SUPPLY CHAIN ANALYSIS FOR SUSTAINABLE ALTERNATIVE JET FUEL PRODUCTION FROM LIPID FEEDSTOCKS IN THE U.S. PACIFIC NORTHWEST

By

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IN THE U.S. PACIFIC NORTHWEST

Abstract

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With the emergence of new technologies that enable the production of renewable hydrocarbon fuels, the production of sustainable alternative jet fuel has become feasible. To encourage adoption of these technologies and fuels, future policy initiatives are expected to drive new demand for sustainable alternative jet fuels. In response to these initiatives, and in response to other national and regional interests, this study provides an analysis of an oilseed-to-sustainable-alternative-jet-fuel supply chain for the United States Pacific Northwest. This research is separated into two components. The first research component quantifies oilseed feedstock in addition to chemically-similar fats, oils, and greases that can also be used to produce fuel. Oilseeds are quantified for future production potential using a high-resolution approach based on compatibility with current crop rotations and expected oilseed yields. Fats, oils, and greases are quantified using population data from large cities and capacities from major slaughterhouses. The second research component uses a transshipment model, constructed and solved as a mixed-integer linear program, to analyze the oilseed-to-sustainable-alternative-jet-fuel supply chain from the production of lipid feedstock to a biorefinery that uses the hydroprocessed esters and fatty acids process. The model has several steps including: feedstock production, short-term storage, long-term storage, oil extraction, and final markets. In addition to fuel markets, the model also includes oilseed meal markets. The most cost-efficient oilseed crusher location combinations are selected by the model solver from an array of possible locations. Multiple model scenarios are used to study varied feedstock scenarios and biorefinery combinations. The results from this study suggest that, under a maximum production scenario, sufficient lipid feedstocks could be sourced from within the Pacific Northwest to supply an existing biodiesel plant and a new biorefinery with jet fuel capacity. The most efficient supply chain operations would require two or three new oilseed crushing facilities located near oilseed production areas.

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CHAPTER ONE: INTRODUCTION

As the United States seeks improved energy independence, environmental sustainability, and economic development, biofuels offer opportunities to simultaneously support these areas. To promote investment in biofuels and technology development, the US Renewable Fuel Standard (RFS) was introduced as part of the Energy Independence and Security Act (EISA) of 2007. With bipartisan support, the bill was enacted later during the same year [1, 2]. The RFS program, which is administered by the EPA, requires petroleum blenders to provide minimum volumes of renewable fuels in addition to petroleum-based fuels [2, 3, 4]. The EPA also delineates national goals that incentivize the production of next-generation biofuels, particularly fuels made from waste or low-value feedstocks and drop-in-quality hydrocarbon fuels that can be burned in unmodified internal combustion engines [4]. Following the introduction of the RFS, biofuels production and consumption have significantly increased in the United States [7].

The RFS does not specifically call for increased production of alternative jet fuel, instead qualifying it as “other advanced biofuels” [4], but policy incentives for alternative jet fuel production do not only stem from the United States. The United Nations’ International Civil Aviation Organization (ICAO) recently released a preliminary statement that declares all international flights will require an unspecified proportion of alternative jet fuel by 2050 [5]. ICAO’s impending requirements have spurred civilian airlines, and industry coalitions such as the International Air Transport Association and the Commercial Aviation Alternative Fuels Initiative, to foster action from stakeholders for all types of alternative jet fuel [6].

As RFS mandates have called for continually increasing quantities of advanced renewable fuels, research analyses and tools were designed to inform the nation’s ability to reach these targets. Significant projects, such as the Department of Energy’s 2016 Billion-Ton Report

[4], Volpe National Transportation Systems Center's Freight Transportation Optimization Tool (FTOT) [8], and the National Renewable Energy Laboratory's Biomass-Scenario Model (BSM) [9], have been established to identify general opportunities for the expanding biofuels production on a national scale. Now, a growing demand for renewable aviation fuels has presented additional opportunities to implement these tools and studies. For instance, a study that compares and contrasts the capabilities of FTOT and the BSM uses nationwide scenarios for alternative jet fuel production is nearing publication [10].

This study is targeted to complement these national tools to further characterize production opportunities on a local or regional basis. By focusing only on sustainable alternative jet fuel produced using the HEFA process (hydroprocessed esters and fatty acids) in the US Pacific Northwest (PNW) an assessment of regional infrastructure, needs and motivations of potential stakeholders, and the roles of regional and local institutions was conducted. The lessons learned in the process of conducting this study may be used to better define regional opportunities as well as inform larger national assessments.

Basis for Study

Although full-scale HEFA refineries currently operate on three continents, most facilities focus on renewable diesel production. A smaller number of facilities produce SAJF, including just one of the three operational HEFA refineries in the United States. That facility, the AltAir refinery (acquired by World Energy in March 2018 [10]) in Paramount, California, first began deliveries of SAJF to United Airlines at Los Angeles International Airport in March of 2016 [11]. Following the initial success of AltAir, an ensuing series of offtake agreements from major airlines suggests that SAJF is attractive for both fuel producers and end users. AltAir has also signed agreements with KLM (Royal Dutch) and Gulfstream (through World Fuel Services)

[12]. SG Preston, a company who expects to begin SAJF production in the Midwest by 2020, has also signed two offtake agreements, with JetBlue and Quantas [12, 13].

The Pacific Northwest does not currently have an alternative jet fuel production facility, although the region offers promising opportunities. As the owner and operator of the Seattle-Tacoma International Airport (SEATAC), the Port of Seattle has demonstrated their interest in alternative jet fuels by signing an agreement with thirteen airline carriers to investigate the necessary steps for all flights to be supplied with at least 10% locally produced alternative jet fuels by 2028 [14]. The Port has also explored other options for encouraging alternative fuels use [15], including funding for the co-benefits of sustainable fuels and biofuels compatible infrastructure investment [16].

Decisions to produce alternative jet fuels depend on a specific technology paired with available feedstocks, existing infrastructure, able investors, and markets. The early adoption of the HEFA fuels and technology can be attributed to three main factors that separate it from other renewable fuels:

- Feedstock Flexibility: HEFA fuels are produced with adaptable processes and allow for a wide variety of feedstocks to be used to produce the same quality product [17]. In particular, waste fats, oils, and greases (FOGs) such as yellow grease (used cooking oil) and animal fats are amenable to the production of HEFA fuels because their high free fatty acid (FFA) content is not a conversion inhibitor. In contrast, the conversion of these feedstocks into biodiesel using the more-common FAME (fatty acids and methyl esters) process requires pre-processing to reduce FFA content [18, 19].
- Process Compatibility: A significant difference between HEFA fuels and other biofuels is the technological accessibility to existing petroleum producing facilities and the relative

inaccessibility to other potential production sites. The hydrotreating process used for HEFA fuels, as well as fuel improvement processes such as cracking and isomerization are key to renewable jet fuel production and can be accomplished at a petroleum refinery by making minimal modifications to existing equipment [17, 20, 21]. Greenfield development of a HEFA refinery requires large capital expenditures as well as a substantial source of hydrogen or equipment to produce hydrogen.

- Drop-In Fuel: In the past, performance differences between petroleum-based hydrocarbon fuels and the esters and alcohols constituting renewable fuels have limited any chance for serious consumer commitment to renewable fuels. HEFA fuels are one of a group of advanced biofuels that are pure hydrocarbons and are nearly identical to their petroleum counterparts [22, 23, 24]. Additionally, HEFA is one of the alternative fuel technologies approved by ASTM for use in jet engines [25]. The development of renewable hydrocarbons will lead to widespread adoption by the average consumer as well as a significant stake in specialized markets, such as the jet fuel market.

Research Objectives:

Objective 1. Create analytical methods to spatially and quantitatively estimate current and future potential production of used cooking oil, animal fats, and vegetable oil lipid feedstocks.

Task 1a. Develop a method to estimate current and potential production of oilseeds that considers competition from other crops and influential local/regional characteristics.

Task 1b. Develop a method to estimate current and future production and availability of used cooking oil and animal fat feedstocks.

Objective 2. Determine the optimal siting of facilities and utilization of feedstocks that lead to the production of HEFA fuel.

Task 2a. Develop siting requirements for intermediate facilities along the supply chain. Apply siting requirements across the PNW to find suitable locations for facilities.

Task 2b. Determine optimal supply chain performance, including site selection of new facilities, by using a mixed-integer linear programming solver. Include a preliminary validation of the model by evaluating the existing wheat supply chain.

Thesis Organization

This thesis is organized into four chapters. The first chapter is this introduction. The second chapter, focuses on estimating potential for lipid feedstock production within the PNW. The chapter begins with a discussion of the basics of oilseed production and then proceeds into the methods and results of oilseed production modelling. A following section, which discusses the production and modelling for FOGs, concludes the second chapter. The third chapter discusses optimal utilization of feedstock and processing facilities for alternative jet fuel production. The chapter begins with a discussion of the supply chain optimization tool that will be used for the study. Then task 2a is addressed with a discussion of methods used to identify potential locations for new facilities. The third section describes a test optimization model of Washington's wheat supply chain. The final section discusses the oilseed-to-alternative-jet-fuel model and optimized solutions. The final chapter contains the conclusions.

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CHAPTER TWO: LIPID FEEDSTOCK INVENTORY ANALYSIS

2 Introduction:

Although each HEFA feedstock possesses some different characteristics and unique logistical challenges, each are in the form of a lipid called a triglyceride. The molecular building blocks of a triglyceride consist of three fatty acid chains connected by a 3-carbon backbone [1, 2, 3]. The quality of a feedstock can be described based on the length of fatty acids, the degree of hydrogen saturation of the fatty acids, and the amount of other impurities present [2, 4, 5]. Impurities are non-triglyceride compounds that may be present, such as water, free fatty acids (FFAs), and other organic compounds. Plant oils are typically considered to be the highest quality feedstocks, as they have relatively low FFA contents, and the distribution of fatty acids in vegetable oils is more predictable [6, 7]. Used cooking oil and animal fats are often classified together with the term FOG (fats, oils, and greases), and are considered waste resources or byproducts of other industries. The quality of FOGs can vary, but they always have higher FFA contents, and typically have shorter fatty acids chains than plant sources [8]. Regardless of a feedstock's quality, it has an existing market, and an associated supply chain [9, 8, 10]. FOGs must either be processed into a new goods, or their producers must pay to dispose of them. FOGs are frequently used for animal feed and chemical products [10]. Competition between processors and collectors has a significant impact on the availability of all lipid feedstocks [10, 11].

The geospatial system boundary for feedstock describes production within Washington, Oregon, and Idaho, and is referred to as the Pacific Northwest (PNW) throughout the study. Annual production is considered for all feedstocks. The depth of supply chain analysis, and processing system boundaries, is not the same for all feedstocks, as more fundamental stages are considered for plant oil production, due to a need to better understand opportunities to expand production in the future.

2.1 Objectives and Organization:

The primary objective of this chapter is to create analytical methods to spatially and quantitatively estimate current and future production potential of lipid feedstocks. This study considers three feedstocks for production of HEFA fuels: plant oils, used cooking oil, and animal fats. The chapter is divided into two primary sections, based on the methods used to produce spatial and quantitative estimates of feedstock production. The first method accomplishes task 1a using a raster-simplification method to determine production of plant oils. The second method accomplishes task 1b using a point-based approach to determine production of animal fats and used cooking oil.

2.2 Oilseeds:

A wide variety of plants can be grown to produce oil. Depending on the climate and other regional characteristics, brassicas, soybeans, sunflower, flax (linseed), cottonseed, and imported palm may all be potential plant-oil sources in the United States [12]. Brassica oilseeds, including rapeseed, canola, mustard, pennycress, and camelina, are some of the most widely cultivated oilseeds throughout the world [5]. The oil from brassica crops is a staple in many cultures' diets and can also be used for a variety of chemical and industrial uses [13].

The plant oil produced from brassicas typically contains high concentrations of saturated, long-chain fatty acids. Oil from most rapeseed and camelina, contains large amounts of erucic acid [5, 6], a long and saturated fatty-acid that is damaging to stomach health for humans and animals. In the United States, high levels of erucic acid have led to restrictions by regulatory agencies for the use of these oils for edible purposes [14, 15]. The creation of a group of low erucic acid rapeseed varieties renamed canola, also sometimes called LEAR (low-erucic-acid rapeseed) outside North America has led to more popular adoption [14]. Canola was originally created through careful breeding of rapeseed, although many varieties currently available are genetically modified.

Brassica oilseeds are dynamic crops grown in many climates using different agricultural practices. Farmers in North America, Europe, Australia, and India typically grow oilseeds in rotation with small grains in dryland conditions [16, 17, 18, 19]. In addition to small grains, brassicas grown in dryland conditions have been sequenced with pulses (dry, edible legumes), sunflower, flax, corn [20], and cotton [21]. China, the world's second leading producer of brassica oilseeds, grows much of its rapeseed in paddy fields in rotation with rice [21]. Canada, which leads global brassica oilseed production, produces exclusively spring varieties of canola due to the harsh winter conditions on the Upper Great Plains that cause low survivability for winter cultivars [17].

The United States is one of the world's overall leading producers of oilseeds, although the US produces a relatively small amount of brassica oilseeds [22]. Most existing brassica production occurs on the Upper Great Plains Region of North Dakota, where spring canola and hard red spring wheat are rotated using the same spring varieties and practices as farmers in Canada [17]. The winter-wheat-growing areas of the Pacific Northwest could potentially benefit from widespread adoption of brassica oilseeds, both for economic and agronomic reasons [16, 18].

The inland Pacific Northwest is the area east of the Cascade Mountain Range, west of the North American Continental Divide, and North of the Wallowa Mountains in Washington, Oregon and Idaho. Like much of the Western United States, most of the region is characterized as having a Mediterranean, semi-arid climate [23]. Rapid spatial variations in terrain lead to changes in climate that fundamentally impact its agricultural economy. Areas that sustain dryland cropping, shown in Figure 2.1, typically expect between 225 and 750 millimeters of precipitation each year. Temperatures during the winter regularly drop and stay below freezing for extended periods of time, although these drops rarely threaten common winter crops, like wheat, in the region like wheat.

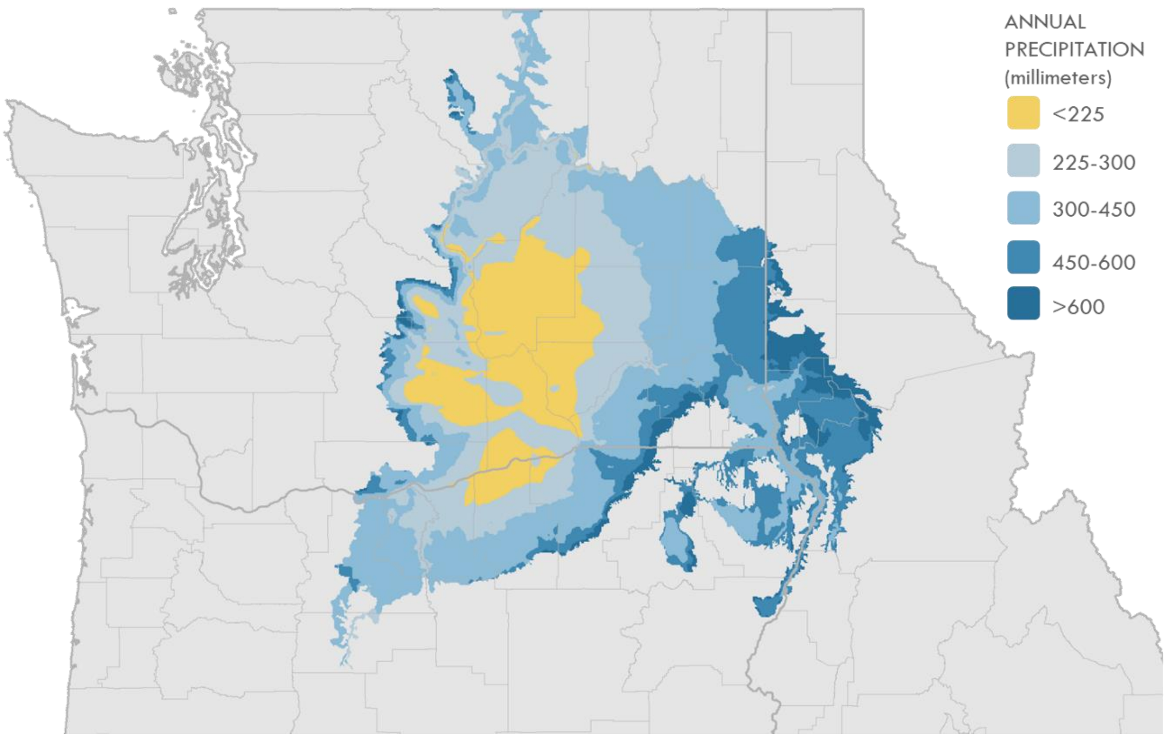

Figure 2.1: PNW Dryland Cropping Region and Precipitation

2.2.1 Cropping Systems as Agro-Ecological Classes:

Agricultural practices change significantly across the PNW as reflections of annual precipitation, winter and summer temperatures, wind intensity, terrain, soil type, and economic opportunity. Incorporating all these factors into a land use model is intensive [24], but multiple years of USDA Cropland Data Layers (CDLs) can provide a simple and relevant empirical analysis [25]. CDLs are rasters that provide information about specific crops and other land use decisions for the entire United States on a 30-meter square grid [26]. A single CDL is used to develop a map of agro-ecological classes (AECs) based on the implementation of fallow around a cell [27, 24]. Three basic types of dryland AECs have been identified for the PNW: grain-fallow, annual crop grain-fallow transition, and annual crop. A map showing the distribution of the agro-ecological classes is shown in Figure 2.2.

The grain fallow AEC is defined as any area that uses more than 40% fallow in its crop rotations [27]. It can be observed on the Columbia Plateau across central Washington and North Central Oregon and is used on dryer parts of the PNW. Almost all crop rotations classified in this AEC consist of a two-year rotation of winter wheat followed by fallow [16, 28].

The annual crop AEC consists of most continuously cropped areas across the region, defined as any area that uses less than 10% fallow [27]. Annual cropping requires more precipitation than is available in much of the PNW. The annual crop zone includes eastern areas of the PNW like the Palouse and Camas Prairies. A strip of annual cropping is also found along the Northern edge of the Blue Mountains near Walla Walla, WA. The annual cropping zone is more flexible towards cropping decisions than other AECs, but the most common rotations consist of winter wheat, a spring small grain, and a spring pulse crop (peas, lentils, or garbanzo beans) [29, 30].

The annual crop grain-fallow transition AEC (transition AEC) accounts for two areas: the area between the grain-fallow and annual-crop zones, and the areas east of the annual cropping zone that can sometimes be too wet in March to plant spring crops. Areas in the transition AEC use 10-40% fallow [27]. The most common crop rotations are three-year rotations consisting of winter wheat, spring wheat or spring barley, and fallow [31, 32]. Some farmers also grow pulse crops in the transition zone, although they often face several agronomic challenges related to pod shatter near or during harvest.

Multiple annual AEC layers can be combined to monitor stability. Areas that are consistently identified as the same AEC are considered stable, while areas that change from year to year are dynamic [27, 33].

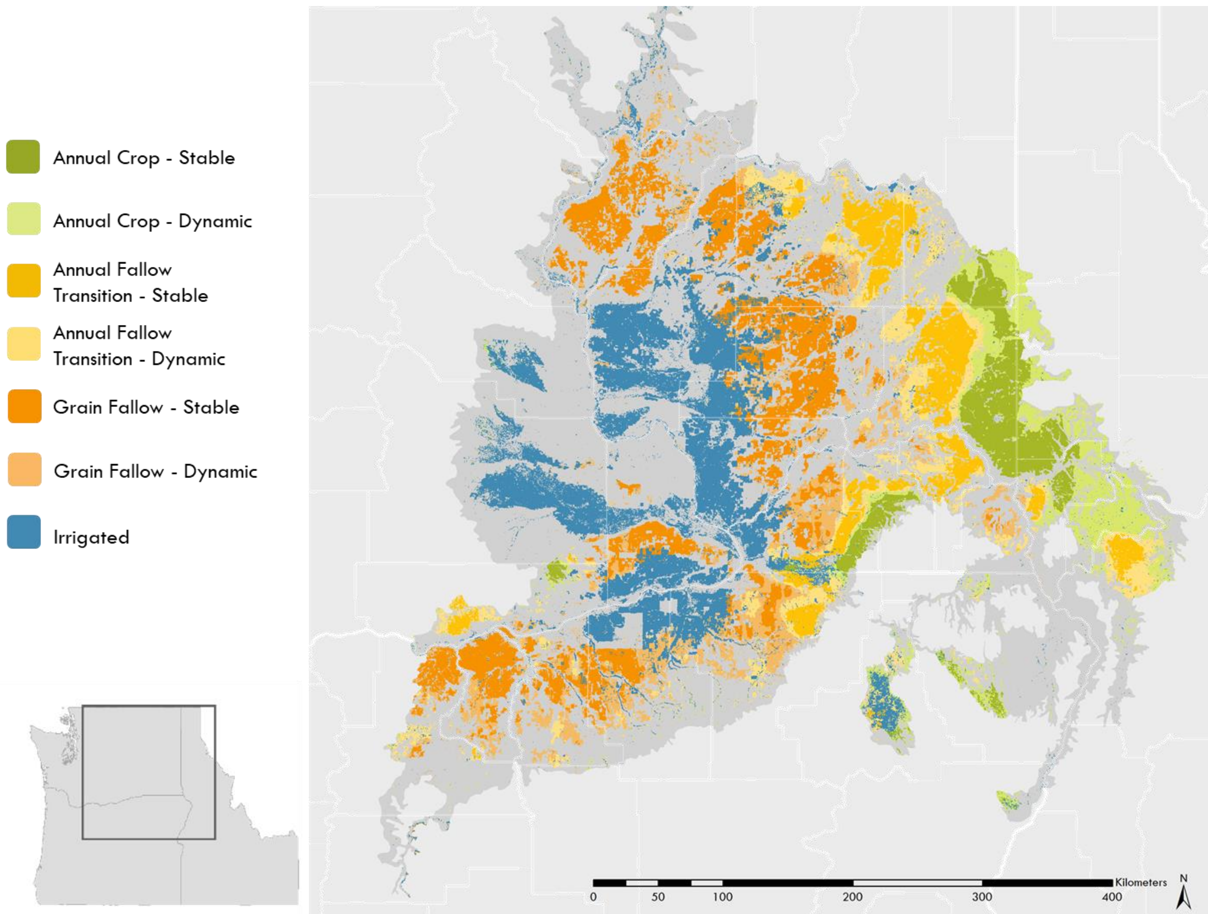

Figure 2.2: PNW Agro-Ecological Classes

2.2.2 Incorporating Oilseeds into Existing Cropping Systems:

The decision by farmers to plant oilseeds does not require new capital investment. The same equipment that is used to plant and harvest wheat is used for brassica oilseeds [34]. Farmers have expressed that although new equipment is not needed, cultivating canola does have a learning curve [29, 31].

