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Is it economically feasible for farmers to grow their own fuel? A study of Camelina sativa produced in the western United States as an on-farm biofuel

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ABSTRACT

This paper models the economic feasibility of growing the oilseed crop *Camelina sativa* ("camelina") in the western United States to produce value-added protein feed supplement and an SVO-based biofuel. Modeled in eastern Colorado, this study demonstrates that camelina can be grown profitably both as a commodity and as an energy biofuel. These findings, along with the stochastic crop rotation budget and profitability sensitivity analysis, reflect unique contributions to the literature. The study's stochastic break-even analysis demonstrates a 0.51 probability of growing camelina profitably when diesel prices reach 1.15 $ L^{-1}. Results also show that the sale of camelina meal has the greatest impact on profitability. Yet once the price of diesel fuel exceeds 0.90 $ L^{-1}, the farmer generates more revenue from the ability to offset diesel fuel purchases than the revenues generated from the sale of camelina meal. A risk analysis using second degree stochastic dominance demonstrates that a risk-averse farmer would choose to grow camelina if the price of diesel equals or exceeds 1.31 $ L^{-1}. The article concludes that camelina can offset on-farm diesel use, making it economically feasible for farmers to grow their own fuel. As a result, camelina production may increase farm income, diversify rural economic development, and contribute to the attainment of energy policy goals.

1. Introduction

1.1. Study objective

Interest in biofuels is driven by many factors, including energy policy goals, the reduction of environmental impacts from the transportation sector, and the emergence of new agricultural markets [1]. An expanding and diverse literature, including biodiesel and straight vegetable oil studies [2,3], has developed to investigate petroleum fuel alternatives. Many of these studies focus on biofuel cost competitiveness [4,5], which is critical for market development. Fore et al. [6], for example, look at biofuel and feedstock costs for small, on-farm production. They find that neither soybeans nor canola are cost

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competitive with petroleum diesel when feedstocks are valued at market price, but that under certain scenarios, the economic feasibility of SVO-based fuels and diesel could be similar. This study explores one such example.

This study models the economic feasibility of growing the oilseed crop *Camelina sativa* (L.) Crantz, Brassicaceae ("camelina") in the western United States to produce value-added protein feed supplement and biofuel. Commonly known as "gold of pleasure" [7], camelina is an ancient oilseed crop that has been cultivated in Europe since the nineteenth century [8], although it has only been recently approved in the U.S. market as an animal feed supplement [9]. The presenting study adds to the literature by investigating the feasibility of locating feedstock production on land that would otherwise be in fallow, thus reducing competition with other crops and lowering production costs. The study identifies the key variables that most impact feasibility and costs of growing camelina in the western United States. The economic analysis also presents the different price and break-even points when camelina grown on fallowed land could profitably produce enough biofuel to complete a three-year crop rotation. The study considers risk and farmer risk preferences.

1.2. Camelina: a source of commodity and biofuel diversification

Camelina has the potential to fill an energy niche for agricultural producers, who can grow the crop on-farm and use it to generate straight vegetable oil (SVO) to power a diesel engine [2]. As a result, there is potential for farmers to "grow their own fuel", thus ensuring that farm-level agricultural production continues even in the event of a disruption in fuel availability or precipitous fuel price increases. Camelina production could provide farms and communities a source of economic diversification, as a commodity and as a fuel. If production is expanded to the regional scale by farmer cooperatives, rural communities could gain a comparative advantage by specializing in camelina production. If it is grown profitably, camelina production could contribute to both energy and agricultural policy goals, by diversifying the nation's energy portfolio and consequentially minimizing the disruptions to agricultural commodity and energy supply chains. Presumably, some farmers would place a positive value on growing their own fuel, which would make camelina-based biofuels more attractive, or even preferred.

From an agronomic perspective, camelina fits into the western U.S. crop rotation of wheat, followed by corn (or similar crops such as sorghum), and fallow [10]. Potentially, producers can generate additional revenue from growing camelina on land that is otherwise in fallow, because there is minimal disruption to the wheat–fallow–corn rotation. Camelina's peak water demands occur early in the season and the crop can be harvested in time to allow for accumulation of late summer precipitation before planting wheat, thus minimizing the water-related effects on wheat yields [10]. Camelina does not require irrigation and can be grown in low water dryland systems, contributing towards the regional energy profile without burdening water resources [11]. In addition, peak water demands for camelina occur early in the season, allowing the farmland more time to accumulate moisture prior to the planting of wheat [10]. Camelina also has a relatively short growing season (about 110 days) allowing the crop to be harvested comparatively early in the summer growing season, usually in late July [11].

Camelina has several characteristics that make it an attractive biofuel co-product or by-product [12]. The crop may provide opportunities to profitably grow a biofuel feedstock in the western United States, a region that has previously lacked a comparative advantage with regards to biofuels [13]. Camelina has lower input requirements compared to other biofuel feedstocks, suggesting that the opportunity cost of growing oilseeds for SVO may be comparatively lower [14]. Camelina demonstrates a longer shelf life relative to other oils high in omega-3 fatty acids [15] and a similar cetane number compared to petroleum-based diesel fuel [16]. Higher cetane numbers yield better engine efficiency characteristics that result in easier starting, quieter engine operations, and lower engine temperatures. The combustion of SVO derived from camelina has also been shown to reduce net greenhouse gases by two thirds compared with the combustion of diesel fuel [17]. Oilseed-based SVO from camelina can replace significant portions of diesel fuel in engine operations [18]. On-farm biofuel production is now more feasible with recent improvements in oilseed production, processing, and diesel engine efficiency [19].

