BIOREFINERY FEEDSTOCK AVAILABILITY AND PRICE VARIABILITY: CASE STUDY OF THE PEACE RIVER REGION, ALBERTA

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

The Faculty of Graduate Studies

(Chemical and Biological Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

July 2008

ABSTRACT

The purpose of this research was to quantify feedstock supply risk over the lifetime of an agricultural residue-based (straw and chaff) biorefinery and to determine the range of delivered prices. The Peace River region of Alberta was used as a case study for analysis, with a geographic information system utilized for data analysis. Inter-year availability of crop residues was highly variable over the 20 year period under study, which created significant differences in the delivered price of feedstock between minimum, average, and maximum availability scenarios. At the four primary study sites (Fahler, Grimshaw, Peace River, and Sexsmith), the range was from double the average availability for the maximum scenario to zero biomass available for the minimum scenario. Biomass availability is a function of grain yield, the biomass to grain ratio, the cropping frequency, and residue retention rate used to ensure future crop productivity. Using minimum, average, and maximum supply scenarios, delivered price was determined using the dynamic (time-dependent) Integrated Biomass Supply Analysis and Logistics (IBSAL) simulation model. Five biorefinery capacities, ranging from 50,000 to 500,000 tonnes of feedstock per year, were analyzed. Since no biomass was available to model in true minimum years, a simulated minimum of half the average availability was used. Delivered cost, including harvest and transportation, for the 50,000 t plant ranged from \$24.01 t^{-1} for the maximum availability scenario at the Sexsmith site to \$42.63 t^{-1} for the simulated minimum scenario at the Fahler site. The range for the 500,000 t plant at the Sexsmith site was \$41.78 for the maximum availability and \$70.98 for the simulated minimum availability. As no biomass is available (and hence the true cost is unknown) in some years, storage strategies must be implemented and alternate feedstock sources

identified to supply biorefineries in low-yield years. Since feedstock cost is a large component of total operating cost of a biorefinery, feedstock supply variability and delivered cost inconsistency should be primary decision criteria for any future biorefinery projects.

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ABREVIATIONS

3PL Third Party Logistics provider
AAFC Agriculture and Agri-Food Canada
AUHDSS Aberdeen University Harvesting Decision Support System
BEAM BioEnergy Assessment Model
C Carbon
CHDSS Coppice Harvesting Decision Support System
CHP Combined Heat and Power
CPM Environmental Benefits Index
CPS Canadian Prairie Spring
CSIRO Commonwealth Scientific and Industrial Research Organization
CWRS Canadian Western Red Spring
DEM Digital Elevation Matrix
DFC Distance Fixed Cost
DSS Decision Support System
DSS4Ag Decision Support System for Agriculture
DSSAT Decision Support System for Agrotechnology Transfer
DVC Distance Variable Cost
EBI Environmental Benefits Index
EPIC Erosion Productivity Impact Calculator
EUROSEM European Erosion Model
FAO Food and Agriculture Organization
G Grain
GAMS General Algebraic Modelling System
GDP Gross Domestic Product
GIS Geographic Information System
ha hectare
HI Harvest Index
IBSAL Integrated Biomass Supply Analysis and Logistics
JIT Just-In-Time logistics
km kilometre
kWh kilo Watt hour
MBtu Mega British thermal unit
MOG Material Other than Grain
MW Mega Watt
N Nitrogen
NGO Non-Government Organization
NPP Net Primary Productivity
NPV Net Present Value
odt oven-dried tonne
PERT Program Evaluation and Review Technique
PFRA Prairie Farm Rehabilitation Administration
RH Relative Humidity
RUSLE Revised Universal Soil Loss Equation
SDSS Spatial Decision Support System
SEK Swedish Kronor
SGR Straw-to-Grain Ratio
SHAM Straw HAndling Model
SLC Soil Landscapes of Canada
SOC Soil Organic Carbon
SOM Soil Organic Matter
SRWC Short-Rotation Woody Crop
t tonne (metric)
tpd tonnes per day
USLE Universal Soil Loss Equation
VMI Vendor-Managed Inventory
WEPP Water Erosion Prediction Project
WEQ Wind Erosion Equation
WGTPP Western Grains Transition Payment Program

ACKNOWLEDGEMENTS

I am indebted to Dr. Shahab Sokhansanj for his invaluable insights and support in preparing this thesis. In particular, his assistance with the IBSAL model, without which this research would not have been possible. Dr. Xiatao Bi provided guidance in structure and support throughout the MSc degree.

I am grateful to the members of the University of British Columbia Biomass and Bioenergy Research Group. Their enthusiasm and dedication to our chosen field was always encouraging. In particular, I would like to thank Dr. Jim Lim and Dr. John Grace of Chemical and Biological Engineering, Dr. Taraneh Sowlati of Wood Science, and Mr. Staffan Melin of the Wood Pellets Association of Canada.

This research would not have been possible without the financial support and collaboration of Agriculture and Agri-Food Canada; in particular, Mark Stumborg of the Semiarid Prairie Agricultural Research Centre and Lawrence Townley-Smith of the Prairie Farm Rehabilitation Administration. Trevor Kloeck of Alberta Agriculture and Rural Development also played a significant role in providing vital feedback and data on the Peace River region.

I would not likely be pursuing a career in biomass and bioenergy were it not for Dr. David Layzell, formerly of Queen's University and BIOCAP Canada. Dr. Layzell's enthusiasm and support throughout the years have had a large impact on my success. I would also like to thank the former staff of BIOCAP Canada, who continue to support my endeavours.

Primary financial support for this project was provided by the NSERC Strategic Grant "Biomass Feedstock Integration for an Emerging Bio Industry in Canada".

Finally, I would like to thank my mother, Dr. Alison Stephen, for always being there for me and providing unwavering support, both academically and otherwise.

CO-AUTHORSHIP STATEMENT

Chapters 2 and 3 of this thesis are manuscripts for submission to an academic journal. I am the lead author on both manuscripts, but received edits on both from the co-authors. A footnote at the beginning of each chapter provides the citation for the manuscripts.

I was responsible for writing the first copy of each manuscript. These were then sent to all co-authors for edits. I incorporated these edits into the final manuscripts.

The study design of using GIS combined with the IBSAL model was my original idea and was refined during discussions with the co-authors. They provided guidance and feedback. This included suggestions on residue retention, biorefinery scaling, and the Peace River region as a good case study. However, the research still followed my original study design. The GIS methodology of vector-based buffers and the comparison over an extended time frame were devised by me. I performed all the GIS data analysis and compiled them for further analysis in IBSAL.

Dr. Shahab Sokhansanj, my research supervisor, is the primary creator of the IBSAL model and he assisted in training me on using IBSAL. We worked on refining the model for this specific case study together, with Dr. Sokhansanj taking the lead on model block design and layout. I performed all the modelling work and runs once the model was in a state we were both content with. This included over 200 runs using varying pieces of equipment, crop yields, and biorefinery sizes. I sourced all the weather data for the study region from Environment Canada. Dr. Sokhansanj has spent many years compiling data on equipment costs, efficiency, and performance, which were required to perform the modelling. I was not involved in sourcing these equipment data.

1 INTRODUCTION

Bioenergy is a rapidly growing industry in developed nations as governments and the private sector seek to increase renewable and carbon neutral sources of energy, materials, and products. Lignocellulosic biomass, such as wood and agricultural residues, is the most abundant biological material on Earth and is the feedstock currently used for biomass-based heat and power production, and shortly, commercial bioethanol. In many applications, fossil fuels can be replaced or used in tandem with equivalent biomass types, such as co-firing wood pellets in coal power plants. Biomass can function as a feedstock for transportation fuels (ethanol and biosyndiesel) and commodity/fine chemical industries. Thousands of bioproducts and structural materials also use biomass as the principal ingredient.

Concerns over energy security, climate change, and the rural economy are driving the push towards biomass utilization. In the United States alone, the Department of Energy has prepared a vision to consume 1 billion tons of biomass by 2020, up from 190 million tons in 2005 (Perlack et al. 2005). This rapid increase will require significant investments in biomass production, but also the systems that supply biomass to facilities for conversion to useful products.

Despite this drive towards renewable energy, biomass still suffers from low energy density, distributed location, and geographical distance between source and markets. In addition, agriculture-based bioenergy systems are largely dependent upon single season productivity. On a purely economical energy basis, it is very hard for biomass (or other renewable energy sources) to compete with fossil fuels. However, with help from government incentives, such as renewable feed-in tariffs, tax credits, and carbon emission penalties, biomass markets have grown rapidly over the past decade. For example, world wood pellet consumption increased from approximately 1.3 million tonnes (Mt) in 2000 to 6.5 Mt in 2006, indicating annual growth of 10.8% (Peska-Blanchard et al. 2007; Melin 2007). United States ethanol production, a good proxy of the anticipated growth of lignocellulosic biofuels such as bioethanol, has achieved an annual growth rate of 11.1% since 1990 (Renewable Fuels Association 2007).

Many top-down assessments of bioenergy potential for various geographic regions, from the local community scale to the country and even global level, have been produced (eg. Wood and Layzell 2003; Hoogwijk et al. 2005). In addition, a bottom-up approach for techno-economic assessments has been utilized by several research teams, including Caputo et al. (2005) and Sokhansanj et al. (2002). While valuable from a technology perspective, most assessments simplify the issue of feedstock supply by assuming a constant productivity over a given region (eg. 2 tonnes per hectare) and also over the life of a processing facility. Since biorefinery processing facilities are likely to have lifetimes of 20 – 25 years, with constant (or near constant) operation, the accuracy of this assumption is vital to the overall success of a bioenergy project. Given that biomass feedstock can account for 40 – 60% of the operating costs of a biomass processing facility (Caputo et al. 2005; Leistritz et al. 2007), accurate feedstock supply and cost predictions should play a central role in processing facility strategic decisions. This includes siting and scale.

Little work has been done on the role of inter-year variability of feedstock supply for biorefining/bioenergy operations. This is a major risk for companies and determining the minimum (in particular) and maximum supply over the lifetime of a plant is as important as the average. It is unrealistic to assume a constant supply and price over 25 years when the feedstock is annually produced, as is the case for agricultural residue-based operations. Those that rely on straw as a feedstock for energy and biorefining will have their operations impacted by productivity variability, primarily caused by weather. Just as farmers have high and low yield years for the grain of their crop, so too will they for the straw and chaff of that crop.

1.1 CENTRAL HYPOTHESIS

Inter-year availability of crop residues will be highly variable over the lifetime of a biorefinery, thereby creating significant inconsistency in the delivered price of feedstock and impacting overall operating costs.

1.2 THESIS OVERVIEW

1.2.1 Objectives

The purpose of this thesis was to quantify feedstock supply variability over the lifetime of an agricultural residue-based (straw and chaff) biorefinery and to determine the range of delivered prices.

The specific objectives for the research were:

1) To identify the best sites for locating an agricultural residue biorefinery in the Peace River region, based upon infrastructure and feedstock supply
2) To determine which croplands could provide biomass to a biorefinery and the average supply available in a given area
3) To determine the variability (minimum, average, maximum) of feedstock production and availability for the Peace River region biorefinery sites over a 20 year timeframe

4) To determine the delivered price, including harvest and delivery, of biomass for a range of biorefinery capacities (50,000 t to 500,000 t) to the best sites and for minimum, average, and maximum supply conditions
5) To create a replicable methodology for crop residue biomass quantification, supply variability analysis, and delivered price determination

1.2.2 Approach

To accomplish the objectives of this thesis, a two stage approach was used. The first used a geographic information system to map crop productivity and a spreadsheet program to calculate availability and variability of biomass feedstocks. This satisfied objectives 1 – 3. Secondly, to satisfy objectives 4 and 5, a dynamic (time dependent) simulation model (Integrated Biomass Supply Analysis and Logistics – IBSAL), created by Sokhansanj et al. (2006), was used to determine variability in delivered price of biorefinery feedstocks for minimum, average, and maximum scenarios. This model has already been used to describe collection and delivery of corn stover (Sokhansanj et al. 2006) and switchgrass (Kumar and Sokhansanj 2007). A full methods description is detailed in the two manuscripts of this thesis, Chapters 2 and 3, but the general approach required:

- Sourcing relevant data on historic crop production for the Peace River region
- Using a geographic information system for biorefinery site selection based upon infrastructure and feedstock supply
- Determination of average, minimum, and maximum agricultural residue (straw and chaff) production in a given area using spreadsheet calculations

- Selection and deduction of residue retention requirements from production values to determine ‘availability’
- Quantification of inter-year agricultural residue supply variability
- Modification of the IBSAL model in terms of productivity and equipment for small grain straw harvest, collection, and transportation
- Comparison of five biorefinery capacities, ranging from 50,000 to 500,000 tonnes, and the impact of scale on supply variability
- Obtaining and reformatting weather data for the 20 year time period from 1980 – 2000 for inclusion in the IBSAL model
- Creation of agricultural residue handling and delivery chains within the IBSAL simulation model and running of that model under a host of varying conditions (60 scenarios)
- Determination of crop residue feedstock delivered price (as calculated by combining separate simulations of harvest and delivery) for varying biorefinery capacities and for minimum, average, and maximum availability scenarios
- Procedures for integrating spatial data on biomass supply with dynamic models projecting delivered cost, emissions, and equipment that could be replicated in other regions and with other feedstocks

1.2.3 Scope

The best way to provide focus and create a robust methodology was the use of a case study. The Peace River region of Alberta was chosen because it can be a relatively high productivity area for small grains but also has a large variation in productivity. It is also a transition land (meaning cropland interspersed with forage land, forests, and shrubs) and could provide other types of biomass for a secondary analysis beyond this thesis. The analysis was limited to:

- The Alberta component of the Peace River region (approximately 80% of the region by land area)
- Agricultural residues from the small grains wheat, barley, and oats
- Data, including weather and grain production, from the period 1980 – 2000
- No-tillage management and equipment already in use in the Peace River region (eg. round balers)
- Feedstock management and pricing for a biorefinery, not including analysis of technology or capital costs of a biorefinery
- Biorefinery capacities ranging from 50,000 to 500,000 tonnes

Chapters 2 and 3 are manuscripts prepared for submission to an academic journal. Chapter 4 provides a conclusion and recommendations for development of an integrated biomass supply and logistics system that can be utilized by farmers, government, and businesses for quantifying feedstock supply and cost variability. This chapter also provides suggestions on avenues for future research and knowledge gaps. Appendices 3 through 5 provide a literature review of applicable research, including logistics, modelling, and residue removal considerations. Breakout boxes ("Research Impact") provide summaries and conclusions on literature review impacts on research methods.

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2 ANALYSIS OF BIOMASS FEEDSTOCK AVAILABILTY AND VARIABILITY FOR THE PEACE RIVER REGION OF ALBERTA, CANADA*

2.1 INTRODUCTION

Yearly variation in feedstock supply and cost is a major risk for many existing and planned biomass-based processing facilities. This is particularly true for businesses that rely upon annual crops, for which availability is dependent largely on single season growing conditions. Several reports and analyses have focused upon the 'potential' of biomass as a feedstock for an 'emerging bio-based economy' (Wood and Layzell 2003; Hoogwijk et al. 2005), but few have addressed the impact of year to year regional differences in availability on commercial viability of a biorefinery. Sokhansanj et al. (2006) calculated the average straw from the Canadian Prairies was slightly over 15 million t (Mt), with a wide annual variation from 27.6 Mt to 2.3 Mt. Raw feedstock costs represent 40 – 60% of the operating costs of a biomass processing facility (Caputo et al. 2005; Leistritz et al. 2007). Quantifying the potential risk of inadequate supply is critical to the long-term viability of biomass-based operations.

Feedstock assessments have been conducted on a national scale. Matsumura et al. (2005) performed a resource assessment for rice straw and husk in Japan. These two types of biomass make up approximately 45% of the available agricultural residues in the country. Elmore et al. (2008) used MODIS and Landsat-sourced high-resolution land cover maps to determine rice crop residue availability in China. MODIS provided data on net primary productivity, and hence, residue production rates. By combining

*A version of this chapter has been submitted for publication.
Stephen, J., S. Sokhansanj, X. Bi, C.J. Lim, M. Stumborg, L. Townley-Smith, and T. Kloeck. 2008. Analysis of biomass feedstock avaialability and variability for the Peace River region of Alberta, Canada. *Canadian Biosystems Engineering*.

production rates with land-use patterns and extending the analysis over a 5 year period, the authors created a general analysis of available residue in China. All data was converted to raster format and analyzed in GIS. Graham et al. (2000) used GIS to determine the delivered cost for energy crop feedstock in 11 US states. Variables that were considered included locations where energy crops could be grown, the potential crop yield, and transportation costs to central processing facilities. Walsh (2000) described a method to estimate biomass feedstock supply, including the economic influences. These include variable costs (fertilizer, herbicides, seeds, cuttings, machinery repair, fuel and lube, hired labour, twine, etc.), fixed costs (taxes and insurance, operating and real estate interest, general overhead), and owned resource costs (land, producer's own labour, depreciation, non-land capital costs).

On a regional biomass availability basis in Canada, Sokhansanj et al. (2006) determined the production and distribution of cereal straw on the Canadian prairies, with a breakdown based on soil type and crop type. Boyden et al. (2001) provided data on wheat straw availability in Saskatchewan. Both studies used straw:grain ratios and historical grain yield data. Kumar et al. (2003) analyzed optimum plant size for biomass processing facilities in Alberta using three different feedstocks: agricultural residues (grain straw), whole boreal forest, and forest harvest residues. They found a strong correlation between biomass density and relative scale, but all three plants are larger (>200 MW) than traditional biomass processing facilities in North America. Simonson and Johnson (2005) used Dominion Land survey data, historical maps, remote sensing data, Alberta Vegetation Inventory data and a digital elevation matrix (DEM) to compare current and historical vegetation patterns in Alberta.

Few studies have addressed the inter-year variability of feedstock to supply a biorefinery and many took an average rounded figure across an entire region to determine the delivered cost (eg. Caputo et al. 2005). To the best of our knowledge, no previous study has used a vector-based technique for biorefinery site identification or determined biorefinery lifetime feedstock supply variability.

2.2 OBJECTIVES AND SCOPE

The objective of this research was to accurately assess the variability in agricultural crop residue biomass availability as a feedstock for potential facilities in the Peace River region of Alberta. This variability was to be assessed over an extended (20 year) timeframe. Available tools and data to carry out the assessment are outlined once these factors affecting availability are clearly defined. The type of facility processing the biomass is specifically not identified; biomass supply reliability is a central concern for any operation regardless of conversion technology choice or product mix. Though a specific region is studied, the methodology is applicable to any crop residue type in any agricultural region of Canada and elsewhere.

2.3 METHODOLOGY

2.3.1 Study Region

The Peace River extends from northern Alberta southwest into northeast British Columbia. The area surrounding the River, known as the Peace River region, is Canada's most northerly agricultural area and is the study region for this research. The Peace River region of Alberta includes approximately 3.9 million hectares (Mha) of farmland, which is 20% of the provincial total. The region is known for boom and bust years in terms of production, but has overall high yields and on average is one of the most productive regions of North America (City of Grande Prairie 2007). A large reason for this high productivity is the relatively low mountains of the Rocky Mountain range in the region. As crop growth in the prairies is largely moisture-limited, the moist Pacific air able to pass over the mountains provides all important precipitation for high yields. Most agricultural land is located within 100 km of the Peace River itself. For this study, only the Alberta portion of the Peace River was considered. In decimal degrees, the study region is between 120° W and 114°W and from 59° N to 54°N (Figure 2-1).

The Peace River region is an example of a transition land, where cropland and forage land meet forest and dense shrubs. The largest employment sectors in the region are forestry, agriculture, and oil and gas. The Peace River region was chosen for this analysis because of the ecosystem characteristics – transition land, large variability in grain yield, and potential high productivity.

2.3.2 Data Sources

All GIS layers were obtained from Agriculture and Agri-Food Canada (AAFC). Two sources of data were used: Soil Landscapes of Canada, Version 3.1 and the Western Grains Transition Payment Program (WGTPP) data from the Prairie Farm Rehabilitation Administration (PFRA), a division of AAFC.

Soil Landscapes of Canada (SLC) consists of data on the major characteristics of land and soil for Canada at a scale of 1:1,000,000. The data set contains such information as surface form, slope, soil type, and water table depth. Water bodies are marked, but information on land use is not included. For this analysis, data were provided on yearly average grain crop yield as part of the SLC layer. The crops used for the analysis were spring wheat, barley, and oats. Also included in the data were flax and canola, although these were not considered for biomass collection in the analysis due to differences in biomass characteristics. Version 3.1 was released in March 2006 and uses the North American Datum of 1983, the geographic coordinate system (GCS) is GCS North American 1983, and the Geodetic Reference System 80 ellipsoid (Agriculture and Agri-Food Canada 2006).

The Western Grains Transition Payment Program (WGTPP) was created to compensate landowners across western Canada when the Crow Benefit subsidy for grain transportation was eliminated. As such, in 1995, PFRA, who administered the program, had to accurately determine land use across Western Canada to assess whether or not compensation would be in order (ie. those claiming compensation actually used the land for the purposes specified) (Auditor General of Canada 1996). The WGTPP landcover maps are at a scale of 1:50,000 and also include road/rail and towns layers. The WGTPP landcover layer was created in a seamless vector format and uses decimal degrees as the coordinate units, the geographic coordinate system GCS North American 1983, the North American Datum of 1983, and the Geodetic Reference System 80 ellipsoid. The primary attribute of interest is the class, which includes values 'cropland', 'forage', 'grassland', 'shrubs', 'trees', 'water bodies', 'wetlands', and 'other'. Also sourced from the PFRA were the Alberta Roads and Railways layer and the Alberta Towns layer at a 1:1,000,000 scale (Auditor General of Canada 1996).

Finally, the Township Fabric layer was also sourced from the PFRA, who developed that layer during the WGTPP. The data set is dated 1996 and covers all points were there is a valid legal parcel of land, down to the legal sub-division or parish/river lot. These are represented as a single point and the layer was used to identify accurate x and y coordinates. All layers are summarized in Table 2-1.

2.3.3 Establishing data overlays and linkages

In order to determine biomass availability, it was first necessary to link the *Soil Landscapes* layer with the *Landcove*r layer. While *Landscapes* provides the average grain yield, it does not accurately reflect land use. For example, crop yield estimates extend into regions that are actually forested. To ensure both layers were covering the same area, *Landcover* was initially manually sliced at the Alberta-BC border so the analysis could focus on the Alberta Peace River section alone. This *Alberta Landcover* was used as a feature to clip the appropriate study area from the *Soil Landscapes* layer, which extended across all of northern Alberta and BC.

Croplands were selected by 'Class' from the *Alberta Landcover* to form a new *Cropland* layer. By identifying the cropland through the *Landcover* layer, it was possible to extract these areas from the *Landscapes* layer and determine crop yield for actual cropland. Given GIS data on yield and availability, this procedure could be replicated for forest or forage land.

Three primary criteria were identified as requirements for locating a potential plant: proximity to a town of at least 1000 inhabitants (infrastructure and population), a primary or secondary road within 1 km (for feedstock receiving), and a railroad within 50 m (for product export). *Roads* and *Rail* layers were buffered to identify sites.

Ten sites were identified in the Alberta Peace River region that matched the criteria laid forth in the analysis. The location and population of the 10 sites are listed in Table 2-2 (Sky Scan Service 2004; Alberta Municipal Affairs 2005).

A new layer was created for each site and the *Cropland* layer was added to the data frames. Buffers, representing supply areas, were created surrounding each site at 10 km intervals up to 100 km (Figure 2-2). By clipping the buffered area radius from the *Cropland* layer, it was possible to determine which lands were producing crops within a specified maximum draw radius from the central biomass processing plant.

2.3.4 Estimating Biomass Quantities

Data on crop yield in the buffered areas from the Cropland layer were exported to Microsoft® Excel™ spreadsheet. Each continuous area of cropland produced individual average crop yield and cropland area figures. Straw-to-grain (S:G) and material other than grain (biomass)-to-grain (MOG:G) ratios were used to calculate biomass production at the study sites. Biomass yield included straw, chaff, and leaves. The MOG:G used were 1.5, 1.0, and 1.5 for spring wheat, barley, and oats respectively. The ratios were constant for all sites and are based upon the black soil figures presented in Stumborg et al. (1996).

After calculating total average biomass production for each buffer zone for each of the 10 sites, 4 sites were chosen for further investigation based upon high yields. They were Fahler, Grimshaw, Peace River, and Sexsmith and each had average annual production of over 250,000 t of biomass (material other than grain) within a 100 km radius of the town (Grimshaw example in Figure 2-3). 100 km was chosen as the land included would be substantial enough in area to determine sub-regional productivity and make a comparison between sites.

Data on grain yield over a 20 year period from 1980 to 2000 were examined for each of the 4 study sites to determine historical maximum and minimum production values.

For Fahler, Grimshaw, and Peace River, 1982 was the least productive year overall, while 1985 was the least productive year for Sexsmith. 1988 was the most productive year for all 4 sites. These historic yields were used to provide the range of productivity that could be expected over the 20 year lifetime of a biomass processing plant. It was also necessary to determine cropping frequency of each crop type. Using data from Alberta Agriculture and Rural Development (2007) and Statistics Canada (2007) on crop area, it was estimated that wheat has a cropping frequency of 30% (i.e. 30% of the time on cropland, wheat will be grown), barley was 17%, and oats was 3%.

Using an MOG:G ratio of 0.75 for all sites and all three small grains, biomass production was calculated for the minimum years 1982/1985. This low ratio is conservative to account for the early season drought possibility. The MOG:G ratio decreases as water availability decreases. An MOG:G ratio of 1.75 for spring wheat and oats and an MOG:G ratio of 1.5 for barley was used to calculate maximum year 1988 biomass production.

Based upon work by Stumborg et al. (1996), 750 kg per hectare was subtracted from minimum, average, and maximum biomass yields to ensure allowable erosion limits were met and soil organic carbon (SOC) levels were maintained. 750 kg per hectare is based on the assumption of zero-tillage management practices and would need to be doubled for conventional tillage. This provides values for available biomass that could be used to feed a processing facility, but is not discounted for in-field losses or losses in transportation and preprocessing. It is particularly important to note the difference in production as compared to availability (production minus 750kg ha^{-1} discount) in this analysis. Availability does not take into consideration other uses of biomass, such as animal bedding and feed. It also assumes that all biomass 'available' will be supplied by the landowner.

