CrossMark

ORIGINAL PAPER

Comparative Farm-Gate Life Cycle Assessment of Oilseed Feedstocks in the Northern Great Plains

Devin Moeller[1] · Heidi L. Sieverding[1] · James J. Stone[1]

Abstract Second generation biofuel feedstocks such as carinata (*Brassica carinata* L. Braun) and camelina (*Camelina sativa* L. Crantz) offer unique advantages over traditional bioenergy alternatives, such as canola (*Brassica napus* L.) or soybean (*Glycine max* L. Merr). As the global demand for food and livestock feed continues grow, the utility of canola and soybeans as a bioenergy resource is uncertain. This work focused on two oilseed alternatives for use as biofuel feedstocks across the semi-arid region of the Northern Great Plains. This analysis compared the geographic distribution of current yields, assessed the environmental impacts, and evaluated the energetic benefit of oilseed production at aggregated crop management zone levels through a life cycle assessment (LCA) methodology. The average regional LCA results for environmental and energetic impacts for carinata and camelina compared favorably to canola and soybeans and were found to represent sustainable biofuel feedstock alternatives for the study region. The estimated climate change impact of carinata and camelina offered a substantial benefit over that of canola and soybeans. The regional results for freshwater and marine eutrophication potential and the net energy results of carinata and camelina also compared favorably to canola and soybeans. The most environmentally and energetically beneficial feedstock varied based on geographic location within the region. Soybeans tended to perform well in southeastern South Dakota, canola performed well in northeastern North Dakota, and camelina and carinata remained strong alternatives comparatively across the region.

Introduction

Biofuel production across the United States (US) has increased exponentially over the last decade. From 2007 to 2016, the production of biodiesel has increased by an average of one billion liters (GL) annually EIA (2017). The US Renewable Fuel Standards (RFS) program established domestic biomass-based diesel annual production requirements for 2017 at 7.5 GL (EPA 2016), a 28% increase from 2016 biodiesel production levels (EIA 2017). Projections estimate a steady world-wide growth of 25% from current global biodiesel production levels to over 41 GL by 2025 (OECD-FAO 2017). As inputs to the production of biodiesel, vegetable oil feedstocks have remained relatively static over time, with soybean (*Glycine max* L. Merr) and canola (*Brassica napus* L.) oils accounting for 71 and 15% of US production inputs (EIA 2017). The bulk (71%) of this biofuel capacity is concentrated within five traditionally agriculturally centric states (Illinois, Indiana, Iowa, Kansas, and Missouri). However, given the environmental concerns of feedstock production and potential displacement of food and feed production (Ajanovic 2011; Escobar et al. 2009; Pimentel and Patzek 2005; Tilman et al. 2009; Youngs and Somerville 2014), the development of alternative feedstock resources throughout the US could support the near-term

✉ James J. Stone
James.Stone@sdsmt.edu

[1] Department of Civil and Environmental Engineering, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA

Springer

RFS growth requirements. As biodiesel production increases in response to energy security concerns (Jacobson 2009), environmental issues (Hill et al. 2006; Joly et al. 2015; Kim and Dale 2003, 2005), and domestic initiatives incorporating economic development programs (Dale et al. 2014; Hull et al. 2014), the evaluation of viable feedstock alternatives is necessary to ensure production sustainability. However, due to natural geographic and climatic variability, there is unlikely to be a 'one-size-fits-all' solution to sustainable feedstock production. Regionally diversifying biofuel feedstock production to leverage agro-ecological strengths will improve energy security and reduce environmental impacts.

Various oilseed varieties and cultivars bred for biofuel production, such as carinata (*Brassica carinata* L. Braun) and camelina (*Camelina sativa* L. Crantz), can be produced in marginal, semi-arid agricultural zones and offer benefits over traditional feedstocks. Carinata, camelina, and canola are in the *Brassicaceae* (mustard and cabbage) family but have varying oil acidic profiles, agricultural production traits, and intended uses; while soybeans are legumes which fix atmospheric nitrogen (N) and exhibit lower seed oil content. However, soybeans do not begin to actively fix atmospheric N until root rhizomes have developed. As a result, N fertilizer is often applied to soybeans to support initial plant growth.

Carinata, commonly referred to as Ethiopian mustard, is particularly well suited to production in semi-arid regions and produces a larger seed size relative to other *Brassicas*, with high oil content and beneficial oil and harvestability characteristics (AAFC 2014; Agrisoma 2015; Seepaul et al. 2015). The acidic profile of carinata oil has a high erucic acid (C_{22}:1) content which provides desirable biofuel characterists (Bouaid et al. 2009; De Domenico et al. 2016). Carinata is currently under consideration as a pathway for renewable fuel under the US RFS program 40 CFR Part 80: Regulation of Fuels and Fuel Additives, Subpart K and M.

