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Estimating the supply of oilseed acreage for sustainable aviation fuel production: taking account of farmers' willingness to adopt

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Abstract

Background: Continued progress towards reducing greenhouse gas emissions will require efforts across many industries. Though aviation is estimated to account for modest portions of global greenhouse gas emissions, these shares may grow as the industry expands. The use of biomass- and crop-based sustainable aviation fuels can help reduce emissions in the industry. However, limited feedstock supplies are a barrier to increased use of these fuels. This study examines the potential supply of feedstock from oilseeds and farmer willingness to produce oilseed crops under contract for sustainable aviation fuel production with a focus on canola and similar oilseed feedstocks (e.g., rapeseed). Stated-choice survey data is used to examine the contract and crop features that drive contract acceptance in six states located in the U.S. Great Plains and Pacific Northwest and then acreage supply curves are estimated for canola using secondary data.

Main findings: The estimated number of acres supplied under contract varies considerably across states and scenarios. Relatedly, estimated supply curves exhibit high degrees of price responsiveness. Of the states analyzed, oilseed acreages supplied under contract are generally found to be greatest in Kansas and North Dakota.

Conclusions: Results suggest that in the absence of favorable contract and crop scenarios canola and other oilseed prices will need to considerably increase from typical levels to induce higher levels of supplied acres. The presence of crop insurance, shorter contract lengths that provide cost sharing and the availability of particular crop attributes are shown to diminish the need for higher canola and other oilseed prices.

Keywords: Oilseed, Canola, Contracts, Supply, Biofuels, Sustainable aviation fuel

Introduction

Global greenhouse gas emissions (GHG) have steadily marched upwards over the past several decades [1]. Air travel has been a contributing factor. Passenger-kilometers on flights, for example, have increased from about 3.6 billion in 2004 to about 8.3 billion in 2018 [2, 3]. Though aviation is estimated to account for modest portions of global greenhouse gas (GHG) emissions, these shares may grow as the industry expands. For example, though international aviation was estimated to account for only 1.3% of global CO2 emissions as recently as 2012; this share could potentially grow to 22% by 2050 [4]. Moreover, achieving significant reductions in global GHG emissions will require a wholistic approach that results in reductions across a broad spectrum of sectors, such as heating, chemicals, road transport, and electricity [5] and some that may be viewed currently as minor contributors, such as aviation. Potentially, these various sectors will be competing for the same bioenergy feedstocks [5], though some assessments have shown that use of sustainable aviation fuels (SAF) can reduce carbon emissions in

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the aviation sector without significant impacts on the rest of the bioenergy sector [6]. Some studies suggested that median greenhouse gas emissions may be reduced by as much as 63% when using SAF (which included those derived from rapeseed and an edible variety of rapeseed, canola, as feedstock options) compared to the use of low sulfur jet fuel based on life cycle assessments [7].

As concerns surrounding climate change and its potential impacts have grown, regulatory bodies have taken steps to curb emissions in the aviation industry. In the U.S., the Federal Aviation Administration (FAA) in 2012 introduced the United States Aviation Greenhouse Reduction Plan. As part of this plan, the FAA set a goal for U.S. annual use of alternative jet fuel of one billion gallons by 2018, which it hoped to meet by supporting SAF research and development [8]. The U.S. Department of Defense has made efforts to incorporate alternative fuel usage into its jet and ship fleets, but with minimal success: Between 2007 and 2014, only 2 million gallons of alternative fuel were purchased compared to 32 billion gallons of petroleum-based fuels [9]. More recently, the Sustainable Skies Act—introduced in the U.S. House in May 2021 and in the U.S. Senate in June 2021—seeks to cut aviation emissions by 50%. In the E.U., aviation emissions were brought into the Emissions Trading Scheme (ETS) in 2008 as part of an overall goal of reducing GHG emissions to at least 20% below 1990 levels [10]. However, SAF usage in the E.U. has been and is expected to continue to be minimal [11]. A draft proposal from the European Commission could change this by imposing a tax on aviation fuels, which had been exempt from previous fuel taxes [12]. Under the draft proposal, sustainable fuels would not be subject to the new taxes [12]. Recent resolutions adopted by the International Civil Aviation Organization (ICAO)—a specialized United Nations agency that sets aviation standards for member countries—suggest emission cutting efforts will increase moving forward. Specifically, the Carbon Offsetting and Reduction Scheme for International Aviation has set a goal of zero global net CO2 emissions above the 2020 level that is to be enforced via the purchase and cancellation of emissions units [13]. To date, 121 ICAO member countries representing 97.5% of revenue tonne kilometers (revenue load in tonnes multiplied by kilometers) have submitted action plans establishing long-term strategies for reducing emissions in the aviation sector [14].

To meet current and future emissions requirements, it has been suggested (by Kousoulidou and Lonza [15] and Gegg et al. [16]) that the most attractive option for airlines may be a switch to drop-in-type SAF, which can be used without infrastructure or engine modifications, rather than an overhaul of fleets for increased fossil-fuel efficiency or for use with non-drop-in-type SAF. Moreover, Wang et al. [17] stated that a switch to low-emission fuels is the only way to meet emissions requirements in the aviation industry due to the limited reductions that can be achieved through other technological updates. In general, biomass-based transportation fuels are increasingly being considered as alternatives to fossil fuels [18, 19]. With respect to SAF in particular, research across biochemistry, bioengineering, and economics suggests oilseeds, such as rapeseed (which includes canola), and camelina are leading candidates [20].

Despite the potential for SAF, barriers to large-scale utilization remain. For SAF in general, uptake has been limited in part due to difficulties in providing them in a cost effective and reliable manner [21, 22]. In interviews with aviation biofuel stakeholders in Europe and North America by Gegg et al. [16], every interview identified the high production cost of aviation biofuels as a key constraint on market development. A key factor in these high costs, meanwhile, was attributed by several stakeholders to a lack of sufficient feedstock supply [16]. For SAF derived from field crops (e.g., corn or soybean), additional concerns are present, such as the "food versus fuel" debate and the GHG emissions associated with direct or indirect land-use change [20].

Production of SAF using oilseeds may help to alleviate some of these concerns. First, if increased production of SAF via oilseeds represents a net SAF increase—i.e., it is not replacing production from other sources or areas—prices should drop just through the supply-demand mechanism. In addition, if enough oilseed was produced as feedstock, it may allow for cost savings via economies of size and/or scale at the point of SAF production. Second, in areas, such as the Great Plains in the U.S., oilseeds can be incorporated into traditional rotations (such as with wheat) by replacing a fallow period [20, 23]. This should help satisfy food versus fuel concerns, as replacing a fallow period is not replacing production that would have gone into the food or animal feed system. This should also alleviate some concerns regarding competition for feedstocks between biofuels, such as biodiesel and renewable diesel in the case of canola or rapeseed oil. If replacing a fallow period, this would represent an increase in the total feedstock supply rather than a diversion of current supply to new uses. Such diversions could still occur though if sufficient "new" supply could not be contracted to make plant operation feasible. However, this could be a short-to-medium-term concern as the transport sector has the technological ability and the societal push for increased adoption of electric vehicles, which could decrease the demand for all liquid fuels in this sector. Furthermore, Shi et al. [20] estimated that there is a potential for net GHG reduction associated with the resulting SAF even when taking the changed land uses into consideration.

Some previous research has looked at the feasibility and potential for SAF feedstock supplies. Murphy et al. [24] provide a framework for assessing the feasibility of a SAF industry within a region along with a Queensland case study. The analysis assumes a long-term supply contract, though the authors note that a variety of arrangements would likely be required and that additional research is needed on acquiring contracts with farmers. Trejo-Pech et al. [25] estimate the farm-level breakeven prices as well as potential profitability and locations for crushing facilities and refineries in an analysis of the potential for pennycress as a SAF feedstock. In a related study, Zhou et al. [26] found that for farmers considering growing pennycress for aviation fuel, key concerns included market access for pennycress as a bioenergy crop and profitability of growing pennycress. The most important benefit for consideration was found to be additional farm income.

However, the potential benefits of using oilseed crops for SAF production will not be realized without farmer buy in. Initial market supply will likely rely on contracting between producers and refineries, as has been established in other biofuel markets [27, 28]. Yet, little research exists on oilseed-feedstock supply, particularly on how contractual conditions impact farmers' willingness to produce oilseed crops. This gap is addressed in this study using farmer survey data to examine willingness to incorporate oilseeds in rotation with traditional wheat under different contractual conditions. Analysis focuses on the use of canola (a variety of rapeseed) as the oilseed of choice, given its crop and oil yield potential, as well as existing production in the region of study [20, 29]. Oilseed crops have been shown to be a beneficial crop for replacement of fallow in wheat rotations and as a break crop, helping to improve wheat yields and soil health by reducing problems due to continuous cereal production [20, 30]. This analysis provides insights into the feasibility of large-scale oilseed production as a SAF feedstock. Empirical analysis utilizes standard econometric techniques that could easily be transferred to other parts of the world pending the availability of or ability to collect the necessary data, such as survey responses and production-economics parameters. In addition, the analyses advance studies of biofuel feedstock supply by directly incorporating producers' willingness to grow these crops under contract.

Data and methods

Primary and secondary data were used (i) to estimate farmers' willingness to grow oilseeds in rotation with wheat (replacing fallow or another crop); (ii) to estimate the amount of land in the "Wheat Belt" that may feasibly be put into contracted oilseed production; and (iii) to provide an estimate of the supply of oilseed feedstock under different contractual and profitability conditions. Primary data was obtained via a survey of producers in the study region (study region and producer survey details provided below). Secondary data was obtained from various U.S. state- and federal-government entities, such as the U.S. Department of Agriculture's (USDA) Economic Research Service (ERS), Farm Service Agency (FSA), and National Agricultural Statistics Service (NASS).

Study region

The study region, depicted in Fig. 1, is comprised of 11 states in the western U.S.: California (CA), Colorado (CO), Kansas (KS), Montana (MT), Nebraska (NE), North Dakota (ND), Oklahoma (OK), Oregon (OR), South Dakota (SD), Texas (TX), and Washington (WA). These states represent six of the farm resource regions as designated by USDA ERS: Fruitful Rim (Pacific Northwest: CA, OR, and WA), the Prairie Gateway (CO, KS, NE, OK, and TX), and the Northern Great Plains (MT, ND, and SD), comprising the majority of the Wheat Belt in the U.S. [31]. The Prairie Gateway and the Northern Great Plains regions accounted for 74% of all wheat acres planted in 2019 [32]. The Prairie Gateway region experiences wide extremes in both temperature and precipitation, having bitterly cold air masses during winter and hot, humid summers. This region is susceptible to floods, severe thunderstorms, summer drought, heat waves, and winter storms [33]. Climate in the Northern Great Plains region is semi-arid with longer and colder winters, as well as shorter and hotter summers. Land management in this region is a mixture of dryland cropping systems and livestock production based on rangeland, pastures, and hay production [34]. In the Fruitful Rim (Pacific Northwest), about two-thirds of rainfall comes between October and March and it is fairly dry during the remainder of the year [35].