Oilseed adoption may lag due to past farming practices [29]. A concern for many farmers is the impact that residual herbicides from past seasons may have on a brassica crop. Researchers have observed cases where the effects have lingered for close to a decade.

Oilseeds can be incorporated into crop rotations in each AEC differently. In the grain-fallow AEC, winter canola can replace a winter wheat crop once every four years (WW-F-WC-F) [16]. Several issues may arise with winter canola in this rotation, as a lack of winter hardiness can cause issues for all winter canola in the PNW, and high summertime temperatures can lead to pod shatter and yield loss [28]. Oilseeds do have potential to add diversity to the grain-fallow region, as there are no other broadleaf crops that are economically justifiable for these challenging conditions [30]. In the future, cultivars of camelina and mustard that are specifically suited for drier conditions may also come into production.

In the annual-crop and transition AECs, spring canola can replace a year of spring grain or spring pulse [16]. Some potential may also exist to eliminate fallow in transition AECs with spring canola or another low-moisture adapted spring oilseed like camelina. Winter oilseeds are not compatible with existing rotations in these AECs because they must be planted before a preceding crop can be harvested. A limited amount of winter-variety industrial rapeseed is grown in transition areas of the Camas Prairie, in sequence with fallow and winter wheat [25].

2.2.3 Recent Oilseed Acreage Trends:

Oilseeds are a relatively new crop to the PNW and have not yet experienced widespread or consistent implementation across the region's more than seven million acres of cropland. Planting trends are affected by the price of oilseeds as well as the price of other crops, especially wheat [35, 36]. Planted acreage in the PNW for canola peaked in 2014 at 39,000 hectares. After a sharp decline in canola price during 2014 and 2015, planted oilseed acreage dropped to 23,000 acres by 2016 [37].

In 2017, PNW planted acreage of canola increased to 37,000 acres [38]. During this period, canola prices have remained relatively low. The increase in acreage is largely credited to struggling wheat prices that have also driven increased acreage for fallow and many secondary crops, particularly pulses [35].

2.2.4: PNW Oilseed Yields:

Oilseed yields are broken into two categories for this study: spring and winter. All oilseeds are assumed to be canola, although industrial rapeseed and camelina will also be important for future production. There are currently more academic resources available about canola in the PNW as it has been the more popular oilseed crop among farmers. Spring canola yields are provided by a CropSyst (Cropping Systems Simulation Model) model [27]. The model run represents spring canola production in the dryland cropping regions of the PNW during the 2017 crop season.

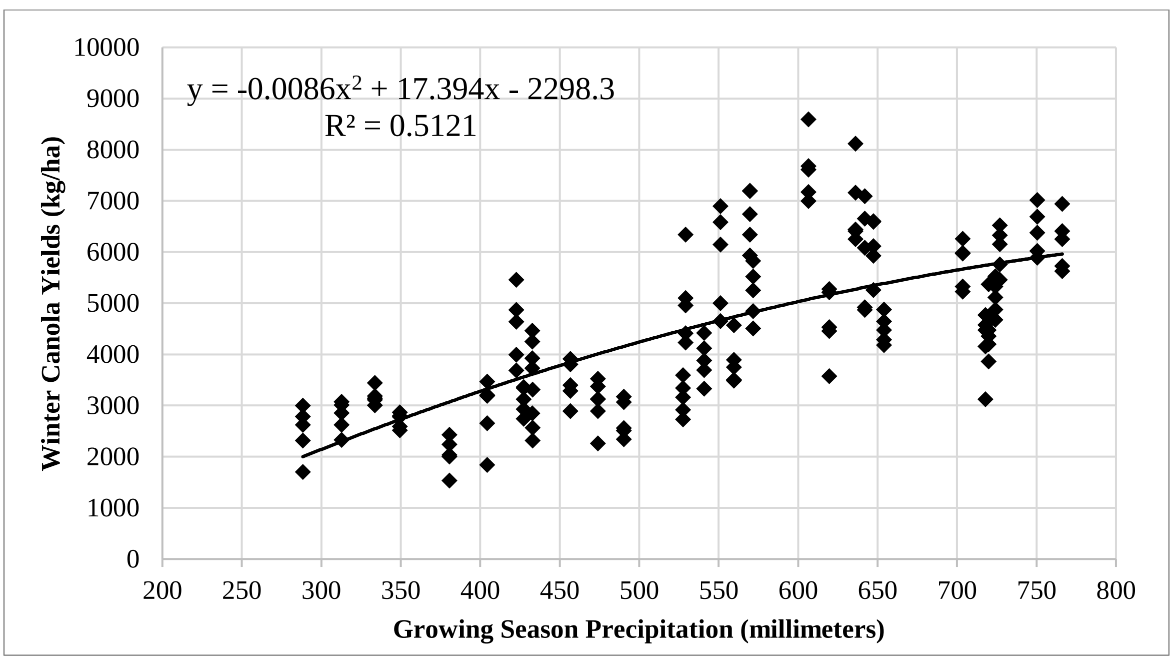

Figure 2.3: Oilseed Yields Versus Precipitation

Although CropSyst model runs are available for estimates of spring canola yields, similar model runs have not been produced for winter oilseeds. In the absence of CropSyst model runs, a procedure was designed to estimate winter oilseed yields that utilized data from University of Idaho Oilseed crop trial yields and annual precipitation [39]. A list of the steps used to produce the winter oilseed yield estimates is given below.

1) Crop trial data were collected from canola trials conducted by the University of Idaho from 2011 to 2017 and Washington State University in 2017. For each group of varieties tested, the five varieties with the highest average yield were selected. At each location, the production of those varieties was recorded.
2) Few trial locations used both spring and winter varieties. Instead of directly comparing performance by location, growing season precipitation was used to relate locations. Growing season precipitation was calculated from monthly precipitation data [40] as the precipitation that falls between the September 1 and August 31 of the following year. For each location and year, precipitation data were collected
3) Crop yields versus precipitation are shown in Figure 2.3.
4) Fit Trendlines to crop yields. Crop yields appeared to follow an arched curve. Equation 2.1, given below, is a polynomial equation that describes crop yields. Yields are given in kilograms per hectare and p is precipitation in millimeters.

$$winter\ yield = -0.086p^2 + 17.394p - 2298.3 \quad \text{(Eq 2.1)}$$

5) Produce the winter oilseed production layer by applying Equation 2.1 to a an annual 30-year normal precipitation raster [40].

2.2.5 Methods for Oilseeds Production Potential Estimates:

A preliminary feedstock production grid for the maximum oilseed production scenario was created using raster data. The grid was produced using the following steps, Figure 2.4 shows the final feedstock layer:

1) When using a multi-year AEC layer, it is necessary to simplify the layer to the three main classes by making assumptions about the dynamic classifications. For the layer proposed, dynamic classes are assigned to the AEC they are most closely associated with. One raster layer is produced for each main AEC classification.

   The spring canola yields layer was masked onto each of the aggregate AEC layers to create a spring yields layer for each AEC raster. The rasters have the 30mx30m resolution of the input AEC rasters, and only contain areas where both types of raster overlap.

2) Production layers were produced from yields raster layers. A minimum yield requirement was used to remove areas with little production potential. A rotation assumption was applied to the yields to account for how often an oilseed crop is likely to be grown. Assumptions are shown in Table 2.1 below.

Table 2.1: Crop Production Assumptions

AEC	Minimum Yield	Projected Rotations with Oilseeds [16, 33]	Equation
Annual	$yield_{sc}$>725 kg/ha	WW-SW-SC WW-SC-Pulse	$yield_{sc}/3$
Annual/Grain Fallow Transition	$yield_{sc}$>725 kg/ha	WW-SC-F WW-SW-SC	$yield_{sc}/3$
Grain Fallow	$yield_{wc}$>900 kg/ha	WW-F-WC-F	$yield_{wc}/4$

3) Create a 4x4-km grid using the projected UTM 11N coordinate system. The grid simplifies data inputs from the 30x30m AEC inputs for supply chain optimization in Chapter 3.

4) Zonal statistics were used to sum the total amount of production that fell within the borders of each grid cell. Total production of the cell was merged with the center points.

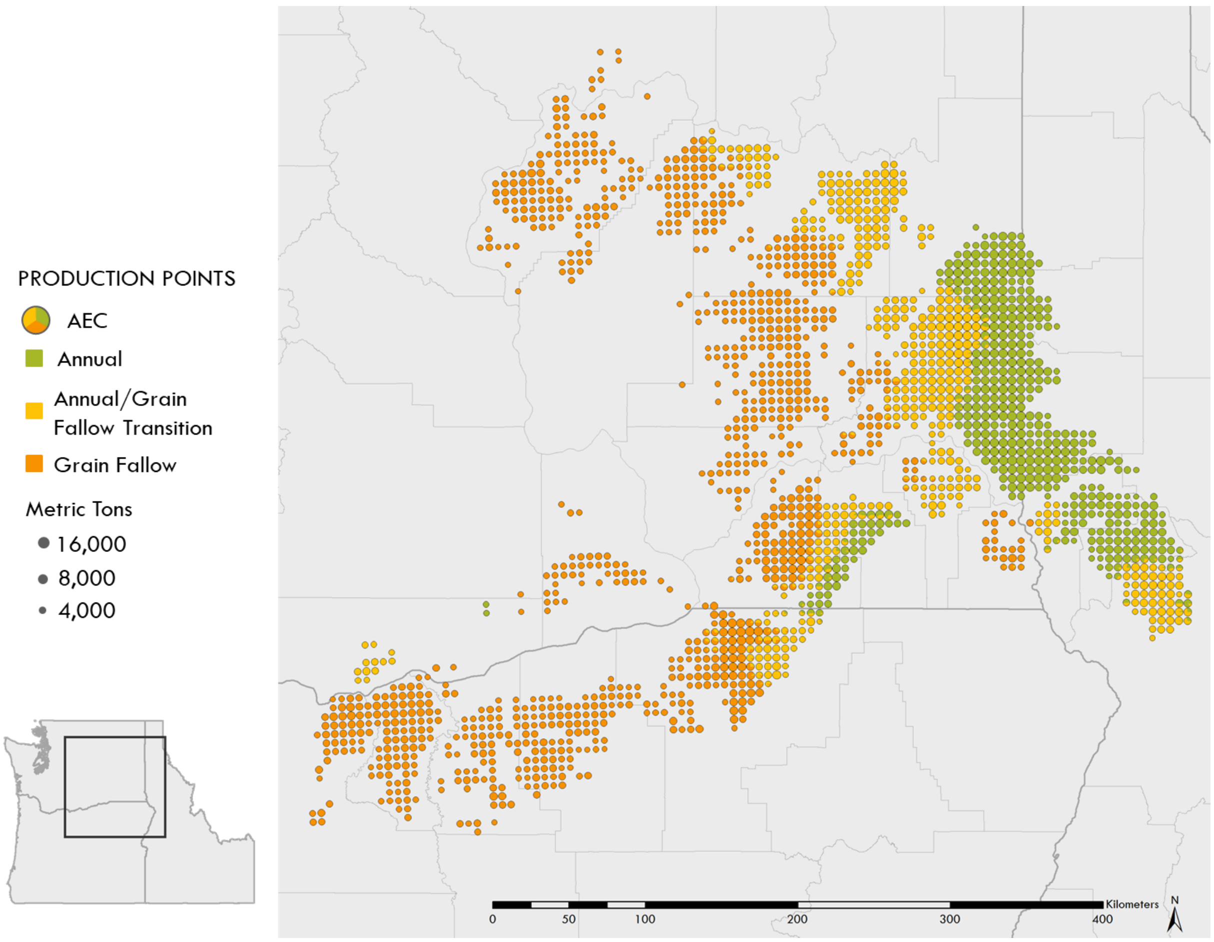

Figure 2.4: Maximum Annual Oilseed Production Points

2.2.6 Oilseed Layer Results:

The initial oilseed layer is the maximum annual production scenario. In this scenario, 65.5 million bushels, or 1.46 million metric tons, of canola are produced. This production has the potential to be converted to 614,000 metric tons of plant oil and 848,000 metric tons of oilseed meal. Figure 2.4 and Table 2.2 describe production for each AEC.

Table 2.2: Maximum Annual Oilseed Production Scenario

AEC	Production (metric tons)
Annual	472,000
Annual/Grain Fallow Transition	367,000
Grain Fallow	646,000

2.3 Fats, Oils, and Greases:

2.3.1 Used Cooking Oil:

Used cooking oil and yellow grease are two terms often used interchangeably to describe nearly the same material. Yellow grease always primarily consists of filtered used-cooking-oil and often completely consists of used cooking oil [10, 41]. The difference between the two materials is the level of precision. Used cooking oil is a loose description of discarded cooking oil while yellow grease is a standardized term that describes a specific commodity. Standards for yellow grease do allow for the addition of some other rendered animal fats, although there are also standards for FFA content and water content that must be met [41].

Most cooking oil begins as vegetable oil but high temperatures during cooking cause hydrolysis, polymerization, and oxidation to occur, affecting the oil's properties [8]. Most notably, the FFA content is increased. Cooking also introduces contaminates such as water and food particles. In all cases, it is assumed that used cooking oil has been contaminated by food particles [10].

Yellow grease is not considered edible for human consumption, although it is used for animal feed [10]. Yellow grease is marketed generically, no distinction is made for the type of vegetable oil it originated from or the types of cooking it was subjected to, meaning only a limited technical standard can be set for quality in relevance to fuel production. In the United States, used cooking oil is frequently sold for animal feed, export, and biofuels production. In

2011, the National Renderers Association (NRA) reported that approximately 68% of yellow grease produced in 2010 was sold to produce livestock feed [10].

2.3.2 Animal Fats:

Many species of animals are raised in the United States, but most animals raised for consumption are either cattle, hogs, or chickens [11, 42, 43]. Animal fats are produced as a byproduct of all industrial slaughter, regardless of the species [10]. During the slaughter process, meats are separated from byproducts such as fat, bones, organs, and hide [44]. The byproducts are transferred to a renderer that uses a rendering process, which includes various forms of grinding and cooking, that results in animal fats, bone meal, and blood meal. Animal fats produced from rendering can be described with several grades and classifications but are typically broken into two general groups: edible and inedible. Edible fats, including edible tallow from cattle, and lard from hogs, are considered fit for human consumption [9, 10, 44]. Inedible fats, including inedible tallow from cattle, choice white grease from hogs, and all poultry fat. Inedible fats can be mixed with animal feed if certain standards are followed [10]. Animal fats are also used to produce oleochemicals. In general, animal fats have medium-length fatty acid chains and have relatively high FFA contents compared to vegetable oil [8].

Most animal fats produced in the PNW come from cattle, as the PNW does not have a large hog or poultry industry [42, 43]. Slaughtered cattle originate from dairy farms or feedlots [45, 46]. Dairy farms are concentrated around several hubs throughout the PNW, including the Skagit and Yakima Valleys in Washington and the Magic and Treasure Valleys in Idaho [47]. Cow-calf ranches send steers and heifers to feedlots that are mostly located on the Central Columbia Plateau and southern Idaho [46]. When the cattle reach maturity, they are usually sent to either Washington Beef, in Toppenish, WA, or Tyson Fresh Meats, in Wallula, WA [45, 46, 48]. Cull cows and bulls are sent to slaughter at one of the region's smaller packing plants, likely Schenck Packing in Stanwood, WA, or CS Beef in Kuna, ID [45].

2.3.3 Roles of Renederers:

Renderers collect used cooking oil and animal byproducts and convert them into yellow grease and animal fats. There are two types of renderers: integrated renderers, whose facilities are adjacent to meat packing plants, and independent renderers, who are typically located near urban areas [10]. The Tyson Fresh Meats packing plant has an integrated rendering facility, it is unknown if the other packing plants in the region also have rendering capacity [49]. Two of the largest independent rendering companies in the United States, Baker Commodities and Darling Ingredients, each own several facilities throughout the PNW [50, 51]. Small biodiesel producers who have their own used cooking oil collection service and rendering capacity include General Biodiesel Northwest in Seattle, WA, and SeQuential in Salem, OR [52, 53].

2.3.4 Methods for Estimating FOG Production:

Production of FOGs naturally aggregates around specific points, as a function of a population and production factors. The basic steps to produce a FOG production layer are given below. Factors for various types of FOGs are discussed in the two following sections.

1) Identify production hubs:

   Production hubs are anywhere production of a FOG occurs in bulk. As part of this step, places that have little production are removed from consideration.

2) Apply production factor:

   A linear production factor(s) is applied to a known population value at each point.

2.3.5 Used Cooking Oil Production:

The factors used to estimate used cooking oil production for future studies are based on the factors used by the Western Governors Association (WGA) [54]. Urban areas, whose populations in 2010 were each greater than 100,000, are considered for used cooking oil production. It is assumed that areas with smaller populations are too sparse to make used cooking oil collection profitable. In 1998, NREL conducted the Urban Waste Grease Assessment [55], whose results have subsequently served as the backbone for a number of studies attempting to spatially locate and quantify used cooking oil production [54, 56, 57], as it is the only study to make a per capita estimate of used cooking oil production that can be applied to known, and regularly updated population values. The assessment suggests that each person in urban areas accounts for 4.1 kilograms of used cooking production per year.

Figure 2.5: Used Cooking Oil Production and Distribution

As shown in Figure 2.5, 14 urban areas in the PNW were found to have populations greater than 100,000 [58]. A total population of 7.4 million people lived in these areas in 2010.

Over 80% of the region's urban population lives west of the Cascade Mountain Range. The Seattle urban area, which also includes Tacoma and several other interconnected cities, is the largest with a population of 3.1 million. The Portland urban area, with its population of 1.8 million, is the second largest area. An estimated 30,000 metric tons of used cooking oil are produced in the PNW each year.

2.3.6 Animal Fat Production:

Figure 2.6: Animal Fat Production and Distribution

Production of animal fats in the PNW only includes tallow produced by cattle. Although many facilities have some slaughter capacity around the PNW, almost all production occurs at a few packing plants. The only facilities included in this analysis are those discussed by a 2014 WSU report that discusses the PNW beef industry, except Walt's Wholesale Meats [45]. Shown in Figure 2.6, these include: Tyson Fresh Meat, Washington Beef, Schenk Packing and CS Beef. Capacities from these facilities came from several resources [42, 46]. The average liveweights of cattle were derived from the 2016 USDA slaughter summary [42]. For each animal that is processed at a packing plant that specializes in steers and heifers, an average liveweight of 646 kilograms was used. For each animal that is processed at a packing plant that specializes in cull cows, an average liveweight of 567 kilograms was used. A liveweight/tallow production factor of 12% was applied to all cattle [11]. Tyson Fresh Meats and Washington Beef processed 910,000 (likely near 510,000 and 400,000 respectively) steers and heifers in 2016, producing an estimated 70,600 tons of metric tons. Schenk Packing and CS Beef processed an estimated 115,800 cull cows, producing 7,900 metric tons of tallow. These combine for a total tallow production of 78,500 metric tons.

2.4 Summary and Conclusions

In chapter two, methods to locate and quantify each feedstock were developed and then implemented. The chapter is broken into two sections, one focused on oilseed feedstocks, and the other focused on FOGs. The section focused on oilseeds used knowledge about existing cropland, oilseed compatibility studies, spring oilseed yield estimates from CropSyst model runs, and winter oilseed yield estimates from a yield-precipitation relationship to develop a dataset that describes potential oilseed production. The section focused on FOGs develops a similar dataset that described current production using data about urban populations and animal slaughter with production factors.

Two feedstock production scenarios that were developed during chapter two will be used for the supply chain analyses conducted in section 3.4. The first scenario uses the initial oilseed layer which represents the maximum feasible oilseed production rate. The second scenario halves the availability of oilseeds at all production points. Both scenarios assume that all FOG feedstock currently produced will also be available in the future. A summary of the scenarios is given in Table 2.3.

Table 2.3: Lipid Feedstock Production Scenarios in Metric Tons

Scenario	Total Feedstock	Plant Oil	FOGs
Maximum Production	721,000	614,000	107,000
50% Production	414,000	307,000	107,000

With the current availability of oilseed feedstocks being nearly non-existent, the PNW cannot sustain its existing biodiesel refinery, with an annual demand of 440,000 metric tons of lipid feedstock, let alone an additional HEFA refinery with an additional demand for 235,00 metric tons of feedstock each year. With limited potential to expand the production of FOGs in the region, increased oilseed production is essential. Farmers would need to increase acreage from approximately 100,000 acres per year to nearly 1.8 million acres per year.

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CHAPTER THREE: OILSEED-TO-ALTERNATIVE-JET-FUEL SUPPLY CHAIN ANALYSIS

3 Introduction:

When judged by minimum necessities, it is not uncommon to identify many locations that could host a new facility. In either the case of an oilseed crusher or HEFA refinery, minimum siting criteria only demand that a location has access to incoming and outgoing logistics, natural gas, water, and electricity. The process of determining how a supply chain will function is thus not a matter of mere feasibility, but a process of finding the best combination of locations from a wide array of feasible locations. In typical cases, the best combination of facilities is the combination that produces the minimum total costs. This can be done using an optimization program that considers capital costs, operating costs, and logistics from all potential locations simultaneously.