2.4 RESULTS

The biomass production analysis for the 10 initial sites identified 4 sites with the highest productivity – an average annual production of over 250,000 t of biomass within a 100 km radius of the plant (Figure 2-3). Production was not directly proportional to distance from plant location and some sites had a levelling off or rapid rise as distance from the plant increased. Several sites had substantially less production than others within the region, with production surrounding High Level and High Prairie less than 125,000 t (or half the cut-off value for further analysis). The four high productivity sites were Fahler with 195,379 ha of cropland within a 100 km radius of the site, Grimshaw with 238,752 ha, Peace River with 212,375 ha, and Sexsmith with 211,565 ha. However, only half these areas are allocated for the three studied small grains.

For all cases, oats provided the greatest amount of biomass on a per hectare basis, followed by wheat and barley. This can be attributed to the high productivity levels of oats and the higher MOG:G ratio used for oats when compared to barley (1.5 vs. 1.0 for the average case).

After discounting 750 kg ha^{-1} from biomass production, the Peace River site had no biomass available in the minimum case. All values less than zero (ie. less than 750 kg ha^{-1} production) were adjusted to zero for availability. Fahler and Grimshaw had less than 4,000 tonnes available in the entire 100 km radius draw area, which is considered effectively zero. Only Sexsmith had notable production levels in the minimum case, with approximately 21,000 t available for processing (Figure 2-4) and even then, per tonne costs would likely prevent any biomass collection. These low availability levels are due to not only the decreased overall crop production levels, but also the lower MOG:G ratio used in the minimum production case analysis.

For the maximum scenarios at all sites and all grain types, a net yield of over 2.6 t ha^{-1} of biomass was available after discounting 750 kg ha^{-1} for soil retention and environmental values. Wheat and oat biomass availability exceeded 3.5 t ha^{-1} at all sites. Total biomass availability ranged from 335,000 t at the Fahler to 415,000 t at the Grimshaw site.

The range in biomass availability between minimum and maximum years was significant. Sexsmith had the smallest range in biomass availability at -91% and +73% from average values, while Grimshaw had the greatest with -99% and +99% (Table 2-3).

2.5 DISCUSSION

The Peace River region is known as a ‘boom or bust’ area, and that is evident in the results of this analysis. Over a 20 year timeframe, it could be reasonably expected that in one or two years, biomass availability will be 10% or less of average levels (Table 2-3). This has significant implications for enterprises wishing to utilize biomass as a feedstock over an extended time frame. Availability is impacted more significantly on a percentage basis by low yields than actual production due to the reduction in MOG:G ratio and the necessity to leave residues for environmental considerations. For example, at the Fahler site, if the biomass yield is calculated based upon average MOG:G ratios, minimum availability increases to 48,387 t from 3,013 t while maximum availability decreases to 271,013 t from 335,961 t. These are changes of +1508% and -19% respectively. Temperature and solar radiation are the principal weather factors causing this variability in cereal yield (Slafer and Andrade 1993), and with projections for a 3 – 5°C warming by 2050 and increased number of degree days in Alberta, this could be even further magnified (Barrow and Yu 2005).

While the inclusion of 3 grain crops increased overall biomass availability, it did not provide a hedge against low yields from one crop type. Wheat, oat, and barley yields were consistently highest in the same years and lowest in the same years. Therefore, in order to maximize biomass availability in a given year from crop residues, it is advisable to plant with the highest yielding grains (oats, followed by wheat) rather than attempt to match crop type with expected seasonal climate conditions. Long-term soil health must be taken into consideration for crop selection to ensure biomass supply over extended time frames. Recent work by Hoskinson et al. (2007) has indicated that extra management and fertilization for increased residue production is not an economically viable option. Over the past 50 years, total plant matter production in grain crops has not increased; grain production increases are the result of increases in the grain-to-straw ratio. While dramatic increases in the grain-to-straw ratio seen during the green revolution have slowed, it is not likely that they will reverse in the near future to supply greater quantities of material other than grain for bio-based commercial operations (Fischer 2007). Gottfried et al. (1996) argued that natural resource managers, such as farmers, are very reluctant to make significant short term investments and changes (including financial and personal) at present to create larger, future public benefits Hence, levels of biomass available in the analysis are not likely to increase in the near future and may in fact decrease.

The vector-based analysis, using buffers around a single point chosen based on user-specified criteria is a simple method that could be utilized by laypersons and made available online. It requires standard computing power and, although solutions are not fully optimized for plant location in a greater region, it is easily modifiable for various processing plant requirements. Raster-based analyses, while providing the potential to identify an optimal solution based on data inputs, can require significant computing power and human resources (Graham et al. 2000). The vector-based approach is easily customizable for business applications. Given the variability and unpredictability in yield, near-optimal solutions may be just as useful as those optimized based upon historical yield data.

The current study does not account for the possibility of extensive storage from especially productive years that could supply low yield years. Therefore, although the analysis examined data over 20 years, it did not look at total production over 20 years. The year-to-year variability was deemed more important for annual crop residues to ensure ongoing processing facility operation and cash flows.

A major source of error with this analysis and many GIS results is data accuracy. The landcover data from the Western Grains Transition Payment Program are from 1995 and therefore over a decade old. The Soil Landscapes of Canada data are more recent, but do not provide a picture of existing biomass resources. They can be viewed more in terms of potential for production. The next step for determining land use data accuracy for the Peace River region should be ground verification of remotely sensed data. For actual implementation of any major capital project, this should be followed by surveys, prospective contracts, or interviews with actual landowners regarding 'buy-in' to sell their crop residues.

Residue retention requirements are very site specific, and therefore the 750 kg ha^{-1} is meant to serve as a conservative figure to ensure long-term soil quality standards and crop productivity. Specific studies on the residue retention requirements in the Peace River region would refine this figure and they may provide a range of values dependent upon site conditions, year-to-year variability, and tradeoffs between residue positive impacts (eg. soil erosion reduction) and residue negative impacts (eg. disease and pest concentration and tillage requirements).

Given the huge amount of variability in biomass availability between years, a bio-based operation in the Peace River region could not depend solely on local agricultural residue as the biomass supply over a 20 year time frame. Therefore, to remain operating continuously over a 20 year time frame, a bio-based operation would need to determine methods to source biomass on low availability years, or identify alternate biomass types that could replace the original type. This could be accomplished through 1) extensive storage of 'excess' biomass from high productivity years; 2) import biomass from longer distances, perhaps via rail transport, or 3) a survey of other biomass types, such as wood residue, that may successfully augment agricultural resources. Of course, the option exists to shut down the processing facility in low yield years. This would be a difficult proposition for new facilities requiring cash flow to meet capital repayments and it would create challenges in labour management.

It is common practice in bioenergy assessments to assume an average biomass yield (eg. Sokhansanj et al. 2002; Caputo et al. 2005). Although analyses of other areas in Canada are not likely to show the degree of variability in yield found in the Peace River region, this work proves that an average yield cannot be broadly applied to determine the actual year-to-year availability of biomass. This will have an impact on the planned size of a processing facility and the location of that facility.

2.6 CONCLUSION

A case study was used to develop a methodology for determining the range of biomass availability over an extended time frame. During average availability years, Fahler, Grimshaw, Peace River, or Sexsmith could support a 250,000 t yr^{-1} biorefinery, with a feedstock draw radius of 100 km. However, it was determined that in some years, no (or virtually no) biomass is available at these study sites. This is a major risk for any bio-based processing facility and means a facility located in the Peace River region faces significant feedstock supply shortfalls. Therefore, it is necessary to plan for alternate biomass sources, such as importing from outside regions, using different types of biomass (eg. forestry residues), or implementing long-term storage systems to reduce the risk of feedstock shortages. The 'available' feedstock quantities determined in this study are highly dependent upon biomass-to-grain ratios. The validity of biomass analyses, such as this, would be increased dramatically if data were available specifically on total plant biomass rather than only grain. Up-to-date remotely sensed data on Canadian cropping areas is required to increase the accuracy of feedstock assessments. Further work is needed to determine the impact of this large variability in biomass availability on delivered price of feedstocks, the key operating cost for biorefineries.

Name of data layer	Source	Uses	Entity type	Data model	Attributes
Soil landscapes - Alberta	Soil Landscapes of Canada, Version 3.1 (1:1,000,000)	Provides grain crop yield over multiple years	Area	Vector	Ecozone, Hectares, Yields of wheat, barley, oats, flax, and canola
Landcover	Prairie Farm Rehabilitation Administration – Agriculture and Agri-Food Canada (1:50,000)	Higher resolution landcover classification	Area	Vector	Acres, Class (cropland, forage, grassland, shrubs, trees, water bodies, wetlands, other)
Township Fabric	Prairie Farm Rehabilitation Administration – Agriculture and Agri-Food Canada	Identifies legal land parcels from the township to quarter sections	Point	Vector	ID, x & y coordinates
Alberta Roads and Railways Network	Prairie Farm Rehabilitation Administration – Agriculture and Agri-Food Canada (1:1,000,000)	Provides location of primary and secondary roads, and railways, in Alberta	Line	Vector	DXF (type): Primary road, secondary road, or railway
Alberta Towns	Prairie Farm Rehabilitation Administration – Agriculture and Agri-Food Canada	Provides name and location of all cities, towns, and settlements in Alberta	Point	Vector	Town name

Table 2-1 Summary of GIS data for the Peace River Region biomass feedstock supply analysis

Site	Latitude	Longitude	Population
Beaverlodge	55°13’N	119°26’W	2,176
Falher	55°44’N	117°12’W	1,109
Grande Prairie	55°27’N	118°45’W	44,631
Grimshaw	56°11’N	117°36’W	2,435
High Level	58°31’N	117°08’W	3,849
High Prairie	55°26’N	116°29’W	2,820
Manning	56°55’N	117°37’W	1,293
McLennan	55°42’N	116°54’W	804
Peace River	56°14’N	117°17’W	6,240
Sexsmith	55°20’N	118°46’W	1,934

Table 2-2 Potential biomass processing plant sites

	Fahler	Grimshaw	Peace River	Sexsmith
Average	192,021	209,105	203,734	225,613
Minimum	3,013	2,460	0	21,349
Maximum	335,961	415,623	369,164	389,650
Variation from Average	-98%/+75%	-99%/+99%	-100%/+81%	-91%/+73%

Table 2-3 Average, minimum, and maximum biomass availability at the four study sites

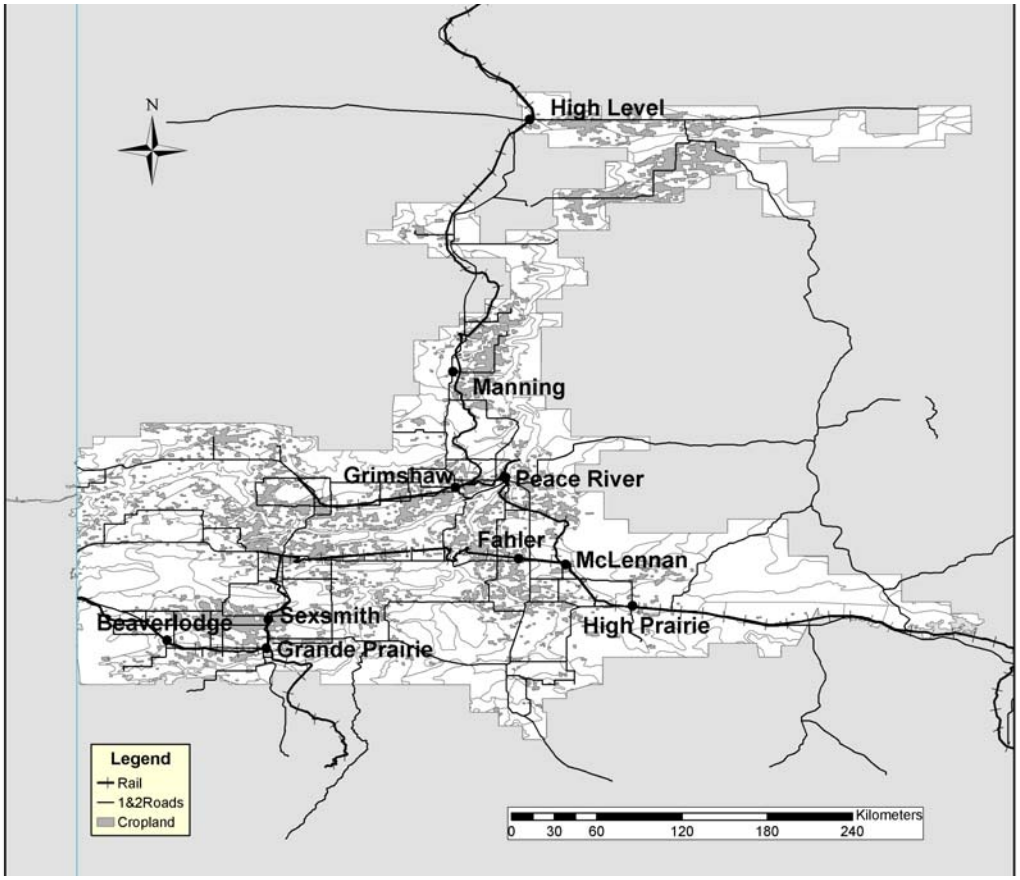

Figure 2-1 Peace River Region with 10 study sites

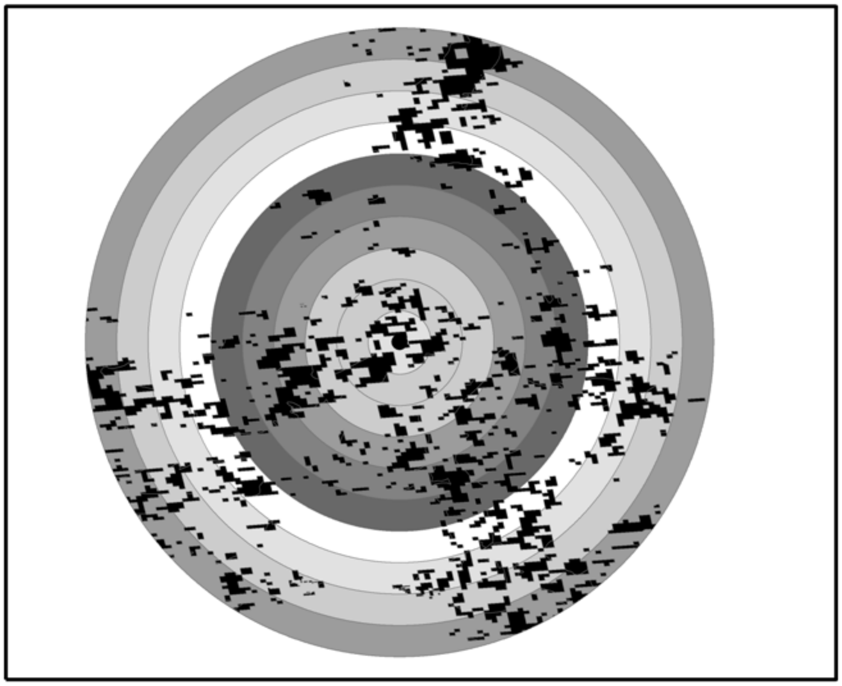

Figure 2-2 Incremental 10 km buffers surrounding the Grimshaw study site with cropland highlighted in black

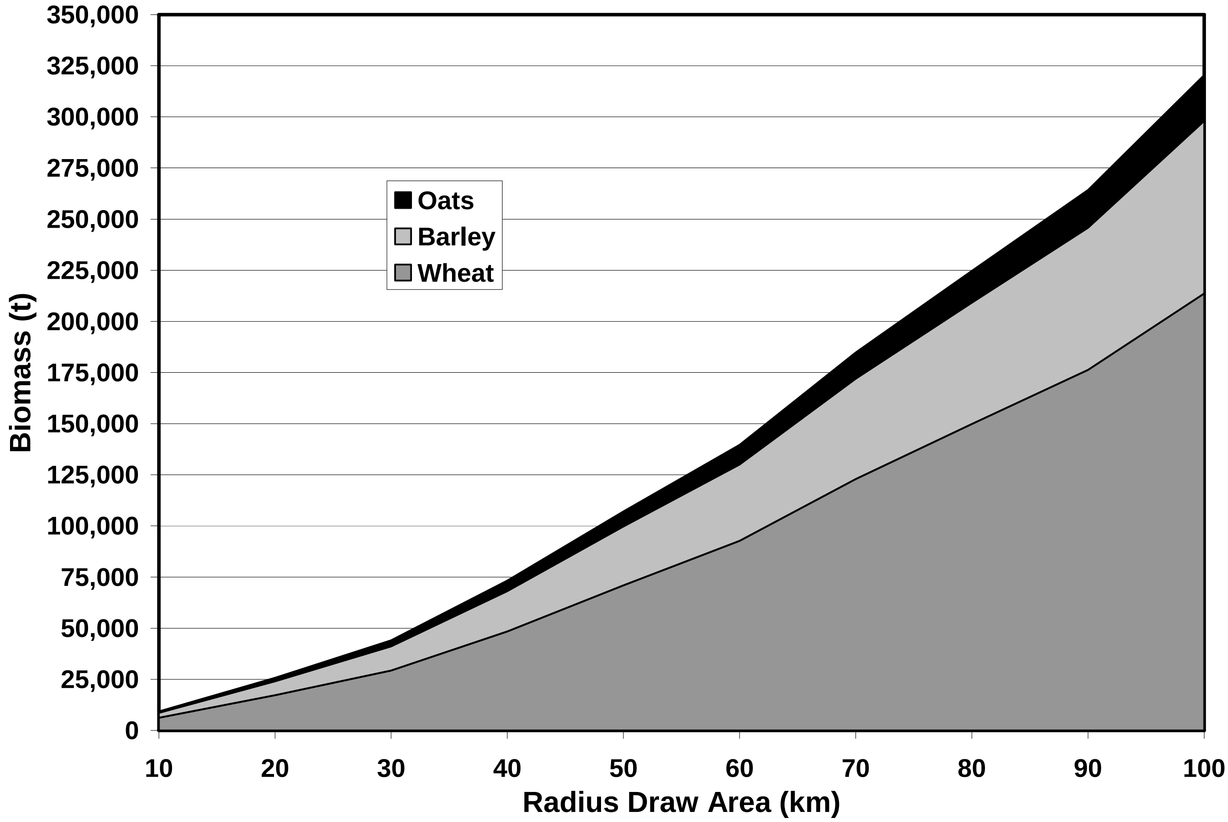

Figure 2-3 Average biomass production within 100 km of Grimshaw study site

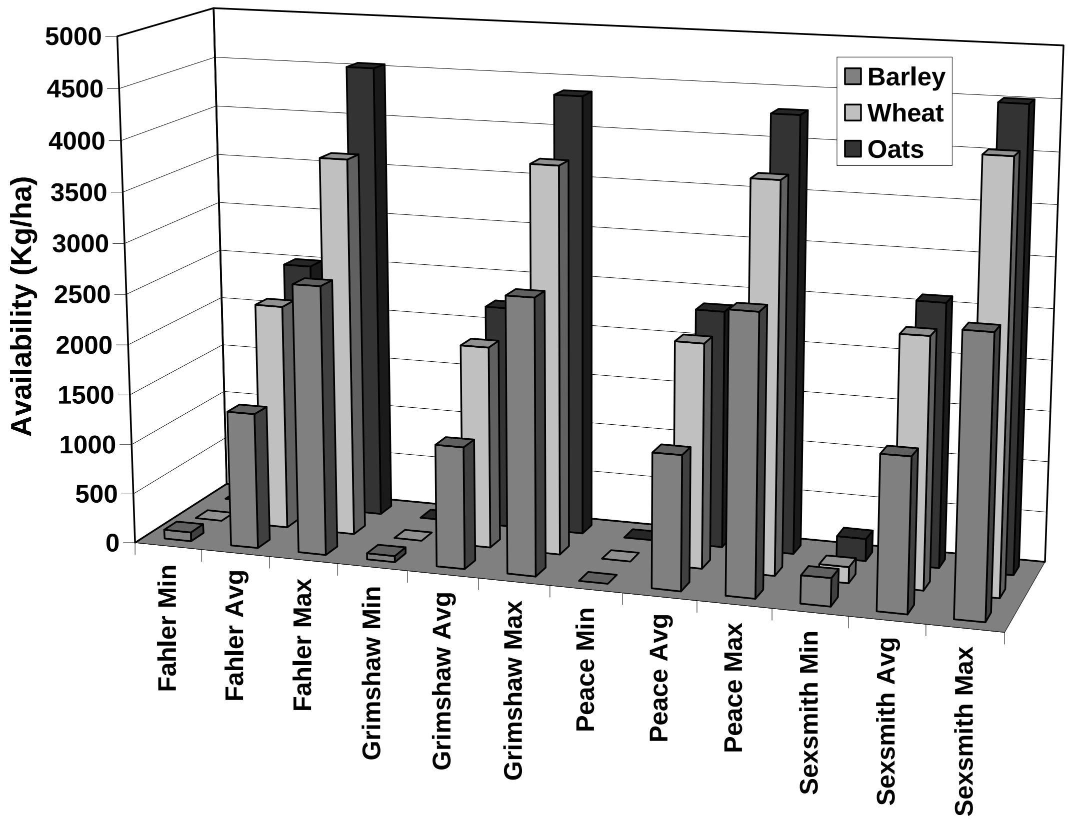

Figure 2-4 Maximum, minimum, and average net yield (kg ha^{-1}) of biomass over 20 years

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3 THE IMPACT OF BIOMASS FEEDSTOCK SUPPLY VARIABILITY ON THE DELIVERED PRICE TO A BIOREFINERY IN THE PEACE RIVER REGION OF ALBERTA, CANADA*

3.1 INTRODUCTION

Adequate, competitively priced, and predictable biomass feedstock supply is essential to the long-term viability of any biomass processing facility (i.e. biorefinery). As feedstocks represent 40 – 60% of the operating costs of a 'typical' biorefinery (Caputo et al. 2005; Leistritz et al. 2007), variation in delivered cost is a major risk factor. As the productivity of annual agricultural crops is dependent upon a single season's climatic conditions, any enterprise relying on crop residues, such as straw and chaff, faces additional risks. Capital investments in processing facilities are made with the understanding that feedstocks will be available to supply the facility throughout its lifetime, which can range from 10 – 25 years (or even longer). Stephen et al. (2008) provided an assessment of the feedstock variability over 20 years in the Peace River region of Alberta, Canada.

The delivered costs of biomass can be divided into harvesting costs and logistics costs. Logistics has three domains: transport, in which something is moved; traffic, which is the flow of transports within a network; and terminal, where loading and unloading take place (Davidsson et al. 2005). Logisticians are always faced with two problems: facility location (and scale) and freight distribution. This paper addresses the

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*A version of this chapter has been submitted for publication.
Stephen, J., S. Sokhansanj, X. Bi, C.J. Lim, M. Stumborg, L. Townley-Smith, and T. Kloeck. 2008. Analysis of biomass feedstock avaialability and variability for the Peace River region of Alberta, Canada. *Canadian Biosystems Engineering*.

second of these two problems and the additional complexities presented by a variable feedstock supply using a multi-component decision support system (DSS).

Biomass feedstock supply scheduling and optimization has been the subject of significant research. Jenkins and Arthur (1983) used network analysis and dynamic programming to simulate processing and transportation steps in a biomass supply chain. They found that as transportation distance changed, the optimal processing route also changed. Tatsiopoulos and Tolis (2003) compared various biomass logistics systems, including farmer transportation and third party logistics (3PL) handling, with linear programming to minimize delivered cost. Olsson and Lohander (2005) used a mixed-integer model and 'near to optimal' heuristics (rules of thumb) to determine the marginal cost of round wood transportation and delivery and optimize this cost with investments in gravel roads. A mixed-integer programming model was also used by Troncoso and Garrido (2005) to optimize forest logistics, taking into consideration forest production, forest facilities locations, and forest freight distribution. Foulds and Wilson (2005) used scheduling models and integer programming to optimize rape seed harvesting in Australia and hay harvesting in New Zealand, with attempts to minimize required equipment, labour, and duration of harvest. The General Algebraic Modelling System (GAMS) used by Kaylen et al. (2000) divided costs into capital cost, operating cost, feedstock cost, and transportation cost. This non-linear algebraic programming model was used by Kaylen et al. (2000) to economically optimize the production of lignocellulosic biomass-based ethanol. A key determinant was the size of the production facility, the optimal size of which is a trade-off between economies of scale and increased transportation cost for biomass feedstock.

Caputo et al. (2005) determined the economics of logistics and their effect on the overall viability of biomass gasification and combustion facilities. In order to focus on the logistic component of bioenergy operations, conversion plants were modelled as a black box with feedstock input and product output. Jenkins et al. (1983) developed a method for creating minimum cost curves on delivered biomass. Although sites processing more than one type of biomass are rare, the method can be applied to any type or combination of biomass types. Thorsell et al. (2004) used a multi-feedstock system of agricultural residues, native grasses, and managed perennials to optimize delivery to a central gasification-fermentation facility. They broke down harvest operations into functional units based upon machinery capacity. Although several studies have performed sensitivity analysis for changes in yield, most have used a standard average yield [eg. 2 tonnes hectare^{-1} (t ha^{-1})]. The authors are unaware of any publications using real-world data on feedstock variability to derive a range of delivered costs of agricultural residues over the lifetime of a biorefinery.

Much of this previous research assumes a static situation and does not account for changes over time. However, Nilsson (1999a) created the Straw HAndling Model (SHAM), a dynamic (time dependent) simulation model for analysis of straw delivery scenarios to optimize handling and reduce costs. The three primary submodels are location submodel, weather and field drying submodel, and harvesting and handling submodel. A spreadsheet was used for data input and output from the dynamic simulation. Location submodel determined transportation distance and infrastructure, while weather and field drying submodel used time limits on harvesting and transportation to determine wait and completion times. SHAM was used to compare straw harvest and handling systems in regards to cost, energy requirements, and overall performance, providing the ability to identify opportunities for system improvement and cost reduction (Nilsson 1999b).

3.1.1 Integrated Biomass Supply Analysis and Logistics model (IBSAL)

Based upon the work by Nilsson (1999a; 1999b), Sokhansanj et al. (2006) created the Integrated Biomass Supply Analysis and Logistics model (IBSAL), a dynamic harvest and transportation model with outputs on operational cost, energy consumption, and carbon dioxide (CO_2) emissions. IBSAL has been used to determine the delivered cost of corn stover (Sokhansanj et al. 2006) and switchgrass (Kumar and Sokhansanj 2007) in the United States. In IBSAL, objects, representing a biomass quantity (eg. 20 t) pass through the system and are 'handled' by the blocks, representing machinery and handling. Each of these blocks has inputs and outputs associated with it, including cost, energy consumption, and emissions. Blocks can be added or removed from a model based upon the equipment used in that system. For example, different types of tractors have different horsepower and fuel consumption levels. The IBSAL model includes fuel pricing, capital and operating costs, carbon content of the fuel, efficiency, financing and depreciation, and an extensive equipment database from which to draw performance data. IBSAL has continued to be updated and refined and Version 4.2 (2007) was used for this work.

