**Spatially Explicit Simulation Modeling of Local, Regional and International Bioenergy Scenarios in the Northern Rockies**

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by

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**Authorization to Submit Thesis**

This thesis of Ryan A. Jacobson, submitted for the degree of Master of Science with a major in Natural Resources and titled "Spatially Explicit Simulation Modeling of Local, Regional and International Bioenergy Scenarios in the Northern Rockies," has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

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## Abstract

I reviewed literature on biomass modeling (Chapter 1) and evaluated production rates and costs for a continuous monoline system removing slash from Pre-Commercially Thinned stands on the UI Experimental Forest (Chapter 2). Optimal line spacing was 34m and treatment costs were $1290.90 per acre on a Scheduled Machine Hour basis. In Chapter 3, I describe development of the Forest Residue Economic Assessment Model (FREAM). FREAM links GIS and dynamic modeling of bioenergy supply chains. A factorial modeling experiment with 20 cities as replicates was conducted. 3 feedstock use scenarios were simulated: local, catalytic pyrolytic production of gasoline (181,437 Mg $yr^{-1}$); regional, biochemical production of bio-jet (725,748 Mg $yr^{-1}$); and pellet production for international markets (272,155 Mg $yr^{-1}$). Pellets cost the least ($10.51 $GJ^{-1}$), followed by gasoline ($22.33 $GJ^{-1}$) and bio-jet ($35.83 $GJ^{-1}$). Total costs and capital costs differed for all pairwise scenario comparisons ($p < 0.0001$). Transportation costs differed between all three scenarios ($p < 0.0001$).

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Finally, I would like to thank my family and friends for all of their support through what was a long and trying process at times. Their continued support, positivity and rational thinking were a guiding light that ensured I never strayed far from the proper path during these last years. There are countless more people and institutions that should be mentioned here and I regret there is not more time to provide the proper acknowledgements, but know that your contributions and support are both remembered and deeply appreciated.

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## 1.1 Introduction

Energy independence has become an important policy issue in the United States. Emphasis has led to significant investments in green and alternative energies that can be developed and deployed using wind, solar and other natural resources. Wind and Photovoltaic (PV) farms require specific atmospheric and geographic conditions to be efficient at a commercial scale (Janke, 2010). The United States is the fourth largest country on the planet and the largest exporter of agricultural products (Simpson, 2012). Ethanol, which requires feedstocks such as corn, soybeans, or other agricultural products, could impact these exports. The development of the biofuels industry has been slow but steadily increasing since the Energy Policy Act of 1978 (Tyner, 2008), which established the first subsidy for ethanol in the United States.

Cautious growth in commercial bioenergy has been well warranted at times due to both economic and social factors (Evans, 2009). Competition between the well-established but volatile fossil fuel industries and renewable energy markets has been difficult in periods of inexpensive petroleum. Conversely, during periods of expensive petroleum, competition among markets has been a major factor driving biofuel development. Woody biomass derived biofuels also may compete with the timber and pulp and paper industries, which can create problems and has led to increased research into using forest residues in place of timber (Cavalieri, Wolcott, & Beltz, 2014). Agricultural feedstocks such as corn and soybeans compete with the food industry and demand-associated price increases have led to significant negative publicity at times (Ajanovic, 2011). Congress has capped ethanol production from corn grain at 15 billion gallons to minimize the impact on food products (Perlack et al., 2011). Cellulosic ethanol is viewed as the more relevant feedstock due to the lack of competition with agricultural food supply and decreased inputs requirements to create a usable fuel (Perlack et al., 2011).

1.2 Billion Ton Study

In 2005, the United States government began work on the Billion Ton Study (Robert et al., 2005).The purpose of this study was to determine if the contiguous United States agricultural and forest resources were capable of producing one billion tons of biomass for energy use in a sustainable manner. One billion tons was selected because it would replace 30% of the United States' current petroleum consumption (Perlack et al., 2011). This study used conservative estimates of biomass supply volume, and assumed that all produced biomass was available. The costs to actually harvest, store and transport the biomass to the refinery were not considered. An update to the Billion Ton Study was performed in 2011, called the U.S. Billion Ton Update (Perlack et al., 2011). This recent study refined the estimates in the 2005 report, as well as adding spatial county-by-county inventory of primary feedstock, the price and quantity of those feedstocks, and improved modeling of resource sustainability. The Billion Ton Study and its update also produced the Billion Ton Database, which houses all of the data used in the production of the Billion Ton reports (Perlack et al., 2011). The database is available on the United States Department of Energy (DOE) Knowledge Discovery Framework (KDF), where the DOE houses publicly available data and reports considered valuable for bioenergy research.

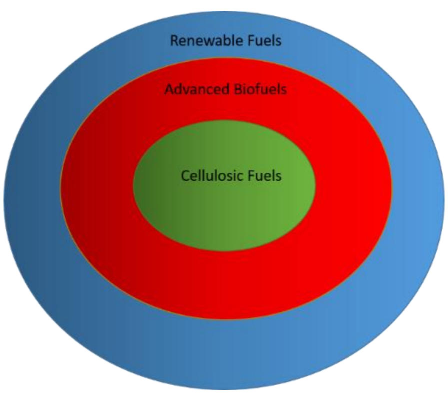


*Figure 1: Levels of fuels classifications, modified from Warner et al. (2014)*

In 2005, The Energy Policy Act of 2005 (EPAct, 2005) established the Renewable Fuel Standard (RFS), which governed what was considered a renewable fuel. In 2007, The Energy Independence and Security Act of 2007 (EISA, 2007) was passed and required the Environmental Protection Agency (EPA) to mandate volumetric targets for 4 categories of biofuels: renewable, advanced, biomass based and cellulosic (Warner, Bush, Levine, Jacobson, & Leiby, 2014),this update was called the Renewable Fuel Standard II (RFS2). RFS2 expanded volumetric targets, added diesel fuel substitutes, created several new categories of biofuels and established the Renewable Identification Number (RIN) market. The RIN market is a credit trading market where producers of qualified biofuels are awarded credits, which can be used as a subsidy on produced biofuels to reduce the production costs that are transferred on to consumers (Warner et al., 2014). The RIN market is established through payments from petroleum producers that match the amount of credits needed for 100% of RSF2 biofuel volumes to be met. The price of a RIN credit has ranged from $0-$0.30, but has experienced volatile price fluctuations at times, primarily based on petroleum price and demand fluctuations (Warner et al., 2014).

The increase in volumes of biofuels produced in the United States, along with the creation of detailed data about primary feedstock availability has spurred myriad efforts to develop models that accurately represent the supply and logistics involved in utilizing biomass feedstocks for energy. Accurate supply curves for woody biomass can be difficult to develop due to the highly variable conditions of each harvest location, while agricultural biomass can be harvested from the same field annually, woody biomass is harvested from a new location every year. Models that look at the biofuels industry as a whole can identify regions that should be targeted for specific types of biofuel technology. This makes long term woody biomass supply curves especially difficult to develop, the ability to provide forecasts of how the industry will progress, provide a testing ground for proposed policy changes and alternate supply chains and develop detailed supply models extremely necessary for successful woody bioenergy projects in the western United States.

### 1.3 Biomass Conversion Pathways

To produce biofuel from agricultural and woody biomass, biomass is broken down into its constituent sugars through one of two process types. The first is thermochemical processes, where biomass is placed in a reactor with chemical reagents and potentially a catalyst, and then heated until the starches are separated from the other material. It is then sorted and sugars are moved to the next step of the process (Wright & Brown, 2007). The second set of processes are biochemical, in which biomass is exposed to algae or bacteria that is designed to separate the sugars. Once separated, the sugars are fed into fermentation reactors to be fermented into ethanol and the waste products, which are either burned, recycled or disposed of. Ethanol can then be refined into biofuel through combination with other chemicals and processes (Wright & Brown, 2007).

Converting biomass to biofuels through a thermochemical process requires the biomass to be pre-processed into a suitable size, treated with chemical reagents, placed in a reactor and heated until the sugars separate from the waste products. There are three common types of thermochemical conversion processes: combustion, gasification and pyrolysis (Damartzis & Zabaniotou, 2011). Combustion processes burn biomass to provide heat that powers a boiler or turbine system, this is considered a primary, or direct use, biofuel (Nigam & Singh, 2011). Gasification processes heat biomass in an anoxic environment to produce syngas that is filtered and treated to separate energy and waste constituents and the energy gas is processed through Fischer-Tropsch synthesis to produce a liquid fuel that can be used in transportation and heating. Pyrolysis processes rapidly heat biomass to produce char, liquids and gasses that are then cooled while being exposed to catalysts that speed the gas condensation to the appropriate forms and separated by density (Mohan, Pittman, & Steele, 2006), this process is similar to gasification in the early steps.

Biochemical conversion processes require biomass to be pre-processed specific size characteristics and an appropriate pH for the conversion process. Pre-treated biomass is exposed to acids and heat to free the constituent sugars from the waste products (Saxena, Adhikari, & Goyal, 2009). The sugars are then exposed to bacteria and other fermentation agents and the ethanol is recovered through various methods (Saxena et al., 2009). Ethanol produced from starches derived from corn and other food products was the first widely successful biofuel production method in the United States and has been used since the 1970's (Solomon, Barnes, & Halvorsen, 2007).

## 1.4 Northwest Advanced Renewables Alliance (NARA)

The Northwest Advanced Renewables Alliance (NARA) was created with a 5 year, approximately $40 million grant from the United States Department of Agriculture's (USDA) National Institute of Food and Agriculture (NIFA) Agriculture and Food Research Initiative (AFRI) for the purpose of comprehensively researching a sustainable supply chain for a regional aviation biofuels plant and bio-based products derived from woody logging residues in the Pacific Northwest. The NARA endeavor is a partnership of universities, government laboratories and private industry with Washington State University being the lead that contribute to the effort to develop and improve bioenergy development processes from feasibility studies through commercialization. The project is broken into five distinct research teams: education, conversion, feedstock, sustainability management, and outreach.

NARA project researchers have performed Techno-Economic Analysis (TEA) of the possible conversion pathways and potential supply chain options associated with a regional biofuel plant. The first supply chain considered is an integrated biorefinery, where biomass is pretreated once at the landing and transported (e.g. chipping or grinding) and the subsequent conversion process is completed entirely within the walls of the conversion facility. The second pathway is a distributed supply chain, where multiple biomass pre-processing steps occur before delivery to the conversion facility, which improves transportation costs by systematically removing material that is unusable at the refinery.

### 1.5 Bioenergy Alliance Network of the Rockies (BANR)

The Biomass Alliance Network of the Rockies (BANR) is a network of research scientists, educators and extension specialists from the Rocky Mountain region to develop a sustainable, acceptable method to reduce fuel hazard loading on the Rocky Mountains, while aiding renewable energy development goals. Beetle-kill timber is an ideal target for biofuels because the timber is plentiful, already dead, easy to harvest, and a potential hazard to the remaining forest. In 2003, mountain pine beetle infestations occurred on approximately 2.22 million hectares of Rocky Mountain forests (Wulder, Dymond, White, Leckie, & Carroll, 2006). Mountain pine beetle outbreaks, in particular, have been identified as problematic for atmospheric carbon removal, due to the large acreage of Rocky Mountain forest killed during recent outbreaks (Kurz et al., 2008). The BANR is using a Cool Planet catalytic pyrolysis unit to process the beetle-kill timber.

Cool Planet is a private company located in Greenwood Village, Colorado that has developed a catalytic pyrolysis process to convert biomass to a drop-in gasoline. The company has received funding from British Petroleum (BP), General Electric (GE), Google Ventures, and several other significant backers from the energy sector. Cool Planet states that their process produces a carbon-negative gasoline for approximately $1.50 per gallon as well as several tons of bio-char (Cool Planet, 2012). Bio-char is marketed as a carbon additive to be used as a soil amendment. Bio-char is added to field or forest soils to help facilitate feedstock growth, creating a positive feedback loop for the system over time. The first commercial scale biofuel plant, producing 10 million gallons, is currently under construction in Alexandria, Louisiana (Cool Planet, 2014).

## 1.6 Field Transportation

Timber production is an important part of the Pacific Northwest economy and provides a significant portion of the United States' timber capacity. Two primary ground-based systems for harvesting timber are commonly used: Cut to Length and Whole Tree. In Cut to Length systems, the trees are debarked, delimbed, and bucked to the specified length at the harvest site. These systems leave distributed slash in the woods, resulting in small, numerous slash piles throughout the harvest area (Keefe, Anderson, Hogland, & Muhlenfeld, 2014). In Whole Tree systems, trees are simply cut from the stump and moved to a central area for debarking, delimbing and bucking (Keefe et al., 2014). This method results in large slash piles located near the primary logging roads in a harvest area. The distribution of slash piles in a harvest area and the proximity to a road can be major factors affecting the feasibility of using woody biomass for bioenergy purposes (Keefe et al., 2014). Another important factor affecting the feasibility of woody biomass utilization for energy is whether primary harvesting systems use ground-based or cable systems for skidding and yarding. Cable logging is more expensive and less productive than ground-based skidding, and the size of available landing space is more restrictive during pre-processing (Keefe et al., 2014).

Minimizing transportation costs for biofuel feedstocks, especially in woody feedstocks that require additional processing, has disproportionate effect of biofuel costs, as growth and transportation of feedstock are significant costs, 35-50% in some cases, in the production cycle (Hess, Wright, & Kenney, 2007; Panichelli & Gnansounou, 2008). Whole tree harvesting limits the need for in-woods transportation of small stems and limbs. Chipper forwarder variations, baling forwarders and pulley or conveyor systems are several different transportation systems that have been utilized to reduce transportation cost of slash in the field. However, pairing these slash collection systems with cut-to-length harvesting is generally more expensive than whole tree processing at the landing.

There are several different variations of chipper-forwarders, the primary two being chipper-forwarders and chipper-harvester-forwarder. A chipper-forwarder, which is a forwarder that gathers the slash and chips it into a bin located on the back of the machine (Stokes, 1986). Chipper-harvesters are a forwarder system that is either tracked or wheeled, equipped with harvesting equipment to fell trees and a chipper and bin system to chip the harvested trees and store them until the bin is filled and the forwarder can return to the landing to load on trucks for transportation out of the field. Chipper-Forwarders are tracked or wheeled systems that have a chipper and a bin, where already felled trees are fed into the chipper and stored in a bin until the filled, when the chipper-forwarder will return to the landing to load the chips onto trucks for transportation out of the field (Stokes, 1986). A new method for collection and transportation of biomass is baling. A forwarder gathers the slash and bales the material into cubes or round bales, similar to how a hay baler operates (do Canto, Klepac, Rummer, Savoie, & Seixas, 2011).

Pre-commercial thinning (PCT) operations are done to provide residual trees with less competition for resources in order to facilitate growth of larger, healthier crop trees for the final harvest (Keefe et al., 2014). Timber operations in the United States generated 178 million metric tons of residues in 2002, 86 million of which were unused and available for recovery (McKeever, 2004). These operations are typically performed at a net cost to the landowner or manager (Keefe et al., 2014). In Finland, in stands containing pine, spruce, birch and other broadleaf trees, it was determined that taking stems over 3cm in diameter and leaving between 600 and 900 stems per hectare was the most efficient method for thinning for energy purposes and generated a profit for every step of the supply chain being studied (Ahtikoski, Heikkilä, Alenius, & Siren, 2008). Continuous winch and conveyor systems can potentially remove the PCT generated small stems and slash to generate a subsidy on management of the stand for the land owner or management agency.

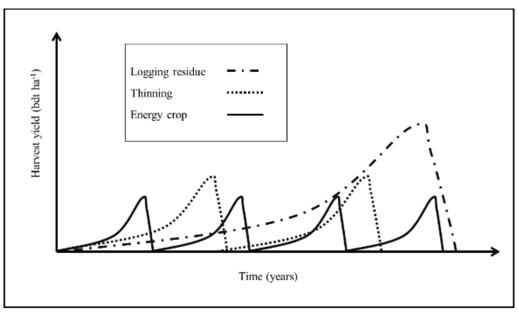


*Figure 2: Temporal dynamics of woody biomass feedstock supply (Keefe et al. 2014)*

## 1.7 Biochar

Black carbon generated from the pyrolysis of biomass is seeing a resurgence of interest as a result of bioenergy research and population pressure on agricultural production. Carbon soil amendments have been used for centuries, and even occur naturally. Use of pyrolysis produced carbon soil amendments improves plant growth, reduced greenhouse gas emissions from treated soils, and reduces microbial degradation to improve carbon sequestration potential (Van Zwieten et al., 2010). Some biofuel companies, e.g. CoolPlanet Energy Systems who is a corporate partner on the BANR project, incorporate marketing and sale of biochar as an important component of their business model.

