

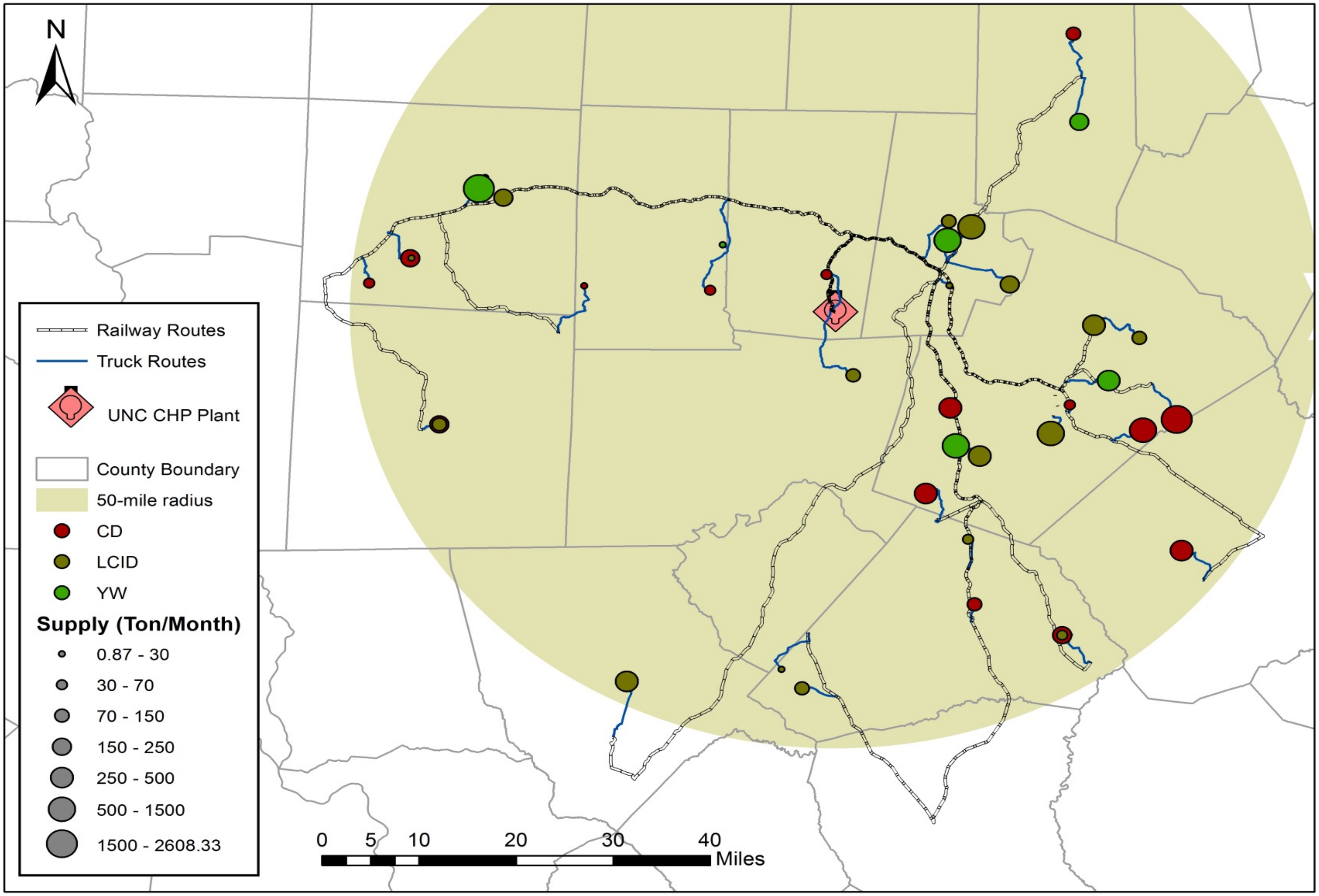
7.1 Appendix A – Parameters used in the model by biomass class