Producer survey

An agricultural producer survey was administered to 10,089 non-irrigated wheat growers in the study region to assess farmers' willingness to adopt specialized oilseed crops under contract for utilization as a feedstock for SAF production. Contact information for the 10,089 wheat farmers was obtained from Farm Market ID (www.farmmarketid.com). Focus groups within the region, as well as experts in the field, were consulted for questionnaire development and testing[1]. The survey was

[1] Focus group interviews were conducted with farmers in each of the USDA ERS crop production regions in the study and were used to help facilitate the design of the stated choice experiment and survey. The focus groups were

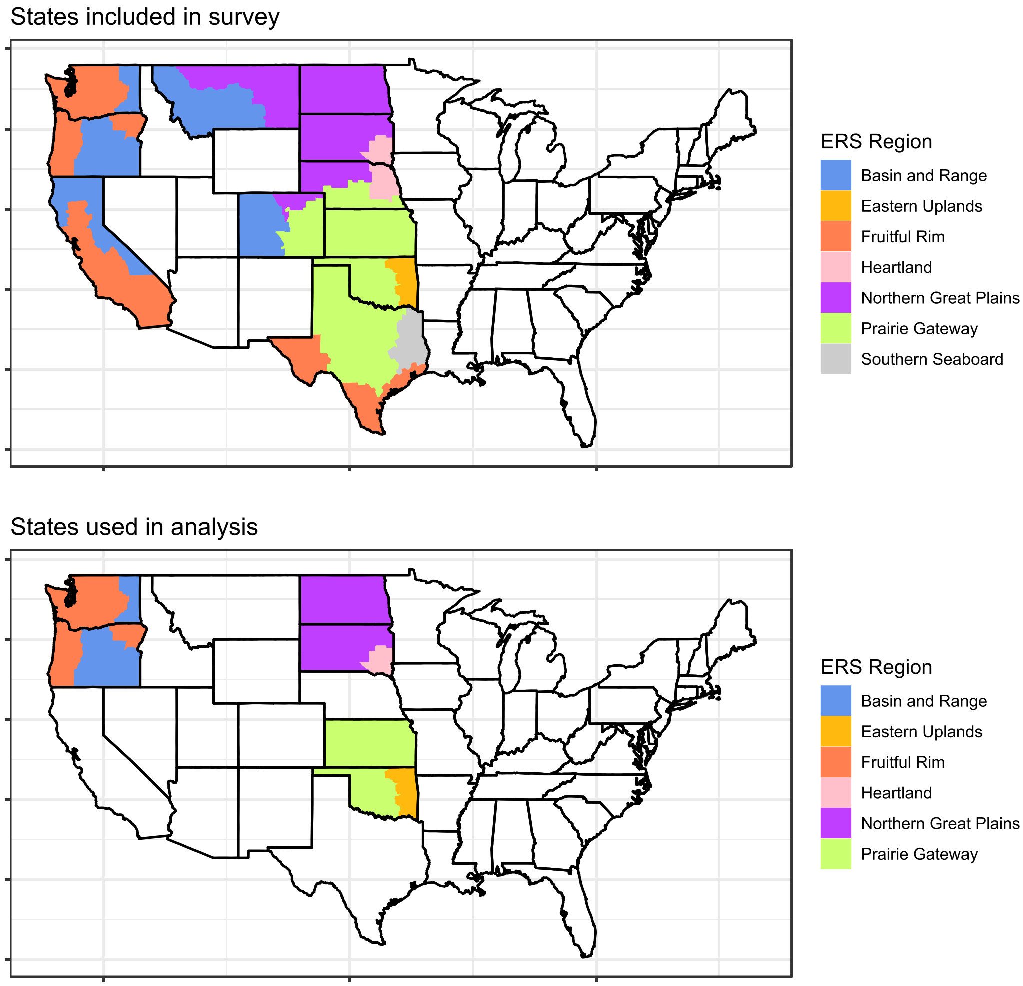

Fig. 1 Study region and analysis region

administered by the Iowa State University Survey & Behavioral Research Services (SBRS) unit. The survey and research approach were reviewed and approved by the Internal Review Board of the Office of Research Compliance at Kansas State University (IRB Protocol #6530). Survey responses from producers were anonymous and a letter accompanying the survey explained the purposes of the survey, indirect benefits to participants, confidentiality and anonymity, and that the survey was strictly voluntary.

The survey was mailed to farmers in April 2013. Reminder postcards were sent to non-responders 10–12 days after the first survey packets were mailed. A second survey packet was mailed 14–16 days after the reminder postcard was mailed. A total of 971 responses were received (a response rate of 9.7%) in 2013. Due to a lower than expected response rate, the survey was sent again to non-respondents (using the same process) in January and February 2014. The low response rate in 2013 may be attributed to the timing when the survey was administered[2]. From the two mailings, 9,723 surveys were sent out that had deliverable addresses and 1,444 surveys were completed, providing a response rate 15%. Usable surveys

Footnote 1 (continued)

held with 5 to 7 farmers to collect information about what crop and contract attributes they would find the most important when growing oilseed crops. Farmer participants were classified as either considering adopting these crops; have produced oilseed crops; or have entered a contract in the past to produce these crops. Focus groups were held in Kansas, North Dakota, Oklahoma and Washington during Fall 2012 and Winter 2013.

[2] The first wave of the survey was sent in April 2013 during crop planting season. Due to unforeseen circumstances and events in the project the survey was sent later than expected, which likely reduced the response rate during the first wave of the survey.

Table 1 Comparison of demographics between survey respondents and 2017 Agricultural Census

State	Age		Percent male		Percent white		Total sales	
	Survey	Census	Survey	Census	Survey	Census	Survey	Census
Kansas	59.0	58.1	98.2	66.1	100.0	98.5	$589,046	$320,694
North Dakota	55.5	56.0	98.4	70.6	100.0	98.8	$832,661	$312,324
Oklahoma	59.4	57.0	93.5	61.6	99.3	84.9	$474,107	$95,065
Oregon	56.1	57.9	100.0	55.8	100.0	96.7	$752,000	$133,104
South Dakota	56.8	56.1	98.1	74.5	100.0	97.2	$1,022,549	$324,397
Washington	57.8	58.1	97.1	57.6	100.0	96.1	$834,286	$269,172

for this analysis included 428 for the Prairie Gateway region (287 in KS and 141 in OK), 241 for the Northern Great Plains region (189 in ND and 52 in SD), and 192 in the Pacific Northwest Region (142 in WA and 50 in OR). Survey responses from CA, CO, MT, NE, and TX were not utilized in analyses due to smaller samples (17, 87, 169, 47, and 47, respectively) and a decision to focus analysis on the larger wheat producing states.

Analysis was conducted separately for the states of KS, OK, ND, and SD, while WA and OR were combined into a single analysis due to the smaller number of observations from each state. Demographics reported by farmers in the survey are compared to the statistics from each state as reported in the 2017 Census of Agriculture [36]. Table 1 shows the comparison between the survey statistics and the census. The survey sample is representative with respect to average age and the percentage of producers who are white. The survey was less representative with respect to the percentage of farmers who are male and with respect to total sales, with both being higher on average when compared to the Census of Agriculture. The total sales result may be attributable, to some extent, to the use of total sales ranges in the survey rather than actual total sales. Average total sales were thus calculated by assigning total sales to a farmer equal to the midpoint of the selected range. Nevertheless, the surveyed farmers likely represent larger operations. In addition, the sample excludes the part of the farming population that does not grow wheat. This could also contribute to the difference between the survey figures and the Census of Agriculture if this population tends to have smaller total sales.

Stated choice experiment

The primary usage of the survey was a stated choice experiment examining farmers' willingness to enter into contracts to produce specialized oilseeds as a feedstock for SAF production. Each choice situation consisted of nine attributes to reflect differing contract and growing conditions. Four attributes were related to oilseed characteristics: shatter resistance, pest tolerance and herbicide resistance, winter hardiness, and extended window to direct combine. The remaining five attributes describe contract features: net returns, length of contract, crop insurance, cost share, and presence of an "Act of God" clause. The attributes used in the experiment represent the significant crop traits and contract attributes participants at focus group interviews indicated were the most important through discussions and surveys of participants. For crop variety attributes, shatter resistance, pest tolerance, and winter hardiness were important for ensuring the viability and yield of the crop, while an extended direct combine window was important for the flexibility it provides for including oilseed crops in rotation with small grains. Farmers have indicated that the length of contract, crop insurance, and net returns are highly important when considering the adoption of a crop [37, 38]. Bergtold, Fewell, and Williams [27] showed that the length of contract, net returns, presence of crop insurance, and financial incentives are important contract considerations in a similar context for production of cellulosic feedstocks for ethanol production.

Survey respondents were asked to consider each contractual scenario and choose if they would enter the contract to grow oilseeds in rotation with wheat or "opt out". Contract attributes were defined in the stated choice experiment and an example question is provided in Fig. 2. In conjunction with the oilseed farmer survey, a supplemental information sheet was provided that highlighted the information about specific oilseed crops, such as costs and potential returns relative to wheat production.

As per the survey instructions, farmers were also asked to take into consideration that oilseed crops would be designated for SAF production and grown in rotation with spring or winter wheat under dry-land conditions. Net returns were presented in the survey as the expected percent gain above the net returns for producing an acre of wheat. Four levels of net returns were considered: -5, 5, 15, and 25 percent above wheat net returns (but do not include cost-sharing). The cost share attribute was described as the percentage of the input costs that the

		Description	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Oilseed Characteristics	Shatter Resistance	The oilseed has improved shatter resistance.	No	Yes	Yes	Yes
	Pest Tolerance and Resistance	Varieties have traits that provide herbicide and insect resistance.	No	No	Yes	No
	Winter Hardiness	Winter varieties that more resistant to winter weather.	No	Yes	No	Yes
	Extended Direct Combine Window	Oilseed has an extended window to direct combine and not swath.	No	No	No	Yes
Contract Features	Net Returns	Expected percent gain above the net returns for producing an acre of wheat.	25 %	5 %	25 %	5 %
	Length of Contract	The time commitment in consecutive years of the contract.	1 Year	3 Years	1 Year	1 Year
	Crop Insurance	Crop insurance is available in the market for this crop.	Yes	Yes	No	No
	Cost Share	Bio-refinery or processor agrees to cover a percentage of the input costs.	30 %	15 %	15 %	30 %
	"Act of God"	The contract includes an "Act of God" clause.	Yes	No	No	Yes
		➡ **I would probably be willing to grow an oilseed crop under contract for this scenario:**	**1 = Yes 2 = No**	**1 = Yes 2 = No**	**1 = Yes 2 = No**	**1 = Yes 2 = No**

Fig. 2 Example stated-choice question from survey instrument

biorefinery or processor agrees to pay. Three levels of the cost share attribute were considered in the survey: 0, 15, and 30 percent. Two levels were considered for contract length: 1 year or 3 years. The 3-year contract was considered, because an oilseed crop is typically only rotated once every 3 years in a crop rotation with small grains. It would be assumed that some portion of the farmer's land would be planted to an oilseed crop each year to meet contract obligations. Oilseed characteristics, crop insurance, and the "Act of God" clause are binary attributes: 1 = Yes (present) and 0 = No (not present).