Camelina, known commonly as false flax, grows optimally in temperate climate zones. Camelina has an oil content ranging from 30 to 40% of the seed grain and is notable for its high rate of omega-3 fatty acids, omega-9 fatty (gondoic) acid, and anti-oxidizing agents (Vitamin E) (El Bassam 2010; Moser 2010). Camelina, however, has a very small grain size and is susceptible to shatter and yield loss during harvest. Camelina is an approved renewable pathway for biodiesel, renewable diesel, biojet fuel, heating oil, naphtha, and propane (LPG) production under the US RFS program.

Canola is a rapeseed cultivar with a low erucic acid content developed to address Canadian dependence on imported edible oils (MacWilliam et al. 2016). Canola production in western Canada has evolved to include various food and industrial uses; as an oilseed biofuel feedstock it globally ranks second, behind soybeans (EIA 2016). The yield, environmental performance, and energy profile of canola

has improved over time, however, the demand for canola cooking oils and global prices have also acutely increased (Bentivoglio et al. 2014; Gui et al. 2008; Rulli et al. 2016). Soybean production, as a biofuel feedstock, began commercially in the 1990s and has become the benchmark by which other biodiesel feedstocks are measured (Sieverding et al. 2015). Soybean yields are the highest within the US corn-belt (NASS 2017) and have global price linkages to protein demand and biofuel production (Ajanovic 2011). In the northern Great Plains (NGP), soybean production often occurs in prime agricultural areas to support corn production and maximize rotational economics. The food demand for soybeans is high; as a result, the long-term viability of soybean as biofuel feedstock is questionable unless robust non-food cultivars are developed.

Recent biofuel production life cycle assessment (LCA) literature (Li and Mupondwa 2014; Shonnard et al. 2010; Sieverding et al. 2016b) points to carinata and camelina as promising dryland oilseed feedstocks for biodiesel production, resulting in lower emission values and reduced energy demand over their oilseed peers. The efficiency of feedstock production is critical to the sustainability of biofuel and bioproduct production. However, agricultural production efficiency varies considerably both spatially and temporally. For example, within the semi-arid NGP, the energy demand of camelina production has been estimated to be between 6 and 31 GJ/ha (Keshavarz-Afshar and Chen 2015; Keshavarz-Afshar et al. 2015b; Petre et al. 2012). This variability is also reflected in the estimated energy return on investment (EROI) across smaller regions such as central Montana where the EROI of a winter wheat and Camelina rotation ranged from 2 to 5.5 (Keshavarz-Afshar et al. 2015a). The agricultural production process is estimated to account for 27–44% of the total energy consumed in bio-based products (Kim and Dale 2003), and as a major contributor to biofuel and bioproduct life cycle impact, the variability of feedstock production and associated impacts needs to be understood.