	Logging Residue	C&D	Mill Residue	Furniture Manuf. Residue	YW	Other Wood Waste	LCID
Plant Parameters							
Heating Value of Coal (Btu/pound)	13000	13000	13000	13000	13000	13000	13000
Heating Value of Coal (Btu/ton)	26E6	26E6	26E6	26E6	26E6	26E6	26E6
Historical average monthly fuel (coal) burn (Ton/Month)	9472.4	9472.4	9472.4	9472.4	9472.4	9472.4	9472.4
Boiler Efficiency (zero moisture)	0.83	0.83	0.83	0.83	0.83	0.83	0.83
Fuel Parameters (dry)							
Heating value wood biomass (Btu/pound)	8560	8600	8570	8570	8500	8560	8500
Heating value wood biomass (Btu/ton)	17.12E6	17.2E6	17.14E6	17.14E6	17E6	17.12E6	17E6
Moisture (%)	37.5	15	25	15	30	15	35
Btu/pound moisture adjusted	5350	7310	6427.5	7284.5	5950	7276	5525
Btu/ton moisture adjusted	10.7E6	14.62E6	12.86E6	14.57E6	11.9E6	14.55E6	11.05E6
Boiler Efficiency after adjusting for moisture	0.75	0.97	0.93	0.97	0.86	0.97	0.8
Remaining Boiler efficiency	0.6225	0.8051	0.7719	0.8051	0.7138	0.8051	0.664
Post combustion heating value (Btu/ton)	6.66E6	11.77E6	9.92E6	11.73E6	8.49E6	11.72E6	7.34E6
Demand requirements							
Wood Biomass (Tons/Month)	30689.4	17366.6	20600.5	17427.4	24065.1	17447.7	27860
Transportation Costs							
Rail cost ($/ton-mile)	0.03961	0.03961	0.03961	0.03961	0.03961	0.03961	0.03961
Truck cost ($/ton-mile)	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654
Additional Transit Cost ($/mile)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Fuel Costs							
Collection & Harvesting Cost ($/Ton)	5	0	0	0	0	0	0
Premium to secure resource ($/Ton)	5	0	5	0	0	0	0
Fuel Processing Cost ($/Ton)	5	12	4	5	12	5	12
Purchase Cost determined through phone calls (low) ($/Ton)	15	2.5			2.5		2.5
Purchase Cost determined through phone calls (high) ($/Ton)		18			41.6		41.6
Fuel Purchase Cost ($/Ton)	15	10	15	18	25	20	25
Total Fuel Cost Assumed in the Model ($/Ton)	**30**	**22**	**24**	**23**	**37**	**25**	**37**
Pre combustion Fuel ($/MMBtu)	2.80	1.50	1.87	1.58	3.11	1.72	3.35
Post combustion Fuel ($/MMBtu)	4.50	1.87	2.42	1.96	4.36	2.13	5.04
Average Transportation Cost ($/Ton)	6.85	2.96	2.54	3.17	2.27	2.87	3.00
Average Transportation Cost ($/MMBtu)	**1.03**	**0.25**	**0.26**	**0.27**	**0.27**	**0.24**	**0.4**
Post Delivered Cost ($/MMBtu)	**5.53**	**2.12**	**2.67**	**2.23**	**4.62**	**2.38**	**5.45**