3.2 OBJECTIVES AND SCOPE

Dennis and Dennis (1991) state that decision support systems "link the information processing capabilities of a management information system with modelling techniques and the judgement of managers to support decision-making in unstructured situations". The purpose of this work was to create the foundations of a decision support system that would determine the impact of biomass availability and its variability over the operating life of a biorefinery, on the delivered cost of feedstock. In particular, address how lower yields affect transportation distance and hence, delivery costs. The Peace River region of Alberta, Canada was used as a case study, although the methodology and modelling can be utilized in other regions of Canada and elsewhere. This work is a continuation of the biorefinery siting and feedstock availability assessment presented in Stephen et al. (2008) and uses straw and chaff from small grains wheat, barley, and oats to supply an unspecified conversion process at a centralized biorefinery.

3.3 METHODOLOGY

3.3.1 Study Region

The Peace River extends from northern Alberta southwest into British Columbia and is surrounded by Canada's most northerly agricultural area. The Peace River region of Alberta includes approximately 4 million ha of farmland, which is 20% of the provincial total. The region's coordinates are between 114 to 120 degrees West and 54 to 59 degrees North (Figure 3-1). The region is known for boom and bust years in terms of production, but has overall high yields and on average is one of the most productive regions of North America (City of Grande Prairie 2007). A major reason for this high productivity is the relatively lower mountains of the Rocky Mountain range in the region, which allows moisture-rich pacific air to pass over the mountains. The Peace River region is an example of a transition land, where cropland and forage land meet forest and dense shrubs.

3.3.2 Data Sources and Inputs

Data on feedstock availability was presented in Stephen et al. (2008), and was based upon GIS layers from the Soil Landscapes of Canada, Version 3.1 and the Prairie Farm Rehabilitation Administration (PFRA), a division of Agriculture and Agri-Food Canada (AAFC).

Stephen et al. (2008) selected 10 sites for feedstock (straw and chaff from wheat, barley, and oats) availability analysis based upon transportation infrastructure (roads within 1 km, rail within 50 m) and population. Of these, 4 were chosen for further analysis based upon average biomass production. These sites were Fahler, Grimshaw, Peace River, and Sexsmith. Minimum and maximum scenarios were produced using yield data over a 20 year time frame (1980 – 2000). The largest range of availability in a 100 km radius from a biorefinery site (Grimshaw), after discounting for sustainable residue retention, was +/- 99% from average levels. These data on availability provide the basis for the present case study on plant sizing and delivered cost.

3.3.3 Biorefinery Capacity

Based upon recommendations by government project partners and comparison to existing and planned agricultural biomass processing facilities, five capacities were chosen to compare the sites. They were 50,000 t, 100,000 t, 150,000 t, 250,000 t, and 500,000 t of feedstock input per year. Given the substantial range in feedstock availability, plant capacity optimization based upon average yield and transportation distance was deemed unlikely to represent real-world performance.

3.3.4 Draw Area

Based upon Stephen et al. (2008), cropping area and biomass yield data was obtained within 100 km of each of the 4 biorefinery sites. The three yield cases presented in

Stephen et al. (2008) (minimum, average, and maximum) were used on each of the four biorefinery sites and five biorefinery sizes, creating a total of 60 scenarios. For each scenario, the draw area radius surrounding the biorefinery was calculated. For scenarios that had the draw radius extended beyond 100 km, the average yield and cropping density from the 100 km radius area was extrapolated to the required distance. The percentage of total area in cropland and percentage of cropland in biomass (ie. a source of biomass) were calculated. Both these figures are inputs into IBSAL.

The average transportation distance from every point of a circle to the centre is given by:

$$d = \frac{2}{3} r \tag{3.1}$$

Where, d is the average transportation distance for a circle and r is the radius of that circle. However, real-world transportation distance is not straight line and is dictated by the tortuosity (τ), or bendiness, of a road network. Therefore, average transportation distance can be given by:

$$d = \tau \frac{2}{3} r \tag{3.2}$$

Or when using a Cartesian coordinate system and two (x,y) points:

$$d = \tau \left[\left(x_i - x_j \right)^2 + \left(y_i - y_j \right)^2 \right]^{\frac{1}{2}} \tag{3.3}$$

For this study, a tortuosity of 1.4 was used to calculate the average transportation distance.

3.3.5 IBSAL Inputs and Utilization

IBSAL is divided into transportation and harvest modules. Equipment blocks, representing typical pieces of equipment used for small grain harvest and straw management in the Peace River region, where created within IBSAL. A standard handling scenario of large round bales was used for all IBSAL runs, as round bales are the standard unit in the Peace River region. Sokhansanj et al. (2006) showed that large rectangular bales 1.2 m x 1.2 m x 2.4 m (4’×4’×8’) are the most cost effective option, but round bales are not substantially higher. Diagrams of the ‘harvest’ and ‘delivery’ modules used for the analysis are displayed in Appendix 1.

Since biomass availability for all sites was near zero for minimum case scenarios and delivered price could not be calculated on zero availability, ‘adjusted’ minimum scenarios were created in which half the biomass from ‘real’ average scenarios was used as the minimum case (hereafter referred to as minimum). Of the four sites, Sexsmith had the greatest availability of the real minimum scenarios (referred to as real minimum) and was used for further analysis and comparison.

IBSAL requires daily weather data for an entire year to determine feedstock moisture content and the ability to harvest. Weather data was obtained from Environment Canada’s Historical Weather Office (Environment Canada 2007) via downloadable Excel® spreadsheets. The required daily inputs for IBSAL are average temperature, snow height, relative humidity (RH), evaporation rate, daily precipitation. Evaporation rate is given by:

$$E_p = (3.21 + 0.078u)(P_s - P_v)^{0.88} \tag{3.4}$$

where E_p = evaporation rate (mm/d)
u = air velocity (km/d)
P_s = saturation vapor pressure (kPa)
P_v = vapor pressure (kPa)

Average RH had to be calculated from hourly recordings. Grande Prairie data was used for Sexsmith and Peace River data was used for Peace River, Grimshaw, and Fahler.

Weather data from 1982 was used for the minimum Peace River weather scenarios, while the minimum year for Grande Prairie data (for the Sexsmith site) was 1985. 1988 weather data was used for the maximum scenario at all sites. These years coincide with the minimum and maximum yields from 1980 – 2000 and are intended to accurately represent crop growth and harvest conditions. Weather data from 1990 was used for the average scenario as this year had average yields and relatively mid-range weather. This mid-range weather was determined by averaging conditions such as temperature, temperature variability, and precipitation. Yields were compared to ensure mid-range weather was consistent with mid-range crop productivity.

Standard situations were created in IBSAL harvest and transportation modules. In the harvest module, biomass and grain production figures, as presented in Stephen et al. (2008), were input to the production (crop) block. The harvest sequence consisted of combining grain, raking straw, baling the straw, collecting and stacking straw bales at the road side. In the transportation module, this straw is loaded on flat bed trucks and transported to the biorefinery. In the transportation module, the major functional blocks are loader, truck travel, and unloader. Both the loader and unloader use a slave truck block, which represents the truck being loaded/unloaded. Output blocks throughout the system send data on cost (associated with each function), emissions, and energy consumption to an Excel® spreadsheet. The focus of this analysis was the economics of biomass harvest and delivery, but did not include an assumption of value from emissions credits. Therefore, the emissions from the system were not quantified for all scenarios. An example of the energy use and emissions from the harvest and delivery modules is available in Appendix 2. The general parameters used for the analysis are summarized in

Table 3-1. All capital costs use 2005 as a base year, with an equipment price index for 2007 of 1.0791. For each piece of equipment, the database contains information on purchase price, operating lifetime (hours), annual usage, repair costs (ratio of purchase price), salvage value, fuel and lubrication usage, efficiency, labour requirements, productivity, combined fixed costs, and combined variable costs.

3.4 RESULTS

The harvest module was used to determine the harvest component price to pay to farmers for their biomass (straw). As contracts with a biorefinery will likely be over extended timeframes (ie. multiple years), and farmers will not sell at a loss, the price of production and harvest for the minimum scenario was deemed the standard purchase price. This figure was \$31.39 for Fahler, \$33.54 for Grimshaw, \$31.78 for Peace River, and \$30.29 for Sexsmith. Harvest cost was dictated by yield and weather conditions and was significantly lower (\$18 – \$19 t^{-1}) for maximum yield scenarios. The interaction between yield and harvest cost is represented in Figure 3-2. The polynomial function relating harvest cost to yield is:

$$Y_{harvest} = 3\times10^{-6}x^2 - 0.0164x + 45.3 \tag{3.5}$$

where, x is the yield in kg ha^{-1}. This is relevant from yields of 500 kg ha^{-1} (0.5 t ha^{-1}) to 3250 kg ha^{-1} (3.25 t ha^{-1}). There were substantial differences in the delivery cost of biomass, which includes loading and unloading in addition to transportation. This cost is likely to be borne by either the biorefinery or a third party logistics provider (3PL). The delivered cost is largely dependent upon transportation distance, which varied substantially based upon crop yield. The average biomass transportation distance for all scenarios is given in Table 3-2.

Average transportation distance and biorefinery capacity were the two key factors affecting the number of trucks needed to transport all biomass in a given year. The number of 36 m^3 (1280 ft^3) trucks required ranged from 1 for maximum yield at all sites for the 50,000 t capacity, to 47 trucks at the Fahler site for minimum yield for 500,000 t capacity. In some cases, the required trucks for minimum were almost twice that of maximum yield. For example, the 500,000 t Grimshaw facility required 23 trucks for maximum yield and 45 for minimum yield. Truck requirements for Fahler are shown in Figure 3-3 as an example. All trucks are assumed to return to the pick-up site empty, meaning no backhaul revenue. For all cases, only one loader and one unloader were required (ie. the yearly capacity was greater than 500,000 t). However, real-world conditions would require a larger number of loaders and unloaders, but these would be under utilized.

All delivery cost curves, including loading, transportation, and unloading, were virtually linear, with R^2 values ranging from 0.999 to 0.995. Total delivery costs ranged from less than \$5 per tonne for 50,000 t Grimshaw, Peace River, and Sexsmith cases to over \$40 per tonne for 500,000 t Fahler, Grimshaw, and Peace River cases. The real minimum 500,000 t case for Sexsmith had a delivery cost of \$89.13. Fahler delivery cost is shown in Figure 3-4.

After determining linear functions for all sites and all yields, it was possible to establish an equation, based upon capacity and average transportation distance, approximating all results:

$$Y_{delivery} = \left(\frac{d \times c}{1000}\right)\left(\sqrt{\frac{0.058}{c}}\right) + 3.8 \tag{6.6}$$

where c is the facility capacity in tonnes per year and d is the average transportation distance in km. Delivered cost is the sum of harvest cost and delivery cost. Combining (3.5) and (3.6) gives the total delivered cost of biomass (or minimum purchase cost) of:

$$Y_{delivered} = 3\times10^{-6}x^2 - 0.0164x + \left(\frac{d\times c}{1000}\right)\left(\sqrt{\frac{0.058}{c}}\right) + 49.1 \qquad (3.7)$$

where, x is the average yield in kg ha^{-1}, fulfilling [$500 < x < 3250$], d is the average transportation distance in km, and c is the facility capacity in t yr^{-1}.

3.5 DISCUSSION

The three major variables affecting delivered price of biomass are transportation distance, yield, and scale (ie. how much biomass is needed in total). These three factors are inter-dependent but encompass other potential variables, such as cropping patterns. The equations presented here are accurate given existing fuel and equipment prices, but a significant change in prices will change the equations. However, they could be adjusted by running a similar scenario with a revised pricing regime.

Harvest costs did not vary significantly on a per tonne basis between capacities once a minimum 'harvest unit' of equipment was reached. This was the case for all capacities, including 50,000 t. The main determinant of harvest cost on a per tonne basis was yield. As yield decreases, biomass costs increase. These are largely driven by increased equipment use (variable costs) on a per tonne basis. Variable costs could be reduced in low yield years by decreasing the amount of residue left on the field for sustainability purposes. However, given the necessity to supply biomass over multiple years and the decrease in crop productivity associated with excess residue removal in the prairies, it would be counter-productive to overstep sustainability retention requirements.

Hoskinson et al. (2007) have also shown that increasing management practices, such as fertilization, do not have a positive net financial return for biomass.

There is a much greater variability both in yield and delivered price between minimum and maximum scenarios for an individual site than between different sites. Therefore, from a feedstock availability perspective, once a given region or ecosystem has been selected for biorefinery feasibility analysis, specific siting is not as important as determining year-to-year variability in regional biomass production. In addition, the inclusion of multiple feedstocks of the same type (ie. annual small grains) does not mitigate the feedstock availability risk. Yields for all three crops studied (barley, oats, wheat) were consistently good in the same years and poor in the same years. Supply risk would have to be mitigated through multi-year storage systems, perennial herbaceous or woody biomass, logging residues, and/or importation of feedstock from outside the region.

It is important to remember that the minimum case for all analyses is an artificial minimum, with productivity set at one-half the average productivity. The real minimum yields were not high enough to justify an analysis. Even Sexsmith residues, which had the highest minimum yield of 0.2 t ha^{-1} (after accounting for sustainability retention) and an average delivery cost of $89.13, would not likely be harvested. Feedstock would have to come exclusively from sources other than regional annual crop residues.

According to Jenkins et al. (1984), consideration needs to be given to biomass seasonality, field conditions, and competition for biomass from other sources (eg. animal bedding). While seasonality and field conditions are accounted for with the weather module of IBSAL, it did not account for competition from other sources. This type of analysis would require ground-truthing, discussions with farmers, and a host of assumptions to arrive at a reasonable figure. This competition for biomass assessment would be the next stage in determining feedstock availability.

The large differences in delivered cost of biomass are largely the result of increased machinery requirements and usage. This is true not only for harvest machinery but also for trucks. One loader and one unloader are required for all cases, so on a per tonne basis, this is cheaper for larger capacity biorefineries. Optimization of equipment and maximization of capacity must be a priority for the economic viability of any biomass-dependent processing facility.

3.6 CONCLUSION

Feedstock supply is a major financial risk for biorefineries. Delivered price of feedstock is highly dependent upon biomass yield. As yield decreases, price increases to a point where it becomes uneconomical to harvest and transport biomass. In some years, after accounting for sustainability residue retention, no biomass is available. Boom and bust agricultural regions, such as the study region of Peace River, Alberta, are not a good choice of location for a biorefinery due to the variability in biomass availability from year to year. Alternative feedstocks beyond local crop residues would be essential for continuous processing over the lifetime (20 years) of a biorefinery. If a facility could only run on crop residues due to the technology employed, feedstocks would need to be imported. This would likely require densification to reduce the shipping cost. Siting biorefineries in regions with lower production variability would allow operators to plan required equipment regimes more accurately and reduce feedstock supply risk.

Parameter	Unit	Value
Annual interest rate	%	6
Equipment operating time	hr/in-field hr	1.1
Labour time	hr/machine hr	1.2
Diesel consumption	gal/hp-hr	0.0438
Fuel cost	$/gal	$2.75
Base labour	$/hr	$15.52

Table 3-1 General parameters used in the harvest and delivery modules of IBSAL Ver 4.2

	Capacity (1000 t)	Distance (km) – Min	Distance (km) – Avg	Distance (km) – Max
Fahler	50	67.4	47.6	36.0
	100	95.3	67.4	50.9
	150	116.7	82.5	62.4
	250	150.6	106.5	80.5
	500	213.0	150.6	113.9
Grimshaw	50	64.5	45.6	32.4
	100	91.3	64.5	45.8
	150	111.8	79.0	56.1
	250	144.3	102.1	72.4
	500	204.1	144.3	102.4
Peace River	50	65.4	46.2	34.3
	100	92.5	65.4	48.6
	150	113.3	80.1	59.5
	250	146.2	103.4	76.8
	500	206.8	146.2	108.6
Sexsmith	50	62.1	43.9	33.4
	100	87.9	62.1	47.3
	150	107.6	76.1	57.9
	250	138.9	98.2	74.8
	500	196.5	138.9	105.7

Table 3-2 Maximum, minimum and average biomass transportation distances to biorefineries of varying biorefinery capacities

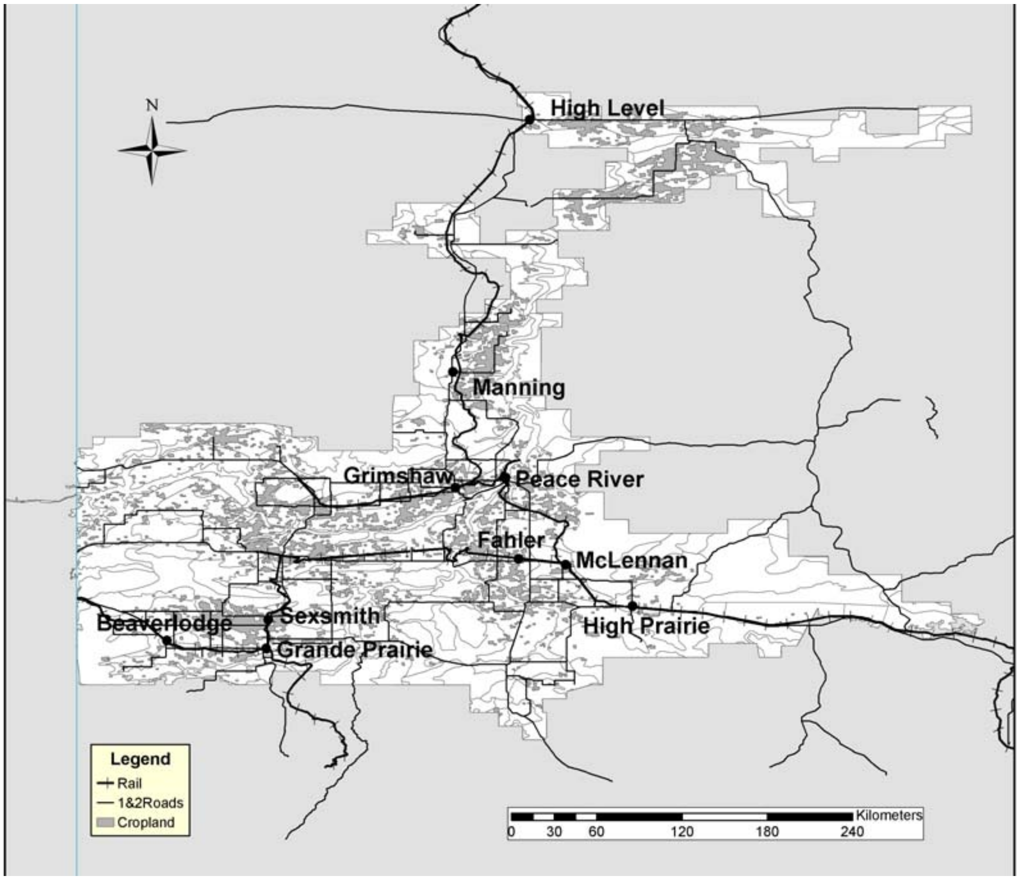

Figure 3-1 Peace River Region with 10 study sites

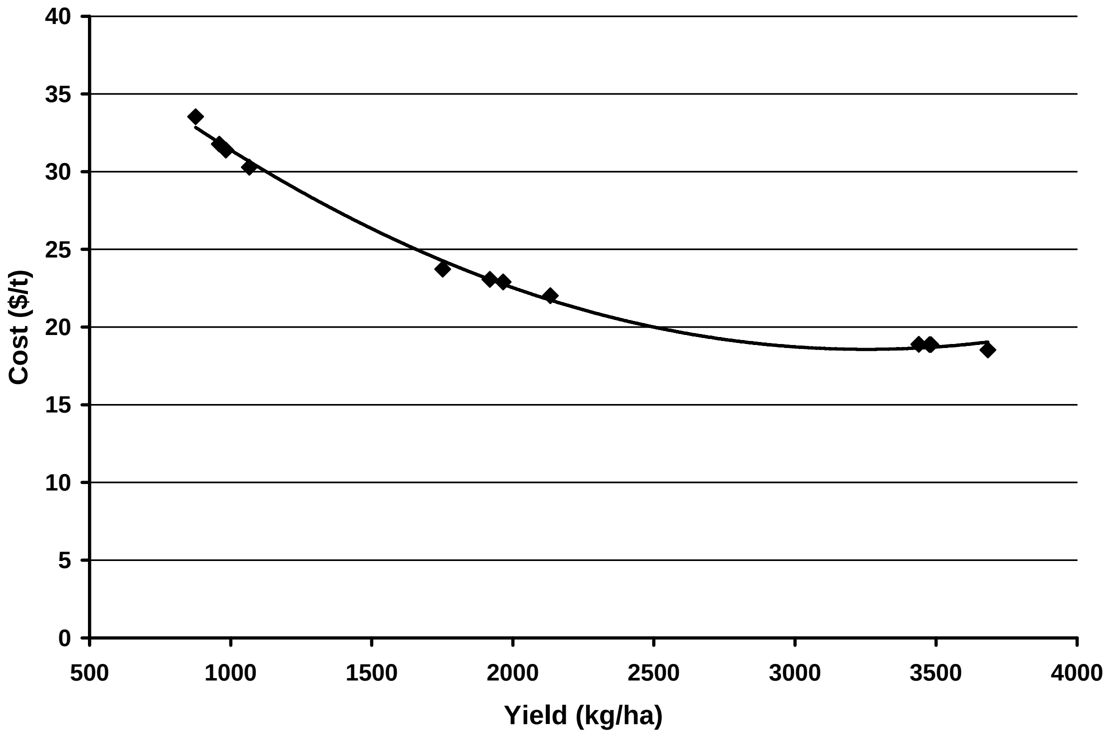

Figure 3-2 Harvest cost vs. biomass yield before sustainability residue retention

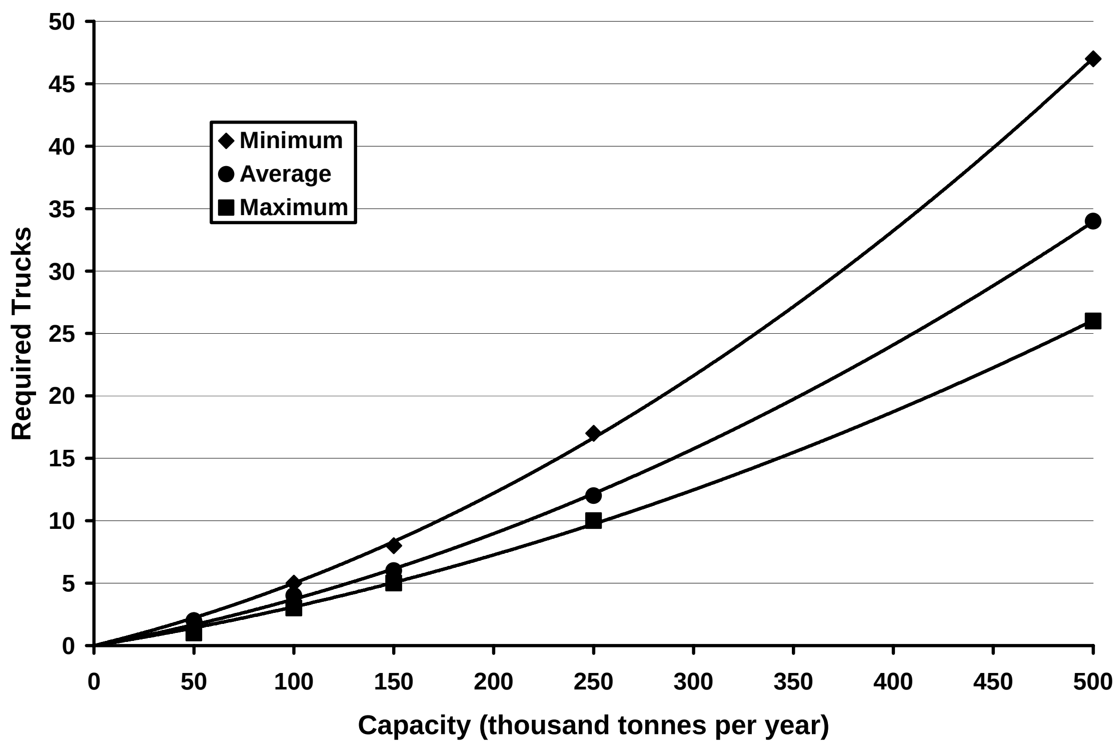

Figure 3-3 Number of trucks required for a Fahler-based biorefinery of varying capacities

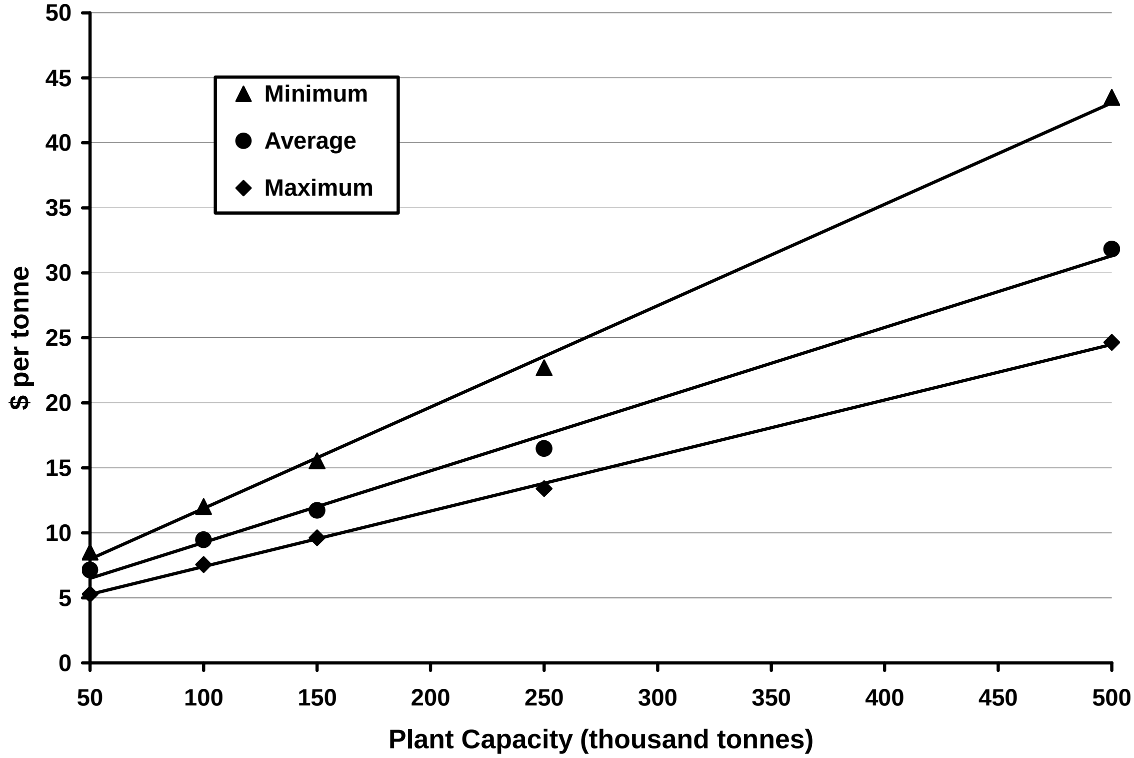

Figure 3-4 Biomass delivery (loading, transportation, unloading) cost vs. plant size for Fahler site

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4 DISCUSSION AND CONCLUSIONS

The purpose of this work was to determine the variability in feedstock supply for a biorefinery operating on annual crop residues from small grains, and to create a methodology that could be applied to any agricultural region for risk quantification. Based upon the case study of the Peace River region of Alberta, it is possible to conclude that feedstock supply variability and risk are significant and should be a central focus of any biorefinery business case analysis. The hypothesis, "Inter-year availability of crop residues will be highly variable over the lifetime of a biorefinery, thereby creating significant inconsistency in the delivered price of feedstock and impacting overall operating costs", has been proven correct. For example, the combined harvest and delivery cost of feedstock for the 500,000 t Sexsmith biorefinery ranges from \$41.78 t^{-1} for the maximum scenario to \$70.98 t^{-1} for the simulated minimum scenario. The transport cost alone for the true minimum is \$89.13 t^{-1} and harvest of the residues is likely both technically and financially unfeasible.