Spatial LCAs are a relatively recent coupling of geographic information systems (GIS) and LCA models, pioneered by research such as Geyer et al. (2010) on regional differences in biofuel production sustainability. This type of analysis was developed to address spatial variances in ecological systems, climate, productivity, infrastructure, and transport which can affect LCA results. Spatial LCAs enable the inherent geographic differences in agricultural productivity (Nitschelm et al. 2016) to be accommodated. Agricultural production differences have been found to affect the climate change impact of biofuels by up to 34% (Tabatabaie and Murthy 2017). This type of sustainability analysis is a necessary step towards accounting for irregularities, distributions, shortcomings, and resiliencies within global food and fuel production systems. To explore the regional variability of feedstock production due to geographic differences
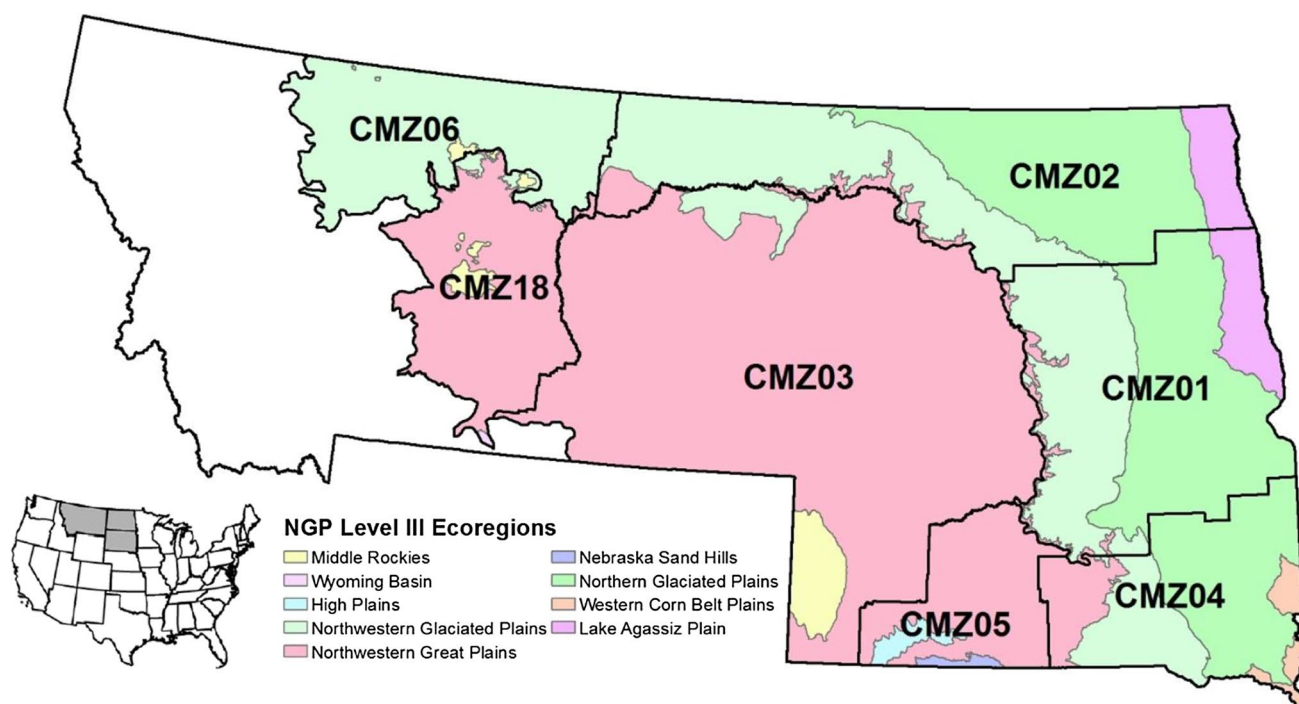
Fig. 1 USDA Crop Management Zones and Level III EPA ecoregions within the Northern Great Plains

in the NGP, this study used seven United States Department of Agriculture (USDA)-defined crop management zones (CMZs) across the NGP (Fig. 1) (NRCS 2017). The dominant ecoregions (EPA 2011) underlying these zones are the Northwestern Great Plains, Northwestern Glaciated Plains, and Northern Glaciated Plains. The Northwestern Great Plains is a largely unglaciated, semi-arid, rolling plain with high summer evapotranspiration rates where agricultural productivity is affected by variable precipitation and limited opportunities for irrigation (EPA 2003). The Northwestern Glaciated Plains is the transition region between rangeland and cropland and contains remarkable terrain and climatic variability (EPA 2003). The Northern Glaciated Plains is characterized by flat and gently rolling glacially-derived landscapes, where shortgrass prairie and temporary seasonal wetlands are supported by sub-humid conditions. Despite the fertile regional soil, agricultural productivity is not consistent (EPA 2003). Yields and the climatic appropriateness of crops vary throughout the NGP due to agro-ecoregional differences. Overall, NGP agricultural production is affected by inconsistent moisture within the growing season. For most of the NGP, dryland production is the norm because surface and ground water resources for irrigation are not economically available. As a result, producers must select agricultural management practices and crops that are agro-ecologically appropriate to sustain production. This research built upon existing literature to conduct a regional LCA incorporating agricultural output (yields) and input

(seeding rate, fertilizer, and agro-chemical) level to identify feedstock impact variability. This comparative assessment evaluated the life cycle environmental impacts and cumulative energy demand of no-till carinata, camelina, canola, and soybean production variability within the NGP states of North Dakota (ND), Montana (MT), and South Dakota (SD).

Materials and Methods

Goal and Scope Definition

The analytical goal was to develop a spatial LCA that incorporated NGP yield variability, agricultural input ranges, and the resulting environmental and energetic impacts of production. This study assessed four oilseed feedstocks across seven contiguous USDA CMZs within the crop producing regions of three states (ND, MT, and SD) (Fig. 1).

The comparative assessment evaluated the production of oilseeds carinata and camelina as alternatives to traditional biofuel feedstocks, canola and soybean. Utilizing mass allocation, this assessment encompassed both the environmental and energy aspects of feedstock production. First, it examined three environmental factors commonly affected by agricultural production practices: (1) climate change potential (g CO_2 eq per kg oilseed), (2) freshwater eutrophication potential (g P eq per kg oilseed), and (3) marine eutrophication potential (g N eq per kg oilseed). Second, the energy

balance of each production system was evaluated utilizing a net energy analysis (NEA) framework (Hall et al. 2011; Murphy et al. 2011a, b, 2016,) to estimate the net energy (NE) and EROI for each oilseed feedstock. The NEA applied in this context evaluated the net energy balance of each feedstock (Eq. 1) and the energy efficiency (Eq. 2), where the inputs and the farm-level production processes are compared via a common energy unit, in gigajoules (GJ).

