LIFE CYCLE ANALYSIS AND PRODUCTION POTENTIAL OF CAMELINA BIODIESEL IN THE PACIFIC NORTHWEST

N. Dangol, D. S. Shrestha, J. A. Duffield

ABSTRACT. Camelina sativa *could be a potential feedstock to help meet the U.S. biodiesel production goal of 36 billion gallons by 2022, as set forth by Energy Independence and Security Act of 2007. This research is focused on assessing the energy balance and greenhouse gas (GHG) emissions of camelina biodiesel production in the Pacific Northwest (PNW) region of the U.S. Field data were collected from a camelina farm in the region, and crushing and transesterification data were measured using facilities at the University of Idaho. It was estimated that use of camelina biodiesel reduces GHG emissions by 69% compared to 2005 baseline diesel. However, camelina biodiesel does not meet the ASTM D6751 specification for oxidative stability without an additive. Camelina has a smaller seed size compared to canola and required 23% more energy for crushing. The net energy ratio for camelina biodiesel was found to be 3.6, and the fossil energy ratio was found to be 4.2. From an agronomic standpoint, camelina can be incorporated into low rainfall areas of the PNW as a rotational crop. Wheat areas of the PNW with annual rainfall of 19 to 38 cm that currently incorporate fallow into their rotations were considered as potential areas for camelina production. There were 846,500 ha (2.1 million acres) of land meeting the criteria in the region that could potentially produce 443.0 million L of biodiesel (117.1 million gal) and 1.2 billion kg of meal per year. This is 12.1% of the approved amount of camelina meal that could be used in livestock feed within the PNW. It was concluded that camelina biodiesel qualifies as an advanced biofuel, and camelina meal has potential to be consumed locally as a feed mix for livestock.*

Keywords. *Biodiesel GHG, Biofuel energy balance, Camelina biodiesel, Lifecycle analysis.*

Camelina (*Camelina sativa*) is an oilseed crop of the Brassicaceae family (USDA-NRCS, 2013) similar to mustard, canola, and rapeseed. It is a relatively new crop in the U.S. and is currently grown on approximately 20,234 ha (50,000 acres) of land, primarily in Montana, eastern Washington, and the Dakotas (USEPA, 2013; Pilgeram et al., 2007). Agronomic trials are being conducted for camelina in the states of Nebraska, South Dakota, Wyoming, Colorado, Kansas, and Minnesota in the U.S. (Pavlista and Baltensperger, 2007; Gesch and Cermak, 2011) and in western Canada (Gugel and Falk, 2006) to better understand the crop behavior. Camelina can be used to make biodiesel as a renewable fuel. Camelina could be a potential biodiesel feedstock crop due to its low moisture requirement, short growing season (85 to 100 days), and relatively high oil content (30% to 40%) (Pavlista et al., 2011; Pilgeram et al., 2007).

According to the U.S. Energy Independence and Security Act (EISA, 2007), a biofuel qualifies as an "advanced biofuel" if the fuel reduces greenhouse gas (GHG) emissions by at least 50% compared to baseline petroleum fuel. The advanced biofuel status allows the producer to receive higher monetary incentives through tax credits or through generation of renewable identification numbers (RINs) per the Renewable Fuel Standard (RFS2) program. Although the federal tax credit for biodiesel and biodiesel mixtures expired on 31 December 2013, it could be reauthorized by Congress. In 2013, the U.S. Environmental Protection Agency identified the fuel pathways for biofuels produced from camelina oil and stated that camelina biodiesel could qualify as an advanced biofuel (USEPA, 2013). Ensuring that biofuels meet the EPA's renewable fuel requirements will play a major role in determining the financial success of the renewable fuel industry.

The relative costs of renewable fuel compared to petroleum fuel vary. In the short term, the price depends on market dynamics, subsidies, inflation, and crude oil price. The net energy ratio (NER) is the ratio of energy output from a biofuel per unit of total energy used to produce the fuel. The fuels used in the production of a biofuel system are mainly diesel, gasoline, natural gas, and electricity, and their relative price shifts in tandem (Pradhan et al., 2011). When calculating emission factors for these inputs, the life cycle energy is used, which includes the energy for extraction, transport, and refining. The NER can be used to compare the production efficiency of a biofuel to a petroleum fuel. For instance, petroleum diesel uses 0.13 units of ener-

Submitted for review in May 2014 as manuscript number PRS 10771; approved for publication by the Processing Systems Community of ASABE in March 2015.

Mention of company or trade names is for description only and does not imply endorsement by the USDA. The USDA is an equal opportunity provider and employer.

The authors are **Namrata Dangol, ASABE Member,** Graduate Student, and **Dev S. Shrestha, ASABE Member,** Associate Professor, Department of Biological and Agricultural Engineering, University of Idaho, Moscow, Idaho; **James A. Duffield,** Senior Agricultural Economist, USDA Office of Energy Policy and New Uses, Washington, D.C. **Corresponding author:** Dev S. Shrestha, Department of Biological and Agricultural Engineering, P.O. Box 442060, University of Idaho, Moscow, ID 83844; phone: 208-885-7545; e-mail: devs@uidaho.edu.

gy for one unit of energy mined (Sheehan et al., 1998). This causes the NER for petroleum diesel to be 0.87/0.13 (≈6.7). The current NER for soybean biodiesel is 5.54 (Pradhan et al., 2011). This indicates that petroleum diesel would yield more energy per unit of energy spent; consequently, for a comparable return on investment, soybean biodiesel would be more costly than petroleum diesel. This situation may change in the future if petroleum extraction becomes more energy intensive.

Life cycle analysis (LCA) evaluates the performance of a biofuel relative to its petroleum fuel counterpart for GHG emission reductions and energy balance. The fossil energy ratio (FER) measures the renewability of a biofuel. The FER is the ratio of energy output from the biofuel per unit of non-renewable or fossil energy input. The FER does not include energy input from renewable sources such as hydropower or solar. A higher FER corresponds to higher renewability of a fuel, but it does not ensure the fuel's economic viability (Pradhan et al., 2008).

Being relatively new, camelina does not have as established a market as other oilseeds such as soybean or canola. In July 2011, the USDA announced that the Biomass Crop Assistance Program (BCAP) would make grants available for expanding camelina production in Montana, California, Oregon, and Washington (USDA-FSA, 2011). However, yield concerns, an uncertain market, and lack of production information deterred farmers from participating (Young et al., 2012). Canola is a close competitor of camelina as a rotational crop and has a higher return on investment than camelina in higher rainfall regions (Young et al., 2012). Camelina can be cultivated and harvested using the same equipment as for canola without the need of any specialty equipment. However, because of the smaller seed size, care must be taken, as camelina can flow out from cracks or holes considered too small for canola. Even a small hole on seed handling or storage equipment needs careful sealing.

Wheat is the primary crop grown in the Pacific Northwest (PNW) and has a higher return on investment than any rotational crops (UI, 2012). Peas, lentil, or canola are rotated with wheat to break the wheat monoculture once every three or four years in higher rainfall (>38 cm) regions. However, in lower rainfall regions (≤38 cm), the land is left fallow (Schillinger et al., 2010). Camelina can be grown in some of these fallow areas because of its relatively short growing season and low moisture requirement (Shonnard et al., 2010).

Camelina is cold pressed using screw presses because of its relatively higher oil content. Cold-pressed camelina meal contains 10% to 14% oil by weight, which potentially can be extracted using a solvent extraction method. However, solvent extraction is usually not performed on the cold-pressed meal, as the current scale of camelina crushing is inadequate to justify the cost. Interviews with farmers also revealed that the high oil content meal has a greater demand as animal feed, further reducing the need for hexane extraction. Therefore, the cold-pressed meal is sold as is. Camelina meal is better suited than rapeseed or mustard meal for animal feed because of its lower glucosinolate levels of 14.5 to 36.2 mmol kg^{-1} (Schuster and Friedt, 1998; Berhow et al., 2013), compared to 100 to 120 mmol kg^{-1} for rapeseed and 62.4 to 77.1 mmol kg^{-1} for mustard (Matthäus and Luftmann, 2000). However, canola has a comparable or slightly lower glucosinolate level of 5 to 20 mmol kg^{-1}. Lower glucosinolate makes a meal more suitable for livestock feed (Pilgeram et al., 2007). As a result, camelina meal had been approved by the FDA for up to 10% in poultry and beef cattle feed mix and 2% in swine feed mix (MDA, 2012; EFSA, 2008).