## 1.8 Dynamic Modeling and Decision Support Systems

System Dynamics (SD) modeling is based on the principles of control systems engineering and non-linear dynamics originating in the works of Forester and first being presented in the Harvard Business Review in 1958 (Ahmad & Simonovic, 2004). This modelling has been extensively applied to resource scarcity decision making, especially in the fields of economics, environmental science, and water usage. SD strength lies in its ability to clearly display the interactions within a system, and the ability to model a changing system through time. SD modeling can estimate the change in the environment of a region, but it struggles to display those changes and has difficulty narrowing the results to a less distributed region.

Decision support systems (DSS) are models that allow a policy to be tested to estimate the effects before that policy is enacted in the real world and risk actual resources and revenues. DSSs allow for policy effects to be observed without risking any real world damage to resources or revenues, and can be useful tools for mitigating potential negative effects a policy may have. The ability to simulate and explore the effects of a policy is relatively new, only available since the rise of the computer and gaining popularity as the power of computers has increased, and has been adopted in part by the United States government to provide insight into how domestic policy and laws will affect the development of industries (Shim et al., 2002).

## 1.9 Benefits of linking simulation modeling and GIS

SD modeling makes it possible to model complex interactions and temporal problems, while the capability of GIS to display spatial data makes any modeling system uniting the two very powerful (Ahmad & Simonovic, 2004). This approach has already been used in a limited capacity for environmental impact assessment and resource management, but has not become mainstream in the SD community (Xu & Coors, 2012). This could be because of difficulty linking the two techniques software, which can be very time consuming and in some cases require integrating an overlaying self-developed programming architecture to communicate data between the different software. Never the less, the ability to generate images and data that accurately details the effects of a biofuels operation, on an area, including the complex interactions of the various parts of the system is important for providing accurate forecasts, mitigating unintended consequences and garnering public support.

## 1.10 Biomass and Bioenergy Research Group (BBRG)

The University of British Columbia’s Biomass and Bioenergy Research Group (BBRG) has developed the Integrated Biomass Supply and Logistics (IBSAL) model for determining the supply chain for developing a bioenergy plant. IBSAL can operate in discrete, continuous, or a mixed mode, allowing the model to help both with planning individual bioenergy plants and longer term analysis (Sokhansanj, Turhollow, Wilkerson, & others, 2008).

The model is set up with several modules that contain equations defining the various tasks performed in each action of the biomass supply chain. The model allows users to drag blocks from a library onto a worksheet, where everything being computed is gathered (Sokhansanj et al., 2008). The blocks are premade operations that occur in the biomass supply chain, such as queues, decision making, input and output functions. Once blocks are on the worksheet, the user establishes connectivity among blocks and supplies required data. The program is written in the ModL programming language, which is similar to C++ and can be used to refine processes being simulated (Sokhansanj et al., 2008).

IBSAL can track biomass from the time it is harvested through final delivery to the facility. The user can decide from among different harvest methods and equipment, storage times and methods, processing techniques and delivery methods. Bales, loose chips and hog fuel can be simulated. Material losses in the supply chain are also represented (Sokhansanj et al., 2008). Using these options, a user can design the best supply chain possible for a specific bioenergy project. Weather patterns and moisture variations are considered in the harvest costs and machinery efficiency computations. By tailoring the simulation to variables at a specific location, the model is capable of offering site-specific, accurate output (Sokhansanj et al., 2008).

### 1.11 Biomass Logistics Model (BLM)

The Idaho National Lab has developed the Biomass Logistics Model (BLM), a continuous model that looks at the cost and energy balance of delivered biomass to a bioenergy refinery (Cafferty, Jacobson, Muth, & Bryden, 2013).The BLM tracks changes in the characteristics of biomass, such as moisture content, ash content and material losses. The BLM can use woody residue feedstock, as well as herbaceous, short-rotation woody crop, algae, and other potential feedstocks. The BLM can be used to simulate the supply chain for both biochemical and thermochemical conversion processes, which require different feedstock characteristics to be most effective. This model can be used to evaluate the efficiency of a particular system, but it can also be used to find the energy balance of delivered feedstock and GHG emissions (Cafferty et al., 2013). These variables are important to track in order to prove the effectiveness of the fuel as an energy source and as a GHG reduction method.

The BLM is operated through a graphical user interface and is broken into 4 sub-models; the location, the unit operation, equipment, and cost sub-models. Each sub-model performs a specific, dedicated function in the whole analysis and all sub-model results are concatenated into a summary report during the simulation process. The assumptions of the model can be altered through a graphical user interface, including the feedstock type, equipment used, and operating parameters (Cafferty et al., 2013). Each sub-model is composed of routines that encompass the various parts of each of the operations being modeled.

The location sub-model tracks the location of biomass throughout the logistics chain. This has four primary areas of consideration, which is used to avoid redundancy. The four locations are: the production location, a first intermediate location (called a depot), a secondary intermediate location (called a terminal), and a conversion facility location (the biorefinery) (Cafferty et al., 2013). The unit operation sub-model consists of the following parts: Harvest and collection, storage, transportation, preprocessing, and handing and queuing at the biorefinery. The model determines what operations occur at each step in the logistics process. Selection of feedstock type and conversion technology are associated with pre-selected processing options and equipment (Cafferty et al., 2013). The equipment sub-model simulates production rates and costs for different systems analyzed. Specific models of combines, feller-bunchers, and all other equipment used in harvesting and pre-processing are simulated (Cafferty et al., 2013). This model works in conjunction with the unit operation sub-model to develop estimates of piece-wise production rates. The cost sub-model tracks costs throughout the system, including capital costs, depreciation, and losses to upgraded material (which is significantly worse than losing raw biomass). This sub-model works in conjunction with all three of the other sub-models to ensure that costs are accurately estimated during the simulation and is the critical sub-model for techno-economic output that is generated (Cafferty et al., 2013).

The modular architecture of the BLM allows for varying logistics supply chains for biomass operations to be evaluated. Herbaceous bioenergy systems conventionally leave processing steps until the material is at the conversion facility. The BLM makes it possible to test setups that process at earlier steps or process with different methods that may change upstream feedstock quality requirements such as ash and moisture content (Cafferty et al., 2013).

The BLM can also perform optimization and sensitivity analysis on specific variables. Optimization of model parameters is done using Monte Carlo methods. Each parameter in the model has an associated probability density function and user-provided maximum, minimum and mean values (Cafferty et al., 2013). Parameter values are randomly assigned using Monte Carlo sampling methods over 1000 iterations. This allows the model to find the most efficient value for the variable with the given system identified. Sensitivity analysis is performed to show the relative importance of each variable on overall system predictions using the same statistical distributions and Monte Carlo method as with the optimization analysis (Cafferty et al., 2013).

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# Chapter 2:
# Mobilization of Pre-Commercial Thinning Slash

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## 2.1 Abstract

The mobilization of Pre-commercial Thinning (PCT) and other thinning slash is important for the reduction of short-term fire hazard in managed forest stands. Slash from thinning operations in the Inland Northwest may also be useful as a feedstock for biofuel production. The use of manual collection with a continuous capstan monoline cable system is one potential rigging configuration being considered for the removal of PCT slash. However, current realistic costs and production rates associated with these systems relative to other fuels reduction and biomass extraction systems have not been quantified. We evaluated one system in a replicated experiment in three 20-25 year old ponderosa pine plantations on the University of Idaho Experimental Forest West Hatter Creek Unit. Manual pre-bunching of slash and yarding with the continuous capstan followed a chainsaw PCT treatment by a contracted thinning crew. A Portable Winch ™ capstan drum with 2.5 HP Honda motor, 100:1 gear reduction and 12.7mm braided polydachron rope was used to haul slash at an observed line speed of 0.18 m $s^{-1}$. Our objectives in the study were three-fold: to estimate realized production rates per Scheduled Machine Hour (SMH) using the system in PCT-aged ponderosa pine plantations in the Inland Northwest; 2) to estimate yarding costs per acre and per ton; and 3) to use a system dynamics approach to quantify the optimal corridor spacing for the system as well as the line speed and line capacity. Resulting data showed that maximum line capacity achieved was 0.13 Mg. The system cost \$65.35 $Mg^{-1}$, or \$1,290.90 $acre^{-1}$. In addition to the PCT treatment cost, this yarding rate is prohibitively high, at the upper end of mastication treatment costs currently used by the USDA Forest Service and

other land management agencies. Further mechanization of the system and scaling to greater winch capacity may increase production and reduce costs.

## 2.2 Introduction

In the Inland Northwest, slash and unmerchantable timber generated from logging and other activities are required to be removed to limit fire potential in the area (Barkley et al., 2015). Due to the cost of transporting and processing slash, this is generally achieved through the piling and burning of residual materials (Carey & Schumann, 2003). If new methods of slash removal can be developed to minimize the cost of slash extraction from stands, additional avenues of slash removal could become available as feedstock for energy production or other activities. Making slash removal cost effective would reduce the atmospheric pollution effects that widespread burning currently produces (Dennis, Fraser, Anderson, & Allen, 2002) and offers the opportunity for logging communities to contribute to alternative energy production.

Determining the optimal spacing of timber corridors and roads has been of interest to the forest operations community for years. Optimal placement of corridors reduces expenses by minimizing the amount of time spent on non-production actions, such as movement of equipment and lateral movement (Ghaffariyan, Stampfer, & Sessions, 2010; McNeel & Young, 1994). Different optimization equations have been developed to aid in the determination of the optimal distance for different harvesting systems. Matthews (1942) showed that optimal road spacing varies directly with road costs (Matthews, 1942), Yeap and Sessions (1988) developed a model that allowed for non-linear skidding costs and other modifications to the Mathews equation (Yeap & Sessions, 1988). Peyton (1973) optimized fixed and variable costs as a function of road intensity (Peyton, 1973). Thompson (1988) developed a novel equation that used profits in place of costs to determine optimal spacing (Thompson, 1988). A more detailed discussion of these equations strengths and weaknesses can be found in Rutherford’s 1992 thesis (Rutherford, 1992).

The movement of small diameter and unmerchantable timber has been an area of increasing research as the timber industry looks to improve profit margins and expand production volumes. Conveyors have shown promise in research performed in Missoula, MT by Rummer and Groenier (2008) (Rummer & Groenier, 2008) and powered pulley systems have also been considered for use by the U.S. Forest Service (Cammack & Tour, 1979; Richardson, 1981). Conveyor and pulley line optimal corridor spacing in Pre-commercial Thinning (PCT) operations closely imitates skyline and skidding corridor spacing but on a smaller scale, as manual labor is used to move slash to the conveyor. Variables that must be quantified in order to determine the optimal corridor spacing include the speed of the conveyor, the maximum weight capacity and speed of the hand crew, and the size and density of slash in the area of study. Using these variables, one can develop a model to determine the optimal spacing of a conveyor system. Our objectives in this study were to:

1) Use a simple system dynamics model to determine the optimal corridor spacing for motor-manual continuous capstan winch slash removal.

2) Determine the treatment costs, on a per-ton and per-acre basis, of manual and continuous capstan winch slash extraction.

## 2.3 Methods

### 2.3.1 Field Study

*Table 1: Site characteristics during study duration (Saralecos et al., 2014).*

| | **University of Idaho Experimental Forest** |
|---|---|
| **Longitude/Latitude** | 46° 50’05.15” N / 116° 50’25.19” W |
| **Elevation (m)** | 892 |
| **Total study precipitation (mm)** | 3.1 |
| **Mean study temperature (°C)** | 21.3 |
| **Temperature range (°C)** | 8-39 |
| **Slope, aspect** | 17%, Southern |
| **Mean daily vapor pressure deficit (kPa)** | 2.58 |
| **Mean daily relative humidity (%)** | 47 |
| **Relative humidity range (%)** | 10-84 |
| **Mean soil temperature (°C)** | 16.7 |
| **Mean soil moisture content (%)** | 7.6 |

A replicated elemental time study was conducted during the setup of a large biomass harvesting and soil nutrient study experiment on the University of Idaho Experimental Forest, using a continuous capstan winch system to move slash between plots. The study was conducted from July 25 to August 8, 2013. The sites were pre-commercially thinned (PCT) by a hand felling crew immediately before the study began and all slash generated from thinning operations were lopped and scattered to comply with state laws and then left untouched until commencement of this study, approximately one week later. The winch system used in this study was a Portable Winch Company PCW5000 with 12.7 mm diameter braided rope used to move slash. Lengths of 11 mm paracord were used as rope chokers to attach small bundles to the mainline. The distal end of the system was a pulley of the same diameter as the rope, anchored to a standing tree with chain. Following inhaul, slash was redispersed in order to create areas of heavy biomass deposition.

Times were gathered using a NIST-calibrated stop watch and recorded on paper data sheets. Each work cycle was composed of the following elements:

1. *Gather*: begins when slash collection worker left the pulley line to collect slash and ends when slash is bundled, choked and in position to be tied to pulley line. This element corresponds to choker-setting and lateral yarding in conventional cable system elemental time studies.
2. *Inhaul*: begins when slash bundle is attached to line and ends when slash is disconnected from line.
3. *Dispersal:* begins when slash bundle is pulled away from line manually and ends when dispersal worker returns to the mainline.

Measurements taken at randomly dispersed sample times during work were the distance travelled to gather the slash bundle, the distance travelled by the slash bundle on the mainline during inhaul, the distance travelled to disperse the bundle, time gathering the slash bundle, the time for the slash bundle to travel on inhaul, time needed to disperse the slash bundle. Additionally, at random sample times, slash bundles were chosen to be weighed. All measurements were green weight basis. Because sampling occurred immediately after stand treatments, moisture content is assumed to be 75 %. For these bundles, individual slash piece lengths and diameters were measured and the number of stem segments per bundle was tallied. Summary data for yarding in each stand are shown in Table 2.

*Table 2: Recorded times from field study.*

| **Table 2** | | | | | | |
|---|---|---|---|---|---|---|
| **Stand** | **Gather time (s)** | **Inhaul time (s)** | **Dispersal time (s)** | **Bundle size (kg)** | **Segment length (cm)** | **Segment diameter (cm)** |
| **Upper** | 62.1 | 407.8 | 51.8 | 19.6 | 289 | 6.6 |
| **Middle** | 92.0 | 440.2 | 66.9 | 23.0 | 291 | 7.4 |
| **Lower** | 76.8 | 343.4 | 94.6 | 23.7 | 345 | 6.9 |
| **AVE** | 79.1 | 403.3 | 57.9 | 21.9 | 308 | 6.9 |

2.3.2 Analysis and modeling

*Table 3: Parameter ranges for the model*

| **Table 3** | | | |
|---|---|---|---|
| | **Gather Distance (m)** | **Line speed (m/s)** | **Line capacity (Mg)** |
| **Min** | 3.04 | 0.09 | 0.07 |
| **Base Scenario** | 30.48 | 0.18 | 0.14 |
| **Max** | 45.72 | 4.5 | 2.72 |

Using data gathered during the initial field research, a model was constructed to allow for the optimal configuration of the system to be determined, particularly with respect to line spacing. This was done by modeling each step of the yarding process and optimizing parameters to find the least expensive system configuration. The mean and range of key parameters used in the simulation model are shown in Table 2.