The literature review Appendix 3 of this thesis shows that significant work has already been done in the fields of logistics and risk quantification. However, modellers of biomass supply, such as those described in Appendix 4, have largely assumed a consistent feedstock production schedule. This thesis has proven that this assumption, over the lifetime of a biorefinery, is inaccurate and does not represent real world outcomes.

4.1 PRODUCTION AND SUPPLY VARIABILITY

Chapter 2, which is the first of two manuscripts, focuses on the variability in feedstock supply over the operating lifetime (20 years) of a biorefinery. While numerous studies have examined the variability in grain production over extended time frame (eg. Fischer 2007), only a select few have studied biomass production variability. This small group includes work by Sokhansanj et al. (2006b). However, many of these studies, including Sokhansanj et al. (2006b), are at the country or multi-ecosystem level. The Chapter 2 manuscript is the first to examine inter-year variability in biomass supply using real-world data and to create a methodology for future study. By using real-world data from the Peace River region of Alberta, it was possible to determine that minimum and maximum yields were ±99% from average availability. This was for the four most productive sites in the region. Availability was a more pronounced measure than production due to the sustainability requirement of 750 kg ha^{-1} of residues remaining on-site. As discussed in Appendix 5, this residue is essential to maintaining adequate soil organic matter and moisture levels. It would be counter-productive to over-harvest the supply area for a biorefinery that requires feedstock over 20 years.

4.2 YIELD VARIABILTY AND SUPPLY COSTS

After quantifying the variability of feedstock supply over 20 years, it was important to determine how this would affect the business model of a biorefinery. As feedstocks represent 40 – 60% of the operating costs of a typical biomass processing facility (Caputo et al. 2005), variability in delivered cost will substantially impact the overall facility economics. Five biorefinery sizes, ranging from 50,000 t yr^{-1} to 500,000 t yr^{-1}, were chosen for study. Using the IBSAL model, first described by Sokhansanj et al. (2006a), harvest and delivery costs were determined in a dynamic simulation. Harvest costs, on a per tonne basis, are largely dictated by crop yield. The closer a piece of equipment is to capacity maximization during use, the lower the per tonne harvest costs will be. Harvest costs (\$ t^{-1}) did not vary greatly between biorefinery capacities when yield was held consistent.

Yield also affected the delivery costs by influencing the primary cost driver of transportation distance. A reduction in yield means a larger area needs to be harvested to supply the same amount of feedstock and fulfill the operating requirements of a biorefinery. Delivery costs were linear in relation to biorefinery capacities, with minimum yield years having the steepest rate of increase (slope). However, a key factor in the analysis is that since no biomass was available in minimum yield years (as per the conclusions of Chapter 2), the minimum case was simulated at half the average and did not represent real world minimum. Since there was no biomass to harvest, it was not possible to determine a delivered price.

4.3 STRENGTHS AND WEAKNESSES OF METHODOLOGY

The Geographic Information System (GIS) vector-based methodology of criteria (rail, road, population) and buffering was effective at selecting and comparing potential biomass sites. While it was not completely optimized, as could be the case with a raster-based methodology, it could be applied to real world scenarios. This work also showed that weighting based upon average yields is not relevant to real-world performance. However, as with all GIS, results are only as good as the data used. Since the newest data available were from 1995, they were somewhat out of date. An updated data source would greatly improve the accuracy of the analysis.

Since historical data were used for the analysis, a major risk factor in the real-world applicability of the analysis is whether future weather and crop yield will differ greatly from historical data. Adding a climate change model, or at least modifying crop yields for climate change, would increase the complexity of the analysis but would better represent projections for the future.

The only GIS data available on agricultural productivity were on grain production and not biomass. The results of this analysis are highly dependent upon material-other-than-grain (MOG) to grain (G) ratios. As these ratios have changed over time, and are also very seasonally variable, the accuracy is questionable. They should be interpreted as an approximation. Accurate GIS data on biomass production would significantly enhance the real-world relevancy.

This analysis assumes all 'available' feedstock (after discounting for sustainable soil requirements) are actually available for use in a biorefinery. This is simply not the case as there are competing uses for this biomass from the animal feed and bedding industry, amongst others. Quantification of this feedstock competition would require ground truthing, interviews with farmers, and identification of specific high-demand users (eg. other biomass processing plants). This would be the next stage in any feedstock analysis for siting a biorefinery.

The IBSAL model was effective at simulating real-world harvest, handling, and transportation conditions. The largest challenge with the model is ensuring that equipment information is up-to-date and that all processing steps have been accounted for. In addition, the real-world accuracy of assumptions on material losses, energy consumption, and emissions will vary by situation and over time. Further research could help refine these data inputs.

Spreadsheets were used as the 'go-between' linking GIS (ArcView®) with IBSAL. This worked acceptably, but involved significant amounts of data transfer and rearrangement. A macro linking these two programs would increase efficiency and minimize potential for data transfer errors.

The largest sources of uncertainty in this research are the large generalizations involved in all aspects of siting, crop production and residue removal rates, and equipment usage. This analysis and case study are meant to give a general approximation of real-world conditions. Results should not be considered definitive and a large margin of error must be assumed.

4.4 APPLICATION OF METHODOLOGY FOR FURTHER STUDY

The Peace River region of Alberta was chosen as the case study site due to the 'boom and bust' productivity of the region. However, any location for which agricultural crop production GIS data are available could be used as a study site. This could also include crops beyond the three species studied here, such as corn, flax, and canola.

This system could also work well with bioenergy crops, such as switchgrass, willow, elephant grass, and poplar. In fact, IBSAL has already been used to model switchgrass harvest and delivery (Kumar and Sokhansanj, 2007). Since these would be newly established crops, GIS data could be updated to reflect the change in cropping patterns.

Currently, IBSAL is geared towards agricultural harvest and biomass supply chains. However, due to the flexibility of the program and the ability to add new pieces of equipment and processing steps, IBSAL could be applied to forest-sourced biomass. GIS data on forest biomass are readily available in Canada and could be used as the primary source. If harvest residues ('slash') were the target feedstock, the user could employ percentage of total biomass ratios, similar to using MOG:G ratios, to determine slash availability. This could be particularly valuable in regions such as the Peace River where both agricultural and forest feedstocks are available. A facility running on different kinds of biomass could choose the cheapest feedstock option in a given time frame based upon results of the GIS-IBSAL system.

4.5 CONCLUDING IMPLICATIONS FOR THE BIOENERGY INDUSTRY

This research has shown that for agricultural-based biorefineries and biomass processing facilities, feedstock is a major operating risk. Being entirely dependent upon the production of residues from a single year in a highly variable region is not a viable strategy over the 20 year lifetime of facility. Therefore, it is important for companies wishing to establish biorefineries to not only focus on their technology, but create a comprehensive feedstock supply management system. This could include siting that takes advantage of existing transportation infrastructure to import feedstocks from other regions. This feedstock would likely come in a densified form, such as pellets or briquettes. Given the feedstock risk for any bioenergy operation, proximity to port and rail facilities may be higher on the location optimization priority list than local feedstock production.

Investors in bioenergy enterprises need to consider not only the technology employed by the project proponent, but also their intended feedstock and the availability and security of that feedstock. The availability needs to be assessed not only as an average, but also in terms of year-to-year variability. The large capital costs involved in constructing a biorefinery, or any processing facility, need to be paid back over an extended operating lifetime. If the plant cannot operate due to lack of feedstock, these become sunk capital costs. Failure of one or two biorefineries would have significant negative impacts on the bioenergy sector as a whole.

Companies planning to establish biorefineries will want to limit their feedstock supply risk by purchasing biomass through contracts well in advance of delivery. Since farmers will likely not be able to guarantee feedstock, it may come down to the biorefinery company growing, harvesting, and managing their own biomass. This will provide greater security and reduce overall operating risks. Supplying the biorefinery with feedstock would be the producer's priority, and not a secondary, add-on product market as it would be for crop residues from farmers. However, if lignocellulosic biomass is the preferred feedstock, there are better options available than crop residues. C4 grasses, such as switchgrass, have much higher productivity and lower nutrient and water requirements. Being perennials, bioenergy crops also do not need to be replanted each year and therefore have much lower active management requirements (Madakadze et al. 1999).

4.6 FUTURE RESEARCH

Many published techno-economic analyses for biomass processing facilities exist (eg. Caputo et al. 2005), but none take into account real world variability in annual crop residue feedstock supply. For future work, researchers wishing to create accurate and industrially relevant techno-economic analyses need to focus on feedstock supply variability as a key cost driver. At a minimum, sensitivity analyses on biomass production are required, but historical crop yield data, combined with future climate conditions and productivity estimates, would substantially increase the value of bioenergy techno-economic analyses. After the findings of the current research, it would be wrong to assume that average production with average operating costs represents real-world conditions.

Research is required to compare the various criteria for siting of facilities, with an emphasis on transportation infrastructure and feedstock supply variability. This would help identify the key cost drivers and the priority site requirements. Essentially, it is a question of whether the processing facility should be brought to the biomass, the biomass to the processing facility, or a combination of the two. As the current research did not deal with technology selection at all, the interaction between technology selection and siting is also an important variable that needs to be further assessed. Feedstock property requirements (eg. size of particles, age, and moisture content) of a specific technology could be used as constraints in IBSAL. Technology selection will also play a role in the scale of processing facilities, which, as the results of this work highlight, significantly impacts delivered cost of biomass.

Chapter 3 of this thesis is the third manuscript to be published on IBSAL. This model has increased in durability and accuracy since its inception, but there are still several improvements and enhancements that could be made. A long-term goal is to enable IBSAL to be used online by companies, governments, and individuals. In combination with a coupled GIS program, it would function as a decision support tool for biomass harvest, handling, and delivery operations. Users could change variables, such as required biomass quantity, available equipment, and siting criteria, while receiving results on delivered price, greenhouse gas emissions, fuel consumption, and available biomass. Agriculture and Agri-Food Canada Prairie Farm Rehabilitation Administration has plans to establish such a 'biomass portal' using IBSAL and real-data driven GIS.

As new types of equipment become available, they can be added as blocks within IBSAL. Information on energy use and capital costs needs to be regularly updated. IBSAL could also be used for other types of biomass, such as biomass crops and forest harvest residues. A forestry version of IBSAL is currently being developed (with various equipment blocks) and a combination of the two would allow users huge flexibility in machinery and feedstock selection.

Linking GIS and IBSAL allowed for relatively accurate modelling of real world conditions. However, as discussed in Appendix 4, several comprehensive agricultural models, such as APSIM and DSSAT, already exist. Integrating IBSAL with these models would allow researchers and feedstock managers to determine how crop management practices affect biomass production and how biomass growing conditions, handling, and management practices impact delivered residue price.

The accuracy of GIS and IBSAL results is dependent upon the accuracy of the data entering the systems. This is also true of the precision. Research into the performance of equipment in terms of energy use, emissions, productivity, and operating conditions will improve the accuracy of blocks within IBSAL. Detailed assessments of land use and productivity in study regions will increase the accuracy of GIS results, just as region-specific MOG:G ratios will increase the precision of biomass production estimates.

As is clearly evident from the analysis, long transportation distance drives up the specific price of biomass. Research into biomass densification and handling systems is essential to attain the economies of scale that benefit fossil fuel processing facilities. Due to higher bulk density, densified biomass feedstocks cost less to transport on a per tonne basis. This could significantly improve the economics for large-scale biorefineries.

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Appendix 1 IBSAL LAYOUT

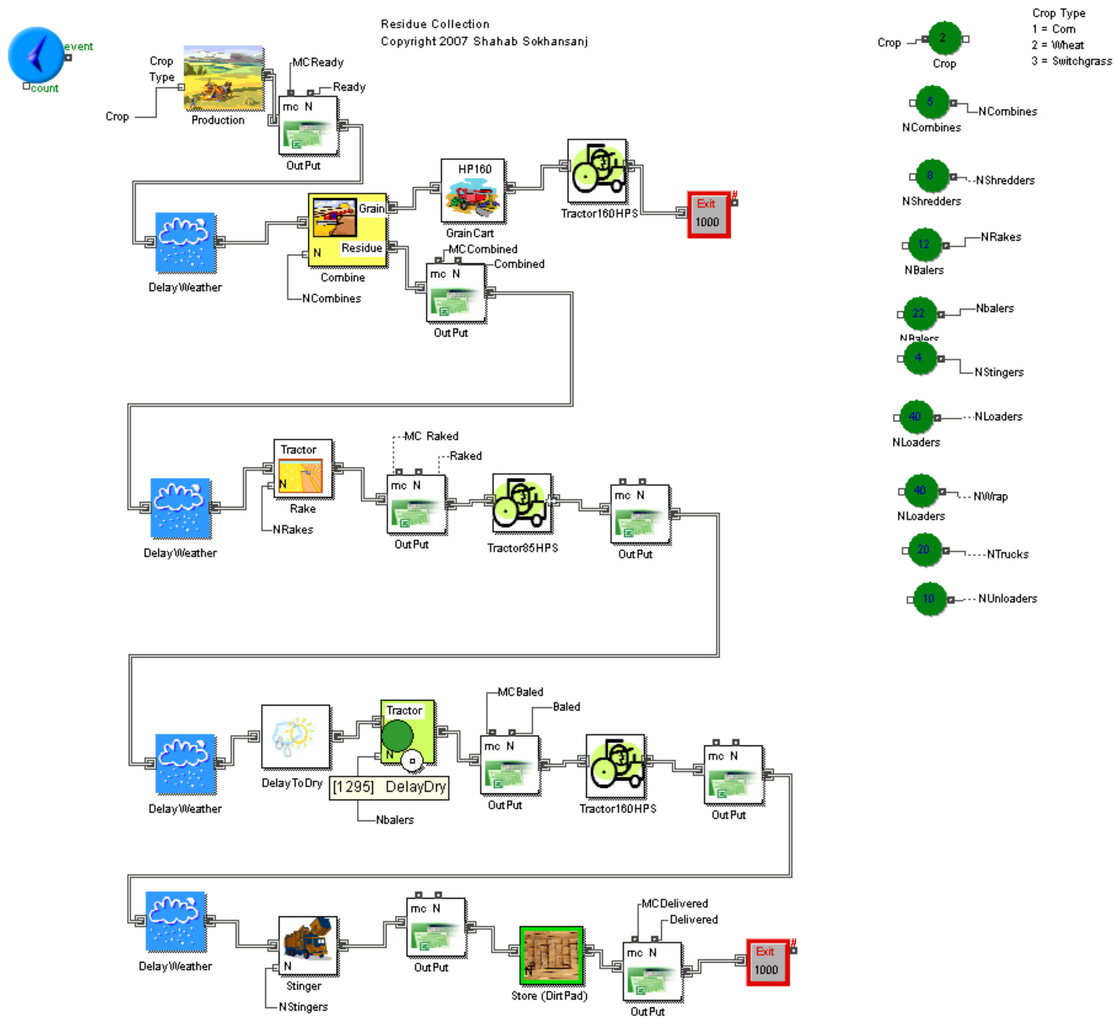

Figure A1-1 IBSAL Harvest Module

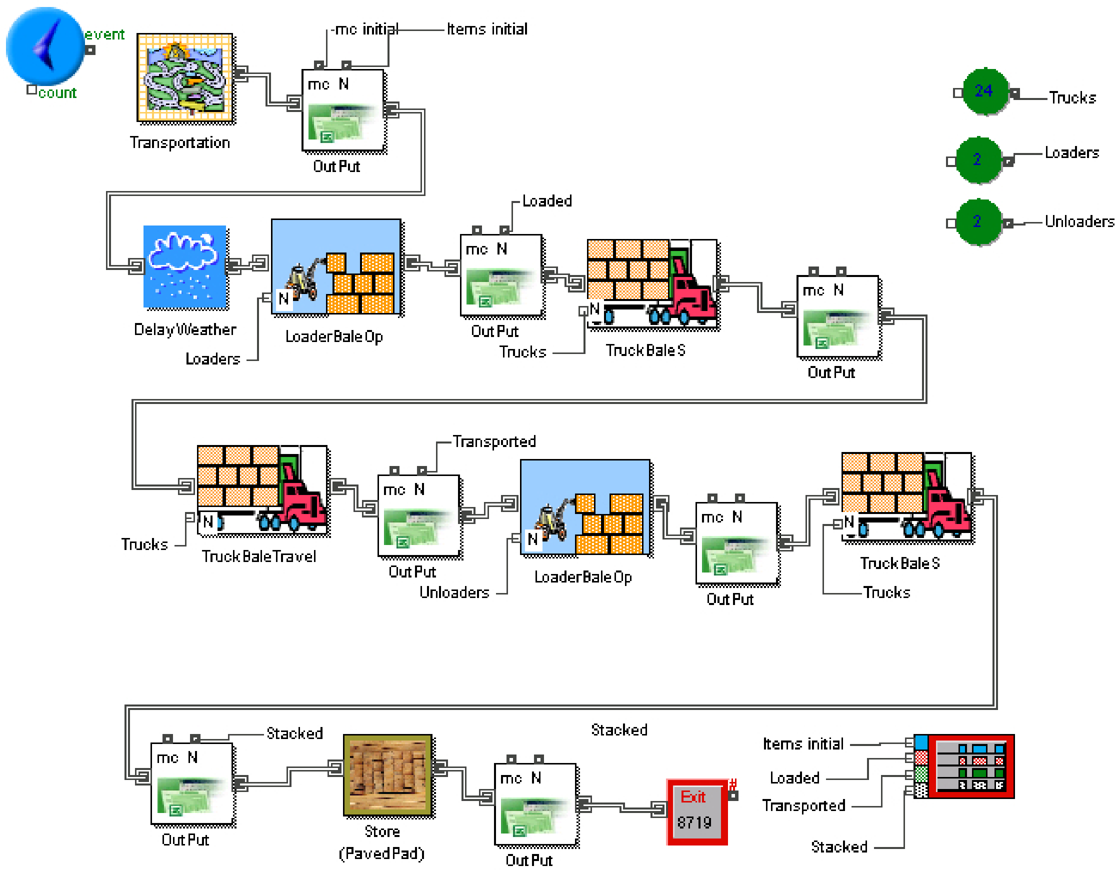

Figure A1-2 IBSAL Transportation Module

Appendix 2 EXAMPLE OF ADDITIONAL IBSAL OUTPUTS

Harvest	Emissions (kg CO_2e t^{-1})	Energy Use (kBtu t^{-1})	Dry Matter Loss (t)
50,000 t	14 – 18	185 – 205	175 – 250
Delivery			
50,000 t	9	113	1,684
100,000 t	36	436	3,367
150,000 t	48	580	4,212
250,000 t	67	815	7,582
500,000 t	86	1,049	15,159

Table A2-1 Emissions, Energy Consumption, and Dry Matter Loss for the Fahler Average Case

Appendix 3 BIOMASS FEEDSTOCK LOGISTICS

A3.1 LOGISTICS INDUSTRY

According to the Council of Logistics Management (1998), "Logistics is that part of the supply chain process that plans, implements, and controls the efficient, effective flow and storage of goods, services, and related information from the point-of-origin to the point-of-consumption in order to meet customers' requirements." Hence, logistics deals with management of material and information flow within and across the supply chain, and therefore supply chain management could be considered a broader subject than logistics. Supply chain management components include planning and control of operations, work structure on task and activity performance, organizational structure of how an individual company fits with a broader supply chain, and product flow facility structure (the network for sourcing, manufacturing, and distributing across the supply chain) (Lambert and Cooper 2000).

Research Impact: Focus on logistics of biomass feedstocks, which is a key component of the bio-based product supply chain.

The logistics industry plays a central role in the economy and represents approximately 10% of US GDP, although this is decreasing due to increasing efficiency (Aoyama et al. 2006). Key trends of the industry include the shift of producers to focus on their core product generation competency and the associated reliance on third party logistics (3PL) firms, both asset and non-asset based. For biomass, this would mean a bioproduct conversion facility may outsource feedstock supply and management to an external party. According to Gordon (2003), the 3PL industry is growing at 20% per year. 73% of Fortune 500 companies now outsource their logistics (Gooley 2002), which allows the logistics companies to take advantage of economies of scale and focus on improving their expertise. The vast majority of these companies are either geographically or product specialized in their logistics management.

According to Davidsson et al. (2005), logistics can be divided into three domains: transport, where something is moved; traffic, which is the flow of transports within a network; and terminal, nodes which are loading, unloading, or reloading points. Transportation is deemed the most important and expensive component of logistics for most industries. There are five basic modes of transportation: road, rail, air, water, and pipeline (Stock and Lambert 2001). Road offers the greatest flexibility and is usually used at the beginning and end of supply chains. It is often used when rapid delivery is required over short distances. Rail and water are used for transportation of bulk goods over long distances, with water usually the cheapest on a per unit basis. Pipeline requires significant infrastructure investments and is reserved for gas or liquid transport of bulk materials. Air is by far the most expensive means of transport and is utilized for high-value products. As stated by Davidsson et al. (2005), selection of transportation mode is dependent upon type of goods, required speed, handling, cost, distance, and schedule flexibility. When goods are moved using more than one type of transport in the same unit without handling the goods themselves, this is called intermodal transportation (European Conference of Ministers of Transport 2001).

Logistics can be also divided into the level of decision-making required, which usually correlates with a time horizon. Strategic level planning involves long term decisions on what to do, while tactical planning involves the establishment of a medium term action list. Operational decisions are usually short term and are associated with how to deliver on specific items (Schneeweiss 1999). In the case of biomass, strategic level planning would include the siting of a conversion facility, which feedstock to use, and the scale of the enterprise. Tactical planning would include the design of a supply system, including how to minimize supply risks and equipment selection. Operational encompasses the day-to-day operations of supplying a conversion facility with a consistent, standardized, and reliable feedstock.

Logistics is always faced with two key questions: the facility/plant location (and scale) problem and the freight distribution problem. For biomass, a third question of biomass production is added to this. Facility location questions were historically addressed by heuristics (rules of thumb) and identifying key selection criteria, but modelling and optimization now dominate the field of siting Freight for bio-based processing facilities has a feedstock (enter) component and processed product (exit) component. This implies that location must not only be dictated by product demand, but also by feedstock availability, which significantly increases the complexity of any analysis. Freight distribution is mathematically modelled and falls within the realm of operations research (Troncoso and Garrido 2005). For an enterprise that is dependent upon a biological feedstock, there is a need to concurrently address production and logistics in an integrated manner.

Research Impact: Research was conducted as if functioning as a 3PL provider, factoring in harvesting and transportation requirements. The work focused on road transportation due to the relatively short distances involved (from field to conversion facility). Dynamic modelling occurred at the tactical level, while site selection occurred at the strategic level.

Meixell and Gargeya (2005) reviewed the literature on global supply chain design and the decision support models used to design those supply chains. A key component of their analysis was the correlation between research literature and model outcomes in relation to real-world practical issues. Classification of the supply chain models was based upon questions addressed by the model, the performance measures, the integration of multiple questions to arrive at singular or multiple decisions, and the scope of the models (ie. domestic vs. international). Key questions for these models were consistently facility site and size selection (and hence scale of shipments), and supplier selection. Other important variables included financial structure, product allocation, and transportation selection. Many used heuristics and tried to incorporate real-world limitations.

A3.2 BIOMASS LOGISTICS

A3.2.1 General Heuristics for Bioenergy Systems

Biomass logistics planning can draw from logistics knowledge and experience in other industries, but many unique characteristics exist. The industries with which bioenergy systems usually function in cooperation (agriculture and forestry) are also the greatest source of information on effective logistics planning. Consideration needs to be given to biomass seasonality, field conditions, and competition for biomass from other sources (eg. animal bedding), according to Jenkins et al. (1984). The authors emphasized the importance of a comprehensive systems approach to biomass supply management. They proposed a strong relationship, in terms of cost and equipment optimization, exists between biomass handling and preprocessing, and the conversion system.

Caputo et al. (2005) analyzed the economics of logistics and their effect on the overall viability of biomass gasification and combustion facilities. The main logistics variables included specific vehicle transport costs, vehicle capacity, specific purchased biomass costs, and distribution density. To focus on the logistical component of bioenergy operations, conversion plants were modelled as a black box with feedstock input and product output.

Feedstock could be supplied to a processing facility through contracts with individual growers, a group of growers through a cooperative, or via long-term land leases and harvest managed by the company running the processing facility or a contract feedstock management company (Thorsell et al. 2004). The ideal situation for the processing facility is to price biomass in relation to the cost of the suppliers. In this manner, suppliers closer to the site would receive the same payback as those further from the site. However, on a practical level, this is more difficult than a standard delivered tonne payment. This format would give advantage to those living closer to the plant and disadvantage those further away. The key figure for biomass transportation decisions is marginal cost. Marginal cost is the cost of collecting and delivering from the most outlying collection site. The marginal cost changes as the most outlying site changes. Knowledge of actual supplier (farmer) costs is essential if feedstock is to be priced based upon return to supplier.