The objectives of this study were to conduct an LCA analysis of camelina biodiesel and to quantify its potential production and demand in the PNW. The PNW states include Washington, Oregon, Idaho, Montana, and Wyoming. This study quantifies the GHG reduction from the use of camelina biodiesel to determine if the fuel meets the RFS2 criterion for an advanced biofuel. The LCA results are reported in terms of the NER, FER, and net GHG emissions of camelina biodiesel compared to baseline diesel. This study also estimates the production potential of camelina as a rotational crop in low rainfall areas of the PNW, where camelina has an economic advantage over canola. Finally, this study compares camelina meal production to its potential demand in the local livestock industry.

METHODOLOGY

LCA SYSTEM BOUNDARY

This LCA covers the following stages of fuel production: (1) camelina production, (2) camelina transport from farm to crushing facility, (3) biodiesel production from camelina oil, and (4) biodiesel transport and distribution. All materials and energies invested in the operation and processing during these stages were included. Equivalent life cycle energy, which is embedded energy plus the energy used in extraction, processing, transport, and distribution of a material, was used in the energy analysis. GHG emissions are the only environmental impact considered in this article, as RFS2 stipulates GHG reduction as the criterion to qualify a biofuel as an advanced biofuel. GHG emission per GJ of energy in biodiesel is considered the functional unit for this LCA.

This LCA is based on data from a camelina farm and biodiesel plant located in LaCrosse, Washington. The farmer had been growing dryland winter camelina (non-irrigated) as a rotational crop on 60 to 120 ha of land since 2009. Annual rainfall during that period was 30 to 36 cm, and the annual average temperature was -1°C to 10°C. Seeding was done in late October (direct seeding followed by harrowing), and the crop was harvested in late March through early April with a combine (same as canola combine). The farmer produced biodiesel from the camelina oil crushed in his oil press, near the seed storage area. The produced biodiesel was used as fuel for his farm operations. The farmer's fields are located within an 8 km (5 mi) radius of the storage area, and the fuel used for seed transport is included as agricultural fuel use. The seed crushing facility is located next to the storage area. Since transport distance to the crusher may vary by farm, a sensitivity analysis showing the impact of hauling distance on the LCA is included in this article. Likewise, the effect on the LCA results from relatively highly variable inputs, such as biodiesel transport, is also included in a sensitivity analysis. Because camelina is being considered as a potential rotational crop during fallow periods (fig. 2), the crop does not replace any other crop. Consequently, the indirect land use change was not considered an issue and was not included in this study.

Data Collection

The data for camelina feedstock production were obtained from the farmer in LaCrosse, Washington. Energy inputs for camelina crushing and biodiesel production were measured experimentally at the University of Idaho Biodiesel Lab. A screw press oil expeller (model S-52, Hander Oil Machinery, Osaka, Japan) run by a 2.95 kW (4 hp) three-phase induction motor was used for crushing. The expeller has a three-stage 1 kW silicone blanket heated seed auger with an insulated jacket. The expeller is rated for 50 kg h^{-1} (110 lbs h^{-1}) of seed throughput. A total of 29 kg (64 lbs) of camelina seed was crushed in the oil expeller. The moisture content of the seed was 9%. The collected oil was passed through a strainer to catch meal particles flowing with the oil. The collected oil was measured to calculate the oil yield. The collected oil was then settled overnight, and the top clear portion was decanted for biodiesel production. The collected oil was measured again to calculate the oil yield. The meal on the strainer and the bottom fraction of the oil after decantation were considered the meal fraction. The meal after crushing was augured to a bin using a fractional horsepower motor. The seed was preheated to 40°C using a seed heater before crushing. The energy used for the motor, heater, and augur were recorded separately using a three-phase power data logger (model 382090, Extech, Nashua, N.H.).

The oil content of the seed was measured following the procedure outlined by Hammond (1991) using a nuclear magnetic resonance (NMR) analyzer (Newport MKIIIA, Oxford Instruments, Inc., Concord, Mass.). The NMR was calibrated with a single reference sample of known oil content, and the sample analysis was carried out as described by Howard and Daun (1991).The procedure is based on ISO 5511-1984. The fatty acid content of the oil was determined using gas chromatography as described by Hammond (1991). The seed moisture content was measured by the oven-drying method per ASABE Standard S352.2 (ASABE, 2012b). The energy inputs for transport and distribution of the feedstock and biodiesel were obtained from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (ANL, 2012).

Seed Size Analysis

Seed size can explain the difference in energy needed for crushing and oil content in comparable oil seeds such as canola and camelina. Assuming an ellipsoidal geometry for camelina seeds with hull thickness t and seed radii a, b, and c in the principal axes, the meal to total volume ratio (M) is given by:

$$M = \frac{(a-t)(b-t)(c-t)}{abc} \tag{1}$$

Equation 1 shows that for the same hull thickness t, the ratio of meal increases non-linearly with the seed radii and asymptotically reaches unity when the hull thickness is negligible compared to the seed radius. Since the hull contains almost no lipid or protein, a larger seed such as canola has a greater overall oil percentage even though the meal and lipid percentages are the same in the cotyledon. In addition to having a smaller meal to total volume ratio, smaller seeds also require more energy to break open. Assuming equal hull tensile strengths, and taking the approximate value of the ellipse circumference as $2\pi\sqrt{\frac{a^2+b^2}{2}}$, the ratio of internal stress required to rupture the outer hull can be expressed as:

$$\frac{P_1}{P_2} \approx \frac{a_2 b_2 \sqrt{a_1^2+b_1^2}}{a_1 b_1 \sqrt{a_2^2+b_2^2}} \times \frac{t_1}{t_2} \tag{2}$$

where subscripts 1 and 2 indicate the radii and thicknesses of two different seed sizes. For the same hull thickness and similar ellipsoid ($a_1/b_1 = a_2/b_2$), the pressure ratio can be simplified to:

$$\frac{P_1}{P_2} = \frac{a_2}{a_1} = \frac{b_2}{b_1} \tag{2a}$$

This relationship shows that crushing pressure is inversely proportional to seed size; that is, the smaller the seed size, the higher the pressure required. Higher pressure translates to more frictional loss and consequently more energy required for crushing per unit volume of seed.

To verify the effect of seed size on energy requirement, camelina seed size and hull thickness were measured from a seed tomogram using an optical microscope (G012001998, Omax Corp., South Kent, Wash.) at 10× magnification (fig. 1). The average seed sizes were determined using sieve analysis per ASABE Standard S319.3 (ASABE, 2012a). The ratio of meal to total seed mass was measured using an electronic scale.

Biodiesel was produced in a 23 L (6 gal) capacity stainless steel drum reactor (Electro-Flex Heat, Inc., Bloomfield, Conn.) using 100% excess methanol to complete the reaction and using sodium methoxide as catalyst. The reactor had a 250 W (1/3 hp) stirrer and 1,000 W silicone belt heater. The excess methanol from glycerol after separation was recovered using a Rotavapor (R-114, Buchi, Flawil, Switzerland). The produced biodiesel was tested for flash point, water content, kinematic viscosity, acid number, oxidative stability, distillation temperature, sulfur content, and cloud point according to ASTM D6751 (ASTM, 2012). Cetane number was estimated from the fatty acid ester composition of the biodiesel using an empirical equation (Ramírez-Verduzco et al., 2012).