Although oilseed feedstocks can be converted into either SVO or biodiesel, this study focuses on the SVO derived from camelina. SVO has been demonstrated to be less costly to produce than biodiesel [6] and does not require chemical inputs such as methanol or conversion catalysts, both of which are used in the biodiesel conversion process [6]. The avoided use of additional inputs may help increase energy independence for local farmers since converting the feedstock to a useable fuel could be done locally and at a smaller scale.

At present, U.S. on-farm SVO use is considered somewhat controversial and legally untested. Some legal scholars report that the use of SVO in engines violates the Clean Air Act [20]. However, the U.S. Environmental Protection Agency (EPA) currently states that SVO is legal for on-farm (defined as "non-road") diesel engine use [21] so long as engine modifications, if needed, are implemented using an EPA certified, tested, engine modification kit [21,22]. Ironically, current agency literature states that no engine modification kits have been certified by the EPA [22]. At this writing the Colorado Department of Public Health and the Environment, which is responsible for monitoring state air quality emissions, verifies that it has limited authority to regulate non-road vehicle engines [23], and would not be able to regulate these non-road farm vehicles. Thus, U.S. agricultural producers desiring to grow their own fuel for SVO should expect policy clarification, should this practice gain considerable momentum. Running SVO also purportedly nullifies engine warranties. However, technology and industry would be expected to advance commensurately with interest and demand for SVO. Keeping legal and policy complexities in perspective, this study expands the literature in a way that might encourage further policy clarification, engines research, and emissions testing.

Farmers may adopt camelina if it proves to be an economically viable commodity. However, growing one's own fuel may also appeal to some farmers, who might be willing to pay a premium or sacrifice economic profits to do so. For the purposes of this study, self-contained energy production is defined as crop production "energy independence" and the willingness to sacrifice economic profits in order to grow a bioenergy crop is defined as an "energy independence premium". Achieving energy independence may provide farmers with a source of energy security, defined as securing reliable sources of energy at affordable prices [24]. Potentially, farm-level energy independence could have an effect on regional and national energy security, which is described as a matter of national strategy [25]. Energy security policies are dynamic. Energy efficiency and demand reduction strategies can also improve energy security [26]. While energy independence is subject to different definitions, the practice of self-contained energy production is frequently addressed in energy security policy.

On-farm energy independence from biomass has been promoted as an environmentally sustainable practice [27]; however, this may also contribute to energy security. Rural regions of the western United States could develop a comparative advantage for camelina production if the practice is expanded to the regional scale by farmer cooperatives. This may provide economic diversification to "farm dependent" counties [28] that are heavily reliant on the agricultural sector for economic development. Commerce in these regions may be disrupted by fuel shocks that interfere with production and transport. In addition, commodity and fuel diversification from camelina may provide a new source of revenue. Although shale and non-conventional natural gas development is expected to expand considerably during the next two decades, there are foreseeable development lags in the transportation sector, particularly for on-farm vehicles [29].

Oilseed-based SVO could also move the U.S. closer to biofuel policy goals. Recent policies such as the Energy Independence Security Act of 2007 (EISA), which promulgates the second U.S. Renewable Fuel Standards (RFS), have targeted biofuel production. These policies are linked with considerable U.S. biodiesel production increases from 8.7×10^7 L y^{-1} in 2004 to 3.108×10^9 L y^{-1} in 2011 [30]. The RFS calls for 1.36×10^{11} L y^{-1} biofuels to be created by 2020 [31]. One of the main deliverables of the EISA (and the subsequent RFS) is the USDA's "Regional Roadmap" report. This set of reports creates specific and attainable goals of biofuel development based on knowledge of each region of the United States [32].

According to the EISA, the arid western states are not expected to provide abundant biofuel development. The low expectations are due in large part to the difficulty of finding a crop that can sustain success in an arid setting. Despite the low EISA projections, energy disruptions and high energy prices would also presumably affect the western U.S. A biofuel crop that facilitates energy security on farms in the western U.S. benefits the region as a whole, and makes the RFS goals more attainable. Irrespective of the EISA biofuel mandates and policy targets, if oilseed bioenergy crops are shown to be economically feasible for agricultural producers, then oilseed crop production and subsequent market development will result. In short, the circumstances for feasible production have not been promising until recently. Camelina production, on what would otherwise be fallowed land, could be a key component to biofuel market development.

Agronomic and economic data have been compiled from four sites in the eastern Colorado plains, in the communities of Iliff, (Latitude 40.768842 and Longitude 103.052444) Rocky Ford (Latitude 38.038048 and Longitude, −103.693447), Yellow Jacket (Latitude 37.532327 and Longitude −108.721218) and Fort Collins (Latitude 40.654385 and Longitude −104.999406), respectively. These areas have been chosen for case study because the region reflects many of the agronomic conditions seen in the western United States and because camelina can be grown on fallowed land without disrupting the current crop rotation. Using a specific location as a test case allows the model to be populated with numbers that more accurately reflect one area, so that variables can be isolated and replicated elsewhere. This approach is supported by the literature, as others have noted that feedstocks must be tailored to be region-specific in order to feasibly grow biofuels throughout the United States [33].

This study contributes to the literature by formalizing an agronomic–economic model of camelina and evaluating the economic feasibility of the crop in the context of crop production energy independence. The research reflects a small but nonetheless positive step towards diversifying regional and national energy portfolios, and the development of a potentially profitable agricultural crop.