Linear programming (LP), and related techniques such as integer programming (IP) and mixed-integer linear programming (MILP), have long been used to practically implement the simplex algorithm for transportation problems and other supply chain management problems [1]. LPs are systems of equations comprising of an objective function that describes some characteristic that will be optimized, and a series of constraints that restrict variables in the objective function. For transportation problems, the objective function usually represents minimized total costs. Variables describe the amount of material transferred between nodes. Constraints describe rules for how material is allowed to interact with nodes along the supply chain [2]. MILP transportation problems are similarly organized but include variables and constraints to make some nodes optional, based on a fixed cost that is only added to the total costs if the node is used by the model [3]. LP and the related techniques have many applications as they optimize an entire supply chain at once, providing the ability to consider material transfers at several locations, or across specific routes, simultaneously.

Since their introduction, LP techniques have been widely used by those studying agricultural transportation to describe overall transportation systems, and to determine the price dynamics between different modes of transportation [4]. The Washington State University School of Economics has used LP transportation techniques to model the wheat supply chain and potential changes to operations of the Columbia and Snake River System [5].

Several studies have focused on siting facilities associated with production of biofuels in the United States, as new biofuels facilities can present a significant disruption to existing supply chains. The Freight and Fuel Transportation Optimization Tool (FTOT), developed at Volpe National Transportation Systems Center, is a "geospatially explicit scenario testing tool" that integrates ArcGIS with the Python-based PuLP MILP solver [6]. FTOT has been used on a national scale for a variety of agricultural byproducts, such as corn stover. A similar model was used by the WGA to assess total biofuels production in the Western United States [7]. In 2016, a thesis from Kansas State University focused on logistical feasibility for oilseeds grown in Kansas as a biofuels feedstock. It used a single-step MILP, from production points modeled as county centroids to potential crusher locations, to select optimal oilseed crusher locations in Kansas [8].

3.1 Objectives and Organization:

This chapter culminates in an oilseed-to-alternative-jet-fuel (OtSAJF) supply chain analysis, although conducting this analysis was only one piece of the research necessary for completing the study. The following chapter is organized into four sections. The first section describes the Many Step Transshipment Solver (MASTRS), a python-based mixed-integer linear programming transshipment model builder and solver that was constructed for analyses of complex supply chains. The second section directly addresses task 2a by discussing how feasible locations for new facilities were found and implemented in supply chain model scenarios. The final two sections discuss the implementation of supply chain models in fulfillment of task 2b. The third section provides an evaluation of the model and data input performance by evaluating the existing PNW wheat supply chain. The fourth, and final, section discusses the OtSAJF supply chain analysis.

3.2 MASTRS, an Optimization Tool:

MASTRS builds and solves MILP transshipment problems. A transshipment model describes nodes and transportation of material between nodes along multiple stages of a supply chain. A node can be any place where production, consumption, modification, transfer, or storage of material occurs. The transportation of material between nodes can be described as a route combination from a transportation network called a link. Each link has an origin node, a destination node, and a per-unit cost to use that link [2]. With MASTRS, links can only be constructed between certain nodes, as the nodes that a link connects must accept the same material and transportation network, and they must be on consecutive levels.

The MASTRS model builder is designed to facilitate flexible supply chain structures, meaning that the model builder does not have an underlying structure. The structure is dictated by inputs from the nodes and network datasets. Three types of node and link descriptors govern how structures are formed:

- Levels: Levels govern the direction that material flows in. The rules of MASTRS state that links can only be formed between consecutive levels, from the lower level to the higher level (1 to 2, 3 to 4). Levels are used to establish a production, storage, and processing hierarchy, so that material is sent through facilities in order.

- Materials: Materials distinguish compatibility with modes of transportation, specified by network datasets, and nodes. Materials can be used to distinguish distinctly different, but related, commodities, like a biofuel and byproduct, or two similar materials that may have different processing properties. Modes of transportation are only enabled to handle specific types of material. System boundary crossings, represented by entry nodes and exit nodes, are each compatible with one type of material. Intermediate nodes can handle materials based on their enabled material combinations. Each material combination has one input material and a ratio of production for each output material. Nodes may have more than one material combination enabled.
- Network Datasets: ArcGIS network datasets are used to form links using network analysis tool. To complete a link, the network dataset must be compatible with a material, start node and end node. Network datasets can also be used to represent "subregions" by using multiple copies of the same network dataset on groups of nodes from the same entity. Nodes that are near each other, and have similar logistics, are grouped into subregions. Each subregion is only given access to one duplicate of the network dataset.

MASTRS does not have inputs that are directly used to specify the constraints for the MILP model. The structure delineated by the nodes is used to construct constraints. Initial constraints are constructed using information from just the nodes. Then a second stage of the model builder assigns information from the links to each constraint. The base constraints that MASTRS can build are shown in Table 3.4, the indexes, variables, and coefficients for those are shown in Tables 3.1, 3.2, and 3.3. The sign of some constraints may change to account for an overabundance of feedstock.

Table 3.1: MASTRS Variable & Coefficient Indexes

Variable & Coefficient Indexes				
i	Origin node of link		m	Network that connects nodes i & j
j	Destination node of link		n	Material being transported
k	Fixed cost node		q	Level of destination node
			r	Material combination

Table 3.2: MASTRS Variables

Variable	**Description**
x_{ijmnq}	The flow of material from node i, to node j, using network m, material n, and ending at level q
x_{iinq}	Material that is stored at node i during the (q-1) through q level.
y_k	Binary integer variable: 1 if activated, 0 if not activated

Table 3.3: MASTRS Coefficients

Coefficient	**Description**
cv_{ijmnq}	The unit cost to transport material from node i, to node j, using network m, material n, and ending at level q
cf_k	Fixed cost to operate node j
p_{in}	Amount of material n that enters the system boundary at node i
d_{jn}	Demand for material n that exits the system boundary at node i
Cap_{qj}	Total amount of material that can enter intermediate node j on level q
$conv_{jnr}$	Conversion rate from input to an output of material n at node j
min	Minimum use coefficient, one value is used for all integer facilities

Table 3.4: MASTRS Solver Equations

Objective Equation	**Description**
Minimize: $\sum_{ijmnq} cv_{ijmnq}\, x_{ijmnq} + \sum_k cf_k\, y_k$	MASTRS searches for the model solution that results in the minimum combined fixed and variable costs
Constraint	**Description**
1) For each entry node: $p_{in} \leq \sum_{in} x_{ijmnq}$	Production Constraint: The amount of material that exits a node must be equal to the amount of material that enters the node
2) For each destination node: $d_j = \sum_{jmn} x_{ijmnq}$	Demand Constraint, primary products: The Demand for the primary product will be exactly met. Refer to notes on "accumulate level" for background on difference between demand constraints
4) For each non-integer intermediate node: $Cap_{jq} \geq \sum_{jmn} x_{ijmnq}$	Capacity Constraint, non-integer: For level a facility functions on, the amount of material that enters the facility cannot exceed its capacity
5) For each level of each integer intermediate node: $0 \geq \sum_{kmn} x_{ikmnq} - Cap_{kq} y_k$	Capacity Constraint, integer: For level a facility functions on, the amount of material that enters the facility cannot exceed its capacity. Capacity can be controlled by an integer that makes it value 0 or 100% of the Cap value.
6) For each integer intermediate node: y variables are binary (0,1)	Integer Constraint: Only applied once per integer facility. An integer point node is used, or it is not.
7) For the final level of each integer node: $0 \leq \sum_{kmn} x_{ikmnq} - Cap_{kq} y_k\, min$	Minimum Use Constraint: Applied to the final level of an integer facility. A used integer node must input some minimum amount of its total capacity.
8) For each level of each intermediate node: $0 = -\sum_{im} x_{ijmnq} + \sum_{jm} x_{ijmnq} \frac{1}{conv_{jnr}} + \sum_{im} x_{iinq}$	Balance Constraint, primary products: The amount of material that enters a node must be proportional to the amount of material that exits it and the amount of material that stays at the facility for that level.

3.3 Optional Facilities:

Optional facilities are groups of entities whose capacities in model runs are regulated by integer variables. For MASTRS, integer variables are used as switches that allow all or none of a facility's capacity. If any capacity is allowed at a facility, then a fixed cost, that represents construction and equipment of the facility, will be added to the objective function. Optional facilities are computationally expensive to add to a model, as each new facility adds new facility combinations to the list of possibilities at a rate of 2^n, where n=number of optional facilities.

3.3.1 Oilseed Crushers:

Limited information is readily available about oilseed crusher siting in North America. To establish a basic understanding, a study of existing crushers was conducted. The study found 22 large-scale oilseed crushers in North America that process canola. The results of this study are summarized in Figure 3.1 and Table 3.5. Crusher characteristics vary depending on nearby production, age, and ownership, but some trends can be drawn from the study. Every crusher has access to a major rail line and nearby access to a highway. In North America's primary canola production zone, comprising much of Western Canada and North Dakota, crushers often process just canola. In other production zones, flexible processing becomes much more common. The solvent extraction process is much more common than just mechanical extraction, as 20 of the 22 crushers use a solvent process. The two mechanical crushers, including Pacific Coast Canola in Warden, WA, are below-average-size facilities that advertise specialized high-quality food-grade products [9].

Oilseed crusher locations are selected from an array of many potential sites across the PNW by finding facility combinations that produce the lowest total installation, operating, and transportation costs. The initial array of sites is developed using the methods and costs discussed below.

Table 3.5: Existing canola crushers in North America

Owner	City	State/ Province	Country	Integrated Processes	Capacity (metric tons/day)
Viterra	Warden	WA	US		1100
Viterra	Bécancour	ON	Canada	Soybean	3000
Viterra	St. Agathe	MB	Canada		1100
CHS	Kennedy	MN	US		1200
Louis Dreyfus-Mitsui	Yorkton	SK	Canada		2400
Richardson International	Yorkton	SK	Canada		3000
Richardson International	Lethbridge	AB	Canada	Refiner	2100
Cargill Limited	Clavet	SK	Canada	Refiner	4500
Cargill Limited	Camrose	AB	Canada		3600
Cargill Limited	West Fargo	ND	US	Sunflower	2000
Archer Daniels Midland	Enderlin	ND	US	Soybean, Sunflower	2500
Archer Daniels Midland	Windsor	ON	Canada	Flaxseed	2950
Archer Daniels Midland	Velva	ND	US	Biodiesel	1100
Archer Daniels Midland	Lloyminster	AB	Canada		2800
Archer Daniels Midland	Goodland	KS	US	Sunflower	?
Archer Daniels Midland	Red Wing	MN	US	Flax, Sunflower	1440
Archer Daniels Midland	Lubbock	TX	US	Cottonseed	?
Bunge	Altona	MB	Canada	Refiner	2500
Bunge	Russell	MB	Canada		1450
Bunge	Nipawin	SK	Canada		1500
Bunge	Ft Saskatchewan	AB	Canada		950
Bunge	Hamilton	ON	Canada	Refiner, Soybean	725

Potential oilseed crusher locations were developed using an infrastructure compatibility analysis. Based on operational needs established by technoeconomic analyses (TEAs) developed by Kristin Brandt [10] and trends identified while studying other oilseed crushers in North America, it was determined that a crusher must be in near proximity to a highway, railroad, and natural gas pipeline. Access to water and electricity may also be important, although these are assumed to be more universally available. The steps for the analysis are given in the list below and Figure 3.2 shows the resulting locations for the study:

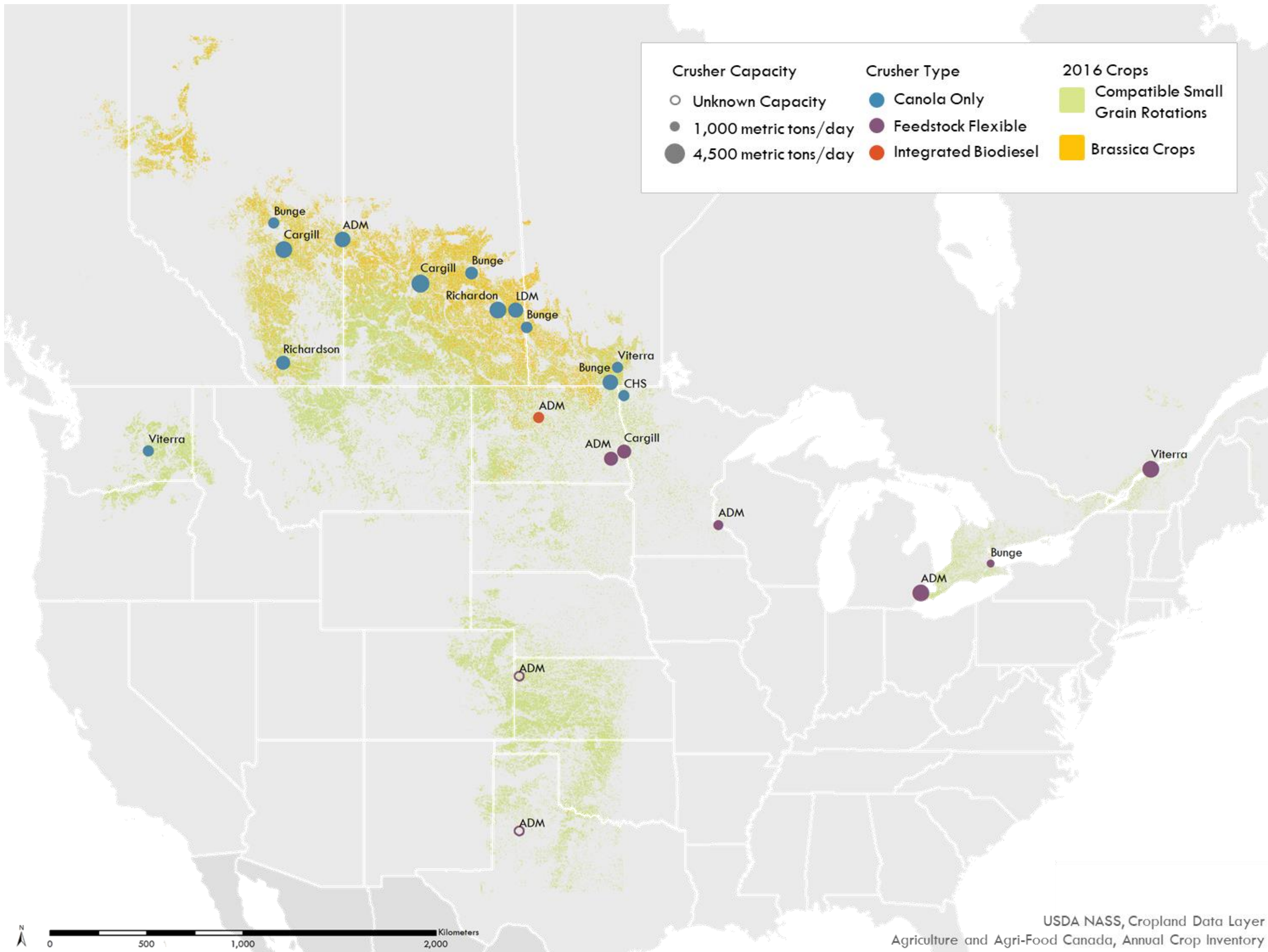

Figure 3.1: Existing canola crushers in North America

1. Using Esri ArcGIS, create buffers for infrastructure line files, including a one-mile buffer for highways, a one-mile buffer for railways, and a two-mile buffer for natural gas pipelines. The two-mile buffer was used for natural gas due to the relative imprecision of the EIA natural gas layer.
2. Convert each buffer file to a raster
3. Use map algebra to add all three rasters together, find areas that overlap.

   Inspect areas of intersection for general feasibility (for instance, all infrastructure should be on one side of a river), place new points at locations determined to be the most feasible. In most cases, the best locations are considered those where each of the three lines files are closest together.

Two oilseed crusher configurations are considered at each location: a mechanical oilseed crusher and a solvent oilseed crusher. Capital and operating expenditures are based on the TEAs by Kristin Brandt. Capital expenditures include equipment costs, installation costs, and working capital. These expenditures are converted to an annual equivalent cost, assuming a facility lifespan of ten years, and are used as integer costs for the OtSAJF supply chain model in section 3.4. This means that if any material is allowed to pass through the facility, the entire capital expenditure for the chosen configuration at the facility must be added to the total costs. Oilseed crusher operating costs are assigned on a per-ton basis for labor, electricity, natural gas, water, and hexane. Costs for labor, water, and hexane are not considered location specific for this model and are applied equally at each facility. Costs for natural gas and electricity are location specific, based on utility data developed by Natalie Martinkus [11].

Table 3.6: Model Inputs from Oilseed Crusher TEAs

Type	Daily Capacity (ton/day)	Fixed Cost ($/yr)	Electricity (kWh/ton)	Natural Gas (MMbtu/ton)	Other OPEX ($/ton)
Chemical	1,360	31,900,000	138.7	0.2058	5.784
Mechanical	910	35,950,000	99.07	0.2087	11.18

3.3.2 HEFA Refineries:

HEFA refineries currently operate on three continents. The world's largest producer, Neste, operates two refineries in Finland, one in the Netherlands, and one in Singapore [12, 13, 14]. Neste has worked with several airports and distributors to begin making regular deliveries of SAJF to several airports in Europe [15]. Eni was the first company to convert an existing petroleum refinery to a HEFA refinery, when the conversion of their aging Porto Marghera (Venice) refinery was completed in 2013 [13, 16]. The United States has three commercial-scale HEFA refineries. The two largest facilities are located near the Gulf Coast. Diamond Green Diesel, in Norco, LA, is a 445,000 metric ton per year joint venture between Valero Energy and Darling Ingredients. Valero, whose St. Charles refinery is directly adjacent, operates the facility [12, 17, 13, 18]. REG Geismar is located 80 kilometers Northwest, in Geismar, LA. The 244,000 metric ton per year refinery, originally named Dynamic Fuels, was acquired by REG in 2014 [17, 13, 19]. AltAir Fuels, in Paramount, CA, operates a 120,000 metric ton per year refinery focused on the production of SAJF. AltAir became the first HEFA producer make regular deliveries of SAJF in the US in March of 2016 [20]. Every existing HEFA refinery is either a converted petroleum refinery or operates near a petroleum refinery. Although this trend may not persist, as interest has been expressed in other areas [21, 22], it has defined early siting for HEFA refineries.

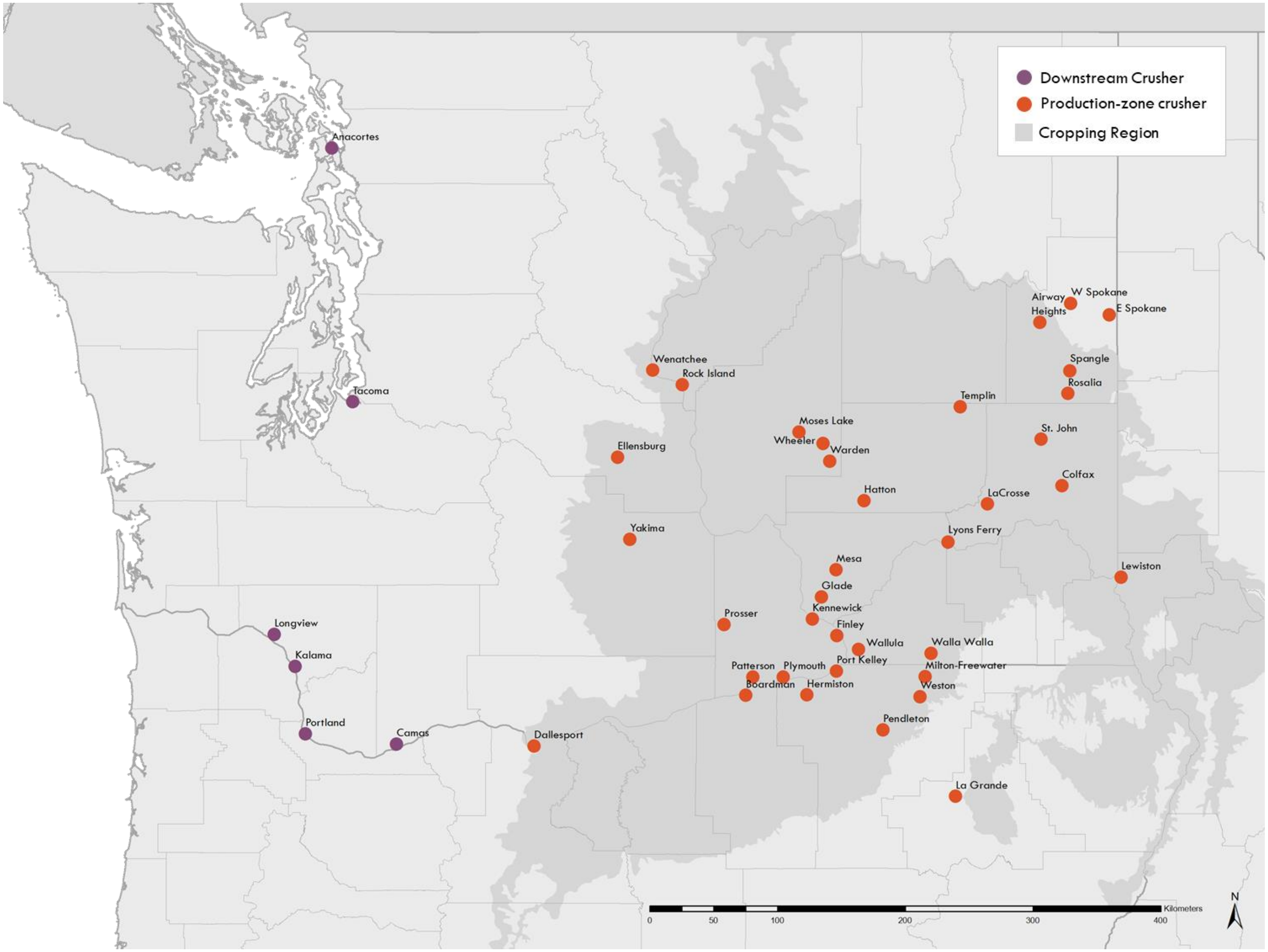

Figure 3.2: Potential Oilseed Crusher Locations in the PNW

Hydrogen is an important input to the HEFA process [17, 23], although hydrogen for processing cannot typically be purchased at industrial quantities. For most industrial uses, hydrogen is produced on, or near site. Currently, 95% of hydrogen in the United States is produced using steam-methane reformation (SMR) [24]. Many petroleum refineries already use the SMR process to produce hydrogen on site or have hydrogen contracts with nearby companies [25]. In addition to SMR equipment, equipment used for the HEFA process is often similar or the same as equipment used at petroleum refineries [17, 13, 26, 23, 16, 27]. Deoxygenation units used for HEFA refining can be converted from desulfurization units that had previously been used for petroleum refining [16]. HEFA refineries and petroleum refineries also use the same equipment for hydrocracking and fractionation. This process compatibility has resulted in significant capital savings of petroleum-to-HEFA facility conversions. Eni S.p.A. has stated that converting its existing petroleum refinery near Venice resulted in significant cost savings versus using a greenfield site [16].