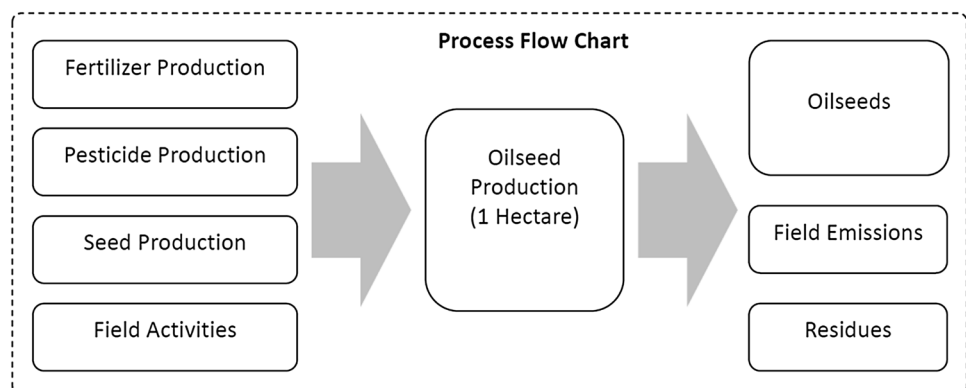$$\text{Net Energy (NE)[GJ]} = \text{Energy Output [GJ]} - \text{Energy Input [GJ]} \quad (1)$$

$$\text{Energy Return on Investment (EROI)[unitless]}$$
$$= \frac{\text{Energy Output [MJ]}}{\text{Energy Input [MJ]}} \quad (2)$$

The system boundary included oilseed production at the farm-level (cradle-to-farm-gate) (Fig. 2). The assessment
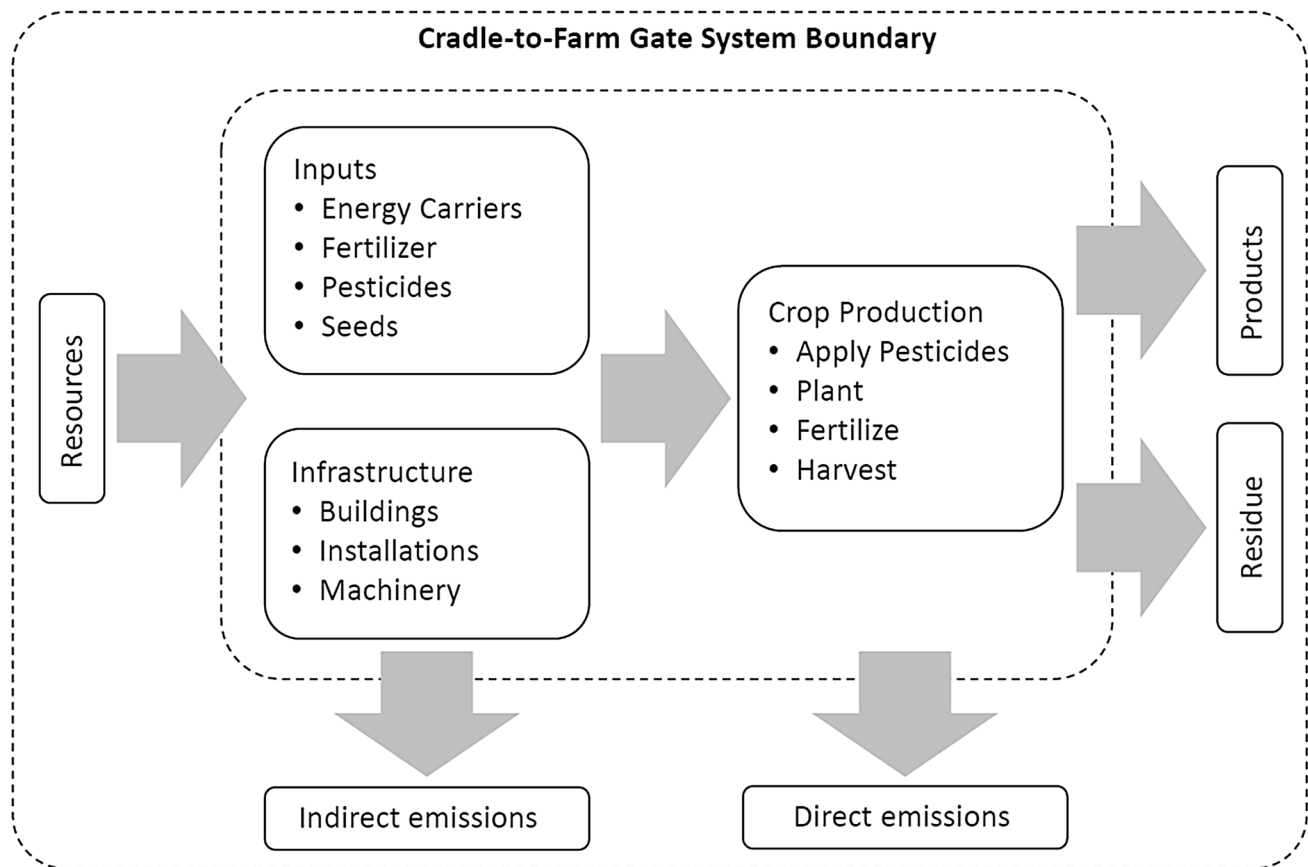
Fig. 2 Cradle-to-Farm-Gate system boundary