2. Methodology

2.1. *Stochastic crop rotation model*

The agronomic–economic model applies four scenarios to a stochastic whole-farm, crop rotation budget for a typical farm in eastern Colorado [34,35], following the small-scale on-farm biofuel production process outlined in Fore et al. [6]. The baseline rotation is wheat followed by corn, followed by fallow. The stochastic crop rotation budget includes all key inputs necessary to produce SVO from camelina on land that would otherwise be in fallow. The projected variable input costs and potential economic revenues are calculated using a stochastic simulation of anticipated ranges and distributions for all key variables to account for uncertainty and to determine the economic profitability of growing camelina in the study region. The variables, ranges, and distributions used in the study are presented (Table 1) and are described in further detail in Sections 2.2 and 2.3. A more thorough discussion of the simulations is also available [34].

Once variables are defined and assigned ranges and distributions, the model is simulated 5.0×10^4 times using a Latin Hypercube Sampling process in Simetar® [35]. The Latin hypercube method creates a seemingly random parameter with a low variance [36,37]. Stochastic simulations are conducted under the four scenarios to determine the probability given different combinations of the variables.

In the first scenario, two hypothetical cases are compared. In one case, camelina is not grown, while the other case reflects the same farm growing camelina on part of the fallow. This basic break-even average model holds all variables at their respective means, and then determines the price of diesel fuel that equates net returns for each of these cases.

Table 1 – Simulated crop rotation budget stochastic variables.

Type	Range	Distribution type
Cost variables		
Seeding costs	25–35 $ ha^{-1}	Triangular
Herbicide costs	25.26 $ ha^{-1}	Fixed input
Labor costs	23 $ h^{-1}	Fixed input
Fertilizer application costs	0–44.8 kg ha^{-1}	Triangular
Cleaning/crushing/filtering costs	68–136 $ t^{-1}	Uniform
SVO storage costs	1849.35 $ 3y^{-1}	Fixed input
Seed hauling costs	6.49 $ t^{-1}	Fixed input
Wheat opportunity cost	0–144 $ ha^{-1}	Triangular
Loan interest	5–10% y^{-1}	Uniform
Revenue variables		
Offset diesel purchases	0–90.59 L ha^{-1}	Triangular
Sale of camelina meal	0.22–0.57 $ kg^{-1}	Triangular
Other variables		
Yield	0–1344 kg ha^{-1}	Triangular
Seed oil content fraction	22.2–32.7%	Triangular

The second scenario consists of a similar break-even comparison, but the values for some of the variables are stochastically chosen, and the accompanying price of diesel fuel is fixed. The break-even stochastic model identifies the price that diesel fuel needs to exceed in order for the farm with camelina to have at least a 0.51 probability of breaking-even.

The third scenario looks at the best case for camelina. This scenario puts into perspective the conservative estimates utilized in scenarios one and two. Yields in the two previous scenarios are held low to reflect the agronomic experience that first adopters are likely to encounter. Researchers in the western U.S. find that the yields will be much higher once farmers gain the experience necessary to manage fertility, weeds and other agronomic considerations [38]. Therefore, the third scenario fixes camelina yields at 1.344×10^6 kg ha^{-1}, as compared to just over 400 kg ha^{-1} in scenarios 1 and 2, to reflect higher yields that are consistent with agronomic research studies [10]. Like the previous scenarios, the other parameters are randomized.

The fourth scenario is a variation of the break-even stochastic scenario (scenario 2) that is designed to examine the impact of risk, and grower risk preferences, by using second degree stochastic dominance to rank choices for risk adverse farmers. This involves identifying the price that diesel fuel needs to exceed in order for the farm growing camelina to dominate the system without camelina for any positive risk aversion level. This essentially reflects a threshold where any risk-averse farmer would prefer the system with camelina. Safety-first criteria also are applied to determine the premium farmers might be willing to pay to grow camelina as a bioenergy crop, given different degrees of risk aversion preferences.

Finally, all results are subjected to a sensitivity analysis in order to determine the variables most likely to affect profitability. All four economic scenarios are based on the amount of camelina grown on fallow, as calculated in Section 2.2.

2.2. *Fuel source calculations*

Three fuel source calculations are made. The first fuel source calculation quantifies the hectares (ha) of camelina that must be grown in order to sustain a three-year crop rotation that includes, respectively, wheat, corn, and a split between camelina and fallow. Camelina is grown every three years, when land is in fallow. The camelina is stored and used to supply a farm's production needs, until it is once again inserted into the wheat-corn-fallow rotation three years later. Storage costs are shown in Table 1. The calculations assume a 90:10 blending rate to operate a diesel-based engine [34] for three production years in order to produce 400 ha of corn, followed by 400 ha of wheat, followed by 400 ha split between camelina and fallow. The amount of SVO supplied is further reduced by a fraction of 1.5% to run engines on diesel instead of SVO during cold winter months.

The second fuel source calculation reflects the establishment diesel necessary to produce the first camelina crop. This should be viewed as a one-time cost. The third calculation reflects the additional diesel required to satisfy the 90:10 SVO and diesel-blending rate used to produce camelina. Results from the first equation are used to calculate the next two equations (establishment diesel and additional diesel requirements, respectively).