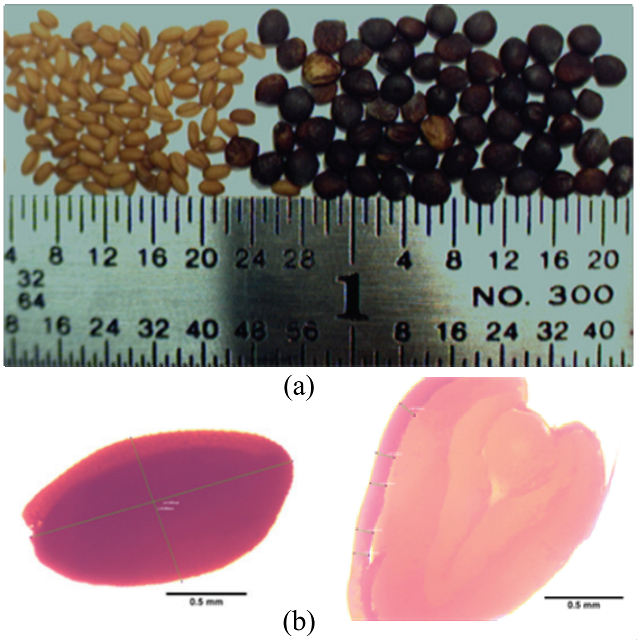

Figure 1. Seed size comparison of camelina (left) and canola (right): (a) ruler lines at 1/32 in., and (b) seed tomograms. Hull thickness and seed diameter were measured using seed tomogram microscopy.

Soil Emissions

The soil emissions from camelina cultivation were obtained from an LCA model in GHGenius 4.03 (GHGenius, 2013a) modeled for western U.S. regions from USDA data. The model takes into account the direct and indirect emissions, as well as the carbon sequestration in the soil. The direct emissions include N_2O emissions related to added nitrogen fertilizer, crop biomass added to the soil, nitrogen present in the soil, and soil carbon changes. The emissions of CO_2 and CH_4 related to nitrogen emission were also included as direct emissions in the model. The N_2O emissions from nitrogen volatilization, leaching, and runoff were regarded as indirect emissions, as escaped nitrogen converts to N_2O offsite. The carbon sequestered in the soil was also calculated and subtracted from the soil emissions to determine the net soil emissions. The soil N_2O emission calculation in GHGenius is similar to the IPCC tier 1 approach (IPCC, 2006) but adds the impact of non-IPCC direct N_2O emissions such as tillage, irrigation, and summer fallow. The methodology is described in detail in GHGenius 4.03 volumes 1 and 2 (GHGenius, 2013b, 2013c).

Energy Conversion Factors and Co-Product Energy Allocation

The materials in the life cycle inventory list were converted to their equivalent life cycle energy contents. The life cycle energy for an input is defined as the total of the embedded energy and the energy expended during extraction, processing, transport, and distribution. The embedded energy for fuel inputs such as diesel, gasoline, and natural gas were taken as their lower heating value (LHV); for all other inputs, the higher heating values (HHV) were taken. Taking the LHV for fuel is justified because the LHV is obtained from burning the fuel. For non-fuel use of chemicals such as methanol, there is no water vapor produced that needs to be evaporated, and hence the HHV is justified. This method is consistent with previous studies, such as Pradhan et al. (2011). The life cycle energy of electricity was based on the eGrid value for the U.S. Northwest (eGrid, 2014). The energy used in the process was allocated among the co-products camelina meal, biodiesel, and crude glycerin based on their relative masses. A mass-based co-product allocation method was used to make a valid comparison with previous relevant studies (Vigon et al., 1993; Pradhan et al., 2008). Mass-based allocation is valid for RFS2 LCA analysis and provides reproducible results over time.

Camelina Potential in the PNW as a Rotational Crop with Wheat

The economic breakeven yield for non-irrigated camelina was estimated to be 980 kg ha^{-1} (875 lbs $acre^{-1}$) at the price of \$0.40 kg^{-1} (Painter, 2011). An estimation using Hergert et al. (2011) showed that a minimum of 19 cm (7.5 in.) of rainfall equivalent is required to obtain this breakeven yield. Using the common crop rotation patterns within the viable rainfall zone (19 to 38 cm), potential camelina areas were identified with ArcGIS (ver. 10, ESRI, Redlands, Cal.). The common three-year and four-year crop rotation patterns were winter wheat, winter wheat, fallow (WWF) and winter wheat, winter wheat, fallow, spring wheat (WWFS), respectively (fig. 2). Crop coverage data from 2009 to 2012 (USDA-NRCS, 2012) were used to identify the crop rotation patterns. The areas of 19 to 38 cm rainfall were determined based on a 30-year (1981-2010) annual average precipitation map obtained from the USDA-NRCS (2012).

Winter wheat, winter wheat, fallow (WWF) rotation

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Year 1	Winter wheat								Fallow	Winter wheat		
Year 2	Winter wheat								Fallow			
Year 3	Fallow			**Camelina (proposed)**					Fallow	Winter wheat		

Winter wheat, winter wheat, fallow, spring wheat (WWFS) rotation

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Year 1	Winter wheat								Fallow	Winter wheat		
Year 2	Winter wheat								Fallow			
Year 3	Fallow			**Camelina (proposed)**					Fallow			
Year 4	Fallow			Spring wheat					Fallow	Winter wheat		

Figure 2. Crop rotation patterns in the PNW in low rainfall (19 to 38 cm) areas. Land proposed for camelina is currently left fallow.

The total potential area for camelina under each rotation pattern was calculated by finding the agricultural land that satisfies both the crop rotation criteria and the rainfall requirement (eqs. 3 and 4) and converting this information to annual available acreage for camelina using equation 5:

$$A_1 = A(\text{WWF}) \text{ and } A(rf) \tag{3}$$

$$A_2 = A(\text{WWFS}) \text{ and } A(rf) \tag{4}$$

where

A_1 = binary raster map layer that follows WWF rotation and lies in 19 to 38 cm rainfall zone = 2.5 million ha

A_2 = binary raster map layer that follows WWFS rotation and lies in 19 to 38 cm rainfall zone = 31.8 thousand ha

A(WWF) = binary raster map layer that follows WWF rotation (obtained from four years of crop data, 2009-2012)

A(WWFS) = binary raster map layer that follows WWFS rotation (obtained from four years of crop data, 2009-2012)

$A(rf)$ = binary raster map layer containing cells that lie in 19 to 38 cm rainfall zone = 45.8 million ha.

$$P = \sum\left(\frac{1}{3}A_1 + \frac{1}{4}A_2\right)Y_R \tag{5}$$

where P is total production (kg year^{-1}), and Y_R is camelina yield (kg ha^{-1}). The camelina yield was estimated as a function of rainfall (R) from Hergert et al. (2011) and is given by equation 6:

$$Y_R = -1.0821R^2 + 133.45R - 1189.1 \quad \text{for } 12 \text{ cm} \le R \le 50 \text{ cm} \tag{6}$$

Camelina Meal Demand Assessment

The potential demand for camelina meal in the PNW was calculated assuming that the meal is used as livestock feed at the limits allowed by the FDA. The livestock population data were taken from the annual livestock inventory by the USDA (USDA-NASS, 2013a, 2013b, 2013c). Feed consumed by each animal-age group was obtained from animal feed guides published by Washington State University (Platt, 2010), the University of Kentucky (Jacob et al., 2011), the USDA (USDA-ERS, 2012), and from Cappellozza et al. (2012). The potential demand was compared with potential supply to estimate the percentage of meal that can be used regionally for biodiesel.

Results and Discussion

Life Cycle Analysis

Feedstock Production and Transport

Average camelina yield from the farmer's field was recorded as 1,570 kg ha^{-1} (1,400 lbs acre^{-1}). This observed yield was lower than the predicted yield (1840 kg ha^{-1}) using equation 6 for 30 cm rainfall, but it was within the 95% confidence interval of research plot data from Washington State University (Painter and Miller, 2009), Montana State University (obtained from correspondence), and the University of Idaho (Painter, 2011), where the yield ranged from 1500 to 1800 kg ha^{-1} for the same rainfall zone. GHGenius estimated 1,020 kg ha^{-1} of yield for Canada ("input" worksheet, row 111; GHGenius, 2013a). The recorded inputs for the camelina field are shown in table 1. The recorded yield from the farmer's field was used in the LCA. The effect of yield on the LCA results is included in the sensitivity analysis.