The PNW has refining and pipeline capacity to produce and move the fuel required to sustain the region. Although Idaho and Oregon do not have any refining capacity, Washington has five petroleum refineries with a total refining capacity of 23.3 million metric tons per year [28]. Most production is clustered among four refineries within 100 kilometers of each other in Northwest Washington. The remaining Washington refinery is located to the south in Tacoma, WA.

For the MASTRS optimization model runs, the locations of HEFA refineries are not optimized. This is due to the complicated nature of siting HEFA refineries, as capital costs vary significantly based on existing equipment at each site and contracts for fuel purchases are not made using traditional economics as SAJF fuel is not cost-competitive with petroleum-based jet fuel. For the MASTRS optimization model, three locations will be considered for a HEFA refinery. A map of the locations is given in Figure 3.3. Two of these locations are near existing petroleum refineries in Tacoma, WA and Anacortes, WA. A third location is placed at an existing biodiesel plant in Hoquiam, WA. REG, the owner of the biodiesel plant, has expressed interest in the location for future hydrocarbon expansion [21]. The refinery design used for supply chain model runs calls for approximately 235,000 metric tons of feedstock annually. Total annual hydrocarbon production is be approximately 210,000 metric tons per year, with SAJF production of 125,000 metric tons per year.

Figure 3.3: Potential HEFA Refinery Locations in the PNW

3.4 The Wheat Supply Chain Assessment:

Information about existing costs required for MASTRS model runs of the PNW OtSAJF supply chain is not readily available from a single source. To construct a model run, a number of sources are brought together, each with a different supplier and date of release. In addition, MASTRS is an untested model builder and solver. To relieve some of the uncertainty that exists with the inputs for the OtSAJF MASTRS model runs and model builder, an analysis of the existing PNW wheat supply chain was used to test and then improve the supply chain function. There are two objectives to the wheat supply chain model:

- Confirm that the components of MASTRS function properly with a large model. Several model functions require practice implementation, such as the loop code blocks in the model builder that interpret the levels system, the route compatibility loop that determines when links are constructed, and the subregion technique.
- Evaluate overall transportation costs and the relative costs of different modes of transportation. This evaluation of costs is conducted by comparing the MASTRS model run to the known performance of the wheat supply chain.

3.4.1 Methods and Setup:

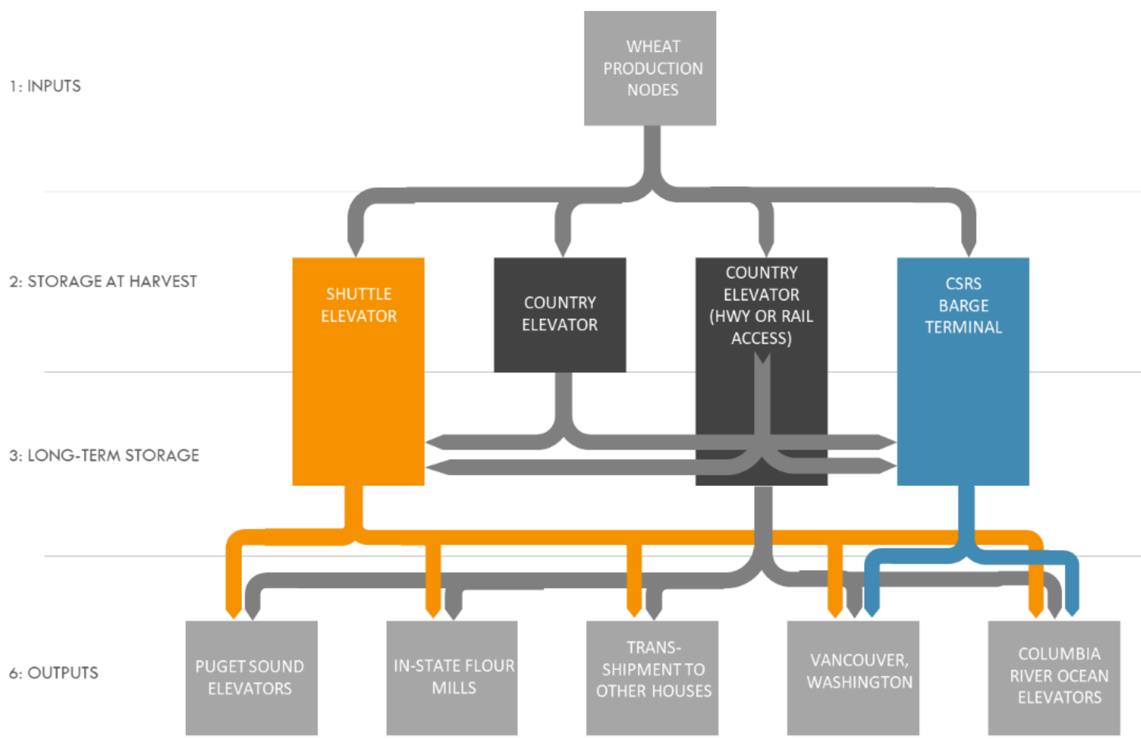

Figure 3.4: MASTRS wheat supply chain model

Washington’s wheat supply chain is a complex system comprised of production units, multiple levels of storage, and multiple modes of transportation. Compared to the overall production, little demand for wheat exists in Southeast Washington, where most of the production occurs. The majority of wheat produced in Washington is exported out of the state using a multimodal transportation system that includes truck, rail, and barge. Because wheat is a seasonal crop with continuous demand throughout the year, an equally complex storage system of on-farm bins, country elevators, barge terminals, and shuttle elevators is used to hold wheat for various lengths of time throughout the year.

Nadreau and Fortenberry provided a detailed description of the industries associated with the Washington wheat supply chain during 2014 [29]. The report details the entire wheat industry with more information than is available for other recent years. It includes data collected from a survey of supply chain participants about the relative usage of various modes of transportation and the total costs associated with transportation and handling. As a way to corroborate the quality of cost inputs of the oilseed-to-jet-fuel supply chain model, a MASTRS wheat supply chain model run that represents the same 2014 industry conditions is compared to the survey results that were included in the report by Nadreau and Fortenberry. Information and methods used to develop transportation costs in Appendix A.

3.4.2 Entities:

The MASTRS model, shown in Figure 4, is organized into four levels: initial production, primary storage following harvest, transfer to a transshipment facility and long-term storage, and final market. Delivery to market occurs at one time-step, instead of continuously throughout the year, so the MASTRS model builder allows unlimited storage and transshipment capacity during the third level to represent the total amount of material that could flow in and out of the facility. A brief summary of the input nodes is given level by level in the following sections.

3.4.2.1 Level 1, Production Points:

Wheat production is added to the model on the first level. Wheat production would be impractical to calculate at the field level, so production is approximated by nodes arranged as a 4x4-km grid. All production is added to the model on the first level. Each production point was given access to one network dataset, based on the subregion the point fell within. The implementation of subregions and subregion network datasets is described in section 3.3.3. The steps used to calculate wheat production at each point are described below:

1. Simplify the 2007-2016 dynamic agroecological classes layer into the three basic dryland cropping classes: annual crop, grain fallow, and annual crop-grain fallow transition [31].
2. Create a 4x4-km grid using the projected UTM 11N coordinate system.
3. Use zonal statistics tools to calculate the acreage of each agroecological class that falls within each grid cell. Calculate total wheat acreage from each AEC using rotation assumptions. For the annual crop and transition classes, wheat is typically grown 2 out of every 3 years, so total acreage is multiplied by 2/3. For the grain fallow class, wheat is assumed to be grown every other year, so half of the total grain fallow acreage is used to produce wheat [31, 32].
4. Calculate average wheat yields for each county using USDA statistics and the equation 3.1, shown below.

$$y_{avg} = \frac{y_{ww}A_{ww} + y_{sw}A_{sw}}{A_{ww} + A_{sw}} \quad (3.1)$$

y_{avg} **Average wheat yield**
y_{ww} Winter wheat yield
y_{sw} Spring wheat yield
A_{ww} Winter wheat acreage
A_{sw} Spring wheat acreage

4. Calculate annual production for each cell by multiplying total wheat acreage by the average wheat yield of the county the cell falls in.

3.4.2.2 Levels 2-3, Storage:

Table 3.7: Demand nodes information [29]

Destination	% of Wheat (N&F)	Adjusted% (for MASTRS)	Quantity of Wheat (metric tons)
Columbia River Ocean Elevators	72.4	75.4	2,176,000
Puget Sound Elevators	4.0	4.2	120,000
Out-of-State Transshipment	12.4	12.9	372,000
In-State Flour Mills	4.0	4.2	120,000
Vancouver, WA	3.2	3.3	96,000
Other	4.0	0	0
Total	96	100	2,884,000

Levels two and three are grain storage layers. Level two represents storage immediately following harvest. Level three represents storage throughout the year. For level three, instantaneous storage capacity is ignored, as not all material transferred through a facility during level three is simultaneously in the facility. For the MASTRS model run, many storage nodes can operate on both levels, meaning that material can remain at one storage facility for both levels. Country elevators, or non-terminal commercial elevators, are often the first location wheat, and other grains and oilseeds, are transported to following harvest. For the MASTRS model run, country elevators are separated into two entities, based on their proximity to highway and railway networks. Elevators that are not within one mile of a highway or railway are only allowed to operate on level two of the model, meaning that the grain must be subsequently transported to a terminal facility before final market. All other country elevators operate on levels two and three, meaning they can send grain to a terminal elevator or send grain to a market using short line rail or highway transportation.

Shuttle elevators and barge terminals have immediate capacity at harvest and may also receive grain throughout the year. For the MASTRS model run, all terminal elevator facilities operate on levels two and three. Shuttle elevators are high-capacity rail terminals that can intake over 100 rail cars at once and deliver grain across the PNW and greater US. Barge terminals, located all along the Lower Snake River and Mid-Columbia River, offer low-cost transportation to ports along the Lower Columbia River.

3.4.2.3 Level 4, Markets and Destinations:

Level four represents markets and destinations for wheat. The demand at these nodes, shown in Table 3.7, are adjusted values from Nadreau and Fortenberry. Each different demand entity has access to different modes of transportation.

3.4.3 Subregions for the Washington Wheat Supply Chain:

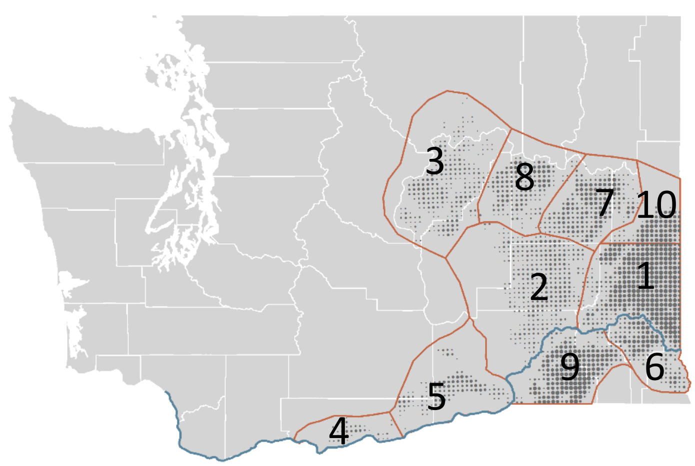

Figure 3.5: Wheat Supply Chain Subregions

For the MASTRS model run, subregions, shown below in Figure 3.8, were developed using two criteria. First, subregions were broken into areas based on agricultural production. Splits were placed between areas that do not employ large amounts of dryland cropping. In eastern Washington, an absence of dryland cropping can typically be identified by the presence of channeled scablands or coulees, and irrigated agriculture. Splits were also placed along major transportation routes that have large amounts of storage capacity and that are likely to be widely used to transport grain during subsequent stages. The most natural case of a transportation split is the Snake River. Another split is used in northern Washington along a BNSF rail line. Each production node within a subregion was allowed access to one network dataset for that subregion. Each second-level storage facility was given access to the network datasets of the subregions whose borders were within 24 kilometers (Euclidean distance) of the storage facility's location. The use of the 10 subregions shown below, in Figure 3.5, reduced the number links between levels one and two from 361,620 to 86,268, a 76% reduction.

3.4.4 Comparison of Results of Wheat Supply Chain Results:

Table 3.8: Comparison of Total Wheat Supply Chain Costs

	N&F Cost	MASTRS Cost	N&F/MASTRS
Total Transportation	40,690,000	55,796,039	72.9%
Total Handling	6,560,000	7,759,511	84.5%
Total Cost	47,250,000	63,555,549	74.3%

As shown by Table 3.8, the MASTRS model run had approximately 25% higher transportation costs than the FPTI study. Table 3.9 shows the modes of transportation used to bring wheat to the final markets or processors. The use of the various modes of transportation is similar, particularly with the use of barge transportation. The use of rail transportation to final market is higher with the MASTRS model, but this may be a product of always assuming bulk shipments, despite specialty varieties with smaller markets being a component of the Washington Wheat Market.

The most significant source of higher costs is likely more expensive transportation costs, as information for MASTRS costs comes from mid-2016 to early 2018 as opposed to the 2014 costs used Nadreau and Fortenberry. Another potential source of inflated costs is the modeling of post-harvest storage capacity. Additional figures for the wheat supply chain assessment results can be found in Diagrams 1 and 2 and Map 1 of Appendix B.

Table 3.9: Modes of Transportation Used to Deliver Wheat to Market for Each Study

Transportation Mode	N&F	MASTRS
Truck	17.4%	11.9%
Total Rail	22.4%	29.9%
Unit Rail	22.4%	4.9%
Shuttle Rail	0.0%	25.0%
Barge	59.9%	58.2%
Other	0.3%	0.0%
Total	100.0%	100.0%

3.4.5 Wheat Supply Chain Conclusion:

The model developed for the wheat supply demonstrates that the actual wheat supply chain functions reasonably well, as the modelled amount of material delivered to market by each mode of transportation is appropriate and consistent with the Nadreau and Fortenberry study. Although costs for the MASTRS model are higher than those reported by Nadreau and Fortenberry, they are proportionally consistent, suggesting that transportation costs have increased between the time the original stakeholder survey was conducted and the costs that from 2017 and 2018 used as inputs for MASTRS.

The methods used to produce costs and links for this model will also be used for the OtSAJF supply chain model. The costs for the initial portions of the oilseed and wheat supply chains are very similar, as the two supply chains run parallel, each using the same production zone, storage, and modes of transportation. The wheat supply chain model has provided an opportunity implement MASTRS on a large supply chain with known incoming and outgoing materials. Doing this has allowed a test of many of MASTRS tools, as well as an opportunity to parameterize and corroborate the cost inputs into MASTRS.

3.5 OtSAJF Supply Chain Model:

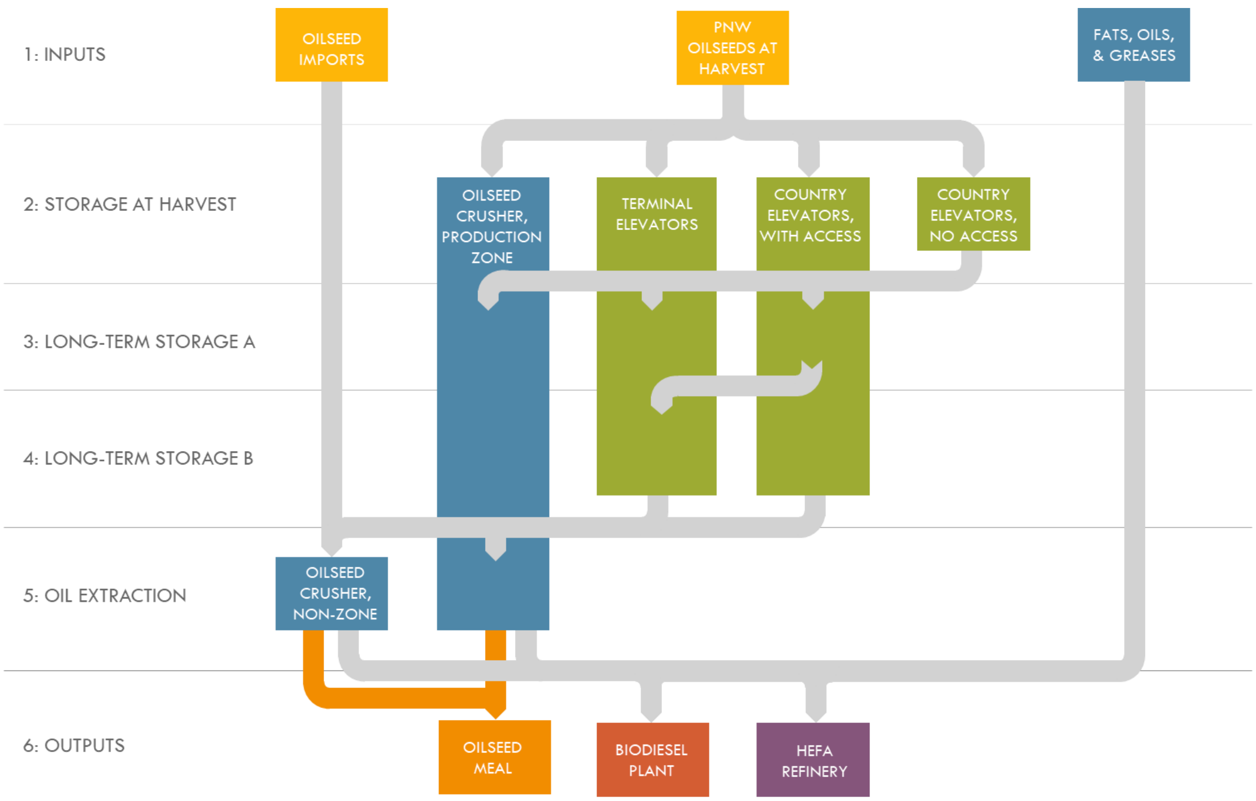

Figure 3.6: OtSAJF Supply Chain Structure

The OtSAJF supply chain is a complex sequence of transactions between entities including multiple stages of transshipment between storage, preprocessing, conversion to fuel, and delivery to market. This section describes how OtSAJF supply chain can be organized into a MILP and then optimized using MASTRS. As shown in Figure 3.6, the model uses six levels of entities, beginning with oilseed production at harvest and ending with lipid feedstock delivery to a HEFA refinery. The conclusion at a HEFA refinery, instead of at a fuel market, is due to the non-optimized decision-making process that often affects refinery siting and market development. Methods and information used to develop transportation costs between levels is given in Appendix A.

Each supply chain model run represents a period of one year to represent one season of oilseed harvest and use. Levels one and two represent the oilseed harvest period, during the late summer and early fall. All subsequent levels represent any time throughout the year, including during harvest.

The MASTRS models for the OtSAJF supply chain scenarios are demand-controlled, meaning that the objective function of the model will always represent the lowest total model cost that can meet all demand. To ensure demand can always be met, a larger amount of feedstock than is required by demand is made available. Feedstock is always sourced from within the PNW region first, but if this feedstock is insufficient, an unlimited pool of oilseed feedstock from outside the region is tapped to meet remaining demand.

For each scenario, new capacity for oilseed crushers and HEFA refineries is required. Oilseed crusher locations are determined by the model solver for each scenario. HEFA refinery locations are controlled on a scenario-by-scenario basis.

3.5.1 OtSAJF Supply Chain Entities:

3.5.1.1 Level 1, Material Inputs:

Level one is used to represent all feedstock inputs into the model. Three entities of feedstocks are used in the oilseeds-to-alternative-jet-fuel supply chain model. The primary feedstock is oilseeds produced in the PNW. These oilseeds are added to the model using locations and quantities from the production grid discussed in Section 2.2. Following harvest, when the oilseeds are added to the model, oilseeds are delivered to the first stage of storage using grain trucks. FOGs are another feedstock produced from within the PNW. The locations and quantities of these feedstocks can be found in section 2.3. Unlike oilseed feedstocks, FOGs do not require pre-processing at another facility, such as an oilseed crusher, before delivery to a biofuels producer, so FOGs are added directly to the conversion stage of the model using a rendering truck.

Imported oilseeds are sourced from outside of the PNW system boundary and may include canola produced in the US Midwest or Western Canada. Imported oilseeds are designed to be the last feedstock used by the model, all FOGs and PNW oilseeds must be used to produce fuel before any imported oilseeds are used. Because the MASTRS model scenarios are constructed so that the amount of fuel produced exactly matches demand, the amount of imports added to the model exactly matches the amount needed to reach fuel demand. Imported oilseeds are sent directly to an oilseed crusher using unit rail from one location.

3.5.1.2 Levels 2-4, Storage:

Oilseed storage is modelled using three levels. The first level of storage, level two, represents instantaneous storage immediately following harvest. The amount of material that enters a storage facility during level two is constrained by the facility's capacity. Levels three and four represent long-term storage. Unlike level two, levels three and four do not represent instantaneous storage, but represent transfers in and out of these facilities over an entire year. Instantaneous storage capacity is not considered for these levels.

Oilseed crusher locations that are in or near the oilseed production zone have storage capacity when the facility is selected by the model. Storage capacity during harvest at crushers is set as one month of the facility's annual production capacity.