A $\left(2^7 \times 3 \times 4\right)$ fractional factorial design was used to find the combinations needed to construct the set of stated choice questions based on the approach from Louviere, Hensher, and Swait [39]. PROC OPTEX was used in SAS (version 9.3) to develop the design and blocking of choice sets. The D-optimality criterion was used to obtain the optimal design and a D-Efficiency score of 99.13 was obtained. The procedure developed 48 choice sets which were randomly assigned into 12 blocks of 4 choice questions yielding 12 survey versions, which were randomly distributed to survey respondents following standard stated choice techniques [39]. That is, each respondent answered 4 choice questions on the survey, providing additional within respondent variation (of their preferences), in addition to variation across respondents.

Estimation of oilseed supply

Estimation of oilseed supply for SAF production began by first estimating farmer willingness to enter contractual obligations to grow the oilseed. The survey instrument presented farmers with four contract scenarios with varying oilseed and contract attributes (Fig. 2). For each scenario, farmers were asked to respond "Yes" or "No" to the statement "I would probably be willing to grow an oilseed crop under contract for this scenario." Oilseed attributes included shatter resistance, pest tolerance and resistance, winter hardiness, and extended direct combine window; contract attributes included net returns (as percent above or below net returns to wheat), length of contract, availability of crop insurance (yes or no), cost sharing by the biorefinery/processor (as percentage of the input costs), and the inclusion of an "Act of God" clause (yes or no).

It is assumed that producers maximize expected utility when deciding whether to enter a contract for oilseed production. Letting $y = 1$ if the farmer enters the contract and $y = 0$ if the farmer does not, then following Hanneman [40] farmers are assumed to have a utility function given by $u = u(y, \mathbf{x}, \mathbf{z})$, where $\mathbf{x}$ is a vector of contract and oilseed attributes and $\mathbf{z}$ is vector of variables that impact utility but are not associated with the production contract or oilseed. While the utility function may be known to the farmer, it is treated as random by the research and written as

$$u(y,\mathbf{x},\mathbf{z}) = v(y,\mathbf{x},\mathbf{z}) + \varepsilon_y \text{ for } y = 0,1 \tag{1}$$

where $\varepsilon_y \sim iid(0,\sigma_\varepsilon^2)$. Then, the farmer will accept the contract if

$$v(1,\mathbf{x},\mathbf{y}) + \varepsilon_1 > v(0,\mathbf{x},\mathbf{y}) + \varepsilon_0 \tag{2}$$

and the probability that the farmer enters the contract can be written as

$$P(y=1) = P(v(1,\mathbf{x},\mathbf{y}) + \varepsilon_1 > v(0,\mathbf{x},\mathbf{y}) + \varepsilon_0) \tag{3}$$

or

$$P(y=1) = P(\varepsilon_0 - \varepsilon_1 < v(1,\mathbf{x},\mathbf{y}) - v(0,\mathbf{x},\mathbf{y})). \tag{4}$$

Defining $\eta = \varepsilon_0 - \varepsilon_1$, $\Delta v = v(1,\mathbf{x},\mathbf{y}) - v(0,\mathbf{x},\mathbf{y})$, and $F_\eta(\cdot)$ as the cumulative distribution function (CDF) for η Eq. (4) then becomes

$$P(y=1) = F_\eta(\Delta v). \tag{5}$$

It is further assumed that $\Delta v = \boldsymbol{\beta}'\mathbf{x} + \boldsymbol{\delta}'\mathbf{z}$ which yields

$$P(y=1) = F_\eta\left(\boldsymbol{\beta}'\mathbf{x} + \boldsymbol{\delta}'\mathbf{z}\right). \tag{6}$$

Assuming $F_\eta(\cdot)$ follows a logistic CDF, the model given by Eq. (6) can be estimated using logistic regression techniques [41]. However, it is assumed that the same contract can be viewed with differing levels of favorability by different farmers due to unobserved heterogeneity in farm and/or farmer characteristics. As such, a random parameters logistic regression model is used to capture this unobserved heterogeneity [39]. Specifically, for farmer i in county k the model allows for farmer-specific intercept terms such that Eq. (6) becomes:

$$\begin{aligned} P_{i,k} &= P(y_{i,k} = 1 \mid \mathbf{x}, \mathbf{z}_{i,k}) \\ &= \left[1 + \exp\left(-\beta_{i,k,0} - \boldsymbol{\beta}'\mathbf{x} + \boldsymbol{\delta}'\mathbf{z}_{i,k}\right)\right]^{-1}, \end{aligned} \tag{7}$$

where

$$\beta_{i,k,0} = \beta_0 + \boldsymbol{\theta}'\mathbf{z}_{i,k} + \sigma_\beta u_{i,k}. \tag{8}$$

The term $\beta_0 + \boldsymbol{\theta}'\mathbf{z}_{i,k}$ represents the conditional mean of the distribution of the intercept; $\mathbf{z}_{i,k}$ is a vector containing a dummy variable for the year of the survey (2013 or 2014), as well as a set of sub-region dummy variables; σ_β is the standard deviation of the distribution of the intercept; and $u_{i,k}$ is assumed to be mean zero and standard normally distributed [42]. Additional spatial heterogeneity is captured by estimating a separate model for each region $r \in (KS, ND, OK, PNW, SD)$. Thus, for farmer i in county k in sub-region s in region r, Eqs (7) and (8) can be expressed as:

$$\begin{aligned} P_{i,k,s,r} &= P(y_{i,k,s,r} = 1 \mid \mathbf{x}, \mathbf{z}_{s,r}) \\ &= \left[1 + \exp\left(-\beta_{i,k,s,r,0} - \boldsymbol{\beta}'_r\mathbf{x}\right)\right]^{-1} \end{aligned} \tag{9}$$

and

$$\beta_{i,k,s,r,0} = \beta_{0,r} + \boldsymbol{\theta}'_r\mathbf{z}_{s,r} + \sigma_{\beta_r} u_{i,k,s,r} \tag{10}$$

where $\mathbf{z}_{i,k}$ has been replaced by $\mathbf{z}_{s,r}$, because these vectors are identical for all farmers and counties in sub-region s in region r. The variables in $\mathbf{z}_{s,r}$ are used only in the distributions for $\beta_{i,k,s,r,0}$ and thus the term $\boldsymbol{\delta}'\mathbf{z}_{i,k}$ drops out in Eq. (9). Equations (9) and (10) serve as the estimable adoption or willingness-to-grow models for each region.

Following estimation of (9) and (10), for a given contract and crop variety with associated attribute vector $\mathbf{x}_j$, adoption probabilities for county k in sub-region s of region r are estimated as:

$$\hat{P}_{s,r,j} = \left[1 + \exp\left(-\hat{\beta}_{s,r,0} - \hat{\boldsymbol{\beta}}'_r\mathbf{x}_j\right)\right]^{-1} \tag{11}$$

where

$$\hat{\beta}_{s,r,0} = \hat{\beta}_{0,r} + \mathbf{z}'_{s,r}\hat{\boldsymbol{\theta}}_r, \tag{12}$$

$\mathbf{x}'_j = [S_j\ T_j\ W_j\ C_j\ R_j\ L_j\ I_j\ O_j\ G_j]$, S_j denotes improved shatter resistance, T_j is pest tolerance, W_j is winter hardiness, C_j is extended combine window, R_j is percent returns above wheat, L_j is contract length, I_j is the availability of insurance, O_j is cost share, and G_j is the "Act of God" clause. All attributes are binary except for L_j, O_j, and R_j. For all binary variables, a value of 1 indicates the presence of the attribute in the contract or crop, while 0 indicates its absence. For sub-region s in region r, the vector $\mathbf{z}'_{s,r} = [t_{2013}\ d_1\ d_2 \cdots d_{S_r}]$, where t_{2013} is the survey-year dummy variable and d_s for $s = 1, \ldots, S_r$ are the dummy variables for sub-regions within region r. The i and k subscripts have been dropped from $\hat{P}_{s,r,j}$ and $\hat{\beta}_{s,r,0}$ to note that this approach uses the same value for all farmers and counties in sub-region s of region r.

One approach for estimating regional crop acreages is to assume that the share of acres devoted to a crop is equal to the probability that any given field in the region is devoted to that crop [43]. Acreages can then be estimated as the total potential acreage (e.g., total cropland in the region) multiplied by the field-level probability. Because the survey asked if respondents would be willing to grow oilseeds in rotation with wheat, the total potential acreage is defined as the total wheat acreage in a county. The amount of oilseed grown annually for SAF production in county k in sub-region s of region r under scenario j, $A^O_{k,s,r,j}$, is then estimated as:

$$\hat{A}^O_{k,s,r,j} = \frac{1}{3}\delta_r \hat{P}_{s,r,j} A^W_{k,s,r} \tag{13}$$

where $A^W_{k,s,r}$ is the total area planted to wheat in the county based on USDA FSA planted acreage data from 2019, δ_r is the adjusted survey response rate for region r, and the 1/3 scaling is applied to account for an assumed 3-year rotation, where oilseeds enter only once every 3 years, following best management practices. By including δ_r it is assumed that farmer participation—and thus the proportion of traditional wheat acreage offered for participation—is capped at the survey response rate for the region. This helps to indicate initial interest in this type of farm enterprise based on survey response in the region, providing a conservative estimate of initial adoption in the study region as the market develops. Sub-regional and regional supplies can be obtained by summing $\hat{A}^O_{k,s,r,j}$ across the counties in the (sub-) region.

For this analysis, a straightforward approach to constructing supply curves would then be to estimate $\hat{A}^O_{k,s,r,j}$ for all counties across a range of values for R_j and then simply chart regional supplies as a function of R_j (e.g., [44]). However, a more useful analysis is to provide estimated supply curves in the traditional way, as a function of oilseed price. This approach is adopted here even though it is complicated by R_j, which expresses oilseed net returns as a percentage of net returns to wheat. To operationalize this, the adopted approach is as follows. First, a range of oilseed prices is selected, $p^O_n \in \{p^O_1, p^O_2, \ldots, p^O_N\}$. Then, for each county k, the net return variable R_k is estimated as:

$$R_k = \frac{\left(p^O_n q^O_k - (1 - O_j)\, VC^O_k - FC^O_k\right) - NR^W_k}{\left|NR^W_k\right|} \times 100 \tag{14}$$

where q^O_k, VC^O_k, FC^O_k, and NR^W_k are the oilseed yield per acre (cwt/ac), variable costs ($/ac) for oilseed production, fixed costs ($/ac), and net returns to wheat ($/ac) in county k and $O_j \in \{0, 0.15, 0.30\}$ is the cost share associated with scenario j. It is assumed fixed costs are the same under the oilseed and wheat production. Due to data availability for the terms in Eq. (14), this analysis looks at the potential supply of canola, a type of rapeseed, for SAF production, which is primarily produced along the wheat belt and can also act as a proxy for other potential oilseeds being considered as feedstocks for SAF production, such as industrial rapeseed [28]. The assumed values and their sources for the terms in Eq. (14) are found in Tables 2 and 3. Once R_k is calculated for a given canola price ($/cwt), county-level acreages are calculated using Eqs. (11)–(13).