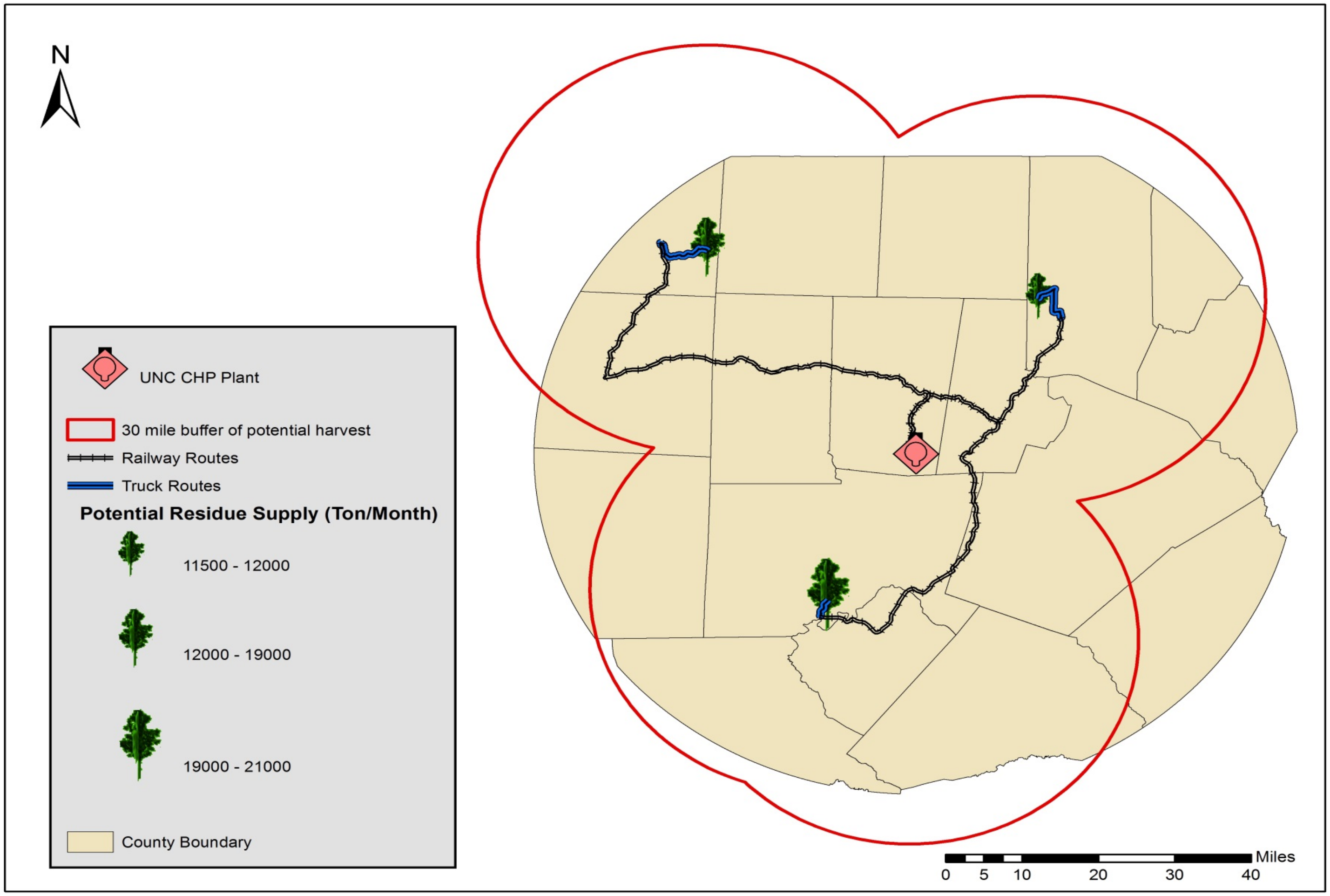
7.1 Appendix B - Wood Manufacturing Sources – Rail and Truck Optimized Routes to UNC



Urban Wood Waste Sources – Truck and Rail Optimized Routes to UNC



Potential Logging Residue Sites and Routes to UNC



7.1 Appendix C

Average annual net growth of live trees on timberland at Location 1 (in cubic feet)[1]

Estimate:

	Species group - Major			
	Total	Softwoods	Hardwoods	not measured
Private Owner	91,166,957	49,166,835	42,890,771	-890,649

Sampling error percent:

	Species group - Major			
	Total	Softwoods	Hardwoods	not measured
Private Owner	17.64	18.46	26	-51.47

Average annual removals of live trees on timberland at Location 1 (in cubic feet)[35]

Estimate:

	Species group - Major			
	Total	Softwoods	Hardwoods	not measured
Private Owner	62,117,217	29,026,285	33,090,933	-

Sampling error percent:

	Species group - Major			
	Total	Softwoods	Hardwoods	not measured
Private Owner	27.73	34.5	35.89	-

[61] Miles, P.D. Sun Nov 10 22:19:24 CST 2013. Forest Inventory EVALIDator web-application version 1.5.1.05. St. Paul, MN: U.S. Department of Agriculture, Forest Service, Northern Research Station. [Available only on internet: http://apps.fs.fed.us/Evalidator/tmattribute.jsp]

Average annual net growth of live trees on timberland at Location 2 (in cubic feet)[35]

Estimate:

	Species group - Major			
	Total	Softwoods	Hardwoods	not measured
Private Owner	70,359,223	35,903,997	36,726,715	-2,271,488

Sampling error percent:

	Species group - Major			
	Total	Softwoods	Hardwoods	not measured
Private Owner	24.1	20.16	40.53	-63.9

Average annual removals of live trees on timberland at Location 2 (in cubic feet)[35]

Estimate:

	Species group - Major			
	Total	Softwoods	Hardwoods	not measured
Private Owner	36,660,181	22,405,193	14,254,988	-

Sampling error percent:

	Species group - Major			
	Total	Softwoods	Hardwoods	not measured
Private Owner	31.96	36.52	38.76	-

Average annual net growth of live trees on timberland at Location 3 (in cubic feet)[35]

Estimate:

	Species group - Major			
	Total	Softwoods	Hardwoods	not measured
Private Owner	64,099,886	14,021,995	51,248,956	-1,171,064

Sampling error percent:

	Species group - Major			
	Total	Softwoods	Hardwoods	not measured
Private Owner	16.5	28.82	18.15	-47.79

Average annual removals of live trees on timberland at Location 3 (in cubic feet)[35]

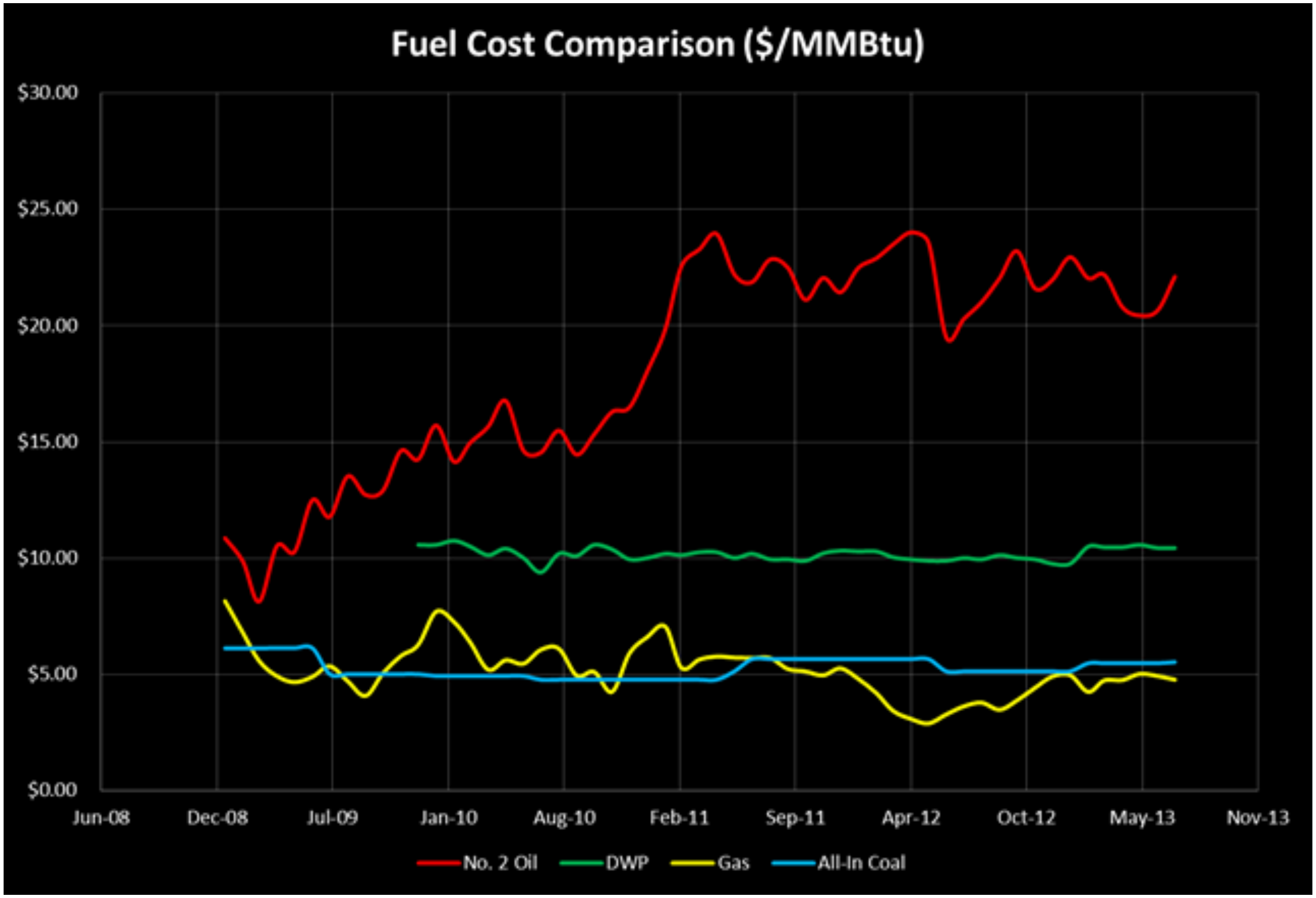
Estimate:

	Species group - Major			
	Total	Softwoods	Hardwoods	not measured
Private Owner	55,702,882	24,398,774	31,304,108	-

Sampling error percent:

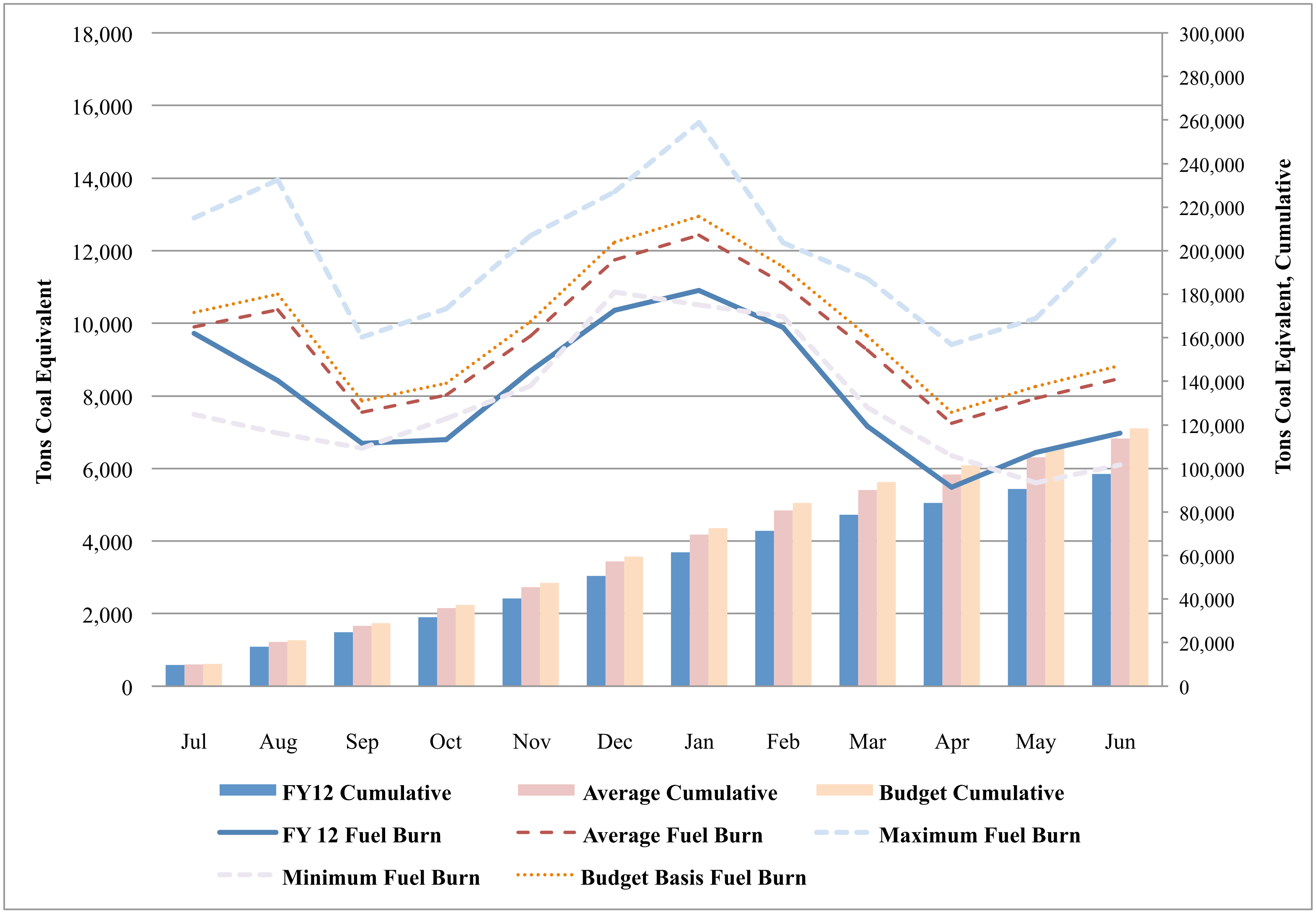
	Species group - Major			
	Total	Softwoods	Hardwoods	not measured
Private Owner	29.47	41.52	37.41	-

7.1 Appendix D – Fuel Prices normalized to $/MMBtu[1]



[62] The chart was provided by Cameron Cogeneration Facility. The coal is delivered to the Facility from mines in central Appalachia; current contracts are with mines in Eastern Kentucky, Western Virginia, and Northeastern Tennessee. The all-in coal price includes the delivered price of coal, as well as limestone and ash removal costs. The biomass prices are taken from a market report for Dried Wood Pellets (DWP) shipped from Wilmington, NC.