Country elevators and terminal elevators are traditionally used for grain storage. The organization of these entities for this supply chain is similar to the organization used for the wheat supply chain previously solved using MASTRS in section 3.3. Country elevators are broken into two groups, based on their proximity to transportation. Country elevators that do not have access to rail or highway transportation only function on level two. On levels after level two, these facilities must transfer grain to either a country elevator that is within fifteen miles of its subregion, or to any terminal elevator or active oilseed crusher location. This transfer occurs using truck transportation. Other country elevators and terminal elevators can operate on levels two, three, and four. Country elevators can transport material to a terminal elevator, to access more cost-effective modes of transportation, but terminal elevators can only transport material to oilseed crushers. Transportation leaving these facilities depends on available transportation at the elevator and destination but may include truck and unit rail from country elevators and shuttle rail, and barge from terminal elevators.

3.5.1.3 Level 5, Oil Extraction:

Oil is extracted from oilseeds at oilseed crushers on level five. Two groups of oilseed crushers are used for this model. The first type of crusher, which has already been introduced for their storage capacity, is the production-zone crusher. These crushers can receive oilseeds at harvest, as well as throughout the rest of the year. Non-production zone crushing facilities do not receive oilseeds at harvest, and do not have an instantaneous storage consideration, so they only operate on level five. No other differences exist between the two oilseed crusher entities. Each has two optional facility settings, as a mechanical crusher or a chemical crusher.

3.5.1.4 Level 6, Material Outputs:

Level six is used to represent all material outputs from the model. Two types of material are included as outputs: lipid biofuel feedstock, including canola oil and FOGs, and oilseed meal. Lipid feedstocks are delivered to a HEFA refinery, the location changes by scenario, and an existing biodiesel plant in Hoquiam, WA. Oilseed meal is delivered to major dairy production hubs throughout the PNW, where it is used as a feed supplement.

3.5.2 OtSAJF Supply Chain Subregions:

The OtSAJF supply chain uses the thirteen subregions shown in Figure 3.7. Subregions are applied on two entities in the supply chain. All production points must be transported to a location within their subregion. This represents the limited distance farmers or oilseed transporters travel at harvest. Subregions are also used between country elevators without access and country elevators with access. In this case, subregions are used to reduce the complexity of network analysis route calculations.

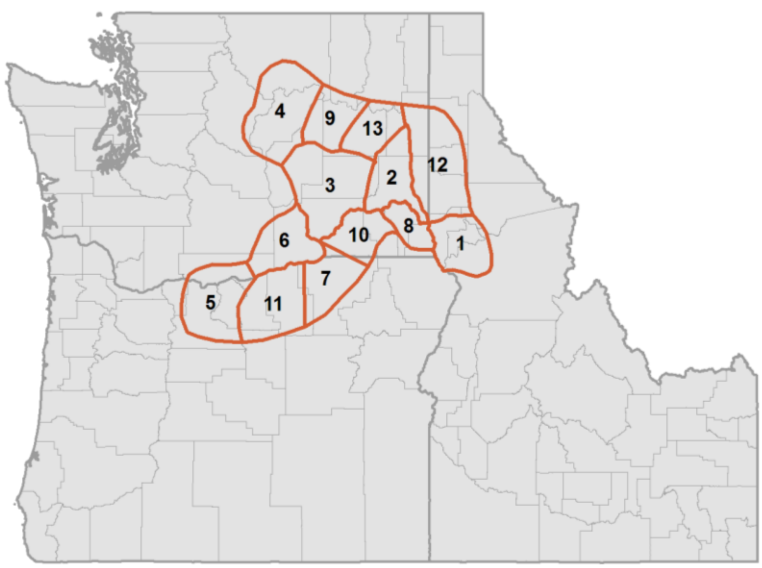

Figure 3.7: Subregions used for the OtSAJF supply chain model

3.5.3 Model Scenarios:

Six OtSAJF supply chain scenarios were constructed and solved with MASTRS. The scenarios, described in Table 3.10 below, include all permutations of two production combinations and three demand combinations.

Table 3.10: OtSAJF Supply Chain Scenarios

	Scenario Name	Production Combination	Market Combination
1	Anacortes100	Maximum Oilseeds, FOGs	Anacortes HEFA, Hoquiam biodiesel
2	Anacortes50	50% of Maximum Oilseeds, FOGs	Anacortes HEFA, Hoquiam biodiesel
3	Tacoma100	Maximum Oilseeds, FOGs	Tacoma HEFA, Hoquiam biodiesel
4	Tacoma50	50% of Maximum Oilseeds, FOGs	Tacoma HEFA, Hoquiam biodiesel
5	Hoquiam100	Maximum Oilseeds, FOGs	Hoquiam HEFA (or biodiesel)
6	Hoquiam50	50% of Maximum Oilseeds, FOGs	Hoquiam HEFA (or biodiesel)

3.5.4 OtSAJF Supply Chain Results:

Table 3.11: Metric Tons Processed at Oilseed Crusher Selections

	Anacortes		**Tacoma**		**Hoquiam**	
	100% production	**50% production**	**100% production**	**50% production**	**100% production**	**50% production**
Lewiston, ID					154,520	
Colfax, WA	190,042	188,006	190,042	187,955		158,859
Plymouth, WA		190,042		190,042	133,030	
Rock Island, WA	187,955		187,955		133,030	174,746
Wallula, WA	190,042		190,042			
Wenatchee, WA		190,042		190,042		
FOGs Use	108,727	108,676	108,727	108,727	21,225	106,461
Total Feedstock	676,767	676,767	676,767	676,767	441,804	440,066

Each MASTRS model run selected several locations for new oilseed crushers. The locations of these selections and operations at these locations are useful indicators for overall function of each supply chain. A brief summary of the oilseed crusher locations is given in the Table 3.11. A complete summary of crusher locations is given in Appendix B. Appendix B also contains complete maps showing all steps for each supply chain scenario.

For five of the scenarios, three oilseed crusher locations were chosen. One scenario, Hoquiam50, selected two oilseed crushers. Regardless of the model run, similar locations were chosen. For each model run that used three crushers, one crusher was selected in the Palouse region of Southeast Washington and Northern Idaho, one crusher was selected in the Mid-Columbia region, and one crusher was selected in Central Washington. The Hoquiam50 model run selected locations on the Palouse and Central Washington. For the model runs produced for this study, locations are explained as a balance between inbound and outbound logistics, processing costs, and feedstock availability.

Table 3.12: Modes of transportation used to transport feedstock to oilseed crushers and plant oil and meal from crushers (metric tons)

	Anacortes		Tacoma		Hoquiam	
	100% Oilseeds	50% Oilseeds	100% Oilseeds	50% Oilseeds	100% Oilseeds	50% Oilseeds
Oilseeds to Crushers						
Truck	1,336,000	749,000	1,336,000	749,000	1,063,000	751,000
Shortline Unit Rail	155,000	2,000	155,000	2,000	41,000	0
Imports by Rail	0	740,000	0	740,000	0	125,000
Oil from Crushers						
Truck	0	209,000	208,000	209,000	0	0
Unit Rail	626,000	417,000	418,000	417,000	463,000	368,000
Meal from Crushers						
Truck	300,000	357,000	300,000	567,000	363,000	263,000
Unit Rail	564,000	507,000	564,000	507,000	276,000	245,000

The model runs selected to use three modes of transportation. Unit trains (including special case shortline railways) and trucks were used for regional transportation and shuttle rail was used for oilseed imports. In most cases, oilseeds harvested in the region were delivered a short distance to crushers by truck, although special-case shortline railways served an important role in the maximum production scenarios for delivering oilseeds to the Wallula, WA location. As shown in Table 3.12, oil and meal leaving crushers were delivered by both truck and rail, depending on the relative location of markets and crushers. Assuming each mode of transportation uses the same route and that trucks have an average road speed of 55 kilometers-per-hour, the MASTRS transportation costs for unit rail are more cost effective for oilseeds and meal at distances greater than 360 miles and more cost effective for oil at distances greater than 631 kilometers. When considering transportation across the Cascade Mountain Range, several restrictions are placed on rail lines, as only the BNSF mainline through the Columbia Gorge is widely used for loaded unit and shuttle trains [36], especially effecting shipments to NW Washington. Shuttle trains and barges were not used to transport oilseeds to crushers across the Cascade Mountain Range, as the lower transportation costs from these modes did not offset increased crushing costs and increased transportation costs for oilseed meal. Per ton chemical crushing cost estimates at Tacoma and Anacortes locations are $14.73 and $19.10, while the average cost for sites used by the model is $13.40 per ton.

For Tacoma50 and Anacortes50 model runs, crushers in the Mid-Columbia and in Central Washington regions were located further west than in runs with maximum oilseed availability. There are two causes for this westward shift. First, these locations leverage the low-cost shuttle rail trains that deliver oilseeds to the crushers, versus the higher cost trucks or unit trains used to transport products from the crushers. The shift west also allows the Colfax location to accept oilseeds from a larger region at harvest, as it receives approximately 27,000 tons of imported oilseeds from imports, while the other locations each receive between 225,000 and 410,000 tons of imports. As shown in Figure 3.8, The westward shift is not large, as there are less than ten miles between the Rock Island and Wenatchee locations in Central Washington and less than thirty miles between the Wallula and Plymouth locations in the Mid-Columbia. Several significant impacts can be observed on the overall supply chain performance. For the maximum production oilseed runs, the PV Hooper and BLMR shortline railways are used to transport 136,000 tons of oilseeds from the Palouse to the Wallula location. With just 1,800 tons transported on the BLMR, the shortline railways are effectively unused for the 50% production scenarios, as the oilseeds that had supplied Wallula by rail in the maximum production scenarios are largely trucked to Colfax. Figure 3.8 displays that the small shift from Rock Island in the Anacortes100 to Wenatchee in the Anacortes50 scenario results in the use of truck transportation to the HEFA refinery instead of unit rail.

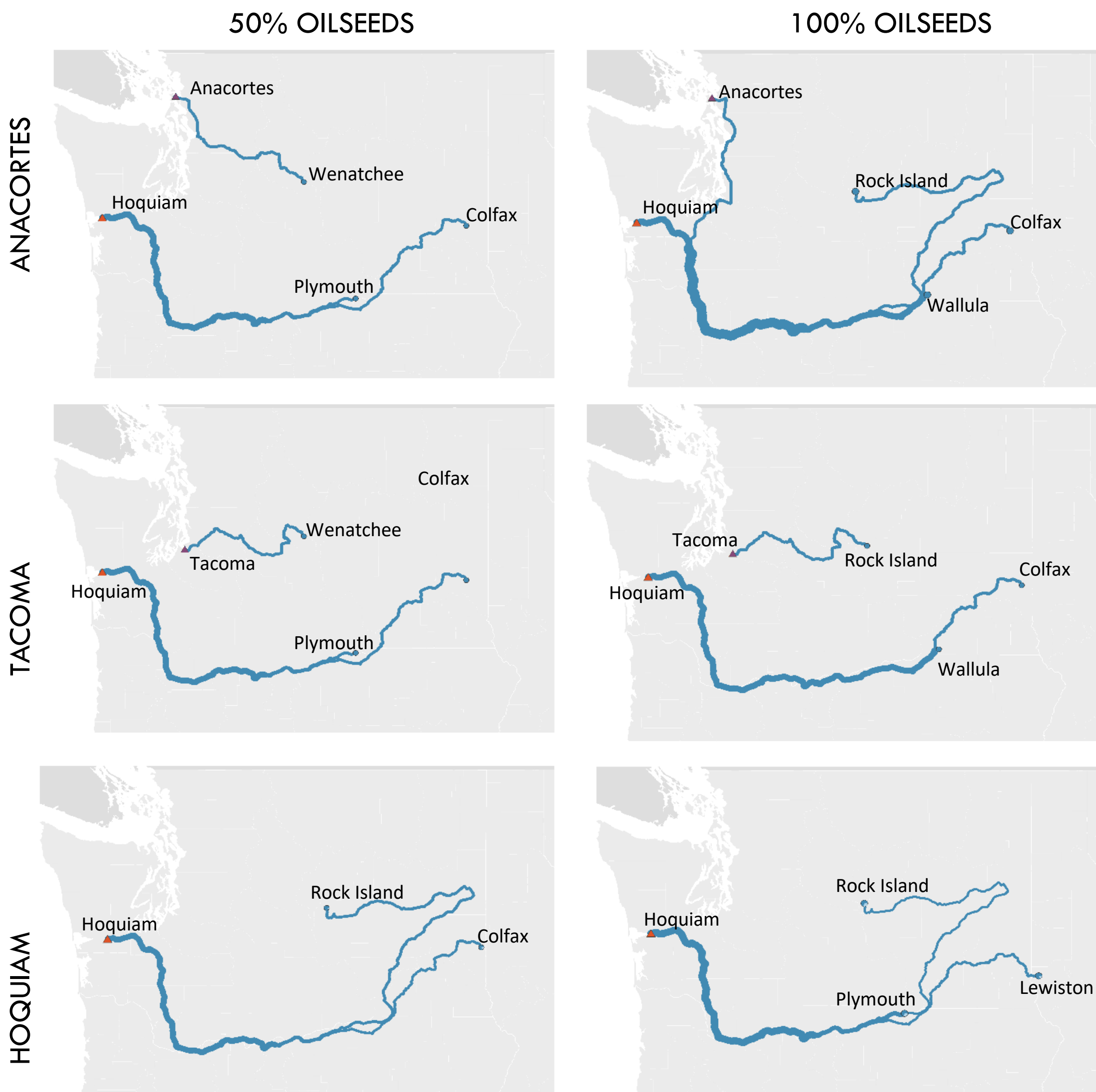

Figure 3.8: Transportation links for plant oil from oilseed crushers to markets for each scenario. Links are shown by blue lines, crushers by blue circles, biodiesel plants by red triangles and HEFA refineries by purple triangles.

3.6 Summary and Conclusions:

The OtSAJF supply chain analysis included several components. The chapter began with an overview of MASTRS, the mixed-integer linear programming model builder and solver used to solve complex supply chain problems. Potential locations for oilseed crushers and HEFA refineries were found using siting criteria consistent with existing facilities. An analysis of the existing PNW wheat supply was used to confirm that assumptions about storage and transportation could accurately portray the flow of agricultural products across the region. The chapter finished with an analysis of several OtSAJF model runs that represented several potential scenarios in the region.

The overall viability of the OtSAJF supply chain is not determined by the models solved for this study. The solver simply finds the most efficient way to operate within the system boundaries of the given model. The links and stages enabled to transport material within these boundaries are sufficient to describe the systems studied during this chapter, although the costs and functions determined by these model runs are incomplete. The model does not determine if the system proposed can make money for the stakeholders, or if the communities and companies linked together by the supply chain are compatible.

No new mechanical oilseed crushers were chosen for the model runs. Without any benefits in the model to represent more desirable products from mechanical crushers, the greater capital and operating costs are not competitive with the chemical crushers.

For five of the six model runs, three oilseed crushers were selected, suggesting that significant infrastructure is required before the supply chain is feasible. The locations of the selected oilseed crushers were varied, and do not suggest that locations for similar scenarios could be selected using non-optimized siting criteria. Each of the three areas that crushers were selected showed different strengths, whether that be oilseed feedstock availability, processing costs, or inexpensive access to downstream markets.

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CHAPTER FOUR: SUMMARY AND CONCLUSIONS

4.1 Summary:

The objectives provided during the introduction for this study were to: 1) create analytical methods to spatially and quantitatively estimate current and future potential production of used cooking oil, animal fats, and vegetable oil lipid feedstocks, and 2) determine the optimal siting of facilities and utilization of feedstocks that lead to the production of HEFA fuel. As discussed in the following paragraphs, these objectives were met with varying levels of success.

In chapter two, methods to locate and quantify each feedstock were developed and then implemented. The chapter is broken into two sections, one focused on oilseed feedstocks, and the other focused on FOGs. The section focused on oilseeds used knowledge about existing cropland, oilseed compatibility studies, spring oilseed yield estimates from CropSyst model runs, and winter oilseed yield estimates from a yield-precipitation relationship to develop a dataset that describes potential oilseed production. The section focused on FOGs develops a similar dataset that described current production using data about urban populations and animal slaughter with production factors.

Due to little available data, it is challenging to verify whether the results for these trials are valid, but the methods used are consistent with other similar, and presumably successful, studies. One area that will require future improvement concerns the implementation of oilseeds in crop sequences. The study proposes two oilseed production scenarios including the maximum production scenario and the flat-rate 50% production scenario. The study does not explore methods to determine how variations in climate and competition with other crops could lead to disproportionate adoption of oilseeds in certain areas.

In chapter three, optimization is used to determine the most efficient way to construct and operate a supply chain to produce alternative jet fuel from oilseeds and FOGs. MASTRS, a mixed-integer linear programming model builder and solver, is introduced as a tool to analyze complex supply chains. Two series of locations compatible with oilseed crushers and HEFA refineries are compiled and prepared for MASTRS model runs. A test of the MASTRS model is performed on the existing PNW wheat supply chain. Optimization results for the OtSAJF supply chain were produced in the final section of the chapter.

Evaluating the success of the second objective is more difficult. MASTRS is able to model multi-material, multi-level, and multi-mode performance successfully in optimized systems. This was demonstrated with the wheat supply chain experiment in section 3.3. Unlike the stated objective, the model did not include the entire oilseed-to-alternative-jet-fuel supply chain, as optimization was concluded at a HEFA refinery instead of a market. This decision was supported with practical reasoning that was not apparent at the beginning of the study. It was determined that it would be impractical to model HEFA refinery selections without a better understanding of existing equipment and availability of resources from nearby facilities. The model runs also use just two configurations for oilseed crushers, although it may be more useful to model several similar configurations. In short, the amount of data required to implement a complex supply chain analysis is immense. Although much of this data has been collected, and used in the model runs provided in this study, additional data and model runs could greatly improve similar model runs in the future.

4.2 Conclusions:

The role of oilseeds in the PNW's cropping system has been limited, despite interest from farmers and research from universities like Washington State University and the University of

Idaho. Ultimately, farmers make decisions based on money, and they will always plant the crops that will provide the highest return. Oilseeds have not yet provided the necessary returns for most farmers in the region. When markets have provided opportunities to make money with new crops, farmers from the PNW have added new crops like lentils and later garbanzo beans to their sequences [1]. Developing a sustainable regional market, through the construction of a HEFA refinery, may be a key step in developing new markets. The scale of adoption suggested for the maximum production scenario, in section 2.3, is immense. Farmers would need to increase acreage from approximately 40,000 hectares per year to nearly 725,000 hectares per year. Nearly thirty percent of the dryland cropping region would be planted with oilseeds each year.

In 2012, SEATAC's total fuel consumption was over 1.6 billion liters. Between 2002 and 2012, annual fuel consumption increased at a compound annual growth rate of 0.3% [2]. Using the 2012 value as a baseline and the growth rate from 2003 to 2012, it is reasonable to assume that by 2028, when SEATAC has pledged to use 10% renewable aviation fuel, that approximately 170 million liters of alternative jet fuel will be required to meet the port's goal. The refinery proposed in the study, operating at full capacity, would produce 37 million gallons of fuel each year. With limited potential to produce more SAJF from regionally-sourced lipid feedstocks, it is likely that SEATAC will need to seek renewable fuels from multiple feedstocks, such as cellulosic sources. Although a HEFA refinery may not be the sole supplier of renewable hydrocarbon fuels to the PNW, HEFA refineries' ease of construction and flexible feedstock handling capabilities suggest an integral role in the future of renewable fuels in the region.

New regulatory requirements for alternative fuels will continue to provide challenges to better utilize existing resources is cost-effective and sustainable ways. This study demonstrates a regional approach to a meeting a regulation that will influence air travel around the world.

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APPENDIX A: ADDITIONAL OPTIMIZATION COST INPUTS

Organization:

The purpose of this appendix is to provide information about costs and data used for supply chain model runs that was not discussed in chapter 3. Sections one through three present data collection and assumptions used for transportation costs calculations. Section four presents data sources and methods used for several node entities.

B.1.1 Grain Truck Transportation Costs:

Costs for truck transportation are broken into two categories based on the material in transportation. Grain, oilseeds, and meal are moved using grain trailer, while plant oil and FOGs are moved using a chemical tanker trailer. This study uses a method outlined by the Western Governors association [1], and includes a time-dependent component and a distance-dependent component. The individual components of the cost equations are suggested by annual studies from the American Transportation Research Institute [2]. A summary of the costs is given below, in Table 1.

Labor calculations are dependent on industry, driver wage, and state (or region) [3, 4]. Wages are provided by the Bureau of Labor Statistics for a tractor-trailer truck driver, earning the median industry wage, in the Pacific Northwest region (WA, OR, ID, MT). Benefits are calculated as a percentage of wages [5]. The average percentage of benefits, per total compensation was averaged over a five-year period from 2016 to 2012. Both labor and benefits costs are considered time dependent.

Fuel price is based on diesel price, ton efficiency, and truck weight. Diesel price is calculated by averaging inflation adjusted diesel prices [6, 7] over a ten-year period. Efficiency (mass*distance/fuel use) is provided by the National Research Council and is based on truck class [8]. Truck weight is calculated for an empty and a loaded truck. Both weights are multiplied by the efficiency value, and then averaged.

Table 1: Summary of truck transportation costs

Totals			
		Grain/Meal	**FOGs/Oil**
Distance Dependent	$/km	$0.82	$0.64
Time Dependent	$/hr	$30.40	$26.80
Capacity		42.6 m^3	26,500 l
Time Dependent			
Labor	$/hr	$19.99	$0.01
Benefits	$/hr	$10.41	$0.01
Distance Dependent			
Fuel	$/mi	$0.53	$0.35
Insurance	$/mi	$0.04	$0.04
Truck Payments/Lease	$/mi	$0.12	$0.12
Trailer Payment/Lease	$/mi	$0.02	$0.02
Equipment Maintenance	$/mi	$0.08	$0.08
Tires	$/mi	$0.02	$0.02
Permitting	$/mi	$0.02	$0.02

Equipment payments are based on the estimated truck and trailer lifetimes [2], as well as equipment costs [9]. Costs are evenly distributed across the lifetime of the equipment using a capital recovery equation and are then converted from cost per payment period to cost per mile based on the average miles a truck can be driven until replacement. Tire costs are dependent on the lifespan of tires [10], the number of axles that a truck and trailer combination has and the cost of replacement [9]. All equipment costs are distance dependent.