Fig. 3 Process flow chart for oilseed production

included the manufacture of fertilizer, pesticides, and seeds as inputs to the farming process and a generalized production system that excluded crop rotations, indirect and direct land use, labor, and transportation to elevator storage (Fig. 3). Because crop rotations are highly variable within the study region and difficult to track, they were omitted from the analysis to better enable selective comparison of feedstock production impacts. Labor was assumed to be similar between the oilseed feedstock types and was not a variable within the metrics calculated. Elevator storage and associated transport was defined as beyond the farm-gate system boundary. The potential land use changes due to evolving versus established crops are fundamentally different. Land use impacts were excluded because the goal was to compare feedstock farm-gate production, not the impacts of crop introduction or expansion. The two dedicated oilseed feedstocks (camelina and carinata) evaluated in this study are proposed as alternatives to the wheat-fallow rotation, therefore it is assumed that the oilseed crops do not displace any other alternative crop rotation system (Keshavarz-Afshar and Chen 2015). In contrast, canola and soybeans have established production areas, inputs, and uses (Kim et al. 2009; Kim and Dale 2003, 2005; Sieverding et al. 2016a). Regional production areas were assumed to be constant for the purposes of this analysis. To enable comparison of oilseed traits, a no-till farm management practice was assumed throughout the study region for all feedstocks.

Life Cycle Inventory

The cradle-to-farm-gate LCA evaluated no-till production of four oilseed feedstocks (canola, soybean, carinata, and camelina) within each of the selected NGP CMZs. SimaPro (v8.0) (PRéConsultants 2016) and ReCiPe midpoint (E) characterization methodology (Goedkoop et al. 2009) was used to estimate the environmental impact. The ReCiPe method was selected to represent a global perspective on feedstock production. Due to similarities between CMZs with respect to characteristics such as population densities and temperate climate, the environmental impact categories

can be applied to the feedstock production processes without affecting the validity of results (Goedkoop et al. 2009; Owsianiak et al. 2014). EcoInvent (v3.0) was employed as the default database library for materials and processes included in the analysis. Within the LCA boundary, inputs from the technosphere included in the production process were assigned to four broad categories: (1) field activities, (2) fertilizers, (2) pesticides, and (4) seed production (Fig. 3).

The general field activities in the assessment were the application of plant protection products, planting, broadcast fertilizing, and direct combine harvesting (SI Fig. 1). The assignment of field activities was allocated per hectare. The production of fertilizer in the analysis covered the manufacture of urea (N), diammonium phosphate, and potassium chloride (K_2O) and transport to the farm. These fertilizer compounds were selected because they are representative of US domestic use and fertilizer products (ERS 2016; Zgola et al. 2016). Nitrogen was assumed to constitute approximately 46% of urea compounds. Glyphosate was assumed to be used in pre-planting burn down and pre-harvest desiccation. Post-emergence weed, insect, and fungal control is highly variable; therefore, a general pesticide manufacturing impact and process within EcoInvent was used to simulate the impact of post-emergence pest control. The application rates of both fertilizers and pesticides were measured in terms of kilograms per hectare. In addition to general pesticide use, seed coatings containing pyrethroid compounds were included for canola, soybean, and carinata because patented commercial varieties with insecticidal coatings are predominant for these oilseeds. Seed production included the manufacture and transportation of each oilseed variety to the farm. Due to the lack of specific information available in the EcoInvent on oilseed variety manufacturing, production data was generalized for the *Brassicaceae* family, where rapeseed manufacturing was used as a proxy for carinata, camelina, and canola.