7.2 Appendix E – Monthly Fuel Burned during Fiscal Year 2012[2]



[63] The chart was provided by Cameron Cogeneration Facility.

7.6 Appendix F – Definitions of Biomass Classes considered

Construction and Demolition Waste – solid waste material produced in the process of construction, renovation, or demolition of structures (both buildings and roads). In addition, this includes the materials generated as a result of natural disasters. Components of C&D debris include materials such as concrete, asphalt, wood, brick, metals, wallboard, and roofing shingles[1]. When calculating the amount of wood waste at C&D landfills this paper considered clean wood available at the landfill and did not include other materials such as brick, concrete and metal. Unlike YW and LCID, this waste has less moisture and hence has lower nitrogen content[2].

Land Clearing and Inert Debris – solid waste such as concrete, brick, concrete block, uncontaminated soil, gravel and rock, untreated and unpainted wood, and yard trash[44].

Furniture Manufacturing Waste – waste resulting from manufacturing furniture frames; include dimension hardwood, hardwood flooring and furniture components, cabinets manufacturing and household furniture; it was assumed that the waste originated from facilities with SIC codes 2511, 2434 and 2426.

Logging Residue – wood material remaining on a site after merchantable timber has been harvested, such as the tops of harvested trees, branches, leaves; standing trees too small to harvest or reserved clones within the harvest area; and wood that has an underdeveloped market or is in a poor form and thus not marketable[3].

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[64] Environmental Protection Agency. (n.d.). *Construction and Demolition (C&D) Debris*. Retrieved from http://www.epa.gov/reg3wcmd/solidwastecd.html

[65] Pers. comm. with Orange County Solid Waste Management Department Education and Outreach Coordinator Muriel Williman

[66] Lance Sorensen. (2006). Minnesota Logged Area Residue Analysis. *Minnesota Department of Natural Resources* , p.3. Retrieved from http://files.dnr.state.mn.us/forestry/um/mnloggedarea_residueanalysis.pdf

Mill Residue –chips, sawdust, and bark that are generated in the process of producing primary wood products such as lumber, veneer, and pulp chips[4]; it was assumed that the residue originated from facilities with SIC code 2431.

Other Wood Waste – waste resulting from manufacturing wood pallets and skids, plywood and veneer; it was assumed that the waste originated from facilities with SIC codes 2421, 2435 and 2448.

Yard Waste - solid waste resulting from landscaping and yard maintenance such as brush, grass, tree limbs, and similar vegetative material[5].

[67] Texas A&M Forest Service. (2005). *A Case Study for a Biomass Logging Operation* . Retrieved from http://txforestservice.tamu.edu/main/popup.aspx?id=893

[68] Solid Waste Management General Provisions. 15A NCAC 13B .0101. (2008). Retrieved from http://portal.ncdenr.org/web/wm/sw/rules/rulelist

8. References

Alderman, D. (1998). Assessing the Availability of Wood Residues And Residue Markets in Virginia (pp. 20–21). Retrieved from http://scholar.lib.vt.edu/theses/available/etd-51898-10750/unrestricted/Deledt.PDF

Association of American Railroads. (2013). *Class I Railroad Statistics*. Retrieved from https://www.aar.org/StatisticsAndPublications/Documents/AAR-Stats-2013-07-09.pdf

Bell, B. (2013). Why Aren't Construction and Demolition Wastes Considered Biomass Fuel? *Power*, *157*(3), 37–38. Retrieved from http://www.kbr.com/Newsroom/Publications/Articles/Bell_Power-Mag_March-2013.pdf

Bentley , J. W., & Johnson, T. G. (2010). *North Carolina harvest and utilization study, 2007*. Retrieved from http://treesearch.fs.fed.us/pubs/37157

Biomass Themal Energy Council. (2011). *Biomass Thermal Public Perception Identifying Sentiment, Overcoming Challenges*. Retrieved from http://www.biomassthermal.org/pdf/WERC_Webinar_8_final.pdf

Bob J.E., Mike K., Roy L., Eric R.S. (2010). *The 4 Rules: Summaries, Impacts, and Recommended Action*. Retrieved from http://www.all4inc.com/the-4-rules-summaries-impacts-and-recommended-action

Bogart, F. (2004). *Evaluations of Industrial Wood Waste in Tennessee*. Retrieved from http://www.cisdb.tennessee.edu/library/pdf/Final_Report_Non_Eng_Wood_Waste_Only.doc.

