Price Transmission in Petroleum Markets and Potential Feedstock Supply for Low-carbon Fuel Production: Implications for Emerging Energy Sources

by

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Abstract

Low-carbon fuels are receiving increasing attention from governments worldwide as sustainable alternatives to fossil fuels. But prospects for these emerging industries are uncertain due to several economic barriers. This thesis presents two studies, each investigating a key factor influencing the prospects of the biofuel industry: (1) price transmission in petroleum markets, and (2) potential bio-feedstock supplies. The first study uses nonlinear time series techniques to investigate price transmission from crude oil to jet fuel and diesel, two important transport fuels with distinctly different industrial characteristics. Our findings suggest that both jet fuel and diesel have long-run equilibrium relationships with oil prices, asymmetric price adjustments and nonlinear price responses to oil price shocks. We also find that jet fuel appears to be more vulnerable to fluctuating oil prices than diesel. These price relationships may provide incentives for fuel producers, especially jet fuel producers, to diversify input sources away from fossil fuels and towards bio-feedstock, thereby resulting in a shift towards increased biofuel production. The second study assesses the availability of non-No. 1 canola in Alberta, a feedstock that is less desirable for human consumption than No. 1 canola, but that could be desirable as a feedstock for biofuel production. Using a township-level GIS approach, we find different spatial distributions of available non-No. 1 and total canola oil, as well as different levels of spatial and temporal variations in non-No. 1 oil. We also model a fuel-grade canola oil supply chain that prioritizes the use of non-No. 1 canola, and then select crushing sites based on the amount of annually accessible non-No. 1 canola oil in Alberta. These findings will be useful to stakeholders, including fuel producers and users, farmers, rural communities, and policymakers. The results of this thesis contribute to a better understanding of the petroleum industries, and provide insights into emerging

low-carbon fuel markets, with implications for investors and policymakers wishing to promote a low-carbon economy.

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Chapter 1: Introduction

Petroleum products play an important role in the current energy system and contribute to economic development (BP p.l.c. 2020). But in response to climate change, governments worldwide are promoting the production of low-carbon fuels to reduce greenhouse gas (GHG) emissions. Switching from fossil fuels to low-carbon fuels can also be beneficial to fuel security and regional development (Bakhtiyari et al. 2017; Yaghoubi et al 2019). Numerous types of government policies are adopted to facilitate fuel switching, such as carbon pricing, biofuel blending mandates, flexible performance standards (e.g., low-carbon fuel standards), and financial incentives for low-carbon fuel research and investment (Saravanan et al. 2020; Sorda et al 2010; Su et al. 2015).

However, the financial viability of the biofuel industry faces two important challenges: price competitiveness with fossil fuels and bio-feedstock availability (Hari et al. 2015; Joshi et al. 2017; Smith et al. 2017). To address these two challenges, investors and policymakers require a better understanding of current price relationships in petroleum markets, and of available feedstock for low-carbon fuel production – both of which are explored in this thesis.

The first study (i.e., Chapter 2) examines price transmission from crude oil to jet fuel and diesel. Jet fuel and diesel are selected due to their important economic roles, as well as the fact that there has been little research on price impacts of oil markets on these two fuels. Specifically, we use time-series techniques tailored to market conditions to investigate asymmetric price adjustments and the dynamic paths of price responses to oil price shocks. Understanding price linkages between current energy inputs and outputs could help develop industrial risk management strategies and provide insights into potential benefits of diversifying input sources away from crude oil towards bio-feedstock. Such information could be important in facilitating the development of emerging energy industries.

The second study (i.e., Chapter 3) takes a closer look at one particular feedstock of emerging energy by evaluating potential supplies of non-No. 1 canola oil for low-carbon fuel production in Alberta. Non-No. 1 canola is a potentially cheaper feedstock than No. 1 canola, and is less desirable for human consumption. The construction of fuel-grade crushing plants focusing on non-No. 1 canola could benefit numerous stakeholders, including fuel refiners and consumers, farmers, rural communities, and policymakers. The objectives of this analysis are to identify how much non-No. 1 and total canola seed and oil could be available, and to determine the best potential fuel-grade crushing sites in Alberta based on the amount of annually accessible non-No. 1 canola oil, while incorporating geographic information and transport considerations. Since seed harvests are spatially varied and transport costs are dependent on actual transportation networks, we employ a township-level Geographical Information System (GIS) approach that integrates economic considerations. Our estimate of canola supply and discussion of potential new fuel-grade crushing sites provide information for low-carbon fuel investors and policymakers.

Chapter 2: Price Transmission and Impulse Responses between Crude Oil, Jet Fuel, and Diesel: Implications for Emerging Energy Sources

2.1 Introduction

Petroleum products account for 93% of transport energy demand (BP p.l.c. 2020) and play a significant role in the current global energy system. Crude oil, which is the main input into petroleum products, can have wildly fluctuating prices, which are felt in downstream markets. The analysis of price transmission between oil and petroleum products such as jet fuel and diesel provides information for business decisions and policymaking. For fuel producers, oil purchasing can account for large production expenditures, and price relationships can potentially affect purchasing and pricing processes (Cannon and Watanabe 2020). These producers, along with financial investors, use transmission information for hedging strategies to mitigate risks of oil price variations (Atil et al. 2014). The impact of oil prices on fuel prices can also disclose underlying market structures and behaviors, such as competitiveness and market power (Scotti and Volta 2018), which are crucial for energy outlooks and policymakers who monitor market efficiency.

Price linkages in petroleum markets have drawn extensive research attention, with a focus on transmission between oil and gasoline (e.g., Bagnai and Mongeau Ospina 2018; Blair et al. 2017; Sun et al. 2019)[1]. However, there is only one price transmission study that has been conducted with respect to jet fuel (i.e., Kaufmann 2017) and a few for diesel (i.e., Bastianin et al. 2014; Fosten

[1] For literature reviews on this topic, see Asche et al. (2003), Ederington et al. (2019), and Perdiguero-Garcia (2013).

2012; Karagiannis et al. 2015; Liu et al. 2010; Valadkhani et al. 2015; Wlazlowski et al. 2012).

This lack of information regarding oil pass-through effects on jet fuel and diesel is surprising considering the ongoing importance and investments in these energy sources. Prior to the COVID-19 pandemic, jet fuel was a fast-growing market. Between 2016-2018, jet fuel demand grew at over 4% per year, while in comparison, petroleum markets in general grew at just 1.3% per year. Projecting forward, jet fuel is one of the few petroleum products expected to exhibit consistent growth through 2040 (Sayal and Vertz 2018). As for diesel, vehicles fueled by diesel dominate ground transportation for freight movement and passenger travel. The share of diesel in the global transportation sector is approximately 32%, and it is expected to grow owing to improved economic growth and trade (Beroe n.d.). During the pandemic, global consumption of jet fuel in July 2020, was 69% less than the previous year's level (U.S. Energy Information Administration (EIA) 2020), but diesel demand was somewhat stable because of its importance in providing freight movement of daily necessities (Camp et al. 2020).

While jet fuel and diesel are continuing their important economic roles, governments worldwide are increasingly attempting to reduce GHG emissions in response to climate change. Accordingly, governments and private companies are investing in the development of biofuel technologies, which would facilitate switching from fossil fuels to low-carbon energy sources. Demand for petroleum products reached a peak in 2019 and is gradually declining, being offset by biofuels and other types of bioenergy (BP p.l.c. 2020). Biojet and biodiesel, which substitute biomass for crude oil as inputs, could play critical roles in decarbonizing the transport sector, because jets, trucks and trains require considerable energy density that neither electricity nor hydrogen is able to deliver (BP p.l.c. 2020).

Understanding current oil price linkages of jet fuel and diesel will be important to understanding the potential for emerging biojet and biodiesel industries. For example, the current starting conditions in these markets may reveal prospects regarding whether financial conditions might improve as these new fuel sources substitute bio-feedstock for oil inputs.

Gaining a better understanding of price relationships for current jet fuel and diesel industries also requires approaches that consider specific characteristics of these industries, including adjustment costs, pricing strategies, and market power. There are tailored price analysis techniques (discussed below) that may be employed to provide insights into price effects in such situations, but to date, these approaches have not been employed to investigate oil pass-through effects on jet fuel and/or diesel.

The objective of our research is to examine price transmission from crude oil to jet fuel and diesel, to better understand current investments and future biofuel prospects for producing these energy types with oil and bio-feedstock inputs. Our main contribution is to use a nonlinear time series approach that considers three specific features of these markets while investigating long-term price relationships, short-term dynamic adjustments, and price response mechanisms to crude oil shocks.

The first feature to address is the potential "stickiness" of firms' responses. When oil prices change, fuel producers do not always respond, because menu costs (i.e., adjustment costs associated with responding to price changes; Meyer and von Cramon-Taubadel 2004) may make it nonprofitable to do so. Other possible reasons for sticky prices are marketing strategies and elastic product demands which can make producers hesitant to increase prices (Figus et al. 2020). Under such conditions, changing prices may be state-dependent, occurring only after the benefits of adjustment exceed the costs. Accordingly, we employ regime-switching models that assume discontinuous price responses. We follow the classic work of Goodwin and Piggott (2001) and a recent application of Ters and Urban (2020), and adopt a three-regime (i.e., positive, negative and no adjustment) threshold model to allow for stickiness in adjustments.

The second feature is that fuel producers may respond differentially to increases versus decreases in oil prices. Asymmetric price adjustments could potentially stem from menu costs, demand elasticity, pricing strategies, and market power (Meyer and von Cramon-Taubadel 2004; Scotti and Volta 2018), all of which are evident in jet fuel and diesel markets. For example, production of diesel is concentrated, relative to dispersed consumers, which allows producers to exercise market power (Fosten 2012). On the other hand, jet fuel purchasers (mainly large airports and airlines) are concentrated (Davidson et al. 2014) and jet fuel demand is elastic, relative to stable refinery yields (EIA n.d.), which may provide fuel purchasers with bargaining power (Davidson et al. 2014). The three-regime threshold models facilitate the investigation of price asymmetries because they allow for differential responses between positive and negative effects.

The third feature is the importance of understanding how markets respond to oil shocks over time. Such information allows investors to appropriately choose hedging positions and time horizons, depending on the asymmetry and persistence of shock effects. Following a recent application (Ramsey et al. 2021), we examine time paths of shock transmission using generalized impulse response functions (GIRFs), as originally developed by Koop et al (1996).

In the next section the methods are introduced, and Section 2.3 presents the data used. Sections 2.4 and 2.5 discuss empirical results and implications.

2.2 Methods

Our empirical procedures involve two parts. First, we employ three-regime threshold vector error correction models (TVECMs) to investigate long-run equilibrium relationships and short-run price adjustments, with particular attention to thresholds and asymmetric price adjustments. Second, we use GIRFs to provide detailed information regarding shock transmissions and asymmetric adjustments over time.

2.2.1 Threshold Vector Error Correction Models

2.2.1.1 Test for cointegration and identify long-run relationships

We adopt TVECMs to analyze price pass-through between crude oil (p^C) and jet fuel (p^J) or diesel (p^D). In the first step, we identify the long-run price relationships among the two pairs of inputs, p^I, (which is p^C) and outputs, p^O, (which is p^J or p^D) at time *t* using Equation 2.1.

$$p_t^O = a + bp_t^I + u_t \tag{2.1}$$

where a and b are parameters to be estimated using OLS. If prices are measured in their logarithmic terms, b represents the price transmission elasticity that measures the long-run impact of a 1% change in p^I on p^O. The term u_t is the disturbance that represents deviations from the long-run equilibrium relationship. After estimation, we save the residuals $\hat{u}_t$ (known as the error correction term) for further analysis.

To test for long-run equilibrium relationships (i.e., cointegration), we use the Engle-Granger's (1987) two-step procedure. The Engle-Granger cointegration test is essentially a unit root test applied to the residuals obtained from the regression of the long-run relationships (in our case, the $\hat{u}_t$).[2] However, the original Engle-Granger tests assume linearity in the error correction process, which may not be appropriate if the true data-generating process is nonlinear (Pippenger and Goering 2000). Caner and Hansen (2001) develop a bootstrap method that accommodates a threshold process, which can improve the power of Engle-Granger test when the price adjustment exhibits threshold behaviors. Though the use of such method is rare in the energy economics literature, some exemptions are Apergis et al. (2017) and Fattouh (2010). We adopt this approach and further expand existing work by extending the two-regime framework to a three-regime case. More details are provided in Sections 2.2.1.2 and 2.2.1.3.

2.2.1.2 Identify threshold values and test for nonlinearity

To identify threshold values, we consider a three-regime threshold autoregressive (TAR) model recently applied by Surathkaland and Chung (2019), which allows for differentiated error-

[2] The trace-based approach proposed by Johansen (1988) is also popular, especially when investigating more than two markets. It allows researchers to test alternative numbers of cointegrating relationships. Since we are conducting pair-wise analyses and the maximum cointegrating relationship for each pair is only one, the Engle-Granger approach is sufficient.

correction behaviors across regimes:

$$\Delta\hat{u}_t = \begin{cases} \alpha_L + \beta_L\hat{u}_{t-1} + \sum_{i=1}^{p}\gamma_{Li}\Delta\hat{u}_{t-i} + \mu_{Lt}, & \hat{u}_{t-1} < \tau_L \\ \alpha_M + \beta_M\hat{u}_{t-1} + \sum_{i=1}^{p}\gamma_{Mi}\Delta\hat{u}_{t-i} + \mu_{Mt}, & \tau_L < \hat{u}_{t-1} < \tau_U \\ \alpha_U + \beta_U\hat{u}_{t-1} + \sum_{i=1}^{p}\gamma_{Ui}\Delta\hat{u}_{t-i} + \mu_{Ut}, & \hat{u}_{t-1} > \tau_U \end{cases} \tag{2.2}$$

where $\hat{u}_t$ is the residuals obtained from Equation 2.1 that represent the deviation from the equilibrium relationship between the two prices in period *t*. Lag length p is selected by the Bayesian Information Criteria (BIC). The threshold variable is $\hat{u}_{t-1}$, and threshold values τ_L and τ_U delineate alternative regimes. The model includes three regimes: lower (denoted as L), middle (denoted as M) and upper (denoted as U) regimes. The threshold value τ_L is expected to be negative and τ_U is expected to be positive and $|\tau_L| \neq |\tau_U|$, if the price adjustments are asymmetric. Accordingly, the lower regime represents adjustments to negative deviations (i.e., a relative increase in oil price) while the upper regime represents adjustments to positive deviations (i.e., a relative decrease in oil price). The middle regime represents no adjustment and exhibits random walk behaviors.

We search for thresholds among the TAR models with the method proposed by Chan (1993)[3]. The idea is that the best threshold values are found where the corresponding TAR model has the smallest sum of squared estimate of errors (SSE). First, we sort the threshold variable $\hat{u}_{t-1}$ from lowest to highest, and confine the thresholds to lie between the 15th and 85th quantiles to ensure

[3] Recent applications are in Gyamfi and Kyei (2016) and Joëts et al. (2017).

that each regime will have sufficient observations. Then, a two-dimensional grid search is employed. Instead of searching all values within this range, Hansen (1999) suggests that potential thresholds can be given by one of N grids, which largely cuts down computation time for large samples[4]. Next, Equation 2.2 is estimated $N \times N$ times to obtain a series of SSEs. The thresholds are identified when the combination of τ_L and τ_U gives the smallest SSE. In the search, we impose τ_L to be negative and τ_U to be positive, indicating relative increases and decreases in oil prices. We set N=200 and the procedures are repeated 40,000 (=200×200) times. Finally, to test whether the TAR model approach is justified, we compare the results of this model to the linear case using the Wald test with a bootstrap distribution proposed by Hansen (1999).

2.2.1.3 Nonlinear unit root tests

To investigate stationary properties of the price series, unit root tests are conducted. Existing studies in the price transmission literature, especially in agricultural and energy economics, tend to use conventional approaches like the Augmented Dickey-Fuller (ADF) tests applicable to a linear process[5]. However, such approaches are inappropriate in the presence of asymmetric adjustment where test statistics have nonstandard distributions. Therefore, we conduct nonlinear unit root tests using Caner and Hansen's (2001) bootstrap approach. Caner and Hansen (2001) discuss a two-regime case, and the few existing studies following this approach (e.g., Fattouh 2010; Maslyuk and Smyth 2009) are also based on two-regime applications. We extend their work to a

[4] A recent application of this shortcut method is Qin et al. (2016).
[5] Recent examples are Bagnai and Mongeau Ospina (2018) and Sun et al. (2019).

three-regime framework as shown in Equation 2.3. The specification is similar to Equation 2.2, but is now formulated in terms of prices p_t, instead of the residuals $\hat{u}_t$.

$$\Delta p_t = \begin{cases} \alpha_L^p + \beta_L^p p_{t-1} + \sum_{i=1}^{q} \gamma_{Li}^p \Delta p_{t-i} + \mu_{Lt}^p, & Z_{t-1} < \tau_L^p \\ \alpha_M^p + \beta_M^p p_{t-1} + \sum_{i=1}^{q} \gamma_{Mi}^p \Delta p_{t-i} + \mu_{Mt}^p, & \tau_L^p < Z_{t-1} < \tau_U^p \\ \alpha_U^p + \beta_U^p p_{t-1} + \sum_{i=1}^{q} \gamma_{Ui}^p \Delta p_{t-i} + \mu_{Ut}^p, & Z_{t-1} > \tau_U^p. \end{cases} \quad (2.3)$$

The price adjustment Δp_t is the dependent variable, and lagged prices p_{t-1} and Δp_{t-i} are regressors. The threshold variable $Z_t = p_t - p_{t-m}$ $(m \geq 1)$ is m-week price difference. We try m=1, 2, 3, and 4 and adopt m=1 because it had the larger p value and was, therefore, least likely to reject the null. Three sets of parameters $(\alpha^p, \beta^p, \gamma_i^p)$ are estimated conditional on threshold values τ_L^p and τ_U^p, following the same procedure as discussed in Section 2.2.1.2. The corresponding linear model (i.e., the linear ADF test specification) is:

$$\Delta p_t = \alpha_0^p + \beta_0^p p_{t-1} + \sum_{i=1}^{q} \gamma_{0i}^p \Delta p_{t-i} + \mu_{0t}^p \quad (2.4)$$

which is compared to the nonlinear model from Equation 2.3. Parameters β_L^p and β_U^p are investigated to test for a unit root. The null hypothesis of the unit root test is H_0: $\beta_L^p = \beta_U^p = 0$, and the alternative H_1: $\beta_L^p < 0, \beta_U^p < 0$ suggests a stationary threshold data generating process. No restriction is imposed for the unresponsive regime. Since the distribution of the statistic is unconventional, we follow Caner and Hansen (2001) and adopt a bootstrap approach (with 1000 replications). The bootstrap distribution of the test statistic is used; we can reject the null of unit roots and in favor of a threshold stationary process if p ≤ 0.05.