In order to maximize efficiency, a farmer would not want to produce more camelina than is necessary, as any additional camelina produced would not be counted in the diesel offset and cannot be sold at premium prices. However, in order to achieve crop production energy independence, the farmer must grow enough camelina in order to satisfy operational requirements. The amount of camelina, as a fraction of ha grown, is calculated as:

$$\begin{aligned} CH = {} & \{FS \times MDO\} \times \{[CY \times OC] \times [0.854 \times (1 - OC)^{-1}]\}^{-1} \\ & + \{FS \times MDO \times DC\} \times \{\{[CY \times OC] \times [0.854 \\ & \times (1 - OC)^{-1}]\}^2\}^{-1} \end{aligned} \tag{1}$$

where CH is the ha of farmland necessary to grow camelina in order to supply the target amount of SVO for maximum diesel offset; FS is farm size, in ha; MDO is the maximum diesel offset (L ha^{-1}, that can potentially be offset with the use of SVO necessary to produce corn, wheat, and fallow); CY is the expected yield of camelina, in kg ha^{-1}; OC is oil content as portion of the camelina seed; 0.854 is a constant used to convert kilograms of SVO into liters; and, DC is the diesel fuel required to produce camelina where it replaces fallow, expressed in L ha^{-1}.

Expected values can be substituted into Eq. (1) since the farmer's operational decision about how many hectares to grow precedes yield. For simplicity, farm size is assumed to be 400 ha, and land is expected to be rotated into fallow every third year, with corn and wheat produced in other years. Crop yield is 448.4 kg ha^{-1}, and oil content is a fraction of 29.2%. It takes 75.78 L ha^{-1} of SVO to produce corn, wheat and fallow, adjusting for the blending rate and winter needs. Camelina production requires 29.73 L ha^{-1} of SVO. Imputing values and replacing variables from Eq. (1) yields Eq. (2):

$$CH = \{400 \times 75 \times 78\} \times \{[448.4 \times 0.292] \times [0.854 \times (1 - 0.292)^{-1}]\}^{-1} + \{400 \times 75.78 \times 29.73\} \times \{\{[448.4 \times 0.292] \times [0.854 \times (1 - 0.292)^{-1}]\}^{2}\}^{-1} \quad (2)$$

Additional details about how these values are generated are provided in Section 2.3. Solving Eq. (2), 227.72 ha of a 400 ha farm should be converted from fallow and dedicated to producing camelina. In other words, using the mean values of all the variables specific to eastern Colorado, a farmer should commit a fraction of about 57% of the fallow to growing camelina, regardless of the size of the farm, in order to generate enough SVO to allow for the maximum diesel offset.

Although the goal is to achieve a form of farm energy independence, some diesel is necessary for camelina establishment and on-going agricultural production. The amount of diesel required is a function of acreage devoted to camelina production. The first year the system is adopted, a farmer must rely on a one-time use of diesel fuel for system establishment. In this example, since camelina has not yet been produced for operational purposes, establishment diesel is required in order to produce the camelina crop that will eventually be used as a biofuel. As a result, diesel would need to be purchased for the first camelina planting. Establishment diesel cost (ED) is calculated as follows:

$$ED = 33.03 \times CH \times PD \quad (3)$$

$33.03 = \text{L ha}^{-1}$ of diesel fuel needed to grow one hectare of camelina while maintaining a fallow; CH is hectares used to grow camelina, which is imputed from Eq. (2); and, PD is the cost of diesel fuel in $\$ \text{L}^{-1}$. This one-time establishment cost is amortized in the model over 10 years at an interest rate of 4% y^{-1}.

After the system is established and camelina has been produced, the model requires "additional diesel" fuel that must be blended with SVO. Some researchers have concluded that blends with pure vegetable oil are potentially good substitute fuels for diesel engines [39], although the high viscosity of the SVO is a concern. A proper SVO to diesel ratio allows for the maximum diesel fuel offset without rendering the mixture unusable, due to either viscosity or cold-start property concerns that are common in pure SVO mixtures [40]. This SVO ratio has been verified by farmers in the plains of eastern Colorado experimenting currently with the rotation [34]. Therefore,

$$\text{Additional diesel} = 0.1 \times \text{establishment diesel} \quad (4)$$

to reflect the 90:10 SVO to diesel fuel ratio required for the operational camelina-based fuel.

2.3. Stochastic crop rotation model variables

This section summarizes the stochastic crop rotation model for camelina production. A summary of the stochastic variables, range, and subsequent distributions are summarized in Table 1. Cost and revenue data are adapted from Enjalbert and Johnson [10] and are further detailed in Brandess [34]. Wheat opportunity cost data are also imputed from extension enterprise budgets [41]. Table 1 costs are generally consistent with Fore et al. [6], but reflect additional detail about agronomic production for camelina, regional price variability, and stochastic simulation. Unless otherwise noted, all values in this paper are expressed in 2011 U.S. dollars and all simulations are conducted using Simetar® simulation software [35].

Agronomic yield and input data are based from field data averages from the three Colorado test sites, and verified against other western U.S. test plots [34]. The crop was harvested and transported in a manner consistent with Enjalbert and Johnson [10] and pilot Colorado camelina management guidelines [42].

Each of the 5.0×10^4 iterations of the simulation model randomly draws one observation from the assigned range and distribution of each variable. Given the distribution type, there may be a higher probability of the observation being drawn from a specific portion of its given range. All variables are either fixed or assigned a range. The variables are assigned a fixed, uniform or triangular distribution. The triangular distribution requires far less data compared to the normal distribution, as only knowledge of the minimum, maximum, and mode [43,44] is required. Fitting the information into a triangular probability density function (PDF) is a common approach when data are scarce [45], as is the case of the regional camelina biofuel production. In contrast, in a uniform distribution, all points within the bounded area are equally probable [46]. A uniform distribution is most applicable when no prior information is known about the data other than the normalization constraint.