Insurance, permitting, and maintenance are provided by ATRI cost estimates [2]. Costs change, based on the nature of the feedstock. Grain is nonhazardous, and requires costs associated with standard trucking.

B.2 Rail Costs:

Three types of rail costs are used for the Washington wheat supply chain. Shuttle train costs represent trains with over 100 rail cars coming from one of Washington's four shuttle loading facilities. Unit train costs represent trains that have 1-23 cars and can represent trains originating from either class I railways or short line railways. Costs for shuttle and unit trains are meant to represent transportation from country elevator to final market, but scoot trains (trains that transfer between two intermediate facilities) operate at much lower rates on some short line railways. These scoot trains are represented with specialized costs and network datasets.

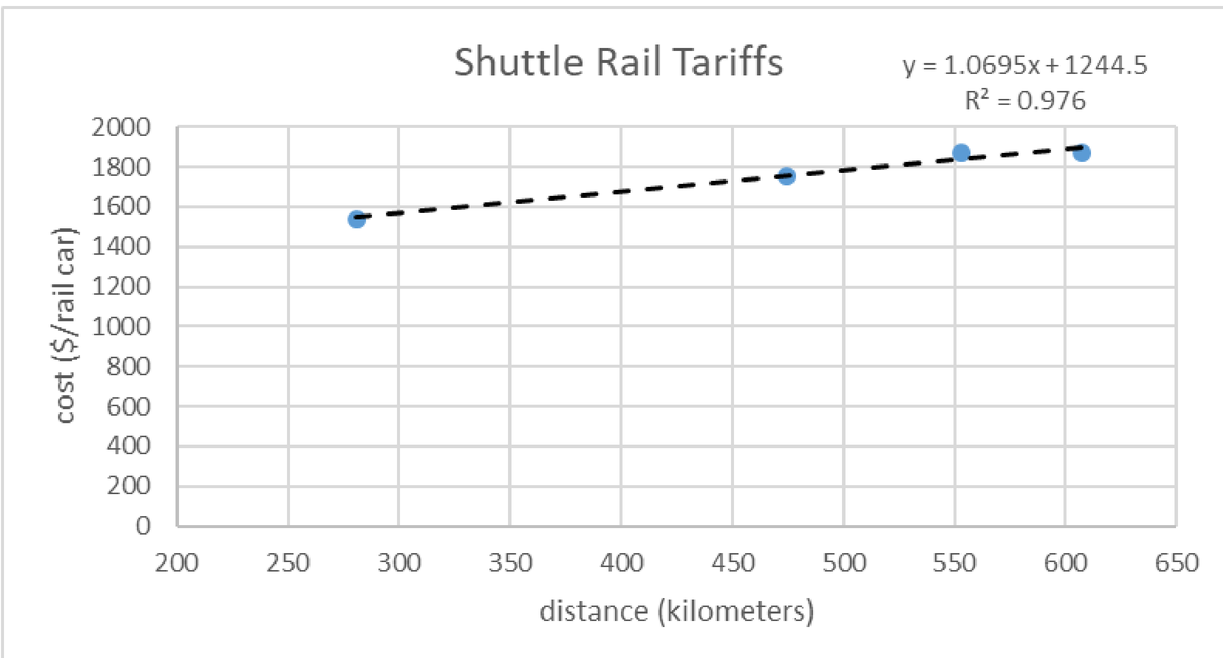

Figure 2: BNSF shuttle rail costs for the PNW

B.2.1 Shuttle Rail:

Shuttle rail costs are derived from the BNSF tariff schedule BNSF-4022-43591-M, which describes shuttle rail tariff rates between Washington's four shuttle loading facilities and Portland, OR from October 2017 to July 2018. The data and shuttle rail equation is given below in Figure 2.

B.2.2 Unit Rail:

Unit rail costs are derived from the BNSF tariff schedule BNSF-4022-43591-M, which describes unit rail tariff rates between suppliers in Washington, Oregon, Idaho, and California and export terminals in Portland, Tacoma, and Seattle from January to July 2018. The data and unit rail equation for 1-23 286k rail cars is given below in Figure 3.

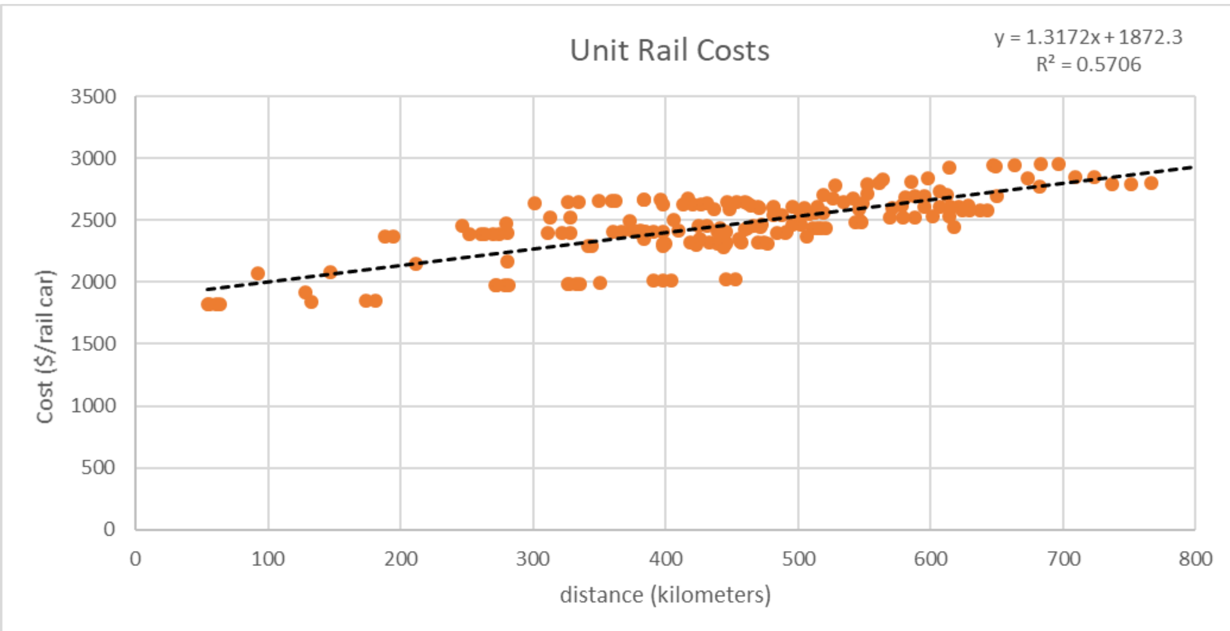

Figure 3: BNSF unit rail costs for the PNW

B.2.3 Special-Case Short Line Rail:

Four sections of the rail are specially organized to operate as scoot railways. Three of these sections, the CW line (EWG), PV Hooper line, and P&L line, are part of the Palouse-Coulee City Railway, owned by Washington state. The fourth section, the Blue Mountain line (BLMR) is owned by Watco Companies. The CW line and the P&L line are allowed to deliver grain to the Cheney flour mill and a BNSF interchange point (for modelling ease this is designated at the location of High Line's Four Lakes shuttle elevator, but is actually at rail line intersections near Cheney, WA and Marshall, WA). A map of the four networks used to represent these relationships is shown below in Figure 4. The PV Hooper Line and P&L Line are each allowed to deliver grain to Northwest Grain Growers barge terminal in Wallula, WA [11, 12]. Based on information from an operator of a short-line railroad who stated distance costs are similar to BNSF rates [13], nationwide-scaled grain shipping costs from BNSF tariff BNSF-4022-45050-M are used to calculate the distance dependent costs ($1.635/car*mile). It has also been determined that short line rail operators typically use lower base tariffs than class I operators, but those tariffs are typically confidential negotiations between individual companies and the railway operator [12, 13]. To calculate base tariffs for the short lines railways, a base cost was assumed and then changed in small increments until 339,000 metric tons (described by state study [14]) were transported on the CW line in the 2014 wheat supply chain model. The $300/car tariff found with this method is used for all special case railways.

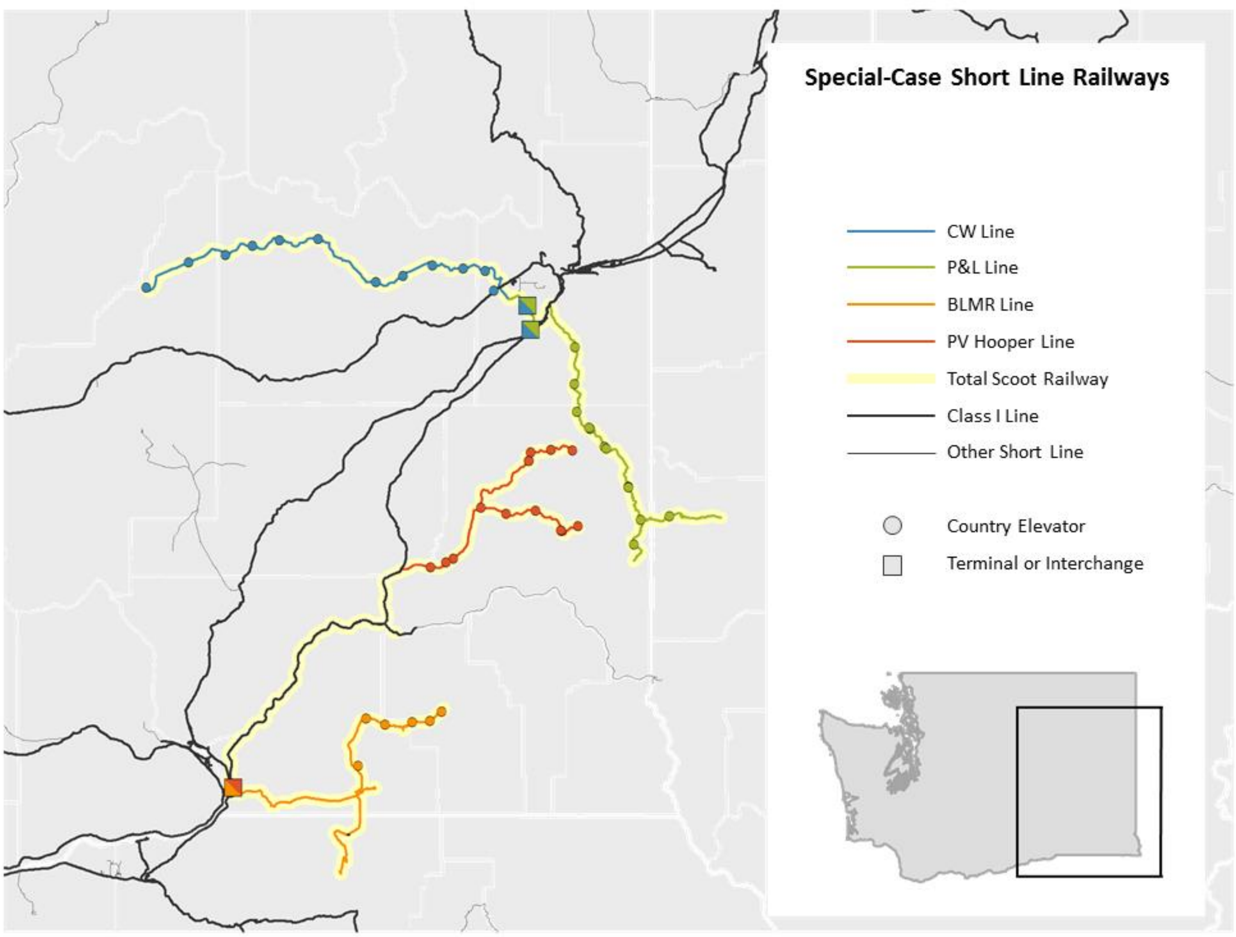

Figure 4: Special case short line railways, 2014 wheat supply chain model

B.3 Barge Transportation:

Barge costs are derived from the Shaver Transportation tariff S-98, which describes barge tariff rates between Lewiston, ID and Longview, WA. The data and shuttle rail equation are given below in Figure 5.

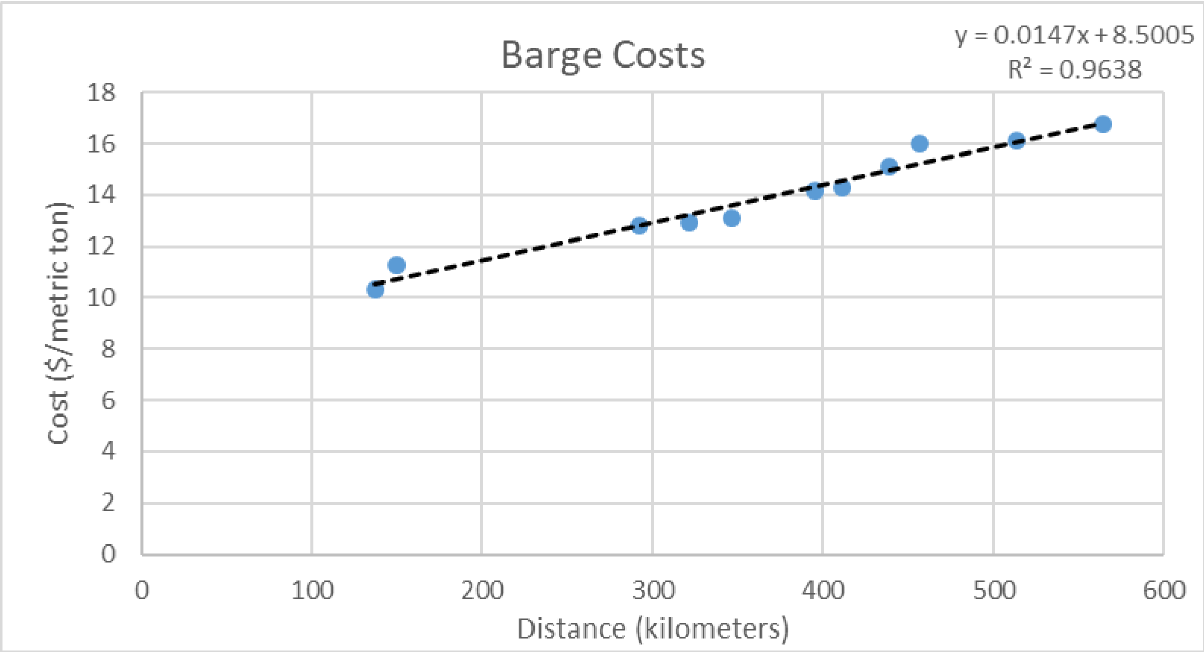

Figure 5: Shaver transportation tariff costs

B.4.1 Grain Elevators:

Elevator locations and capacities were obtained from publicly available databases, including those assembled to regulate the Washington Grain Warehouse Audit Program [5] and the United States Warehouse Act [15]. Three types of grain elevators were used as inputs for optimization models: country elevators, shuttle elevators, and barge terminals. Country elevators, or non-terminal commercial elevators, are often the first location wheat, and other grains and oilseeds, are transported to following harvest. Grain leaving these elevators can be sent directly to markets or to other elevators in the region that have better access to transportation. Shuttle elevators and barge terminals are the primary means of transporting grains and oilseeds out of the inland PNW. Shuttle elevators are high-capacity rail terminals that can load up to 110 rail cars at once. Four shuttle elevators currently operate in Washington. Barge terminals are located along the Lower Snake River and Mid-Columbia River, beginning at Lewiston, ID and ending near The Dalles, OR. The inland PNW has 25 barge terminals.

B.4.2 Dairies Layer:

Oilseed meal is typically used as an animal feed supplement. According to a representative from Pacific Coast Canola, canola meal produced in the PNW is primarily sold to dairy farmers across the entire PNW, from Northwest Washington to Southern Idaho [16]. For this study, it is assumed that most oilseed meal deliveries are only made to dairies in the twenty-largest dairy producing counties in the PNW. It is assumed the amount of meal each county is delivered is proportional to its dairy cow population according to the 2012 USDA Census of Agriculture [17]. The top-twenty approach captures 87% of dairy cows in the region. For modelling, the delivery points are placed along highway and rail intersections near dairy production.

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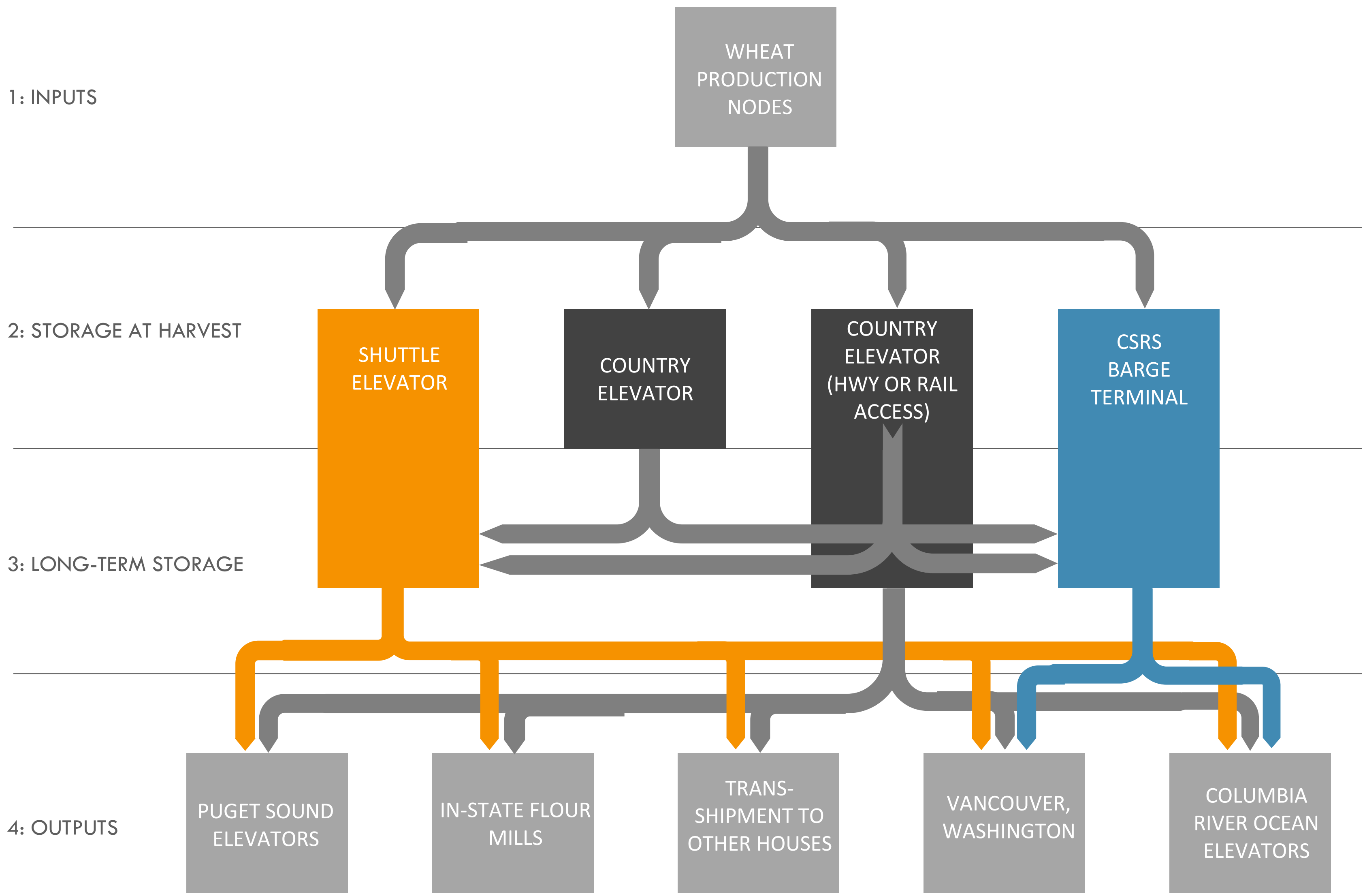
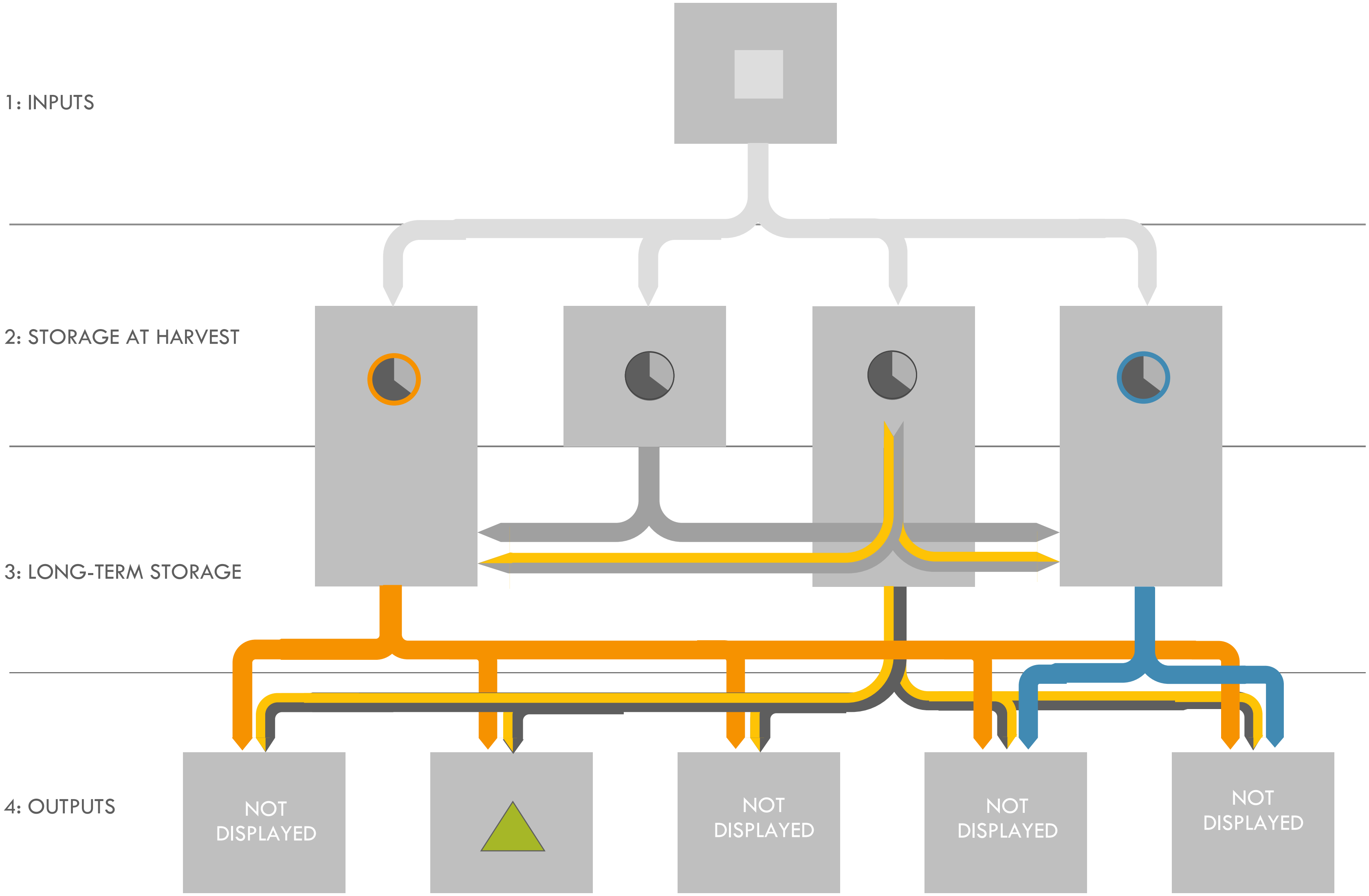
APPENDIX B: SUPPLY CHAIN MODEL RUN MAPS