2.2.1.4 Estimate the threshold error correction models

To capture short-run adjustment patterns, we estimate three-regime vector error correction models conditional on the identified thresholds:

$$\Delta \boldsymbol{y}_t = \begin{cases} \boldsymbol{\pi}_L + \sum_{i=1}^{p} \Pi_{Li} \Delta \boldsymbol{y}_{t-i} + \boldsymbol{\delta}_L \hat{u}_{t-1} + \boldsymbol{\varepsilon}_{Lt}, & \hat{u}_{t-1} < \tau_L \\ \boldsymbol{\pi}_M + \sum_{i=1}^{p} \Pi_{Mi} \Delta \boldsymbol{y}_{t-i} + \boldsymbol{\delta}_M \hat{u}_{t-1} + \boldsymbol{\varepsilon}_{Mt}, & \tau_L < \hat{u}_{t-1} < \tau_U \\ \boldsymbol{\pi}_U + \sum_{i=1}^{p} \Pi_{Ui} \Delta \boldsymbol{y}_{t-i} + \boldsymbol{\delta}_U \hat{u}_{t-1} + \boldsymbol{\varepsilon}_{Ut}, & \hat{u}_{t-1} > \tau_U \end{cases} \tag{2.5}$$

where $\Delta \boldsymbol{y}_t = [\Delta p_t^I, \Delta p_t^O]'$ is a vector of price returns of input (oil) and outputs (jet fuel or diesel). The threshold variable $\hat{u}_{t-1}$, often known as the error correction term, is composed of the lagged residuals obtained from Equation 2.1. The subscripts L, M, and U denote lower, middle and upper regimes respectively. The threshold values τ_L and τ_U are specified with the procedure discussed in Section 2.2.1.2. Lag length p of price returns is determined by BIC. The vector parameter $\boldsymbol{\pi}$ includes constant terms. Matrix parameters Π_i capture lagged effects of own and cross price adjustments, and the vector $\boldsymbol{\delta}$ represents speed of adjustment, which describes the direction and magnitude of price adjustments. The parameters are estimated with Vector Autoregression (VAR). If threshold effects are present, we anticipate the estimated $\widehat{\boldsymbol{\delta}}_L$ and $\widehat{\boldsymbol{\delta}}_U$ to be different. The middle, unresponsive regime, $\widehat{\boldsymbol{\delta}}_M$, is expected to be statistically insignificant.

2.2.2 Generalized Impulse Response Functions

Studies that use regime switching models do not generally calculate impulse responses (e.g., Surathkal and Chung 2019; Ters and Urban 2020), largely because nonlinear impulse response functions depend on histories (i.e., initial states) and sizes and signs of shocks. Performing nonlinear impulse response analyses and organizing/presenting the results in a meaningful way are challenging. To provide information about how markets respond to oil price shocks over time, we follow Koop et al.'s (1996) approach to investigate the behaviors of GIRFs[6].

GIRFs can be computed by simulating two sets of realizations over a forecast horizon, with and without an initial shock, and then averaging out differences between the two realizations. The GIRF formula is:

$$GIRF_{\Delta y}(n, V_t, \Omega_{t-1}) = E[\Delta y_{t+n} | V_t, \Omega_{t-1}] - E[\Delta y_{t+n} | \Omega_{t-1}] \tag{2.6}$$

where n denotes the forecast horizon, V_t represents an initial shock of specific sign and size at time t, and Ω_{t-1} incorporates historical information.

The adjustment dynamics are initially governed by parameters of the corresponding regime of the starting point (i.e., history), but can be affected by parameters of other regimes during the forecast horizon, depending on the size and sign of the shocks as well as the history. Larger shocks, or shocks with a starting point closer to thresholds, are more likely to trigger regime-switching behaviors than other situations. We simulate possible histories using each observation as a starting point. For each history, we simulate 800 pairs of realizations with and without the initial shock.

[6] Recent applications of GIRFs include Joëts et al. (2017) and Valadkhani et al. (2015).

GIRFs are calculated based on averages of the 832,000 (=800×1,040 histories) simulated results. This approach differs from traditional practices (e.g., Goodwin and Piggott 2001), which compare realizations at only one point in the sample and may therefore lose generality. To compare adjustment patterns across different regimes, we calculate regime-specific GIRFs for positive and negative shocks following Goodwin et al. (2011). We restrict the initial draw of histories from a specific regime, so the initial responses are simulated using the estimated coefficients in that regime. However, we do not limit the sequential responses to behave according to the coefficients of the initial regime; we allow the adjustment path to be regime-dependent depending on the forecasted threshold variable $\hat{u}_{t-1}$. We also investigate the 2007-2008 financial crisis by simulating GIRFs using the 2007-2008 data as initial draws. Such analysis can provide valuable information of market performance under extreme conditions.

Shocks are randomized from the variance-covariance matrix, obtained from the TVECM, which requires normalization by Cholesky factors. The unit of shock size is defined as the value of standard deviations of price returns. In other words, one unit of oil shock refers to a standard deviation (SD) of price return. In the empirical analysis, we investigate impacts of one- and three-SD shocks, both positive and negative, which we denote as $+$ and $-$.

2.3 Data

Our empirical application uses weekly price data of crude oil, jet fuel, and diesel from January 2000 to December 2019. For crude oil, we select West Texas Intermediate Oil Prices since they are a benchmark in the United States (U.S.). U.S. Gulf Coast Kerosene-Type Jet Fuel Spot Prices are selected to analyze the jet fuel market, and U.S. No 2 On-Highway Diesel Prices are selected for the diesel market. These data are from the EIA.

Figure 2-1 plots the price series of crude oil, jet fuel and diesel prices. All three series show substantial fluctuations over time and appear to be nonstationary. Visual inspection discloses a high degree of price co-movements, for up- and downturns, between the three series. The highest prices during our sample period occur around the 2007-2008 global financial crisis. Summary statistics are provided in Table 2-1.

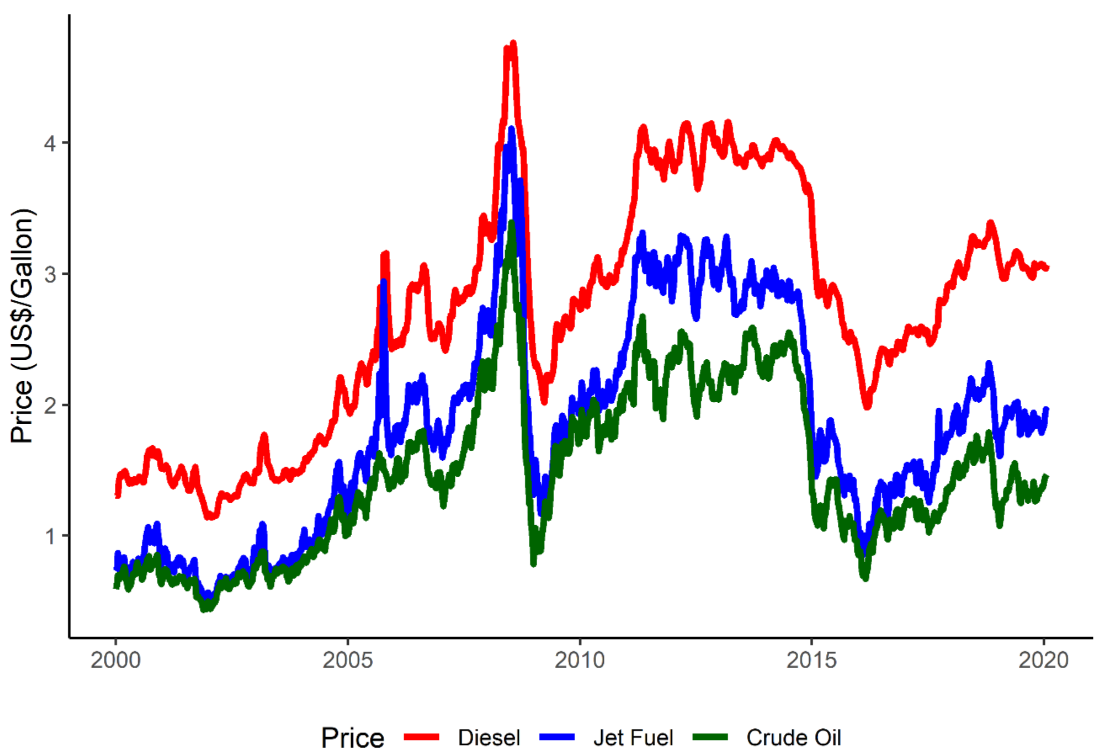


Figure 2-1: Weekly prices: crude oil, jet fuel and diesel in the U.S.

Source: EIA n.d.

Table 2-1: Summary statistics of price levels for crude oil, jet fuel and diesel (N = 1044)

	Crude Oil p_t^C	Jet Fuel p_t^J	Diesel p_t^D
Mean	1.471	1.834	2.712
Std. Dev.	0.624	0.813	0.895
Minimum	0.435	0.475	1.140
Maximum	3.393	4.109	4.764
Skewness	0.390	0.328	0.006
Kurtosis (excess)	-0.709	-0.785	-0.983

2.4 Results

2.4.1 Threshold Error Correction Models

2.4.1.1 Unit root tests

Table 2-2 contains nonlinear and linear unit root tests. We use logarithmic transformations of the three price series with the tests presented in Section 2.2.1.3. Results from the nonlinear unit root tests indicate a failure to reject the null hypothesis of unit roots. Therefore, we have no evidence that the price series exhibit nonlinear stationarity, and the conventional linear tests shall be appropriate. According to Table 2-2, the conventional ADF unit root test results fail to reject the null hypothesis of unit roots when price levels are examined, but reject the null when first differences are investigated. Taken together, results support the notion that the price series are integrated of order one (i.e., $I(1)$).

Table 2-2: Unit root tests

	Crude Oil p_t^C		Jet Fuel p_t^J		Diesel p_t^D	
	Test Statistics	P-Values	Test Statistics	P-Values	Test Statistics	P-Values
Nonlinear Unit Root Test	7.749	0.327	10.801	0.086	3.148	0.628
ADF Test: for price levels	-2. 091	0.248	-1.999	0.287	-1.813	0.374
ADF Test: for first-differenced prices	-15.214	0.000	-17.812	0.000	-12.279	0.000

Note: Price series are in natural logs. We use the BIC to specify the optimal lag length in the tests: 4 periods for crude oil price, 3 periods for jet fuel price, and 4 periods for diesel price. ADF tests for first-differenced prices use lag lengths that are one period less those used for tests on price levels.

2.4.1.2 Long-run price relationships

With the price series accepted as being $I(1)$, we test for long-run price relationships with cointegration tests. Results of cointegration tests are presented in Table 2-3. Results indicate that the pair-wise series are cointegrated, and that there are long-run price relationships between crude oil and jet fuel/diesel. Table 2-3 also reports estimation of the long-run price relationships; the coefficient of p_t^C represents price pass-through elasticities and is our focus. For jet fuel, the p_t^C coefficient is 1.06, suggesting that a 1% change in oil price is associated with a 1.06% change in jet fuel price. For diesel, the p_t^C coefficient indicates that a 1% change in oil price is associated with a 0.76% change in the price of diesel. These results are similar to prior studies estimating long-run price relationships between oil and jet fuel or diesel (Asche et al. 2003; Gjølberg and

Johnsen 1999; Liu et al. 2010). Overall, in the long run, both jet fuel and diesel markets are associated with oil market and thus vulnerable to oil price fluctuations.

Table 2-3: Cointegration tests and estimation of long-run relationships

	Jet Fuel and Oil		Diesel and Oil	
	Test Statistics	P-Values	Test Statistics	P-Values
Engle-Granger Cointegration Test	-5.795	0.000	-4.292	0.000
Cointegrating relationship	$p_t^J = 0.189 + 1.063 p_t^C$ (0.003) (0.006)		$p_t^D = 0.718 + 0.757 p_t^C$ (0.004) (0.006)	

Note: Standard errors are reported in parentheses.

2.4.1.3 Short-run asymmetric price adjustments

Table 2-4 presents results of nonlinearity tests for model selection using the bootstrap procedures of Hansen (1999) discussed in Section 2.2.1.2. The p-values suggest threshold models outperform the linear models. We thus present the results of the identified threshold values and coefficients obtained from the TVECMs that use Equation 2.5.

Table 2-4: Nonlinearity tests

	Jet Fuel and Oil		Diesel and Oil	
	Test Statistics	P-Values	Test Statistics	P-Values
Nonlinearity Test	72.051	0.000	28.767	0.036

For jet fuel (Table 2-5), the threshold values are found to be -0.013 and 0.082. The $\hat{u}_{t-1}$ coefficients represent speeds of adjustment toward the long-run price equilibrium for each regime.

For the upper regime ($\hat{u}_{t-1}$ >0.082), the speed of adjustment is -0.210, whereas for the lower regime ($\hat{u}_{t-1}$ <-0.013) the coefficient is insignificant. These results suggest that jet fuel prices only react to large positive deviations (i.e., relative drops in oil prices) that are greater than 8.2% of jet fuel returns, and correct for 21.0% of the deviation in the following week. In response to large negative deviations (i.e., relative increases in oil prices), jet fuel refiners might hesitate to raise jet fuel prices; otherwise they could lose price-sensitive purchasers (e.g., airports) because demand for air travel and for jet fuel are relatively elastic and concentrated fuel purchasers might exercise market power (Davidson et al. 2014). These results are consistent with the findings of Kaufmann (2017), that jet fuel prices adjust faster to oil price decreases than oil price increases. Kaufmann (2017) argues that the (upward) price rigidity of jet fuel stems from pricing strategies of fuel refiners based on considerations of inventory holding costs and consumer demand. Given the rigidity of refinery yields, jet fuel refiners pay careful attention to inventory management. If fuel refiners rapidly transmit increased oil costs to jet fuel prices, price-sensitive consumers might slow down purchasing, which would add to the inventories of refiners. Conversely, if the increased oil costs are slowly transmitted, the anticipation of additional increases in jet fuel prices might promote consumption. However, the slow transmission of decreased oil costs could drive purchasers to postpone consumption in anticipation of additional decreases in jet fuel prices. Therefore, fuel refiners may adjust jet fuel prices quickly to falling oil prices. For the middle band, the speed of adjustment value is insignificant, confirming a band of no adjustment. The lack of adjustment could arise from prohibitive menu costs that exceed benefits of adjustments. Jet fuel price adjustments are also affected by own and cross price adjustments with different lags, suggested by significant estimates of lagged price differences. Crude oil prices are shown to not adjust toward deviations, which is intuitive given the large size of the crude oil market relative to the smaller jet fuel market.

For diesel (Table 2-6), the threshold values are -0.037 and 0.069. The speed of adjustment in the lower regime ($\hat{u}_{t-1}$ <-0.037) is estimated to be -0.064, but is insignificant in the upper regime ($\hat{u}_{t-1}$ >0.069). That is, diesel prices only react to relative increases in oil prices that are greater than 3.7% of diesel returns, and in the following week correct for 6.4% of the deviation. These results are consistent with some prior studies on diesel asymmetric pricing (Bastianin et al. 2014; Fosten 2012; Valadkhani et al. 2015). Diesel producers could exercise market power to increase profits owing to concentrated production and limited competition (Fosten 2012) along with relatively inelastic demand (Dahl 2012; Liu et al. 2010). As per jet fuel, a non-adjustment middle regime is also confirmed in the diesel results.

Table 2-5: Estimation of TVECM for jet fuel and crude oil

	Jet fuel return Δp_t^J		Crude oil return Δp_t^C	
	Coefficient	Std Error	Coefficient	Std Error
Lower Regime: $\hat{u}_{t-1} < -0.013$				
Constant	0.005	0.004	0.000	0.003
$\hat{u}_{t-1}$	-0.025	0.047	-0.008	0.045
Δp_{t-1}^J	0.335***	0.076	0.192***	0.072
Δp_{t-2}^J	-0.109	0.076	-0.002	0.072
Δp_{t-1}^C	-0.092	0.081	0.086	0.076
Δp_{t-2}^C	0.021	0.082	-0.062	0.077
Middle Regime: $-0.013 < \hat{u}_{t-1} < 0.082$				
Constant	-0.003	0.003	-0.002	0.003
$\hat{u}_{t-1}$	0.024	0.073	0.060	0.070
Δp_{t-1}^J	-0.008	0.073	0.110	0.070
Δp_{t-2}^J	-0.001	0.067	0.013	0.065
Δp_{t-1}^C	0.218***	0.076	0.152**	0.073
Δp_{t-2}^C	-0.104	0.073	-0.029	0.070
Upper Regime: $\hat{u}_{t-1} > 0.082$				
Constant	0.023*	0.011	-0.008	0.013
$\hat{u}_{t-1}$	-0.210**	0.080	0.044	0.090
Δp_{t-1}^J	0.345***	0.088	-0.129	0.098
Δp_{t-2}^J	-0.014	0.101	0.331***	0.113
Δp_{t-1}^C	0.094	0.085	0.059	0.095
Δp_{t-2}^C	-0.132	0.084	-0.325***	0.094

Note: ***, **, * denote 1%, 5% and 10% levels of significance, respectively.

Table 2-6: Estimation of TVECM for diesel and crude oil

	Diesel return Δp_t^D		Crude oil return Δp_t^C	
	Coefficient	Std Error	Coefficient	Std Error
		Lower Regime: $\hat{u}_{t-1} < -0.037$		
Constant	-0.005***	0.001	-0.000	0.005
$\hat{u}_{t-1}$	-0.064***	0.014	-0.027	0.051
Δp_{t-1}^D	0.434***	0.049	0.091	0.176
Δp_{t-2}^D	-0.117**	0.053	-0.126	0.191
Δp_{t-3}^D	0.098***	0.034	-0.129	0.123
Δp_{t-1}^C	0.252***	0.016	0.180***	0.056
Δp_{t-2}^C	-0.024	0.020	-0.107	0.072
Δp_{t-3}^C	0.036***	0.019	0.060	0.068
		Middle Regime: $-0.037 < \hat{u}_{t-1} < 0.069$		
Constant	-0.001	0.001	0.003	0.002
$\hat{u}_{t-1}$	-0.001	0.022	-0.110	0.072
Δp_{t-1}^D	0.429***	0.051	0.217	0.169
Δp_{t-2}^D	-0.113**	0.057	0.434**	0.187
Δp_{t-3}^D	0.045	0.056	-0.513***	0.185
Δp_{t-1}^C	0.195***	0.018	0.252***	0.059
Δp_{t-2}^C	0.029	0.019	-0.283***	0.062
Δp_{t-3}^C	0.055***	0.020	0.030	0.067
		Upper Regime: $\hat{u}_{t-1} > 0.069$		
Constant	-0.002	0.002	-0.016**	0.007
$\hat{u}_{t-1}$	0.003	0.010	0.125**	0.049
Δp_{t-1}^D	0.347***	0.056	0.359	0.263
Δp_{t-2}^D	-0.078	0.058	-0.231	0.273
Δp_{t-3}^D	0.176***	0.044	0.218	0.209
Δp_{t-1}^C	0.122***	0.013	0.200***	0.059
Δp_{t-2}^C	0.058***	0.015	-0.027	0.071
Δp_{t-3}^C	0.036**	0.015	0.145**	0.070

Note: ***, **, * denote 1%, 5% and 10% levels of significance, respectively.

2.4.2 Generalized Impulse Response Functions

In the previous section, we demonstrate that jet and diesel prices have different adjustment dynamics in three different regimes, as reflected in three sets of different coefficients. Now, we present the results of price responses to specified shocks originating from the oil market using GIRFs illustrated in Section 2.2.2.