2.3.1. *Production costs*

Only variable or operating costs are modeled since no additional equipment or land is required to produce camelina on fallowed land. Ownership and other long-term fixed costs are not considered. The price of camelina seed is fixed at approximately 4.45 $\$ \text{kg}^{-1}$ and the seeding rate is determined by a continuous uniform distribution between 5.6 kg ha^{-1} and 8.4 kg ha^{-1}. Seeding cost is ultimately represented by a uniform distribution, ranging from 25 to 35 $\$ \text{ha}^{-1}$. Herbicide costs are fixed at 25.26 $\$ \text{ha}^{-1}$, which is 18.75 $\$ \text{ha}^{-1}$ less than a farmer would typically spend to maintain fallow in eastern Colorado where the fraction of land is devoted to camelina is 57%. An additional 2.25 h of labor is needed to grow one hectare of camelina than is needed to maintain a fallow, resulting in 23 $\$ \text{ha}^{-1}$ fixed cost when the labor rate is 10.22 $\$ \text{h}^{-1}$ [34].

Fertilizer costs are calculated as nitrogen rate multiplied by price. Nitrogen fertilizer costs are assigned a triangular distribution with a minimum value of 0 kg ha^{-1} and modal value of 0 kg ha^{-1}, as there is agronomic debate as to whether camelina production requires additional fertilizer [34]. The maximum value of the distribution is fixed at 44.8 kg ha^{-1} [10]. The nitrogen price is estimated jointly with the price of diesel fuel using a correlated uniform standard deviate (CUSD) matrix, since nitrogen is produced using petroleum fuels, and is thus correlated with petroleum price. The CUSD matrix yields a stochastic deviate drawn independently for each simulation, based off the positive correlation (0.77) between the price of diesel fuel and the price of nitrogen fertilizer.

Seed crushing, cleaning, and filtering costs are necessary to process the feedstock into oil. These variables are assigned a continuous uniform distribution 68 $ t^{-1} to 136 $ t^{-1} in the model. A uniform distribution is used since no information exists to assign differential probabilities within the range for processing camelina. The relatively large range is due to a lack of consensus and limited published information regarding costs, as the western U.S. camelina refining values are not widely available. Cost and substrate storage/handling processes are based on the experiences of regional producers associated with Rocky Ford Crushing Cooperative, a crushing facility in southeastern Colorado [34]. The range of costs and consistency in substrate handling will be refined in the future as the cooperative's protocols for handling and processing evolve from a pilot scale.

Regional SVO storage costs are fixed at 5000 dollars for the entire storage system, per farm [34]. Using a ten year amortization and 4% interest rate, the annual SVO storage cost is 616.45 $ y^{-1}. This is multiplied by 3 to account for a complete crop rotation, for a total of 1 849.35 $ $(3\ y)^{-1}$. Seed hauling costs are fixed at 6.49 $ t^{-1} [41]. Wheat is used as a proxy since no hauling costs are published for camelina.

The model also accounts for a possible reduction of the subsequent wheat harvest on land that is growing camelina and not in fallow [34,41]. Wheat following fallow has less moisture when camelina is produced on the fallow. This is defined as wheat opportunity cost. The model averages the estimates and assigns a triangular distribution to wheat reduction, where the fractional change in the minimum value is 0, the fractional change for the modal value is 12.38% (half of the maximum value), and the fractional change for the maximum value is 24.75%. For example, the maximum opportunity cost of foregone wheat used in the model is calculated by reducing 1.246×10^{-3} kg ha^{-1} (the average wheat production in northeast Colorado) by the fraction 24.75%, the maximum wheat reduction used by the model. This equates to a reduction of 309.72 kg ha^{-1}. This reduction is multiplied by 6.65 dollars, the fixed price of wheat, and results in a maximum opportunity cost of foregone wheat production of 144 $ ha^{-1}.

The final cost is interest on the operation loan. It is assumed that the farmer takes out a 6-month operating loan before the initial camelina planting in order to raise sufficient capital to grow camelina. The interest rate is assigned a uniform distribution that is set between 5% y^{-1} and 10% y^{-1} to account for volatility in available loan rates [41]. The interest rate used in the "loan payment" calculation is higher than the real interest rate for typical farming operations because biomass production may carry more risk than established commodity crops due to less farmer knowledge regarding biomass feedstocks.

2.3.2. *Revenue*

Revenues from camelina are also depicted in Table 1. Income from camelina is received in two forms: cost savings from volumes of avoided diesel purchases and the sale of the camelina meal co-product. If camelina were used to offset diesel fuel in the proposed crop rotation, then the maximum diesel fuel savings volume from camelina-based SVO would be 75.78 L ha^{-1}. To break this down by crop, it is demonstrated [41] that wheat, corn, and fallow require 44.28 L ha^{-1}, 29.96 L ha^{-1}, and 11.24 L ha^{-1} of diesel, respectively, for a sum of 85.48 L ha^{-1} per rotation. A fraction equal to 90% of this total can be offset in order to maintain the needed 90:10 SVO to diesel ratio, which equates to 76.93 L ha^{-1}. An additional fraction of 1.5% of the fuel is anticipated for winter SVO cold-start, resulting in 75.78 L ha^{-1} theoretically available for the maximum diesel offset. Recall that the SVO needed for camelina production has already been computed as additional diesel. However, in the event of a camelina crop failure it is possible that no revenue would be offset. The PDF is estimated using a triangular distribution, with 0 L ha^{-1} as the minimum value and 90.59 L ha^{-1} as the maximum value. In the results and discussion section, different diesel prices are imputed to calculate cost savings, and the subsequent impacts on profitability.