The GHG emissions for seed were calculated recursively by dividing the total GHG emissions by yield. The fossil fuel fraction of electricity generation in the Northwest region was 46% (eGrid, 2014), and the efficiency of electricity generation, transmission, and distribution was 32.9% (USEIA, 2013). Electricity was used for camelina crushing and transesterification. The fossil fraction of the energy sources for electricity generation was used for calculating the FER. In fact, the renewable fraction of electricity production was the only difference in the FER and NER calculations in this study.

The field inputs provided by the farmer were similar to the amounts used in the research plots except for nitrogen. The amount of nitrogen used (28 kg ha^{-1}) was less than in the research plots. This was because the farmer adjusted the amount of nitrogen applied based on soil test nitrogen before planting, which was about 22 kg ha^{-1}. If soil nitrogen was added to the additional nitrogen input, the total would comparable to the nitrogen reported in the research plots, which varied from 41 to 88 kg ha^{-1} (Painter and Miller, 2009; Painter, 2011; Shonnard et al., 2010; Wysocki et al., 2013).

The LCA analysis conducted by the U.S. EPA for the RFS2 final rule published in March 2013 (USEPA, 2013) assumed 44 kg ha^{-1} of added nitrogen, which was higher than the value used in our study (28 kg ha^{-1}; table 1). Other inputs used in the EPA study were adapted from McVay and Lamb (2004), Ehrensing and Guy (2008), and Shonnard et al. (2010), and the values were similar to this study.

Table 1. Total energy input and GHG emissions in feedstock production.

Item	Amount[a] per ha	Life Cycle Energy Equivalent	Life Cycle Energy (MJ ha^{-1})	GHG Equivalent (g CO_2e)	Total g CO_2e ha^{-1}
Diesel	42.0 L	42.5 MJ L^{-1} [b]	1,785	3,231 L^{-1} [c]	135,702
Nitrogen	28.0 kg	51.5 MJ kg^{-1} [d]	1,442	3,592 kg^{-1} [e]	100,576
Phosphorus	16.1 kg	9.2 MJ kg^{-1} [d]	148	1,197 kg^{-1} [e]	19,272
Sulfur	11.2 kg	1.5 MJ kg^{-1} [f]	17	154 kg^{-1} [f]	1,725
Seed	5.6 kg	30.4 MJ kg^{-1} [g]	170	517 kg^{-1} [h]	2,895
Herbicide	5.0 kg	319 MJ kg^{-1} [d]	1,595	25,745 kg^{-1} [e]	128,725
Insecticide	1.6 kg	325 MJ kg^{-1} [d]	520	29,937 kg^{-1} [e]	47,899
Soil emission	-	-	-	-	374,710[f]
Total			5,677		811,504

Sources: [a]Collected farm data, [b]Huo et al. (2008) and Shapouri et al. (2002), [c]DOE (2008), [d]Hill et al. (2006), [e]USEPA (2012), [f]GHGenius (2013a), [g]Shonnard et al. (2010), and [h]Calculated from production data.

Seed Crushing

The oil content of the camelina seed was 34.2%, and the mechanical press was able to extract 80% of that oil (0.274 kg of oil kg^{-1} of seed crushed). The oil content and extraction efficiency were both lower than reported in the literature. GHGenius assumed the average oil content of camelina to be 43% and used 0.376 kg of oil extracted per kg of seed (GHGenius, 2013b), while GREET assumed 96% oil extraction efficiency with 0.36 kg oil kg^{-1} seed (ANL, 2012). GHGenius assumed camelina to have similar oil extraction efficiency as canola (96%) based on an industrial survey of canola processing facilities in North America that use mechanical pressing followed by hexane extraction. However, for a farm-scale biodiesel production facility, hexane extraction is usually not economically feasible.

The fatty acid profile of the camelina oil showed higher percentages of double and triple bonds (polyunsaturates) (table 2). Polyunsaturates are more susceptible to autooxidation compared to single bonds, leading to rancidity in the oil. Higher amounts of polyunsaturates are shown to increase NO_x emissions during engine tests (Peterson et al., 2000). Producers of biodiesel from oil with high polyunsaturates need to pay attention to the oxydative stability of the biodiesel, as it may not meet ASTM D6751 for the Rancimat test.

Despite higher levels of polyunsaturates, Crowley and Frohlich (1998) showed that camelina oil stored for two years in intermediate bulk containers at ambient temperature had peroxide levels of 4 to 20 mmol kg^{-1}, which was acceptable for raw oil. The presence of natural antioxidants such as polar phenolic compounds (total 128 mg kg^{-1}), α-tocopherol (41 ±8 mg kg^{-1}), γ-tocopherol (710 ±19 mg kg^{-1}), and δ-tocopherol (12 ±3 mg kg^{-1}) in camelina oil facilitates storage stability (Abramovič et al., 2007). Frohlich (1999) showed that camelina biodiesel remained stable against autooxidation for eight months.

The energy input in the camelina crushing process was 1.8 MJ L^{-1} of biodiesel (table 3). GHGenius estimated the crushing energy to be 0.9 MJ L^{-1} of biodiesel, while GREET estimated 0.59 MJ L^{-1} of biodiesel. The GHG emission from the electricity used in camelina crushing was equivalent to 68.4 g CO_2e L^{-1} of biodiesel. Crushing accounted for 2% of the total life cycle GHG emissions. The RFS2 final rule (USEPA, 2013) obtained crushing data from Shonnard et al. (2010). It estimated the GHG emission from camelina crushing to be 64 g CO_2e lb^{-1} of refined oil, compared to 43 g CO_2e lb^{-1} of refined oil in our study. The higher emission is attributed to the hexane extraction assumed in the EPA study.

Camelina had a geometric mean diameter of 0.81 mm and geometric standard deviation of 0.14 mm, compared to canola with a geometric mean diameter of 1.67 mm and geometric standard deviation of 0.13 mm. Camelina seeds were more ellipsoidal, with a diameter along the longer axis of 1.70 mm and a diameter along the shorter axis of 0.4 mm (fig. 1). The average hull thickness of camelina was 0.05 mm, compared to 0.06 mm for canola. This gave a cotyledon to seed volume ratio for camelina of 74%, compared to 90% for canola (eq. 1). Compared to canola, camelina required 23.9% more energy per kg of seed to crush the seeds, and 46.2% more energy per L of oil expelled. The data confirm the proportionality relationship of seed size to energy consumption from equation 2.

In addition to requiring lower crushing energy, canola also had higher oil content. The average oil content of canola was 40.5%, compared to 34.2% for camelina. Of the 40.5% oil in canola, the extraction process removed 31.9%, leaving 8.6% in the meal.

Transesterification

For every 100 g of oil, 22 g of methanol (100% excess) and 2.4 g of sodium methoxide were used in the transesterification reaction. The reaction produced 88.6 g of biodiesel and 35.8 g of crude glycerol. The density of camelina oil was 0.92 g mL^{-1} and that of biodiesel was 0.88 g mL^{-1} at 20°C. The produced biodiesel met the tested ASTM D6751 specifications except for oxidative stability. Higher levels of polyunsaturates in camelina oil (table 2) may be the reason that camelina biodiesel did not meet the ASTM D6751 specification for oxidative stability. However, oxidative stability can be easily corrected with an anti-oxidant additive. The effect of an anti-oxidant additive on the LCA is discussed in the "Effects of transport and additional inputs on LCA results" section.

The electricity required for heating, stirring, and metha-

Table 2. Fatty acid profile (% of total fatty acid) of camelina and canola oil.

	Fatty Acid Chain[a]									
	16:0	18:0	18:1	18:2	18:3	20:0	20:1	20:2	20:3	22:1
Camelina oil	5.4	2.4	16.8	18.8	30.9	1.8	15.2	1.7	1.1	3.5
Canola oil	3.9	2.1	59.3	18.4	7.8	0.0	2.1	0.0	0.0	4.4

[a] 16:0 = palmitic acid, 18:0 = stearic acid, 18:1 = oleic acid, 18:2 = linoleic acid, 18:3 = linolenic acid, 20:0 = arachidic acid, 20:1 = eicosenoic acid, 20:2 = eicosadienoic acid, 20:3 = mead acid, and 22:1 = erucic acid.