Research Impact: All information on equipment specifications and requirements was included in the dynamic modelling to determine an accurate delivered cost. Harvest cost to a farmer or third-party harvester was determined so that purchase cost could be based upon supplier costs.

In an early analysis of biomass processing and handling, dynamic programming was used by Jenkins and Arthur (1983) in a node network to minimize overall chain cost. As operations are often not mutually exclusive, an entire preprocessing chain was essential for comparison. Each node within the network represented a handling operation. Network analysis can be displayed at two levels – the first showing every possible system, regardless of viability – and the second, a feasibility analysis including technical, economic, financial, social, biological, and political limitations. Jenkins and Arthur (1983) found that as transport distance changes, the optimum processing route also changes. At longer distances, chains with more processing but higher density feedstock (eg. cubes, briquettes, pellets) become more viable than undensified feedstock (eg. loose, bales). For example, the authors found that at 10 miles transportation, biomass cubing should occur at a central site following transport, while at 50 miles, cubing should occur in the field prior to transportation. Jenkins et al. (1984) noted that since round bales do not maximize the payload of a truck as square or rectangular bales can do, the unit transportation costs are higher. They are volume limited rather than weight limited. However, round bales have an advantage in reduced losses by withstanding uncovered storage. In their calculations, Jenkins et al. (1984) did not account for payment to farmers, costs of nutrient removal, erosion losses, or soil organic matter.

Ranta and Rinne (2006) assessed the economics of transporting forest harvest residues (slash) in the form of stumps, chips, and bundles. In all these configurations, transportation was limited by volume rather than weight. Both bundling and chipping doubled the bulk density of loose slash. The efficacy and economics of transportation are dependent upon form of the transported material, bulk density, moisture content, transportation distance, and technical specifications of transportation equipment. As is common with modelling, real world results did not perfectly match model results. Two of the key factors identified by Ranta and Rinne (2006) were variations in loading time (especially for loose, uncomminuted slash) and driver/operator experience and skill in handling stages.

Research Impact: As the research objective was to determine the impact of crop productivity variability on delivered cost and not to compare preprocessing regimes, an optimized preprocessing and handling procedure (large round bales) from previous research was used as the standard for all scenarios.

The delivered biomass price is given by the sum of the collection, transportation, and warehousing. In order to minimize the costs and optimize the delivery schedule, Tatsiopoulos and Tolis (2003) calculated the optimum quantity required from each producer using linear programming. They compared producers based upon quantities and where that biomass should be delivered. The authors found that farmers using their own vehicles were much cheaper than engaging a 3PL provider. Farmers should therefore engage in the logistics network and use as large vehicles as possible. Economies of scale develop as transport vehicle capacity increases (Tatsiopoulos and Tolis 2003).

Roos and Rakos (2000) examined the validity of models for bioenergy operations and their applicability to real-world situations. They found modelling methodologies used a standard sequence of problem awareness, formulation of the problem, modelling, validation, problem solving, analysis of the results, presentation of the results, and implementation. Several common features of bioenergy systems were identified by Roos and Rakos (2000). They included the use of local feedstocks as fuel, limitations on the number of full scale biomass installations in existence (making data and costing estimates inaccurate), and by-products of agriculture and forestry industries used as feedstocks for bioenergy. This makes bioenergy dependent upon the success of those industries. Cost structures are often site and condition specific and do not fit a general mould. Specific opportunity cost and personal preferences can significantly alter the setup and success of a project. Public perception is another issue which can completely change the face of a project and Roos and Rakos (2000) found projects that experienced resistance from the local community were on average 30% more expensive than those that had little or no resistance. Subsidies and government support are also something that is often required for biomass to compete with fossil fuels, but the long term availability and form of this support can be unpredictable. These can completely alter the financial structure of a bioenergy project. Individual discount rates and option values can help quantify risk for a project and assist investors make a decision on their desired return on investment (ROI).

Research Impact: As the research focus was on biomass feedstocks, conversion technology was not included in the assessment. The processing facility was considered the final destination and product mix was not the major focus of this work.

A3.2.2 Transportation Distance

Most analyses for biomass feedstock transportation involve calculation of a feedstock draw area to a central point. This central point can be the conversion facility itself or a storage hub from which biomass is further transported to a plant. A plant can have multiple storage hubs.

A Cartesian co-ordinate system is generally used to determine distance from delivery region to facility site. Jenkins et al. (1984) assumed uniform distribution of the biomass in an equivalent circle area. Therefore, average intra-regional transport distance, d, is given by:

$$d = \frac{2}{3} r \qquad \text{(A3.1)}$$

where r is radius of the draw circle area. For irregular areas and assuming transportation to a weighted central point, this becomes:

$$d = \frac{k}{2} \sqrt{a} \qquad \text{(A3.2)}$$

where a is area and k is a factor dependent upon the ratio of the short side to the long side of a rectangular field that varies from 0.75 when short/long is 1 and 1.6 when short/long is 0.1. The equivalent circle method is used to relate distance, d, to the area, a, by:

$$d = \frac{1}{\sqrt{2\pi}}\sqrt{a} = k'\sqrt{a} \tag{A3.3}$$

where k' = 0.4 and serves as an approximation for all rectangular regions.

Once the intraregional transportation distance has been calculated, interregional distance also needs to be determined for transport from supply area to central processing facility. The Cartesian coordinates of the conversion plant and storage depot are utilized to determine the straight line distance and are multiplied by the road tortuosity (bendiness), τ.

$$d = \tau\left[\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2\right]^{\frac{1}{2}} \tag{A3.4}$$

Where x and y are used for coordinate location. This is the standard equation used in determining the distance from two objects and is included in work by Nilsson (1999), as an example.

Research Impact: A central conversion facility with feedstock suppliers surrounding the conversion facility was assumed. Storage was at roadside and therefore, only one movement of the feedstock occurred – from field to plant. Distributed storage depots were not used for this analysis.

Based upon the average transportation distance, Caputo et al. (2005) used an equation for total travelled distance (km) in a year.

$$d_t = \frac{4}{3}\left(\frac{M}{D_b \Pi}\right)^{0.5} \times \left(\frac{M}{V_c}\right) \tag{A3.5}$$

Where d_t is the travelled distance, M is the annual biomass delivered to the plant, D_b is the biomass distribution density, and V_c is the average vehicular capacity.

Jenkins (1997) took a different approach to determining total yearly transportation distance. A rectangular supply region was assumed with the facility in a central location. According to Jenkins (1997), a rectangular shape should not alter the result from a circular supply region significantly. Initially, feedstock consumption is given by Q (t y^{-1}) and is the product of the average feedstock distribution q (t km^{-2} y^{-1}) in the region bound by X and Y (km).

$$Q = 4qXY \tag{A3.6}$$

The supply region can be further divided into rectangles with sides of x and y (km):

$$xy = \frac{nw}{q} \tag{A3.7}$$

where n is the number of truckloads of feedstock and w is the truck capacity. Therefore,

$$x = 2X\left(\frac{nw}{Q}\right)^{\frac{1}{2}} = \left(\frac{nw}{qb}\right)^{\frac{1}{2}} \tag{A3.8}$$

And the number of xy subregions in XY is given by m:

$$m = \frac{X}{x} = \frac{Y}{y} = \left(\frac{Q}{4nw}\right)^{\frac{1}{2}} \tag{A3.9}$$

Finally, total transport distance for the entire yearly fuel supply is given by d (km y^{-1}):

$$d = \tau 4nm^2(m-1)(x+y) = \tau\left(\frac{\mathrm{Q}}{\mathrm{w}}\right)(X+Y)\left(1-\frac{1}{m}\right) \tag{A3.10}$$

where τ is road tortuosity.

Research Impact: A circular draw area was used instead of a rectangular one. As biomass distribution will not be continuous and consistent throughout the system, a Monte Carlo simulation was used for random distribution. Yearly transportation distance could be approximated by adding Monte Carlo results for each trip. While subregions may increase the accuracy of assumptions, Monte Carlo simulation was considered more realistic for real-world conditions. A road tortuosity of 1.4, appropriate for the study region, was used.

Assuming full truckloads, total yearly vehicle trips were calculated by Caputo et al. (2005) using the formula:

$$T = \frac{4}{3}\left(\frac{c}{d}\right)\left(\frac{c}{x}\right) \tag{A3.11}$$

where c is the yearly biomass requirement of a facility, d is the average (uniform) biomass distribution density, and x is the standard capacity.

As time is a key factor in the economics of biomass transportation, accurate predictions are essential. Driving speed and time is a function of distance. Velocity is not consistent but approaches the maximum allowable speed as transportation distance increases. Ranta and Rinne (2006) proposed the following estimation for velocity, v, (km h^{-1}):

$$v = 9.3 + 1.27 \times \ln(l) \tag{A3.12}$$

where l is the driving distance in km.

Total time for transportation is given by the sum of loading, driving time, and unloading time, with additional consideration for delays and waiting time. Since total time (T) is given by:

$$T = \left(t_{load} + t_{drive} + t_{unload}\right) \times c \tag{A3.13}$$

where c is a multiplier coefficient. The coefficient c takes into account delays, queues, administration, and service breaks. As an example, Ranta and Rinne (2006) used a figure of 1.33. The time for driving, using a broad generalization multiplier, is estimated by:

$$T_{drive} = 11.6 + (2.009 \times l) - \left(0.00398 \times l^2\right) \tag{A3.14}$$

where l is the driving distance in km.

Research Impact: Loading and unloading times and cost were separated from transportation time and cost, as loading and unloading were considered standard regardless of location, while transportation costs vary depending upon distance travelled and time required. The difference in transportation cost resulting from variances in biomass availability is an essential output of this research. The methodology used dynamic modelling instead of static equations.

Ianooni and Morabito (2006) found that truck waiting and congestion of vehicles in the reception area of the processing facility could disrupt the integration of agricultural and industrial operations. A backlog of material waiting in trucks costs the operation in terms of lost productivity, labour, fuel for idling trucks, and opportunity cost for the use of trucks. Work by Kadam et al. (2000) focused on queuing and wait times for rice straw management. If P_0 is the probability of no transport units being in a queue or loading, the delivery rate is given by:

$$D_e = r(1 - P_0) \qquad \text{(A3.15)}$$

where D_e is the delivery rate and r is the loader rate. For a single loader system, P_0 can be given by:

$$P_0 = \left[\sum_{n=0}^{U} \frac{U!}{(U-n)!} \left(\frac{C}{r(2t+M)} \right)^n \right]^{-1} \qquad \text{(A3.16)}$$

where U is the number of transport units in the system, t is the field to plant trip time (h), M is the unloading and loading time for each trip (h), and C is the capacity of the transport units (t). Kaylen et al. (2000) assumed a grid system for transportation rather than determining road tortuosity.

A3.2.3 Transportation Cost

Total delivered cost of biomass feedstock is given by collection, processing, storage, and transportation costs. Collection, processing, and storage can fall under the general banner of collection, while transportation, due to its variable nature, stands alone. Transportation cost is dependant upon the package (form), biomass physical properties (including density, moisture content, etc.), transport mode, transport distance from field to processing facility, and unit transportation costs (per km or per hour). Transportation usually accounts for 50 – 70% of the delivered biomass cost (Caputo et al. 2005). Complications arise from the seasonality of biomass, its dispersed nature, and its low energy density, which make collection, transport and storage more expensive on a per unit basis than fossil fuels.

Jenkins et al. (1983) developed a method for creating minimum cost curves on delivered biomass. Although sites processing more than one type of biomass are rare, the method can be applied to any type or combination of biomass types. According to Jenkins et al. (1984), delivered cost, P (\$ t^{-1}), can be simplified into:

$$P = ax + b + c \tag{A3.17}$$

where a is the variable cost of transportation (\$ $(t\ km)^{-1}$), b is the fixed cost of transportation (\$ t^{-1}), c is the collection and processing cost exclusive of transportation (\$ t^{-1}), and x is the transportation distance (km). For example, Kumar et al. (2003) used a variable cost of transport of green biomass (straw) of \$0.11 t^{-1} km^{-1} and \$14 t^{-1} for acquisition (\$4 t^{-1} for purchase and \$10 t^{-1} for time in harvesting to the farmer).

Caputo et al. (2005) only used two variables and found that biomass transportation costs are the sum of vehicular costs (a function of distance) and transportation personnel costs (a function of time). Hence,

$$P = (d_T \times c_v) + (t_p \times c_l) \tag{A3.18}$$

where P is total cost for a trip, d_T is distance travelled (km), c_v is the specific vehicular transportation rate (\$ km^{-1}), t_p is the time used (h), and c_l is the personnel costs (\$ hr^{-1}).

Ranta and Rinne (2006) found the marginal cost of transport increased €0.35 ($0.55) MWh^{-1} $10km^{-1}$. Average transportation cost was assumed to be 2/3 of the marginal one since average distance is 2/3 of radius. Transportation distance is affected by the geometry and geography of the procurement area, the road network (both primary and secondary), and the processing site location relative to the procurement area.

According to Kumar et al. (2003), fuel transportation costs rise in approximate proportion to the square root of capacity. Biomass yield is extremely important to the overall costing, as it is directly related to transportation distance. However, as the authors noted, they assumed truck transportation for feedstock and currently no power generation facility of significant size relies on truck delivery of fuel via highways.

Research Impact: Logistics was divided into harvesting and delivery components. For delivery, accurate fixed loading and unloading cost were determined for the standard scenario. Variable costs were distance based, which, given accurate assessments of transportation rate (km hr^{-1}), reflected variable costs based upon time.

Cameron et al. (2007) determined the impact of feedstock cost on optimum conversion facility size and the technology employed at that facility. They found optimum plant size to be dependent upon plant cost (capital cost) and the distance variable cost (DVC) for feedstock transportation. DVC and distance fixed costs (DFC) constituted the delivered feedstock cost to the plant. DFC, including acquisition, harvesting, loading, and unloading costs, did not affect the study results on optimum size as they varied little with scale of facility. That is not to say they do not vary over the life of a conversion facility, but simply that the scale of that facility does not impact the DFC on a per tonne basis. The conclusion of Cameron et al. (2007) was that as feedstock cost increases (due to increases in DVC), higher cost facilities with a greater conversion efficiency become more economical. On the other hand, if delivered feedstock costs are low, a lower capital cost (and lower efficiency) facility is preferred. Hence, since transportation is the largest component of the DVC, longer transportation distances suggest using a higher efficiency conversion technology (such as gasification). Transportation distance is a function of biomass yield, and therefore the authors suggested high yielding biomass sources should be utilized in lower efficiency, cheaper plants to maximize economic gain. A figure of \$0.125 dry t^{-1} km^{-1} was used for the biomass trucking cost. A scale factor of 0.75 for plant sizing was used in the study. The final conclusion of the authors was that "technology selection for biomass processing is not independent of feedstock cost" (Cameron et al. 2007).

Research Impact: 50,000 t to 500,000 t processing plant capacities (in terms of feedstock input) were compared to quantify the impact of scale on variability in delivered cost of biomass.

A3.2.4 Comparison of Supply and Handling Chains

Hamelinck et al. (2005) created 12 bioenergy feedstock supply chains to compare the economics of locally produced and imported biomass. Various pre-treatment and handling options were compared to deliver feedstock to a plant in Western Europe. While they focused on woody biomass, several of their conclusions are highly applicable to crop residue systems. Due to the significantly lower production costs in Latin America and Eastern Europe, imports of densified biomass, namely pellets, could compete economically with locally grown biomass despite the long transportation distances. A high yield per hectare was vital to any of the systems due to high cost of truck transportation and the relatively much cheaper bulk transport by ocean and, to a lesser extent, rail. Hamelinck et al. (2005) determined chips were too low in density to be transported long distances (eg. by rail or ship). Truck transport was generally used for distances less than 100 km and when flexibility in schedule and sourcing locations was required. On a \$ t^{-1} km^{-1} basis, shipping was by far the cheapest and had the lowest environmental impact. According to the authors, "Densification strongly reduces the number of transport movements, although at a certain point the weight becomes restrictive instead of volume..." (Hamelinck et al. 2005). Despite the longer distances, the low production costs of biomass in importing countries (particularly in Latin America) meant the delivered cost of feedstocks could be half that of biomass produced in Scandinavia. Densification is essential, but given appropriate supply chains and sufficient scale, international trade in biomass is highly competitive. Delivered cost of biomass European biomass residues and biomass crops could be delivered at €90 (\$142) and €70 (\$111) t^{-1} (dry) respectively. This compared with South American pellets at €40 (\$63) t^{-1}.

Forsberg (2000) performed a life cycle analysis on biomass energy transport over medium distance (1200 km) via several different carriers: biomass bales, pellets, and electricity transmission grids. The producing region was Sweden and Holland was the destination. Forsberg (2000) concluded that transportation of biomass energy 1200 km, in any form, has a minimal impact on the overall net system emissions. Bioenergy system emissions are dominated by harvesting, hauling, and processing at the local level. Net energy inputs for bioenergy systems, when using modern processing and handling methods, are typically in the range of 7 – 9% of delivered electrical energy. Pellets were by far the worst performer for net energy requirements. Had pellets been shipped from another continent (eg. North or South America), this may not have been the case. The authors found that as transportation distance increased, more preprocessing (and hence densification) could be justified.

Research Impact: As the study was local region-based, investigation of long-distance transportation was not a priority. However, future research should address the issue of importing biomass to large central processing facilities that are strategically positioned to take advantage of large volume transportation infrastructure.

A3.2.5 Plant Scaling

As capacity of processing facilities increases, the marginal cost of biomass rises due to the increased transportation distance required. This is usually not the case when fossil fuels (eg. coal) are the energy source. Hence, more expensive, more efficient technology may be justified given low biomass distribution density and large transportation distance. Caputo et al. (2005) found this is not yet the case for gasification in the 5 – 50 MW range, but it may be the case at larger (or smaller) scales. Cameron et al. (2007) identified the three primary non-feedstock factors affecting financial success of a biomass conversion facility. They were the end product, the technology of conversion, and the scale of the conversion facility.

Jenkins (1997) explored biomass processing facility sizing, and the interaction between scale and feedstocks. The author found that a lack of information and data on facilities of larger sizes limit the accuracy of scaling factors for capital costs. The economy of scale for capital cost is given by:

$$\frac{C}{C_0} = \left(\frac{M}{M_0}\right)^s \qquad \text{(A3.19)}$$

where C is the installed cost of a study case facility, C_0 is the installed cost of the base case facility, M is the capacity of the study case facility, M_0 is the capacity of the base case facility, and s is the scaling factor. As s approaches 1, economies of scale are reduced and at 1, no economy of scale exists. While non-fuel operating costs also scale with size in a similar equation to capital costs, *s* may be a different value. To determine an optimal size for processing facilities, Jenkins (1997) needed to balance the economy of scale with biomass supply.

Combining estimates of delivery requirements with the economies of scale equation, Jenkins (1997) found the formula for optimization at:

$$M_{opt} = \left(\frac{2a_1}{a_2(1-s)M_0^{1-s}} \right)^{\frac{1}{1.5-s}} \tag{A3.20}$$

where M_{opt} is the optimal capacity of a facility, M_0 is the capacity of the base case facility, *s* is the scaling factor, and *a* is the constant coefficient.

Using a fuel density of 1000 t km^{-2} yr^{-1}, Jenkins (1997) found an optimal size of 305 MW with a variable *s* value (ie. as scale increases, the scaling factor changes as well). With *s* fixed at 0.9179, the optimal size was much larger at 1252 MW. Biomass processing facilities have been assumed to have a much lower *s* value than coal or nuclear (above 0.9), but Jenkins (1997) found biomass was similar to coal. However, *s* is a function of capacity and changes depending upon scale of the base case and testing case. Hence, analyses with a fixed scaling number may be inaccurate depending upon base and test plant sizes. Jenkins (1997) concluded that above a small size, true optimum is not critical for the financial viability of a biomass processing facility and a near-optimum is acceptable.

Kumar et al. (2003) also analyzed optimum plant size for biomass processing facilities using three different feedstocks: agricultural residues (grain straw), whole boreal forest, and forest harvest residues. The optimum size for agricultural residues was found to be 450 MW, while forest slash was less at 137 MW and whole forest double at 900 MW. There was a strong correlation between biomass density and relative scale, but all three plants were larger than traditional biomass processing facilities in North America. The authors found that none of the plants could be economically competitive with fossil fuel alternatives, but could become so if adequate emission credits were in place. Agricultural residues had a power production cost of \$50.30 MWh^{-1}. Fuel cost variability was negligible and therefore the major source (and hence change in marginal cost) was transportation distance. Despite identifying an optimal solution, the authors found that plants could be built from 145 – 900 MW with an output power price within 10% of optimum. For the optimum straw case, they assumed 0.416 dry tonnes ha^{-1} (gross) with a draw area of 61,000 km^2 (Kumar et al. 2003).

Research Impact: A scaling equation for feedstock costs was determined. As this research was not focused on the actual conversion facility, a capital cost scaling factor was inappropriate. However, it would be very important for a full techno-economic analysis of a biorefinery operation (despite the limited data).

A3.2.6 Feedstock System Considerations

As identified by Jenkins et al. (1983), processing facility siting must include environmental impacts, social impacts, financial viability including incentives, and proximity to market and feedstocks. General units used for management of biomass are yield ($t\ ha^{-1}$) and a transportation rate in \$ $t^{-1}\ km^{-1}$. Tembo et al. (2003) performed a sensitivity analysis by doubling the land costs, doubling the process facility capital costs, doubling the per distance unit feedstock transport costs, changing the project life from 15 to both 10 and 20 years, and using a variety of discount rates from baseline.

Elmore et al. (2008) highlighted the deficiencies in their analysis of rice residue availability in China regarding competing uses for feedstock. These competing uses included local energy production, feed for livestock, bedding for livestock, and soil organic stock contributions. Omission of these uses was largely due to lack of accurate data. However, the methodology and system created by the authors should allow incorporation of data as it becomes available, including application of the system to other sources of biomass (eg. biomass crops).

Gallagher and Johnson (1999) estimated the three primary costs of delivered biomass, nutritive value, harvest cost, and transportation cost, to equal \$17 - \$19 per ton in 1999 dollars. However, they did not provide incentive for the farmer, not did they discuss issues surrounding harvest timing, storage (including losses), and transportation (with associated congestion and unexpectancies).

Research Impact: This research focused on the theoretical availability of feedstocks based upon sustainability considerations. A constant yield across area and time was not assumed, as has been the case with many previous studies. A standard yield unit of $t\ ha^{-1}$ was used. Competing uses for available biomass will vary significantly by region and will need to be taken into account on a case by case basis. However, accurate data on these competing uses is difficult to find and is likely best accomplished through feedstock supplier (farmers) interviews.

Bio-based facilities require inventories of available biomass, preferably extended over several years, for tactical and operational planning. This includes production levels, transportation networks, and labour (Shi et al. 2008). However, a growing trend in forestry is to have harvesting operations controlled by industry rather than the forest owner (at least in Europe), and to have roundwood delivered just in time (JIT) (Hultqvist and Olsson 2006). This is part of larger JIT logistics trend across many industries and will likely be the case for most bio-based products. However, Gottfried et al. (1996) argued that natural resource managers, such as farmers, are very reluctant to make significant short term investments and changes (including financial and personal) to create larger, future public benefits.

Kadam et al. (2000) note the large variation in straw yield relative to grain, a result of environmental conditions, cultivar type, and management methods. Timeliness of straw collection is very important, as piles of straw left in the field can foster fungus, disease, and rodents. The authors noted that farmers will not allow interference with primary harvest operations and need significant economic motivation to change harvest practices. When it comes to straw collection, it can occur either after crop harvest (post-harvest) or simultaneously with collection of the primary crop (total harvest). Straw must be dry for baling (moisture content <25%). The general operations are raking, swathing, baling, stacking, and transport to roadside/field edge. Transportation of loose straw is very expensive on a per tonne basis and densification of some sort is usually required. At high bulk densities, weight can become the limiting factor.

Shah and Goh (2006) sought to improve the performance of supply hubs and create heuristics for their management. In this context, a supply hub can be defined as a location sited near a processing facility where some or all of the materials needed for manufacturing are located. These can be paid for only when consumed. Shah and Goh (2006) found the relationship between supply hub policy and standard performance measures is highly complex and non-linear. There are significant costs associated with both over- and under-stocking, but vendor managed inventory (VMI) puts the risks of those costs on the supplier (farmer). The supplier needs to determine how much and when to replenish the customer's inventory. Freshness clauses mean the customer (processor) takes ownership of the materials to be processed after a set amount of time.

The normal structure for a supply hub is for a third party logistics provider (3PL) to manage and operate the hub on behalf of the processor. Although variable by industry, 2 weeks supply is normally housed at the supply hub and shipments to the processor are handled by the 3PL. Shah and Goh (2006) found 3PL hub operators can ensure smooth operation of the facility by changing the over- and under-stocking penalties by suppliers.

Lignocellulosic biomass is less dense and irregular than grain, and harvest is complicated by weather conditions. This is particularly true when harvest occurs after grain harvest (ie. not in tandem). Due to the seasonality of biomass, 1 year's supply may be required in storage.

Research Impact: Storage was assumed to be at the edge of the field and central supply hubs were not employed for this analysis. As scale increases, or if on-field storage was not a possibility, the analysis could be extended to include central supply hubs. Farmer holding area is also a consideration, as small holdings may justify a central storage facility. However, most western Canadian farmers operate at a significant scale and the volume from a single farmer was considered to justify a storage site on farm.

Walsh (2000) described a method to estimate biomass feedstock supply, including the economic influences. These included variable cash costs (fertilizer, herbicides, seeds, cuttings, machinery repair, fuel and lube, hired labour, twine, etc.), fixed cash costs (taxes and insurance, operating and real estate interest, general overhead), and owned resource costs (land, producer's own labour, depreciation, non-land capital costs). Labour hours were assumed to be 1.2 time machine hours, while lubrication costs were 15% of fuel costs. Year-to-year variability was not accounted for and an average yearly cost was used. The supply curves developed by Walsh (2000) assumed that bioenergy crops must be as profitable as the average profitability of land in a given region. As this was a large-scale study, broad generalizations such as this were utilized by Walsh (2000) for methodology simplification.