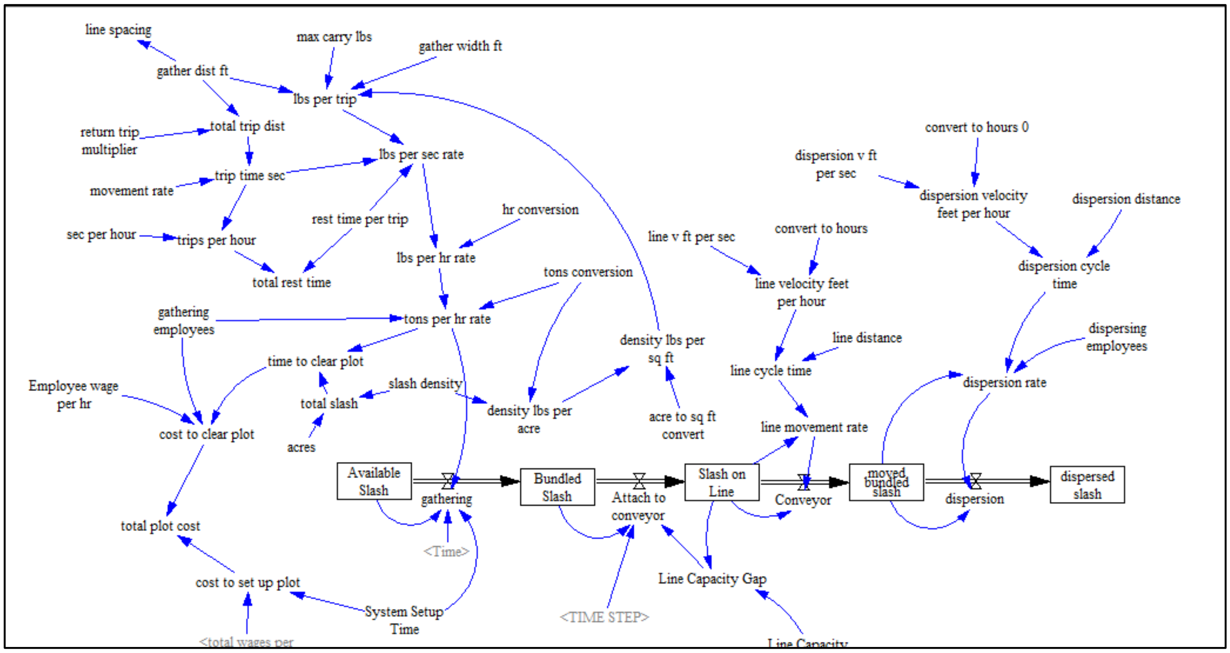


*Figure 1: An image of the model structure*

## 2.4 Results

Using the data collected during field testing of the system, the model was used to calculate the costs of operation. The smallest stand incurred the highest cost per ton due to low density of slash, which results in longer collection times and more lines being needed to effectively gather the slash. Each line set up requires 113.75 minutes and all employees, resulting in a quickly rising costs and lost production time as more lines are needed.

*Table 4: Results of model analysis for field study.*

| **Table 4** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Stand** | **Acres** | **Density (Mg/acre)** | **Gather Dist. (m)** | **Line Speed (m/s)** | **Carry Capacity (Mg)** | **Cost per Stand ($)** | **Cost per Acre ($/Acre)** | **Cost per Mg ($/Mg)** |
| **Upper** | 13.0 | 13.78 | 22.1 | 0.19 | 0.13 | 10,265.70 | 758.70 | 57.02 |
| **Middle** | 7.5 | 15.24 | 36.5 | 0.16 | 0.13 | 8,262.17 | 1,099.86 | 72.17 |
| **Lower** | 17.6 | 30.12 | 29.3 | 0.20 | 0.13 | 35,461.50 | 2,014.14 | 66.87 |
| **AVE** | **12.7** | **19.71** | **29.3** | **0.18** | **0.13** | **17,996.46** | **1,290.90** | **65.35** |

The stands used in this study had similar dimensions, but widely ranging slash densities. When the recorded values from the field test were applied to the model as a benchmark, the cost to clear the upper stand of slash was $10,265, for middle stand the cost was $8,262 and for the lower stand the cost was $35,461. The upper stand cost $57.02 $Mg^{-1}$ to clear, the middle stand cost $72.17 $Mg^{-1}$ to clear, and the lower stand cost $66.87 $Mg^{-1}$ to clear [table 3]. During the field testing of the system the upper stand recorded an average gather distance of 22.1m, the middle stand recorded a gather distance of 36.5m and the lower stand recorded a gather distance of 29.3m. The upper stand's gather distance was 2% higher than the optimal gather distance according to the model, the middle stand was 87% higher than the optimal value and the lower stand was 191% higher than the optimal gather distance for the stand.

*Table 5: Optimized results for each stand used in field testing.*

| **Table 5** | | | | |
|---|---|---|---|---|
| **Stand** | **Variable** | **Optimized Value** | **Cost per Acre ($)** | **Cost per Ton ($)** |
| **Upper** | Gather Dist. | 21.64 (m) | 792.52 | 57.51 |
| **Middle** | Gather Dist. | 19.51 (m) | 774.51 | 50.82 |
| **Lower** | Gather Dist. | 10.06 (m) | 1357.34 | 45.06 |
| **AVE** | **Gather Dist.** | **17.07 (m)** | **974.79** | **51.13** |
| **Upper** | Line Speed | 4.5 (m/s) | 743.69 | 53.97 |
| **Middle** | Line Speed | 4.5(m/s) | 823.91 | 54.06 |
| **Lower** | Line Speed | 4.5 (m/s) | 1595.80 | 52.98 |
| **AVE** | **Line Speed** | **4.5 (m/s)** | **1,054.47** | **53.67** |
| **Upper** | Line Capacity | 2.7 (Mg) | 745.72 | 54.12 |
| **Middle** | Line Capacity | 2.7 (Mg) | 825.36 | 54.16 |
| **Lower** | Line Capacity | 2.7 (Mg) | 1574.49 | 52.27 |
| **AVE** | **Line Capacity** | **2.7 (Mg)** | **1,048.53** | **53.52** |

Using a 22.68 kg carry limit for gathering employees, the most cost efficient line spacing was 17.07m on average. For the upper stand, the optimal gather distance was 21.64m, the middle stand was 19.51m and the lower stand was 10.06m [table 4]. The optimal gather distance was closely tied to the dimensions and slash density of the stands. Width is a driving factor because it controls the overall number of lines that are established, length determines how fast the slash on the line can be mobilized to the edge of the plot, as line speed is a severely limiting factor in this model. Density controls the distance needed to gather a full bundle weight (22.68 kg), too short of a distance under-utilizes the gathering employees and too long of a distance results in significant amounts of wasted gathering time that yields no extra production as carrying capacity is met before the point of return.

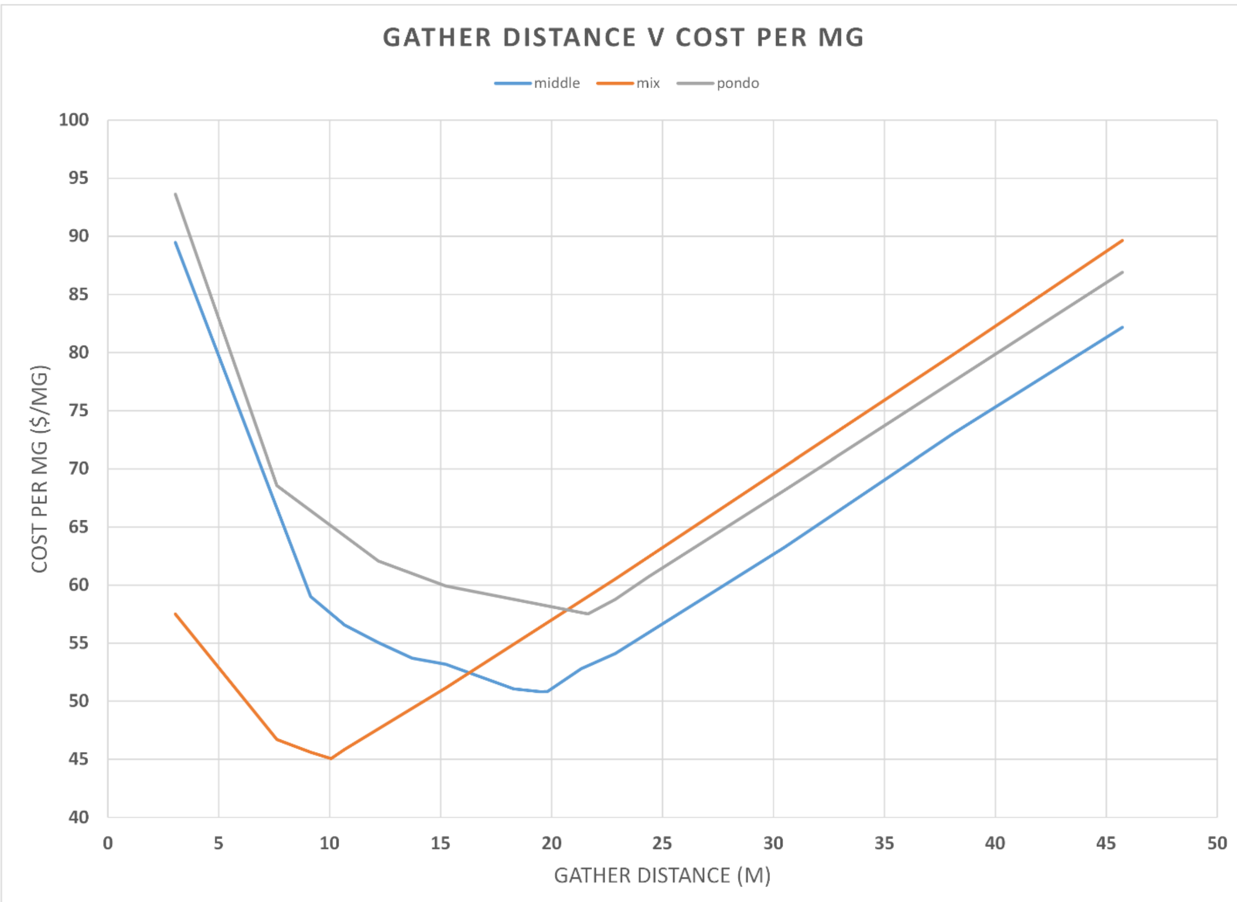


*Figure 2: Cost curves for different gathering distances*

When optimizing the line speed and line weight, both approach \$50 $Mg^{-1}$. This is due to the inhaul outpacing the production of the gathering employees, as only one parameter was optimized at a time. If all parameters were to be optimized together, it is likely that significantly lower production costs could be reached, but may not reflect realistic working conditions.

The optimal line speed for all three stands was faster than 4.5 m $s^{-1}$, which is an unrealistic speed to attain with the current configuration of the system. The costs to clear the upper stand at 4.5 m $s^{-1}$ was $743.69, the cost to clear the middle stand at 4.5 m $s^{-1}$ was $823.91 and the cost to clear the lower stand at 4.5 m $s^{-1}$ was $1,595.80 [table 4]. The optimal line speed was stopped at 4.5 m $s^{-1}$ due to the extensive overloading of the current system capabilities, both of the mechanical and human components. The system in its current configuration uses a 2.5 HP Honda motor that cannot exceed 40 ft $min^{-1}$, which was also the observed safe limit of human interaction with the winch and capstan system.

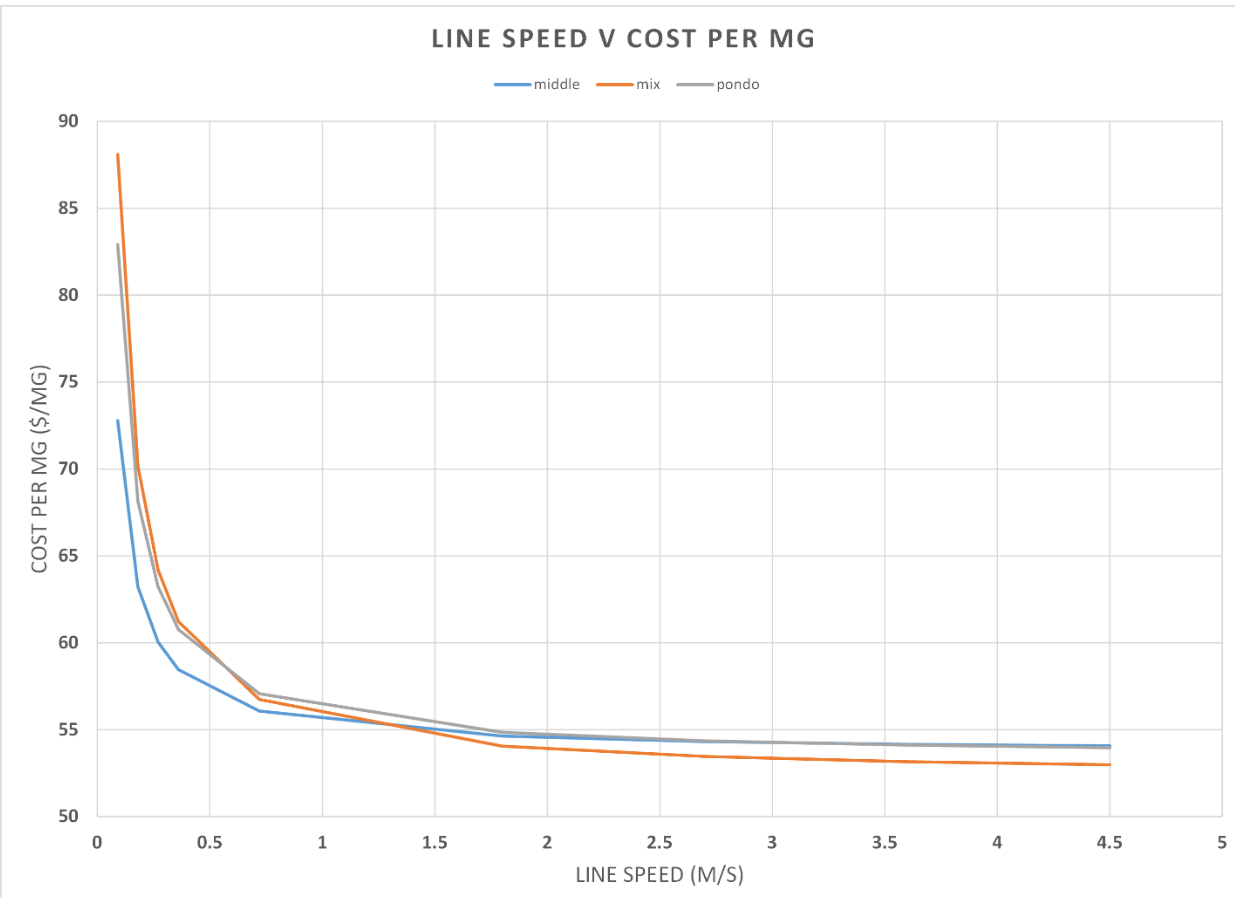


*Figure 3: Cost curves for different line speeds*

The optimal line capacity for all three stands was more than 2.7 Mg, which is also unrealistic with the current system configuration. The cost to clear the upper stand with a 2.7 Mg capacity was $745.72, the cost to clear the middle stand with a 2.7 Mg capacity was $825.36

and the cost to clear the lower stand with a 2.7 Mg capacity was $1574.49 [table 4]. The winch used in the current configuration of the system is a 2.5 HP Honda motor that is capable of handling approximately 907 kg of load. The optimization for the line capacity was stopped at 2.7 Mg due to extensive overloading that was present on the current system configuration.