Table 3. Energy input and GHG emissions from camelina crushing and transesterification.

Stage	Inputs	Amount[a] per L of biodiesel	Life Cycle Energy	Life Cycle Energy Equivalent (MJ L^{-1} of biodiesel)	g CO_2e Factor	Total g CO_2e L^{-1} of Biodiesel
Crushing	Electricity	0.165 kWh	10.9 MJ kWh^{-1} [b]	1.8	414.6 kWh^{-1} [c]	68.4
Transesterification	Electricity	0.212 kWh	10.9 MJ kWh^{-1} [b]	2.3	414.6 kWh^{-1} [c]	87.9
	Methanol	0.100 kg	34 MJ kg^{-1} [d]	3.4	67.7 MJ^{-1} [e]	230.2
	Sodium methoxide	0.020 kg	31.7 MJ kg^{-1} [f]	0.6	7.9 g^{-1} [f]	158.0
Total				6.3		476.1

Sources: [a]Measured values, [b]Direct unit conversion and USEIA (2013), [c]eGrid (2014), [d]MI (2011) and Wang and Huang (1999), [e]USEPA (2012), and [f]Sheehan et al. (1998).

Table 4. Total energy input and GHG emissions from biodiesel production.

Stage	Life Cycle Energy (MJ L^{-1} of biodiesel)	GHG Emissions (g CO_2e L^{-1} of biodiesel)	Allocation to biodiesel (%)	Allocated Life Cycle Energy: MJ L^{-1} of biodiesel	Allocated Life Cycle Energy: Percentage (%)	Allocated GHG Emissions: g CO_2e L^{-1} of biodiesel	Allocated GHG Emissions: Percentage (%)
Agriculture	13.1[a]	1874.9[a]	24	3.1	34	450	49
Crushing	1.8[b]	68.4[b]	24	0.4	4	16	2
Transesterification	6.3[b]	476.1[b]	89	5.6	62	424	46
Biodiesel combustion	-	21.7[c]	100	-	-	22	2
Total				9.1		912	

Biodiesel total energy output (MJ L^{-1} of biodiesel)[d]	32.7
Net energy ratio (NER)	3.6
GHG emissions from biodiesel production and use (g CO_2e GJ^{-1})	27,890
GHG emissions from 2005 baseline diesel production and use (g CO_2e GJ^{-1})[e]	90,047
Net GHG reduction from biodiesel (%)	69.0

Sources: [a]From table 1 for 433 L of biodiesel ha^{-1}, [b]From table 3, [c]USEPA (2012), [d]Pradhan et. al. (2011), and [e]DOE (2008).

nol recovery during the transesterification process was 2.3 MJ L^{-1} of biodiesel (table 3). GHGenius and GREET estimated the energy to be 1.1 and 0.86 MJ L^{-1} of biodiesel, respectively (GHGenius, 2013b, 2013c; ANL, 2012). Both systems accounted for the energy expended on methanol recovery. However, the form of energy input was different in the three processes. Electricity was used as the only source of energy in this research, whereas GHGenius and GREET used both natural gas and electricity. The life cycle energy value of electricity (table 4) was calculated by dividing the electrical energy use (0.165 kWh = 0.59 MJ) by the electricity generation and distribution efficiency of 33% (USEIA, 2013). Similarly, the methanol life cycle energy equivalent was calculated by dividing the HHV of methanol of 22.7 MJ kg^{-1} (MI, 2011) by its life cycle efficiency of 66.7% (Wang and Huang, 1999).

With 1,570 kg ha^{-1} of camelina yield, 27.4% oil extraction efficiency, and oil to biodiesel conversion rate of 88.6%, 381 kg of biodiesel were produced per hectare. Camelina biodiesel has a density of 0.88. Therefore, each hectare of land with this yield would produce 433 L of biodiesel. This value was used to calculate the energy and emissions per liter of biodiesel from the energy used per hectare of land.

The total energy invested in transesterification was 6.3 MJ L^{-1} of biodiesel (table 3). The transesterification process produced 476.1 g CO_2e L^{-1} of biodiesel and contributed 46% of total GHG emissions. The NO_x and CH_4 emissions from biodiesel combustion were taken from a value in the literature, which was 21.7 g CO_2e L^{-1} of biodiesel (table 4). The CO_2 emission from biodiesel combustion was excluded from the calculation as it is assumed to be biogenic (i.e., CO_2 captured by camelina during photosynthesis). The RFS2 final rule (USEPA, 2013) assumed the design of a camelina biodiesel plant to be similar to that of a soybean biodiesel plant (402 g CO_2e L^{-1} of biodiesel) (USEPA, 2010). The mass-based percent allocation to biodiesel is shown in table 4.

GHG Reduction, NER, and FER

The allocated life cycle energy input for camelina farming was 3.1 MJ L^{-1} of biodiesel (table 4), which was 34% of the total lifecycle energy input for camelina biodiesel. Nitrogen, herbicide, and diesel were the major energy contributors. The GHG emission from camelina farming was 450 g CO_2e L^{-1} of biodiesel, which was 49% of the total emissions. Soil was the biggest contributor of agricultural emission, followed by diesel.

The total energy input for the production of camelina biodiesel was 9.1 MJ L^{-1} of biodiesel, and the total GHG emission was 912 g CO_2e L^{-1} of biodiesel (table 4). The biodiesel production from the farmer's field was 433 L of biodiesel ha^{-1}, and the estimated NER was 3.6 (table 4). This means that one unit of energy (not counting the solar energy captured during photosynthesis) is required to produce 3.6 units of energy in the form of camelina biodiesel. When only the fossil fuels used in the process were included, the FER was 4.2. The FER of petroleum diesel is 0.87 (Sheehan et al., 1998). Thus, camelina biodiesel is about five times more renewable than petroleum diesel.

Likewise, the GHG reduction from the use of camelina biodiesel was 69% (table 4) compared to 2005 baseline diesel. This qualifies camelina biodiesel as an advanced biofuel per EISA (2007). The GHG reduction calculated in this article is lower than the values estimated by Shonnard et al. (2010) (80%) and GREET (80%) (ANL, 2012) but higher than the values calculated by Krohn and Fripp (2012) (37% to 73%) and GHGenius (61.50%) (GHGenius, 2013a).

The RFS2 final rule (USEPA, 2013) did not provide a definite number for the GHG reduction from camelina biodiesel. However, it stated that "the GHG emissions from the camelina-based biodiesel would be similar to the GHG emissions from the soybean-based biodiesel at all stages of the lifecycle but would not result in land use changes as was the case for soy oil as a feedstock." As a result, camelina biodiesel could qualify as an advanced biofuel. The RFS2 final rule also stated that biodiesel produced from camelina oil is included under the same pathways by which biodiesel from soybean oil qualifies (USEPA, 2010).

Effects of Transport and Additional Inputs on LCA Results

The transport of oil or biodiesel was not included in this study, as the biodiesel production, seed crushing facilities, and the point of use were co-located. If that is not the case, then the energy used for transport needs to be added to the LCA inventory. If exact data are not available, then literature values can be used. Sheehan et al. (1998) estimated the energy for oil transport to be 0.20 kJ L^{-1} of biodiesel km^{-1}. ANL (2012) estimated 2.25 kJ L^{-1} of biodiesel km^{-1} for feedstock transport and 3.89 kJ L^{-1} of biodiesel km^{-1} for biodiesel transport. For each MJ of energy from conven-

Table 5. Sensitivity analysis of camelina yield and transport.

	Δ NER	Δ GHG Reduction (%)
Yield increase 112 kg ha^{-1} (100 lbs acre^{-1})	0.10	1.10
Camelina transport (per 100 km)	-0.09	-0.69
Biodiesel transport (per 100 km)	-0.15	-1.19

tional diesel used for transport, 90.0 g CO_2e of GHG is emitted (DOE, 2008).