Table 1 Weighted average of fertilizer inputs and resulting yield data within the Northern Great Plains

Feedstock	Fertilizer (kg/ha)									Yield (kg/ha)			LHV (MJ/kg)	Energy content of biomass (GJ/ha)		
	Nitrogen (N)			Phosphorous (P_2O_5)			Potassium (K_2O)									
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max		Min	Mean	Max
Canola	110	118	130	20	23	30	25	28	35	875	1527	2375	24	21	37	57
Soybean	19	27	52	41	44	48	24	25	27	397	1909	2535	18	7	34	46
Carinata	29	51	60	6	7	10	1	1	2	1000	2056	2891	18	18	37	52
Camelina	3	5	8	5	16	25	4	14	15	391	1259	1480	23	9	29	34

The average values were weighted by available crop land within each crop management zone (Grady and Nleya 2010; MAES 2017; NASS 2017; NDSU 2017)

Fig. 4 Crop management zone boundaries with each oilseed variety yield and equivalent oil content. (Grady and Nleya 2010; MAES 2017; NASS 2017; NDSU 2017). Oil seed content was applied from Sieverding et al. (2016a)
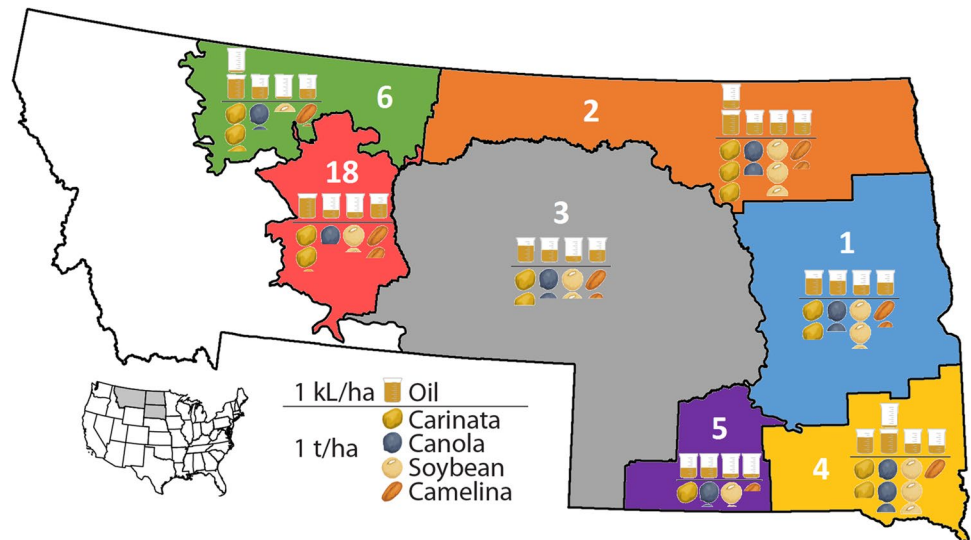
Biomass Production

Regional fertilization and yield data were based on aggregated CMZ statistics, field trials, and available literature (Table 1; Fig. 4). To assess the impacts of oilseed type, no-till agricultural management practices were generalized and applied throughout the region assuming a standardized management practice. The field activities process included: a pre-planting burn down, planting, broadcast fertilizer application, post-emergence pesticide application, and a pre-harvest desiccation followed by a direct combine harvest. The process input levels were modified to reflect the geographic distribution of seeding rates, pesticide application, yield, and fertilization rates (Table 2, SI Fig. 2). Seeding rates for soybeans and canola were

estimated from existing literature (Kim and Dale 2003, 2005; Mousavi-Avval et al. 2011; Sieverding et al. 2015) and regionally adjusted to each CMZ based on regional trial recommendations (Grady and Nleya 2010; MAES 2017; NDSU 2017). The seeding rates for carinata and camelina were obtained from the regional field trial data (Grady and Nleya 2010; MAES 2017; NDSU 2017; Sieverding et al. 2016a) and industry best management practice literature (AAFC 2014; Agrisoma 2015). The resulting average NGP seeding rates for canola, soybeans, carinata, and camelina were 8, 65, 14, and 6 kg/ha, respectively. Seeding rates were reflective of both seed size and optimal plant density differences. The application of pre-emergence and post-emergence pesticides was generalized using active ingredients and application rates

Table 2 SimaPro system inputs and process stages (PRéConsultants 2016)