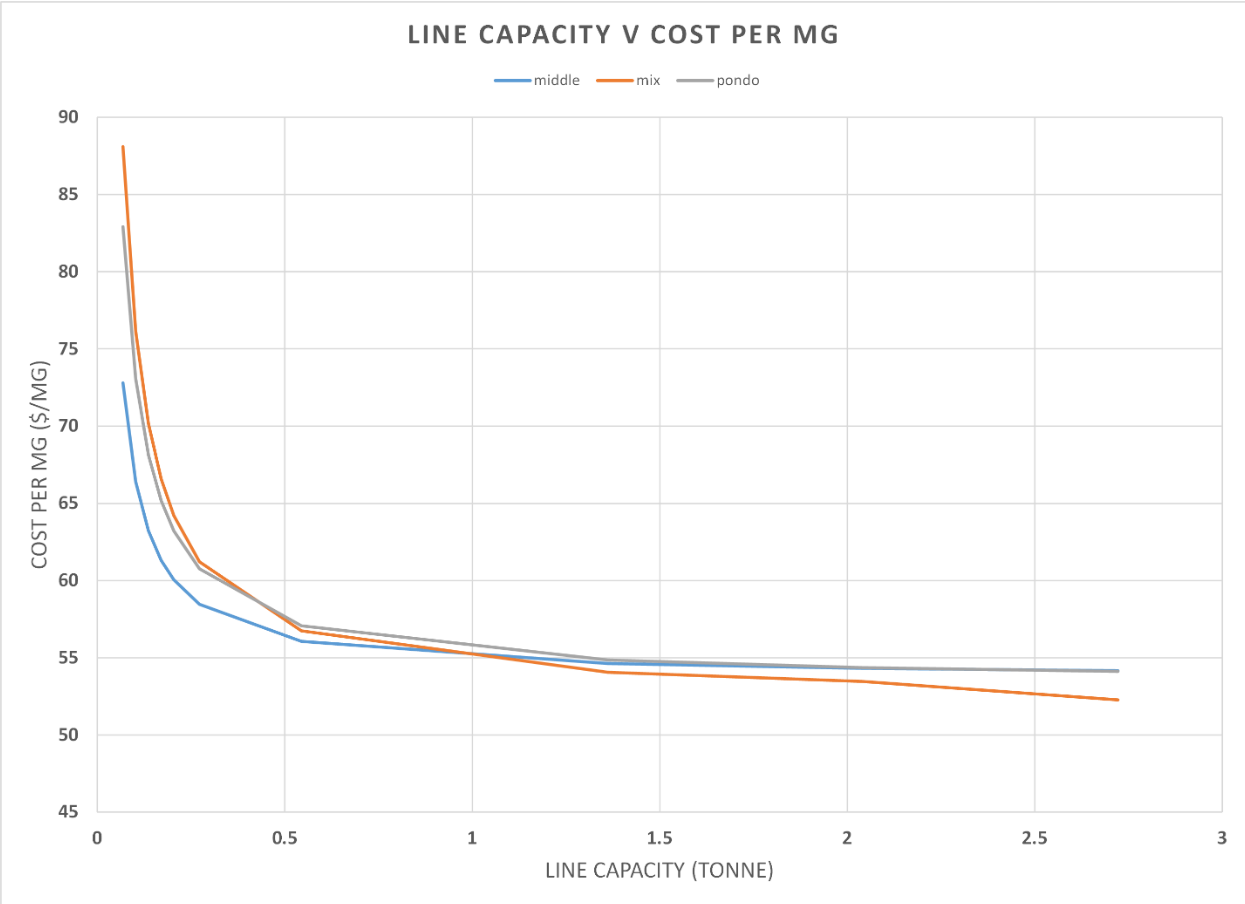


*Figure 4: Cost curves for different line capacities*

## 2.5 Discussion

After analysis of the field tested configuration of the slash mobilization system, the overall cost is too high to be used in widespread slash removal applications. Thinning treatments cost $100-150 acre$^{-1}$ (Dubois, McNabb, Straka, & Watson, 1999) and chipping or other densification of removed slash cost $5-10 ton$^{-1}$ (Cafferty et al., 2013). These additional costs create a total cost of $1,000-1,500 acre$^{-1}$ to effectively remove and treat PCT slash in a stand using this system.

Fire exclusion tactics employed in western forests during the 20th century has led to historically uncharacteristically intense forest fires in the western United States (Agee & Skinner, 2005). Hazard treatments are becoming more common on national forest lands that suffer from high mortality rates, poor forest health and high wood volumes (D. L. Peterson et al., 2005). Typical PCT involve mastication of downed woody material for roughly $550-1300 acre$^{-1}$ (Vitorelo, Han, & Varner, 2009), or lopping and scattering of thinned trees for $100-150 acre$^{-1}$. These material are left in situ after treatment to prevent removal of forest nutrients that facilitate regeneration of the remaining live trees and because there is no current industrial demand for the woody material. If costs for these materials can be reduced to $20-30 ton$^{-1}$ (Searcy & Hess, 2010) before any transportation costs are accounted for, the bioenergy industry could begin to subsidize the costs of treatment by purchasing a portion of the chips or masticated fuels to supplement traditional bioenergy supplies.

By increasing the mechanization of the line setup/movement process and improving the winch and line technologies to handle industrial scale volumes, there is potential for significant improvements in the economics of the system. These improvements could make the system a feasible option for slash removal and hazard treatment. Mounting the winch to a machine, such as a Bobcat, would likely result in significant reductions in line setup times. Improving the line to a metal cable and increasing the winch machinery to handle the increased weight and possibly increasing the maximum speed would also likely result in significantly higher and more economical production rates.

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# Chapter 3:
# Multi-Spatial Analysis of Forest Residue Utilization for Bioenergy

Submitted to Biofuels, Bioproducts, Biorefining

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## 3.1 Abstract

The alternative energy sector is expanding quickly in the United States since passage of the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007. Increased interest in wood-based bioenergy has led to the need for robust modeling methods to analyze woody biomass operations at landscape scales. However, analyzing woody biomass operations in regions like the US Inland Northwest is difficult due to highly variable terrain and wood characteristics. We developed the Forest Residue Economic Assessment Model (FREAM) to better capture variations, integrate with Geographical Information Systems and overcome analytical modeling limitations. FREAM analyzes wood-based bioenergy logistics systems and provides a modeling platform that can be readily modified to analyze additional study locations. We evaluated three scenarios to test the FREAM's utility: a local-scale scenario in which a catalytic pyrolysis process produces gasoline from 181,437 Mg $yr^{-1}$ of forest residues, a regional-scale scenario that assumes a biochemical process to create aviation fuel from 725,748 Mg $yr^{-1}$ of forest residues, and an international scenario that assumes a pellet mill producing pellets for international markets from 272,155 Mg $yr^{-1}$ of forest residues. Using FREAM's default assumptions, the local scenario produced gasoline for a modeled cost of 22.33 \$ $GJ^{-1}$, the regional scenario produced aviation fuel for a modeled cost of 35.83 \$ $GJ^{-1}$ and the international scenario produced pellets for a modeled cost of 10.51 \$ $GJ^{-1}$. Results show that combining multiple techniques provides a promising approach to modeling the complex characteristics of woody biomass harvesting.

Key Words

Bioenergy, Supply Chain Analysis, Catalytic Pyrolysis, Modeling, Inland Northwest,

## 3.2 Introduction

Firewood and charcoal from forests have been used as heating sources for much of human history; new research is producing transportation fuels from forest residues and fast-growing feedstocks. Forest residues are a plentiful resource: an estimated 392 million dry tons of woody biomass will be available for use in 2017, and an estimated 12.4 million dry tons of forest residues will be used for energy production annually by 2022, when it will provide 14% of the woody biomass contribution to renewable energy.[1] Biomass is estimated to provide between 50 and 450 exajoules of energy by the year 2050, representing ~10% of likely world primary energy usage at the lowest estimate and over 100% at the highest estimates.[2] To be competitive with traditional energy markets, renewable sectors will need accurate and robust projections of their capacity to meet market share projections. Although projection systems are limited, logistic models have been shown to provide details and reasonable estimates of the volume and costs associated with producing energy feedstock.

Two models currently used to assist in the development of US renewable energy policy are the Biomass Logistics Model (BLM) developed by the Idaho National Lab (INL)[3] and the Integrated Biomass Logistics and Supply (IBSAL) model developed by the Biomass and Bioenergy Research Group (BBRG) at the University of British Columbia.[4] The BLM allows users to set feedstock specifications and general logistic operations (e.g., single-pass versus multi-pass harvest) and define the location of the bioenergy plant before estimating the cost and volume of delivered feedstock. The BLM is primarily used to determine regional feedstock costs and characteristics.[3] The IBSAL model allows users to select the type of feedstock and equipment used for harvest, transport, and pre-processing. The BLM is used to estimate regional logistics costs based on average equipment specifications, whereas IBSAL is primarily used for analyzing individual locations and specific equipment.[4] Both systems are user and data intensive and time consuming to set up and run if varied from default conditions.

Developing models that accurately simulate the complex vegetation, topography, and woody biomass harvesting variables associated with non-plantation industrial forestry presents major challenges. Existing modeling systems are complex, do not integrate insights from timber experts into the modeling process, and do not regularly incorporate spatial datasets, such as Geographical Information Systems (GIS) layers.

Because forest landowners create harvest schedules to maximize profit, the rotation of harvest stands can lead to highly variable annual transportation costs and feedstock characteristics.[5,6] Each harvest location possesses unique characteristics that affect the harvest and collection costs: slope affects the type of equipment and harvesting systems available for collecting biomass,[7] streams and sensitive soils require special accommodations in the harvest area,[8] and geography affects the seasonal operating window,[9] the topographic and spatial variability of forested landscapes can lead to challenges in parameterizing models, especially if individual landowners are not forthcoming with data. This can be somewhat overcome by using models that incorporate GIS data layers derived from public data sources such as the Timber Products Output (TPO) database, Forest Inventory Analysis (FIA) database, and remotely sensed data.[10]

Biofuels industry-level dynamic models, such as the Biofuel Scenarios Model (BSM) developed by the National Renewable Energy Lab, analyze the biofuels industry at every step of the production process from harvest and collection, to refining, biofuel distribution, and end use. These models can use feedstock model (e.g., BLM, IBSAL) estimates as inputs.[11] Linking models is a powerful way to reduce assumptions and increase resolution; however, the model must be carefully validated to minimize error propagation from the feedstock models to the BSM.

Models that accurately estimate woody biomass costs and supply must rely on assumptions with significant uncertainty.[1] Incorporating data from timber industry stakeholders can help reduce uncertainty, refine assumptions, improve credibility, and increase the realism of simulations and likelihood that decisions based on model results are accepted.[12,13] Collaboration between modeling teams and stakeholders during the model-building process facilitates trust in model results and conclusions, and can reduce legal challenges to management practices.[14] Collaborative model-building techniques have been used in public land management to reach decisions among parties with diverse interests.[15] Collaborative modeling may be useful when projects seek to use woody biomass from national forests.

Quantitative and qualitative data inform scenarios that, when presented to stakeholders, provide alternatives they can identify with and build upon to develop mutual understanding.[12]

Current models operate under either GIS or dynamic modeling theories, but linking both approaches is less common. Combining GIS (e.g., ArcGIS) and system dynamics modeling (e.g., Vensim) can be expensive and difficult without the proper software. INL and Sandia National Laboratories have explored various techniques to link the two methods. INL created a tool in ArcGIS that links to dynamic modeling software and provides an interface between the two programs to display temporal changes in a geographic area (per. Comm. INL). The second approach is to create a programmatic architecture using a compatible programming language (i.e. Python, C, C++, C#) for ArcGIS and the system dynamics software, where the map and the system dynamics data are stored inside the programming architecture. The second method has been used to provide online analysis services, but is more computationally intensive than operating the analysis inside of ArcGIS. A third method is to create a system dynamics model that can take input from existing models, generally in the form of spreadsheets, and run a quick and robust analysis to provide additional results.[16]

To advance wood-based bioenergy modeling, we integrated dynamic modeling, spatial data, and collaborative modeling practices to develop a new model: the Forest Residue Economic Analysis Model (FREAM). FREAM was used to evaluate the feasibility of collecting and delivering forest residues to biorefinery or pellet plant facilities in the Inland Northwest. Specifically, we asked three questions:

(1) Out of three currently proposed wood-based bioenergy production scenarios, what is the most cost-efficient for northern Idaho?
(2) How do varying capital costs affect the cost of biofuel or pellet production in each scenario?
(3) How do varying transportation costs affect the cost of biofuel or pellet production in each scenario?

## 3.3 Methods

### 3.3.1 The Forest Residue Economic Analysis Model (FREAM)

The FREAM is a discrete supply chain analysis model that simulates forest residue collection, transportation, and conversion. FREAM estimates total costs for every step of the supply chain from harvest through conversion, as opposed to BLM and IBSAL, which stop at the infeed into the biorefinery. FREAM allows users to evaluate the advantages of different supply systems based on available local resources. FREAM also takes advantage of spatial data, in the form of GIS layers including county-level unused forest residues provided by the USDA, networked roads, and city locations. The incorporation of GIS data into the supply chain analysis is unique among models with similar analysis goals, and is important for accurate woody biomass supply chain analysis.

FREAM was used to evaluate three scenarios using different technologies and scales of operation based on proposed bioenergy projects in the Inland Northwest. For each scenario, the model was run for individual towns or cities in north-central Idaho, eastern Washington, and western Montana [Figure 1]. FREAM does not directly model the basic components of the supply system: instead using referenced data for each component, it analyzes costs based on demand for biomass flowing through the system. By integrating GIS data, FREAM analyzes spatially explicit supply chain logistics. Anchoring biorefinery and pellet mill locations to geographic coordinates makes the supply chain analysis more accurate. Further, the modular design and relatively simple data requirements allow users to easily modify FREAM to analyze other study areas. Only a biomass supply layer and a networked road layer for the new region are required to conduct analysis. While BLM and IBSAL require in-depth knowledge of the systems being modeled to deviate from the default systems, FREAM's simplified requirements allow users to make changes quickly.

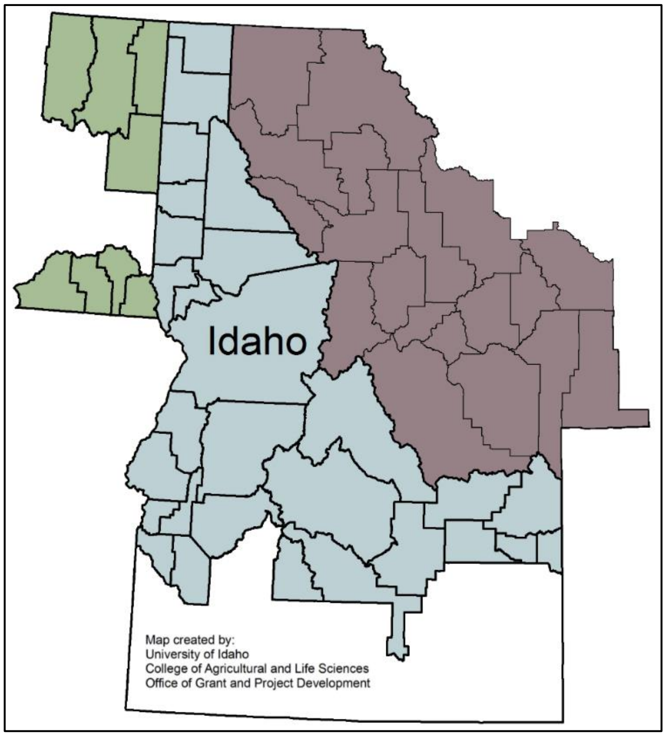


*Figure 1: Map of study area*

3.3.2 Stakeholder Engagement

We used multiple methods to engage stakeholders throughout the project. In spring 2013, a focus group involving six participants (forest industry representatives and tribal and state land managers) helped confirm interest and define realistic wood-based bioenergy scenarios for the study region. The international wood pellet scenario was added to the analysis based on focus group participant interest.

In fall 2013, we interviewed 48 stakeholders throughout the study region, including forest industry professionals, logging contractors, public land managers, non-industrial private forest landowners, conservation organizations, economic development professionals, and elected officials. Among other topics, interview participants shared their perspectives on potential tradeoffs and feasibility as well as specific questions about each scenario (Newman et al, in preparation). Interview results were incorporated into scenario and model design.

We facilitated two meetings with our stakeholder advisory committee: in July 2014, the committee helped inform and refine model assumptions with their real-world experience, and in June 2015, we presented the preliminary model for critique, validation, and feedback. We also communicated with researchers from the Northwest Advanced Renewables Alliance (NARA) and Bioenergy Alliance Network of the Rockies (BANR) projects and incorporated their input during model development.

### 3.3.3 Bioenergy Scenarios

The three bioenergy scenarios analyzed with FREAM are based on projects currently proposed or researched in the Inland Northwest [Table 1, Figure 1].