Table 2 Variable costs and yields for canola production

State	Yield (cwt/ac)		Variable costs ($/ac)	
	Value	Source	Value	Source
Kansas	1,328	NASS	243.91	[49]
North Dakota—East Central	17.96	NASS	126.71	[50]
North Dakota—North Central	17.96	NASS	126.48	[51]
North Dakota—North East	17.96	NASS	165.15	[52]
North Dakota—North Red River Valley	17.96	NASS	162.45	[53]
North Dakota—North West	17.96	NASS	197.95	[54]
North Dakota—South Central	17.96	NASS	114.86	[55]
North Dakota—South East	17.96	NASS	160.54	[56]
North Dakota—South Red River Valley	17.96	NASS	168.44	[57]
North Dakota—South West	17.96	NASS	104.86	[58]
Oklahoma	12.08	NASS	234.70[b]	[59, 60]
Oregon	18.62	NASS	199.47[c]	[61]
South Dakota	17.96[a]		137.81[d]	
Washington	17.04	NASS	168.64[e]	[62]

[a] No data available, set equal to North Dakota value

[b] Averaged across the two budgets

[c] Updated from October 2012 values to January 2020 values using Bureau of Labor Statistics CPI Inflation Calculator

[d] No South Dakota specific budgets available, set equal to North Dakota county average

[e] Updated from March 2006 values to January 2020 values using Bureau of Labor Statistics CPI Inflation Calculator; averaged across all budgets in report

For policy and industry, there exists a significant interest in the elasticity of this oilseed supply. In this analysis, acreage elasticities are estimated by treating the points along the simulated supply curves as observational data arising from an underlying supply function given by:

$$A^O_{r,j,n} = \gamma p_n^{\alpha} \tag{15}$$

where $A^O_{r,j,n}$ is the simulated canola acreage in region r, $p^O_n \in \{p^O_1, p^O_2, \ldots, p^O_N\}$ is the price of canola, and γ and α are parameters to be estimated. The functional form was chosen, because, following a natural log transformation, the model can be estimated using simple linear regression and elasticity estimates are easily obtained. Thus, elasticity estimates are obtained via the simple regression given by:

$$\ln\left(A^O_{r,j,n}\right) = \ln(\gamma) + \alpha \ln(p_n) + \varepsilon_n \tag{16}$$

where the parameter α represents the acreage elasticity with respect to price. Equation (16) is estimated using ordinary least squares. The acreage elasticity provides a measure of the potential volatility in the market while

Table 3 Variable costs, fixed costs, and net returns ($/ac) for wheat by state and ERS region, 2017-2019 average

State	ERS region	Variable costs	Fixed costs	Net return
Kansas	Prairie Gateway	102.48	159.09	− 83.80
North Dakota	Northern Great Plains	125.60	195.43	− 51.74
Oklahoma	Eastern Uplands[a]	102.48	159.09	− 83.80
	Prairie Gateway	102.48	159.09	− 83.80
Oregon	Basin and Range	154.00	204.44	− 31.51
	Fruitful Rim	203.69	294.88	− 94.00
South Dakota	Heartland	187.88	280.46	− 120.17
	Northern Great Plains	125.60	195.43	− 51.74
Washington	Basin and Range	154.00	204.44	− 31.51
	Fruitful Rim	203.69	294.88	− 94.00

[a] No data available, set equal to Prairie Gateway values

Table 4 Attribute vectors for sensitivity analysis 1—"Scenario Favorability"

		Sensitivity analysis				
		1. Scenario favorability			2. Net returns	3. Cost share
Variable	Description	Low	Medium	High		
S_j	Equal to 1 if oilseed has improved shatter resistance, equal to 0 if it does not.	0	0	1	0	1
T_j	Equal to 1 if oilseed exhibits pest tolerance and resistance, equal to 0 if it does not.	1	1	1	1	1
W_j	Equal to 1 if oilseed exhibits winter hardiness, equal to 0 if it does not.	0	1	1	1	1
C_j	Equal to 1 if oilseed allows for extended direct combine harvest, equal to 0 if it does not.	0	0	1	0	1
R_j	Percent net returns above net returns to wheat.	Base	Base	Base	Variable	Base
L_j	Length of contract in years.	1	1	1	1	1
I_j	Equal to 1 if crop insurance is available, equal to 0 if it is not.	0	1	1	1	1
O_j	Percent of input costs covered by the biorefinery or processor.	0	15	30	15	Variable
G_j	Equal to 1 if "Act of God" clause is included, equal to 0 if it is not.	1	1	1	1	1

accounting for the responsiveness to contract, plant, and market conditions, as volatility will be dependent upon the adoption probabilities and market conditions.

Sensitivity analyses

Understanding how well this model will hold up and the impacts from changes to the assumptions that have been made requires sensitivity analyses. These analyses show how the potential supply of canola (or rapeseed) may change due to contract, market, or external conditions. The following sensitivity analyses are included in this paper:

1. Supply Estimation for "Low", "Medium", and "Highly" Favorable Scenarios—Separate analyses were conducted for "low-", "medium-", and "high-" favorability scenarios, where favorability is considered from the farmer's perspective. The attribute vectors associated with these scenarios are presented in Table 4. It could be argued that from a purely profit and risk perspective, the ranking of contract favorability may be the opposite for SAF producers with respect to the contract attributes.
2. Wheat Net Returns Scenarios—Because so much is assumed with respect to returns to wheat and there is little spatial heterogeneity in the assumed returns, sensitivity analysis is conducted with respect to this variable. To limit the set of results, analyses are restricted to just the "medium" favorability scenario (see Table 4). The sensitivity analysis is conducted by re-estimating supply curves for this contract with net returns to wheat that are 25% greater and less than in the "baseline" case (see Table 3).
3. Cost-Share Scenarios—The percentage of oilseed input costs that are paid by the SAF production facility will have a significant impact on the refinery's bottom line. Thus, the degree to which this cost share may impact the supply of feedstock is an important

Table 5 Random parameter logit regression results

Variable	Kansas	North Dakota	Oklahoma	Pacific Northwest	South Dakota
$\hat{\beta}_S$	0.121* (1.81)	0.049 (0.70)	0.126* (1.76)	0.187*** (2.78)	0.371* (1.84)
$\hat{\beta}_T$	0.368*** (5.38)	0.146** (2.06)	0.068 (0.88)	0.211*** (2.92)	0.284 (1.51)
$\hat{\beta}_W$	0.273*** (3.94)	−0.041 (−0.59)	0.005 (0.08)	0.207*** (3.04)	0.195 (1.07)
$\hat{\beta}_C$	0.460*** (7.09)	0.242*** (3.26)	0.185*** (3.02)	0.317*** (4.25)	0.543*** (2.96)
$\hat{\beta}_R$	0.060*** (8.53)	0.049*** (7.55)	0.032*** (4.07)	0.026*** (4.43)	0.059*** (3.09)
$\hat{\beta}_L$	−0.329*** (−5.05)	−0.089 (−1.25)	0.019 (0.26)	−0.199*** (−2.89)	−0.188 (−1.19)
$\hat{\beta}_I$	0.396*** (5.63)	0.279*** (3.64)	0.264*** (3.83)	0.304*** (4.48)	0.577*** (3.00)
$\hat{\beta}_O$	0.017*** (3.04)	0.011** (2.01)	0.022*** (3.60)	0.012* (1.74)	0.013 (0.87)
$\hat{\beta}_G$	0.390*** (5.84)	0.543*** (7.40)	0.138** (2.04)	0.157** (2.22)	0.504** (2.32)
Parameters for individual intercepts distributions					
$\hat{\beta}_0$	−1.650*** (−3.64)	−1.696*** (−4.84)	−1.037** (−2.02)	−0.618 (−0.44)	0.531 (0.56)
$\hat{\theta}_t$	0.191 (1.44)	0.399 (1.31)	−0.552*** (−2.92)	−0.244 (−1.62)	−0.819** (−2.34)
$\hat{\theta}_1$	0.309 (0.71)	0.615** (2.06)	−0.194 (−0.43)	−0.278 (−0.19)	−0.774 (−0.84)
$\hat{\theta}_2$	−0.345 (−0.75)	0.223 (0.76)	−0.108 (−0.23)	−0.169 (−0.12)	−1.551* (−1.70)
$\hat{\theta}_3$	−0.294 (−0.70)	0.400 (1.25)	−0.097 (−0.20)	−0.048 (−0.03)	−2.127** (−2.14)
$\hat{\theta}_4$	0.152 (0.37)	−0.316 (−0.96)		−0.445 (−0.32)	−1.715* (−1.85)
$\hat{\theta}_5$		0.467*** (3.21)		−0.103 (−0.07)	−2.004** (−2.10)
$\hat{\sigma}$	1.803*** (13.55)	1.196*** (10.40)	0.001 (0.01)	1.000*** (9.09)	1.744*** (5.46)
Number of individuals	287	189	141	192	52
Number of observations	1,148	756	564	768	208

***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively

Values in parentheses are z-statistics

measure. To gain insights here, supply curves are re-estimated across a cost-share range of 0-30%. This analysis is limited to consideration of only the "highly" favorable scenario, where this attribute is included.

Results

Stated-choice regressions

Results of the stated-choice regressions for each region are presented in Table 5. Whether the estimated coefficients for the oilseed and contract attributes are positive or negative indicate whether the attribute has a positive or negative impact on the probability a farmer is willing to grow the oilseed under the proposed scenario. In general, results in this regard were as expected. Except for one instance, all oilseed attributes—shatter resistance $\left(S_j\right)$, pest tolerance $\left(T_j\right)$, winter hardiness $\left(W_j\right)$, and extended combine window $\left(C_j\right)$ —increased the likelihood a farmer would enter the proposed contract. The exception was for winter hardiness in North Dakota, but this result was not statistically significant. Increases in net returns relative to wheat net returns $\left(R_j\right)$, the availability of crop insurance $\left(I_j\right)$, increases in the cost share level $\left(O_j\right)$, and the presence of an "Act of God" clause $\left(G_j\right)$ had positive impacts across all regions. Longer contract lengths $\left(L_j\right)$ generally decreased the probability of entering a contract except in Oklahoma. These results are in line with economic theory-based expectations and with the limited prior research conducted in this area (e.g., [27]).