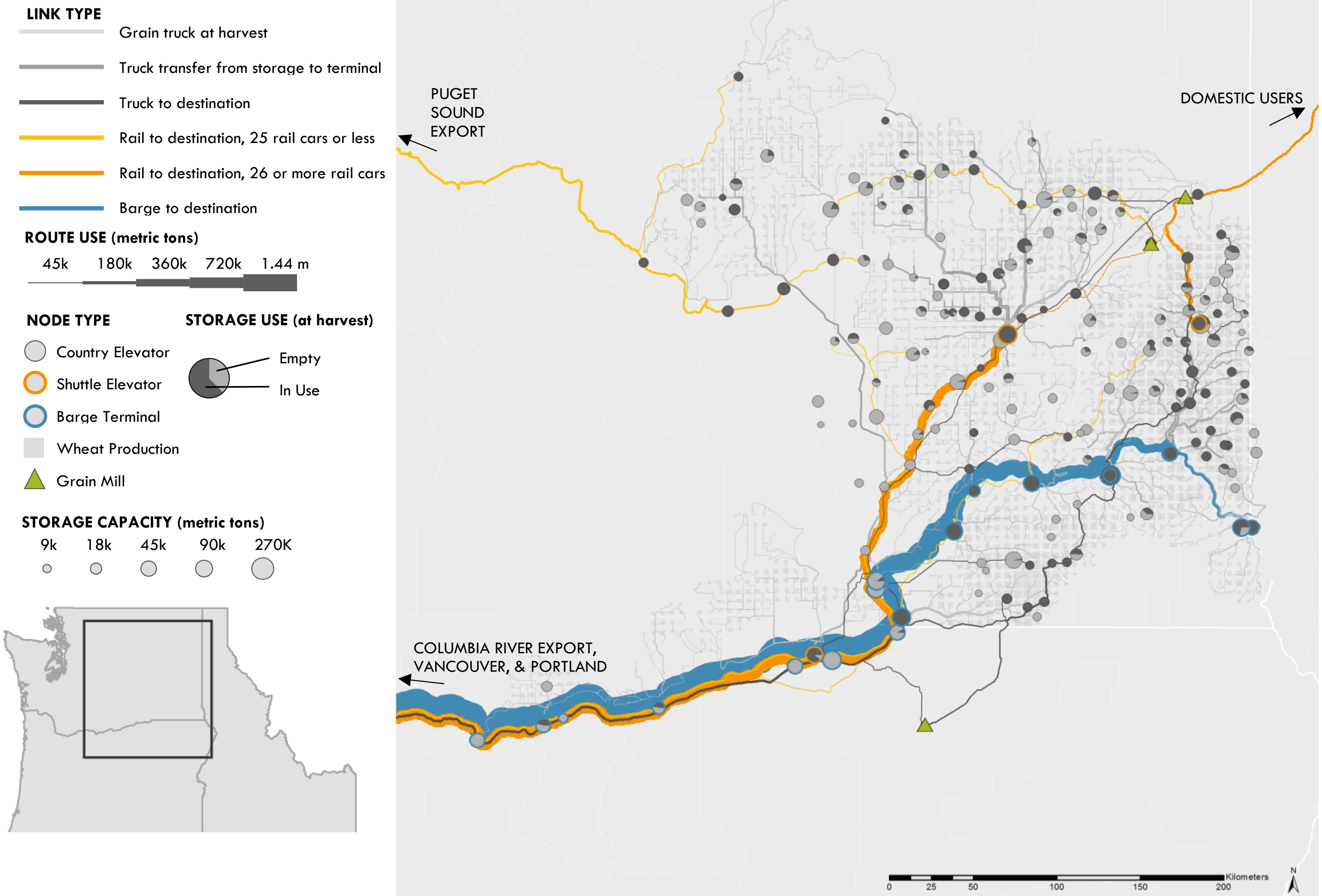
Contents:

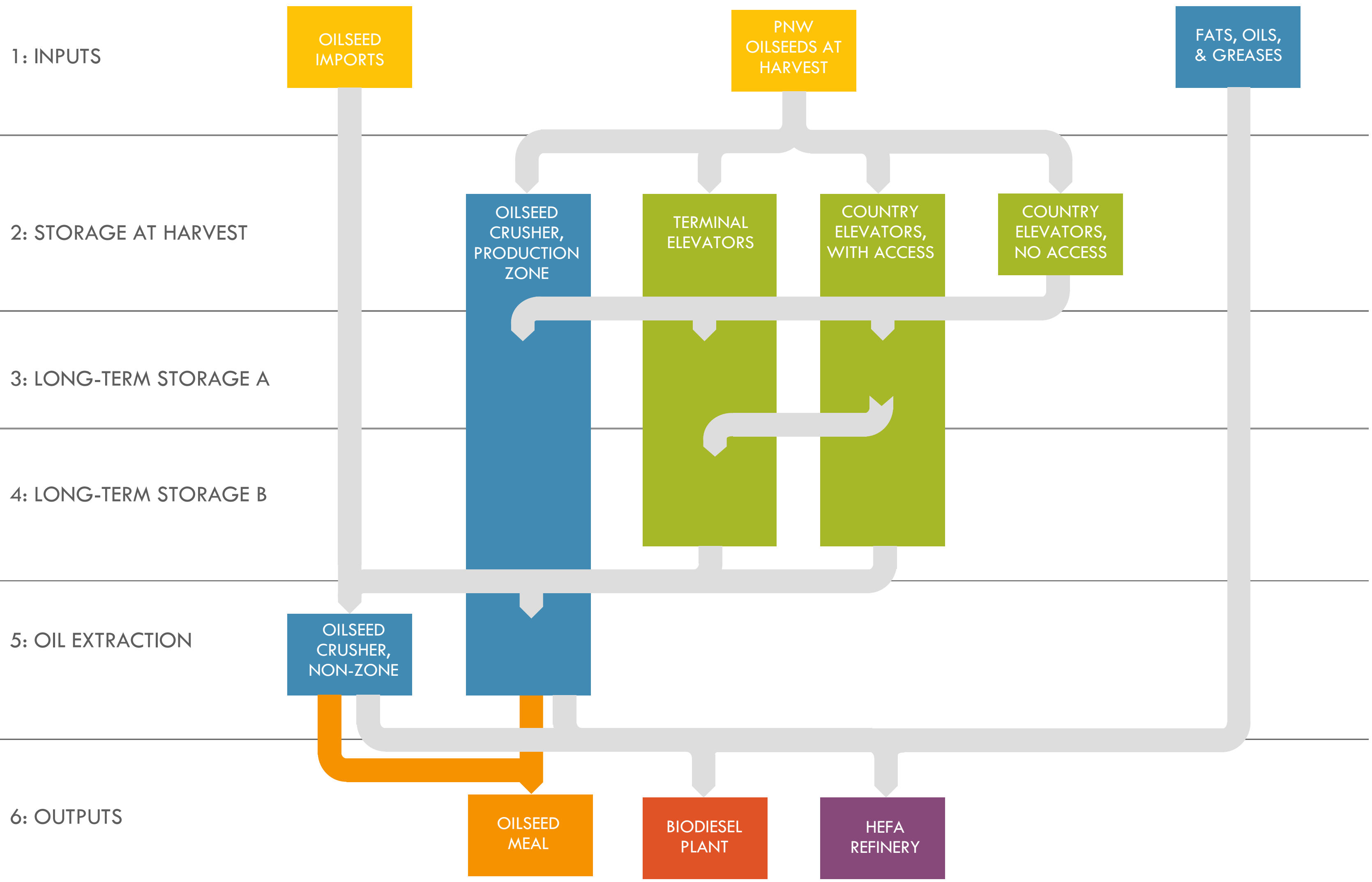


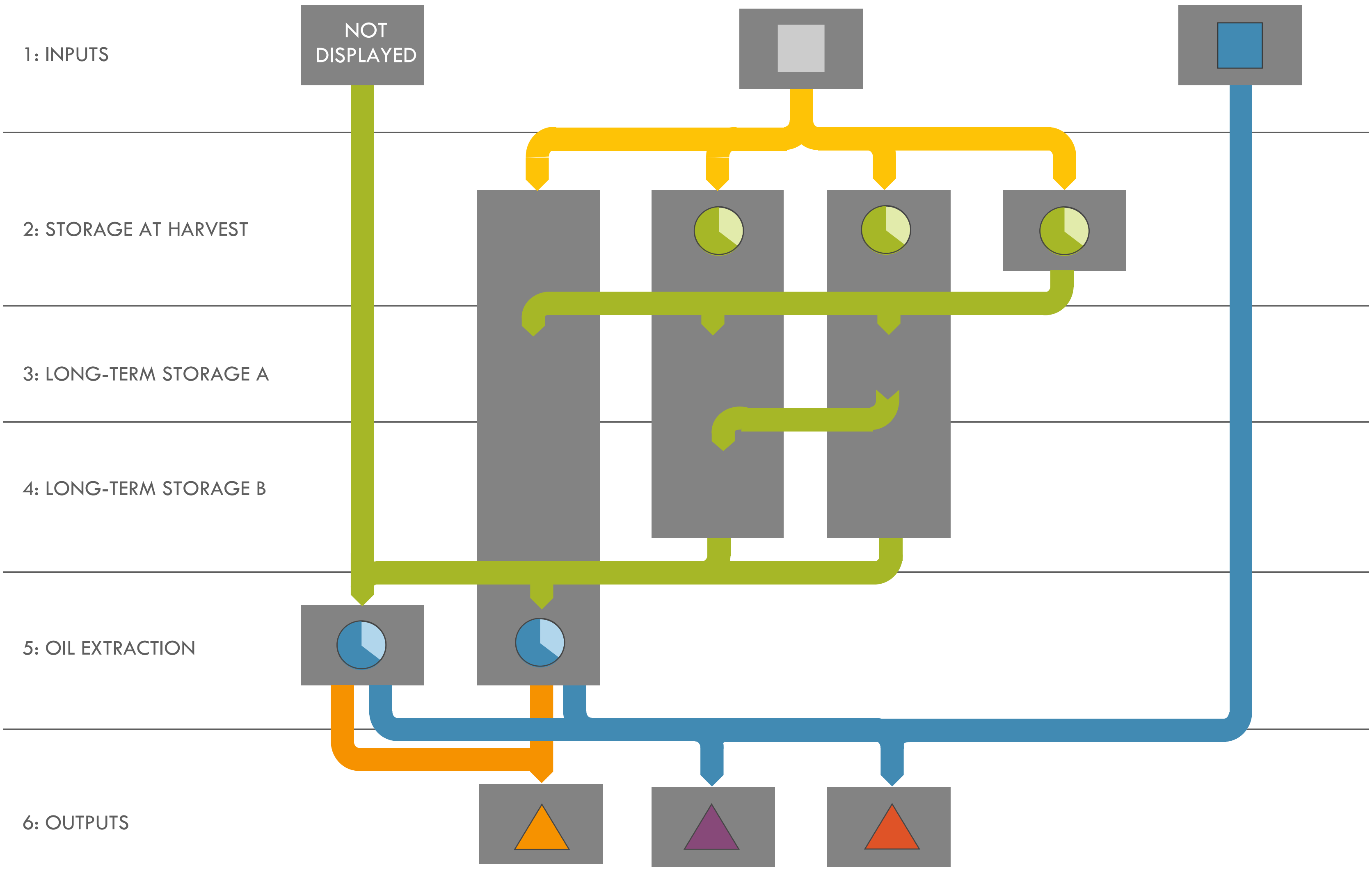
1: INPUTS
2: STORAGE AT HARVEST
3: LONG-TERM STORAGE
4: OUTPUTS
WHEAT PRODUCTION NODES
SHUTTLE ELEVATOR
COUNTRY ELEVATOR
COUNTRY ELEVATOR (HWY OR RAIL ACCESS)
CSRS BARGE TERMINAL
PUGET SOUND ELEVATORS
IN-STATE FLOUR MILLS
TRANS-SHIPMENT TO OTHER HOUSES
VANCOUVER, WASHINGTON
COLUMBIA RIVER OCEAN ELEVATORS