In Figure 2-2, we present GIRFs that show 30-week projections of jet fuel and diesel return responses to positive and negative oil shocks simulated at 2 levels: a 1-SD (i.e., 4%) change in oil price returns, and a 3-SD change in oil price returns. For jet fuel (Panel A), price responses to a 1-SD shock are much smaller than large shocks, both positive and negative, with a greater instantaneous response to negative shocks. The impact of small shocks (i.e., responses below 0.1%) lasts about 20 weeks and large shocks are more persistent and gradually die out after the 30th week. The response to a 3-SD negative shock has a quick drop-and-rebound, and a temporary overshoot, while the response pattern to a 3-SD positive shock is simpler with less fluctuations. The reaction of jet fuel prices to rising oil prices is much smaller than that of falling oil prices. This finding is consistent with the conclusion drawn by our short-term error correction analysis. This performance of jet fuel prices may reflect relatively fixed yields of jet fuel production and an elastic demand for air travel and for jet fuel, which might provide fuel purchasers with bargaining power (Davidson et al. 2014; Kaufmann 2017). This response may also reflect the pricing strategy of refiners who may have different pricing strategies in response to rising and falling oil prices (Kaufmann 2017).

In a linear setting, the generated impulse response functions would be symmetric and proportional; a situation that our GIRF results contradict. Panel A clearly shows that jet price responses are asymmetric to positive and negative oil shocks (where negative shocks have larger instantaneous impacts than positive shocks) and are disproportional to small and large oil shocks. These nonlinear attributes for jet fuel price adjustments add complexity for managing price risks in this industry.

The price responses of the diesel market to oil shocks are different to those in jet fuel markets. Panel B illustrates diesel prices respond to both small and large shocks, and the price reaction to a large positive shock is greater than to a large negative shock. The impact of the shock disappears within 8 weeks, indicating that the diesel market is more efficient than the jet fuel market in adjusting to shocks. In jet fuel markets, as shown above, the impact of a big oil shock can last for more than 30 weeks. The GIRF plots also indicate that diesel responses are simpler than jet fuel, as there are no up and down fluctuations as the response diminishes. This result could be because the diesel market is large and stable, and less demand-elastic than jet fuel, therefore exhibiting more stable adjustment patterns. Conversely, the jet fuel market is concentrated and has relatively price-sensitive purchasers, whose price adjustments might be sensitive to reactions of a few purchasers. The nonlinear attributes, including asymmetry and disproportionality, are not as obvious with diesel as in the jet fuel market.

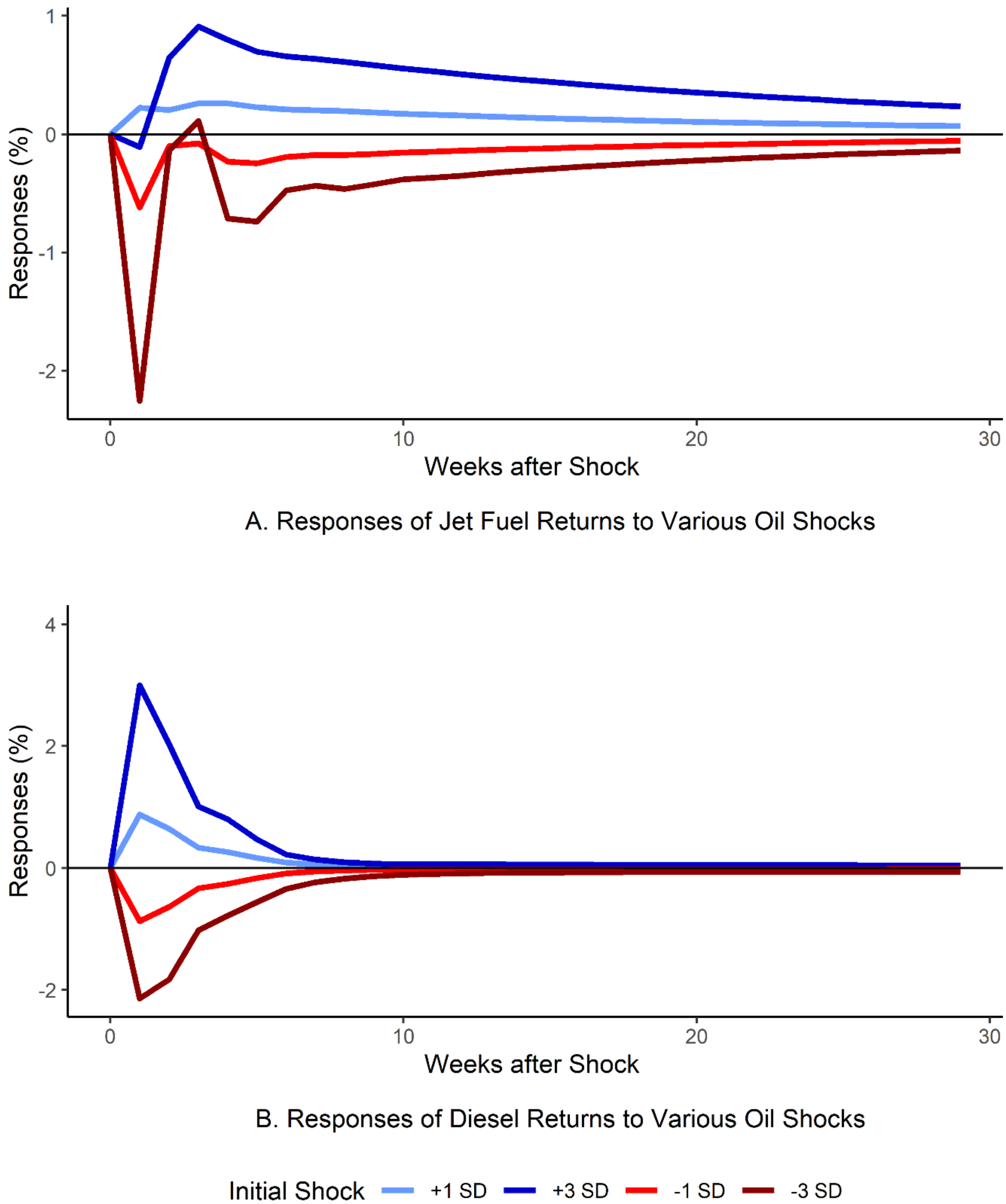


Figure 2-2: General-case GIRFs: nonlinear responses of jet fuel and diesel returns to oil price shocks

Results so far, we have been simulating general-case GIRFs, which are based on histories drawn from anywhere within the three regimes. Next, we investigate GIRFs from histories within each regime by generating regime-specific GIRFs. If regime-switching happens only occasionally, then we would expect the general-case GIRFs to be similar to the regime-specific results. If regime-switching happens frequently, we would expect the two sets of results to be substantially different from one another.

Figure 2-3 presents, respectively, the regime-dependent GIRFs of jet fuel and diesel for 1-SD oil price shocks. Results indicate that for jet fuel (Panel A), the GIRF paths vary considerably across regimes in terms of the response magnitude and persistency. Jet fuel price has the greatest response to the oil shock in the upper regime, which has a higher probability of inducing regime-switching than other regimes. Compared with the general-case GIRFs in Figure 2-2A, the instantaneous response of jet fuel price adjustments to the oil shock in the upper regime is more than twice as large as the shock that is non-regime-specific, but the positive oil shock in the lower regime causes a much smaller, almost zero, instantaneous response. The negative 1-SD middle-regime shock leads to a temporary overshoot, which does not happen for the non-regime-specific shock. But the general patterns of the regime-specific and general-case GIRFs are similar in that all paths have ups and downs. Unlike the jet fuel results, the GIRFs of diesel prices display similar patterns (e.g., trend, magnitude and persistence) across regimes (Panel B), despite differences in the magnitude of responses in the first two weeks. The regime-specific GIRFs are also similar to the general-case GIRFs (Figure 2-2B). These results indicate that the diesel price responses are more robust and less sensitive to shocks from different market conditions. Diesel prices have the largest initial response to the oil shock in the lower regime. Although the regime-dependent GIRF behaviors are consistent with the regime-switching short term price adjustments, note that GIRF and TVECM measure two different aspects of price dynamics. The former focuses on price response to market shocks, while the latter emphasizes price adjustments toward the long-term equilibrium.

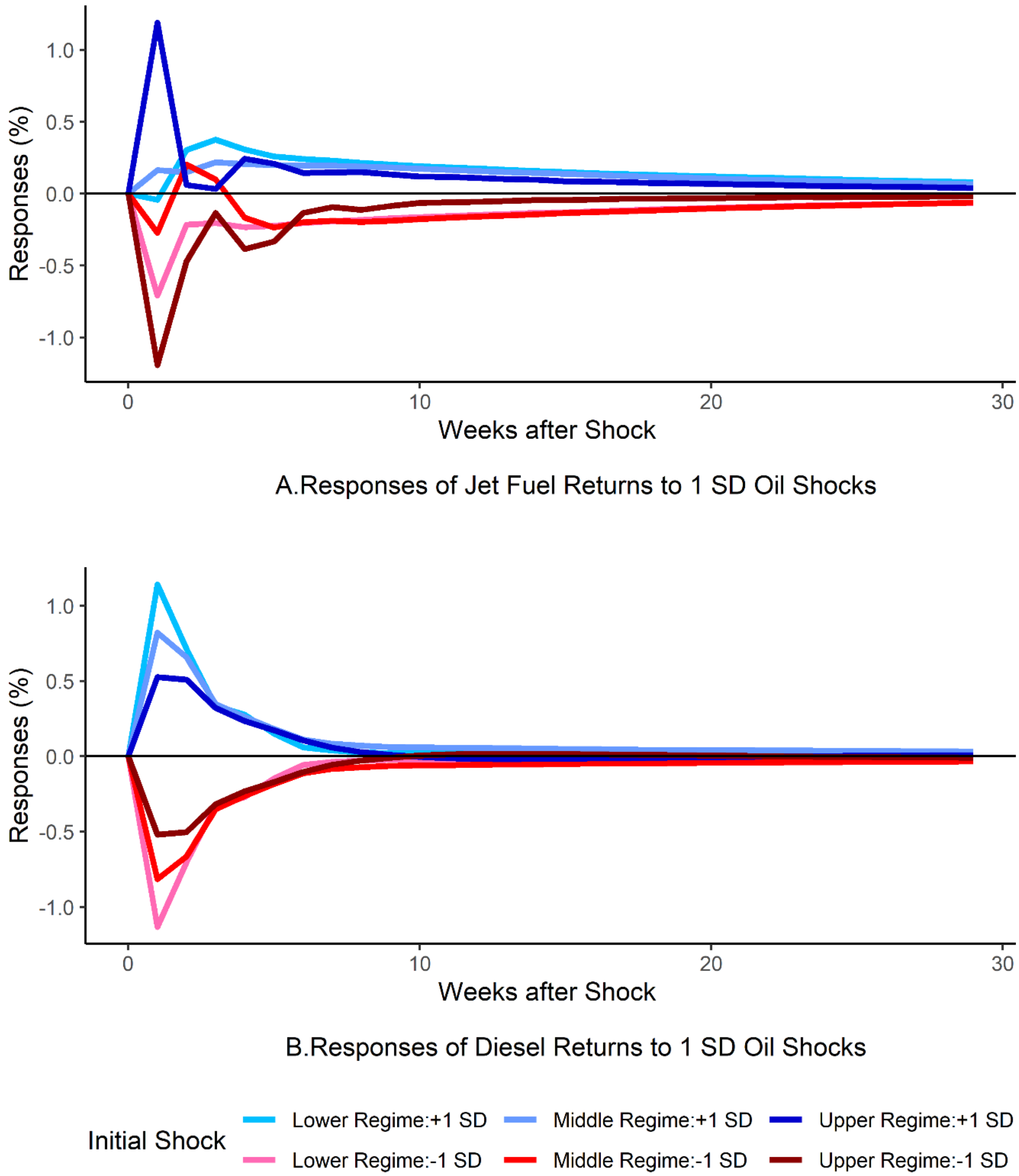


Figure 2-3: Regime-specific GIRFs: nonlinear responses of jet fuel and diesel returns to oil price shocks

Thus far we have shown GIRFs that reflect shocks across the entire study period. Figure 2-4 shows GIRFs at a specific history, associated with the largest oil spike during our sample. That is, we use a starting point on September 22nd, 2008, during the financial crisis, when oil prices increased by $0.33/gallon. The patterns of price responses are quite different from those in the general cases presented in Figure 2-2. For example, as shown in Panel A, in response to negative 3-SD shocks, jet fuel returns decrease by over 4% during the oil spike, while decreasing only by approximately 2% during a normal period (Figure 2-2A). Regardless of whether jet fuel is affected by positive or negative shocks, during the oil spike period, the initial market reaction is always a sharp drop in prices and then a rebound. The lagging, or sometimes opposite-direction, responses to positive shocks potentially show that jet fuel refiners might be hesitant to raise prices instantaneously for their price-sensitive purchasers. Panel B displays the GIRFs of diesel price. Unlike the jet fuel case, diesel prices react in the same direction with oil shocks; a positive oil shock causes a positive adjustment to diesel price, and a negative shock causes a negative adjustment. Different from the general market situation (Figure 2-2B), diesel price GIRFs show obvious asymmetry during the oil spike. The magnitude of responses to a large positive shock is greater than a large negative shock. However, the impact from a large negative shock lasts longer, persisting after 20 weeks. These results indicate that jet fuel and diesel prices are much more vulnerable to oil shocks during special events (such as oil price spikes) than more normal periods, indicating that special considerations in risk management may be useful.

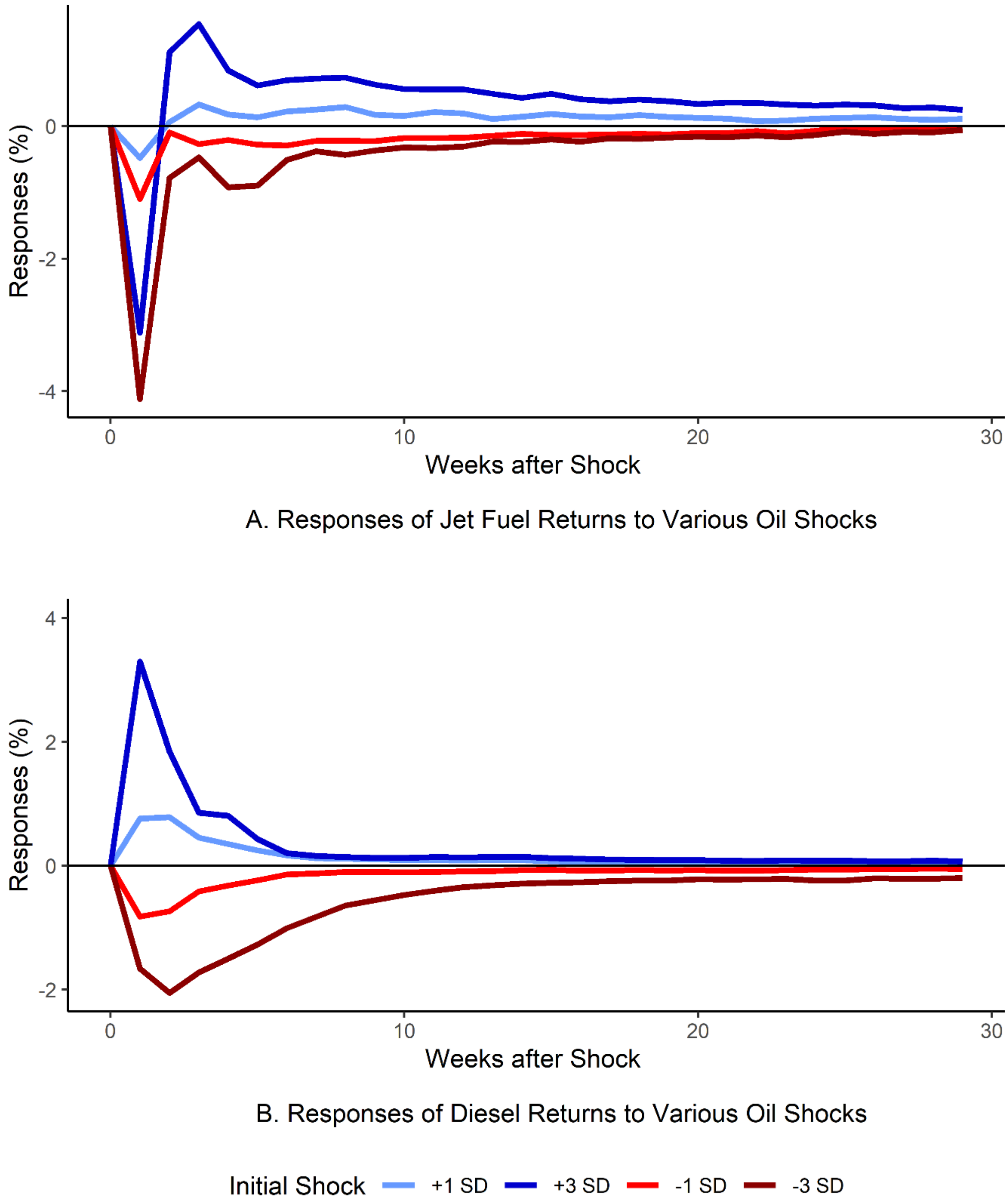


Figure 2-4: GIRFs during the financial crisis: nonlinear responses of jet fuel and diesel returns to oil price shocks

Finally, to visualize the overall asymmetric impacts of positive and negative oil shocks, following Rahman and Serletis (2011) and van Dijk et al. (2007), we plot the density distribution of asymmetry measures for jet fuel and diesel overall GIRFs in Figure 2-5. If the distribution is symmetric with a zero mean, then positive and negative shocks have identical effects. In contrast, if the distribution exhibits skewness and a nonzero mean, we can conclude that the shock responses exhibit asymmetry. The results indicate that jet fuel prices react differently to positive and negative oil shocks in the first few weeks, and that negative shocks have larger instantaneous impacts on jet fuel returns (Panels A and B). However, over time, usually after 4 to 5 weeks, the asymmetry decreases to zero. The diminishing asymmetry may be because the price responses to positive and negative shocks tend to be the same, or because the influences of both positive and negative shocks die out over time. For diesel returns (Panels C and D), small shocks have relatively symmetric effects while large positive shocks have larger impacts than large negative ones within the first two weeks.