A3.3 FACILITY AND MANAGEMENT ASSESSMENTS

Thorsell et al. (2004) used a multi-feedstock system of agricultural residues, native grasses, and managed perennials to optimize delivery to a central gasification-fermentation facility. They broke down harvest operations into functional units based upon machinery capacity. Each harvest unit contained nine tractors, 10 labourers, three mowers, three rakes, three balers, and one bale transporter, with a total capacity of approximately 50,500 t yr^{-1} and a capital cost of $590,000. However, this was based on a 9-month harvest window due to the multi-feedstock system. The cost of the primary harvest operations – mowing, raking, baling, gathering, and staking – ranged from $11.26 to $14.01 t^{-1}. Based upon previous work by Nilsson (1999), Thorsell et al. (2004) assumed a large rectangular bale (1.2 m x 1.2 m x 2.4 m) system for harvest optimization. Given the rectangular bale selection, a 150 hp (112 kW) tractor was required.

The Thorsell et al. (2004) study used the AGMACH$ agricultural machinery cost computer program for machinery (mower, rake, baler) selection to minimize cost. The MACHSEL program was used to coordinate machines and determine a functional harvest unit (ie. lowest common denominator), which included operational and maintenance costs. Labour hours were estimated to be 10% more than machine hours to account for set up, maintenance, and breaks.

Research Impact: IBSAL includes costing for all equipment included in the harvest and transportation supply chain. An outcome of the research was the identification of the simplest functional unit that can be multiplied depending upon scale of the operation. For transportation, this was loaders, trucks, and unloaders. A large round bale was assumed as the standard handling regime. A multi-feedstock system of biomass with similar properties – small grains (wheat, barley, oats) straw and chaff was used.

Grado and Chandra (1998) used a factorial design analysis of bioethanol production to determine the sensitivity of each system component to changes from the baseline. For lost opportunity cost from harvesting inefficiencies and storage costs, a penalty cost was applied to the selling price of the final product and represented unsatisfied demand cost. The authors found facility size was the largest component of cost variability at 45.3%, followed by price of alternative feedstocks (17.6%) and storage deterioration (17.4%). Interaction between facility size and storage deterioration was significant at 17.4%. A second factorial analysis that included ethanol production yield variability, harvesting capability, and plantation yield showed a smaller component assigned to facility size. In this second scenario, conversion efficiency to ethanol accounted for 44.0% of variability, followed by harvesting equipment productivity at 36.8%. Using a woody plantation as the feedstock, only 8.7% of cost variability could be attributed to feedstock yield. This low attribution may be increased when less reliable and lower yielding feedstocks are used (eg. crop residues).

Research Impact: Dry matter losses from handling, preprocessing, and storage of biomass feedstocks were included in the dynamic logistics system.

Caputo et al. (2005) sought to determine the relative importance of feedstock logistics on the overall economics of biomass combustion and gasification plants. The capacity range investigated was 5 – 50 MW, and the authors stated that the form in which the energy is required drives technology selection, immediately followed by decisions on appropriate biomass supplies. Although many techno-economic analyses investigate product mix and technology types, Caputo et al. (2005) simplified that portion of the analysis by focusing on the overall energy conversion efficiency. This was appropriate for an electricity or combined heat and power (CHP) facility. Their economic evaluation was broken into three components: capital costs, total operating costs, and revenues from electricity sales. Operating costs were broken down into operating labour costs, ash transport costs, ash disposal costs, purchased biomass costs, biomass transport costs, maintenance costs, insurance and general costs. The authors focused on the main biomass logistics variables of vehicle transportation costs, vehicle capacity, biomass cost (or farm-gate cost), and biomass distribution density. As clearly identified, this analysis assumed a uniform biomass distribution, a common approach for biomass-based techno-economic analyses. However, this is far from reality and does not account for year-to-year variability. To ensure a conservative result for the techno-economic analysis, Caputo et al. used a conservative figure of 5 t km^{-2} $year^{-1}$. This compares with real-world yields in the study region (Italy) of 50 t km^{-2} $year^{-1}$ for crop residues and therefore, plant size was not optimized to take full advantage of the available biomass. However, they also assumed 5 t km^{-2} yr^{-1} was the average for the entire catchments area, including those areas that do not grow crops or have no residues available. This further distorts the accuracy of their analysis from a feedstock perspective.

Matsumura et al. (2005) performed a resource assessment for rice straw and husk in Japan. These two types of biomass make up approximately 45% of the available agricultural residues in the country. They found that 61.5% of rice straw was ploughed into fields, which could reduce productivity of the next year's crop because of organic acid production during decomposition. No rice straw was being used for energy in Japan, but Matsumura et al. (2005) found that 3.8 billion kWh of electricity could be produced yearly from the 12 Mt of available residue, assuming an electrical efficiency of 7%. They assumed a highly distributed storage and generation system, with an average transportation distance of 3.0 km and a storage capacity of 1900 t. Plants were assigned a capacity of 1.25 t h^{-1}, with 5600 plants required to consume the available resource. The analysis was highly simplified, with units only running 2 months a year during peak summer demand. Since residues were harvested in the fall, this meant 10 months of storage. The authors estimated there would be no dry matter loss during this time. An important finding of the study was that, due to high labour and land costs in Japan, it was often cheaper to import residues than harvest domestic resources. The authors suggest "overseas contracts could be broadened to encompass not only food, but also all forms of biomass, including agricultural residue and/or energy produced from that residue" (Matsumura et al. 2005).

Spinelli et al. (2005) calculated the cost of recovery and delivery of root biomass in Italian poplar plantations. They found a huge range of delivered cost from €28 – 66 (\$44 – 104) t^{-1} or €47 – 118 (\$74 – 186) oven dried tonne $(odt)^{-1}$, with transportation the largest component of the cost at 40%. 10 tonne trucks were used with investment costs of € 106,000 – 118,000 (\$167,000 – 186,000) each. To model supply chain timing, the researchers used Siwork3® time-study software. However, as the studies did not extend for a sufficient amount of time, delays could not be calculated and therefore an additional 30% was added to the net work time to account for delays including preparation, service, and minor repairs. This is obviously a major generalization for the timing of operations and represents a significant source of uncertainty. Machinery costs were estimated using a method developed by Miyata (1980), with an interest rate of 8% and insurance and tax rate of 7%.

Kaylen et al. (2000) used a non-linear algebraic programming model to economically optimize the production of lignocellulosic biomass-based ethanol. A key determinant was the size of the production facility, the optimal size of which is a trade-off between economies of scale and increased transportation cost for biomass feedstock. The General Algebraic Modelling System (GAMS) used by Kaylen et al. (2000) is divided into capital cost, operating cost, feedstock cost, and transportation cost. Purchase prices for feedstock were paid to producers at supply points. This feedstock was then transported for the supply points to the processing facility, which is the product of a per ton-mile cost, the number of tons (capacity of truck) and the round-trip distance. Hence, costs for feedstock producers (farmers) were not detailed and a figure of \$1 $MBtu^{-1}$ of cellulosic residue was used. Ethanol and co-products such as furfural are linear functions of the feedstock composition: lignin, cellulose, and hemicellulose. Kaylen et al. (2000) used a scaling factor of 0.67, which they deemed conservative for chemical production facilities. From a feedstock perspective, Kaylen et al. (2000) assumed 10% of the total production of crop residues (corn stover, grain straw) was available for conversion, while 1/3 of wood biomass residues were available. Crop residues were given a price of \$25 ton^{-1} (\$25.58 t^{-1}) for in-field round bales.

Kaylen et al. (2000) found the optimal size of an ethanol production facility to be 47.5 million gallons (180 million litres) of ethanol per year or 1.44 million tons (1.41 Mt) of feedstock. At plant capacities below 1300 tons (1271 t) per day, net present value (NPV) was negative, while above 4360 tons (4262 t), marginal costs exceeded marginal revenue and NPV was declining. Therefore, between 1300 tons (1271 t) per day and 4360 (4262 t) tons per day, NPV was both positive and increasing. In the overall yearly costs, transportation of feedstocks was 26% while feedstock purchases costs were 21%. Therefore, delivered feedstock costs represented almost 50% of the annual costs of a bioethanol production operation. Despite these high feedstock costs, the model used by

Kaylen et al. (2000) did not call for production of high-yielding biomass crops. Above \$45 ton^{-1} (\$46 t^{-1}) for biomass purchase cost, NPV was negative across the entire scale spectrum.

Kumar et al. (2003) used Alberta as a case study, and highlighted the availability of straw in the province. They expected the province to be able to supply enough crop residues for 2000 MW of power generation. The authors used an average grain yield of 0.52 t ha^{-1} and a broad generalization straw yield of 0.416 t ha^{-1} in the draw area. This was sourced from a straw-to-grain ratio of 0.80. Kumar et al. (2003) assumed two weeks worth of storage at the processing site with all other biomass stored in field until required. A scale factor, *s*, of 0.75 was used.

Research Impact: Costs were separated into capital and operating. Operating costs were further divided into labour, fuel, maintenance, and other. Transportation and harvesting costs were handled separately and calculated as if functioning as a third party. This was thought to give an accurate price point on which biomass processing companies could base their payment to a farmer or transportation provider for their biomass product/services.

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Appendix 4 BIOMASS SUPPLY AND DELIVERY MODELLING

A4.1 DECISION SUPPORT SYSTEMS

Decision support systems (DSSs) have been developed for logistics in many different industries. A DSS is intended to assist decisions by the user by providing key outputs, but does not in fact make or coordinate decisions itself. The user can use or ignore the information provided by a DSS. Decision support systems "link the information processing capabilities of a management information system with modelling techniques and the judgement of managers to support decision-making in unstructured situations" (Dennis and Dennis 1991). According to Alter (1980), DSSs are composed of 1) an interface for users to interact with the system; 2) a management information system (eg. database) containing relevant information; 3) data manipulation systems to understand or simulate relationships; and 4) a component to display and interpret results.

Parunak (1999) identified characteristics of an ideal logistics DSS:

- Modular – each entity has a well-defined set of variables
- Decentralized – each application can function as a stand-alone software process without continuous direction for another application
- Changeable – structure of the application can change quickly and frequently
- Ill-structured – all information about the system may not be available when the system is designed but can be added in
- Complex – models a large number of behaviours that have multiple and interdependent interactions

Research Impact: Variables and inputs for each modular section of the system (GIS, spreadsheets, dynamic model) were identified. Data were transferred between the programs to arrive at the required final results. The system is structured so that others may use or adapt it for their own purposes.

However, DSSs and simulation models require complete or near complete concrete data, otherwise conclusions and abstractions will be inaccurate and will not represent real-world situations (Davidsson et al. 2005). A conceptual model is a broad strokes application that has the basic characteristics of the desired DSS. This is followed by simulation, in which real world data is utilized. An alternative option is to carry this out with artificial, simulated data to test the system. DSSs can be used in concert with field experiments to test the application in the real world, and once adjustments are made and the application is ready for general use, it can be deployed to users (Davidsson et al. 2005).

Decision support systems allow users to understand the links between choices and consequences, thereby enabling decisions to be made based upon sound information. Most land use planning does not include input from the public and stakeholders and tend to be deterministic and predicatively modelled. Decision support tools for agricultural planning that can be utilized by policy makers, farmers, and other stakeholders are incredibly powerful. They can forecast future outcomes based upon changes in policies and other key factors such as consumption/demand. Scenarios can be examined for tradeoffs (Sharma et al. 2006).

Mitchell (2000) pointed out that "when developing [decision support tool] applications of this nature the question of who the product is aimed at needs to be addressed". Mitchell (2000) added that there is a need amongst academics, policy makers, and industry for a model to assist in the planning and decisions for development of bioenergy projects. However, these different parties require different kinds of information and on different scales. For example, industry (practitioners) tend to need localized information for operational level functioning, while policy makers and those involved in high level corporate strategy require answers to questions at the regional, country, or even international scale.

Research Impact: The system was designed to utilize accurate yield data, provided by the Canadian and/or Provincial government. It is intended to provide the basis for a decision support system, which would need to include an interface for users such as farmers, biomass project developers, NGOS, and policy makers. This interface could be web-based.

Design criteria for a decision support system, as proposed by Sharma et al. (2006), that can be used by a wide variety of stakeholders include:

- User friendly, simple interface
- Involvement of stakeholders – address real issues and choices faced by the stakeholders
- Integrated approach – integration of physical and social sciences, with the ability to showcase the social, economic, and environmental outcomes and tradeoffs
- Complex, invisible, quick back-end model – while the interface should be simple, the systems supporting it need to function rapidly (ie. so they can be deployed through the internet) but still incorporate all necessary components
- Scenarios approach – instead of focusing on past trends, decision making should consider society has significant control of the future and scenarios provide a simple way to convey and compare the impacts of choices

- Address uncertainty – the future behaviour of systems and all variables cannot be completely predicted and therefore a certain amount of uncertainty exists that needs to be quantified

Decision support systems can be classified according to many criteria. Table A4-1 describes a classification system adapted from Davidsson et al. (2005).

Research Impact: This research focused on transportation and harvest. Road was the transport mode and the time horizon was tactical (although site selection is a strategic, long-term decision). It is dynamic (time dependent) and this research was at the simulation – real data stage. It is largely quantitative, although some qualitative measures regarding siting are employed.

Decision support systems for bioenergy were addressed by Mitchell (2000) for applicability and usefulness in short rotation woody crop (SRWC) bioenergy systems. Mitchell (2000) identified the two primary problem types that DSS attempt to address: 1) determine best practices for biomass production, harvest, and transformation/conversion; and 2) understand bioenergy applications and the implications of bioenergy systems through data and relationship modelling and manipulation. This data manipulation occurs when information is used to model 'what if' scenarios for biomass production and utilization. DSSs allow the user to compare different scenarios for the outcomes and reach a desired optimization condition. Model validation is used to ensure the assumptions and simplifications of the model do not strongly affect the real-world applicability of the results.

The decision support system described by Sharma et al. (2006) enables untrained users to select criteria and choices that can be simulated using remotely sensed data and future scenario projections. A similar type of system could be implemented for future biomass supply scenarios. The system would need to be accessible to farmers and industry, with choices such as amount of residue left on the field and plant size (in feedstock but also output in terms of energy/products). Sharma et al. (2006) chose 6 key indicators of agricultural sustainability, including availability of land base, land productivity potential, economic outputs, economic costs, water quality, and availability of wildlife habitat. These could be modified as necessary.

Research Impact: This assessment used a complex back end model (IBSAL) and GIS analysis to arrive at the final results. A simple, easy-to-use interface would be required for utilization by other parties.

When comparing deterministic and stochastic models, Hultqvist and Olsson (2006) found that the deterministic did not return accurate solutions but the stochastic model required many more computer and human resources to assemble and run. Uncertainty measures were used by the authors to determine when a stochastic model would be needed for supply chain optimization. The models returned very different results, with harvest sites present in the stochastic model that did not exist in the deterministic. However, the stochastic model could not be run with commercial software or on a standard desktop computer. Both could reach near optimum, but only the deterministic could reach true optimum in a reasonable time.

Lant et al. (2005) described a genetic algorithm as a "robust, heuristic search procedure that relies on stochastic search rules to solve complex decision problems...[and] attempt to adapt the evolution observed in nature to problems in which traditional, deterministic search techniques fail." They created a genetic algorithm to determine land-use patterns that optimized farm income and an Environmental Benefits Index (EBI). Zitzler and Thiele (1999) also used a genetic algorithm to minimize mean annual sediment yield and maximize annual economic benefit (optimize) for a farm field.

The analysis considered such criteria/impacts as water quality, hydrological processes, crop growth (and hence crop yield), and commodity markets.

A4.1.1 Linear Programming

Linear programming is used to optimize linear functions and is highly prevalent in operations research. Numerous algorithms, representing a variety of processes, can make up a single linear programming problem. Linear programming is often used for network flow and multi-commodity flow optimization.

If all the variables in a problem are integers, the problem is considered integer programming. If only some of the variables are integers, then the problem is mixed integer. Mixed-integer models have two types of variables; continuous and binary. Continuous are the most common and represent flows in a network. Binary represent whether or not a decision or action takes place.

As an example, the three primary components of biomass logistics, collection, warehousing, and distribution, were analyzed by Tatiopoulos and Tolis (2003) using a linear programming model for optimization. Transportation was provided by either the farmers (producers) themselves, using their own machinery, or a third party (3PL) logistics company. Biomass preprocessing steps of drying, baling, and pelleting were also included in the logistics analysis. Three scenarios representing centralized and decentralized options were used; 1 x 20 MW power plant, 4 x 5 MW power plants, and 1000 x 150 kw power plants. A geographic information system (GIS) was used to locate the facilities at real-world demand centres in Thesally, Greece, with the distributed network consisting of hospitals, schools, hotels, farms, and other users. Trip time is given by:

$$t = \frac{2a^{0.5}}{v} \tag{A4.1}$$

where t is the trip time, a is the draw area, and v is the velocity. If biomass collection must be completed in 60 days due to the seasonality of the feedstock, then the number of trips (T) is given by:

$$T = \frac{a \times p}{c \times 60} \tag{A4.2}$$

where a is the draw area, p is the yield in kg m^{-2}, and c is the vehicle capacity. The total number of daily trips (T_d) is given by:

$$T_d = \frac{d_h \times 24}{c \times n} \tag{A4.3}$$

where d_h is the hourly demand, c is the vehicle capacity, and n is the storage depot number. The number of transport vehicles (M) is given by:

$$M = \int \frac{2p \times a^{1.5}}{v \times c \times w \times 60} \tag{A4.4}$$

where p is the yield, a is the area, v is the vehicle velocity, c is the vehicle capacity, and w is the man hours per day.

Tatsiopoulos and Tolis (2003) used GANTT diagrams to model harvesting and transportation operations timing. The schedule was created for both farmer-delivered biomass and 3PL providers.

Research Impact: Timing regimes, including yearly uptime, were determined for each piece of machinery in the IBSAL simulation.

Olsson and Lohander (2005) sought to determine the marginal cost of round wood transportation and delivery and optimize this cost with investments in gravel roads. They used a mixed-integer model and a simple 'near to optimal' heuristic method. This model constrained the flow of roundwood by the gravel thickness on the road (ie. road conditions) and hence accessibility of the road. Accessible or not (two distinct values) meant the use of a binary variable, with the road conditions dictated by weather and use of the road. LINGO™ 6.0 standard software for mixed integer programming was used. By including binary variables in the equations, the authors determined it was impossible to identify a global optimum within a reason period of time. Heuristics are therefore useful in reducing the computational and man-resources required in optimization.

Troncoso and Garrido (2005) used mixed-integer programming to optimize forest logistics, taking into consideration forest production, forest facility locations, and forest freight distribution. The final outcome was to determine an optimal size and location for a new forest product processing facility; for example, a sawmill. As with Olsson and Lohander (2005), Troncoso and Garrido (2005) used LINGO™ software for optimization to compare variables and outcomes such as demand, transportation costs, timber prices, and lumber recovery factor. Due to the complexity of optimizing production, location, and freight distribution (both arriving and leaving), the authors used a node network. Nodes were identified for forest property, intermediate, and demand nodes, and distances between nodes were calculated. By using a node networks (and hence generalization), it was possible to arrive at a global optimal solution without the use of heuristics.

Research Impact: Heuristics, or rules of thumb, were used to identify potential biorefinery sites. This was much more practical that trying to find a global optimum that is likely not accurate in real-world conditions. A node network would allow identification of a global optimum without significant computing power, but would require generalization – something that this research was initiated to minimize.

Foulds and Wilson (2005) used scheduling models and integer programming to optimize rape seed harvesting in Australia and hay harvesting in New Zealand, with attempts to minimize required equipment, labour, and duration of harvest. They identified the limitations associated with heuristic solution techniques, which were primarily related to consistency and accuracy, with modelled outcomes not necessarily closely representing real-world situations.

The schedule in Foulds and Wilson's (2005) research involved both minimum and maximum time lags; the former requiring a certain amount of time to pass after the conclusion of one operation before another could start, and the latter requiring one operation to start following the conclusion of another before a certain amount of time had passed. Resource levelling was used to ensure fluctuations in equipment requirements were minimized and it was assumed that while weather affected operational cost, it did not influence the sequence of operations. Resource constraints were limited by costs, time, worker skill level, and machines. The authors concluded that project scheduling software using critical path method (CPM), program evaluation and review technique (PERT), and Gantt charts were effective at creating sequence of events schedules. However, they lacked dynamic operation and did not have the ability to accept time lags, interdependence of operations, conflicting priorities, partial allocation, sharing, or mutual exclusivity.

Research Impact: Time lags were included in the dynamic model. Historical weather data was included in the scenarios to simulate real-world conditions – including ability to harvest and collect feedstocks.

Heuristics present simple priority rules, but have a hard time dealing with conflicting priorities and interdependence. That is why Foulds and Wilson (2005) used integer programming, which can take all variables into account when determining optimal solutions. The authors found that solutions created by the mixed integer programming were more flexible in the timing of any given operation that the two comparative heuristic methods used. With the mixed integer programming, they were able to create schedules that showed a 36% reduction in total harvesting time.

A mixed integer programming model, applicable to a variety of regions and time periods, was developed by Tembo et al. (2003) to assess the financial feasibility of biomass-to-ethanol processing facilities. The model was used to identify primary cost components, process and supply bottlenecks, and cost reduction and process improvement opportunities. The model included all cost components in producing and delivering ethanol to market, including biomass sources, harvest and storage timing and capacity, inventory management, processing facility size and location. In this case gasification-fermentation technology was used as the means of conversion. The integrated model included feedstock production, field losses, harvest, storage, storage losses, transport, and biorefinery size and location. It functioned at the policy or large industrial scale, with the ability to optimize the number, size, and distribution of biorefineries for a given region to maximize total industry net present value (NPV).

Plant site locations and sizes, identified by the Tembo et al. (2003) model, changed between scenarios based upon the conditions and constraints of each scenario. The researchers altered the baseline scenario by doubling the land costs, doubling the process facility capital costs, doubling the per distance unit feedstock transport costs, changing the project life from 15 to both 10 and 20 years, and using a variety of discount rates. The study site was the State of Oklahoma. Doubling plant costs led to fewer, larger plants, while doubling shipping costs resulted in more, smaller processing facilities. In the base case scenario, Oklahoma could support six biorefineries with total feedstock consumption of 7.3 million tons (6.6 million tonnes) annually from 2.56 million acres (1.04 million hectares). Multiple feedstocks were considered, including wheat straw, corn stover, native prairie, forages, and switchgrass, with the integer programming model identifying which feedstocks were most economically viable for a given processing facility. Given the variety of feedstocks, harvest was estimated to occur from June through October, with feedstock in the other seven months coming strictly from in-field storage. Crops with high yield and large harvest windows were preferable.

The breakdown for \$0.89 per gallon (\$0.24 per litre) ethanol, as determined by Tembo et al. (2003), was land rental costs (17%), harvest costs (8%), in-field storage (9%), transportation of biomass (18%), and biorefinery construction, operation, and maintenance (44%). As with other studies on biorefinery economics, Tembo et al. (2003) identified a trade-off between feedstock transportation distance and biorefinery size. The model tended to smaller processing facilities when yield was low. The estimated marginal cost used for the base-case scenario was \$1 per mile (\$0.63 km^{-1}) per truckload (17 tons/16.6 t). This trade-off was further compounded by a general restriction imposed by the researchers of limiting harvested acreage to 10% of the total. The authors identified questions on applicability of feedstock assumptions to real world and yield levels over time as large source of error/unknown.

Research Impact: Processing plant capacities of 50,000 t to 500,000 t were assessed to determine scale impact on average and range of delivered biomass cost. These various plant sizes were compared for average, minimum, and maximum yield scenarios over the lifetime of a processing facility (20 years).

Hultqvist and Olsson (2006) highlighted the risk weather presents to biomass supply in the forestry sector and quantified this risk using stochastic and deterministic models with mixed-integer quadratic programming. Although they focused on the capacity of the ground and roads to accommodate harvest and transportation of woody biomass, the strong influence of weather on overall operations was evident. In order to meet the needs of pulp and paper mills running year round with an intermittent feedstock, significant storage planning was required to enable continuous operation of the mills. Considerations for storage cost include weather, time of year, industrial process utilizing the biomass, and storage location. The authors used heuristic rules for creating a supply chain; these were derived from industry standard practice. Similar to Olsson and Lohmander (2005), roads were considered accessible or not and therefore employed binary variables. According to the authors, storage is often the most complicated component of the biomass supply chain and several questions need to be addressed: How does storage affect the biomass quality? How do different grades of biomass affect processing performance? What are the material losses and associated cost in storage? How should the biomass be stored? The answers to these questions are variable and dependent upon the biomass type and variability, weather and season, process technology, and storage time and location.

Research Impact: Binary variables are used in the IBSAL model to determine whether or not harvest can occur. Below a specified temperature and above a specified biomass moisture content, harvest does not occur. However, most variables in the system are continuous.

A4.1.2 Biomass Modelling Systems

Mitchell (2000) created the Aberdeen University Harvesting Decision Support System (AUHDSS) for optimization of traditional forestry practices (harvesting, storage, and drying of wood). Results could be displayed in terms of tree species, size, terrain, and harvest system (eg. clear cut vs. select cut), combined with cost per unit of output (eg. $\$ m^{-3}$, $\$ odt^{-1}$, $\$ GJ^{-1}$). After several versions of the AUHDSS, the third version was written in Visual Basic™ and built on a Microsoft® Access™ platform. The database was directly linked to the harvesting model and could be manipulated and updated with ease.

The Coppice Harvesting Decision Support System (CHDSS) was also written in Visual Basic™ 3 and was intended to replicate a coppice supply chain, from harvest to transportation and storage (Mitchell 2000). Information on harvesting equipment (including energy use and productivity) was included in the model. Data to supply the model was sourced from site trials of supply chain functions (harvest, drying, and delivery) in Europe, and was therefore targeted at European operations of short rotation woody crops/coppice (SRWC). A series of consecutive screens allowed the user to define and alter the system. These included 1) machinery and crop selection; 2) product qualities, including moisture content; 3) comminution timing and method; 4) primary and secondary transportation; and 5) storage properties, including product form, length, and method.

As part of the IEA Bioenergy international collaboration, a comprehensive biomass management model, the BioEnergy Assessment Model (BEAM), was created (Mitchell 2000). This spreadsheet model incorporated data and functionality from several previous models (eg. CDSS and AUHDSS) and allowed the user to understand and manipulate relationships between biomass feedstock supply and conversion. Various scenarios, including different biomass feedstocks and conversion technology, could be assessed from a techno-economic perspective for real world viability. However, BEAM, being a spreadsheet model, was found to be limited in temporality and also lacked flexibility in feedstocks and conversion processes. An updated version, BEAM3, is intended to be an improvement on the original, and although still spreadsheet based (and hence limited in terms of temporality), allows greater flexibility for feedstocks and conversion technologies (Mitchell 2000).