Use of additives to meet ASTM specifications was also included in the sensitivity analysis. Baynox Plus (pure) was added as anti-oxidant agent to correct the oxidative stability of camelina biodiesel, as it was shown to be effective and was the least expensive option (BAE, 2011). The least amount of Baynox Plus required to meet the ASTM D6751 specification was measured to be 600 ppm. This added 21.28 kJ L^{-1} of biodiesel energy input to the LCA (the energy content of Baynox Plus is equal to that of toluene, per correspondence with the manufacturer, LANXESS Deutschland GmbH, Leverkusen, Germany). When secondary inputs are included in the base case, the NER is calculated using equation 7.

$$\mathrm{NER}' = \frac{E_{output}}{E_{Base} + E_{secondary}} \tag{7}$$

where

NER′ = NER after adding secondary inputs

E_{output} = energy per unit of biodiesel = 32.7 MJ L^{-1} of biodiesel

E_{base} = energy input in base case = 9.1 MJ L^{-1} of biodiesel (from table 4)

$E_{secondary}$ = case-dependent secondary energy inputs not included in base case per L of biodiesel.

For this study, the energy for camelina transport was already included in E_{base}, and there was no oil or biodiesel transport. The only secondary energy added was for the fuel additive, which changed the NER from 3.6 to 3.59. The fuel additive had practically no effect on the final LCA results.

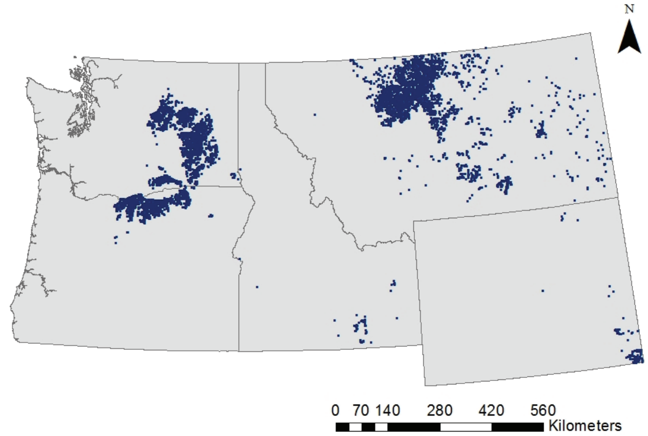

Figure 3. Potential camelina cultivation areas in the PNW.

Although the NER′ has a nonlinear relationship with $E_{secondary}$ (eq. 7), they can be treated as linear in the proximity of a set operating point without introducing a significant error in the results. Table 5 shows the impact of yield and transport on the NER and on GHG reduction near the base case where the NER was 3.6 and the GHG reduction was 69%. The value from table 5 should be added to the base case LCA results in proportion to the change in yield or transport, if any.

Camelina Production Potential

When camelina is planted as a rotational crop in existing wheat land instead of keeping the land fallow, the available land area for camelina production with 19 to 38 cm of rainfall is estimated to be 846,553 ha (2.1 million acres) in the PNW region (figs. 3 and 4). Adjusting for rainfall, the area has potential to produce 1.6 billion kg of camelina seed. The average production per hectare for all rainfall zones weighted by available acres was found to be 1,895.7 kg ha^{-1}. The potential biodiesel production from this land was estimated to be 442.7 million L year^{-1} (117.1 million gal year^{-1}).

The estimated area in this study agrees with literature

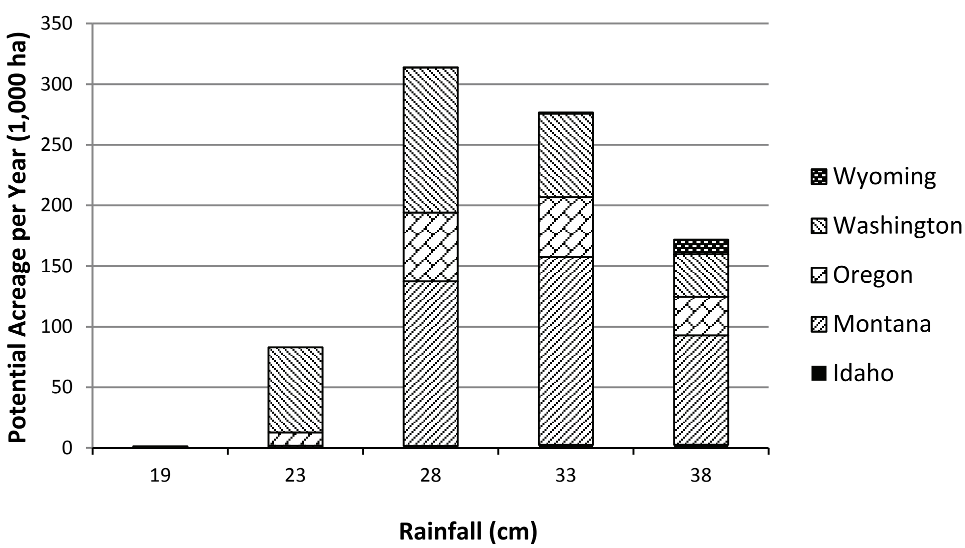

Figure 4. Distribution of potential camelina acreage across the rainfall zones.

Table 6. Potential of camelina meal for livestock feed (kg year^{-1}).[a]

Region	Broiler Chickens	Layers	Beef Cattle	Hogs and Swine	Total
U.S.	3.2×10^9	2.3×10^7	3.8×10^{11}	2.9×10^8	3.9×10^{11}
PNW	1.0×10^8	6.4×10^5	9.1×10^9	2.1×10^6	9.6×10^9

[a] Sources: Jacob et al. (2011), USDA-NASS (2013a, 2013b, 2013c), USDA-ERS (2012), and Platt (2010).

values. Shonnard et al. (2010) estimated that over 2 million ha of camelina can be grown in a sustainable manner with no impact on food supply. This corresponds to 3 billion L of biodiesel per year. Similarly, Johnson and McCormick (2010) projected that 3.6 million ha of wheat/fallow have appropriate climate, soil profile, and market access for camelina production. Based on this land availability, the EPA predicted the availability of approximately 380 million L of camelina-based renewable fuels (USEPA, 2013). However, farmers are apathetic toward camelina due to factors such as volatile camelina market conditions, competition with canola, low yield, etc. (Young et al., 2012).

Camelina Meal

Assuming that the allowed percentage of camelina meal would be fed to the livestock population, the total potential consumption is 40 billion kg year^{-1} in the U.S. and 10 billion kg year^{-1} in the PNW (table 6). There is a potential production of 1.2 billion kg of camelina meal as a co-product. As this is only about 12.1% of the total potential demand for the PNW, it shows that the meal can be consumed in local markets, adding an economic benefit to the biodiesel industry.

Conclusions

This study performed life cycle analysis on camelina biodiesel produced in the PNW region, estimated potential acreage for camelina production, and estimated potential market demand for camelina meal. Data were collected from a camelina farmer, laboratory experiments, life cycle models (GREET and GHGenius), and the literature. Comparative analysis of seed size, fatty acid profile, and biodiesel quality were made between camelina and canola, a close competitor.

The comparative advantage of camelina over canola is its low moisture requirement and short growing season. When rainfall is limited to 38 cm, camelina has a comparative advantage over canola. In higher rainfall areas, canola may be a more lucrative alternative to camelina because of its marketability, higher yield, and favorable seed size. Seed size analysis showed that smaller seeds require more energy for crushing, and experimentation verified that camelina requires 23% more energy compared to canola and has a lower cotyledon to seed volume ratio. Additionally, canola has a better fatty acid profile, with a higher percentage of monounsaturates, compared to camelina, which has a higher percentage of polyunsaturates. Oils with higher polyunsaturates tend to increase NO_x emissions and have reduced oxidative stability. Camelina biodiesel does not meet the ASTM D6751 specification for oxidative stability without the use of an additive.

Despite the higher energy required for crushing, the net energy ratio (NER) and fossil energy ratio (FER) of camelina biodiesel were found to be 3.6 and 4.2, respectively. GHG emissions are reduced by 69% by the use of camelina biodiesel compared to 2005 baseline diesel. Thus, it was concluded that camelina biodiesel meets the GHG reduction criterion of 50% set by the Energy Independence and Security Act (EISA, 2007) to qualify as an advanced biofuel. Camelina has potential production of 1.6 billion kg seeds year^{-1} as a rotational crop in wheat fields in the PNW. The 1.2 billion kg of meal produced as a co-product can supplement 12.1% of the livestock feed in the PNW region.