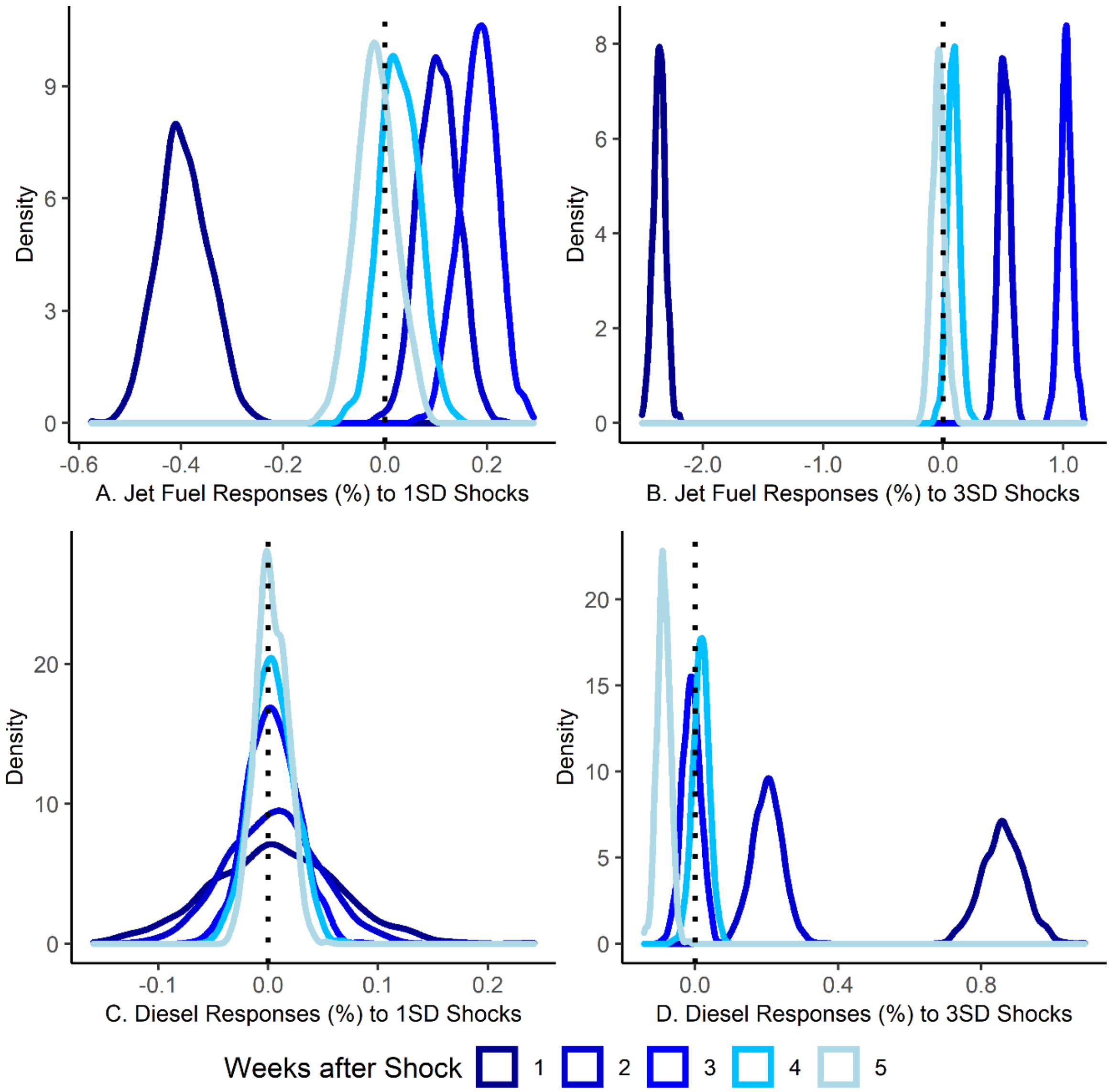


Figure 2-5: GIRF asymmetry measures to oil price shocks

2.5 Conclusions and Implications

This study uses time-series techniques, tailored to market conditions, to investigate linkages between oil prices and jet fuel and diesel. We find that both jet fuel and diesel have long-run equilibrium relationships with oil prices, but that these relationships differ. If oil prices change 1%, jet fuel prices adjust 1.06% while diesel prices adjust only 0.76%. In the short term, both price adjustments are asymmetric, but in opposite directions because of the distinct differences in industrial characteristics. Jet fuel only responds to relative decreases in oil prices while diesel only responds to relative increases. Jet fuel and diesel are unresponsive to minor changes, which is consistent with the menu costs or pricing strategy hypothesis. Impulse response analysis shows the dynamic paths of oil shock effects and exhibits nonlinear responses, with varying amplitudes and diminishing periods.

The empirical results contribute to a better understanding of the fuel industries and offer implications to businesses and policymakers. Due to the linkages with volatile oil prices, jet fuel and diesel undergo substantial price fluctuations, which expose fuel-refining and fuel-consuming companies to commodity price risks and require appropriate risk management strategies. These strategies currently involve hedging with swaps, futures, and options (Adams and Gerner 2012), but could also include adopting alternatives to oil as an input source, such as biomass feedstock, to make biojet and biodiesel. Such a change could work as an effective risk mitigation strategy to make production less susceptible to oil price fluctuations by diversifying input supply (Valadkhani et al. 2015). Reducing the price fluctuation risks from crude oil shocks could be a key factor incenting the development of biofuel industries.

Such risk management considerations may not weigh heavily for diesel producers who are able to take advantage of producer market power (Fosten 2012) and a relatively inelastic demand (Liu et al. 2010), allowing them to maintain, or perhaps even expand, profit margins when oil prices decrease. Impulse response functions also indicate that, if hedging tools are desired by diesel refineries and consumers, a horizon of two months with decreasing intensity may be sufficient.

The story is somewhat different for jet fuel. Our results show that jet fuel prices, both in the long and short terms, are more vulnerable to oil price fluctuations than diesel prices. In the long term (long-run factors like environmental regulations and switching to alternative fuels; Davidson et al. 2014; EIA 2021), prices of jet fuel inventories fluctuate with oil price changes to a higher degree than diesel. In response to short-term price adjustments (e.g., natural disasters and refinery outages; EIA 2021), jet fuel producers with stable refinery yields (Kaufmann 2017) might be hesitant to pass increased oil costs through to relatively price-sensitive purchasers. Therefore, risk management is especially important for jet fuel producers.

The information from the impulse responses to oil shocks is also relevant to jet fuel market participants in terms of hedging horizons. In general, the effect of an oil shock on jet fuel returns can be long lasting; approximately six months in our simulations, indicating the need for a long hedging horizon. But jet fuel futures contracts with maturities longer than three months tend to be illiquid (Adams and Gerner 2012) and thereby increase holding costs and decrease hedge effectiveness (Lim and Turner 2016). Therefore, it could be advantageous for producers (large refineries such as Exxon Mobil, Chevron, and BP p.l.c.) to purchase multiple, overlapping contracts to cover longer time horizons.

Given the importance of stabilizing input costs in businesses, major consumers of jet fuel, such as airlines, also require hedging as jet fuel constitutes approximately 33% of operating costs incurred by the airline industry (Berghöfer and Lucey 2014). Besides financial hedging, airlines are reducing price risk exposure with an increasing use of operational hedging, which involves replacing real options with high fuel efficiency (Swidan and Merkert 2019). Some airlines (e.g., Delta Air Lines Inc.) have considered purchasing refineries, thereby hedging through vertical integration. But the hedging strategies above still rely on crude oil as the input source and might not help jet fuel industrialists mitigate oil price impacts from a long-term perspective (Berghöfer and Lucey 2014). Moreover, the large variations of impulse responses to changing markets indicate difficulties in predicting impacts of oil prices, particularly on jet fuel, and uncertainty to how successful hedging efforts can be. Therefore, diversifying away from fossil fuels to an alternative energy source, like biojet, could be an important risk management strategy.

Though many discussions regarding opportunities for biojet center around government policies and prospects for reducing GHG emissions, the underlying price structures of markets could also promote their development. The difficulty of jet fuel producers to pass on increased costs from fluctuating oil prices, and difficulties with long-term hedging strategies, could increase incentives for jet fuel producers to move towards input diversification with biojet in the long run (Davidson et al. 2014). Though technology may take years to be financially viable, the price relationships underlying current production could attract biojet producers to such technology, eventually allowing them to penetrate the aviation fuel market. If government policies wish to work in concert with underlying market phenomenon, information about underlying price relationships can be critical.

Chapter 3: Potential Fuel-grade Supplies of Canola Oil for Low-Carbon Fuel Production: An Economic GIS-Based Analysis in Alberta

3.1 Introduction

Governments worldwide are promoting low-carbon fuels – such as biodiesel, renewable diesel, biojet, and other blended and co-processed fuels – to reduce GHG emissions in response to climate change. To meet its Paris Agreement commitment, the Government of Canada proposed new regulations for the Clean Fuel Standard (CFS) in 2020 aiming to reduce the carbon intensity of fuels, which could provide a considerable demand-pull for biofuel and bio-feedstock.

Vegetable oil is a commonly used biofuel feedstock (Carvalho et al. 2019; van Dyk et al. 2019) particularly in Canada (BBI International 2020; Zemanek 2018). For generating vegetable oil, canola[7] is the predominant oilseed produced in Canada, accounting for approximately 74% of Canadian oilseed production (U.S. Department of Agriculture (USDA) 2021) and 28% of global canola/rapeseed production (Statista 2021). In 2020, 8.4 million hectares of canola were planted in Canada (mostly in the prairie provinces of Alberta, Saskatchewan and Manitoba; Canola Council of Canada 2021) with an average yield of 2.25 tonnes per hectare, producing 18.7 million metric tonnes (MMT) of seed (Canola Council of Canada 2020). Canola/rapeseed is also an important oilseed worldwide, accounting for 12% of global oilseed production in 2020, ranking second after soybean (61%) (Statista 2021).

[7] Canola, the name of which derives from Canadian oil, is a variety of rapeseed (originally cultivated in Europe and Asia) that was developed for production in Canada and has low erucic acid for human consumption (Canola Council of Canada n.d.).

Canola has excellent lifecycle carbon intensity characteristics (Ge et al. 2017) and has been widely studied and used for low-carbon fuel production worldwide (Canadian Canola Growers Association 2018; Jang et al. 2012; Miller and Kumar 2013; Ukaew et al. 2016). For example, canola/rapeseed oil is the dominant feedstock for biodiesel and renewable diesel production in the European Union (EU), accounting for 38% of total feedstock use in 2020 (USDA 2021). Canola is also an approved feedstock under the U.S.' Renewable Fuel Standard II (RFS; U.S. Environmental Protection Agency (EPA) n.d.) and canola oil biodiesel qualifies as both advanced biofuel and biomass-based diesel, which meets the lifecycle GHG emission reduction threshold of 50% (EPA 2010). It is a common biodiesel feedstock choice in the U.S., ranking third after soybean and corn oil in 2020 (EIA 2021).

Canada also uses canola oil as the main feedstock for biodiesel production. The annual capacity of Canadian biodiesel plants was 650 million liters in 2020 (Biodiesel Magazine 2020), with over 50% produced from canola oil (BBI International 2020). Archer-Daniels-Midland's (ADM) biorefinery in Lloydminster, Alberta, is the largest Canadian biodiesel plant with an annual capacity of 284 million liters, and uses canola oil (BBI International 2020).

Global markets for canola-based biodiesel and renewable diesel are established, but the canola-based biojet market is still under development (Canadian Canola Growers Association 2018). The market potential for canola-based biojet could be large given environmental and fuel security concerns of the aviation industry (Wang and Tao 2016). The global aviation sector is currently responsible for 12% of transport-related CO2 emissions and around 2% of humaninduced CO_2 emissions (Air Transport Action Group 2020). Consequently, the International Air Transport Association has established goals to reduce GHG emissions by 50% by 2050, relative to 2005 levels. Within the Canadian context, Air Canada has also committed to an ambitious net-zero emissions goal by 2050 (Air Canada n.d.). Canola-based biojet could play a role in meeting these targets because it can reduce lifecycle CO_2 emissions by over 60% compared to conventional jet fuel (Zemanek et al. 2020).

There are also operational considerations which could favor canola-based biojet. Given that jet fuel costs account for approximately 33% of airlines' operating expenses (Berghöfer and Lucey 2014), the security of fuel supply is a concern. By replacing volatile crude oil with bio-feedstock like canola, biojet could help increase supply security (Davidson et al. 2014; Wang and Tao 2016). Therefore, canola-based biojet has gained increasing research attention (Sieverding et al. 2016; Ukaew et al. 2016; Zemanek et al. 2020).

Co-processing operations, which use bio-feedstocks together with crude oil to produce low-carbon fuels (e.g., gasoline, diesel, and jet fuel; van Dyk et al. 2019), also present opportunities for canola (Canadian Canola Growers Association 2018). With intensified low-carbon fuel regulations that are planned or enforced in both the U.S. (e.g., RFS) and Canada (e.g., CFS), traditional petroleum companies are increasingly considering co-processing to meet local regulations (Sanicola 2021). Several major U.S. petroleum companies (e.g., Exxon Mobil Corporation and Chevron Corporation) have announced planned investments regarding co-processing within their facilities. Canola is one of a few feedstocks available in North America to provide the large scale to serve these large petroleum refineries (Pratte 2020). Similar announcements and trials of co-processing canola oil with crude oil are occurring in Canada. For example, to meet the requirements of the British Columbia Low Carbon Fuel Standard, Parkland's refinery in Burnaby, British Columbia co-processed about 44 million liters of Canadian-sourced canola (and tallow) in 2020, with plans to increase this volume to 100 million liters in 2021 (Parkland Corporation 2021). The only other petroleum refinery in British Columbia, Tidewater Midstream's refinery in Prince George, also modified its operations to co-process canola (Tidewater Midstream and Infrastructure Ltd. 2021). Given that the requirements of Canada's federal CFS are similar to the requirements of the British Columbia Low Carbon Fuel Standard, the market potential of canola for co-processing applications across Canada will likely be quite large.

Though there have been sustainability concerns over using oilseeds for biofuel production (Miller and Kumar 2013; Sieverding et al. 2016; Zemanek 2018), Canadian canola production is widely recognized as environmentally sustainable and efficient. For example, the GHG emissions from Canadian canola cultivation meets sustainability criteria in the EU's Renewable Energy Directive (European Commission 2017). Canadian canola also meets renewable biomass requirements under the U.S.' RFS (EPA 2011). Moreover, canola is the only Canadian crop certified as sustainable by the International Sustainability and Carbon Certification (ISCC) system (Canadian Canola Growers Association 2018), where sustainability is evaluated based on considerations like net lifecycle GHG savings, biodiversity, and indirect land use change (ISCC n.d.).

With these desirable properties, about 3 MMT of Canadian canola seed were used for global biofuel (mainly biodiesel) production in 2020 (Pratte 2020) – representing approximately 15% of the total Canadian canola production, with about 2 MMT exported in seed to the EU and less than 1 MMT crushed into oil for the North American biofuel market (Canola Council of Canada 2021; Chris Vervaet, personal communication).

With low-carbon fuel regulations expanding beyond British Columbia to the rest of Canada, and growing interests in low-carbon fuels and advanced production technologies (e.g., co-processing) worldwide, demand for Canadian canola as a biofuel feedstock could increase significantly (Pratte 2020). For example, Imperial Oil Ltd., the largest petroleum refiner in Canada, has proposed building a renewable diesel complex with an annual capacity of over one billion liters at Strathcona Refinery in Alberta using canola and other vegetable oils, which would double the Canadian current capacity (Imperial Oil Ltd. 2021) and require about 2.27 MMT of canola seed[8], approximately 40% of Alberta's canola production in 2020 (5.21 MMT; Canola Council of Canada 2020).

Crushing oilseeds is a major processing activity in the canola supply chain. Currently, Canadian canola seeds are crushed in 14 plants nationwide, with 11 canola-specific plants located in the prairie provinces of Alberta, Saskatchewan, and Manitoba[9] (A map of the plants is provided

[8] A detailed calculation is provided in the appendix.
[9] The other three crushing plants (two in Ontario and one in Quebec) crush canola and soybean.

in Figure 3-1; Canadian Oilseed Processors Association n.d.). The existing crushing plants are primarily designed for making edible oil. In 2020, these plants crushed about 10.3 MMT of canola seed and produced 4.4 MMT of canola oil (Statistics Canada 2021). The majority (about 90 percent; Chris Vervaet, personal communication) of the oil products is for human consumption and the remaining is for industrial use including biofuels (USDA 2021). The crushing plants follow different quality specifications for edible and biofuel-use oil products, but the differences are minor; transport of both types of oil occur in similar rail tank cars or tank trucks (Canadian Oilseed Processors Association 2020).

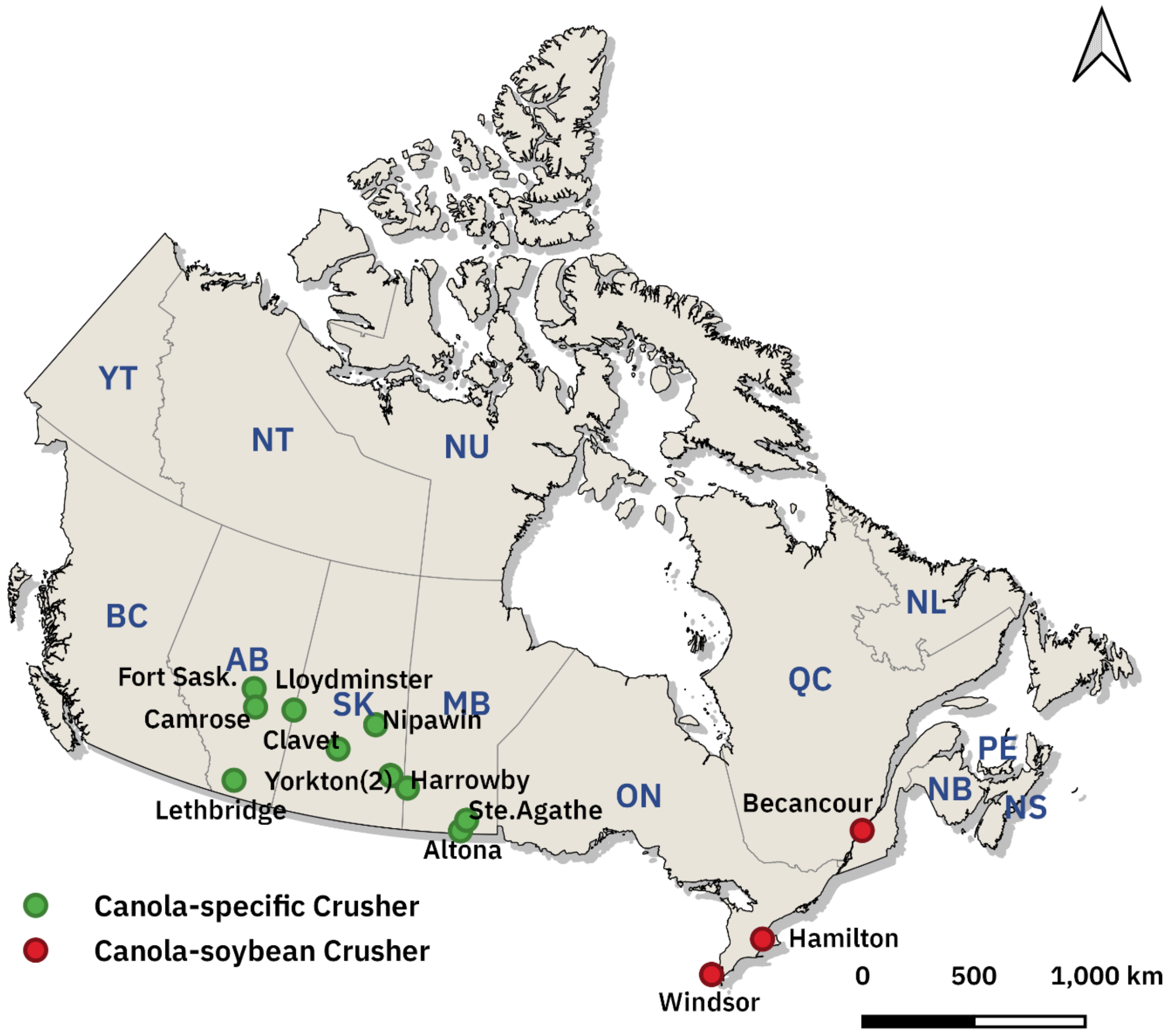


Figure 3-1: Current Canadian food-grade canola crushing plants

Source: Canadian Oilseed Processors Association n.d.
Note: There are 14 crush facilities in Canada; the 11 plants in Alberta (AB), Saskatchewan (SK), and Manitoba (MB) crush canola and the 3 plants in Ontario (ON) and Quebec (QC) crush canola and soybeans.