Projections for the price of camelina meal are calculated using soybean meal prices as a proxy, as the camelina market has not yet been fully developed in the western United States. However, it has been demonstrated [47] that camelina co-products, including meal, are suitable replacements for soybean meal and that camelina co-products could be economically feasible supplemental ingredients. The 5 year average commodity price of soybean meal is averaged and assigned a triangular distribution with a minimum value of 0.20 $ kg^{-1}, a modal value of 0.42 $ kg^{-1}, and a maximum value of 0.51 $ kg^{-1}. The revenue from meal is presented in the formula:

$$M = 1 \times (OC \times CY)^{-1} \quad (5)$$

M is revenue in $ ha^{-1}, OC is the oil content fraction of the camelina seed, and CY is camelina yield expressed as kg ha^{-1}.

Revenue estimates depend on yield and oil content. Yield is estimated between 1344 kg ha^{-1} and 1568 kg ha^{-1} [42]. In the model, a triangular distribution is projected with a minimum value and mode value of 0 kg ha^{-1} and a maximum value of 1344 kg ha^{-1}. The conservative, 0 modal value reflects the learning curve faced by farmers in eastern Colorado who are likely to start harvesting with low yields. The resulting average yield is about 448 kg ha^{-1}. After accounting for inefficiencies in oil extraction, the minimum-fraction of the seed oil content is 22.2% and the maximum-fraction is 32.7%. The mean value found in the simulation reflects the fraction 29.21%. The mean value takes into account the correlation with yield and is therefore different than the median percentage of seed oil content. It is also worth noting that there is typically a high correlation between yield and seed oil content [48].

3. Results and discussion

The results for the first two scenarios (Table 2.) reflect a break-even comparison of a farm with and without a fraction of the fallow producing camelina.

The values reflect the probability that a farmer who grows camelina covers all costs, or "breaks even", compared to an identical farm where the farmer chooses not to grow camelina for a biofuel. These probabilities are relative to current price of

Table 2 – Expected profits and likelihood of increasing profits when camelina is added into a traditional corn-wheat-fallow rotation in eastern Colorado.

Diesel price ($ L^{-1})	Scenario 1, break-even, static model (expected profit in dollars)	Scenario 2, break-even, stochastic model (probability of increased profits)[a]	Scenario 3, best-case model (probability of increased profits)[b]
0.53	(7411)	0.244	0.824
0.80	(680)	0.364	0.889
0.83	**(7)**	0.40	0.896
1.07	6051	0.473	0.942
1.15	8069	**0.51**	0.96
1.33	12,781	0.571	0.983
1.60	19,512	0.629	0.99
1.87	26,243	0.658	0.997
2.13	32,974	0.684	1.0
2.67	46,436	0.720	1.0

a Probability that profits will increase for 400 hectare farm when adding camelina to rotation.
b Holding all but one assumption the same as Scenario 2, where a higher camelina yield assumption is made. Agronomic research yields are used as opposed to current, observed agronomic yields.

diesel fuel. The first scenario, a static model, determines the break-even price for diesel while holding all input values to their means. With this assumption, a farmer breaks even when the price of diesel fuel exceeds 0.83 $ L^{-1}. However, the static scenario fails to account for unpredictable situations like drought, and results in a comparatively optimistic assessment of camelina than a stochastic analysis. Scenario 2 takes stochastic draws for each input variable using means identical to Scenario 1. When inputs are stochastic, the camelina system has a 0.51 probability of being profitable when the price of diesel exceeds 1.15 $ L^{-1}. As demonstrated in Table 2, the chance of being profitable never reaches a probability of 1.0 in the stochastic scenario, regardless of diesel fuel prices, because the stochastic model incorporates the possibility of a year with a crop failure, due to unpredictable events such as drought.

The third scenario reflects a best-case yield situation. This scenario allows all variables to be stochastically simulated with the exception of the yield variable, which is set at the best case of 1344 kg ha^{-1}. The "best-case" yield scenario is reflective of an experienced farmer in a setting where the camelina rotation is already established. When the price of diesel fuel is at 0.53 $ L^{-1} (the lowest diesel price modeled) the probability of profitability is 0.83, which is considerably higher compared with the Scenario 2 likelihood of profitability of 0.24 for that same price. When the price of diesel fuel is 0.83 $ L^{-1} the probability that camelina will be profitable increases to 0.91, compared to only 0.40 in Scenario 2.

3.1. Risk

The final scenario investigates the inclusion of risk by using second degree stochastic dominance and safety-first criteria. In agriculture, stochastic dominance occurs when one management system or regime always brings more utility to the decision maker than another [49]. In this case, the decision maker must choose between the camelina system and traditional wheat rotation, but neither clearly makes the farmer better off. However, systems can be ranked by second degree stochastic dominance, which assumes that the producer demonstrates a degree of risk aversion. Risk is influential to the model because it represents the price diesel fuel must exceed to entice risk-averse farmers, or farmers that do not want to grow camelina out of fear of losing money, to invest in the crop. The break-even diesel price of 1.31 $ L^{-1} is derived for this scenario by comparing cumulative density functions for profits between a system with and a system without camelina, as required for second degree dominance [34]. That is, a risk-averse farmer would choose to grow camelina if the price of diesel equals or exceeds 1.31 $ L^{-1}.