Acknowledgement

The authors would like to thank the USDA Office of Energy Policy and New Uses for partial funding for this study.

References

Abramovič, H., Butinar, B., & Nikolič, V. (2007). Changes occurring in phenolic content, tocopherol composition, and oxidative stability of *Camelina sativa* oil during storage. *Food Chem., 104*(3), 903-909. http://dx.doi.org/10.1016/j.foodchem.2006.12.044.

ANL. (2012). GREET model. Argonne, Ill.: Argonne National Laboratory, Transportation Technology R&D Center. Retrieved from http://greet.es.anl.gov/.

ASABE. (2012a). S319.4: Method of determining and expressing fineness of feed materials by sieving. St. Joseph, Mich.: ASABE.

ASABE. (2012b). S352.2: Moisture measurement—Unground grain and seeds. St. Joseph, Mich.: ASABE.

ASTM. (2012). D6751-12: Standard specification for biodiesel fuel blend stock (B100) for middle distillate fuels. West Conshohocken, Pa.: American Society for Testing and Materials.

BAE. (2011). Comparison of oxidative stability additives for biodiesel. Biodiesel TechNote. Moscow, Idaho: University of Idaho, Department Biological and Agricultural Engineering. Retrieved from http://web.cals.uidaho.edu/biodiesel/files/2012/11/Oxidativestability.pdf.

Berhow, M., Polat, U., Glinski, J., Glensk, M., Vaughn, S. F., Isbell, T., Ayala-Diaz, I., Marek, L., &Gardner, C. (2013). Optimized analysis and quantification of glucosinolates from *Camelina sativa* seeds by reverse-phase liquid chromatography. *Ind. Crops Prod., 43*, 119-125. http://dx.doi.org/10.1016/j.indcrop.2012.07.01843.

Cappellozza, B. I., Cooke, R. F., Bohnert, D. W., Cherian, G., & Carroll, J. A. (2012). Effects of camelina meal supplementation on ruminal forage degradability, performance, and physiological responses of beef cattle. *J. Animal Sci., 90*(11), 4042-4054. http://dx.doi.org/10.2527/jas.2011-4664.

Crowley, J. G., & Frohlich, A. (1998). Factors affecting the composition and use of camelina. Dublin, Ireland: Teagasc. Retrieved from www.teagasc.ie/research/reports/crops/4319/eopr-4319.pdf.

DOE. (2008). Development of baseline data and analysis of life cycle greenhouse gas emissions of petroleum-based fuels. Pittsburgh, Pa.: U.S. Department of Energy, National Energy Technology Laboratory.

EISA. (2007). Energy Independence and Security Act of 2007 (Public Law 110-140). Washington, D.C.: U.S. Government Printing Office. Retrieved from www.gpo.gov/fdsys/pkg/

PLAW-110publ140/pdf/PLAW-110publ140.pdf.
EFSA. (2008). Glucosinolates as undesirable substances in animal feed. *J. EFSA, 590*, 1-76, doi: 10.2903/j.efsa.2008.590. Parma, Italy: European Food Safety Authority.
eGrid. (2014). eGrid 9th ed. ver. 1.0, 2010 summary table. Washington, D.C.: U.S. Energy Information Administration. Retrieved from www.epa.gov/egrid.
Ehrensing, D., & Guy, S. O. (2008). Camelina. EM 8953-E. Corvallis, Ore.: Oregon State University Extension. Retrieved from http://extension.oregonstate.edu/gilliam/sites/default/files/Camelina_em8953-e.pdf.
Frohlich, A. (1999). Storage stabilities of fuel-grade camelina, sunflower, and rapeseed methyl esters. Dublin, Ireland: Teagasc. Retrieved from www.teagasc.ie/energy/research/pdf_files storage_stability_biofuels.pdf.
Gesch, R. W., & Cermak, S. C. (2011). Sowing date and tillage effects on fall-seeded camelina in the northern corn belt. *J. Agron., 103*(4), 980-987. http://dx.doi.org/10.2134/agronj2010.0485.
GHGenius. (2013a). GHGenius: A model for lifecycle assessment of transportation fuels. Ottawa, Ontario: Natural Resources Canada. Prepared by $(S\&T)^2$ Consultants, Inc., Delta, British Columbia, Canada. Retrieved from www.ghgenius.ca.
GHGenius. (2013b). GHGenius model 4.03: Volume 1. Model background and structure. Ottawa, Ontario: Natural Resources Canada. Prepared by $(S\&T)^2$ Consultants, Inc., Delta, British Columbia, Canada. Retrieved from www.ghgenius.ca/reports/GHGenius403Volume1.pdf.
GHGenius. (2013c). GHGenius model 4.03: Volume 2. Data and data sources. Ottawa, Ontario: Natural Resources Canada. Prepared by $(S\&T)^2$ Consultants, Inc., Delta, British Columbia, Canada. Retrieved from www.ghgenius.ca/reports/GHGenius403Volume2.pdf.
Gugel, R. K., & Falk, K. C. (2006). Agronomic and seed quality evaluation of *Camelina sativa* in western Canada. *Canadian J. Plant Sci., 86*(4), 1047-1058. http://dx.doi.org/10.4141/P04-081.
Hammond, E. G. (1991). Organization of rapid analysis of lipids in many individual plants. In H. F. Linskens, & J. F. Jackson (Eds.), *Modern Methods of Plant Analysis, Vol. 12: Essential Oils and Waxes* (pp. 321-330). Berlin, Germany: Springer-Verlag.
Hergert, G. W., J. Margheim, J., Pavlista, A., Lyon, D., Hazen, A., Martin, D., Supalla, R., & Thompson, C. (2011). Yields and ET of deficit to fully irrigated canola and camelina. In *Proc. 23rd Ann. Central Plains Irrigation Conf.* (pp. 190-198). Colby, Kans.: Central Plains Irrigation Association.
Hill, J., Nelson, E., Tilman, D., Polasky, S., & Tiffany, D. (2006). Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proc. Natl. Acad. Sci., 103*(30), 11206-11210. http://dx.doi.org/10.1073/pnas.0604600103.
Howard, H. K., & Daun, J. K. (1991). Oil content determination in oilseeds by NMR: Method of the Canadian Grain Commission Grain Research Laboratory. Winnipeg, Manitoba, Canada: Agriculture Canada.
Huo, H., Wang, M., Bloyd, C., & Putsche, V. (2008). Life cycle assessment of energy and greenhouse gas effects of soybean-derived biodiesel and renewable fuels. ANL/ESD/08-2. Argonne, Ill.: Argonne National Laboratory, Energy System Division. Retrieved from www.transportation.anl.gov/pdfs/AF/467.pdf.
IPCC. (2006). Chapter 11: N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. In *IPCC Guidelines for National Greenhouse Gas Inventories* (vol. 4, pp. 11.1-11.54). Geneva, Switzerland: Intergovernmental Panel of Climate Change.
Jacob, J., Pescatore, T., & Cantor, A. (2011). How much will my chickens eat? Lexington, Ky.: University of Kentucky Extension. Retrieved from www2.ca.uky.edu/agc/pubs/ASC/ASC191/ASC191.pdf.
Johnson, S., & McCormick, M. (2010). Camelina: An annual cover crop under 40 CFR Part 80 Subpart M. Memorandum dated 5 November 2010.
Krohn, B. J., & Fripp, M. (2012). A life cycle assessment of biodiesel derived from the "niche filling" energy crop camelina in the USA. *Appl. Energy, 92*, 92-98. http://dx.doi.org/10.1016/j.apenergy.2011.10.025.
Matthäus, B., & Luftmann, H. (2000). Glucosinolates in members of the family Brassicaceae: Separation and identification by LC/ESI-MS-MS. *Agric. Food Chem., 48*(6), 2234-2239. http://dx.doi.org/10.1021/jf991306w.
McVay, K. A., & Lamb, P. F. (2004). Camelina production in Montana. Bozeman, Mont.: Montana State University Extension. Retrieved from http://store.msuextension.org/publications/AgandNaturalResources/MT200701AG.pdf.
MDA. (2012). Approved uses of camelina meal in feed. Helena, Mont.: Montana Department of Agriculture. Retrieved from http://agr.mt.gov/agr/Programs/Commodities/Camelina/FeedUses.html.
MI. (2011). Properties of methanol. Alexandria, Va.: Methanol Institute. Retrieved from http://methanol.org/Technical-Information/Properties-of-Methanol.aspx.
Painter, K. (2011). Camelina: Cost and returns estimates for Idaho. Moscow, Idaho: University of Idaho Extension.
Painter, K., & Miller, E. (2009). 2009 Crop rotation budgets, over 18″ precipitation zone under direct seeding (no-till), eastern Washington. Pullman, Wash.: Washington State University Extension.
Pavlista, A. D., & Baltensperger, D. D. (2007). Phenology of oilseed crops for biodiesel in the high plains. In J. Janick, & A. Whipkey (Eds.), *Issues in New Crops and New Uses* (pp. 60-63). Alexandria, Va.: ASHS Press.
Pavlista, A. D., Isbell, T. A., Baltensperger, D. D., & Hergert, G. W. (2011). Planting date and development of spring-seeded irrigated canola, brown mustard, and camelina. *Ind. Crops Prod., 33*(2), 451-456. http://dx.doi.org/10.1016/j.indcrop.2010.10.029.
Peterson, C. L., Taberski, J. S., Thompson, J. C., & Chase, C. L. (2000). The effect of biodiesel feedstock on regulated emissions in chassis dynamometer tests of a pickup truck. *Trans. ASAE, 43*(6), 1371-1381. http://dx.doi.org/10.13031/2013.3034.
Pilgeram, A. L., Sands, D. C., Boss, D., Dale, N., Wichman, D., Lamb, P., Lu, C., Kirkpatrick, M., Thompson, B., & Johnson, D. L. (2007). *Camelina sativa*, a Montana omega-3 and fuel crop. In J. Janick, & A. Whipkey (Eds.), *Issues in New Crops and New Uses* (pp. 129-131). Alexandria, Va.: ASHS Press. Retrieved from www.hort.purdue.edu/newcrop/ncnu07/pdfs/pilgeram129-131.pdf.
Platt, T. (2010). Feeding your market hogs: A youth guide. Pullman, Wash.: Washington State University Extension.
Pradhan, A., Shrestha, D. S., Van Gerpen, J., & Duffield, J. (2008). The energy balance of soybean oil biodiesel production: A review of past studies. *Trans. ASABE, 51*(1), 185-194. http://dx.doi.org/10.13031/2013.24203.
Pradhan, A., Shrestha, D. S., McAloon, A., Yee, W., Haas, M., & Duffield, J. A. (2011). Energy life cycle assessment of soybean biodiesel revisited. *Trans. ASABE, 54*(3), 1031-1039. http://dx.doi.org/10.13031/2013.37088.
Ramírez-Verduzco, L. F., Rodríguez-Rodríguez, J. E., & Jaramillo-Jacob, A. D. R. (2012). Predicting cetane number, kinematic viscosity, density, and higher heating value of biodiesel from its fatty acid methyl ester composition. *Fuel, 91*(1), 102-111. http://dx.doi.org/10.1016/j.fuel.2011.06.070.