*Table 1: Assumptions for the biofuel refinery and pellet mill operational variables*

**Table 1**

| **Scenario** | Biorefinery Type | Capital Cost ($ million) | Fuel Type | Production Capacity (Mg/year) | GJ/Mg |
|---|---|---|---|---|---|
| **Local** | Catalytic Pyrolysis | 56 | Gasoline | 181,437 | 53.681 |
| **Regional** | Biochemical | 800 | Jet Fuel | 725,748 | 46.005 |
| **International** | Pellet Mill | 60 | Pellet | 272,155 | 15.816 |

The local scenario is relatively small scale, drawing approximately 181,437 Bone Dry Megagrams (BDMg) year$^{-1}$ of forest residues from within 10s to 100s km of the biorefinery. It is based on the Cool Planet Energy Systems catalytic pyrolysis process, using an integrated supply chain. Forest residues are collected and chipped before transport to the refinery to be converted to bio-gasoline and a biochar coproduct [Figure 1.1]. The bio-gasoline produced will be mixed with petroleum-based gasoline and distributed to nearby communities, with the biorefinery acting as the distribution point. This scenario is related to the USDA-funded BANR project.[1] The local scenario biorefinery capital costs were based on Cool Planet Energy Systems experimental biorefinery being constructed in Alexandria, LA.[17]

The regional scenario draws approximately 725,748 BDMg year$^{-1}$ of forest residues from within 100s to 1000s km of the biorefinery. It is based on Gevo's integrated fermentation aviation fuel technology that the USDA-funded NARA project is researching.[18] This scenario assumes a distributed supply chain with multiple processing depot cities to complete feedstock pre-processing before delivery to the biorefinery. Forest residues are collected and

* Http://banr.nrel.colostate.edu/

chipped within a 90-minute driving distance of a depot city with a dryer and grinder to complete preprocessing operations [Figure 1.2]. Feedstock from the depot is delivered to the biorefinery where thermochemical processes convert it to aviation fuel and coproducts. Bio-aviation fuel is then transported to Spokane International Airport for blending and use. The regional scenario is based on.[18]

The international scenario draws 272,155 BDMg year$^{-1}$ of forest residues from within 10s to 100s km of the pellet mill. This scenario assumes a distributed supply chain with multiple pre-processing depots preceding the pellet mill [Figure 1.3]. Forest residues are collected and chipped within a 90-minute drive time of a depot city with a dryer and grinder to complete preprocessing. Feedstock from the depot is delivered to the pellet mill, where it is processed to industrial wood pellets. Produced pellets are then transported to the Port of Seattle for delivery to Chinese markets. The international scenario cost assumptions were based on a newly commissioned pellet mill of similar size on the Olympic Peninsula, WA.[19]

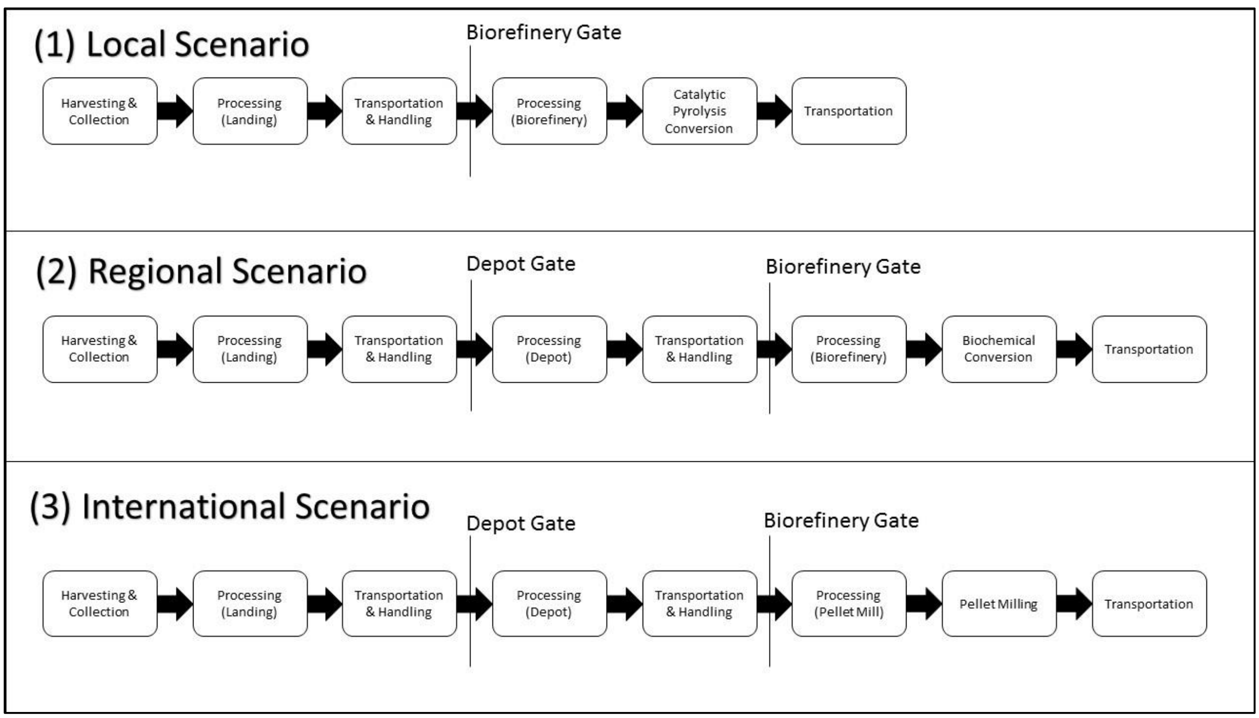


*Figure 2: Process flow of forest residues*

3.3.4 Refinery Location and Residue Volumes

FREAM calculates forest residue volumes available to Inland Northwest communities using county-level forest residue volume data provided in the Timber Products Output (TPO) database [20] and ArcGIS Network Analyst extension. The TPO database was modified to provide a forest residue density per square mile by combining a GIS layer detailing geographic coordinates of land owned by private, state, and tribal sources. The area in each county owned by non-federal sources is calculated and used to determine the volume of residues available to each city. The city housing the biorefinery or pellet mill is used as the initial depot city in the analysis as well. Each depot city's gather radius is generated from road speeds and segment lengths, and defaults to a 90-minute drive in all directions [Figure 3].

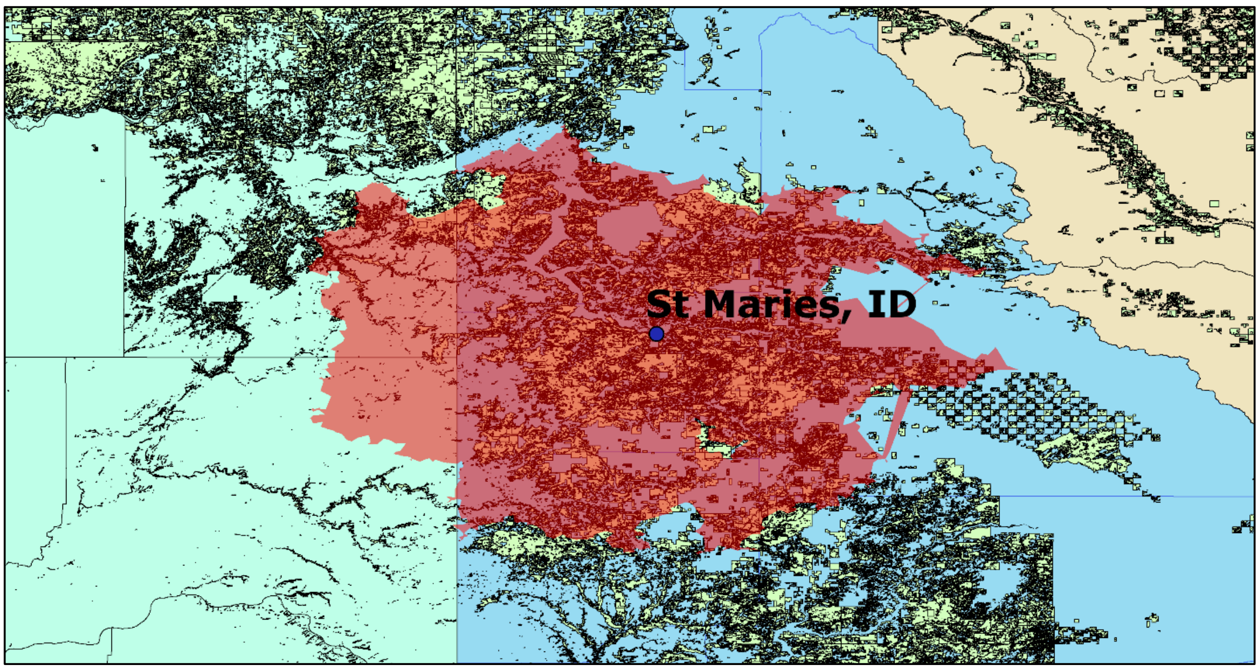


*Figure 3: A 90-minute draw radius for Coeur D'Alene, ID.*

In each depot city the draw radius is populated with county-level estimates of forest residue volumes available from private, state, and tribal sources. The area of allowed ownership polygons inside the draw radius is multiplied by the forest residue density for each county to determine the potential supply of residues. Forest residues available are summed to determine the overall volume available in the supply area. If the operational capacity of the biorefinery is not met by the residue supply within the 90-minute draw radius, the program finds the next closest depot city that is more than 45 minutes[2] away and appends the additional forest residues supply to the total. This process continues until operational capacity is reached. The transportation costs for moving forest residues from the forest to the depot is calculated based on assumed supply and transportation cost and distance parameters. The shortest route between depot cities and the biorefinery is calculated as well as from the plant to end-use locations [Figure 4].

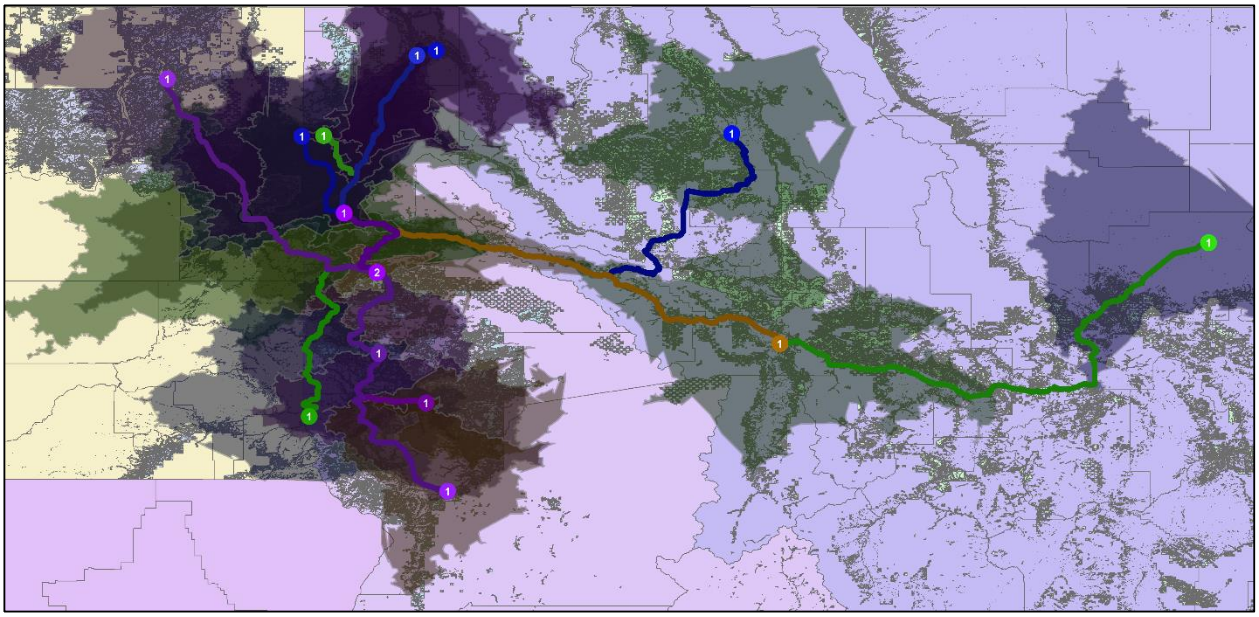

*Figure 4: Demonstration output of the draw radii for a regional scenario needing 800,000 BDT with the shortest route from each depot (1) to the aviation fuel biorefinery (2) at St. Maries, ID. Gray zones represent valid ownership plots for harvest*

### 3.3.5 FREAM Modules

FREAM uses a number of assumed-costs variables, some from the literature and some assumed [Table 2]. Five modules in FREAM perform the cost and volume analyses: the forest landing, depot, biorefinery, capital-cost, and fuel-cost modules. Each module is designed to simulate real-world biorefinery operations.

[2] A 45-minute minimum distance was selected to prevent extreme overlap in the 90-minute supply geometries and to avoid eliminating too many potential locations from the analysis.

*Table 2: Table of assumed costs used in FREAM for this analysis.*

| Table 2 | | | |
|---|---|---|---|
| **Variable** | **Value** | **Unit** | **Module** |
| **Harvest Cost** | 20.67 | $/Mg | Forest Landing |
| **Chipping Cost** | 5.86 | $/Mg | Forest Landing |
| **Forest Landing Employees** | 4 | Employees | Forest Landing |
| **Drying Cost** | 12.97 | $/Mg | Depot |
| **Depot Employees** | 8 | Employees | Depot |
| **Storage Costs** | 3.31 | $/Mg/year | Depot |
| **Transport Cost** | 100 | $/hr | Depot |
| **Cost to Produce Liter of Gasoline** | 0.53 | $/L | Biorefinery |
| **Cost to Produce Liter of Aviation Fuel** | 0.53 | $/L | Biorefinery |
| **Cost to Produce** Pellets | 23.28 | $/Mg | Biorefinery |
| **Biorefinery Employees** | 30 | Employees | Biorefinery |
| **Shipping Cost** | 44.09 | $/Mg | Biorefinery (International Scenario only) |
| **Transport Cost** | 0.04 | $/Mg/km | Biorefinery |
| **Chipper Capital Cost** | 500,000 | $ | Capital Costs |
| **Dryer Capital Cost** | 2,000,000 | $ | Capital Costs |
| **Grinder Capital Cost** | 615,850 | $ | Capital Costs |
| **Local Scenario Reactor Capital Cost** | 56,000,000 | $ | Capital Costs |
| **Regional Scenario Reactor Capital Cost** | 800,000,000 | $ | Capital Costs |
| **International Scenario Pellet Mill Capital Cost** | 60,000,000 | $ | Capital Costs |

3.3.5.1 Forest Landing Module

Figure 5 diagrams the forest landing module, which simulates forest residue collection and densification operations at the forest landing. Available forest residues are the material available in BDTs across the scenario and are generated from the manipulation of the TPO database.[20] The amount drawn from this stock is determined by the operational capacity of the biorefinery or pellet mill, and any excess material is left for use in future simulation cycles. The amount of harvested material is used to calculate supply costs and is in $ yr$^{-1}$. The cost to harvest biomass is derived from the literature, assumed to be $20.67 Mg$^{-1}$, and tracked annually.[3,21]

Forest residues are then chipped at an assumed rate of \$5.86 $Mg^{-1}$.[22] After chipping, the residues are stored and then removed from the forest for \$4.13 $Mg^{-1}$, which was calculated by taking the midpoint of a 90-minute collection radius around the depot city (45 min), and charging \$100 $hr^{-1}$. Trucks are assumed to hold 18.14 Mg of chipped residues. Each forest landing is assumed to have four employees, each paid a yearly salary of \$35,000, based on the average income of forest industry workers.[23]