Safety-first criteria measures the risk associated with failing to achieve a minimum target or predetermined safety margin [50]. Table 3 shows the approximate amount a farmer must be willing to lose to reach the given 0.90, 0.95, and 0.99 thresholds of profit certainty for three diesel prices commensurate with scenario 1 (0.83 $ L^{-1}), scenario 2 (1.15 $ L^{-1}) and stochastic dominance in scenario 4 (1.31 $ L^{-1}). Safety first is not applied to the results from the best-case scenario. For example, in the 0.83 $ L^{-1} diesel price scenario, there is a probability of 0.95 that no more than 39,000 dollars is at risk for loss when choosing to incorporate camelina. The farmer also knows that there is a 0.99 probability that no more than 47,000 dollars is at risk for loss. Referring again to the 0.83 $ L^{-1} example, if the farmer wants to be at the 0.99 safety threshold, the farmer must be willing to lose at least 47,000 dollars, although there is still a 0.01 risk of losing more than 47,000 dollars.

Table 3 – Minimum expected net farm income using safety-first criteria, with certainty thresholds of 0.90, 0.95, and 0.99 probability.

Diesel price	0.90 Probability threshold	0.95 Probability threshold	0.99 Probability threshold
0.83 $ L^{-1}	34,000 $	39,000 $	47,000 $
1.15 $ L^{-1}	35,000 $	41,000 $	49,000 $
1.31 $ L^{-1}	38,000 $	44,000 $	52,000 $

3.2. *Crop rotation budget results and influence of camelina meal on profitability*

A sensitivity analysis on inputs is conducted using the profits sensitivity tree feature in Simetar®, which shows the change in profit for a change in an input variable by a fraction of 1%. This is shown in Fig. 1.

As demonstrated at the top of the diagram, the sale of camelina meal has more influence on profitability than any other variable. An increase in the revenue generated from the sale of camelina meal by the fraction of 1% is associated with an increase by the fraction of 3.3% in total expected profits. In contrast, nitrogen fertilizer has the least amount of influence on the total profit, because nitrogen fertilizer comprises a relatively small portion of the overall production inputs in this scenario. After corn harvest, ample amounts of nitrogen remain in the soil for the camelina rotation. Little, if any, nitrogen is required. Subsequently, the minimum and the mode values are 0 kg ha^{-1}. A decrease in the fraction of 1% in the price of nitrogen fertilizer only increases total profits by a fraction of 0.28%. In essence, it is important for a farmer to find a market for camelina meal before committing to grow camelina.

Due to its seemingly large influence on profits, the incremental impacts of meal price on break-even costs are modeled, holding diesel prices constant. Not unexpectedly the farmer can anticipate generating more income from the sale of camelina meal than savings from offsetting diesel fuel purchases until the price of diesel fuel surpasses 0.91 $ L^{-1}. Once the price of diesel fuel exceeds 0.91 $ L^{-1}, however, the farmer generates more revenue from the ability to offset diesel fuel purchases than the revenues generated from the sale of camelina meal. It is important to note that meal sales and fuel offsets are cooperative co-products, as they do not preclude each other. A farmer typically would generate meal after pressing the seed for SVO.

3.3. *Energy independence premium*

As noted in the Section 1, some producers might value energy independence. These producers would be willing to lose money growing camelina because it still provides a bioenergy feedstock option, in the event of a fuel disruption. The value of the "energy independence premium" can be calculated by comparing the break-even price to a given fuel price at which a producer would be willing to incur a loss. For example, as shown in Scenario 1 in Table 2, at 0.83 $ L^{-1} of diesel fuel, the cost per liter of camelina-based SVO is nearly identical to purchasing diesel. However, in this same scenario, a farmer would lose 680 dollars if the price of diesel fell to 0.80 $ L^{-1}. If the farmer is willing to still grow the camelina at a 0.80 $ L^{-1}

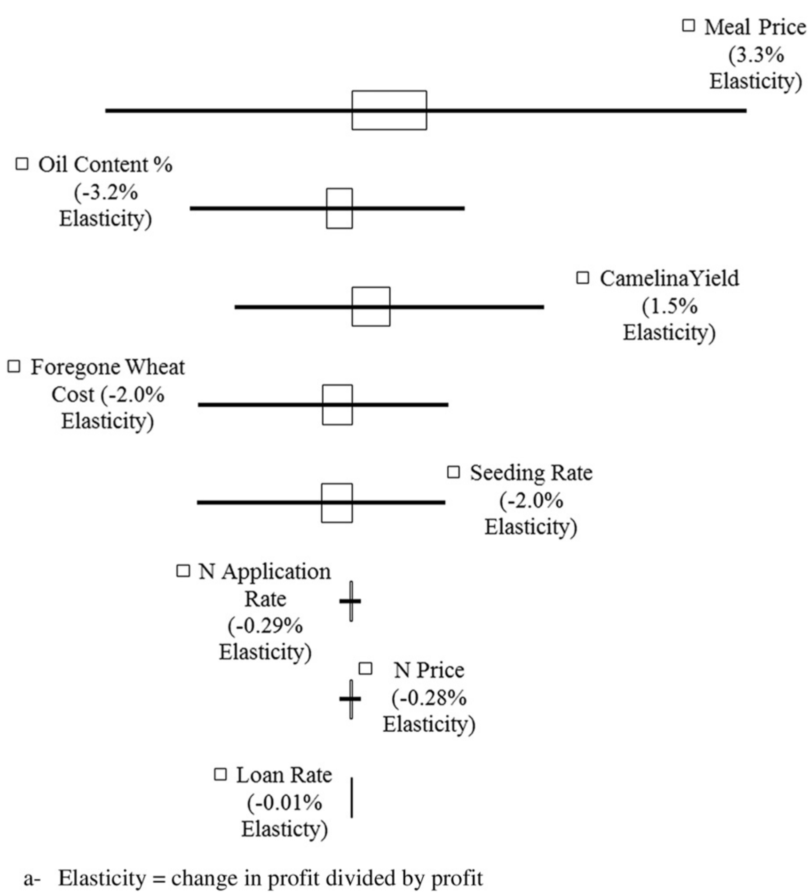

Fig. 1 – Camelina profit sensitivity (change in each variable with respect to total profits, elasticity = change in profit divided by profit).

diesel price, he would essentially exhibit a willingness to pay a 0.03 \$ L^{-1} premium for energy independence. Farmers that place more value on energy independence will be more likely to adopt the camelina system at low diesel prices.