Supply estimation for "Low", "Medium", and "Highly" favorable scenarios

Estimated probabilities of entering a canola-production contract under the "Low", "Medium", and "Highly" favorable scenarios are presented by state in Fig. 3 as a function of the percentage increase or decrease in net returns relative to wheat. These probabilities were estimated by varying R_j in Eq. (11). The remaining variables for each scenario were set according to Table 4. For each scenario, probabilities were estimated across canola prices ranging from \$0 to \$50 by increments of \$0.10. In general, estimated probabilities perform as expected with increases seen (1) when

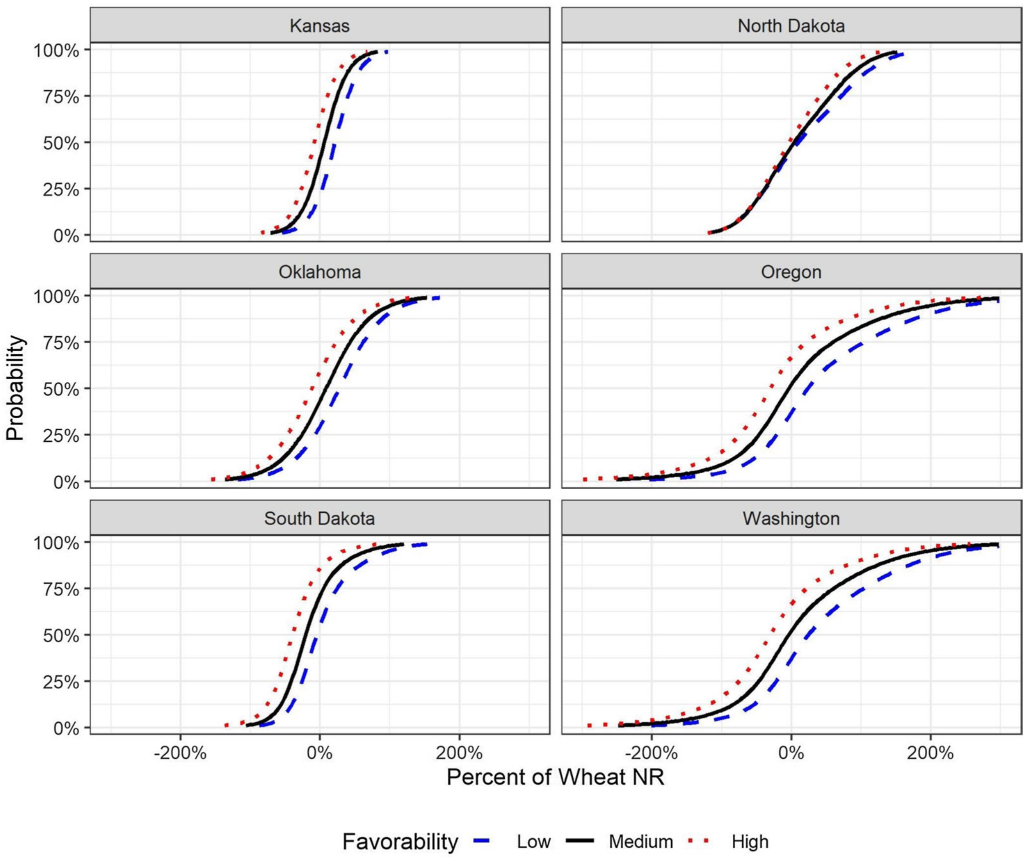

Fig. 3 Estimated probabilities of entering oilseed production contract under "Low", "Medium", and "Highly" favorable scenarios

moving from "Low" to "Medium" to "High" favorability and (2) as canola net returns increase (relative to wheat net returns). Regional similarities are also present. The probability functions for KS, ND, OK, and SD tend to (approximately) reach their upper and lower bounds at net returns of approximately ±100% of net returns relative to wheat. In contrast, the probability functions of OR and WA reach their bounds at around ±200% of net returns relative to wheat. The implication of these results is that a given change in R is likely to have a greater impact in KS, ND, OK, and SD than will be seen in OR or WA.

The probability functions in Fig. 3 form the basis for the acreage supply estimates under these scenarios, which are depicted in Fig. 4. Immediately evident is the variation in maximum acreage supplies across states, ranging from about 40,000 acres in OR to about 375,000 acres in KS. This is of interest, given OK and ND—the largest canola producing regions — have maximum estimated acreages of about 123,000 and 309,000, respectively. Some of this is driven by the underlying probabilities of adoption and maximum acreages are also limited by wheat acreages, survey response rates, and a rotation adjustment as seen in Eq. (13). Survey responses from oilseed producers were lower than expected in these regions, potentially indicating a lack of interest in this potential enterprise that would compete with canola or oilseed production for food markets. Because the associated probabilities at these extremes are, for all intents and purposes, equal to 1, these values represent the variation in wheat acreages and the adjustment factors from Eq. (13). Differences are also seen in the prices at which upper and lower acreage thresholds are met. For example, in SD and under the "High" favorability scenario, canola acreage is maximized at a price of $21.50/cwt and does not exceed 1,000 acres until the canola price is about $10.00/cwt[3]. In contrast, canola acreage in OK for the "High" favorability scenario is maximized at a price of $47.10/cwt and exceeds 1,000 acres at a price of about $8.70/cwt. Additional price-quantity combinations for these and the remaining states and scenarios are presented in Table 6 and Figs. 7, 8, 9, 10, 11, 12.

[3] Not every price point was simulated and thus the exact price at which an acreage is estimated to arise was not always available.

Table 6 Estimated acreages across states and scenarios

State	Favorability	Wheat net returns	Cost share	Canola price ($/cwt)						
				5	10	15	20	25	30	35
Kansas	Low	Base	0%	0	0	7	2328	153,490	370,169	375,005
	Medium	25% Increase	15%	0	0	1	7143	341,225	374,997	375,049
	Medium	Base	15%	0	0	697	65,633	359,338	374,901	375,047
	Medium	25% Decrease	15%	0	170	7,515	175,179	365,288	374,819	375,041
	High	Base	0%	0	0	74	7922	263,596	373,638	375,034
	High	Base	15%	0	1	1,253	102,592	366,084	374,963	375,048
	High	Base	30%	0	191	20,896	323,999	374,528	375,041	375,050
North Dakota	Low	Base	0%	0	70	90,816	294,106	309,087	309,093	309,093
	Medium	25% Increase	15%	0	14	130,135	308,224	309,093	309,093	309,093
	Medium	Base	15%	0	495	166,319	308,275	309,093	309,093	309,093
	Medium	25% Decrease	15%	2	3794	197,603	308,259	309,091	309,093	309,093
	High	Base	0%	0	119	108,646	299,256	309,089	309,093	309,093
	High	Base	15%	0	663	175,449	308,482	309,093	309,093	309,093
	High	Base	30%	0	3623	248,114	309,063	309,093	309,093	309,093
Oklahoma	Low	Base	0%	0	36	382	3638	28,265	91,675	119,016
	Medium	25% Increase	15%	0	11	277	5623	61,633	117,585	122,917
	Medium	Base	15%	25	260	2574	21,276	82,667	117,319	122,569
	Medium	25% Decrease	15%	256	1589	9277	41,341	93,344	117,154	122,178
	High	Base	0%	0	68	675	6349	42,761	103,310	120,824
	High	Base	15%	32	362	3482	27,313	90,630	118,830	122,733
	High	Base	30%	191	1888	16,309	73,750	115,290	122,336	123,104
Oregon	Low	Base	0%	2	27	350	11,962	36,446	39,074	40,019
	Medium	25% Increase	15%	0	9	297	27,570	39,108	40,014	40,047
	Medium	Base	15%	9	120	1597	31,033	39,097	39,971	40,041
	Medium	25% Decrease	15%	73	548	4143	33,033	39,087	39,919	40,031
	High	Base	0%	5	74	931	21,370	38,534	39,921	40,037
	High	Base	15%	15	199	2508	33,633	39,459	40,000	40,043
	High	Base	30%	41	535	7898	37,486	39,828	40,031	40,047
South Dakota	Low	Base	0%	0	3	16,022	43,585	43,779	43,783	43,783
	Medium	25% Increase	15%	0	0	30,968	43,734	43,783	43,783	43,783
	Medium	Base	15%	0	52	39,603	43,754	43,783	43,783	43,783
	Medium	25% Decrease	15%	5	740	42,015	43,762	43,783	43,783	43,783
	High	Base	0%	0	17	31,647	43,743	43,783	43,783	43,783
	High	Base	15%	0	124	41,800	43,770	43,783	43,783	43,783
	High	Base	30%	1	1042	43,427	43,779	43,783	43,783	43,783
Washington	Low	Base	0%	10	115	1219	31,229	101,007	119,034	121,586
	Medium	25% Increase	15%	1	41	926	66,777	114,221	121,489	121,850
	Medium	Base	15%	44	457	4950	80,354	114,938	121,131	121,796
	Medium	25% Decrease	15%	307	1970	12,944	89,364	115,327	120,774	121,698
	High	Base	0%	31	319	3257	57,592	112,296	120,811	121,765
	High	Base	15%	75	757	7854	90,498	117,491	121,421	121,825
	High	Base	30%	175	1790	21,151	105,972	119,962	121,681	121,850

Overall, the results suggest that a highly favorable scenario may be needed for oilseed SAF production to be feasible in any of the study region states. Across 2017-2019 the average price received for canola across the study region was about $14.72/cwt (USDA-NASS, 2020). As shown in Table 6, at a price of $15/cwt and under the low-favorability scenario and baseline wheat net returns, KS, OK, and OR are all estimated to supply less than

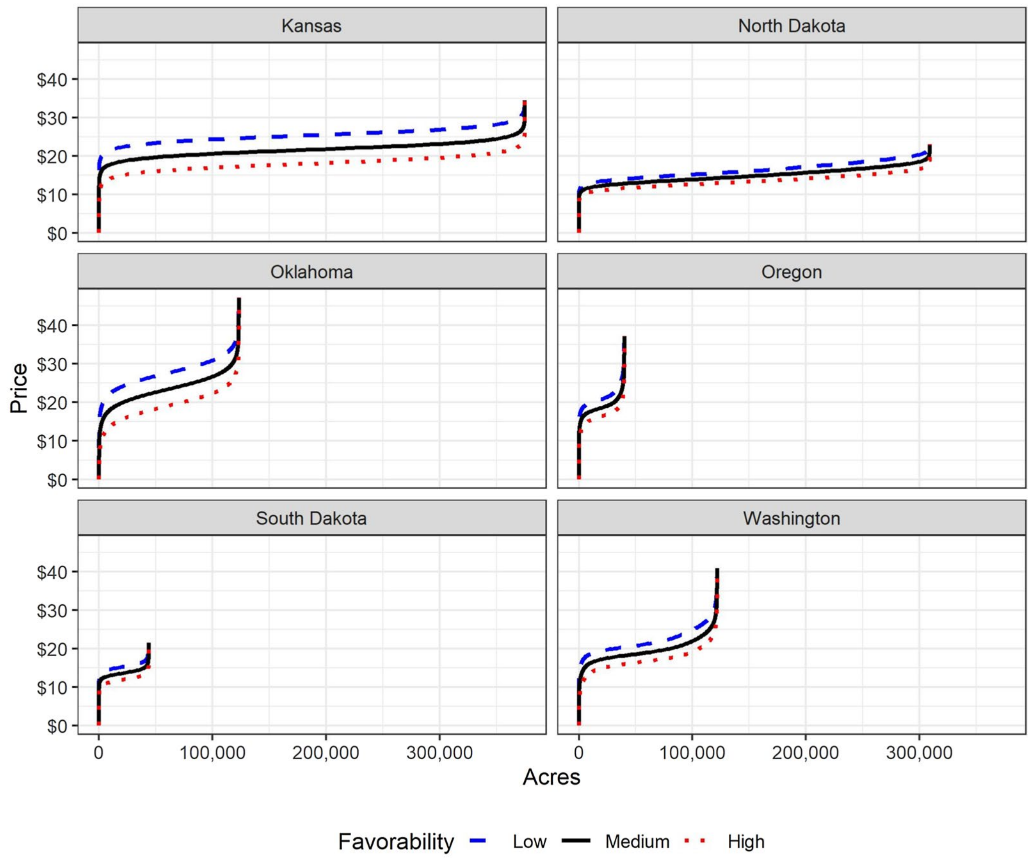

Fig. 4 Estimated inverse acreage supply curves under "Low", "Medium", and "Highly" favorable scenarios

1,000 acres of canola for SAF production. Washington exceeded 1,000 acres but only marginally at 1,219. Thus, in the absence of more favorable scenario characteristics, supplies are likely to be negligible in these states at recent market prices. Production may be more feasible in ND and SD under this scenario, which had estimated acreages of 90,816 and 16,022, respectively. Under the high-favorability scenario, however, SAF may be more feasible across each of the states. In this case, the lowest estimated acreage is seen in OR at 7,898 and the remaining states all have estimated acreages of greater than 15,000.