Schillinger, W. F., Papendick, R. I., & McCool, D. K. (2010). Soil and water challenges for Pacific Northwest agriculture. In T. M. Zobeck, & W. F. Schillinger (Eds.), *Soil and Water Conservation Advances in the United States* (pp. 47-80). Madison, Wisc.: SSSA.

Schuster, A., & Friedt, W. (1998). Glucosinolate content and composition as parameters of quality of camelina seed. *Ind. Crops Prod., 7*(2-3), 297-302. http://dx.doi.org/10.1016/S0926-6690(97)00061-7.

Shapouri, H., Duffield, J. A., & Wang, M. (2002). The energy balance of corn ethanol : An update. AER-813. Washington, D.C.: USDA Office of Energy Policy and New Uses. Retrieved from www.transportation.anl.gov/pdfs/AF/265.pdf.

Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., & Shapouri, H. (1998). Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. NREL/SR-580-24089. Golden, Colo.: National Renewable Energy Laboratory. Retrieved from http://dx.doi.org/10.2172/658310.

Shonnard, D. R., Williams, L., & Kalnes, T. N. (2010). Camelina-derived jet fuel and diesel: Sustainable advanced biofuels. *Environ. Prog. Sustain. Energy, 29*(3), 382-392. http://dx.doi.org/10.1002/ep.10461.

UI. (2012). Crop enterprise budgets 2012. Moscow, Ida.: University of Idaho Extension. Retrieved from http://web.cals.uidaho.edu/idahoagbiz/enterprise-budgets/.

USDA-ERS. (2012). Hogs and pork. Washington, D.C.: USDA Economic Research Service. Retrieved from www.ers.usda.gov/topics/animal-products/hogs-pork/background.aspx#.UaalhJy0T-U.

USDA-FSA. (2011). Fact sheet: BCAP project area 6 (July 2011). Washington, D.C.: USDA Farm Service Agency. Retrieved from www.fsa.usda.gov/Internet/FSA_File/bcap_6_fact_sheet.pdf.

USDA-NASS. (2013a). United States and Canadian cattle and sheep. Washington, D.C.: USDA National Agricultural Statistics Service.

USDA-NASS. (2013b). Chickens and eggs (March 2013). Washington, D.C.: USDA National Agricultural Statistics Service.

USDA-NASS. (2013c). United States and Canadian hogs (March 2013). Washington, D.C.: USDA National Agricultural Statistics Service.

USDA-NRCS. (2012). Geospatial data gateway. Washington, D.C.: USDA Natural Resources Conservation Service. Retrieved from http://datagateway.nrcs.usda.gov/.

USDA-NRCS. (2013). Plants database: *Camelina sativa* (L.) Crantz ssp. *sativa*, gold-of-pleasure. Washington, D.C.: USDA Natural Resources Conservation Service. Retrieved from http://plants.usda.gov/core/profile?symbol=CASAS2.

USEIA. (2013). U.S. electricity flow. Washington, D.C.: U.S. Department of Energy, Energy Information Agency. Retrieved from www.eia.gov/totalenergy/data/monthly/pdf/flow/electricity.pdf.

USEPA. (2010). Regulation of fuels and fuel additives: Changes to renewable fuel standard program: Final rule. *Federal Register, 75*(58), 14670-14903.

USEPA. (2012). Lifecycle greenhouse gas (GHG) impacts calculations (February 1, 2010). Washington, D.C.: U.S. Environmental Protection Agency. Retrieved from www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2005-0161-3174.

USEPA. (2013). Regulation of fuels and fuel additives: Identification of additional qualifying renewable fuel pathways under the renewable fuel standard program. *Federal Register, 78*(43), 14190-14217.

Vigon, B. W., Tolle, D. A., Cornaby, B. W., Battelle, H. C., Harrison, C. L., Boguski, T. L., Hunt, R. G., & Sellers, J. D. (1993). Life cycle assessment: Inventory guidelines and principles. EPA/600/R-92/245. Cincinnati, Ohio: U.S. Environmental Protection Agency.

Wang, M. Q., & Huang, H. S. (1999). A full fuel-cycle analysis of energy and emissions impacts of transportation fuels produced from natural gas. ANL/ESD-40. Argonne, Ill.: Argonne National Laboratory. Retrieved from www.transportation.anl.gov/pdfs/TA/13.pdf.

Wysocki, D. J., Chastain, T. G., Schillinger, W. F., Guy, S. O., & Karow, R. S. (2013). Camelina: Seed yield response to applied nitrogen and sulfur. *Field Crops Res., 145*, 60-66. http://dx.doi.org/10.1016/j.fcr.2013.02.009.

Young, D. L., Galinato, S. P., & Marsh, T. L. (2012). Feasibility of camelina as a biofuels feedstock in Washington. Pullman, Wash.: Washington State University. Retrieved from http://impact.wsu.edu/marshfiles/camelinareport2-14-12final.pdf.