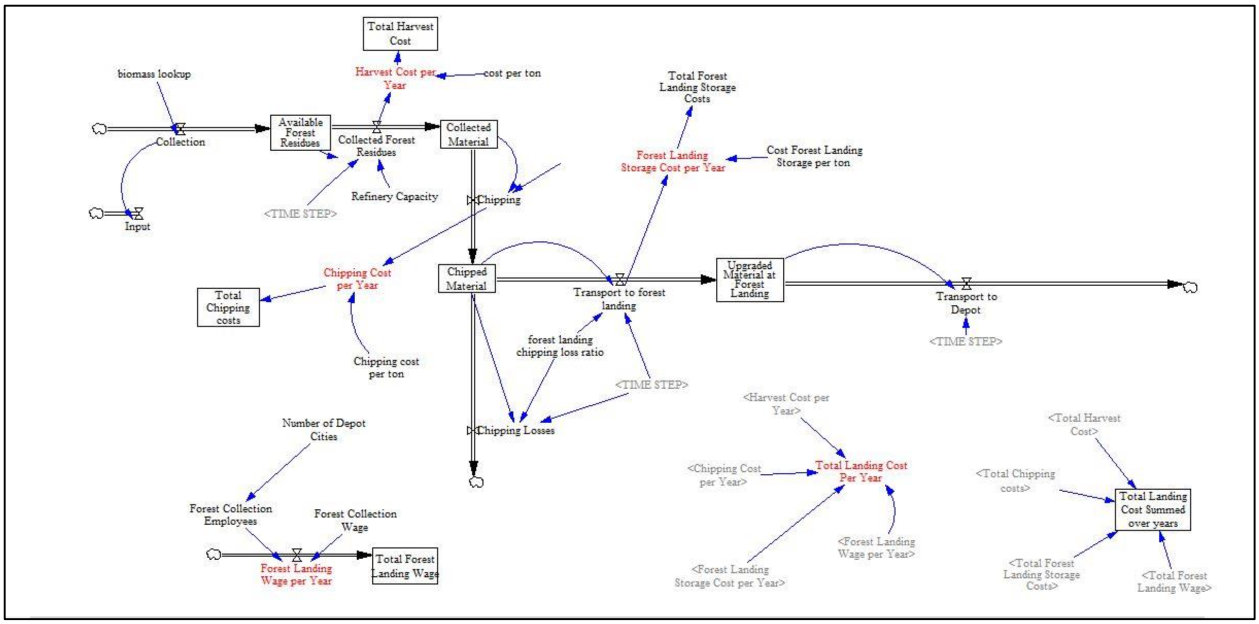


*Figure 5: Flow of material and operations in the forest landing module.*

### 3.3.5.2 Depot Module

Figure 6 illustrates the reception and processing of material from the forest landing at the depot before transportation to the biorefinery [Figure 6]. Biomass is stored at depot locations until dried and processed. Storage costs are \$3.31 $Mg^{-1}$ $yr^{-1}$.[24] Residues are then dried and processed for \$12.97 $Mg^{-1}$, which is a modified number based on Cafferty and Hartely.[22] Next, residues are stored for transport to the biorefinery for \$3.31 $Mg^{-1}$ $yr^{-1}$. Biomass is moved from the depot to the biorefinery for a cost of \$0.04 $Mg^{-1}$ $km^{-1}$.[25] Labor is also calculated in this module, with eight employees per depot. Each employee is given a yearly salary of \$35,000.

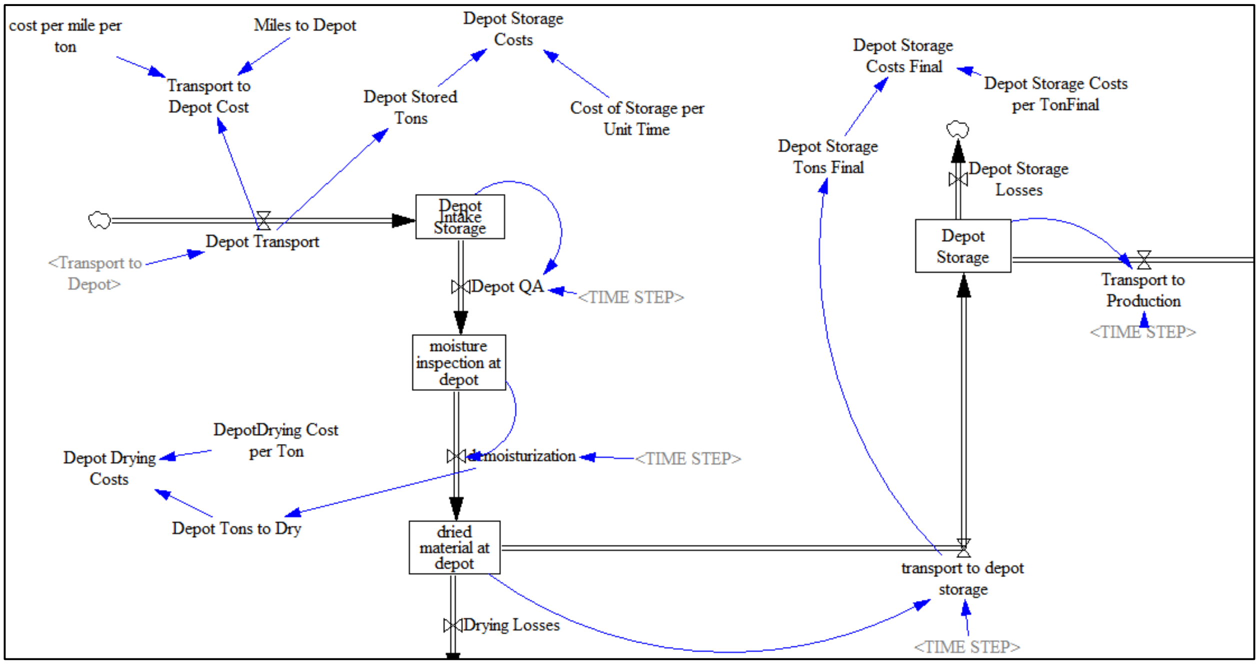


*Figure 6: Operation and flow of material at the depot.*

### 3.3.5.3 Biorefinery Module

Figure 7 illustrates the biorefinery module where biomass is transported from the depot and processed into a final product (pellets or biofuel) [Figure 7]. Arriving biomass is stored inside the refinery gate for a cost of \$3.31 $Mg^{-1}$ $yr^{-1}$. The material is then processed, either to a gasoline or aviation fuel for \$0.53 $L^{-1}$, based on numbers from NREL Techno-Economic Assessments (TEA) with modifications due to technology differences,[26] or to a pellet for \$23.28 $Mg^{-1}$.[27] When calculating the conversion process, the model uses a conversion ratio of 189.27 L to 1 Mg of feedstock for the local scenario's catalytic pyrolysis process from Wang (1997), a ratio of 282.39 L to 1 Mg of feedstock for the regional scenario's biochemical conversion process from the NARA second cumulative report,[18] and 0.95 Mg to 1 Mg of feedstock for the international scenario's pelletization process from Pirraglia, Gonzalez, and Soloni (2010). After processing, the resulting product is stored onsite at a cost of \$2.72 $Mg^{-1}$ $yr^{-1}$. For the local scenario, the biorefinery is assumed to be the distribution point for the gasoline, and no additional transportation costs are incurred. In the regional scenario, the material is transported to Spokane International Airport at a price of \$0.04 $Mg^{-1}$ $km^{-1}$. The international scenario transports the pellets via rail to the Port of Seattle at a price of \$0.008

Mg$^{-1}$ km$^{-1}$. After storage in the Port of Seattle, the pellets are shipped to China for a price of $44.09 Mg$^{-1}$.[28]

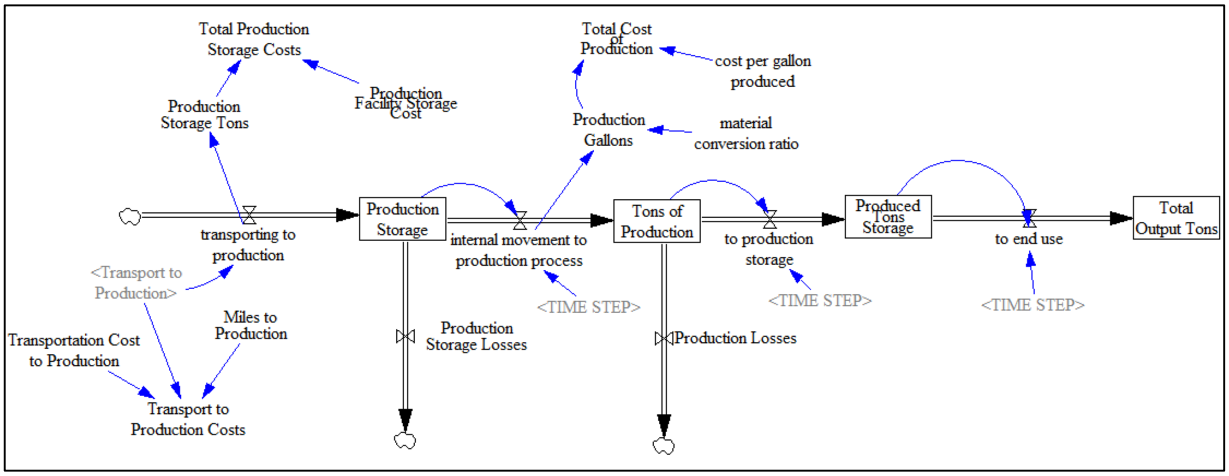


*Figure 6: Biorefinery operations and flow of material*

3.3.5.4 Capital Cost Module

The capital cost module calculates the capital costs for all the large equipment and processes in the logistics supply chain, including harvesters, chippers, and reactors [Figure 8]. The assumed biorefinery costs are $56 million for the local scenario, $800 million for the regional scenario, and $60 million for the international scenario. Each biorefinery is assumed to have a 20-year lifetime, over which the capital costs are annualized. The purchasing price of a chipper-forwarder is $450,000, has a five-year lifetime, and is multiplied by the number of depot cities needed to reach the necessary supply. The Onix ONL-165 tub grinder has a capital cost of $2 million and an assumed lifetime of 10 years.[29] This is multiplied by the number of depot cities. The capital costs for transportation were assumed to be $225,000 per truck based on Jacobson and Cafferty (2013) with a lifetime of three years. The total number of trucks needed was highly dependent on the volume of residues required; with 12 trucks assumed for the local scenario, 47 for the regional scenario, and 18 for the international scenario. The grinder used is a Morbark 3800 WT Horizontal Feed Wood Hog with a capital cost of $615,850 and an assumed five-year lifetime.

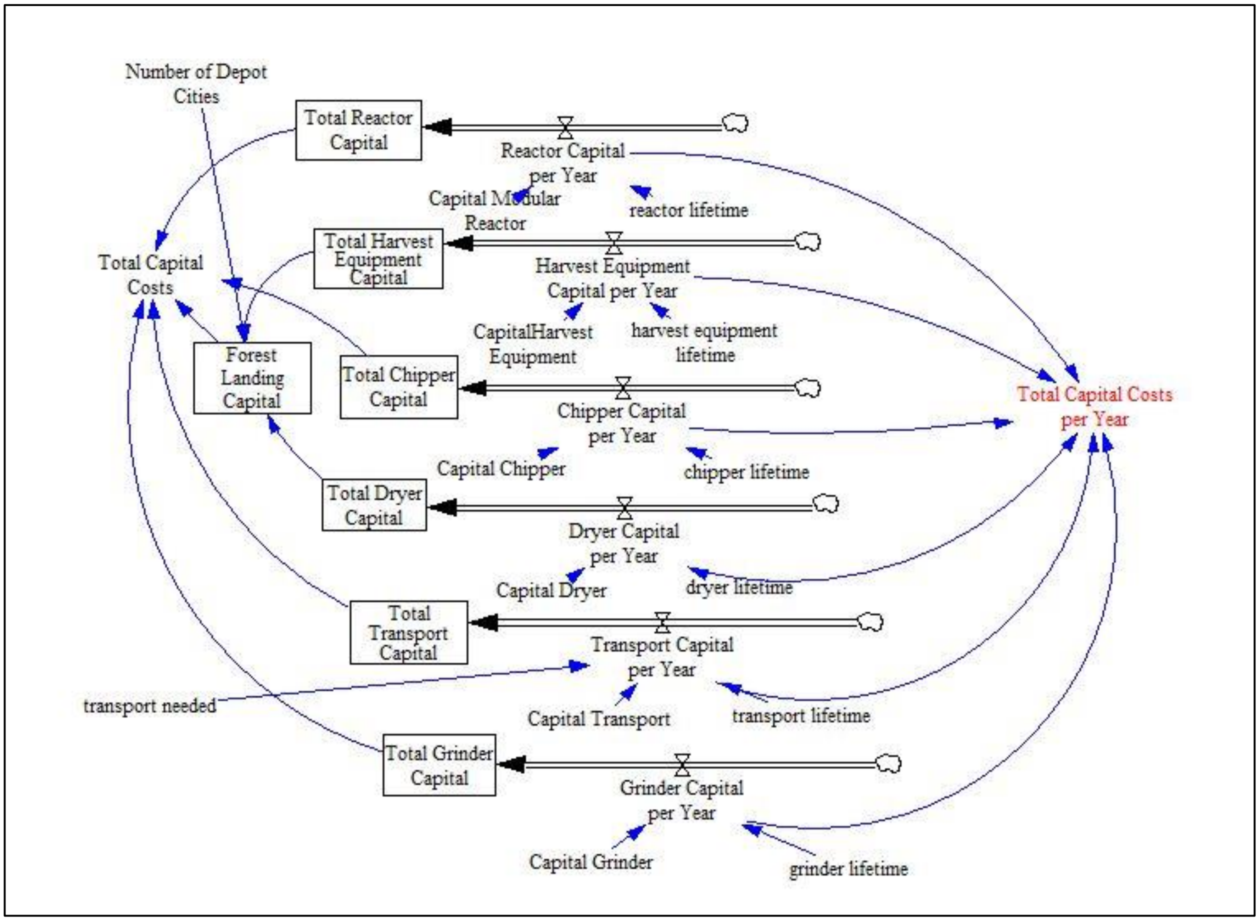


*Figure 8: Cost estimates for high capital equipment in the supply chain.*

### 3.3.5.5 Fuel Costs Module

All costs in the fuel costs module are summed and used to calculate a price per unit (Liters for the local and regional scenarios and Mg for the international scenario). From the unit price, a price per gigajoule (GJ) is calculated by dividing the produced volume by the joules per unit of the fuel and multiplying by one million. The gasoline produced in the local scenario is chemically similar to petroleum gasoline and has 53.681 GJ $Mg^{-1}$;[30] the regional scenario's aviation fuel has 46.005 GJ $Mg^{-1}$;[31] and the international scenario's pellets have 15.816 GJ $Mg^{-1}$.[32] The modeling team modified all assumptions for energy to adjust for differences between the fuel produced in the model and current petroleum equivalents.

### 3.3.5.6 Model Communication

A governing programmatic architecture was developed to streamline the model, managing and automating the transfer of data between GIS and dynamic modeling software.[33] The user selects the scenario and location and the program completes the analysis by calculating the number of depots needed to fully supply the plant, the transportation distances between depot cities and the biorefinery or pellet mill, and the transportation distance between the biorefinery and end-use. All GIS results are passed to a spreadsheet that is read by Vensim to develop cost and volume calculations, which are then recorded in a summary spreadsheet.

## 3.4 Model Assessment

### 3.4.1 Sensitivity and Statistical Analysis

Sensitivity analyses were performed to determine the overall effect of the assumed costs on the final cost of the fuel produced in each scenario. Sensitivity analyses identify variables where small changes result in significant changes to the overall costs.[34] High impact variables with disproportionate effects on the system need to be identified and studied to guarantee accuracy. Low-impact variables are less important to precisely define, as large changes in the variable result in small changes in overall costs.

Based on the outcome of stakeholder interviews, FREAM was run for 20 locations for each scenario. For each simulation, output variables of interest were the total cost per GJ, transportation costs per GJ, and the capital costs per GJ. To control for spatial auto-correlations between the forest residue collection locations, a mixed-effects model was used to test the following hypotheses: $H_0$: Total cost per GJ does not differ between local, regional, and international scenarios; $H_0$: Transportation costs per GJ does not differ between the local, regional, and international scenarios; and $H_0$: Capital costs do not differ between the local, regional, and international scenarios.