System inputs & process stages	Unit	Average input
Field activities		
Application of plant protection products, by field sprayer/CH U	ha	3.0
Planting/CH U	ha	1.0
Fertilizing, by broadcaster/CH U	ha	1.0
Combine harvesting/CH U	ha	1.0
Seed production (seeding rate)	kg/ha	27.1
Fertilizer production		
Urea, as N, at regional storehouse/RER U	kg/ha	50.3
Diammonium phosphate, as P_2O_5, at regional storehouse/RER U	kg/ha	22.5
Potassium chloride, as K_2O, at regional storehouse/RER U	kg/ha	17.0
Pesticide production		
Pyrethroid compounds, at regional storehouse/CH U	kg/ha	0.8
Pesticide unspecified, at regional storehouse/RER U	kg/ha	3.0
Glyphosate, at regional storehouse/RER U	kg/ha	2.4

The average input value represents the average oilseed system input per hectare across the NGP region. Field activity inputs were held fixed across each oilseed type, while seeding rate, fertilizer and pesticide production were varied by oilseed and crop management zone across the study area

from the North Dakota Herbicide Compendium (Zollinger et al. 2016) recommendations (SI Fig. 2). It was assumed that pesticide application rates for canola, soybeans, and carinata were 6.2 kg/ha, while camelina was 5.4 kg/ha to account for the lack of seed coating. Canola and soybean yields were estimated based on historical values from the USDA National Agricultural Statistics Service (NASS 2017) and supplemented with regional trial data (Grady and Nleya 2010; MAES 2017; NDSU 2017). Camelina and carinata yields were determined based upon CMZ aggregated field trial data and assigned a 15% yield penalty based on the assumed decline associated with trial production versus commercial production result (AAFC 2014; Agrisoma 2015; Sieverding et al. 2016a). The fertilizer base application rates for soybeans were derived from the historical state-level NASS survey data sets for South Dakota and North Dakota (NASS 2017) for N-P-K levels. However, intrastate application rates across CMZs were geographically adjusted based on field test management recommendations across the region (Grady and Nleya 2010; MAES 2017; NDSU 2017). The regional application rates of fertilizer for canola, carinata, and camelina were estimated from field trial data and existing literature (Fore et al. 2011; Grady and Nleya 2010; Keshavarz-Afshar and Chen 2015; Keshavarz-Afshar et al. 2015b; MAES 2017; NDSU 2017; Shonnard et al. 2010; Sieverding et al. 2016a).

Uncertainty Analysis

Because of the inherent level of uncertainty associated with the assumptions made at each geographic location, and given the variability of material inputs and energy requirements in the farm production process, an uncertainty analysis was conducted across the various CMZs for each oilseed type evaluated. Complying with ISO 14044 suggested guidelines, a Monte Carlo simulation and probability distribution was used to address model variability. A log-normal distribution was assumed for all model parameters based on a SimaPro data pedigree and simulation analysis was conducted for each feedstock type in across the seven CMZs. The impact results were expressed at a 95% confidence interval. The floor for the number of runs for each simulation was set at 1000 with a stop factor set to minimize the standard error of the mean at 0.005. The results for mean, median, standard deviation, and the coefficient of variation are presented in the supplementary information. The results include each CMZ and corresponding feedstock individually and a weighted average across the NGP region (SI Fig. 10–17).

Results and Discussion

The driving factor behind NGP environmental and energy impacts was yield which varied regionally. Oilseed yield performance was most strongly controlled by climatic differences across the region, not management practices. This created agro-ecological 'niches' where different oilseeds were agronomically best suited, thereby improving energy production while reducing environmental burden.

Climate Change Impact

Overwhelmingly, the largest drivers of climate change for NGP oilseed production were field activities and fertilizer use which contributed on average 69% of the total impact. Average NGP results indicated that canola production had the highest climate change impact across the region (648 g CO_2 eq per kg oilseed produced), 8% greater than that of soybean (602 g CO_2 eq per kg soybean) and considerably (81 and 43%) greater than carinata and camelina (359 and 452 g CO_2 per kg oilseed, respectively) (Figs. 5, 6). The contribution of field activities toward total climate change impact ranged from one-third of the total impact (soybean) to 57% for camelina production. Fertilizer contributed 46% of the climate change impact from canola production across