Buggeln, R., & Young, T. (2001). *Wood Waste Generation by Secondary Wood Products Manufacturers*.

Bureau of Transportation Statistics. (2007). *National Transportation Statistics*. Retrieved from http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_03_21.html

Campbell, N., & Stasio, F. (2013). *State of Things: Wood Pellets Industry Booming In Eastern Carolina*. Retrieved from http://wunc.org/post/wood-pellets-industry-booming-eastern-carolina

Climate Action Program. (2009). *2009 Climate Action Plan*. Retrieved from http://www.climate.unc.edu/ClimateActionProgram/ClimateActionPlan

Combs, S. (n.d.). *Municipal Waste Combustion*. Retrieved from http://www.window.state.tx.us/specialrpt/energy/renewable/municipal.php

Cooper Fielding , D. (2011). *Perceptions of Biomass Harvesting Guidelines in North Carolina: A Qualitative Analysis of Forest Managers, Loggers and Landowners* . Retrieved from http://repository.lib.ncsu.edu/ir/bitstream/1840.16/7139/1/etd.pdf

Crowley, R. M. (2010). *A Biomass Fuel Assessment for Duke University's Chilled Water Plant #2*. Retrieved from http://dukespace.lib.duke.edu/dspace/bitstream/handle/10161/2200/Crowley_Rich_MP.pdf?sequence=1

Energy and Environmental Analysis Inc., Biomass Combined Heat and Power Catalog of Technologies, in Combined Heat and Power Partnership. 2007, U.S. Environmental Protection Agency: Washington, DC.,113.

Energy and Environmental Analysis, Inc. (2007). *Biomass Combined Heat and Power Catalog of Technologies.* U.S. Environmental Protection Agency, v.1.1.

Environmental Protection Agency. (1990). *The Clean Air Act: Section 129*. Retrieved from http://www.epa.gov/ttnatw01/129/sec129.pdf

Environmental Protection Agency. (2011). *Emissions Standards for Boilers and Process Heaters and Commercial / Industrial Solid Waste Incinerators*. Retrieved from http://www.epa.gov/airquality/combustion/index.html

Environmental Protection Agency. (n.d.). *Combined Heat and Power Partnership*. Retrieved from http://www.epa.gov/chp/basic/efficiency.html

Environmental Protection Agency. (n.d.). *Construction and Demolition (C&D) Debris*. Retrieved from http://www.epa.gov/reg3wcmd/solidwastecd.html

Grushecky, S., Buehlmann, U., Schuler, A., & Luppold, W. (2006). Decline in the U.S. Furniture Industry: A Case Study of the Impacts to the Hardwood Lumber Supply Chain. *Wood and Fiber Science*, *38*(2), 365–376.

Hazel , D., & Bardon, R. (2008). Evaluating wood energy users in North Carolina and the potential for using logging chips to expand wood fuel use. *Forest Producst Journal*, *58*(5), 34–39.

Holman, S. C. (2013). *CISWI NHSM Determinations*. Retrieved from http://daq.state.nc.us/permits/memos/CISWI-NHSM_Determinations.pdf

Koppejan, Sokhansanj, Melin, & Madrali. (2012). Status overview of torrefaction technologies. *IEA Bioenergy Task 32 report* . Retrieved from http://www.ieabcc.nl/publications/IEA_Bioenergy_T32_Torrefaction_review.pdf

Lance Sorensen. (2006). Minnesota Logged Area Residue Analysis. *Minnesota Department of Natural Resources* , p.3. Retrieved from http://files.dnr.state.mn.us/forestry/um/mnloggedarea_residueanalysis.pdf

Mann, M. K., & Spath, P. L. (2003). The Environmental Benefits of Cofiring Biomass and Coal. *National Renewable Energy Laboratory*, p.8.