To put the above results in perspective, Archer et al. [20] report it would take about 2.1 kg of rapeseed oil to produce 1 kg of SAF. Assuming 44% oil content in its feedstock, a small SAF refinery with a 100-million-kg-per-year capacity would require approximately 477 million kg of feedstock. Assuming a standard canola yield of 3,600 lbs. (1,633 kg) per acre and the same 44% oil content, this would require approximately 292,000 acres of canola production within the vicinity of the refinery. Based on the estimates from this analysis, only KS and ND could meet this requirement (see Table 6). In KS, this acreage could be attained at a canola price of around $20/cwt and a highly favorable scenario. It could also be met under the "Low" and "Medium" favorability scenarios, but it would require a higher canola price. For ND, the acreage requirement is met for each of the favorability scenarios provided the canola price is at least $20/cwt. Smaller scale refineries—about 40 million kg per year requiring about 117,000 acres—could be supported in OK and WA, though this would again require market prices significantly higher than recent levels. Moreover, because supplies are estimated at the state level, there is no guarantee enough canola could be contracted within a distance acceptable to the refinery. These results highlight the need to consider producers' willingness to produce oilseed crops for SAF production under contract and the potential volatility in starting up this market.

Wheat net returns scenarios

To examine the sensitivity of results to the assumptions made regarding net returns to wheat, two additional scenarios were simulated for each state. Using the "Medium" favorability scenario as a starting point, acreages are

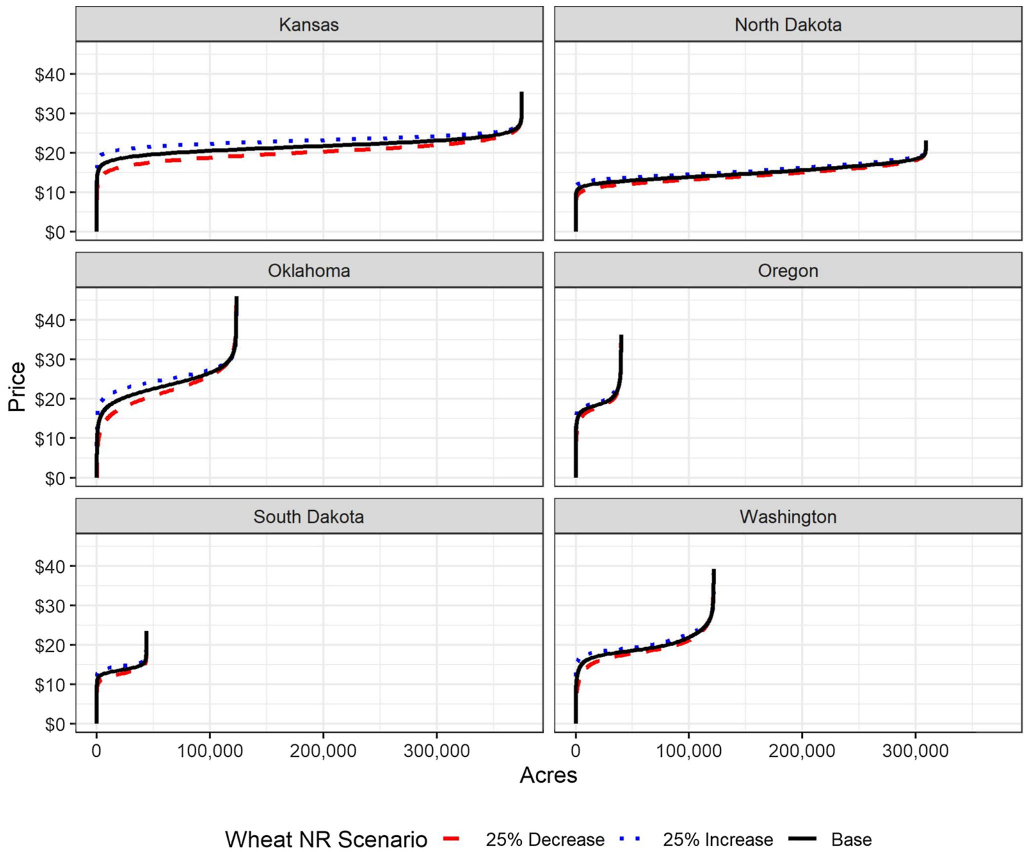

Fig. 5 Estimated inverse acreage supply curves under changes in net returns to wheat for the "Medium" favorability scenario

re-estimated under a 25% increase and a 25% decrease in the baseline net returns to wheat (Table 3). Results for these simulations are depicted in Fig. 5 and presented for select prices in Table 6. In general, the results were as expected: As net returns to wheat increase (decrease), the estimated canola-acreage supply decreases (increases). The largest impacts (in gross acreage) were seen towards the middle of the price range. For example, at a canola price of $15/cwt, the total estimated acreage across all six states decreases by about 53,000 when net returns to wheat are increased by 25%. In contrast, when net returns to wheat are decreased by 25%, the estimated acreage increases by about 58,000. Given the spatial and temporal variability of wheat net returns, these results suggest that identifying areas which, on average, have lower net returns to wheat could play an important role in determining the feasibility of future biorefinery and SAF processing facility locations.

Cost-share scenarios

The results from varying the cost-share level between 0%, 15%, and 30% for the "High" favorability scenario are presented in Fig. 6 and Table 6. These results were also as expected: As the cost-share percentage increases (decreases), the estimated acreage supply also increases (decreases). Though not directly comparable ("Medium" versus "High" favorability), varying the cost-share level had a greater impact than varying the net returns to wheat. For example, looking again at a canola price of $15/cwt, changing the cost-share from 0% to 15% increases estimated acreage by about 87,000 acres across all states. An additional increase in the cost-share from 15% to 30% adds roughly 125,000 acres. It should be noted that these estimates are the result of two components. First, there is the direct impact on the probability of adoption via O_j in Eq. (11). Second, there is an indirect effect on the probability via O_j in Eq. (14) through net returns. A more conservative approach would be to remove this indirect effect. However, given the overall conservative nature of these estimates—due to the response rate adjustment (see Eq. (13))—the inclusion of the indirect effect is not believed to be of major concern. Thus, it may be in the interest of SAF biofuel producers and refineries or government to offer cost share incentives to promote production under contract, especially when the market for these feedstocks are beginning to grow. The contracting literature on biofuel production has shown that cost-share incentives may increase

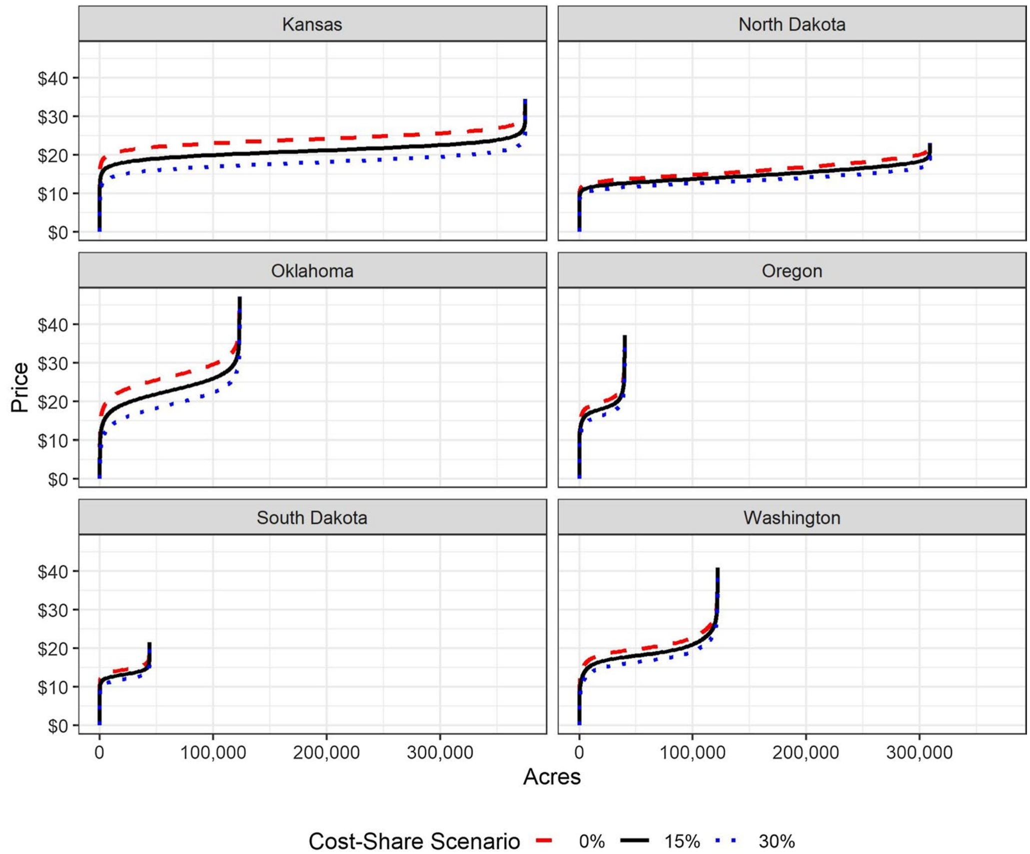

Fig. 6 Estimated inverse acreage supply curves under changes in cost-share level for the "High" favorability scenario

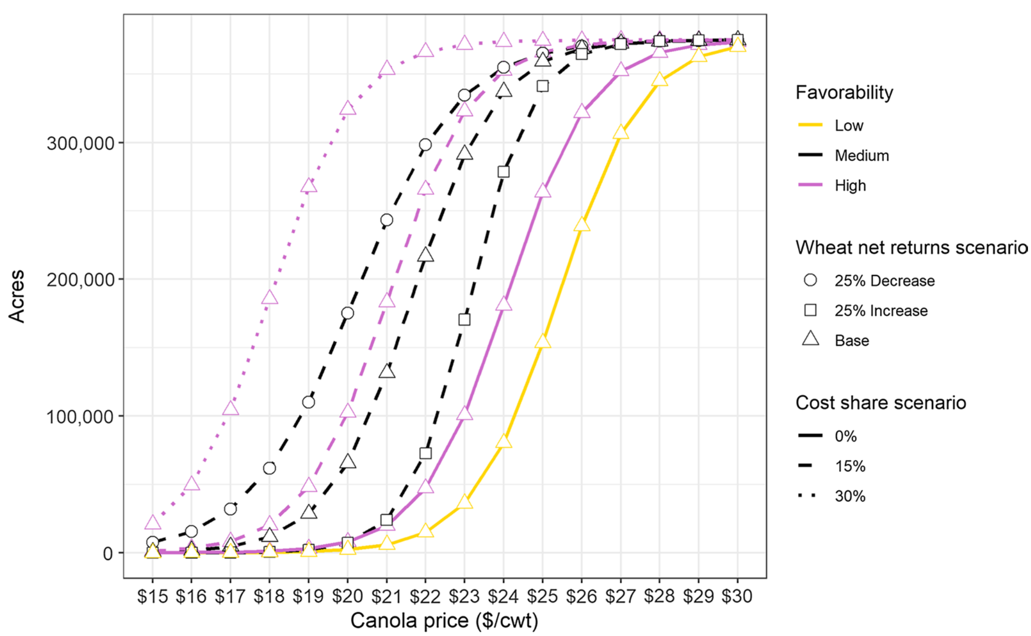

Fig. 7 Estimated acreage supply curves for select scenarios and prices, Kansas

farmers' willingness to grow [27], which is further supported by the cost-share results from the stated choice regressions.