Linear mixed-effects models are used for describing relationships between data that are collected and summarized in groups, using both the fixed and random effects.[35] In our modeling experiment with FREAM, the independent variables of interest are the total cost per GJ, transportation costs per GJ, and the capital costs per GJ. The single fixed effect in our model was the biomass scenario, which is a factor with three levels (local, regional, and international). Each city in each scenario was initially analyzed for each of the 3 scenarios using FREAM. In the mixed-effects model evaluating costs components, a random intercept was fitted for each city. If scenario was a significant predictor, post-hoc hypotheses comparing among the one-way factor levels (each of our three biomass development scenarios) were conducted in R using generalized linear hypothesis tests with the multcomp package.[36]

Forest landing wages, depot wages, biorefinery wages, transportation costs, and capital costs were tested in the FREAM sensitivity analysis [Table 3]. The forest landing and depot yearly wages were varied by $5,000 from $25,000 to $55,000. The biorefinery yearly wages were varied by $5,000 from $45,000 to $70,000. The transportation costs per Mg per km were varied by $0.014 from $0.014 $Mg^{-1}$ $km^{-1}$ to $0.068 $Mg^{-1}$ $km^{-1}$. The local scenario capital costs started at $56 million and were varied by $50 million to $500 million. The regional scenario capital costs were varied by $50 million from $600 million to $1,200 million. The international costs were varied by $50 million from $60 million to $500 million.

*Table 3: Sensitivity analysis variables with test ranges*

| **Table 3** | | | |
|---|---|---|---|
| **Variable** | **Units** | **Low** | **High** |
| **Forest Landing Wage** | $ $year^{-1}$ | 25,000 | 55,000 |
| **Depot Wage** | $ $year^{-1}$ | 25,000 | 55,000 |
| **Biorefinery Wage** | $ $year^{-1}$ | 45,000 | 70,000 |
| **Transportation Cost** | $ $Mg^{-1}$ $km^{-1}$ | 0.014 | 0.068 |
| **Capital Cost Local Scenario** | $ million | 56 | 500 |
| **Capital Cost Regional Scenario** | $ million | 600 | 1200 |
| **Capital Cost International Scenario** | $ million | 60 | 500 |

## 3.5 Results and Discussion

Statistical analysis of the FREAM simulation results showed that local and international costs per GJ were significantly different (p=.05) from the regional scenario cost per GJ (p= 0.0001 and p= 0.0001) but were not significantly different from each other (p= 0.612) [Table 4]. Transportation costs per GJ for the regional scenario was significantly different from the local scenario (p= 0.001), but not the international scenario (p= 0.85). The capital costs for all three scenarios were significantly different from one another (p=0.001) [Table 4].

*Table 4: Statistical test for significance of costs of production, transportation, and capital per GJ (*** Significant at 0.001)*

| **Table 4** | | | | | | |
|---|---|---|---|---|---|---|
| | | Estimate | Std. Error | Z Value | P(>\|z\|) | Significance |
| **Total Cost/GJ** | Scen.Local - Int == 0 | 10.514 | 1.397 | 7.527 | <1e-10 | *** |
| | Scen.Regional - Int == 0 | 13.226 | 1.893 | 6.987 | <1e-10 | *** |
| | Scen.Regional - Scen.Local == 0 | 34.044 | 1.893 | 17.985 | <1e-10 | *** |
| **Transport Cost/GJ** | Scen.Local - Int == 0 | 18.29 | 12.36 | 1.479 | 0.295 | |
| | Scen.Regional - Int == 0 | -10.07 | 16.36 | -0.615 | 0.85 | |
| | Scen.Regional - Scen.Local == 0 | 118.07 | 16.36 | 7.215 | <0.001 | *** |
| **Capital Cost/GJ** | Scen.Local - Int == 0 | 13.3985 | 0.3448 | 38.863 | <1e-10 | *** |
| | Scen.Regional - Int == 0 | 3.1724 | 0.4876 | 6.507 | 1.13E-10 | *** |
| | Scen.Regional - Scen.Local == 0 | 42.9188 | 0.4876 | 88.027 | <1e-10 | *** |

Of the three scenarios, the international scenario represented the lowest production costs, specifically when located in Coeur D'Alene, ID, which cost \$9.53 $GJ^{-1}$ and Spokane, WA, which cost \$9.60 $GJ^{-1}$. The average cost of the local scenario was \$23.74 $GJ^{-1}$ and had a standard deviation of 0.76 [Figure 9]. The regional scenario had an average cost of \$44.56 $GJ^{-1}$ and a standard deviation of 10.49. The international scenario had an average cost of \$10.51 $GJ^{-1}$ and a standard deviation of 0.77. The local scenario, using the catalytic pyrolysis technology, resulted in the second lowest cost of production on average, and the regional scenario generated the largest cost of production of the three scenarios [Figure 9]. The international scenario had the lowest cost of production by a large amount, to be expected when only converting to a pellet, and had little variation in anticipated costs between different cities. The local scenario was the next best scenario and had minimally more stable costs of production than the international scenario. The regional scenario had the highest cost of production in all locations and had the most variation in production costs.

The modeled biofuels supply systems would generate between 42 and 196 jobs in the Inland Northwest through the harvesting, processing, and refining of biofuels and a significant number of additional transportation jobs.

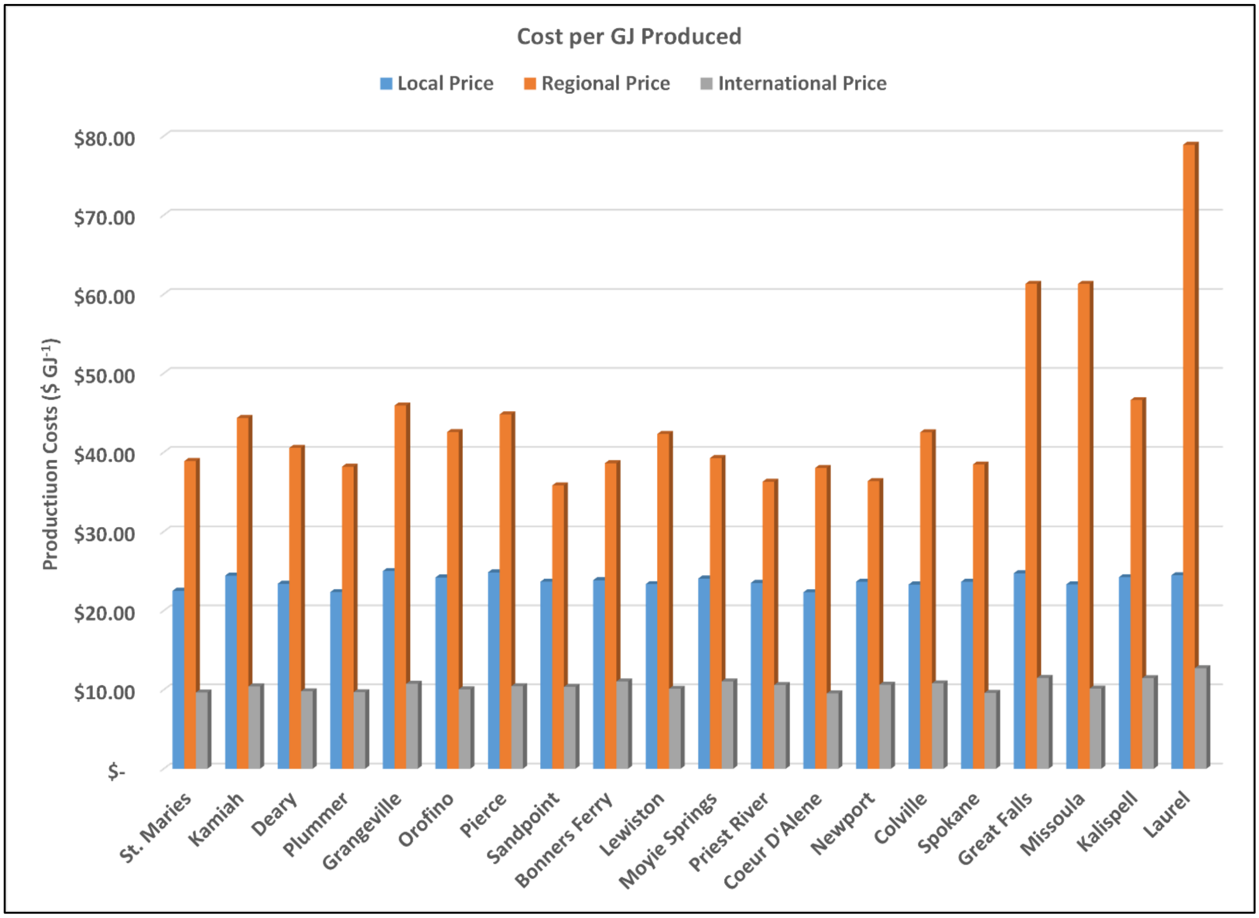


*Figure 9: Cost per GJ to produce bioenergy for each biorefinery or pellet mill*

On average, transportation costs accounted for 4% of the total costs per Mg for the local scenario, 32% for the regional scenario, and 12% for the international scenario. The local scenario has the lowest transportation costs due to needing fewer depots and the lack of transportation after conversion. The regional biorefinery has longer transportation distances after refining to Spokane International Airport (Spokane, WA, USA), but the most significant factors in increasing costs were the large number of depots and their distance from the biorefinery. The international scenario has slightly more depots compared to the local scenario and the largest transportation distance from the pellet mill to the Port of Seattle.

Pellets were assumed transported by rail from the mill to the port with a transportation cost of $0.008 $Mg^{-1}$ $km^{-1}$ and international shipping costs were assumed to be $44.09 $Mg^{-1}$.

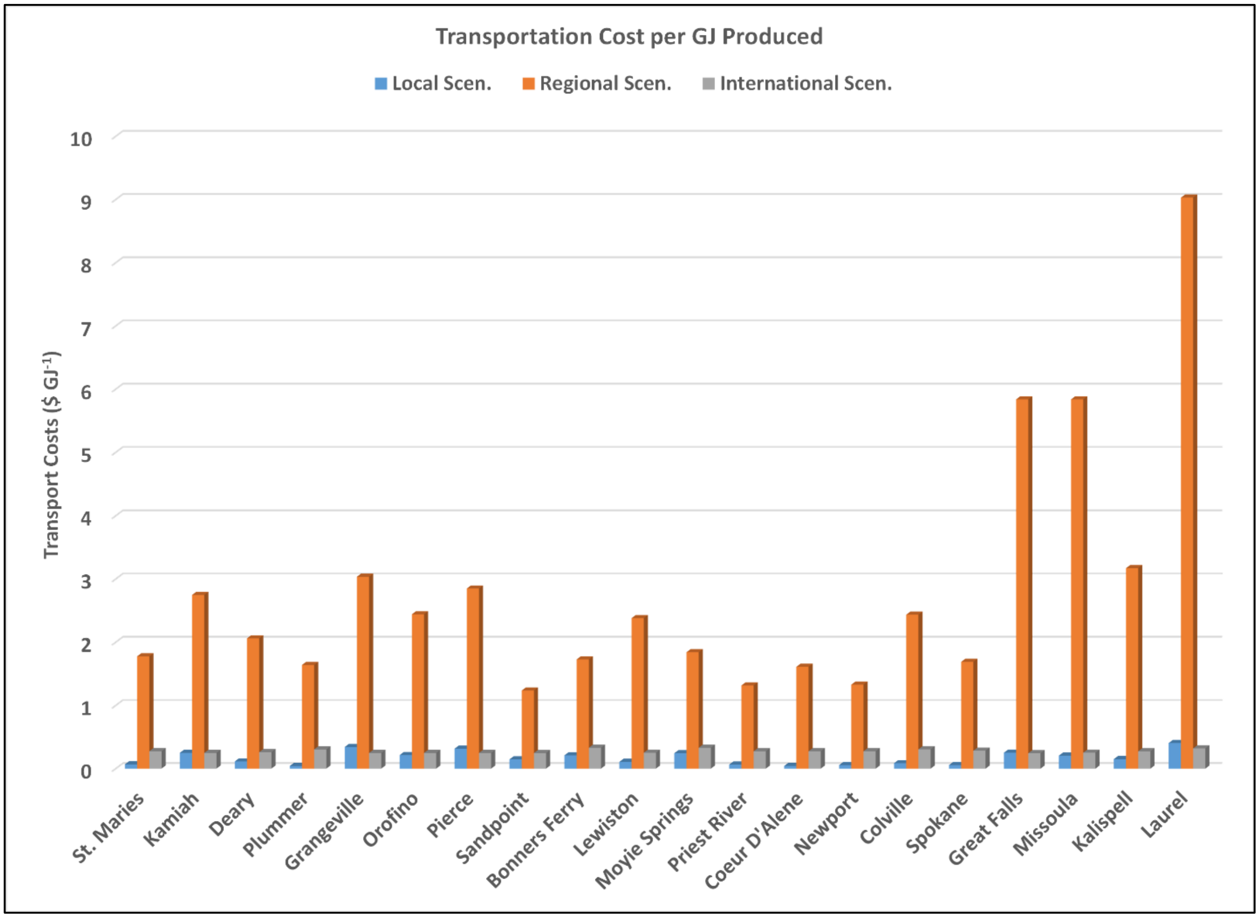


*Figure 10: Transportation costs per GJ produced for each biorefinery or pellet mill*

On average, capital costs account for 9% of local scenario costs per Mg, 15% of the regional scenario costs per Mg, and 9% of the international costs per Mg. The local scenario has a smaller capital cost than the other two scenarios, but the costs are distributed over a smaller production volume, which increases its overall impact. The regional scenario has significantly more capital costs because of the significant size and experimental nature of the biorefinery and the large number of depots and forest residue collection operations. The international scenario incurs slightly higher capital costs than the local scenario, but distributes the costs over 50% more production volume.

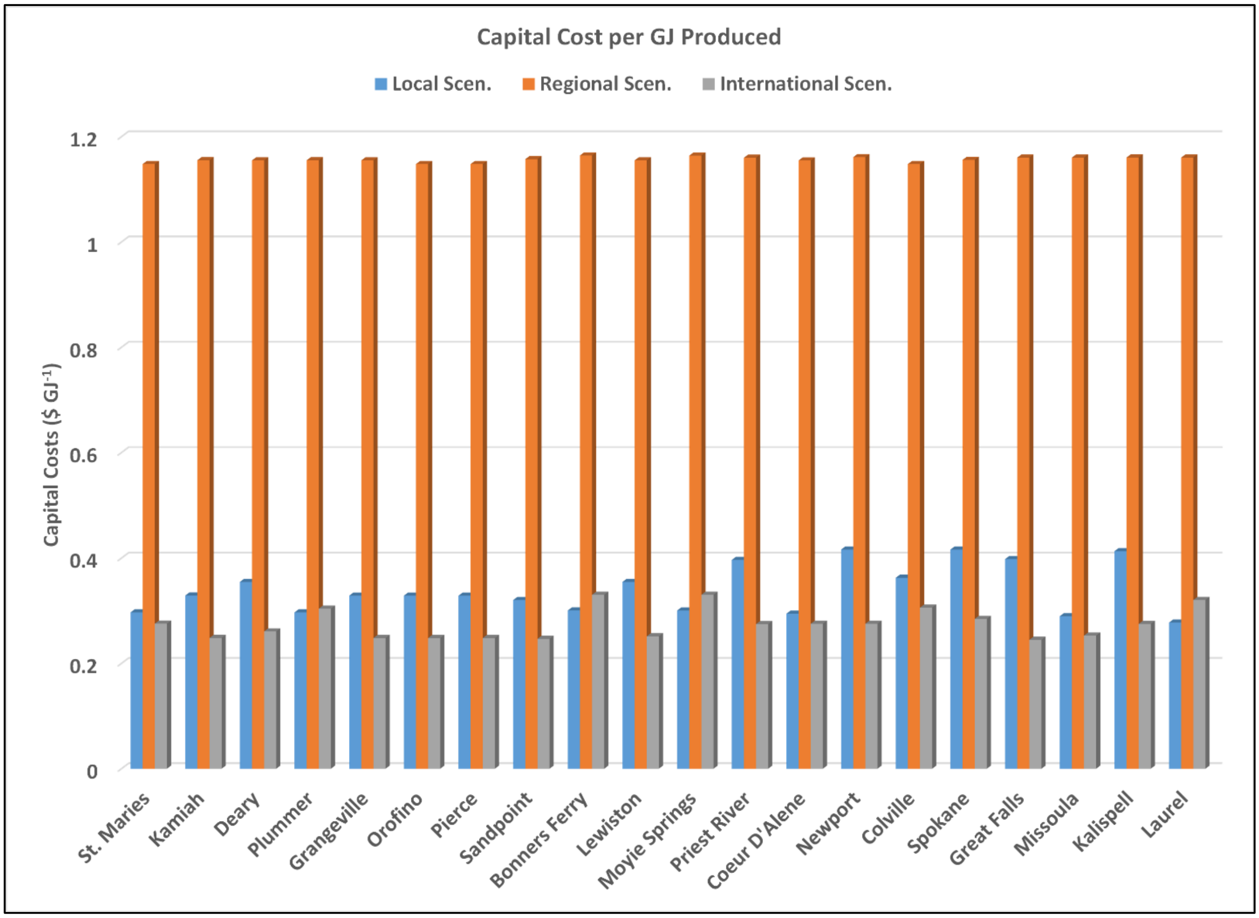


*Figure 11: Capital costs per GJ produced for each biorefinery or pellet mill location*

Assuming no increase in production capacity, capital cost increases' effect on production price for the local scenario followed the equation y = 0.0238x + 22.436. The regional scenario follows the equation y = 0.007x + 35.506, and the international scenario follows the equation y = 0.0259x + 23.127.