MathWorks Documentation Center. (n.d.). *Minimization: Linear Programming*. Retrieved from http://www.mathworks.com/help/optim/linear-programming-and-binary-integer-programming.html

Megan E. Lawler. (n.d.). Assessing Potential of Municipal Biomass Residue for Renewable Energy, (2001), 3. Retrieved from http://repository.lib.ncsu.edu/ir/bitstream/1840.16/7125/1/etd.pdf

Miles, P.D. Sun Nov 10 22:19:24 CST 2013. Forest Inventory EVALIDator web-application version 1.5.1.05. St. Paul, MN: U.S. Department of Agriculture, Forest Service, Northern Research Station. [Available only on internet: http://apps.fs.fed.us/Evalidator/tmattribute.jsp]

Natural Resources Defense Council, & Dogwood Alliance. (2013). Enviva's Wood Pellet Mill in Ahoskie, North Carolina Threatens Endangered Ecosystems and Wildlife. Retrieved from http://www.nrdc.org/energy/forestnotfuel/files/enviva-wood-pellets-FS.pdf

NESCAUM. (2006). Emissions from Burning Wood Fuels Derived from Construction and Demolition Debris, 2.

Nienow, S., McNamara, K. T., & Gillespie, A. R. (2000). Assessing plantation biomass for co-firing with coal in northern Indiana: A linear programming approach. *Biomass and Bioenergy*, *18*(2), 125–135.

Nienow, S., McNamara, K. T., Gillespie, A. R., & Preckel, P. V. (1999). A Model for the Economic Evaluation of Plantation Biomass Production for Co-firing with Coal in Electricity Production. *Agricultural and Resource Economics Review*,*28*(1), 106–118.

Orange County Board of County Commissioners. (2010).*UNC-Chapel Hill Energy Task Force: Interim Report*. Retrieved from http://www.co.orange.nc.us/occlerks/1006157d.pdf

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Pirc, A., & Vlosky, R. (2010). A Brief Overview of the U.S. Furniture Industry. *Louisiana Forest Products Development Center*. Retrieved from http://www.lfpdc.lsu.edu/publications/working_papers/wp89.pdf

Roger C. Conner and Tony G. Johnson. (2011). Estimates of Biomass in Logging Residue and Standing Residual Inventory Following Tree-Harvest Activity on Timberland Acres in the Southern Region. *U.S. Forest Service, Southern Research Station*, p.2.

Sega Inc. (Sega), University of North Carolina, Affiliated Engineers Inc., and Foster Wheeler. (2011). Sustained Biomass Co-Firing Test - Final Report, pp. 3.2–3.5.

Solid Waste Management General Provisions. 15A NCAC 13B .0101. (2008). Retrieved from http://portal.ncdenr.org/web/wm/sw/rules/rulelist

Solid Waste Management General Provisions. 15A NCAC 13B .0101. (2008). Retrieved from http://portal.ncdenr.org/web/wm/sw/rules/rulelist

Speight, J. (2008). Fuels from Biomass. *Synthetic Fuels Handbook: Properties, Process and Performance* (p. 221). New York: McGraw-Hill Education.

Texas A&M Forest Service. (2005). *A Case Study for a Biomass Logging Operation* . Retrieved from http://txforestservice.tamu.edu/main/popup.aspx?id=893

TriData Corporation. (2002). Landfill Fires: their magnitude, characteristics, and mitigation, 7.

U.S. Energy Information Administration. (2013). *Natural Gas Prices*. Retrieved from http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_SNC_a.htm

U.S. Environmental Protection Agency. (n.d.). *Sources of Greenhouse Gas Emissions*. Retrieved from http://www.epa.gov/climatechange/ghgemissions/sources/electricity.html

UNC submits Climate Action Plan as part of commitment to carbon neutrality. (2009). Retrieved from http://uncnews.unc.edu/content/view/2865/68/

University of North Carolina at Chapel Hill Climate Action Plan Update 2010. (2010). Retrieved from http://sustainability.unc.edu/Portals/Sustainability2009/2010-2011%20Climate%20Action%20Plan%20Update.pdf

Waste Reduction and Recycling. (n.d.). *UNC Climate Action Plan*. Retrieved from http://www.wastereduction.unc.edu/WhyRecycle/UNCsClimateActionPlan

Zhang, F., Johnson, D. M., Johnson , M. A., & Sutherland , J. W. (2011). Development of a Biomass Supply Chain for Biofuel Production, p. 4.