Harvested canola is of varying quality. Depending upon the percentage of green and heated seeds and other criteria, canola is categorized into one of four grades: No. 1, No. 2, No. 3, and Sample. No. 1 canola generally accounts for over 80% of total production (Canadian Grain Commission 2020) and was priced at 500 CAD/tonne on average in 2020[10] (Trading Economics n.d.). The lower grades have higher levels of chlorophyll content and other impurities, increasing purification costs for food purposes (García 2016). Therefore, crushing plants owned by grain companies may reject non-No. 1 canola (Alberta Agriculture and Forestry 2019; ADM 2015) when they have sufficient No. 1 canola.

Limited use of non-No. 1 canola for food may make it a good feedstock source for biofuel production (García 2016). Research on the pre-treatment of green seed canola oil (i.e., a low-quality oil) for biofuel production has been carried out (Baroi and Dalai 2015; Issariyakul and Dalai 2010). Moreover, non-No. 1 canola is available at lower prices, dropping by 10 to 15 CAD per tonne, per grade on average (ADM 2015; Government of Saskatchewan n.d.; Intercontinental Exchange Inc. n.d.). It has been used for renewable fuel applications (e.g., Wright Ag Renewables Ltd., Alberta that produces agriculture-based biofuels), as well as animal feed (e.g., G.V. Colony Farming Company Ltd., Alberta; Canola Council of Canada 2020).

In this analysis we investigate a fuel-grade canola oil supply chain that prioritizes the use of

[10] The price of canola can vary greatly. Between September 2020 and July 2021, the price of canola price rose from 500 to 900 CAD per tonne and reached a record high at 1,045 CAD per tonne in May 2021 (Trading Economics n.d.). The recent price upturn resulted from a supply shortage due to extreme weather and droughts, and increased demand for export and domestic biofuel production (Marowits 2021; Nickel 2021).

non-No. 1 canola as biofuel feedstock. We specifically investigate the potential for fuel-grade crushing plants that may be able to supply bio-feedstock at a lower cost than current supply chains. The fuel-grade crushers would use as much non-No. 1 canola seed as possible within a feasible service area, before purchasing No. 1 seed to fill out supply needs. In addition to the lower oilseed prices discussed above, our proposed fuel-grade canola oil supply chain would likely incur lower transportation, storage and production/refining costs than the existing food-grade supply chain. Pre-treatment procedures to process canola for biofuel feedstock are similar to processes used for food use, but given the absence of food safety concerns, fuel production has lower requirements for oil purification (Canadian Oilseed Processors Association 2020; Zemanek 2018). Moreover, fuel-grade canola oil could be transported in the same rail tank cars and tank trucks that move crude oil and bitumen, thereby taking advantage of existing transportation infrastructure for fossil fuels, which could be especially attractive to co-processing operations (Ng et al. 2019). Table 3-1 summarizes some key differences between the food- and fuel-grade supply chains.

Table 3-1: Differences between food- and fuel-grade supply chains

	Food-grade supply chain	Fuel-grade supply chain
Facilities	Existing crushing plants owned by grain companies	New crushing plants likely owned by biofuel companies
Feedstock	Focus on No. 1 canola, and blend with No. 2 as supplement	Focus on non-No. 1 canola, then use No. 1 as supplement
Production	Process and purify following similar specifications for food and fuel uses	Process and purify without concerns over food safety
Transportation	Transport in food-grade rail tank cars and tank trucks	Transport in the same rail tank cars and tank trucks as crude oil and bitumen

The existing 14 crushing plants have an average capacity of about 0.7 MMT of seed. Given the potential cost reductions discussed above, fuel-grade crushing plants could be vertically integrated with biorefineries and therefore be viable at a smaller scale than food-grade crushing plants. For example, recall from above that in 2020 Parkland's Burnaby Refinery co-processed about 40 thousand tonnes of canola oil (=44 million liters×0.915 kg/liter; Parkland Corporation 2021; Sahasrabudhe et al. 2017). Similarly, the FORGE Hydrocarbons' biorefinery under construction in Sombra, Ontario is expected to process approximately 35 to 40 thousand tonnes of feedstock (Neil Vanknotsenburg, personal communication).

The construction of fuel-grade crushing plants which prioritize non-No. 1 canola could benefit biorefineries with lower priced feedstock, especially those that currently purchase canola oil from food-grade crushing plants, such as SBI BioEnergy in Alberta. For biorefineries that vertically integrate or are planning to integrate their own crushing facilities, there may a benefit from reduced feedstock prices and lower processing/transport costs as discussed above. The investigation of feedstock supply and site selection for fuel-grade canola crushing plants could provide relevant information for investors and governments interested in low-carbon fuels.

Moreover, new crushing plants would add to canola crushing capacity, which corresponds with the goals of the Canadian canola industry. According to the strategic plan "Keep it Coming 2025" proposed by Canola Council of Canada, in response to increased canola yields and increased global demand for biofuels, domestic processing capacity of seed is targeted to grow from 7.7 MMT in 2015 to 14 MMT in 2025. Given that the existing 14 crushing plants in Canada are operating close to full capacity (Arnason 2019), additional crushing plants for food and biofuel will likely be required to achieve these aggressive growth targets. Since 2021, three grain companies (Viterra, Cargill, and Ceres Global Ag Corporation) have announced plans to build canola crushing plants in Saskatchewan. In particular, the planned facility of Ceres Global will primarily target the U.S. renewable fuel industry, but will also have the ability to produce food-grade canola oil (Ceres Global Ag Corporation 2021; Cross 2021). Our analysis below could be useful to companies in the process of selecting a site for a new canola processing facility.

A fuel-grade canola oil supply chain could benefit farmers and rural communities as well. Low-carbon fuels could provide alternative value-added markets for non-No. 1 canola seed, thereby creating more options for farmers and diversifying market risk (Adhikari and Illukpitiya 2021; Canadian Canola Growers Association n.d.). New fuel-grade crushing plants could also contribute to regional economic development by increasing investment and employment opportunities (Canola Council of Canada n.d.).

Whether and where to locate these fuel-grade canola crushing plants is an important investment decision, influenced by feedstock availability and transport costs. The objectives of this analysis are: 1) to assess how much non-No. 1 and total canola seed and oil could be available, and 2) to identify the best potential crushing sites in Alberta based on the amount of annually accessible non-No. 1 canola oil incorporating geographic information and transport considerations. Since non-No. 1 canola harvests are spatially varied and transport costs are dependent on actual transportation networks, we employ a GIS approach that integrates economic considerations. We calculate township-level (approximately 9.7 km by 9.7 km) estimates of available and accessible canola using data from 2016 to 2019 and identify locations and plant sizes of the top 3 potential sites in Alberta under different scenarios. Our estimate of canola supply and discussion of potential new fuel-grade crushing sites provide insights for biofuel investors and policymakers, and potentially facilitate an increase in the production of low-carbon fuels. Though we use Alberta as a case study, our approach could be expanded and applied to a broader scope, where multiple provinces or other jurisdictions could be investigated.

Our study provides three main contributions to the literature. First, our consideration of non-No. 1 canola as a biofuel feedstock is novel in the site location literature. Literature tends to discuss different species of feedstocks for biofuel production (e.g., Mupondwa et al. 2016; Shila and Johnson 2021), without taking feedstock grade or quality into account. The investigation of a fuel-grade canola oil supply chain focusing on non-No. 1 canola has to our knowledge, not been undertaken.

Second, our analysis is based on high-resolution data that reflects spatial and temporal variation. In assessing feedstock availability, some literature calculates county- or even provincial-level estimates (e.g., Mupondwa et al. 2016; Sahoo et al. 2016), which may fail to reflect geographic heterogeneity. With these levels of resolution, the literature also tends to use constant values for yield and/or oil content across regions and between years (e.g., Alam and Dwivedi 2019; Mupondwa et al. 2016; Shila and Johnson 2021). But crop yield is spatially heterogeneous due to varying soil and climate conditions, and exhibits substantial temporal fluctuations due to crop rotations, short-term weather variability, and long-term climate change. Harvests of non-No. 1 canola typically fluctuate with occurrences of frosts that occur during seed development and prevent the chlorophyll-clearing process, thereby resulting in green seeds (Canola Council of Canada 2020). To provide accurate estimates, we calculate the amount of non-No. 1 canola produced at the township level based on geographically dependent variables, including seeded area, yield, grade percentage and oil content information. Such detailed information exhibits heterogeneity across townships and helps portray township-specific prospects of locating fuel-grade crushers for canola-based biorefineries. To account for crop rotations and weather variability, we use estimates of four-year (2016-2019) average harvests of non-No. 1 canola in the analysis, and additionally investigate scenarios around years with high (i.e., using 2018 estimates) and low (i.e., using 2016 estimates) non-No. 1 harvests. The results suggest important implications for potential biorefinery investors in terms of feedstock risk, and for policymakers interested in encouraging low-carbon fuel industries.

Our third contribution is that our assessment of feedstock accessibility considers heterogenous transport costs conditional on the actual location and speed limit of roads. Previous bio-feedstock studies tend to use a supply-radius approach based on Euclidean distances (e.g., Gonzales and Searcy 2017; Mupondwa et al. 2016; Sharma et al. 2017; Sultana and Kumar 2014), which could underestimate actual travel distances and overestimate accessible feedstock (Zheng and Qiu 2020). Existing service-area-based assessment often fails to capture heterogeneity in speed limits due to driving conditions like road types and loading statuses (Martinkus et al. 2017; Sharma et al. 2020; Voets et al. 2013). Therefore, we improve the service-area method by incorporating road-dependent speed limits used for a round trip to better represent actual transport costs.

In the next section our methods are presented, and Section 3.3 describes the study area and data. Sections 3.4 and 3.5 discuss results and relevant implications.

3.2 Methods

Our approach involves four steps: 1) calculation of available canola seed and oil, 2) candidate site pre-exclusions, 3) calculation of accessible canola seed and oil, and 4) site selection. Following Zheng and Qiu (2020), we define available feedstock for crushing plants as the amount of canola seed that is present in fields whereas accessible feedstock represents the amount of canola seed that can be hauled to the candidate site after the relevant pre-exclusions, as will be explained in detail below. Figure 3-2 summarizes the flow of steps and elements within each of these steps.

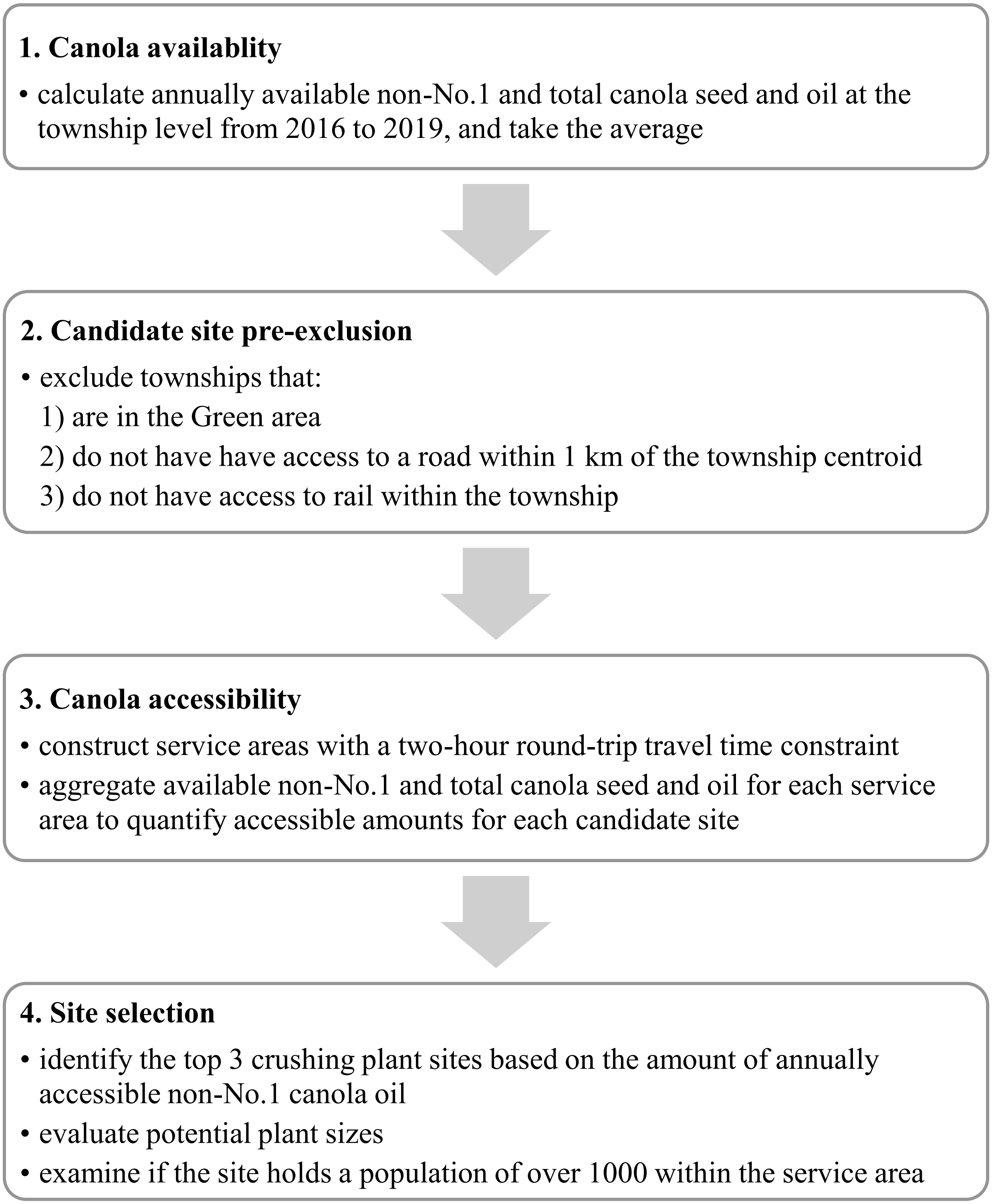


Figure 3-2: Procedures for feedstock calculations and site selection

3.2.1 Calculation of Available Canola Seed and Oil

Canola availability is assessed at the township level from 2016 to 2019, years for which data on seeded area are available. Estimates are expressed in terms of seed and oil. The seed estimates provide information about the crushing capacity (i.e., the amount of feedstock processed by crushing plants) that would be needed, whereas the oil estimates represent the amount of output produced by crushing plants and are used for site location selection. Following the oilseed literature (Mupondwa et al. 2016; Shila and Johnson 2021), the seed and oil estimates for total canola (Equations 3.1 and 3.2) and non-No. 1 canola (Equations 3.3 and 3.4) for a given year are calculated as:

$$total\_seed = acreage \times yield \tag{3.1}$$

$$total\_oil = total\_seed \times oil\_content \tag{3.2}$$

$$non.1\_seed = total\_seed \times non.1\_percent \tag{3.3}$$

$$non.1\_oil = non.1\_seed \times oil\_content \tag{3.4}$$

where $acreage$ is the area of land seeded to canola, $yield$ is the amount of canola seed harvested per area of land, $non.1\_percent$ denotes the percentage of non-No.1 canola seed out of total canola production, and $oil\_content$ represents the amount of lipid that can be obtained from the seed.

To account for yield fluctuations associated with crop rotations and weather changes, we use the four-year (2016-2019) average for annual production in the analysis. We also develop scenarios around years with low (i.e., using 2016 estimates) and high (i.e., using 2018 estimates) non-No. 1 harvests.

3.2.2 Candidate Site Pre-exclusions

After assessing the availability of non-No. 1 seed and oil, we pre-exclude some townships by imposing relevant economic constraints for crushing plants such as economically viable road and rail access (Sahoo et al. 2016). Pre-exclusion eliminates non-feasible sites and thereby reduces computations in the site location analysis (Jayarathna et al. 2020; Kheybari et al. 2019).

We begin by pre-excluding the townships in environmentally reserved areas, such as areas dominated by forests, where crop planting and processing are generally not allowed. To ensure access to travel infrastructure for feedstock and products, we constrain proximity to existing transportation networks (both road and rail). Sahoo et al. (2016) assume that plants are located within 1 km of a road, and within 3 km of a rail-line. Sharma et al. (2017) use 1.5 km for road access and 1 km for rail access, while Gonzales and Searcy (2017) use 1.62 km for both road and rail access. We follow Sahoo et al. (2016) and impose the threshold of road access within 1 km. For rail-lines, we ensure that there is access within the township.

In calculating distances to transportation access, we assume that potential sites are located at the centroid of each township, following the practice of the site selection literature (e.g., Gonzales and Searcy 2017; Jeong et al. 2019; Sharma et al. 2020; Zheng and Qiu 2020). The assumption is reasonable in our case given the fine level of resolution in our analysis (i.e., the township level).

3.2.3 Calculation of Accessible Canola Seed and Oil

Transportation costs are critical for seed-crushing facilities. There are generally two approaches used to capture transport costs in assessing accessible feedstock. One approach is to employ a supply radius defined by a certain Euclidean distance from the centroid of a geographical unit (e.g., Gonzales and Searcy 2017; Mupondwa et al. 2016; Sharma et al. 2017; Sultana and Kumar 2014). However, the radius approach, by not considering actual road availability and travel time, can underestimate travel costs and overestimate accessible feedstock (Zheng and Qiu 2020). Compared with the radius approach, a service-area approach, based on real road networks, is more precise in representing transport costs. But existing service-area-based assessment (e.g., Van Holsbeeck and Srivastava 2020; Zheng and Qiu 2020; Zupko 2019) often fails to capture heterogeneity in speed limits due to driving conditions like road types and loading statuses (Martinkus et al. 2017; Perpiñá et al. 2009; Sharma et al. 2020; Voets et al. 2013). Therefore, we improve the service-area method by incorporating road-dependent speed limits used for a round trip to better capture heterogenous transport costs.

Given a round trip with different speeds for loaded (i.e., v_{load}) and unloaded (i.e., v_{unload}) statuses, we calculate the average speed[11] as:

$$v_{\text{avg}} = \frac{s_{\text{total}}}{t_{\text{total}}} = \frac{s + s}{s/v_{\text{load}} + s/v_{\text{unload}}} = \frac{2}{v_{\text{load}}^{-1} + v_{\text{unload}}^{-1}} \quad (3.5)$$

[11] Applications of the average speed in the context of biomass feedstock transportation can be seen in Perpiñá et al. (2009).

where v_{avg} denotes average speed limits. The parameter s_{total} is the total travel distance for a round trip, and t_{total} is the total time spent on the road. We denote a one-way distance as s. The formula of the average speed v_{avg} for a round trip is also known as the harmonic mean of the speeds, which recognizes the inverse relationship between time and speed and is more accurate than the arithmetic mean.