4. *Summary and conclusions*

This study models four scenarios to demonstrate the circumstances under which camelina can be grown profitably and for crop production energy independence in the western United States. If a farmer feels comfortable using the expected values of input prices and quantities, the farmer would grow camelina once the price of diesel fuel passes 0.83 \$ L^{-1}. However, stochastic crop rotation budget results demonstrate that producers have only a 0.40 probability of breaking even at that price. The farmer would have a 0.51 probability of breaking even when diesel prices reach 1.15 \$ L^{-1}. An experienced producer who can grow camelina to its full potential has a 0.90 probability of profitability when diesel is at 0.83 \$ L^{-1}. A risk-averse farmer anticipating diesel fuel prices greater than 0.83 \$ L^{-1} would have a probability of 0.90 of exceeding 34,000 dollars and 0.99 probability of exceeding 47,000 dollars. Any risk-averse farmer would choose to produce camelina if diesel prices rise to 1.31 \$ L^{-1}. Finally, a farmer who puts a value on crop production energy independence might adopt the camelina system at even lower diesel prices.

Results from the sensitivity analysis show that the sale of camelina meal has the greatest impact on profitability until the price of diesel fuel exceeds 0.90 \$ L^{-1}, when the farmer generates more revenue from the ability to offset diesel fuel purchases than the revenues generated from the sale of camelina meal.

This study contributes to the literature by collecting primary data to develop a stochastic crop budget generator for camelina production in the western United States. The study makes a case for growing camelina that can be sold as meal and converted into SVO to power a diesel engine. At this writing, the U.S. market for camelina meal is in an early phase of development. Early adopters would presumably face some risk of finding a market for the camelina meal. However, with knowledge of the break-even prices and expected profitability thresholds, producers can make informed decisions. Producers who also place a premium on energy security might be willing to become early adopters of camelina production at low diesel prices, thereby adding momentum to market development and possibly earning a first mover advantage.

This crop rotation budget and simulation exercise should be viewed in context as a first step towards isolating the agronomic and economic variables that influence the profitability of camelina production. Risk and profitability estimates provide necessary information to agricultural producers who must decide whether or not to grow camelina. The crop budget and profitability estimates are steps in building a camelina market that might ultimately lead to a critical mass of agricultural producers who are willing and able to cultivate a crop that can be used for a large portion of their on-farm energy needs.

While camelina is a legacy crop in many parts of the world, commercial camelina production in the United States is only beginning. From an agronomic perspective, camelina shows promise for fitting into a traditional Colorado wheat rotation, at relatively minimal opportunity cost of growing wheat, the cash crop. However, if there is not a market for the meal, according to the results of the sensitivity analysis, the farmer faces a low probability of profitability. Thus, until demand increases for camelina meal and camelina as a biofuel feedstock, it remains a risky crop that becomes profitable only at high energy prices.

Based on the positive results in this manuscript, policy makers should consider instituting policies that encourage oilseed crop production and further refinements to SVO-based engines. Policies are already in place that target energy independence and oilseed crops reflect a critical link between agricultural and energy production. Agricultural production is the economic and cultural lifeblood of many western rural communities [51]. In the event of a fuel supply disruption, it would be important to these rural communities and the agricultural supply chain to ensure that agricultural production continues. Oilseed crops like camelina can be sold for meal or converted to energy, thus ensuring that agricultural production continues in these rural areas. Given its versatility as an animal feed, camelina can also ensure the continuation livestock production.

Returning to the question posed at the beginning of the paper, these four scenarios demonstrate that it is economically feasible for farmers to grow their own fuel. Much of this success is attributable to the low opportunity cost of growing camelina because the crop is grown on land that would otherwise be in fallow during the third year of a corn–wheat rotation. Some producers might even be willing to pay a premium to grow energy biomass because camelina production might insure against disruptions in overall commodity production. Camelina and SVO cooperatives could establish camelina production as a regional comparative advantage that could lead to regional energy independence. A few SVO production cooperatives have already formed in Colorado, forming the basis of this regional case study [34]. Bioenergy production could be particularly advantageous in counties that are farm dependent, and where disruptions to commodity production would have resounding economic impact. In fact, in these farm dependent counties, camelina and energy biomass production present opportunity to diversify the economic base.

At a national scale, energy independence is closely aligned to national strategy, which should consider the relationship between food and energy availability. Reducing dependency on foreign oil must be a mosaic of small steps, as it is unlikely a single source of replacement energy would be sufficient. If the price of diesel fuel rises, the value of energy self-sufficiency for the farmer also rises. Even on the national level, camelina may offer a small stride away from the national dependence on foreign oil by giving farmers in the western United States the ability to grow a biofuel that can replace diesel fuel demands. Camelina shows the potential to assist a farmer with a new source of revenue while alleviating some of the burden on fuel imports. It is once again essential to emphasize that the successful of integration of camelina would only eliminate a small fraction of the need for oil. However, small fractions can quickly add up to significant sums if other biofuel and energy options are implemented elsewhere.

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