The Decision Support System for Agrotechnology Transfer (DSSAT) cropping system model enables users to evaluate a host of environmental and management options for 16 different crop types. The history and development of the model was described in detail by Jones et al. (2003), who provided an overview of the hundreds of studies and publications that have utilized DSSAT for cropping assessments. These assessments have occurred at various levels, from field level tactical management to policy and industry strategy. The entire purpose of utilizing DSSAT (and for that matter any model), was to reduce the time and resources required to analyze and provide answers on complex system options and questions. DSSAT was built in a modular fashion, which allows new modules to be added (eg. for a new management practice) or removed, creates clear boundaries for each set of data/discipline, enables modules written in different programming languages to be linked, and permits DSSAT to be partnered with other models. This could prove extremely useful when trying to determine the impact of various cropping systems on biomass availability and delivered price. Databases back up DSSAT; these include weather, soil, crop properties, and genotype information. The newest version of DSSAT was built around a cropping system module which includes all crop types using a single soil model. Other key modules include weather, soil, plant, soil-plant-atmosphere interface, and management. DSSAT uses daily weather inputs (maximum and minimum air temperature, solar radiation, precipitation, relative humidity and wind speed). The four soil components are soil water, soil temperature, soil dynamics, and soil carbon and nitrogen. A CENTURY-based module is included to simulate crop rotation impacts on soil organic matter. This includes consideration for C:N ratios, soil texture, and important for biomass supply, crop residue retention. This could provide an accurate figure on retained soil organic matter (SOM) under various crop residue removal scenarios.

DSSAT calculates daily plant growth using values for solar radiation, water and nutrient availability, and competition (spacing). These numbers could be used for determining the optimal day to harvest not only the primary product (eg. grain) crops but also for crop residues. Crop residue removal is considered an option for management and provides feedback information on impact on soil quality and future year productivity (Jones et al. 2003).

The Decision Support System for Agriculture (DSS4Ag) was developed by the Idaho National Laboratory. Hoskinson et al. (2007) used the system to economically optimize wheat fertilization to produce both grain and straw for use as a bioenergy feedstock. According to Sinclair (1998), total plant biomass has not increased over the past half century; the grain-to-straw ratio has simply risen. Hence, if straw and other non-grain biomass is given a value, Hoskinson et al. (2007) hypothesized that extra fertilization may be justified to increase straw yield. However, their results from the DSS4Ag model showed that growers should not invest more in production costs to increase straw yield, even when straw is valued at \$50 t^{-1}. In fact, producers should decrease fertilization and thereby decrease production costs. They will still have straw production, and value for the straw will offset any decrease in grain yields.

Another cropping and farming system model is APSIM, the Agricultural Production Systems Simulator, developed by the Agricultural Productions Systems

Research Unit of the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia (Keating et al. 2003). It is particularly useful for modelling future climate scenarios, combined with management practices, and their impact on economic and ecological outputs. Like DSSAT, it is broken into manageable modules that include individual crop types, soil processes (eg. water, N, P, soil pH, erosion), and management. These are all fed into a central dynamic simulation engine. It has been used for farm level analysis as well as policy making. Supply chain projections (eg. truck and infrastructure requirements) have been a major use of the model. APSIM can predict crop yields based upon inputs of climate, plant genotype, soil, and management strategies. These can include multi-year assessments and projections that consider rotations, fallows, residues, crop establishment and death, and dynamic management systems related to changing ecological conditions. A specific module was created called RESIDUE that determines residue retention impact on soil water balance and nutrients (Keating et al. 2003).

Research Impact: Factors such as soil type, weather conditions, cropping systems, and agricultural management strategies determine crop yield. They were taken into account when predicting biomass yields and delivered costs. A system that can handle these data inputs would be incredibly useful to link with a supply logistics model/tool. Modular systems (eg. those that separate harvesting from weather) are most easily adaptable to new data and new applications. Therefore, all components of this system were designed to be able to stand alone as a functional unit. Although this work linked a GIS system to spreadsheets and a dynamic model, linking these units to one of the mentioned agricultural management models could yield a very valuable and powerful tool.

A4.1.3 Dynamic Simulation

While linear programming and static models can optimize supply chains at a strategic and sometimes tactical level, they do not make adjustments over time and do not simulate an actual delivery scenario. Dynamic simulation models are able to accurately simulate real world feedstock management by incorporating delays, equipment operations and maintenance, and labour constraints. As a system is simulated, it changes over time and the results are reflected in the model.

Nilsson (1999a) created the Straw HAndling Model (SHAM), a dynamic simulation model for analysis of straw delivery scenarios to optimize handling and reduce costs. The model is composed of several submodels that address infrastructure, geography, field drying, and weather. The three primary submodels are location submodel, weather and field drying submodel, and harvesting and handling submodel. A spreadsheet is used for data input and output from the dynamic simulation. Location submodel determines transportation distance and infrastructure, while weather and field drying submodel uses time limits on harvesting and transportation to determine wait and completion times. The harvesting and handling submodel allows the user to select different types of machinery in a complete chain. Overall management strategies can then be compared via simulation, which is a process-oriented scheme that allows entities to flow through the system. Entities are delayed in queues and during processing, replicating real-life delays. Outputs include cost, machinery uptime and downtime, harvest capacity, and queue waiting times.

The location submodel uses a circular supply area to draw feedstock for a central processing facility. The draw radius (r) required to fulfill the feedstock requirement of a plant is given by:

$$r = \left(\frac{nS}{100\pi Y_x \Phi} \right)^{\frac{1}{2}} \tag{A4.5}$$

where n is the useful area (proportion of area where straw is available), S is the required amount of straw (t yr^{-1}), Y_s is the average yield (t ha^{-1}), and Φ is the fraction of area occupied. This assumes a uniform distribution of straw within the harvestable area. To determine transportation distance, the central plant location is assigned x and y coordinates. Distance is given by:

$$d_{ij} = \tau\left[\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2\right]^{\frac{1}{2}} \tag{A4.6}$$

where τ is road tortuosity and x and y are coordinates.

The weather and field drying submodel uses the semi-empirical thin layer drying equation from Lewis (1921), calculating the rate of change of moisture content:

$$\frac{dM}{dt} = -k\left(M - M_{eq}\right) \tag{A4.7}$$

where k is the drying constant (h^{-1}), and M is the moisture content. M_{eq} (moisture content at equilibrium) is given by:

$$M_{eq} = \frac{1}{100}\left[\frac{\ln(1 - RH}{-k_1\left(T + k_2\right)}\right]^{k_3} \tag{A4.8}$$

where RH is the relative humidity, T is the temperature, and k_1, k_2, and k_3 are constants. This is known as the Henderson-Thompson formula (Duggal and Muir, 1981).

Weather data was obtained from the Swedish Meteorological and Hydrological Institute (SMHI) and includes daily variables on precipitation, relative humidity, temperature, and accumulated evapotranspiration. These are input into the spreadsheet for use in the simulation.

The harvesting and handling submodel uses a specific reference date as a starting point (in this case, July 16). Nilsson (1999b) assumed this to be the earliest possible harvest date. Data on weather were used to determine whether or not harvest would occur on a given day. Precipitation controlled the accessibility of the field for harvest. 2 mm was considered the cut-off for the night prior to prevent harvest, or 9 mm the day before. Precipitation totalling 24 mm or more during the previous 48 hours also made conditions unsuitable for harvest. "MoistureStatus" is a binary variable that allows or does not allow harvesting due to high equilibrium moisture content or wet straw.

The SHAM simulation involves straw in entity bundles that proceed through the system chain. The entities are held in queue until conditions are appropriate for a set task (eg. mowing, baling) or until equipment is available. Equipment is classified to be in one of four states: busy, idle, breakdown, or inactive.

The cost component of SHAM is divided into fixed costs, variable costs, and labour costs. Variable includes operation and maintenance costs and costs for general purpose machines (eg. tractors) (Nilsson 1999a).

Nilsson (1999b) used the SHAM model to compare straw harvest and handling systems in regard to cost, energy requirements, and overall performance. The author was able to identify opportunities for system improvement and cost reduction by using SHAM. The delivered cost of the straw at a central processing facility was found to be 29.9 SEK (Swedish Kronor; CAD \$5.03) GJ^{-1}. Using the SHAM model, Nilsson (1999b) compared traditional high-density baling to both compact rolls and chopped straw systems. The results indicate that high-density baling is superior to the two alternatives. The high-density balers, producing bales of 1.2×1.3×2.5m, had a capacity, C (t hr^{-1}), of:

$$C = 10.9 + 1.0Y_s \tag{A4.9}$$

where Y_s is the average yield (t ha^{-1}).

Chopped straw systems became increasingly competitive at a smaller scale as transportation distance was decreased. Nilsson (1999b) used assumptions of a 1.8 tortuosity and fields smaller than 5 ha were not harvested. The author noted the opportunity to increase the harvest season length by including crops that can be combined before primary feedstocks (eg. perennials). SHAM assumes intermediate stores, drawing biomass from a circular draw area. Feedstock is then transported from these intermediate stores to the central processing facility.

SHAM was used to determine the number of machines required to deliver the lowest total fuel costs. The machines required to complete a chain were combined into a discreet minimal unit. Hence, to increase scale, the user simply needs to increase the number of complete units. Capital costs were significantly reduced if machinery could be used for other operations on the farm, and hence the allocation to biomass harvesting reduced.

Nilsson (2000) used SHAM to identify the factors important in plant siting and sizing. They included weather variables such as frequency and duration of precipitation, potential evapotranspiration, and equilibrium moisture content. As previously identified, this equilibrium moisture content is dependent upon temperature, relative humidity, radiation, and wind speed. Field size, fraction of land with available straw, and transport distance from harvest sites to processing facility, straw yield, and duration of harvest season were found to be also critical to the viability of a straw-based enterprise. When moisture content of the biomass is below 18%, straw units are placed in a queue to pass through the system. Performance measures are output in the spreadsheet component of SHAM, including quantity of the straw, time straw has to wait for different machines, queue lengths and time, and resource utilization. A standard average yield is calculated based upon a general straw:grain ratio and historical yields, which acts as a broad generalization for the system.

In general, the "machinery capacity/investment costs" ratio should be as high as possible to minimize operating costs. Nilsson (2000) used a sensitivity analysis to determine longer transportation distances and lower straw yields per hectare were the key variables for a higher delivered straw cost in some sites.

Research Impact: As IBSAL was originally designed based upon SHAM, they share many components. These include queuing, dry matter losses, resource allocation, and weather impacts on ability to harvest. The techniques used by Nilsson are similar to those presented in Chapters 5 & 6. However, Nilsson has not published work using the dynamic model to compare yearly variability in delivered cost of biomass. It has primarily been used to compare harvest and handling systems. IBSAL also uses a coordinate system to determine transportation distance and provides the user with the ability to run a Monte Carlo simulation of random feedstock supply pickup locations in a given area. IBSAL is explained in further detail in Chapter 6.

Iannoni and Morabito (2006) highlighted the importance of integrating agricultural and industrial operations for agro-industries that utilize continuous processing. They addressed the issue of truck waiting times at the reception area of a sugarcane processing facility, but stated their analysis and suggested solutions are applicable to other biological-industrial systems such as orange and wood processing. Processing facility feedstock managers are primarily concerned with ensuring continuous and uniform delivery while they attempt to minimize wait times and maximize unloading rate. Iannoni and Morabito (2006) sought to address real-world problems and included several different types and combinations of trucks in their analysis. Using Arena™ software, they simulated the delivery of sugarcane. This supply system is termed non-terminal or steady-state, as operations and delivery occur continuously 24-hours per day. This contrasts with batch systems, in which a start and stop operation occurs with a determined simulation run-length. With system optimization modelling, they were able to reduce mean waiting times by 13.5% and increase total deliveries by 1.1%. The authors concluded that inbound logistics system coordination is essential for the integration of agricultural and industrial operations.

A4.2 GEOGRAPHIC INFORMATION SYSTEMS

Geographic information systems (GIS) are computer systems that utilize data to show and describe places. GIS uses geographic or spatially referenced data that can be analyzed and used as a decision support tool. It also has the ability to output the data in the form of maps, graphs, charts, and statistics. GIS eases the difficulties in evaluation and resource planning for large areas and can provide a simplified projection of complex spatial analysis work. It also enables integration of multiple evaluation methods with a multitude of data sources (Saroinsong et al. 2007).

GIS can be used to incorporate many factors and make decisions based upon numerous criteria. The United Nations Food and Agriculture Organization (FAO) uses GIS extensively to determine land suitability and cropping system selection. As there are always competing uses of land, the 'best' use of land is highly subjective, but can become more objective when criteria for selection are agreed upon. These criteria can be environmental, economic, or societal, or a combination of all (Miranda 2001). The challenge with applying broad concepts across a landscape or region is that every area has unique characteristics and challenges that may not be addressed with broad-sweeping policies and plans. A key characteristic of GIS is that it is poor at dealing with dynamic spatial models and temporal aspects of ecosystems (Sharma et al. 2006).

According to Haines-Young and Watkins (1996), "High quality data sources are a prerequisite of the successful application of GIS technology." Policy decisions utilizing GIS tend to be at a larger scale for agriculture and examine broad trends. However, both policy and business benefit from more detailed data at the farm-level. This may be available in remotely-sensed (satellite) data, but can also be sourced from aerial photographs and field surveys.

GIS is useful as a cropping systems management tool, with production variables including climate, soil characteristics, crop management including tillage and irrigation, and socio-economic influences, all of which have a spatial component that can be mapped and overlaid with other variables. However, many GIS approaches to agricultural management assume static environmental conditions and "ignore temporal variation due to year-to-year variation in climatic conditions." (Hodson and White 2007)

Research Impact: Year by year scenarios were presented in GIS, with identification of average, minimum, and maximum yields over 20 years. As GIS has a hard time with temporal data, IBSAL was used for this aspect of the system. Data was obtained from government to ensure accuracy of results. The most up-to-date data available was utilized.

There are many variables to consider when making predictions about crop productivity and these can be aggregated by using overlays in GIS. Information garnered from remote sensing can include variables such as vegetation cover, crop type, crop yield, crop water stress, crop water use, and leaf area. Ground truthing becomes very important in determining the accuracy of satellite data and analysis results (Wesseling and Feddes 2006).

Although agricultural application of GIS for business has largely focused on precision farming applications to optimize management at the farm level, higher level remote sensing and assessment are increasingly being used by decision makers in large business and government. The knowledge provided by GIS can significantly improve the accuracy of information on which decisions are based. Not only can a user look at where something is grown, but increasingly, they can determine where it could be grown. This potential for exploring management and cropping system scenarios allows simulation without the expenditure for actual implementation. According to Hodson and White (2007) "This widespread use of GIS is driven by increasing availability of geospatial data, rapid advances in software and hardware capabilities, and greater awareness among researchers of how a geospatial perspective can enhance their research."

Increased use of GIS, particularly utilizing remotely-sensed data, has produced improved crop distribution data. By combining crop data and biophysical information with socio-economic analyses, it has become possible to compare various future crop production and management scenarios. These can include projections for altered future climates and disease trends. However, as Hodson and White (2007) highlight, GIS systems still lack the functionality of incorporating temporal data, and it is difficult to make accurate assessments on probabilities or frequencies of occurrence. Real-time weather data, combined with improved GIS modelling systems (or GIS linked to models), enable dynamic assessment of trend progression over time. Limiting factors for use of GIS for agricultural modelling and planning in research include accurate data at an appropriate scale, limited uptake by the research community, access to software and training, and existing norms.

Several researchers (Elmore et al. 2008; Graham et al. 2000) have taken a raster-based GIS approach to determining crop yield and biomass availability. Elmore et al.

(2008) used MODIS and Landsat-sourced high resolution land cover maps to determine rice crop residue availability in China. MODIS satellite provided data on net primary productivity, and hence, residue production rates. By combining production rates with land-use patterns and extending the analysis over a five year period, Elmore et al. (2008) created a general analysis of available residue in China. Although productivity varied widely between years, data on land-use (specifically sown rice area) was identified as the greatest source of error.

Net primary productivity (NPP) is a function of climate, soil type, and management practices. Elmore et al. (2008) characterized NPP at a 1 km^2 resolution and used straw to rice yield ratios to determine available rice straw. General assumptions included 80% of total biomass as above-ground biomass, moisture content at 9%, and carbon content in total biomass of 45%. In addition to remotely sensed NPP measurements, Elmore et al. (2008) utilized census-derived data to determine the accuracy of satellite data. They found a strong correlation between the two data sets, although NPP tended to overestimate production levels. However, as the authors noted, actual availability for large bioenergy operations is determined not only by production and recoverable yield, but also by competing uses for straw; feed for livestock, paper making, small-scale energy production, and soil fertility support. Their methodology could be applied to other biomass sources, assuming accurate remotely-sensed data is available.

GIS was used to manage the soil and land productivity data of agricultural systems in China (Zhang et al. 2004). This GIS data, coupled with a Delphi method and fuzzy analysis evaluation system, was intended to assist decision makers and farmers to maximize soil productivity and sustainable soil use while ensuring adequate revenue streams. Soil productivity is a better indicator of soil health and future yield than land productivity. Land productivity is largely influenced by management practices and climate, which change over time. On the other hand, soil productivity is a function of the underlying soil properties and site topography. These do not change as dramatically year by year. When soil productivity is taken into account when planning management practices and cropping schedules, the overall system can be optimized to ensure sustainability and maximum value for farmers. By using GIS, Zhang et al. (2004) found they could update the system, incorporate ongoing monitoring efforts, improve accuracy with further analysis, and use the results as a basis for further agricultural research.

Simonson and Johnson (2005) used Dominion Land survey data, historical maps, remotely-sensed data, Alberta Vegetation Inventory data, and a digital elevation matrix (DEM) to compare current and historical vegetation patterns. The Alberta Vegetation Inventory data was available at 1:20,000 scale, with cover type categories of parkland, cleared or ploughed land, closed forest, urban or industrial land, and water or marsh. Simonson and Johnson (2005) focused on how terrain, particularly elevation, slope and aspect, affected agricultural expansion in Alberta's southern forest-grassland transition. This GIS work showed strong expansion by agriculture into historically grassland areas, particularly at lower elevations and gently sloping land.

Saroinsong et al. (2007) created a process for agricultural landscape planning by using a multi-criteria analysis approach. Specifically, they sought to address soil erosion concerns while maintaining necessary revenues for farmers. Utilizing topographic maps and remotely sensed data in a GIS database, they were able to create a planning scenario that would reduce soil loss by 75%, while decreasing farmer profit by only 3.1%. They selected values for acceptable soil loss and compared them to estimated soil loss to identify problematic areas, for which they proposed solutions. Saroinsong et al. (2007) classified areas as suitable, moderately suitable, marginally suitable, and unsuitable for each plant type based on erosion limits.

Research Impact: Remotely-sensed data is available for croplands in Canada and can be utilized to provide information on soil type, weather patterns, cropping systems, and overall growing conditions. This data was combined with historical survey and census data on crop yield to map crop production on a yearly basis.

A4.3 MODEL AND GIS COUPLING

According to a review article by Sui (1998), GIS suffers from the lack of temporal data incorporation. The linkage of dynamic, interrelated data with spatial data can add significant value to GIS. This has been made possible in various studies that link dynamic models and simulations with GIS spatial analysis. The most common and practical method for most GIS modelling is loose coupling of standard GIS software with a modelling program or a statistical package via data exchange in a common linkage program. Computer programming is minimized and is thus an accessible solution for most research questions. However, due to the large amount of data organization and conversion between platforms, errors can occur and the process is time consuming. This contrasts with embedding modelling into GIS software or vice-versa, which requires extensive programming, but once established, minimizes processing time and errors. This option is usually the domain of software developers. Tight coupling is a fourth option that uses macro or conventional script programming to link GIS and modelling software. As with embedding, this option requires programming knowledge but can be completed by a competent 3rd party (Sui 1998).

Several teams have used GIS coupled with modelling software to create multi-criteria decision support systems for resource management. This includes work by Leavesley et al. (1996) and Watson and Wadsworth (1996). According to Lant et al. (2005), spatial decision support systems (SDSS) "were created to support the analysis of complex spatial problems where it is not possible to completely define a problem of fully articulate the objectives of the solution in mathematical terms".

From a global perspective, the greatest challenge in accurately assessing cropping systems via coupling dynamic simulation models with GIS is limited daily weather data. However, as Hodson and White (2007) note, "Perhaps the greatest opportunities are found in advancing beyond the static definitions of environments and incorporating temporal variability to estimate the probability or frequency of occurrence of different environment types."

Research Impact: Due to the limited programming knowledge of the researcher and need for flexibility of systems, loose coupling was chosen as the means of linking GIS with spreadsheets and ultimately the IBSAL dynamic model. GIS can provide outputs for specified geographic regions (in this case, crop yield and area), which were utilized for further data analysis in Microsoft® Excel™. IBSAL, built on the EXTEND™ platform, uses Excel™ for all model inputs and outputs. Weather data was available from Environment Canada, and with some manipulation and rearranging, fit a format required for IBSAL.

Graham et al. (2000) used GIS to determine the delivered cost for energy crop feedstock in 11 US states, including North Dakota, South Dakota, and Minnesota. Variables that were considered included locations where energy crops could be grown, the potential crop yield, and transportation costs to central processing facilities. Utilizing raster-based optimization with the specified criteria, the researchers were able to determine the marginal cost of delivering biomass from any point to a processing facility, and also how many facilities (and the optimal size) could be supported by the biomass in a given state. Hence, given the state-wide optimization, this tool is ideal for policy makers who wish to maximize the economic potential of biomass crops in a specific state. However, many of the features are also highly relevant to bio-based enterprises.

Graham et al. (2000) included attribute data for each pixel on yield, identity of the destination facility, and farmgate and delivered prices of the biomass. Considerations for price included land rent, biomass yield, soil type, road networks and nodes, and distance from biomass sources to road nodes. Although a state-wide analysis, the mapping of processing facilities allowed for selection of priority sites based upon lowest delivered marginal feedstock cost. However, as with many other bioenergy techno-economic models, simplifying assumptions decreased the validity for real-world conditions. One of these was that traditional crop mix and profitability will not change over the life-time of the crop stand. However, Graham et al. (2000) did account for soil erosion, nutrient loss, and pesticide seepage. The overall system was quite complex and, as the authors indicate, not suited for a casual, non-specialist user. Graham et al. (2000) highlight one of the major challenges in maximizing value from GIS systems – users who understand the data the most are likely not the most qualified persons to utilize the system itself.

In their analysis, Graham et al. (2000) divided transportation cost into the fixed loading and unloading of biomass ($\$ t^{-1}$), distance dependent cost (eg. fuel), and time dependent cost (eg. wages). The authors calculated the return to the farmer based on net present value (NPV) over the lifetime of the crop using a regression model that utilizes output data from BIOCOST, the US Energy Crops model. Using their combination of models, including GIS and BIOCOST, and further analysis, Graham et al. (2000)

determined the delivered cost for biomass ranged from \$33 to \$55 t^{-1} for a 100,000 tonne facility. For a 630,000 tonne facility, the range rose to \$36 to \$58 t^{-1}.

Research Impact: While most studies have taken a raster-based GIS approach, this requires significant computing power and limits its usability for unskilled users. Therefore, a vector-based approach was chosen to map cropping sites and compare productivity. This allowed the use of vector analysis tools, such as buffer and overlay. Vector-based applications could also be made available online in the future.

Tan and Shibasaki (2003) used an 'interface engine' to integrate the Erosion Productivity Impact Calculator (EPIC) model with GIS. EPIC was originally created by the United States Department of Agriculture to examine the relationship between crop yields and soil erosion (Williams 1995). By coupling EPIC to GIS, the authors created a system that was applicable to larger, regional scales, or even a global scale, thereby increasing the overall scope of EPIC. EPIC takes into account hydrology, weather, erosion, nutrient management, plant growth, soil temperature, tillage, and economics at the field level (Williams 1995). Tan and Shibasaki (2003) linked EPIC and GIS by first creating a GIS database, which fed data into the EPIC model. The results of EPIC modelling could then be incorporated into another field in the GIS database. GIS was also used to display the results of the EPIC model. They used a raster format for data computation and display in GIS. The integrated system was then used to determine the impact of climate change [weather (precipitation), temperature (mean, max, min), and CO_2 concentration] on global crop productivity using Intergovernmental Panel on Climate Change (IPCC) data derived from the Canadian Global Coupled Model (CGCM1). Planting and harvesting dates were automatically selected based upon weather and crop condition data.

Luo et al. (2005) used GIS, combined with the APSIM wheat module, to model three environmental change scenarios and their impact on wheat production in South Australia. Their work showed that under worse case scenarios, grain yield could decrease 42 – 100% from baseline. Spatial data on climate and soil were used within GIS to present the results in maps. Under the most likely case, grain yield dropped 3 – 58%, with a large component of the decrease due to decreased water availability (ie. water limited). Climate scenarios for 2080 were sourced from CSIRO Atmospheric Research. The researchers highlighted the importance of including spatial variation on soil information for crop productivity assessments, especially future scenarios. Using a single soil profile at a regional level is inaccurate and will produce misleading results.

Lant et al. (2005) used GIS as a basis to create a spatial decision support system for evaluating agricultural watersheds. Specifically, they examined how certain policy decisions (and hence agricultural management practices) affected the functioning of watersheds. The Cache River basin in Southern Illinois was used as a study area. A large component of their work was investigating the value of ecosystem services, including nutrient cycling, soil management, sediment trapping, and carbon flux. GIS was utilized to link two models – GEOLP, a farmer decision support profit maximizing model, and AGNPS, a water hydrology and quality model – within a single spatial and temporal system. GEOLP, a linear programming model that utilizes GIS for providing information on variables such as soil type to predict land use, was developed by Kraft and Toohill (1984), while AGNPS was created by Young et al. (1989). Lant et al. (2005) concluded that GIS-based modeling frameworks are highly useful for watershed and natural resource management, and can be used as valuable decision support tools. They allow users to go beyond simple profit or environmental benefit maximization and create a strategy for optimization of the selected variables.

Research Impact: GIS is excellent for displaying and analyzing spatial information. However, it is not the best tool for handling temporal information and was therefore linked to the IBSAL dynamic models to incorporate the 'fourth dimension' of time in analysis. As all biological systems are inherently temporal, this accurately quantified the impact of geoclimatic impacts on biorefinery operating costs.