To represent actual transport costs, we consider road classes and associated average speed limits, and impose a time constraint for a round trip (i.e., the time spent on the road, not including loading time) to establish service areas. Lemire et al. (2019) assess different travel time performances for facilities pre-processing biomass feedstock in southern Quebec, Canada and suggest that optimal one-way travel time is about one hour (55-59 minutes). Following Lemire et al. (2019), we define the round-trip time threshold as two hours[12]. Service areas with a maximum 2-hour round-trip are constructed for each township centroid.

Figure 3-3 shows how the 2-hour round-trip service area differs substantially from the supply radius for a distance of 80 km (assuming an average speed of 80 km/hour), using a random township (i.e., an Alberta township with ID: TWP-078 RGE-05 MER-6) centroid as a potential site. The supply radius has a circle shape while the boundary of the service area is irregular because the latter considers actual road network and heterogenous speed limits. The supply radius also

[12] Distance thresholds used to define a service area for oilseed crushing plants in the North American literature typically range from 20 to 200 km (e.g., Fan et al. 2013; Leão et al. 2011; Mupondwa et al. 2016; Sieverding et al. 2016; Trejo-Pech et al. 2019).

covers a larger collection area than the service area, which may overestimate the amount of accessible canola seed and oil to the site.

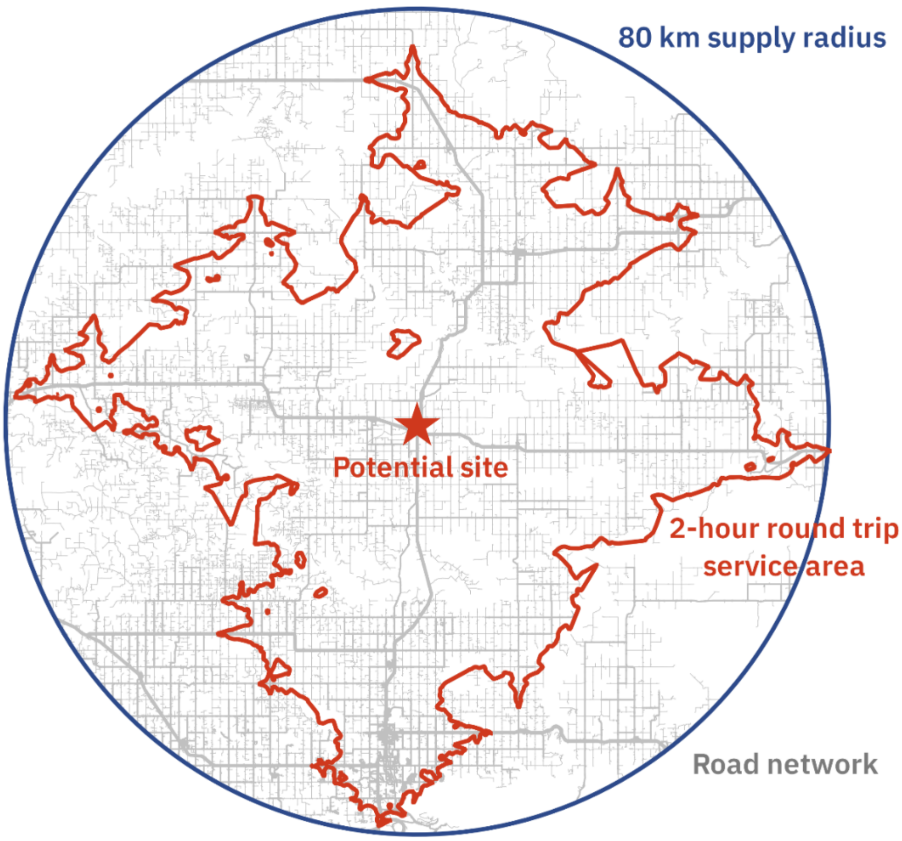


Figure 3-3: An illustration of service area versus supply radius methods for a random site (i.e., the centroid of an Alberta township with ID: TWP-078 RGE-05 MER-6)

Source: Altalis n.d.

Given the availability, exclusions, and service areas, we proceed with quantifying accessible canola seed and oil for each township. For each township, we aggregate the amounts of available canola within its 2-hour, round-trip service area. All the nearby townships that are within or overlap the service area boundary are included into the aggregation. Since non-No. 1 harvests may fluctuate over years, potential investors could be interested in a feedstock portfolio that would sometimes include both non-No. 1 and No. 1 canola seed to produce oil for low-carbon fuel applications. Therefore, we also show the results for total canola production that is available in each service area.

3.2.4 Site Selection

We identify the top 3 sites based on the amount of annually accessible non-No. 1 canola oil. To avoid overestimation, we follow a no-double-counting rule (Zheng and Qiu 2020). The first site is selected with the maximum non-No. 1 oil amount within its service area. Then the corresponding canola seed and oil are assigned to the site and are removed from the subsequent calculations and selections. After identifying the top 3 sites for new fuel-grade crushing plants, we analyze their potential plant sizes to provide information associated with economic feasibility.

We also consider minimum population availability in the site selection to ensure proper infrastructure access and sufficient workforce supply. Following Zhang et al. (2011) and Zheng and Qiu (2020), we double-check if the identified site holds a population of higher than 1000 within its service area.

3.3 Study Area and Data

Our case study takes place in Alberta, a prairie province that contributed 28% of Canadian canola production in 2020. Figure 3-4 maps the study area and displays counties and crop districts in Alberta. Alberta is an ideal case study site because it usually contains the highest percentage of non-No. 1 canola in Canada. In 2019, non-No. 1 seed accounted for 24.3% of the canola harvested in Alberta, whereas the canola harvested in Saskatchewan and Manitoba had 11.7% and 1.0% non-No. 1 seed, respectively (Canadian Grain Commission n.d.).[13]

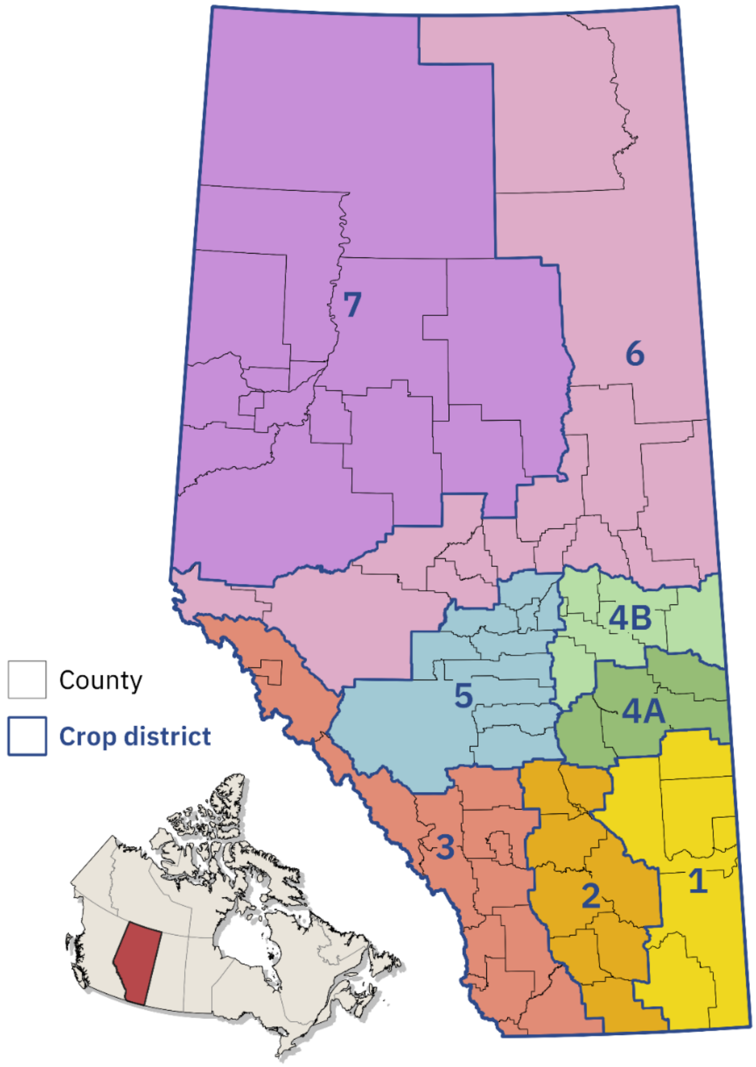


Figure 3-4: Alberta, counties and crop districts

Source: Canadian Grain Commission 2020.
Note: Numbers (in blue) are crop district numbers.

[13] Though some other years have smaller percentages of non-No. 1 harvests, Alberta still had the highest percentage of non-No. 1 harvests in the Canadian Prairies. For example, in 2016, Alberta, Saskatchewan and Manitoba had 5.9%, 3.3% and 3.8% non-No. 1 seeds, respectively.

Variables to calculate the amount of non-No. 1 and total canola seed and oil include $acreage$, $yield$, $non.1\_percent$, and $oil\_content$, as Equations 3.1 to 3.4. Our data, from 2016 to 2019, are collected from multiple sources. The acreage data are obtained from the Annual Crop Inventory, a land cover raster map with a spatial resolution of 30m (Government of Canada 2021). The yield data are provided by Agriculture Financial Services Corporation at the county level. We aggregate the acreage data at the township level and disaggregate the yield data by assuming all townships in one county have the county-level yield amount. The total canola seed production is calculated by multiplying the acreage and yield at the township level, as per Equation 3.1. The township-level estimates better reflect geographic heterogeneity in feedstock availability than county- or provincial-level estimates.

To calculate the amount of non-No. 1 seed production, we multiply the total seed production by the percentage of non-No. 1 canola, as per Equation 3.3. Given the quality of canola seed can be spatially and temporally varying, we use percentages of non-No. 1 canola at the crop-district level from 2016 to 2019 (Canadian Grain Commission n.d.). Similarly, we assume all townships in one crop district have the crop-district-level non-No. 1 percentages. Table 3-2 presents the non-No. 1 percentage data and shows that there are substantial spatial and temporal variations in non-No. 1 harvests. Crop District 7 has the highest percentage of non-No. 1 canola among all crop districts in 2018 and 2019. The percentage of non-No. 1 canola is the lowest in Crop District 1 during our sample period. In 2018 and 2019, Alberta experienced early frosts (Canadian Grain

Commission 2020) and non-No. 1 canola accounted for a much higher share of total canola production than 2016 and 2017.

Table 3-2: Percentage of non-No. 1 canola by crop district in Alberta from 2016 to 2019

Crop District	2016	2017	2018	2019
1	0.0%	0.0%	3.3%	0.0%
2	4.6%	4.6%	4.2%	9.6%
3	7.7%	2.8%	26.0%	38.8%
4A	7.8%	14.3%	31.2%	22.3%
4B	7.8%	14.3%	31.2%	22.3%
5	6.1%	11.5%	55.0%	24.0%
6	2.9%	5.7%	50.8%	22.4%
7	6.4%	12.4%	84.5%	40.8%

Source: Canadian Grain Commission n.d.

For converting seed production into oil, as per Equations 3.2 and 3.4, studies tend to multiply a fixed oil content for a specific type of feedstock. In North America, literature for canola (e.g., Fore et al. 2011; Obnamia et al. 2020; Ukaew et al. 2016; Zemanek 2018) use values ranging from 41% to 46%. The application of a fixed oil content can also be seen for other oilseeds like camelina (e.g., Mupondwa et al. 2016; Shila and Johnson 2021; Stein 2012) and carinata (e.g., Alam and Dwivedi 2019). However, oil content can also vary cross-sectionally and temporally depending on soil and weather conditions. Therefore, we use crop-district-level oil content data from 2016 to 2019 (Canadian Grain Commission n.d.). The data is presented in Table 3-3. We find the oil content fluctuates spatially and temporally, but to a much smaller degree (i.e., a range of 42.1% and 45.5% with an average of approximately 44%) than the percentage of non-No. 1 canola.

Table 3-3: Oil content by crop district in Alberta from 2016 to 2019

Crop District	2016	2017	2018	2019
1	44.9%	42.6%	42.9%	42.1%
2	44.2%	44.0%	42.2%	43.0%
3	45.0%	44.7%	42.6%	44.6%
4A	43.8%	45.1%	43.5%	44.7%
4B	43.8%	45.1%	43.5%	44.7%
5	43.5%	45.0%	43.2%	44.6%
6	42.8%	44.5%	45.5%	45.0%
7	44.1%	45.1%	45.4%	44.4%

Source: Canadian Grain Commission n.d.
Note: Oil content data are expressed on an 8.5% moisture basis, following the convention of the canola industry, and are based on an extraction efficiency of 98% associated with a commercial solvent extraction system.

For analyzing these data geographically, boundary shapefiles are necessary. We use Alberta township (approximately 9.7 km by 9.7 km), county, and green/white area divisions (Altalis n.d.). In the assessment, we exclude townships located in the green zone because the green zone in Alberta is reserved largely for forestry operations, where crop planting and processing are generally not allowed. Geographical information on crop districts is retrieved from the Canadian Grain Commission (2020). Population census data at the census-subdivision level is collected from Statistics Canada (2017).

For the network analysis to calculate transport costs and select site locations, we obtain road network (Altalis n.d.) and the national railway network (Government of Canada 2021). The assumptions we use for speed limits by road class and loading status (loaded and unloaded) are presented in Table 3-4. After rounding, the average speed limits used for a round trip given by Equation 3.5 are 85 km/h for primary provincial highways and 70 km/h, 60 km/h and 25 km/h for other paved roads, two-lane gravel roads and one-lane roads, respectively.

Table 3-4: Speed limits (km/hour) by road class and loading status, and average speeds

Road class	Loaded speed	Unloaded speed	Average speed
Primary provincial highways	80	95	85
Other paved roads	65	80	70
Two-lane gravel roads	50	70	60
One-lane roads	20	30	25

Note: The average speed is calculated as $2/(v_{\text{load}}^{-1} + v_{\text{unload}}^{-1})$ and then rounded.

We use the QGIS software (version 3.18) to conduct the GIS analysis. For the coordinate reference system (CRS), data from the Alberta government or Altalis have a custom map projection for its territory, NAD83 / Alberta 10-TM (Resource), with CRS code 3401. To ensure consistency of our data and estimates with national data, all spatial information is finally transformed to NAD83 / Alberta 10-TM (Forest) (CRS code 3400).

3.4 Results

3.4.1 Canola Availability

We calculate estimates of available total and non-No. 1 canola seed and oil for each township in Alberta. The summary statistics, based on estimates of four-year (2016-2019) average annual production, are presented in Table 3-5 (Panel A). There are 2,807 townships seeded with canola, with an average annual seeded area of 1.04 thousand hectares and an average annual total seed production of 2.44 thousand tonnes per township. The average seed yield per township is 2.14 tonnes/hectare. Of these townships, 2,763 (98.4%) have non-No. 1 canola seed production, with an average of 0.51 thousand tonnes per township annually. In total, we estimate that Alberta seeded 2.97 million hectares of canola per year and had a total seed production of 6.85 MMT/year, with 1.41 MMT/year being non-No. 1 grade. If all seeds were crushed, the yield would be approximately 3.03 MMT/year of oil, and 0.63 MMT/year would be from non-No. 1 seed.

We also find large variation across townships in seeded areas and total and non-No. 1 canola production, suggested by standard deviations and extreme values. Panel B (Table 3-5) reports estimates of average (2016-2019) annual production of canola by crop district. Among the 8 crop districts, No. 7 had the most land seeded to canola and the most total and non-No. 1 canola production, whereas the yield of canola was the highest in No. 5. To show yield fluctuations over years, Panel C presents information on canola annual production from 2016 to 2019. Among the four years, 2016 ended with the least non-No. 1 canola, but the most total canola; whereas 2018 had the largest amount of non-No. 1 canola, but the second least amount of total canola.

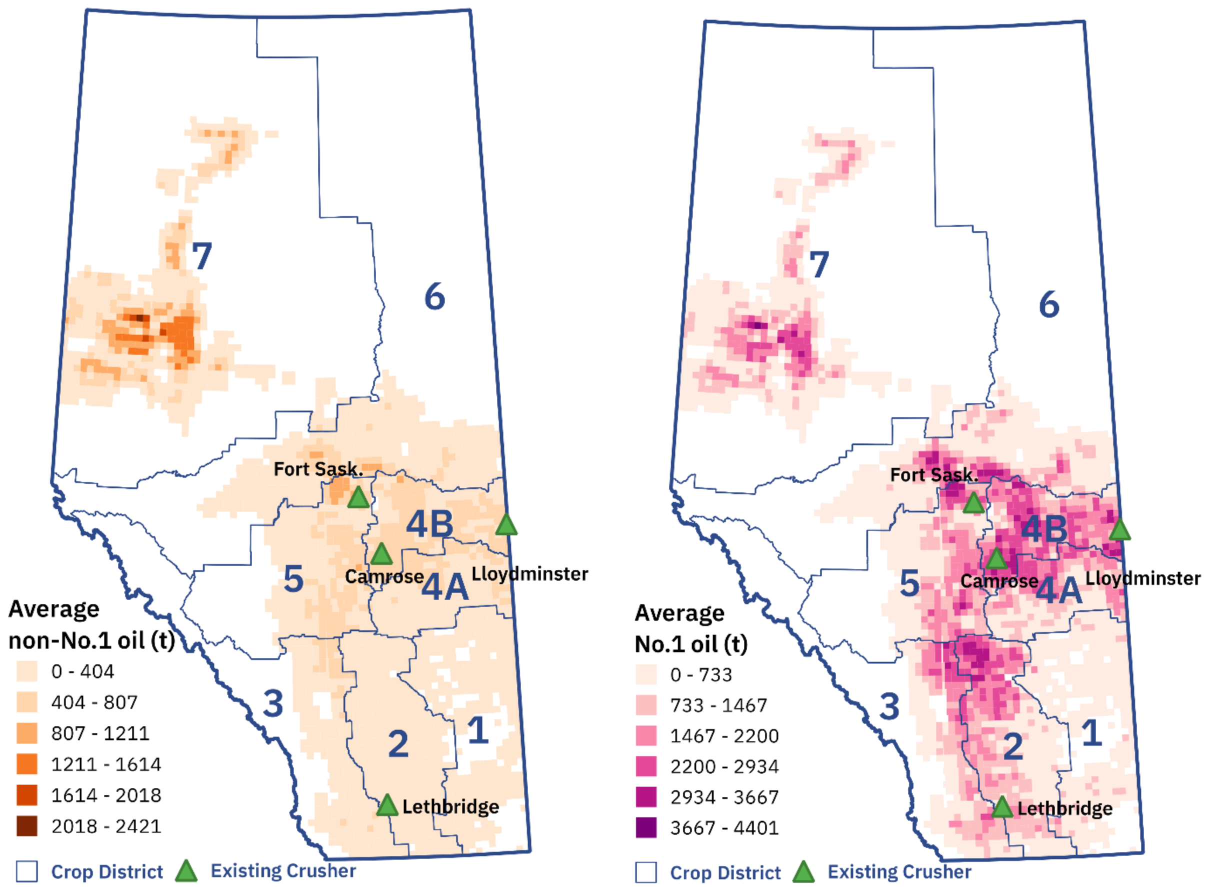
Table 3-5: Summary statistics of canola annual production estimates from 2016 to 2019 for Alberta

	Seeded area (thousands of hectares per year)	Yield (tonnes of seed per hectare)	Total seed (thousands of tonnes per year)	Total oil (thousands of tonnes per year)	Non-No. 1 seed (thousands of tonnes per year)	Non-No. 1 oil (thousands of tonnes per year)
Panel A. Summary statistics of average (2016-2019) annual estimates at the township level						
Mean	1.04	2.14	2.44	1.10	0.51	0.23
Std.Dev.	1.00	0.43	2.47	1.09	0.64	0.29
Maximum	5.94	3.02	15.23	6.82	5.37	2.42
Minimum	0.00	0.63	0.00	0.00	0.00	0.00
Obs	2846	2807	2807	2763	2763	2763
Panel B. Sum of average (2016-2019) annual estimates at the crop-district (denoted as CD) level						
CD 1	123.22	1.62	200.02	89.69	1.74	0.75
CD 2	461.67	2.20	1,017.25	442.11	57.27	24.84
CD 3	270.28	2.34	632.18	279.98	108.63	47.74
CD 4A	285.54	2.35	669.97	296.73	123.13	54.45
CD 4B	494.18	2.51	1,238.00	548.00	234.00	103.38
CD 5	359.54	**2.63**	946.69	417.88	222.81	97.59
CD 6	327.75	2.31	756.83	336.54	156.64	70.83
CD 7	**649.43**	2.13	**1,386.15**	**621.10**	**500.81**	**225.75**
Alberta	2,971.61	2.30	6,847.08	3,032.03	1,405.02	625.33
Panel C. Sum of annual estimates for a given year						
2016	2,889.47	**2.56**	**7,383.57**	**3,145.28**	443.71	195.12
2017	**3,135.39**	2.25	7,049.26	3,067.73	678.38	304.96
2018	3,035.05	2.22	6,739.14	2,955.03	**2,939.89**	**1,307.34**
2019	2,826.52	2.20	6,216.38	2,686.38	1,558.09	693.92

Note: The estimates of canola annual production are based on Equations 3.1 to 3.4. In Panel B, maximum values of the estimates among crop districts are in bold. In Panel C, maximum values of the estimates from 2016 to 2019 are in bold.