Elasticity estimates

Acreage elasticities were estimated using Eq. (16). For estimation purposes, acreage and price values of 0 were set equal to 0.001. Results are presented in Table 7 for all states and scenarios. The elasticity scenarios are the same as those presented in Table 4 except that wheat net returns and the cost share percentage were varied across the low-, medium-, and high favorability scenarios. In all cases, acreage elasticities were greater than one, suggesting supplies will be sensitive to prices. The mean elasticity across all scenarios was about 4.4, which would imply a 1% increase (decrease) in the canola price would increase (decrease) contracted canola acres by about 4.4%. The smallest estimated elasticity of about 1.5 was seen in Oklahoma when scenario favorability was "High", wheat net returns were decreased by 25%, and the cost-share level was 30%. The largest elasticity of about 6.4 was in Kansas for "Low" favorability, wheat net returns that were increased by 25%, and a cost share level of 15%. On average, estimated elasticities were highest in Kansas (about 5.9) and lowest in Washington (about 3.2). Elasticities tended to decrease as scenario favorability changed from "Low" to "Medium" to "High". These decreases though were relatively minor with elasticities changing between 4.5 and 4.2. With respect to wheat net returns, elasticities increased from about 3.4 under the "25% Decrease" scenario to about 5.5 for the "25% Increase" scenario. Conversely, elasticities tended to decrease as the cost-share level increased, going from about 4.8 at 0% cost share to about 4.0 at the 30% level. The highly elastic estimates are not unexpected, given this would be a nascent market and could be highly variable until a more mature market is established [45]. However, it should be noted that because the analysis uses a 1-year contract length, these supply curves essentially represent the supply curve for a single growing season and the number of acres provided via new or renewed contracts. If biorefineries can obtain multi-year contracts, they may be able to help smooth this volatility.

The results above imply that the ability of biorefineries to contract with farmers could be highly dependent upon market prices for canola and/or similar substitutes. This has both good and bad consequences for the biorefineries, especially if operating with 1-year contracts. On one hand, a decrease in price could drastically reduce the number of acres enrolled in contracts. Conversely, the same change but as an increase in price could significantly increase

Table 7 Estimated acreage-supply elasticities

			Favorability		
State	**Wheat net returns**	**Cost share**	**Low**	**Medium**	**High**
Kansas	25% Decrease	0%	6.09	5.99	6.41
		15%	5.63	5.44	6.40
		30%	4.82	4.50	6.20
	Base	0%	6.36	6.34	6.31
		15%	6.19	6.12	6.05
		30%	5.79	5.65	5.52
	25% Increase	0%	6.38	6.40	5.88
		15%	6.42	6.41	5.25
		30%	6.29	6.24	4.17
North Dakota	25% Decrease	0%	5.21	5.16	5.93
		15%	4.91	4.85	5.77
		30%	4.56	4.48	5.57
	Base	0%	5.64	5.62	5.58
		15%	5.42	5.39	5.35
		30%	5.18	5.13	5.09
	25% Increase	0%	5.97	5.95	5.10
		15%	5.81	5.79	4.78
		30%	5.63	5.60	4.40
Oklahoma	25% Decrease	0%	2.69	2.55	5.82
		15%	2.18	2.09	5.51
		30%	1.73	1.65	4.83
	Base	0%	5.12	5.02	4.87
		15%	4.18	3.95	3.64
		30%	2.43	2.32	2.22
	25% Increase	0%	5.86	5.85	2.43
		15%	5.62	5.57	1.99
		30%	5.06	4.95	1.55
Oregon	25% Decrease	0%	2.64	2.46	5.09
		15%	2.35	2.17	4.75
		30%	2.06	1.89	4.29
	Base	0%	4.18	3.84	3.41
		15%	3.45	2.88	2.74
		30%	2.74	2.55	2.38
	25% Increase	0%	5.29	5.19	2.29
		15%	5.03	4.90	2.00
		30%	4.67	4.48	1.73
South Dakota	25% Decrease	0%	4.67	4.41	5.47
		15%	4.29	3.96	5.30
		30%	3.81	3.39	5.09
	Base	0%	5.26	5.13	4.96
		15%	5.02	4.87	4.67
		30%	4.73	4.54	4.29
	25% Increase	0%	5.58	5.53	4.03
		15%	5.45	5.38	3.48
		30%	5.28	5.20	2.71

Table 7 (continued)

State	Wheat net returns	Cost share	Favorability Low	Medium	High
Washington	25% Decrease	0%	2.44	2.28	5.17
		15%	2.20	2.04	4.75
		30%	1.96	1.80	4.17
	Base	0%	3.73	3.04	2.85
		15%	2.90	2.70	2.54
		30%	2.58	2.41	2.25
	25% Increase	0%	5.46	5.32	2.12
		15%	5.14	4.96	1.88
		30%	4.70	4.46	1.64

enrollable acres. Depending on whether a higher degree of responsiveness is favored by biorefineries, the results here suggest actions that can be taken to move this responsiveness in the desired direction. For example, if lower responsiveness is desired, it may be best to locate in states such as OK, OR, and/or WA as opposed to KS, ND, and/or SD. Oilseed for SAF production likely faces competition from other oilseed production in these latter states. With respect to contract attributes, biorefineries could decrease price responsiveness by increasing cost-share levels. Other scenario-favorability factors that may impact supply volatility, such as the availability of insurance, are likely to be outside the control of the biorefineries.

Discussion

This work aimed at looking at the viability of oilseed supply for SAF by (1) identifying the factors that may impede or aid efforts at contracting oilseed supplies for SAF production needed to establish a viable supply chain and (2) estimating the potential acreages that could be contracted in select U.S. states under various scenarios (assuming the oilseed would be rotated with a wheat crop). Expanded use of SAF will likely be crucial to reducing emissions in the aviation industry [5, 46, 47], but the limited availability of SAF feedstock could hinder progress [5, 16, 47].

Feasibility of SAF production may depend on the ability of a refiner to enter contracts with farmers for feedstock supply, particularly if these feedstocks do not have established markets in the area [48]. Moreover, contract attributes and scenarios have been shown to impact farmer willingness to accept them [27, 28, 48]. Similarly, results in this study indicated that canola-acreage supplies will be heavily influenced by location, contract attributes, and scenario context. With respect to location, potential supplies are, on average, estimated to be largest in Kansas and North Dakota. Across all states, however, the canola prices needed to considerably increase from typical levels to induce the higher levels of estimated acreages, which may not be

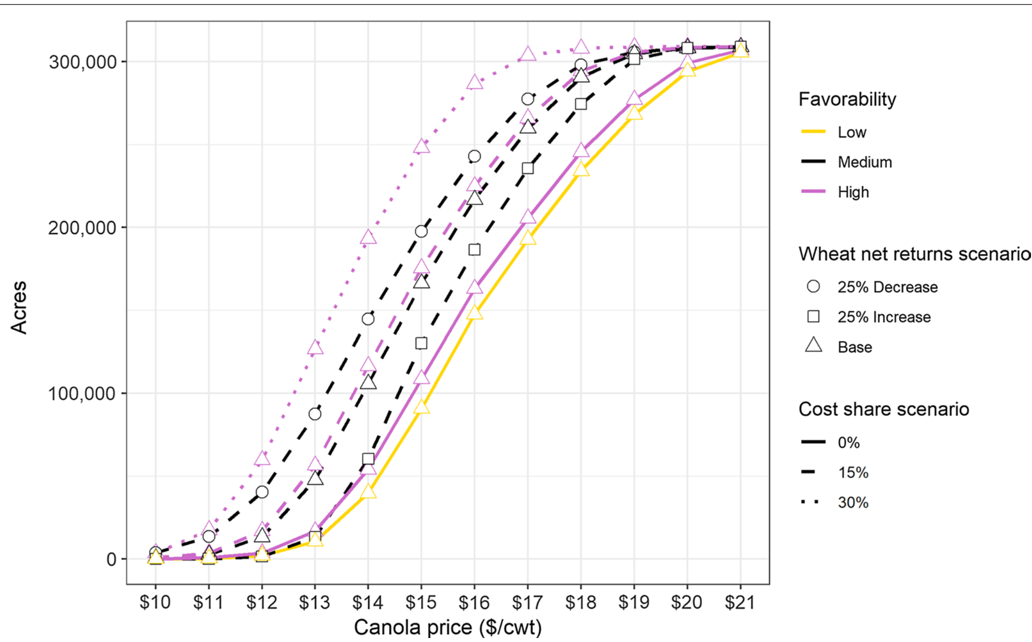

Fig. 8 Estimated acreage supply curves for select scenarios and prices, North Dakota