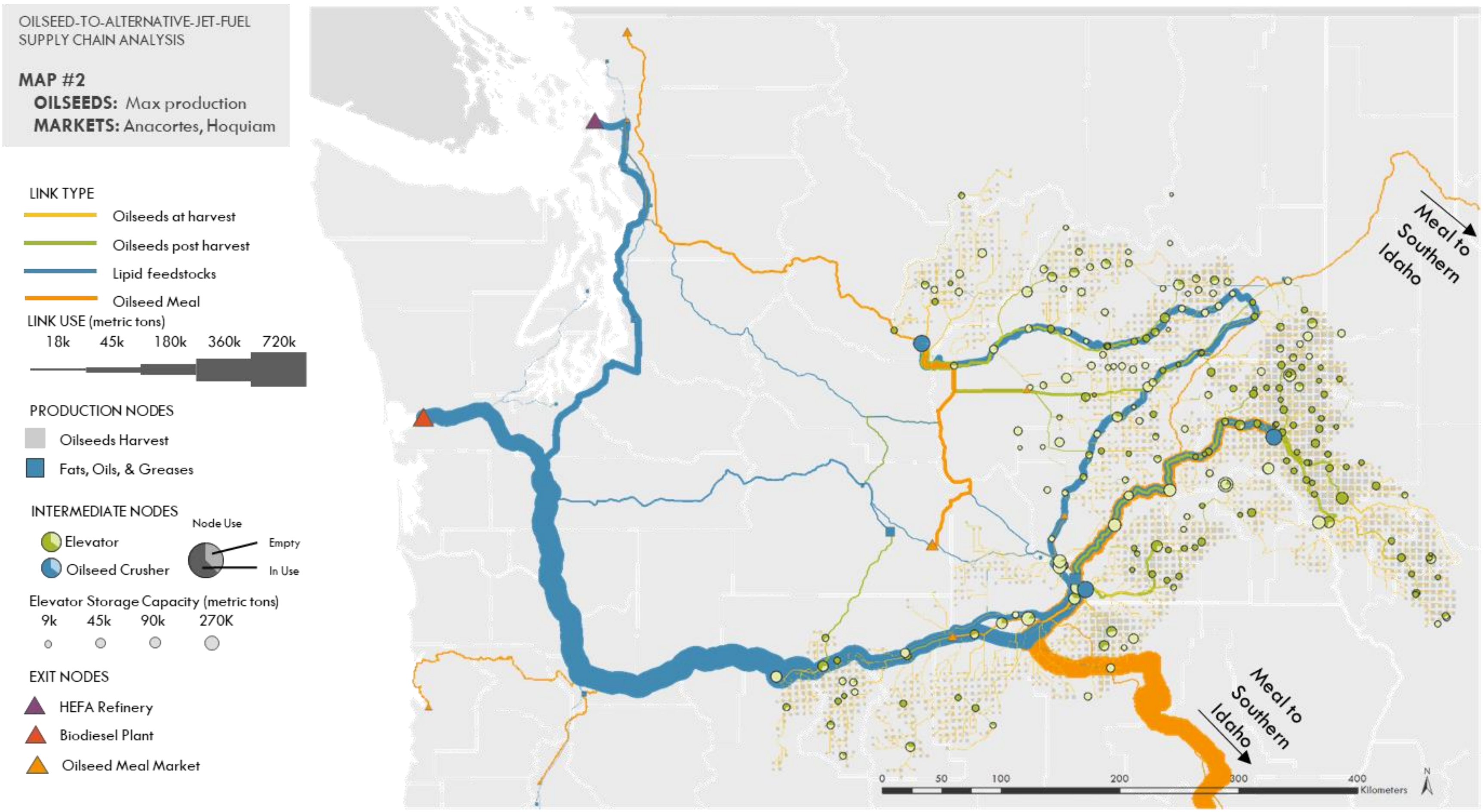

1: INPUTS
2: STORAGE AT HARVEST
3: LONG-TERM STORAGE
4: OUTPUTS
NOT DISPLAYED
NOT DISPLAYED
NOT DISPLAYED
NOT DISPLAYED

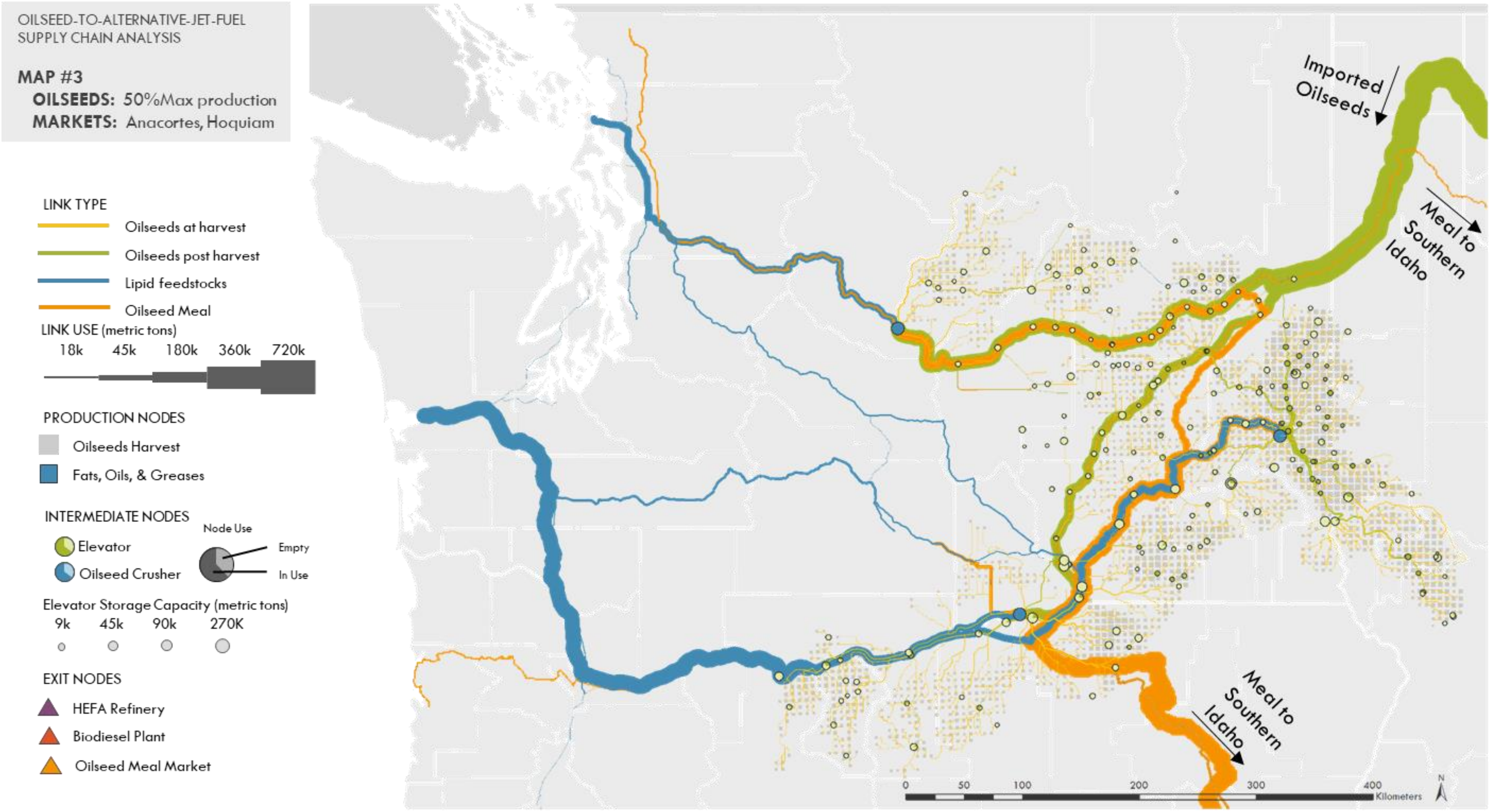
MAP #1
WHEAT SUPPLY CHAIN
PRODUCTION-TO-MARKET FOR WASINGTON



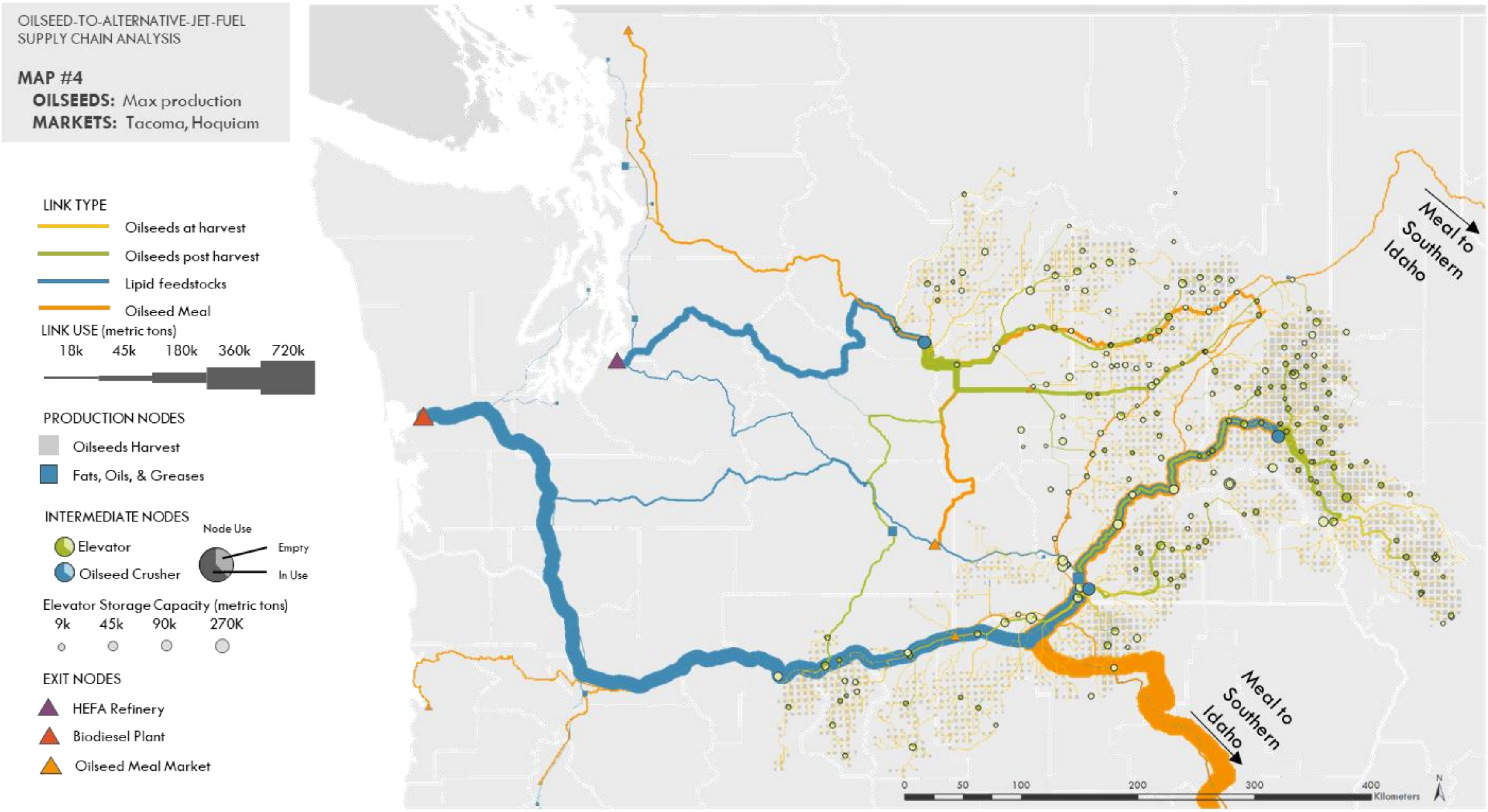

1: INPUTS
OILSEED IMPORTS
PNW OILSEEDS AT HARVEST
FATS, OILS, & GREASES
2: STORAGE AT HARVEST
OILSEED CRUSHER, PRODUCTION ZONE
TERMINAL ELEVATORS
COUNTRY ELEVATORS, WITH ACCESS
COUNTRY ELEVATORS, NO ACCESS
3: LONG-TERM STORAGE A
4: LONG-TERM STORAGE B
5: OIL EXTRACTION
OILSEED CRUSHER, NON-ZONE
6: OUTPUTS
OILSEED MEAL
BIODIESEL PLANT
HEFA REFINERY

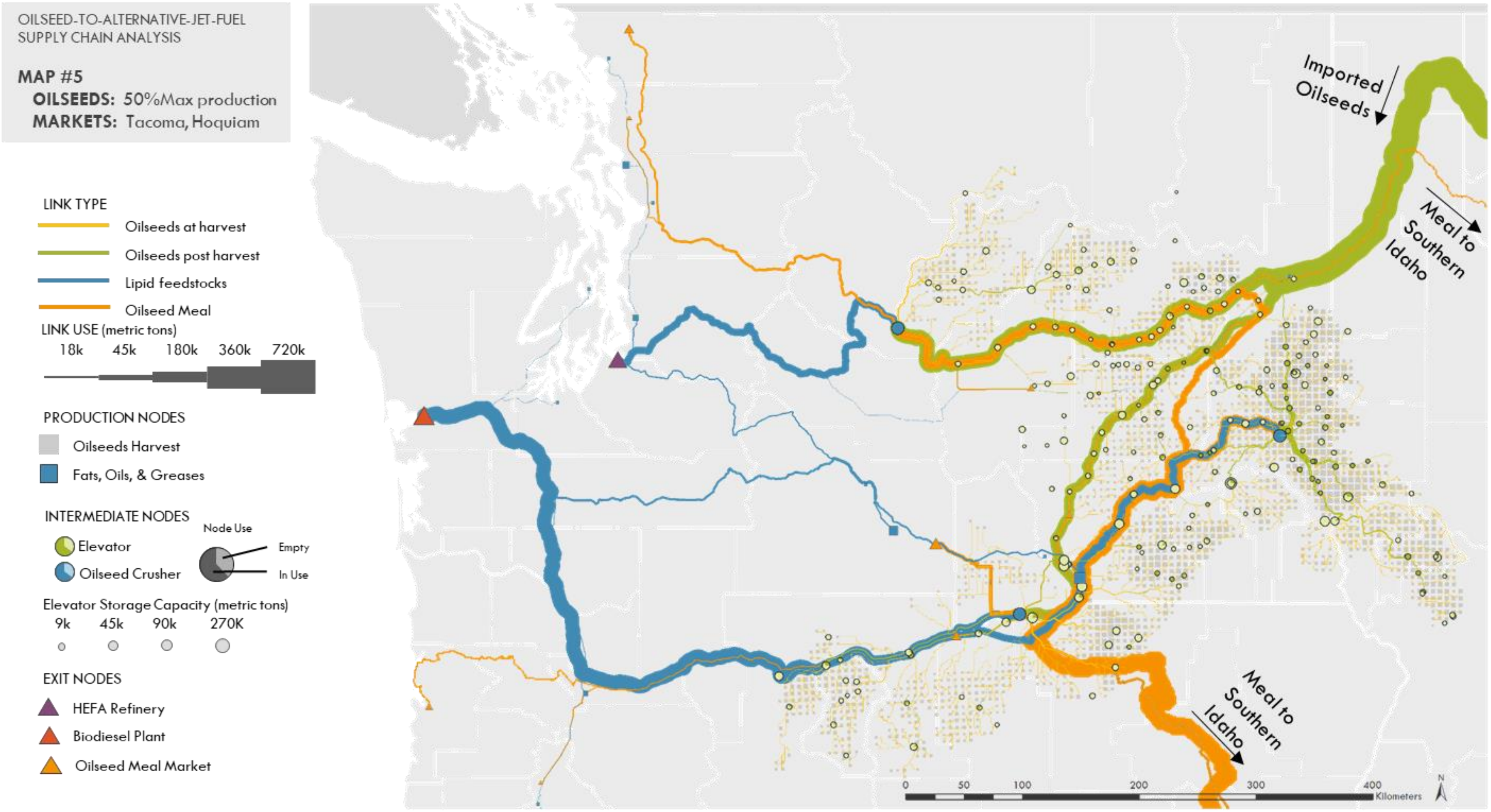

1: INPUTS
NOT DISPLAYED
2: STORAGE AT HARVEST
3: LONG-TERM STORAGE A
4: LONG-TERM STORAGE B
5: OIL EXTRACTION
6: OUTPUTS

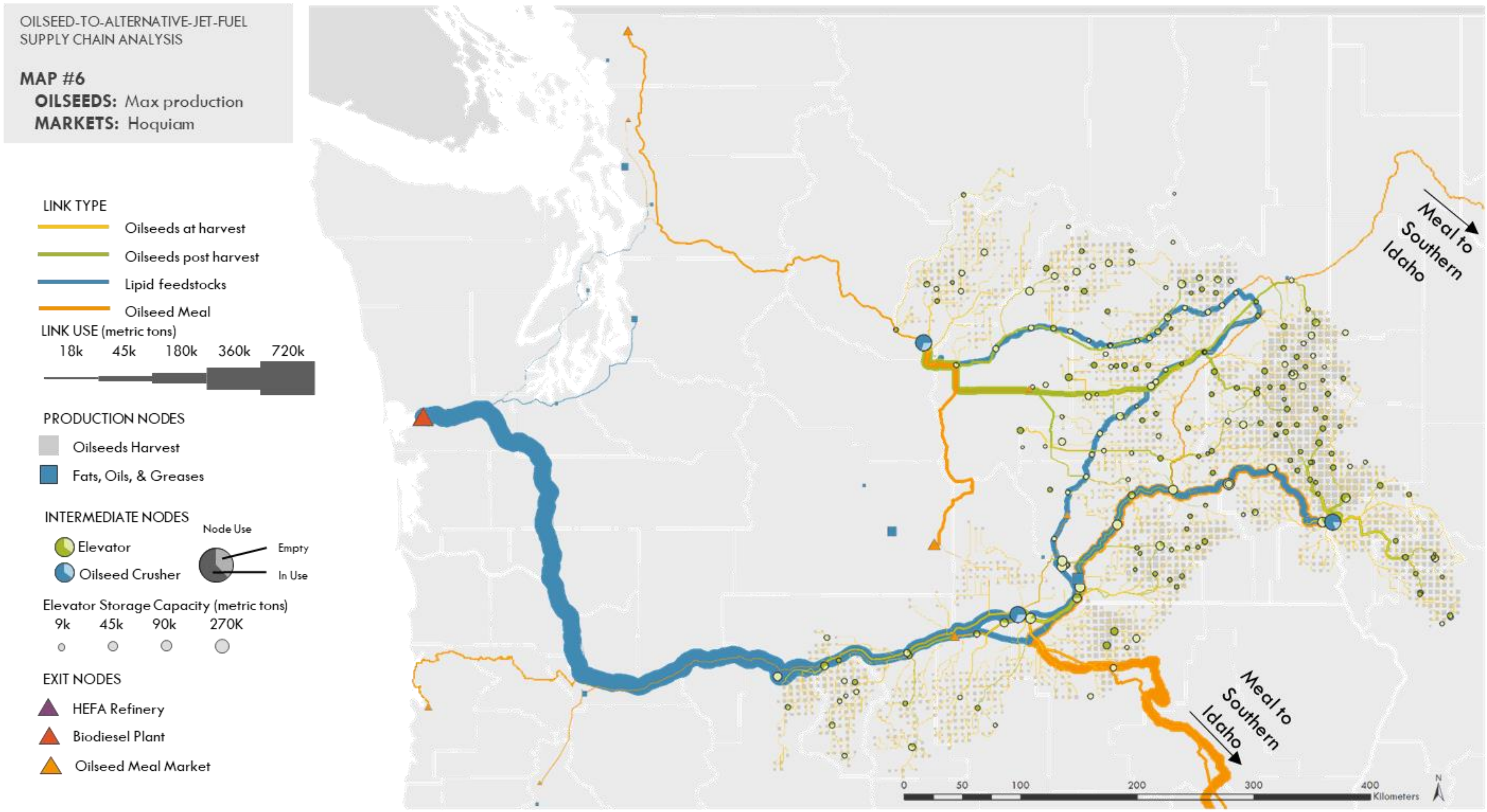

OILSEED-TO-ALTERNATIVE-JET-FUEL
SUPPLY CHAIN ANALYSIS
MAP #2
OILSEEDS: Max production
MARKETS: Anacortes, Hoquiam
LINK TYPE
Oilseeds at harvest
Oilseeds post harvest
Lipid feedstocks
Oilseed Meal
LINK USE (metric tons)
18k 45k 180k 360k 720k
PRODUCTION NODES
Oilseeds Harvest
Fats, Oils, & Greases
INTERMEDIATE NODES
Node Use
Elevator
Oilseed Crusher
Empty
In Use
Elevator Storage Capacity (metric tons)
9k 45k 90k 270K
EXIT NODES
HEFA Refinery
Biodiesel Plant
Oilseed Meal Market
Meal to Southern Idaho
Meal to Southern Idaho
0 50 100 200 300 400 Kilometers
N

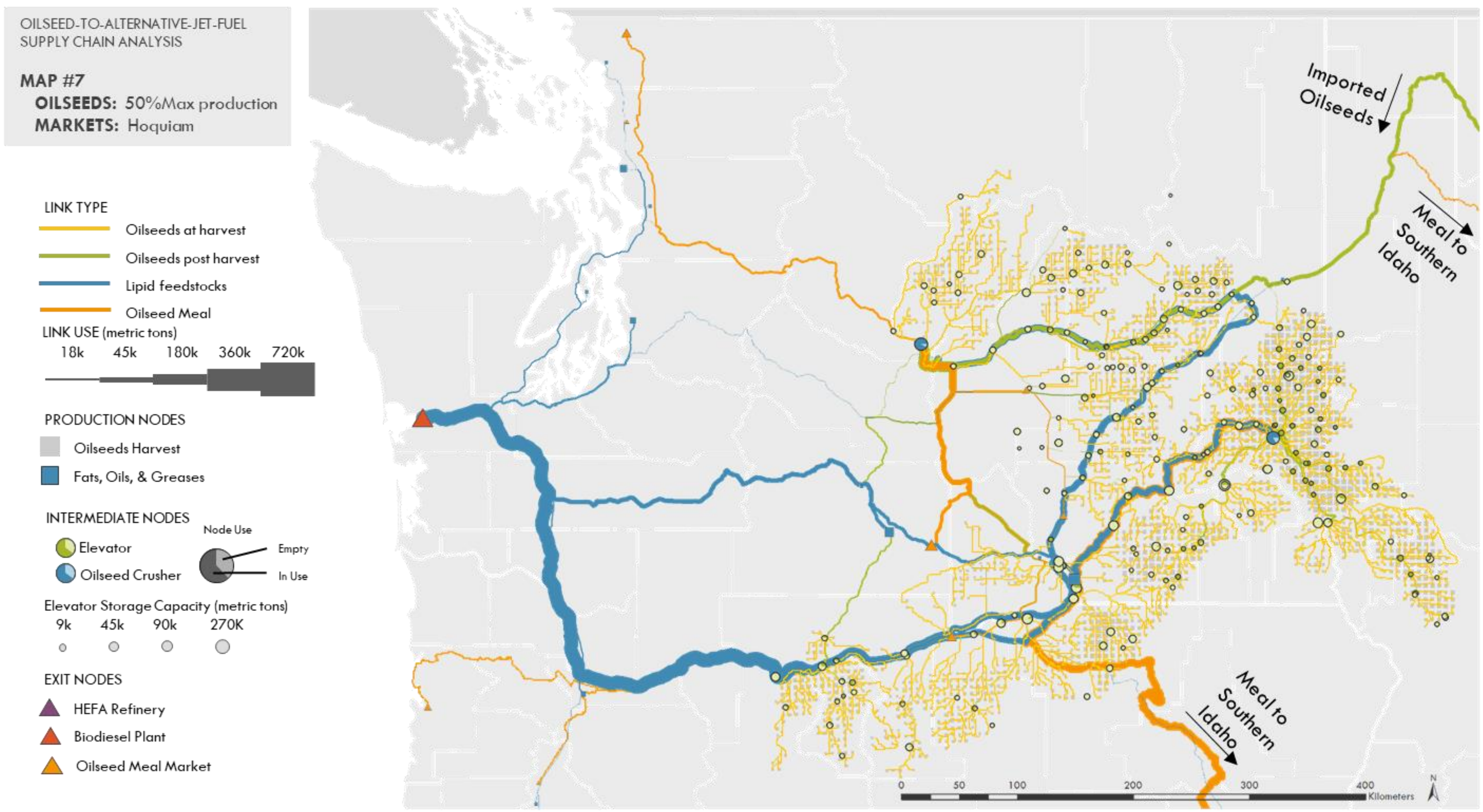


OILSEED-TO-ALTERNATIVE-JET-FUEL
SUPPLY CHAIN ANALYSIS
MAP #3
OILSEEDS: 50%Max production
MARKETS: Anacortes, Hoquiam
LINK TYPE
Oilseeds at harvest
Oilseeds post harvest
Lipid feedstocks
Oilseed Meal
LINK USE (metric tons)
18k 45k 180k 360k 720k
PRODUCTION NODES
Oilseeds Harvest
Fats, Oils, & Greases
INTERMEDIATE NODES
Elevator
Oilseed Crusher
Node Use
Empty
In Use
Elevator Storage Capacity (metric tons)
9k 45k 90k 270K
EXIT NODES
HEFA Refinery
Biodiesel Plant
Oilseed Meal Market
Imported Oilseeds
Meal to Southern Idaho
Meal to Southern Idaho
0 50 100 200 300 400 Kilometers
N


OILSEED-TO-ALTERNATIVE-JET-FUEL
SUPPLY CHAIN ANALYSIS
MAP #4
OILSEEDS: Max production
MARKETS: Tacoma, Hoquiam
LINK TYPE
Oilseeds at harvest
Oilseeds post harvest
Lipid feedstocks
Oilseed Meal
LINK USE (metric tons)
18k
45k
180k
360k
720k
PRODUCTION NODES
Oilseeds Harvest
Fats, Oils, & Greases
INTERMEDIATE NODES
Node Use
Elevator
Oilseed Crusher
Empty
In Use
Elevator Storage Capacity (metric tons)
9k
45k
90k
270K
EXIT NODES
HEFA Refinery
Biodiesel Plant
Oilseed Meal Market
Meal to Southern Idaho
Meal to Southern Idaho
0
50
100
200
300
400
Kilometers
N


OILSEED-TO-ALTERNATIVE-JET-FUEL
SUPPLY CHAIN ANALYSIS
MAP #5
OILSEEDS: 50%Max production
MARKETS: Tacoma, Hoquiam
LINK TYPE
Oilseeds at harvest
Oilseeds post harvest
Lipid feedstocks
Oilseed Meal
LINK USE (metric tons)
18k
45k
180k
360k
720k
PRODUCTION NODES
Oilseeds Harvest
Fats, Oils, & Greases
INTERMEDIATE NODES
Node Use
Elevator
Oilseed Crusher
Empty
In Use
Elevator Storage Capacity (metric tons)
9k
45k
90k
270K
EXIT NODES
HEFA Refinery
Biodiesel Plant
Oilseed Meal Market
Imported Oilseeds
Meal to Southern Idaho
Meal to Southern Idaho
0
50
100
200
300
400
Kilometers
N


OILSEED-TO-ALTERNATIVE-JET-FUEL
SUPPLY CHAIN ANALYSIS
MAP #6
OILSEEDS: Max production
MARKETS: Hoquiam
LINK TYPE
Oilseeds at harvest
Oilseeds post harvest
Lipid feedstocks
Oilseed Meal
LINK USE (metric tons)
18k
45k
180k
360k
720k
PRODUCTION NODES
Oilseeds Harvest
Fats, Oils, & Greases
INTERMEDIATE NODES
Elevator
Oilseed Crusher
Node Use
Empty
In Use
Elevator Storage Capacity (metric tons)
9k
45k
90k
270K
EXIT NODES
HEFA Refinery
Biodiesel Plant
Oilseed Meal Market
Meal to Southern Idaho
Meal to Southern Idaho
0
50
100
200
300
400
Kilometers
N


OILSEED-TO-ALTERNATIVE-JET-FUEL
SUPPLY CHAIN ANALYSIS
MAP #7
OILSEEDS: 50%Max production
MARKETS: Hoquiam
LINK TYPE
Oilseeds at harvest
Oilseeds post harvest
Lipid feedstocks
Oilseed Meal
LINK USE (metric tons)
18k 45k 180k 360k 720k
PRODUCTION NODES
Oilseeds Harvest
Fats, Oils, & Greases
INTERMEDIATE NODES
Node Use
Elevator
Oilseed Crusher
Empty
In Use
Elevator Storage Capacity (metric tons)
9k 45k 90k 270K
EXIT NODES
HEFA Refinery
Biodiesel Plant
Oilseed Meal Market
Imported Oilseeds
Meal to Southern Idaho
Meal to Southern Idaho
0 50 100 200 300 400 Kilometers
N

Complete oilseed crusher selections and usage rates from oilseed-to-alternative-jet-fuel supply chain model runs (metric tons)

	Anacortes		Tacoma		Hoquiam	
	100% production	50% production	100% production	50% production	100% production	50% production
Lewiston, ID					154,520	
Boardman, OR						
Dallesport, OR						
Hermiston, OR						
Milton-Freewater, OR						
Pendleton, OR						
Weston, OR						
Airway Heights, WA						
Anacortes, WA						
Camas, WA						
Colfax, WA	190,042	188,006	190,042	187,955		158,859
Ellensburg, WA						
Finley, WA						
Glade, WA						
Hatton, WA						
Kalama, WA						
Kennewick, WA						
LaCrosse, WA						
Longview, WA						
Lyons Ferry, WA						
Mesa, WA						
Moses Lake, WA						
Patterson, WA						
Plymouth, WA		190,042		190,042	133,030	
Portland, WA						
Port Kelley, WA						
Prosser, WA						
Rock Island, WA	187,955		187,955		133,030	174,746
Rosalia, WA						
Spangle, WA						
E Spokane, WA						
W Spokane, WA						
St. John, WA						
Tacoma, WA						
Templin, WA						
Walla Walla, WA						
Wallula, WA	190,042		190,042			
Warden, WA						
Wenatchee, WA		190,042		190,042		
Wheeler, WA						
Yakima, WA						
FOGs Use	108,727	108,676	108,727	108,727	21,225	106,461
Total Feedstock	676,767	676,767	676,767	676,767	441,804	440,066