Figure 3-5 (Panel A) plots the spatial distribution of the 2016-2019 average non-No. 1 canola oil at the township level. The amount of available non-No. 1 oil varies spatially, highlighting the importance of a high-resolution geographical analysis. We compare the spatial distribution of non-No. 1 oil with that of No. 1 oil (Panel B), which is the focus of existing food-grade crushing plants. The distribution patterns of non-No. 1 and No. 1 oil are different. Townships with the potential to produce high levels of non-No. 1 oil are concentrated in Crop District 7, whereas townships with large No. 1 oil estimates are relatively evenly distributed across all crop districts except Crop District 1. Based on the different spatial distributions of non-No. 1 and No. 1 oil, fuel-grade crushers focusing on the former would potentially be in different locations from existing crushers, and there may be potential to add additional crushing capacity for the new fuel-grade crushers.

Figure 3-6 summarizes estimates of average (2016-2019) available canola oil by county and highlights the top 3 counties in terms of non-No. 1 (Panel A) and No. 1 oil (Panel B). There are 79 counties/municipal districts in Alberta. Smoky River Municipal District had the largest estimate of available non-No. 1 oil whereas Vermilion River County had the largest amount for No. 1 oil. Currently, there is no canola crusher in the Smoky River Municipal District, whereas there is already a food-grade canola crusher (i.e., Lloydminster) located in Vermilion River County. Based on these results, it appears as though a fuel-grade crushing plant could potentially be located in Smoky River Municipal District given the abundant supply of non-No. 1 canola in this area and the absence of any competition from existing crushers.

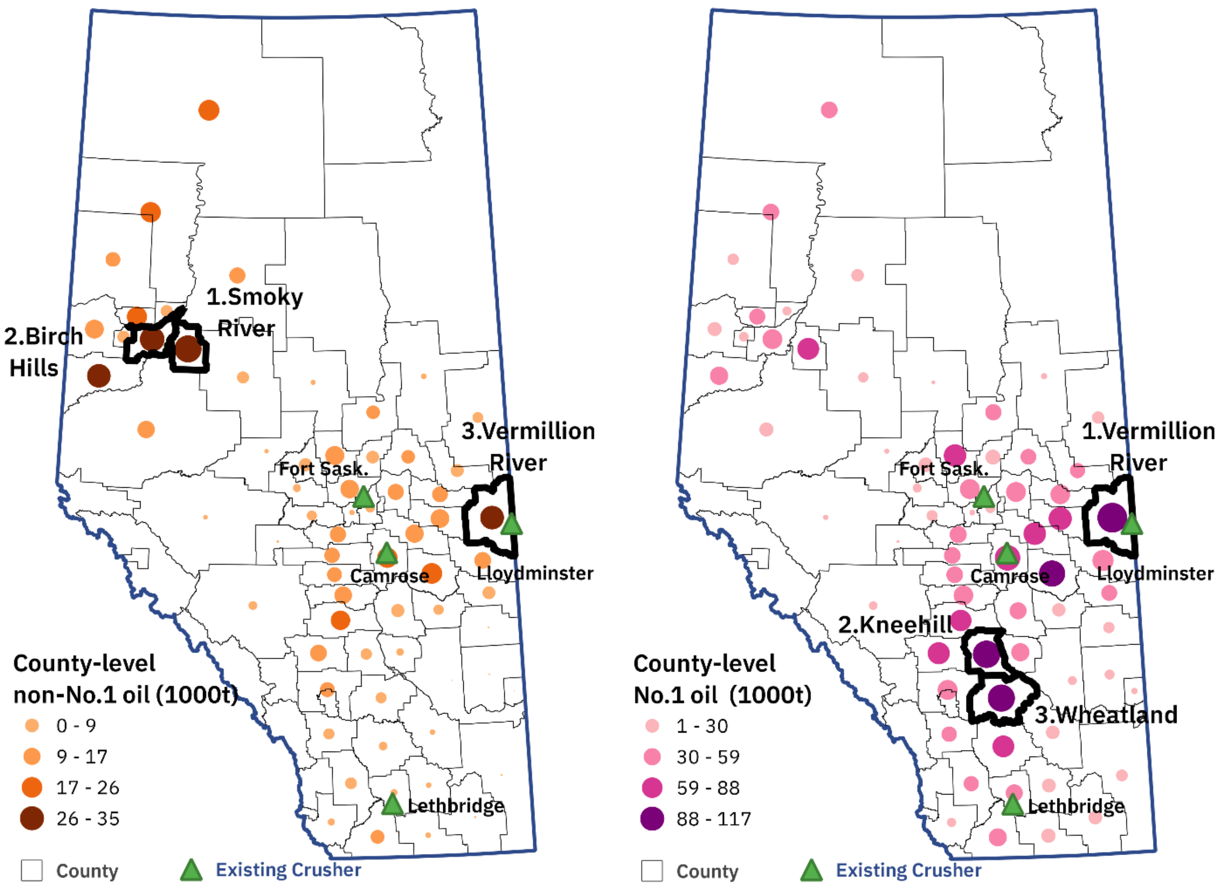


A. Average non-No. 1 oil at the township level B. Average No. 1 oil at the township level

Figure 3-5: Spatial distributions of average (2016-2019) canola oil (tonnes) at the township level in Alberta

Source: Agriculture Financial Services Corporation n.d.; Canadian Grain Commission n.d.; Government of Canada 2021.

Note: The estimates of average available canola oil are based on the 2016-2019 annual production estimates from Equations 3.2 and 3.4.



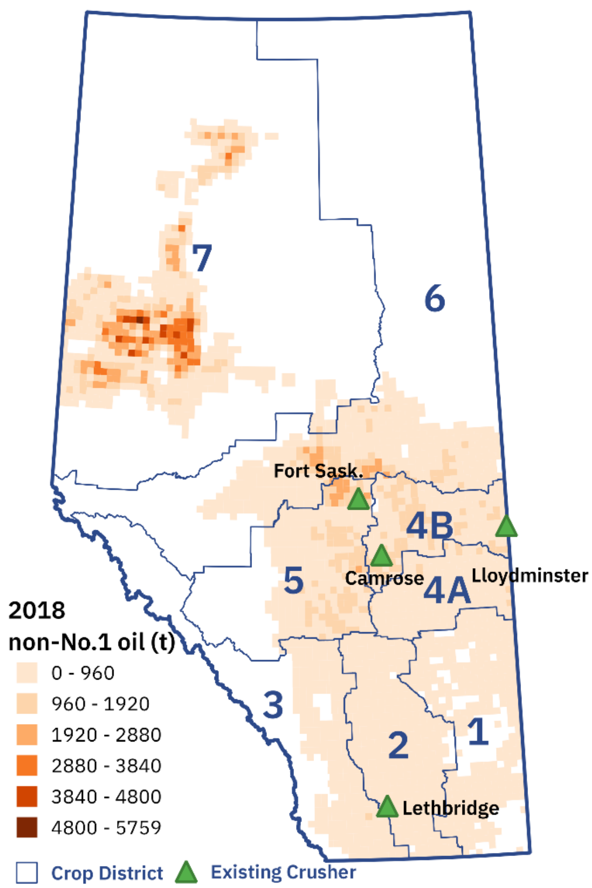
A. Average non-No. 1 oil at the county level B. Average No. 1 oil at the county level

Figure 3-6: Spatial distributions of canola oil (thousands of tonnes) at the county level in Alberta

Source: Agriculture Financial Services Corporation n.d.; Canadian Grain Commission n.d.; Government of Canada 2021.

Note: The estimates of average available canola oil are based on the 2016-2019 annual production estimates from Equations 3.2 and 3.4. The top 3 counties/municipality districts in terms of average available non-No. 1 oil are Smoky River Municipal District, Birch Hills County, and Vermillion River County. The top 3 counties/municipality districts in terms of average available No. 1 oil are Vermillion River County, Kneehill County, and Wheatland County.

Given the temporally varying data, we also present spatial distributions of annual production of non-No. 1 canola oil in 2018 (i.e., a high non-No. 1 harvest year; Panel A) and 2016 (i.e., a low non-No. 1 harvest year; Panel B) in Figure 3-7. Compared with the average (2016-2019) case (Figure 3-5A), more townships in Crop District 4B could supply high amounts of non-No. 1 oil in 2016, whereas top townships were more located in Crop District 7 in 2018. Therefore, site selection relying on one year of data could differ, highlighting the need to consider variability over time.



A. 2018 non-No. 1 oil at the township level B. 2016 non-No. 1 oil at the township level

Figure 3-7: Spatial distributions of non-No. 1 canola oil (tonnes) in 2018 and 2016 at the township level in Alberta

Source: Agriculture Financial Services Corporation n.d.; Canadian Grain Commission n.d.; Government of Canada 2021.

3.4.2 Potential Sites

There are 7254 townships in Alberta, and 552 candidate townships meet the pre-exclusion requirements presented in Section 3.2.2. We identify the top 3 sites to build fuel-grade crushing plants based on annually accessible non-No. 1 canola oil within the service areas under three different scenarios: four-year (2016-2019) average, high non-No. 1 harvest year (i.e., 2018), and low non-No. 1 harvest year (i.e., 2016). Figure 3-8 maps locations and service areas of the potential crushers and Tables 3-6, 3-7, and 3-8 list detailed information on their township location and canola accessibility.

In the four-year (2016-2019) average scenario (Table 3-6), the top 3 sites in Alberta identified at the township level are denoted as Rycroft site (in Spirit River Municipal District), Edmonton site (in Edmonton), and Viking site (in Beaver County)[14]. These identified sites could potentially yield 86.66, 74.07, and 67.77 thousand tonnes of non-No. 1 oil annually. All three sites could satisfy the feedstock demand of refineries such as Parkland's Burnaby Refinery (40 thousand tonnes) and FORGE's Sombra Biorefinery (35-40 thousand tonnes). We also find there are substantial temporal fluctuations in accessible non-No. 1 canola oil. These sites could produce much more non-No. 1 oil in 2018 than the other years, especially for the Rycroft site. But the amount of accessible non-No. 1 oil in 2016 was much lower. Under such circumstances, the potential crushers may wish to plan on a feedstock portfolio made up of canola seeds of varying

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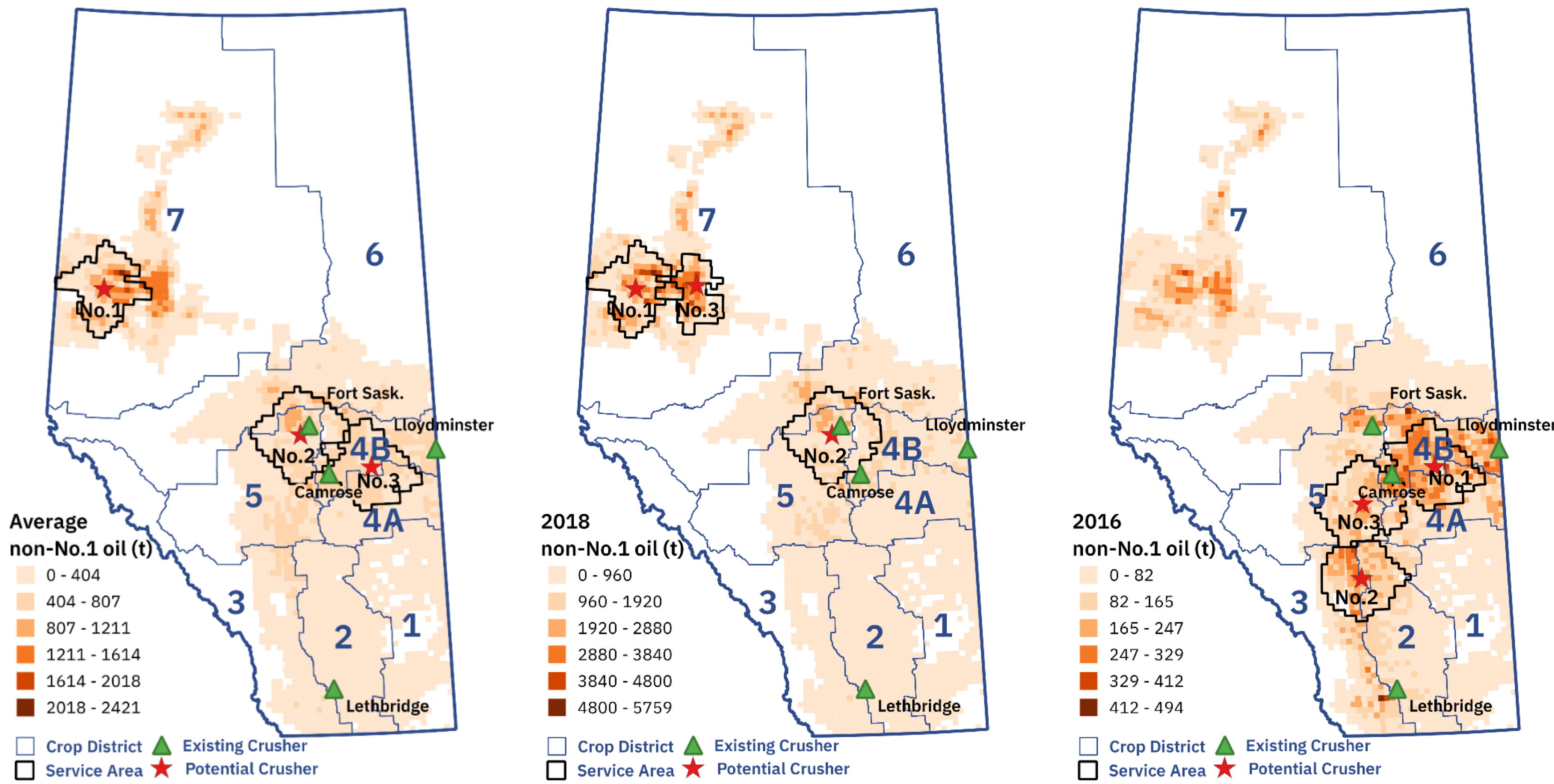
[14] The sites are identified at the township level and the township IDs are provided in Table 3-6. In the text, they are referred to by villages or cities that are within or close to the identified townships.

grades, with purchases of more expensive No. 1 canola to fulfill capacity requirements in years when non-No. 1 amounts are low. The accessible total oil estimates for the sites are presented in the last column of Table 3-6. Each site's service area could produce sufficient total canola oil per year. The Viking site holds a larger amount of total canola oil than the Rycroft and Edmonton sites.

Table 3-6: Top 3 crushing sites based on estimates of four-year (2016-2019) average annually accessible non-No. 1 canola oil

Year	Non-No. 1 seed (thousands of tonnes per year)	Non-No. 1 oil (thousands of tonnes per year)	Total seed (thousands of tonnes per year)	Total oil (thousands of tonnes per year)
No. 1: Rycroft site (Township ID: TWP-078 RGE-05 MER-6, MD: Spirit River, CD 7)				
Average	192.21	**86.66**	525.78	235.49
2016	33.19	14.64	522.72	230.52
2017	69.89	31.52	563.59	254.18
2018	485.49	220.41	574.87	260.99
2019	180.27	80.06	441.95	196.28
No. 2: Edmonton site (Township ID: TWP-053 RGE-24 MER-4, MD: Edmonton, CD 5)				
Average	167.86	**74.07**	760.17	336.33
2016	44.66	19.44	754.57	328.52
2017	88.94	40.01	799.44	359.62
2018	373.24	163.20	779.74	340.94
2019	164.61	73.63	706.92	316.23
No. 3: Viking site (Township ID: TWP-047 RGE-12 MER-4, MD: Beaver, CD 4B)				
Average	153.32	**67.77**	816.93	361.73
2016	66.86	29.28	853.84	373.98
2017	114.91	51.82	801.31	361.39
2018	250.69	109.05	802.73	349.19
2019	180.84	80.91	809.85	362.34

Note: The sites are identified at the township level and are referred to by villages or cities that are within or close to the identified townships. MD is short for municipal district (or county) and CD is short for Crop District. The sorting values are in bold.



A. Four-year (2016-2019) average scenario B. A high non-No. 1 harvest year (i.e., 2018) C. A low non-No. 1 harvest year (i.e., 2016)

Figure 3-8: Potential fuel-grade crushing plants in Alberta in different scenarios

Source: Agriculture Financial Services Corporation n.d.; Canadian Grain Commission n.d.; Government of Canada 2021.
Note: The estimates of average available non-No. 1 canola oil are based on the 2016-2019 annual production estimates from Equation 3.4.

We compare locations of existing and potential crushers in Figure 3-8 (Panel A). As mentioned above, there are no existing food-grade crushers in the collection area of the Rycroft site (No. 1), whereas the Edmonton and Viking sites (respectively Nos. 2 and 3) are located close to existing crushers in Fort Saskatchewan and Camrose. The Rycroft site suffers less feedstock competition from existing plants than the other two sites, especially when it might require No. 1 canola seed to maintain operations during years with low amounts of accessible non-No. 1 seed.