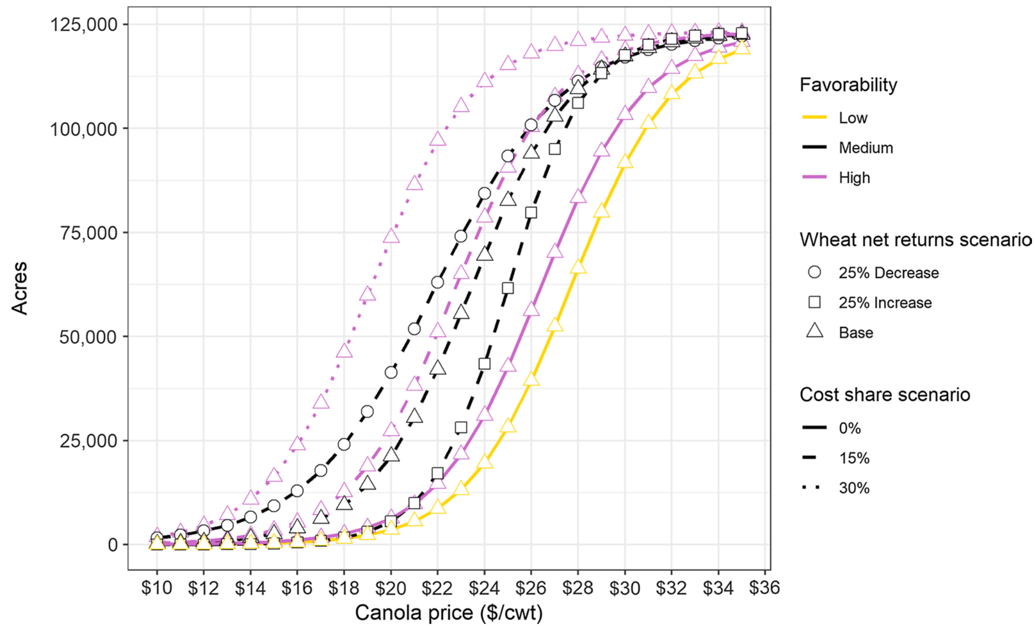

Fig. 9 Estimated acreage supply curves for select scenarios and prices, Oklahoma

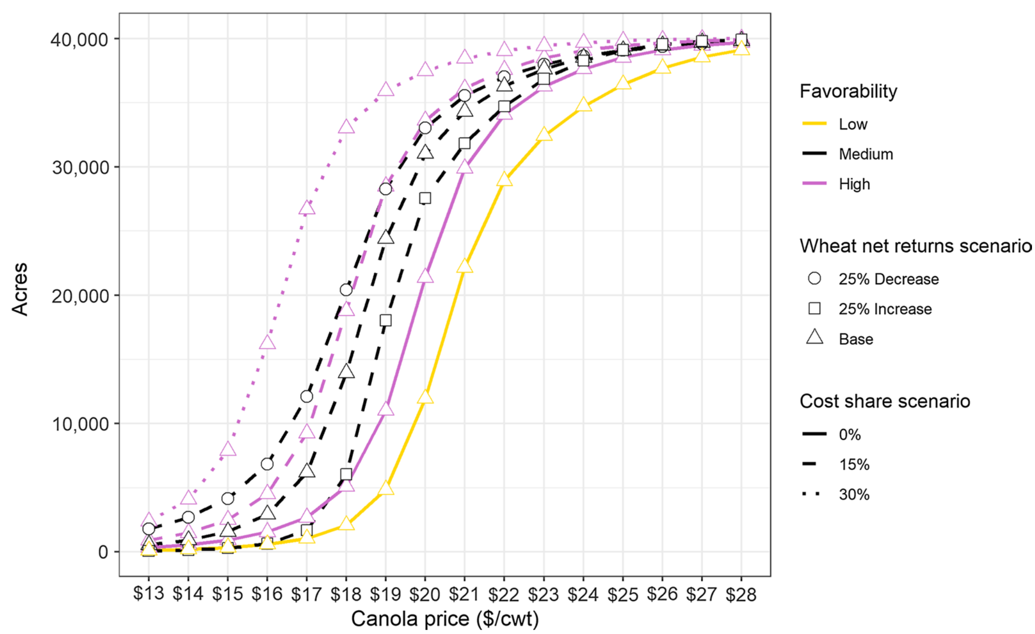

Fig. 10 Estimated acreage supply curves for select scenarios and prices, Oregon

realistic in all scenarios. The results with respect to scenario attributes, however, indicate the potential to alleviate these concerns. In general, and particularly across a realistic range of canola prices, estimated acreage supplies increase as scenario favorability moves from "Low" to "High", as wheat profitability decreases (making canola a stronger substitute crop), and as cost share levels increase. Thus, to maximize potential supplies, biorefineries may want to (1) target areas, where wheat is relatively less profitable and (2) consider compensating producers for a share of the variable costs of production. To the extent possible, biorefineries should also target locations, where more desirable oilseed varieties are feasible to produce.

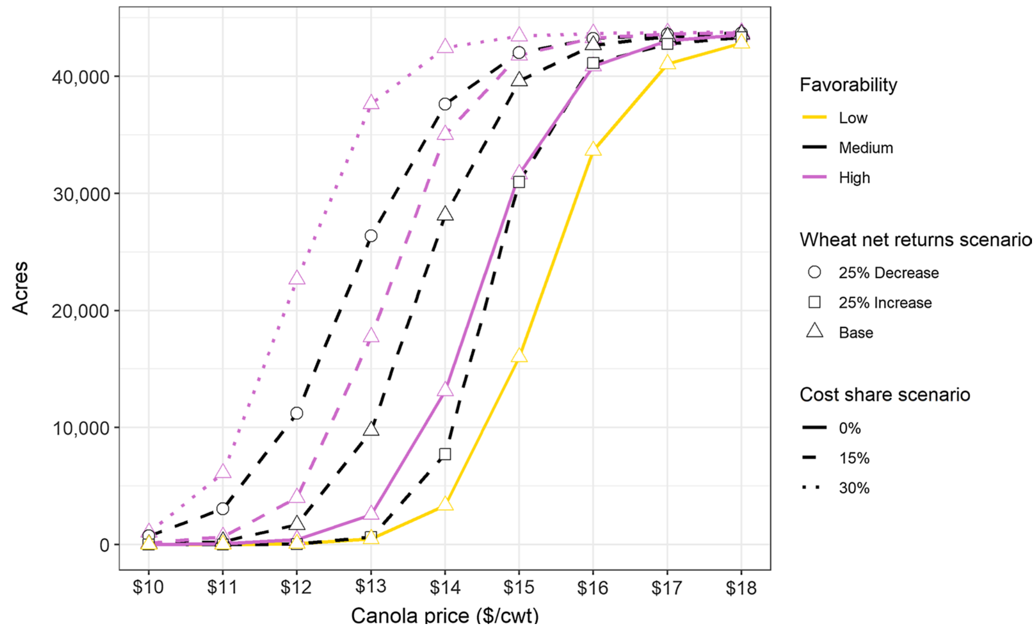

Fig. 11 Estimated acreage supply curves for select scenarios and prices, South Dakota

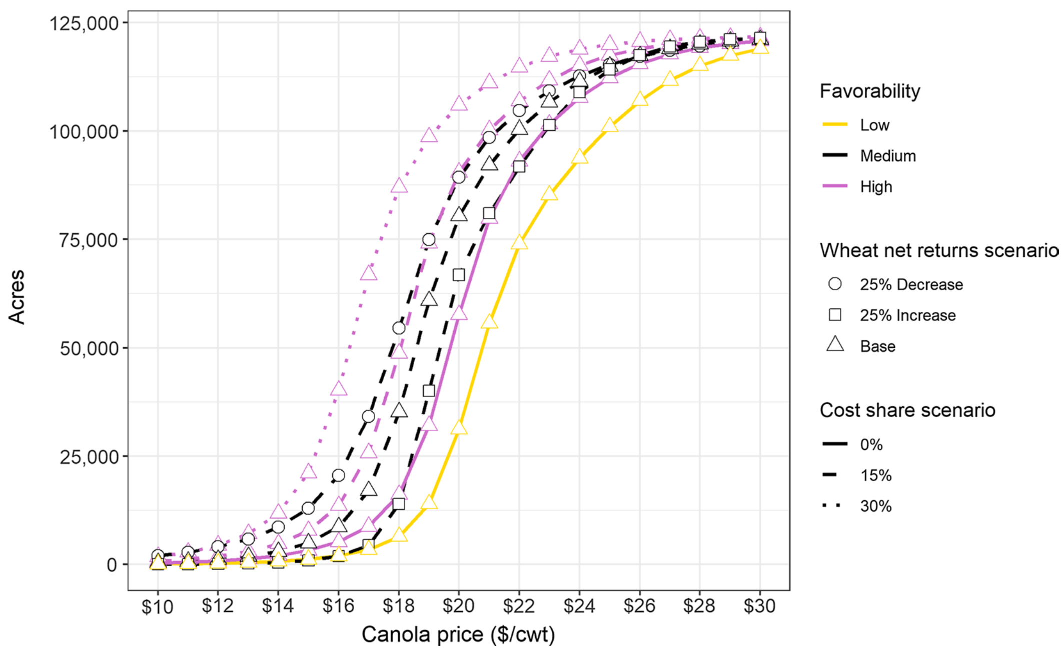

Fig. 12 Estimated acreage supply curves for select scenarios and prices, Washington

The need for canola (and other oilseed) prices well above what have been seen historically suggests that policy actions may be needed to achieve sufficient oilseed feedstock supplies. Options could include tax incentives for production of SAF using oilseed feedstocks, such as those that have been proposed in the United States for biofuel production. These incentives are not provided at the farmer level, so it may require SAF producers to ensure that some of the benefits are passed on to farmers through favorable contract prices above what market prices may suggest (or indexing contract price to market prices and setting a minimum guaranteed price).

Though this analysis focused on the creation of new supplies through contracting, such policies may also create enough new demand to increase market prices to requisite levels to induce production in a spot market. Another option could be monetary incentives directed at farmers, though policymakers would need to be cognizant of any trade-based liabilities and conflicts with other federal programs.

While this study provides an important component in determining the feasibility of oilseed markets and supply chain for SAF production, additional research is needed. One issue that needs addressing is the updating of existing and creation of missing enterprise budgets for potential oilseed feedstocks. This analysis focused on canola because of the presence of reliable state-level budgets for this crop. However, canola budgets were not always available for every state and for those states with budgets some were not current. Updating and expanding the set of oilseed budgets would provide a more realistic model of the economic situation farmers may face. In addition, analysis for a particular oilseed could be improved with survey instruments focused solely on that crop. For this analysis, the primary objective of the survey instrument was to gain insights regarding a suite of potential feedstocks rotated with wheat. As such, stated-choice questions were framed in general for a nonspecific feedstock with respect to net returns to wheat. A more detailed analysis could pose stated-choice questions with respect to market prices for specific oilseed feedstocks of interest. In addition, a more narrowly focused survey could possibly bring in other oilseed specifics, such as yields, costs of production, etc.

Conclusions

This study examined the factors that drive willingness to produce oilseed feedstocks under contract for sustainable aviation fuel (SAF) and how different combinations of these factors could translate into actual acreage supplies. Analysis was conducted using farmer survey data from Kansas, North Dakota, Oklahoma, Oregon, South Dakota, and Washington. Factors included attributes of the oilseed under consideration and production-contract attributes. Farm-level probabilities for entering these contracts under various scenarios were estimated via random-parameter logistic-regression models. Separate models were estimated for Kansas, North Dakota, Oklahoma, and South Dakota and a Pacific Northwest region comprised of Oregon and Washington. Estimated probability models were then used to estimate canola-acreage supply curves for each state under multiple scenarios to examine the consequences of changing particular attribute(s). First, the analysis examined overall scenario favorability—"Low", "Medium", or "High"—which employed simultaneous changes to multiple attributes to make scenarios more (or less) favorable from the farmer perspective. Additional analyses examined the impacts of fluctiations in (1) wheat profitability and (2) the level to which biorefineries cost share the variable costs of production. Finally, acreage-supply elasticities were estimated for all scenarios. Results from each model indicated that net returns to canola will have crucial impact on the supply of contracted acreage. Results also suggested that refiners may be able to induce contract acceptance by offering farmer-friendly contract attributes, such as input cost sharing. Moreover, elasticity estimates indicated contract and scenario attributes would also impact the responsiveness of supplied acreages to canola prices. Overall, the results suggest that acquiring sufficient feedstock is likely to be the most feasible in Kansas in North Dakota, though smaller-scale SAF operations may be feasible in Oklahoma and Washington at historically high canola prices.

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Authors' contributions
CM was a major contributor in writing the manuscript, preparing data, and conducting initial supply analyses. JB and GA conducted the survey. JB performed logistic regression analysis and was a major contributor in writing the manuscript. SR collected data for and conducted oilseed supply analysis and was a major contributor in writing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The data sets generated and/or analysed during the current study are available from the corresponding author on reasonable request. The survey data is available once human subjects approval has been obtained from the requesting party. All survey data will by anonymized.

Declarations

Ethics approval and consent to participate
The survey was administered by the Iowa State University Survey & Behavioral Research Services (SBRS) unit. The survey and research approach were reviewed and approved by the Internal Review Board of the Office of Research Compliance at Kansas State University (IRB Protocol #6530).

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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