### 3.5.1 Sensitivity Analysis

FREAM was sensitive to changes in capital and transportation costs and was highly resistant to changes in all other variables. The scale of operations in all three scenarios allowed the model to absorb small changes from variables with relatively small overall cost impacts, such as employee wages.

3.5.2 Wages

*Table 5:Sensitivity of FREAM to wage changes*

| **Table 5** | | | |
|---|---|---|---|
| **Scenario** | Variable | Base Value ($ $yr^{-1}$) | Average % change in overall cost per $1000 change in variable |
| **Local** | Landing Wage | 35,000 | 0.015 |
| | Depot Wage | 35,000 | 0.032 |
| | Facility Wage | 55,000 | 0.058 |
| **Regional** | Landing Wage | 35,000 | 0.017 |
| | Regional Wage | 35,000 | 0.035 |
| | International Wage | 55,000 | 0.009 |
| **International** | Landing Wage | 35,000 | 0.009 |
| | Regional Wage | 35,000 | 0.017 |
| | International Wage | 55,000 | 0.063 |

Changes to the wages at any location in the model had negligible effects on the model and have been excluded from this discussion for brevity [Table 5].

3.5.3 Capital Cost

The capital cost of the biorefinery changes the price of the local scenario by $0.044 $L^{-1}$ for every $50 million in capital cost change. The biorefinery capital cost was $56 million for the local. If the capital costs rise to $100 million, the cost of production rises 4.44% from $0.904 $L^{-1}$ to $0.943 $L^{-1}$. The regional scenario cost of production changes by $0.011 $L^{-1}$ for every $50 million in capital cost change. The biorefinery capital cost was $800 million for the regional scenario. If the capital costs rise to $850 million, the cost of production rises 0.85% from $1.22 $L^{-1}$ to $1.23 $L^{-1}$. The international scenario cost of production changes by $8.01 $Mg^{-1}$ for every $50 million in capital cost changes. The biorefinery capital cost was $60 million in the international scenario, if the capital costs rise to $100 million, the cost of production rises 4.21% from $152.55 $Mg^{-1}$ to $58.95 $Mg^{-1}$.

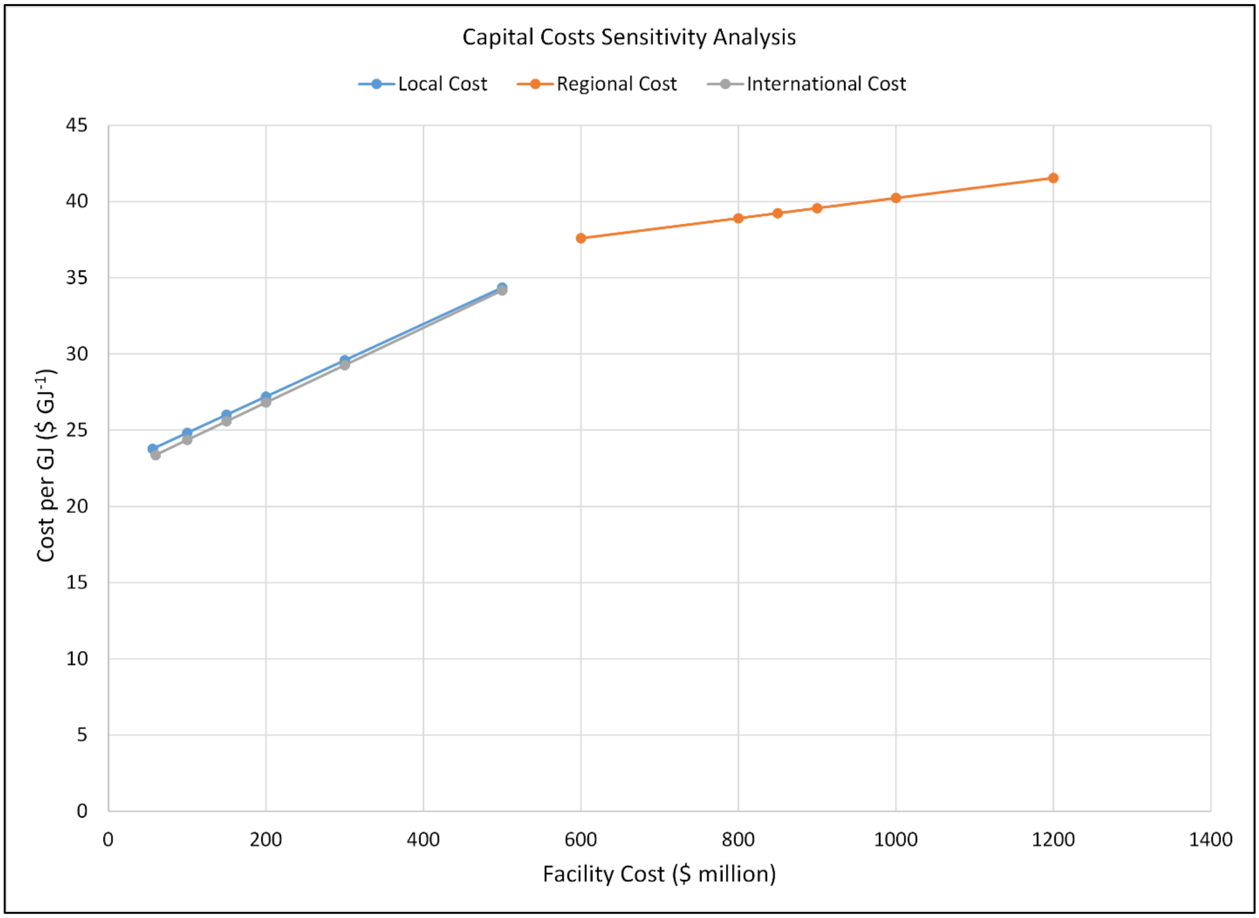


*Figure 12: Percent of cost of production as capital costs change with production capacity held constant.*

### 3.5.4 Transportation

The cost of transportation changes the cost of production of the local scenario by \$0.008 $L^{-1}$ for every \$0.014 $Mg^{-1}$ $km^{-1}$. The transportation costs were \$0.04 $Mg^{-1}$ $km^{-1}$ for the local scenario test runs. If the transportation costs rise to \$0.055 $Mg^{-1}$ $km^{-1}$, the cost of production rises 0.88% from \$0.904 $L^{-1}$ to \$0.911 $L^{-1}$. The regional scenario cost of production changes by \$0.103 $L^{-1}$ for every \$0.014 $Mg^{-1}$ $km^{-1}$. The transportation costs were \$0.04 $Mg^{-1}$ $km^{-1}$ for the regional scenario. If the transportation costs rise 8.44% to \$0.055 $Mg^{-1}$ $km^{-1}$, the cost of production rises from \$1.22 $L^{-1}$ to \$1.32 $L^{-1}$. The international scenario cost of production changes by \$2.88 $Mg^{-1}$ for every \$0.014 $Mg^{-1}$ $km^{-1}$. The transportation costs were \$0.04 $Mg^{-1}$

km$^{-1}$ for the international scenario. If the transportation costs rise to \$0.055 Mg$^{-1}$ km$^{-1}$, the cost of production rises 1.89% from \$152.55 Mg$^{-1}$ to \$155.43 Mg$^{-1}$.

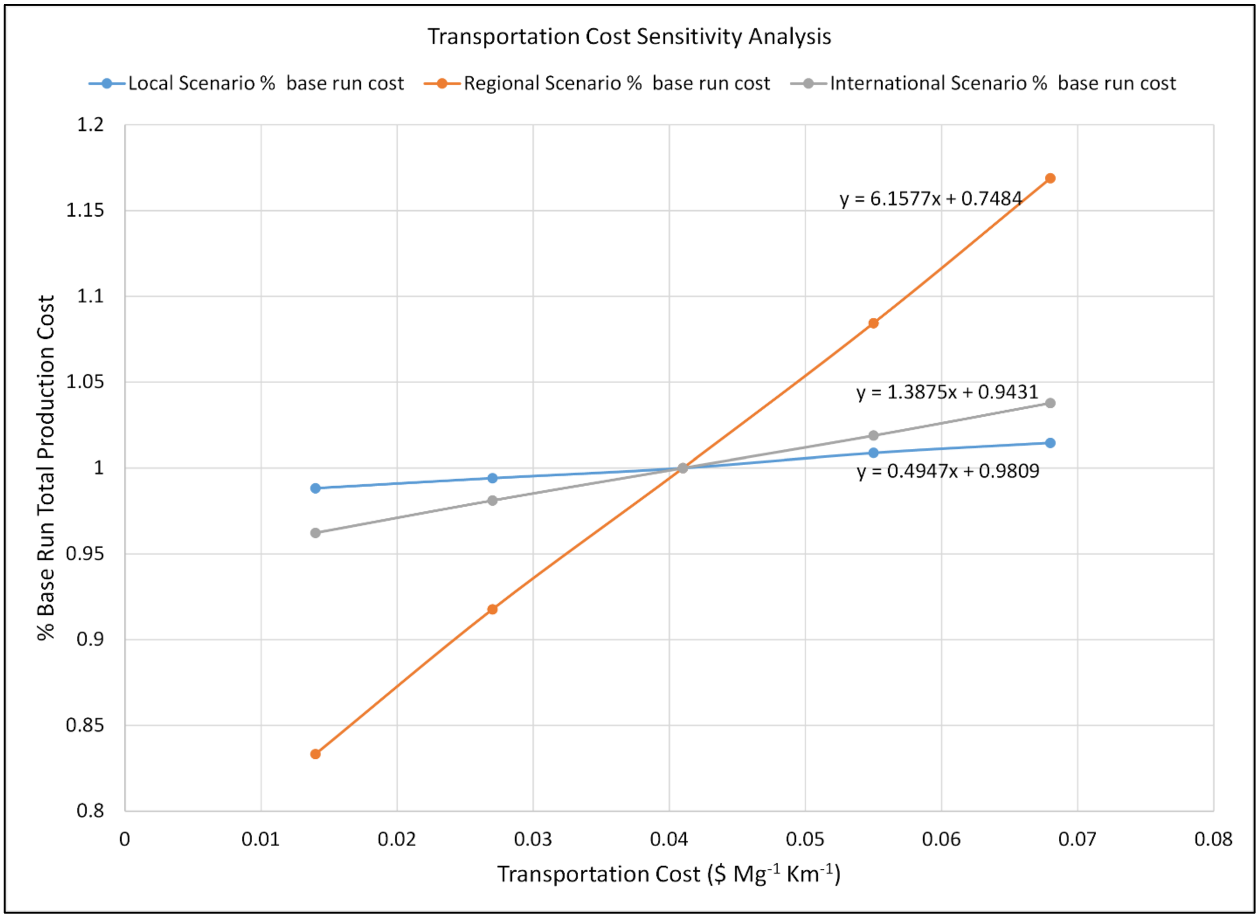


*Figure 13: Percent of cost of production as transportation costs increase*

## 3.6 Conclusion

We used a new, spatially-explicit logistics model, FREAM, to conduct a designed modeling experiment for wood-based bioenergy development in the Inland Northwest. FREAM provided a modeling framework that provided reliable estimates of volume, routing, and costs. Our approach compared bioenergy development options at a wide range of spatial scales, from local to international market scenarios. Combining stakeholder interaction with system dynamics models linked to GIS proved to be an effective method for developing accurate, relevant models simulating bioenergy development alternatives. We found that including GIS data on roads and harvest volumes made it is possible to accurately characterize a region's potential supply of feedstock. Interaction with stakeholders refined the list of variables needed to be studied and help provide effective results and answer important questions.

We found that reducing transportation costs is critical to improving the overall effectiveness of forest residue-based logistics. Well-sited, centralized facilities are important for reducing transportation distances, but can be difficult to plan due to the annual movement of harvest locations. Finally, framing our simulation analysis in the context of a designed, replicated modeling experiment allowed us to make inferences about the potential benefits of alternative bioenergy scenarios for communities in the Inland Northwest.

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# Chapter 4:

# Thesis Conclusions

Renewable energy is a fast growing sector that will face significant challenges as new startup companies compete with fossil fuel production. Improvements in our ability to gain and store feedstocks for bioenergy conversion could yield important progress, as can the maturation of conversion technologies. The Inland Northwest is the site of two major USDA bioenergy grants that have created significant progress in the research and maturation of cutting edge conversion technologies. Pellet producing entities in the region are also being actively pursued as in order to reduce pollution and guarantee adequate energy supplies. Recently, a pellet mill has been commissioned in northern Idaho for the purpose of exporting pellets to Southeast Asia. This development pathway is consistent with analysis that resulted from our FREAM modeling experiment.

Removing slash from the forests in northern Idaho is an expensive and difficult proposition. Increasing the size and speed of the monoline collection system that was field tested could yield positive results and could make the system a reasonable option for mass implementation. Other options that have been considered to mitigate the need for such systems is to require harvest operations to utilize whole-tree harvesting techniques that leave large piles of slash nearer to roads than cut-to-length systems.

The monoline continuous capstan winch system that was tested cost \$1290.90 acre$^{-1}$ to remove slash from the field, but is highly dependent on stand dimensions and slash density. This system was operated using a four man hand crew and had a maximum capacity of 0.13 Mg. The setup time for the system was 113 minutes. If the setup time can be reduced by mounting both ends of the system to heavy machinery, there would be significant room for improvement. Increasing the line speed and capacity could also yield dramatic effects on the productivity of the system.

The FREAM model was effective in identifying outcomes that match data from previously used models such as IBSAL and BLM. Our analysis using FREAM showed that mills producing pellets (272,155 Mg) for international export was the most likely scenario to succeed, with costs of production averaging \$10.51 GJ$^{-1}$. The local scenario, using a small

(181,437 Mg) pyrolysis plant to produce gasoline, cost of production averaged \$22.33 $GJ^{-1}$. The regional scenario, using a large (725,748 Mg) biochemical conversion refinery, cost of production averaged \$35.83 $GJ^{-1}$. The ability of the model to identify a bioenergy development option that is currently being pursued in the real world, and in the same location, speaks to its utility and the future potential of the model. It is important to note that we would expect pellets to be the least expensive option of those evaluated, as pellet production is a well-researched technology that has existed for many years. By contrast, the other two technologies being analyzed have only recently come into use, and the associated biorefining processes are still undergoing development and testing. There are many ways in which FREAM can be improved upon as it continues to develop in the future. For example, FREAM does not currently consider subsidies and other forms of cost mitigation that are available to biofuels producers. The resolution of geospatial data drawn upon by the model can be improved and refined. Further detail in cost calculations can be added. That said, the model is quite useful in its current form and provides a novel example of directly linking SD modeling with spatially explicit geospatial analysis.