In the Appendix, we do a detailed investigation for the proposed renewable diesel project (2.27 MMT of canola seed) at Imperial's Strathcona Refinery in Alberta. Figure A1 presents Strathcona Refinery's service areas of different round-trip travel time and Table A1 reports estimates of annually accessible canola within the service areas based on an average (2016-2019) year. We find that Strathcona Refinery would need to expand its service area to a round trip of approximately 4 hours in order to collect enough canola seed to meet the proposed capacity. Of this total, approximately 20.7% could come from non-No. 1 canola seed. These estimates assume that Strathcona Refinery will collect all canola seed that is available in the service areas. But there are currently existing canola crushers in Fort Saskatchewan and Camrose. Unless the seed from these crushers is acquired, the refinery would need to expand its service area even farther, perhaps using rail cars.

Table 3-7 presents results in a high non-No. 1 harvest year (i.e., 2018). The identified top 3 township sites are denoted as Rycroft site (in Spirit River Municipal District), Edmonton site (in Edmonton), and Falher site (in Smoky River Municipal District). The expected average (2016-2019) annual yields of these fuel-grade crushing plants could be 86.66, 74.07, and 57.09 thousand tonnes of canola oil, respectively. From Figure 3-8B, we find two out of the three potential sites (i.e., the Rycroft and Falher sites (respectively Nos. 1 and 3)) are in Crop District 7.

Table 3-7: Top 3 crushing sites based on estimates of annually accessible non-No. 1 canola oil in a high non-No. 1 harvest year (i.e., 2018)

Year	Non-No. 1 seed (thousands of tonnes per year)	Non-No. 1 oil (thousands of tonnes per year)	Total seed (thousands of tonnes per year)	Total oil (thousands of tonnes per year)
No. 1: Rycroft site (Township ID: TWP-078 RGE-05 MER-6, MD: Spirit River, CD 7)				
Average	192.21	86.66	525.78	235.49
2016	33.19	14.64	522.72	230.52
2017	69.89	31.52	563.59	254.18
2018	485.49	**220.41**	574.87	260.99
2019	180.27	80.06	441.95	196.28
No. 2: Edmonton site (Township ID: TWP-053 RGE-24 MER-4, MD: Edmonton, CD 5)				
Average	167.86	74.07	760.17	336.33
2016	44.66	19.44	754.57	328.52
2017	88.94	40.01	799.44	359.62
2018	373.24	**163.20**	779.74	340.94
2019	164.61	73.63	706.92	316.23
No. 3: Falher site (Township ID: TWP-079 RGE-20 MER-5, MD: Smoky River, CD 7)				
Average	126.71	57.09	358.60	160.58
2016	21.95	9.68	345.66	152.44
2017	50.55	22.80	407.67	183.86
2018	302.82	**137.48**	358.57	162.79
2019	131.54	58.42	322.48	143.22

Note: The sites are identified at the township level and are referred to by villages or cities that are within or close to the identified townships. MD is short for municipal district (or county) and CD is short for Crop District. The sorting values are in bold.

We also present potential sites in a low non-No. 1 year (i.e., 2016) in Table 3-8. The sites are denoted as Viking site (in Beaver County), Beiseker site (in Rocky View Municipal District), and Morningside site (in Lacombe County). The site selection is quite different from the case above. The underlying average (2016-2019) supplies of non-No. 1 oil are 72.93, 33.23, and 64.04 thousand tonnes per year. The Beiseker site would suffer a deficiency in oil supply (again assuming a requirement of 40 thousand tonnes of oil per year) if it sources non-No. 1 canola seed alone. The consideration of feedstock portfolios (e.g., information on total canola seed and oil) would be particularly important to fuel-grade crushing plants in a low non-No. 1 harvest year.

Figure 3-8C shows the potential fuel-grade crushers for the Viking and Morningside sites (respectively Nos. 1 and 3) would be close to existing food-grade crushers in Camrose, Fort Saskatchewan, and Lloydminster. If built, these new plants might be vulnerable to competition from the existing crushers, and farmers would have more selling opportunities. On the other hand, low non-No. 1 harvest years are associated with high harvests of total canola. These high volumes could provide purchasing opportunities for fuel-grade crushing plants.

Table 3-8: Top 3 crushing sites based on estimates of annually accessible non-No. 1 canola oil in a low non-No. 1 harvest year (i.e., 2016)

Year	Non-No. 1 seed (thousands of tonnes per year)	Non-No. 1 oil (thousands of tonnes per year)	Total seed (thousands of tonnes per year)	Total oil (thousands of tonnes per year)
No. 1: Viking site (Township ID: TWP-047 RGE-12 MER-4, MD: Beaver, CD 4B)				
Average	164.99	72.93	878.39	388.94
2016	71.63	**31.37**	914.82	400.69
2017	123.61	55.75	862.12	388.81
2018	269.89	117.40	864.06	375.86
2019	194.85	87.18	872.54	390.39
No. 2: Beiseker site (Township ID: TWP-028 RGE-26 MER-4, MD: Rocky View, CD 3)				
Average	75.94	33.23	711.98	313.06
2016	48.28	**21.55**	816.10	364.28
2017	29.94	13.24	784.04	346.78
2018	88.73	37.75	601.82	256.02
2019	136.81	60.39	645.99	285.14
No. 3: Morningside site (Township ID: TWP-041 RGE-25 MER-4, MD: Lacombe, CD 5)				
Average	145.94	64.04	658.94	290.82
2016	45.86	**19.98**	713.24	310.75
2017	81.20	36.56	676.81	304.71
2018	303.19	131.08	597.63	258.38
2019	153.53	68.57	648.10	289.44

Note: The sites are identified at the township level and are referred to by villages or cities that are within or close to the identified townships. MD is short for municipal district (or county) and CD is short for Crop District. The sorting values are in bold.

3.5 Conclusions and Discussion

In this study, we conduct a township-level GIS analysis to assess the availability of non-No. 1 and total canola seed and oil in Alberta, and identify potential fuel-grade crushing sites based on the amount of annually accessible non-No. 1 canola oil. For the average from 2016 to 2019, we find Alberta had 6.85 MMT of total canola seed and 1.41 MMT of non-No. 1 canola seed per year. If all crushed, the yield would be 3.03 MMT/year of oil, and 0.63 MMT/year would be from non-No. 1 seed. Results show different spatial distributions of available non-No. 1 and No. 1 canola oil, and geographic and temporal variations in available non-No. 1 oil. We find that multiple sites in Alberta could support fuel-grade crushing plants with an annual supply of over 40 thousand tonnes of oil, focusing on the use of non-No. 1 canola.

The spatial distribution of available non-No. 1 canola for fuel-grade crushing plants is different from that of available No. 1 canola. This difference suggests that there may be potential to add additional crushing capacity to feed biorefineries. Areas such as Crop District 7 (i.e., in northwestern Alberta) appear to be especially suitable for such fuel-grade facilities. On average, this area generates the highest amounts of non-No. 1 seed, and it does not have an existing crusher, thereby alleviating competition for No. 1 seed in years when non-No. 1 volumes are low. The establishment of new fuel-grade crushing plants would also increase economic opportunities for local communities and farmers.

In sum, building a fuel-grade canola oil supply chain may bring promising opportunities for market participants. The fuel-grade supply chain could provide canola-based refineries (e.g., Parkland's Burnaby Refinery and Imperial's Strathcona Refinery) with access to lower priced feedstocks, thereby potentially improving the financial viability of low-carbon fuels. Using canola oil from the fuel-grade supply chain in the production of low-carbon fuels could also benefit fuel users such as the aviation industry. The fuel-grade supply chain may reduce the vulnerability associated with solely relying on petroleum products and may reduce costs when large-scale biorefineries become commercially available. The potentially enhanced prospects for low-carbon fuel industries may also help governments meet emission reduction targets and transition to a low-carbon economy. To this end, governments might consider policy incentives that promote research and investment for the fuel-grade canola oil supply chain.

The fuel-grade canola oil supply chain also has welfare implications for canola growers and rural communities. With the new supply chain, canola growers could have more access to high-value-added options (Kulshreshtha and Musaba 2016). The diversified markets could potentially improve growers' bargaining power, especially in dealing with grain elevators that are situated close to potential fuel-grade crushers, thereby contributing to revenue growth. Given its importance to multiple beneficiaries, the fuel-grade canola oil supply chain is worthy of further detailed study.

When estimating the availability of feedstock and undertaking site selection, it is important to take spatial and temporal variations into consideration. The spatial heterogeneity in canola harvests and actual transportation networks could influence investment decisions, such as whether and where to locate fuel-grade canola crushing plants. Biomass-dependent facilities, such as crushing plants and biorefineries, require predictable feedstock supplies over many years to pay back capital investments (Stephen et al. 2010). Determining inter-year variability in biomass availability is essential to quantify the feedstock supply risk, and therefore warrants more research. Preliminary investigations can be seen in Alam et al. (2012), Stephen et al. (2010), and Zheng et al. (2021). However, further research on risk mitigation strategies associated with feedstock variability will be required, perhaps involving techniques such as feedstock portfolios (Gülşen et al. 2014).

Chapter 4: Conclusions

The purpose of this thesis is to investigate two key factors influencing the prospects of biofuel industries: price transmission in petroleum markets and potential bio-feedstock supplies for low-carbon fuel production.

Chapter 2 uses nonlinear time series techniques to investigate price transmission from crude oil to jet fuel and diesel, two important transport fuels with distinctly different industrial characteristics. We find that both jet fuel and diesel have long-run equilibrium relationships with oil prices, and have asymmetric price adjustments, in opposite directions. The responses of the two fuel prices to oil shocks show nonlinear dynamic paths, with different amplitudes and decay periods. Due to the linkages with volatile oil prices, jet fuel and diesel undergo substantial price risks. Appropriate risk management strategies can be desirable to relevant market participants (Adams and Gerner 2012). One such strategy for jet fuel and diesel producers might be to diversify input sources by using bio-feedstock, thereby making fuel production less susceptible to fluctuations from the oil market (Valadkhani et al. 2015). Indeed, risk management could be an important incentive in the shift towards low-carbon fuels.

We also find, however, that risk management considerations may not weigh as heavily for diesel producers as for jet fuel producers. Diesel producers could take advantage of producer market power (Fosten 2012) and a relatively inelastic product demand (Liu et al. 2010), to maintain, or even expand, profit margins when oil prices decrease. Hedging tools with a horizon of two months and with decreasing intensity may be sufficient to mitigate oil price risks.

But risk management may be especially important for jet fuel producers, since jet fuel prices are more vulnerable to oil price fluctuations than diesel prices. In the long term, jet fuel prices fluctuate with oil price changes to a higher degree than diesel. In response to short-term price adjustments, jet fuel producers with relatively stable refinery yields (Kaufmann 2017) might be hesitant to pass increased oil costs through to relatively price-sensitive purchasers. Moreover, to mitigate the impacts of oil price shocks, jet fuel producers may need a long hedging horizon, approximately six months, and the hedging effects may suffer substantial uncertainty due to the large variations of price responses to changing markets. The difficulty of jet fuel producers to pass on increased costs from fluctuating oil prices, and difficulties with long-term hedging strategies, could increase incentives for jet fuel producers to move towards biojet in the long run (Davidson et al. 2014). In short, Chapter 2 suggests that current price relationships between crude oil and refined fuels could provide information that assists the development of emerging low-carbon fuel industries.

Chapter 3 explores another factor that affects the future development of low-carbon fuel industries; namely feedstock availability. Non-No. 1 canola is less desirable for human consumption than No. 1 canola but can be used as a feedstock in biofuel production. We employ a township-level GIS approach to assess the availability of non-No. 1 and total canola seed and oil in Alberta, and identify potential crushing sites designed for low-carbon fuel applications.

For the amounts of average (2016-2019) canola production, we find Alberta had 6.85 MMT of total canola seed and 1.41 MMT of non-No. 1 canola seed per year. If all seeds were crushed, the yield would be 3.03 MMT/year of oil, and 0.63 MMT/year would be from non-No. 1 seed. Our analysis shows that the spatial distribution of available non-No. 1 canola oil, which could be used for low-carbon fuel production, is different from the spatial distribution of available No. 1 canola oil, thereby suggesting that there may be potential to add additional crushing capacity to feed biorefineries. Some areas that currently do not have crushing plants, like in Northwestern Alberta, are found to be especially suitable for such fuel-grade facilities because there would be limited competition for feedstock. But supplementing feedstock with No. 1 canola seed may be necessary in years when non-No. 1 volumes are low. In short, we find spatial and temporal variations in non-No. 1 canola oil, which are important for investors to make site selection decisions and develop feedstock portfolio strategies to ensure predictable feedstock (Gülşen et al. 2014; Stephen et al. 2010).

Our GIS-based analysis is used to identify multiple sites in Alberta to build fuel-grade crushing plants that focus on the use of non-No. 1 canola, with each producing a minimum of 40 thousand tonnes of oil per year. The establishment of fuel-grade crushing plants and supply chains could potentially reduce costs and increase profitability for biorefineries, and increase fuel options for consumers, thus helping governments to reduce carbon emissions through the increased use of low-carbon fuels. Fuel-grade canola oil supply chains could also bring new opportunities for local communities and farmers.

The prospects of emerging low-carbon fuel industries can be affected by price relationships in current petroleum markets and potential supplies of bio-feedstock. The information from this thesis may be significant for potential investors and policymakers to develop appropriate strategies to facilitate the future success of a low-carbon economy.

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Appendix: Estimates of Available Canola for the Proposed Renewable Diesel Project at Imperial's Strathcona Refinery

1. One billion liters of renewable diesel per year require approximately 2.27 MMT of canola seed or 1 MMT of canola oil.

Assuming 1 liter of canola oil can produce 0.9 liters of renewable diesel (Biodiesel Education n.d.) and canola has an oil density of 0.915 kg/liter (Sahasrabudhe et al. 2017) and oil content of 0.44 (Zemanek 2018),

1 billion liters of renewable diesel $\div$ 0.9 $\times$ 0.915 kg/liter = 1 MMT of canola oil

1 MMT of canola oil $\div$0.44 = 2.27 MMT of canola seed

This is approximately 33% of average (2016-2019) total canola annual production (6.85 MMT) in Alberta.

2. From Table A1, we find that Strathcona Refinery would need to expand its service area to a round trip of approximately 4 hours in order to collect enough canola to meet the proposed capacity. Of this total, approximately 20.7% could come from non-No. 1 canola seed based on an average (2016-2019) year.

3. These estimates assume that Strathcona Refinery will collect all canola that is available in the service areas. But there are currently existing canola crushers in Fort Saskatchewan and Camrose (Figure A1). Unless the seed from these crushers is acquired, the refinery would need to expand its service area even farther, perhaps using rail cars.

Table A1: Estimates of average (2016-2019) annually accessible canola within Strathcona Refinery's service areas

Travel time (hour/round)	Total seed (thousands of tonnes per year)	Total oil (thousands of tonnes per year)	Non-No. 1 seed (thousands of tonnes per year)	Non-No. 1 oil (thousands of tonnes per year)
0.5	37.3	16.4	8.9	3.9
1	180.2	79.4	43.2	18.9
1.5	389.3	171.9	89.4	39.3
2	747.1	330.2	164.3	72.4
2.5	1,150.8	508.6	246.0	108.7
3	1,635.4	722.9	343.2	151.9
3.5	1,999.6	883.7	417.2	184.7
4	2,401.6	1,061.6	499.0	221.0
4.5	2,754.1	1,217.5	570.1	252.5
5	3,093.5	1,367.7	637.0	282.1
5.5	3,469.3	1,533.5	699.4	309.7

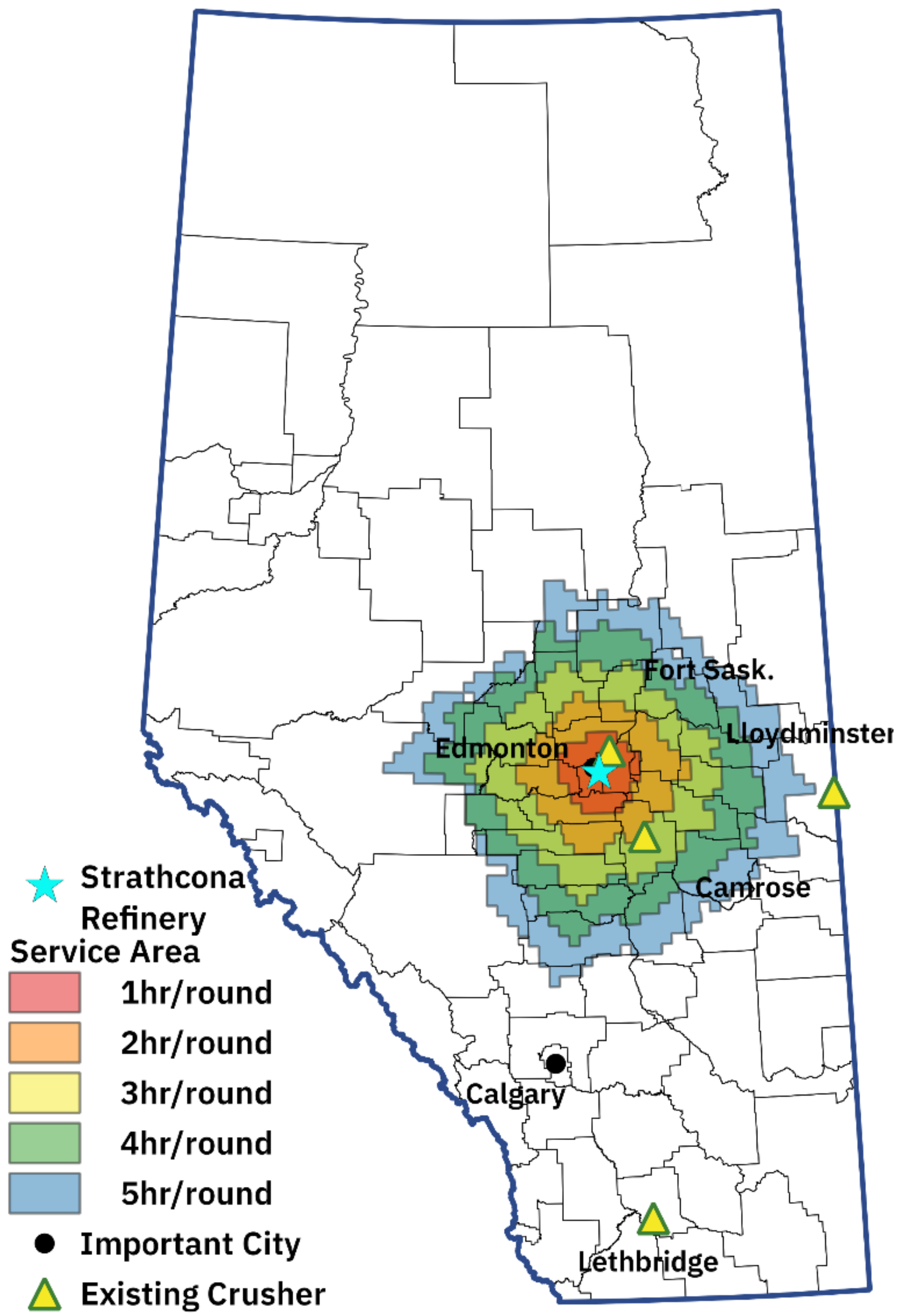

Figure A1: Strathcona Refinery and its service areas