	Aspect	**Categories**				
Description	Domain	Transport	Traffic	Terminal		
	Transport mode	Air	Rail	Road	Sea	Intermodal
	Time horizon	Operational	Tactical	Strategic		
Approach	Usage	Automation system	Decision support system			
	Control	Centralized	Distributed			
	Structure	Static	Dynamic			
Results	Maturity	Conceptual	Simulation – Artificial data	Simulation – Real data	Field experiment	Deployed
	Evaluation	None	Qualitative	Quantitative		

Table A4-1 Decision Support Systems

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Appendix 5 CROP RESIDUE REMOVAL

A5.1 SUSTAINABILITY CONSIDERATIONS

The amount of small grain crop residues that can be removed while still maintaining soil quality is highly site dependent on, and involves consideration of, many competing impacts. The amount available for residue removal is very dependent upon cropping systems and landscape management (Nelson 2002). According to Malhi et al. (2006), "Successful integration of crop residue management strategies into cropping systems requires understanding of how crop residues influence cycling of nutrients from soil and fertilizers, as well as their effects on soil chemical, physical and biological properties, and crop production. Information is needed as to whether crop residues can be removed from cropping systems for alternative uses without detrimental impact on soil properties, productivity and the environment."

The Food and Agriculture Organization (FAO) has developed a land suitability evaluation method that takes into account numerous factors including: radiation regime, including daylight duration; temperature regime, including mean, maximum, and minimum values; water availability, including rainfall and other sources; humidity, including mean, maximum and minimum values; root development support, including soil quality, drainage, and depth; nutrient availability and retention; flood risk; and erosion susceptibility (Food and Agriculture Organization 2003).

Crop residues are important for water retention. They create a water barrier layer between the soil and the atmosphere, thereby limiting solar radiation reaching the soil surface. Less solar radiation in turn leads to decreased evaporation rates. The efficacy of crop residue as an evaporation barrier changes over time; as it weathers, increasing amounts of moisture are released to the atmosphere (Cutforth and McConkey 1997). In addition, crop residue layered on the soil surface reduces wind-induced evaporation and drying (Steiner 1994). As most of the Canadian prairies are water-limited in growth, this is perhaps the most important aspect for consideration of crop residue removal. In a study by Zentner et al. (2003) on the Canadian prairies, 63% of the variability between years was attributed to water deficiency. By using spring water level as a determining factor in the crop/fallow decision, Zentner et al. (2003) increased overall grain yield by 24%.

Work on the prairies by Steppuhn (1994) indicated that stubble height is directly proportional to snow (and hence water) retention. Therefore, a significant tradeoff exists between residue removal and soil moisture levels affecting productivity for the following year. Residue decomposition is dependent upon moisture levels and temperature, with wide variances between years. This will affect the timing of residue removal if the intention is to minimize in-field losses.

Research Impact: Water availability and the role of residues in water retention is a primary factor in determining how much residue should remain on the Canadian prairies. It was included as a consideration in the residue removal rate used in this work.

Crop residues are essential to the formation and adequate levels of soil organic matter (SOM). If SOM is removed, through processes of erosion such as water runoff and high winds, crop productivity decreases. Residues have therefore been deemed a key component of erosion control, particularly in dry regions. Crop residue removal must be limited to that which allows adequate soil cover to maintain (or increase) SOM and buffer against the effects of erosion (Nelson 2002). According to a review by Wilhelm et al.

(2004), "Carbon input will change with crop, year, and management practice. Suitability of different crops to different climates changes the amount of residue produced."

Short-term studies are inadequate for assessing the impact of crop residue removal on SOM. They cannot determine the effects of yearly variation in weather conditions (and hence cannot determine long term trends), nor do they allow sufficient time for SOM levels to change (Karlen et al. 1994). However, some research on cereal crops has shown residue retention has a negligible effect on increasing SOM (Nicholson et al. 1997). In an extended study over 30 years in fallow-wheat-wheat rotation, SOM differences were insignificant between residue-removed and residue-retained sites (Campbell et al. 1991). An important part of this SOM maintenance is the translocation of photosynthetic C into the roots (20 – 30% in cereals) (Kuzyakov 2001).

Biomass yield for wheat in eastern Colorado is in the range of 2 t ha^{-1}, while corn yield in Iowa is 12 t ha^{-1} (Wilhelm et al. 2004). Therefore, very different management practices are required to maintain or increase SOM depending upon crop type. Several plot studies have found increased yields in those plots with 100% or 150% of small grain crop residue left on site. Yield differences between no residue and 150% residue have been significant. For example, Maskina et al. (1993) found a 750 kg ha^{-1} difference, with the increased productivity attributed to higher soil water content and increased nutrient cycling. Since SOC content is directly proportional to the quantity of crop residue entering the soil (Larson et al. 1972), the rate of change of SOC (*dC*) in an agricultural soil, as presented in Parton et al. (1996), is given by:

$$\frac{dC}{dt} = hA - kc \qquad \text{(A5.1)}$$

where c is the soil carbon (C) level (g C m^{-2}), h is the C storage constant, k is the decomposition rate of C in the soil (yr^{-1}), dt is time change in years, and A is the addition of organic C to the soil (g C m^{-2} yr^{-1}).

Straw removal shows a significant decrease in input of C and nitrogen (N) to soil. C and N soil levels are closely linked to inputs provided by straw, chaff, and roots. Therefore results indicate that retaining residues should lead to better soil quality and greater organic matter (Campbell et al. 1998; Malhi et al. 2006). However, the black soil zone, such as that in the Peace River, has been found to benefit from no-tillage, effective management strategies in crop rotation and rotation length, and adequate fertilization (Campbell et al. 1991). These activities can potentially offset soil organic matter losses from crop residue removal.

An option to garner the benefits of residues, such as reduced erosion and evaporation, while gaining a valuable feedstock for bioproduct production is returning solid by-product from conversion processes (eg. ethanol production) to the soil. This byproduct could prove to be a valuable source of C (particularly in the form of lignin). The lignin-based C has a much longer half-life than cellulose or hemicellulose C and could thus be released over an extended period (Kumar and Goh 2000).

The effect of residue removal on productivity, nutrient use efficiency and soil quality was assessed by Malhi et al. (2006) at a site near Star City, Saskatchewan. Following four crop seasons, there was a general trend of higher organic carbon, light fraction of organic matter, carbon and nitrogen soil content in straw retained than straw removed plots. However, fertilization was a much better indicator of N uptake than inconsistent results from residue removal. According to Malhi et al. (2006), “High and sustainable crop production is linked to improved soil physical, chemical and biological properties, which in turn are a primary function of soil organic matter." They pointed out that large quantities of straw are produced in Western Canada, which must be removed to minimize negative impacts on soil and future cropping. Retention of stubble can also negatively impact the following year's growth by allowing disease (such as fungus and viruses) to develop and spread. Depending upon site conditions, optimum soil organic matter levels may be maintained even while removing the residues.

While legumes and oilseeds can contribute both organic C and N to soil, cereal residues contribute little N to the soil that is available for future crops. This is because of the large C:N ratio found in cereal crops (Malhi et al. 2006).

Research Impact: Soil organic carbon levels are impacted by residue removal, but this interaction is very site dependent. Residue retention rates used in this research are based upon previous research in similar regions, with similar soil types. They should not be used across the board for all of Canada, nor for all cropping systems. Nitrogen levels were not considered to be a critical consideration for small grain residue removal in this study.

Cutforth and McConkey (1997) addressed the impact of stubble height on crop yield and water use at a site in Swift Current, Saskatchewan. They showed that the amount of stubble left standing after harvest had a direct impact on future productivity by comparing tall (>30cm height), short (~15cm) and cultivated stubble for hard red spring wheat *(Triticum aestivum* L.). All residues were retained on site (ie. nothing was removed). Tall stubble increased water use efficiency and grain yield by approximately 12% over cultivation. In addition, total dry matter was significantly greater in wheat seeded into tall stubble and had a lower harvest index (due to a lower proportion of biomass as leaves). Cutforth and McConkey (1997) also showed that tall stubble changed the microclimate for crops, reducing average wind speed, soil temperature, and incoming solar radiation. The combination of reduced soil erosion and increased water retention, largely due to snow catchment and reduced evaporation from lower wind speed, increased overall productivity. They concluded that prairie farmers should seed into stubble as tall as possible to maximize grain yield.

Nelson (2002) also highlighted the importance of physical conditions of the soil, or soil tilth, which affected productivity and soil retention. Potential study characteristics include soil granulation, density, SOC content, moisture content, porosity, aeration, and drainage. The number of factors involved and their variability between sites highlighted the complexity and potential error in determining a sustainable crop residue removal quantity.

Soil erosion, which relocates soil particles to other locations, is caused by two primary forces – rainfall and wind. Rainfall erosion, in sheet and rill forms, is caused by rain impacting the soil, releasing particles which flow with the water down the slope of the field. Wind erosion also dislodges particles and moves them around the field. The extent of soil erosion is dictated by numerous factors, including cropping systems, field operations (eg. tilling, timing), climate, soil type, residue retention, and field slope. Soil erosion is increased when soils are cropped monoculture and continuously to cereals, or crop residues are removed. This is especially true in the Canadian Prairies, where approximately 0.9 Mha of agricultural land was negatively impacted by soil erosion in the 1980's (Alberta Department of Agriculture and Rural Development 2001).

Tolerable soil loss limits have been determined by the USDA that indicate the maximum rate of soil erosion without compromising soil productivity or extended soil deterioration. Considerations for tolerable soil loss limits include rate/roll of topsoil formation, erosion rate influencing gully formation, erosion control factors by farmers, and nutrient loss (Nelson 2002).

Empirical models, such as the universal soil loss equation (USLE) (Wischmeier and Smith 1965) and the Revised USLE (RUSLE) (Renard et al. 1997) are used to calculate soil loss, and according to Fistikoglu and Harmancioglu (2002), provide many more options and potential for validation than process-based models. Examples of these process-based models include the water erosion prediction project (WEPP) and the European soil erosion model (EUROSEM).

The universal soil loss equation is used as the standard method for determining weather, site, and management impacts on erosion (Wischmeier and Smith 1965). It is expressed as:

$$ESL = R \times K \times L_s \times C_m \times C_p \tag{A5.2}$$

where *ESL* is the estimated soil loss in t ha^{-1} yr^{-1}, *R* is the rainfall-runoff erosivity factor in MJ mm ha^{-1}h^{-1}, *K* is the soil erodibility factor in t ha h ha^{-1}mm^{-1}, which is based on soil type and characteristics, L_s is the slope length and steepness factor, C_m is the cropping and management factor, which is dimensionless and is related to crop type and tillage method, and C_p is the dimensionless conservation control factor.

Many studies have used a generalized average for crop-residue removal values. Nelson (2002) used the RUSLE and wind erosion equation (WEQ) on a county level basis for determining 'available' quantities, as field level analysis was determined to be impractical for the scope of the study (37 Midwestern and Eastern states). According to WEQ results from Nelson (2002), wind-induced soil erosion is negligible beyond 3.37 tonnes of crop residue retention per hectare per year. So this value can be taken as a virtual maximum of required residue retention. As harvest yield increases, soil losses can be expected to decrease throughout the year. Nelson (2002) found that corn stover availability greatly exceeded that of straw (46.2 Mt vs. 8.8 Mt).

Research Impact: While soil loss risk is highly site dependent, for the sake of simplicity, a standard residue retention rate was used across the study area. If a company uses crop residue as a feedstock, it is recommended that removal levels consistent with accepted tolerable soil loss be followed. These need to be conducted at the field level, based on the specific field characteristics. A conservative figure was used in this research to ensure minimal soil loss across the study area.

Tillage operations are a large determinant of soil losses from erosion. Type, timing, and the interplay with cropping system type are of primary importance. No tillage agriculture, combined with standing stubble, has been proven to conserve soil, organic matter and water, and increase overall crop yield (Phillips et al. 1980). Singh and Malhi (2006) compared the effect of tillage (vs. no-tillage) and residue removal (vs. retention) on soil erosion at two sites in Alberta. The first site at Innisfail had Black Chernozem soil and an average straw yield of 3.5 t ha^{-1}, while the second, at Rimbey, had Gray Luvisol and an average yield of 2.4 t ha^{-1}. Both sites were cropped to monoculture spring barley (*Hordeum vulgare* L.). The authors found that no-till management increased soil aggregation (and hence reduced the wind-erodible fraction) to a greater degree than residue retention. However, no-till reduced the water infiltration rate by 33%, indicating a firmer soil. Therefore, a switch to no-till from tillage can more than make up for residue removal in terms of erosion resistance, although future productivity may be negatively affected by increased soil penetration resistance (Ehlers et al. 1983).

Soil compaction is "the process whereby soil particles are pushed closer together with an accompanying decrease of total pore space in the bulk soil mass." (Wilhelm et al. 2004) Soil compaction in agricultural soils is a function of soil type (and properties), tillage strategy, and equipment used in farming operations. Soil water content and the force applied to the soil are the two most important factors determining amount of compaction. This force should not exceed 0.70kg cm^{-2} (Vermeulen and Perdock 1994). However, a high bulk density soil that has already been compacted has a greater durability to more and heavier equipment than a lower bulk density soil; ie. changes are larger from a standard applied force to a low density soil as compared to a high density soil.

The extent of soil compaction has a significant impact on crop productivity by decreasing the overall pore space available to store water (and hence soil water content) and the mean pore diameter (size of pores). This latter impact decreases the water infiltration rate and creates physical impedance problems for root growth. Removal of residues can increase soil compaction through extra machinery (and hence applied force) on-field to harvest the biomass. Compaction is also increased when residues are removed as the organic matter provides a resistance barrier between the soil and machinery. The extent that this barrier inhibits compaction is difficult to quantify (Soane 1990).

Research Impact: The case study assumes a no-till system to maximize SOC retention, as this is the direction agriculture continues to head. However, the issue of compaction is noted as a subject of concern.

Even when there is no market for crop residues, they can be removed or burned on-field. The primary reasons for this management strategy are to reduce the barriers to cropping in the following season and disease prevention. Crop residues can serve as over-wintering sites/buffers for insects and disease, which will affect the following years' crops. Research on corn stover has shown removal can actually increase yields in the following years due to disease and insect infestation reduction (Swan et al. 1994).

These numerous considerations mean that sustainable removal rates vary on a field by field, or even sub-field level and are strongly impacted by yearly climatic condition, management strategies (including fertilization, rotation, and tillage), and cultural practices (Wilhelm et al. 2004).

A5.2 VARIABILITY

Year-to-year variability in biomass availability will greatly impact the long-term commercial viability of a bio-based operation. Although the study only covered a 3-year production window, Nelson (2002) found a massive variability in the amount of residues available for removal. For example, Kansas had an 80% increase in corn stover availability year over year and 116% variability over the 3 year study window.

The earlier that biomass yield can be known, the earlier planning for harvest and handling can be arranged. While historic yield can be a strong indicator of current yield, other factors can also be used. Summers et al. (2003) found the length of pre-heading period is the strongest indicator for straw yield in rice. This was largely a factor of additional solar energy reaching the plant, and although yield was higher, stand density decreased. Hence, larger and fewer stems were available. A non-linear distribution of biomass in the stem meant that cut height influenced the ‘available’ residue yield and straw composition.

The major considerations for residue removal are summarized in Table A5-1. According to Wilhelm et al. (2004), “Best management practices and aboveground residue harvest rates need to be established for minimum amount of stover that must be retained on the soil to maintain and/or increase SOM, minimizing erosion and protecting soil quality and productivity. This very complex issue must be addressed regionally if not on a field or even subfield basis. Current estimates on the annual residue inputs range more than an order of magnitude, from 0.8 to 14 t ha^{-1}. Rotation, tillage and fertilization management; soil properties; and climate will all play major roles in determining the amount of stover that can be removed in a sustainable system." While that study focused on corn stover residues, the importance of best management practices is also true for cereal residues.

A5.3 GRAIN RATIOS

Crop residues from small grains include chaff, leaf blade, leaf sheath, stem internode, node, and even grain not separated in the harvesting processing. Each of these components has different characteristics, including density, energy content, and moisture content. Yields of each component compared to the primary product, grain, can vary greatly depending upon cultivar type, soil and nutrient characteristics, and weather conditions.

Since available yield data is only reported for the grain/seed component of crops, residue production must be calculated using straw-to-grain (SGR) or material other than grain (MOG) to grain (G) ratios. Summers et al. (2003) pointed out that accurate, regional grain yield data is usually readily available and collected over extended periods (>50 years). Therefore, "dependable straw-to-grain factors become critical for estimating available biomass..." (Summers et al. 2003). While their study was on rice, the findings indicated that straw and grain ratios are highly dependent upon weather and moisture availability, which stays true for cereals as well. As straw yield estimates are so dependent upon selected ratios, there can be considerable error and variance.

Straw production is calculated as:

Straw Yield (kg/ha) = grain yield x SGR (A5.3)

Other ratios, such as MOG:G are calculated in a similar manner. The ratios vary considerably by location, year, weather conditions, and cultivar. However, most studies have used a singular number applied across many variables and large geographic distances. Nelson (2002) used 1.3 for spring wheat and 1.7 for winter wheat in a study on the United States Midwest. Aase and Siddoway (1981) found total biomass other than grain equalled yield of grain for spring wheat; hence, a ratio of 1:1. In stark contrast, 6 cultivars studied by Kernan et al. (1984) had an average 39.1% (0.64:1) of total biomass present as residues. Given this large range (from well above 1.5 to less than half that value), external factors play a large role on the ratio. Stumborg and Townley-Smith (2004) found that the type of soil had a large impact on MOG:G ratio, with 0.61 for barley and 0.75 for wheat on brown soils, 0.75 for barley and 1 for wheat on dark brown soils, and 1 for barley and 1.5 for wheat on black soils. However, beyond soil type, moisture deficit also affected residue proportion; as moisture deficit increased, the MOG:G ratio decreased. Stumborg et al. (1996) provided a MOG:G summary for small grains in the Canadian prairies. This information is adapted and modified for Table A5-2.

In rice, Summers et al. (2003) found greater stem weight was correlated with decreased stem density. However, the best indicator of biomass yield was not grain-to-straw ratios, but heading date (and hence when a higher proportion of energy is directed towards the grain). They suggested heading date as an accurate indicator of biomass yield may well apply to other agricultural residues. This does not seem unreasonable, given other studies into drought affect on residue availability. Drought in early stages of growth causes a lower MOG:G ratio due to shorter and thinner stems, while drought later in the season affects grain yield to a greater extent and thus increases the MOG:G ratio (Spratt and Gasser 1970).

Harvest Index (*HI*), which measures the grain yield relative to the rest of the plant (Wilhelm et al. 2004), is calculated by:

$$HI = \frac{g}{(g + r)} \tag{A5.4}$$

where *g* is the grain yield and *r* is the residue yield.

Several equations have been developed to describe straw yield for different cultivars. Campbell et al. (2000) expressed straw yield in Canadian Western Red Spring (CWRS) wheat as:

$$Y = 58 + 1.64G_y \tag{A5.5}$$

where *Y* is straw yield and G_y is grain yield in kg ha^{-1}. Zentner et al. (2003) describe Canadian Prairie Spring (CPS) wheat straw yield as:

$$Y = 303 + 1.17G_y \tag{A5.6}$$

And also use a different equation for CRWS wheat grown on fallow vs. on stubble.

Fallow:

$$Y = -69.5 + 1.75G_y \tag{A5.7}$$

Stubble:

$$Y = 471 + 1.44G_y \tag{A5.8}$$

However, the accuracy of these equations varies year by year depending on weather and growing conditions.

Research Impact: Material other than grain (MOG) to grain ratios, as provided by Stumborg et al. (1996) for the black soil zone, were used to determine biomass production. A conventional combine was assumed. MOG:G ratios for the average case were 1.5 for wheat and oats, and 1 for barley. This droped to 0.75 for all crops in the minimum scenario and rose to 1.75 for wheat and oats and 1.25 for barley in the maximum case scenario.

A5.4 TRENDS AFFECTING YIELD

Historically, straw height has varied tremendously. It has been when straw had little or no value that crops were bred for a high HI, while low HI has dominated in times when straw was required (eg. fertilizer, animal manure management, bedding, thatching). Valuing crop residues as a feedstock for bioproducts may in turn cause a decrease in HI. However, unless overall plant biomass increases, a decreasing HI will cause lower grain yield (Sinclair 1998). Research reviews have also found that above ground biomass has remained relatively constant over the past half century, despite rapid advances in breeding techniques and genetic improvements (Slafer and Andrade 1993). With some cultivars in Canada, such as CWRS, yield increases have been difficult to attain because of the prairie climate of low moisture and high summer temperatures, combined with a demand for high quality grain (Wang et al. 2002).

According to Fischer (2007), an optimum plant height for wheat has been determined to be 0.7 – 1.0 m. The author suggested that research efforts are moving away from work on dwarfing genes in cereals (such as Norin 10 and *Rht* in wheat) and into improvement of performance under water-limited conditions. It is recognized that yield progress (and increases in productivity) from traditional plant breeding are slowing significantly and payback on research has been reduced.

Fischer (2007) identified increases in harvest index as the main component of increases in yield. This means less biomass is available as straw and more as grain, although the overall weight of the plant does not change significantly. This indicates a trade-off between grain yield and straw yield. However, current values are near the HI limits of 60% calculated by Austin (1980), and therefore any further efforts will have minimal results. If these findings and calculations can be considered accurate, it is possible to assume that straw yield will not decrease any further due to dwarf breeding. Fischer (2007) suggested that overall biomass yield should be the focus of any further breeding and genetic research. Under current systems and genetics, a high HI is considered essential for a high yield potential in cereals.

Harvest index is directly proportional to the allocation of photosynthate in the plant between the grain and the vegetative portions of the plant (stem, leaves, etc.) It is a good indicator of the carbon distribution in a plant and rising harvest indexes throughout the 20th century have been the primary reason for significant increases in crop yields (Sinclair 1998). For plant stability, stems have been bred to be shorter and stronger to support the larger grain heads. While photosynthate plays an important role in growth area of the plant, nitrogen allocation plays an equally important role in maximizing harvest index. A high HI has been associated with low lignocellulosic biomass production and the centurial trend has been towards decreasing lignocellulose production in agricultural crops. Selection may not have been for high harvest indexes directly, but for plants that responded to applied nitrogen and using that nitrogen to produce grain (Sinclair 1998). In fact, recent research has shown that higher nitrogen yields in grain amongst newer and higher yielding cultivars can be attributed to more efficient allocation and utilization in the seed rather than an increased uptake of nitrogen from the soil (Wang et al. 2003).

Cultivar selection will significantly alter residue production, and thus, trends in cultivar cropping frequency are important in determining availability of residues. Investigations by Zentner et al. (2003) in southern Saskatchewan showed the differences in harvest index for traditional CWRS wheat and newer, higher-yielding Canada Prairie Spring (CPS) wheat. Although CPS out-produced CWRS by 17% from a grain perspective when grown on stubble, CWRS produced 11% more residues. Over a 12-year study period, harvest index for CPS averaged 44% while CWRS was 37%. Water use efficiency, which is a determining factor in yield, was greater in CPS that CWRS (9.4 kg ha^{-1} mm^{-1} and 7.2 kg ha^{-1} mm^{-1} respectively). These are similar to values reported for CPS and CWRS by Clarke et al. (1990) of 45% and 40% respectively.

In the Western Prairie region of Canada, water availability is the normally the limiting factor in crop productivity (Campbell et al. 1997). By introducing cultivars, such as CPS wheat, which have higher water use efficiency, fallowing can be reduced and soil quality maintained. Stubble is used to capture snow in the winter and retain water, but the improved water use efficiency in short-stemmed cultivars means that although less water may be captured, it can be used more efficiently. Crop rotation and fallowing frequency not only determine the residue availability in a given year, but have implications for residue yield in future years and long term land productivity. This is not only related to nutrient levels and erosion, but also water retention. Fallowing increases soil moisture levels but can have negative effects on soil quality and over extended periods can cause a reduction in crop yield.

Research Impact: The majority of gains in increasing grain yield have been at the expense of decreasing straw yield. This may change if a price is applied to straw as a biorefinery feedstock, but overall plant productivity has changed little in the past century and thus, the analysis does not include projections for future increases in availability of biomass. Historical yield data, as provided by Agriculture and Agri-Food Canada, was the primary source of data on productivity.

Factor	Residue Role	Quantification and Comments
Moisture	Snow retention, create water barrier to evaporation, reduce wind-enhanced evaporation, solar radiation block	Most of the Canadian prairie crops are water-limited and therefore, removal levels must take into account current and projected moisture levels to ensure sustainable yields
Soil organic matter and erosion	Increase soil retention, improve soil structure, reduce wind at the surface	To ensure long term yields, nutrient-rich topsoil needs to be retained. The long-term availability of residue is dependent upon managing erosion pressures from wind and rain. Field slope is a key determinant.
Soil organic C and N	Residues contain organic C and N that can be used by crops in future years	Cereal residues, unlike legumes, contribute little available N to the soil because of the large C:N ratio.
Soil tilth (physical characteristics)	Residue organic matter provides a barrier between soil and machinery, reducing compaction	Residue removal increases soil compaction by removing the compression barrier between soil and machinery, and also by increasing the equipment on the field. Soil compaction decreases productivity by lowering the water infiltration rate and causing root impedance.
Disease and pests	Residue retention can increase the risk of disease and pests	Like many characteristics, this is site dependent but excess organic matter increases the chance of plant viruses, fungi, and pests. Effective crop rotation can significantly reduce these risks.
Tillage and management	Several of the drawbacks of residue removal can be partially offset by changing management practices	No-till agriculture can reduce the risks from erosion and SOM loss. However, compaction becomes a greater issue without tillage.

Table A5-1 Possible Considerations for Residue Removal

Soil Zone	Combine Type	Wheat MOG:G	Wheat C:MOG	Barley MOG:G	Barley C:MOG	Oats MOG:G	Oats C:G
Brown	Conventional.	0.75:1	0.15:1	0.6:1	0.13:1	0.75:1	0.15:1
	Rotary		0.25:1		0.20:1		0.25:1
Dark Brown	Conventional	1:1	0.15:1	0.75:1	0.13:1	1:1	0.15:1
	Rotary		0.25:1		0.20:1		0.25:1
Black	Conventional	1.5:1	0.15:1	1:1	0.13:1	1.5:1	0.15:1
	Rotary		0.25:1		0.20:1		0.25:1

Table A5-2 Ratio of Material Other than Grain (MOG) for Wheat and Barley in Different Soil Zones

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