		Total	Field Activities	Fertilizer Production	Pesticide Production	Seed Production	Field Emissions
Canola	Climate change (g CO2 eq)	647.73	33.0%	45.5%	7.0%	1.1%	13.4%
	Freshwater eutrophication (g P eq)	0.33	11.5%	18.1%	13.6%	0.8%	56.0%
	Marine eutrophication (g N eq)	5.20	1.8%	1.7%	0.9%	1.9%	93.6%
Soybean	Climate change (g CO2 eq)	602.30	38.4%	23.8%	8.2%	13.9%	15.6%
	Freshwater eutrophication (g P eq)	0.36	11.6%	10.6%	13.7%	7.4%	56.7%
	Marine eutrophication (g N eq)	6.22	1.7%	0.6%	0.8%	12.0%	84.9%
Carinata	Climate change (g CO2 eq)	358.97	44.9%	24.8%	9.5%	2.5%	18.3%
	Freshwater eutrophication (g P eq)	0.22	12.9%	7.7%	15.2%	1.5%	62.7%
	Marine eutrophication (g N eq)	3.94	1.8%	0.7%	0.9%	3.2%	93.4%
Camelina	Climate change (g CO2 eq)	451.65	57.0%	8.7%	9.8%	1.4%	23.2%
	Freshwater eutrophication (g P eq)	0.34	13.7%	3.6%	15.3%	0.7%	66.7%
	Marine eutrophication (g N eq)	6.14	1.9%	0.2%	0.9%	1.5%	95.6%
	Per 1 kg of product		Percent contribution				

Fig. 5 Summary of weighted NGP environmental impacts results based on specific activities for canola, soybean, carinata and camelina. The results are based on 1 kg of product and include the percent contribution from each activity

Fig. 6 Summary of weighted NGP and crop management zone for climate change impacts results based on specific activity and organized by feedstock type and crop management zone. The results are indicated by g CO_2 eq per 1 kg of product
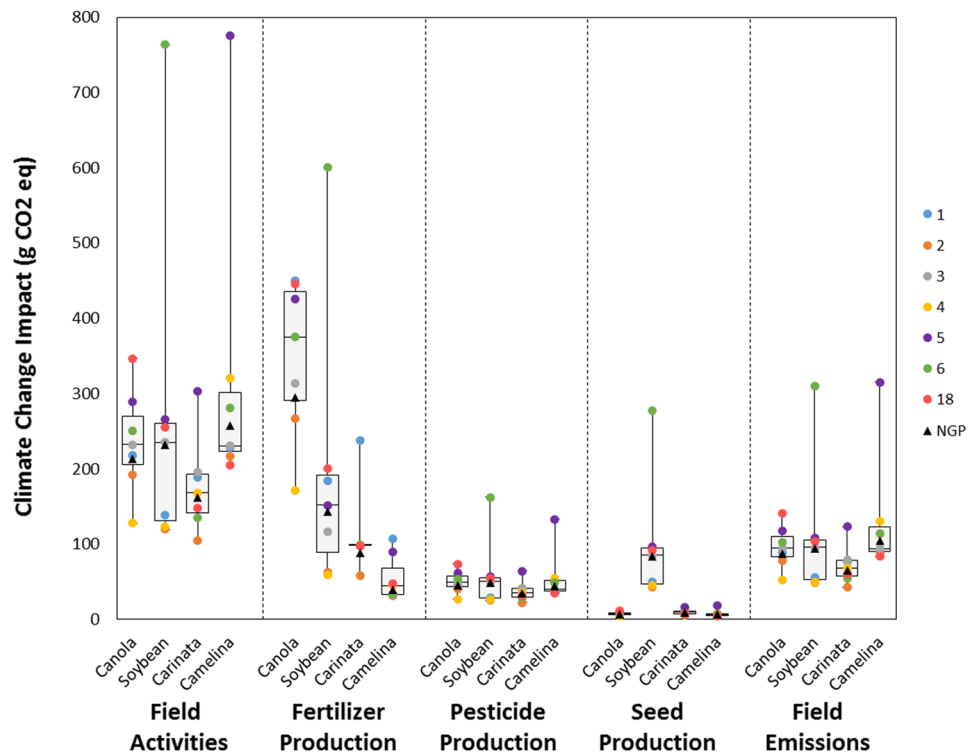
the NGP, nearly double that of soybeans and carinata (24 and 25%), and over a five-fold increase from camelina production (9%). Model input values for field activities were fixed for 1 ha across the study region. For example, the LCA modeling estimated that 79 kg of diesel fuel was directly consumed during the application of plant protection products, planting, fertilizing, and harvesting. As diesel fuel combustion was a substantial factor toward climate change impact, the contribution was proportional to the yield. Given the average canola yield across the NGP of 1.5 t/ha, the level of diesel fuel consumed per unit of production was 20 and 26% lower than that of soybeans and carinata, respectively. Alternatively, while camelina exhibited similar characteristics to that of canola, in terms of fuel consumed per unit of production, the field activity impact toward climate change was magnified (as a percentage of the total) due to the low fertilizer and pesticide input across the NGP. Climate change pesticide contributions were similar across the region (7–10%). If additional cultivation practices (other than no-till) were simulated, then pesticide application rates and associated impacts would be more variable. Seed production, as a function of seeding rate, for canola, carinata, and camelina contributed relatively little toward climate change impact (1–3%) in comparison to soybean seed production (14%) due predominantly to larger seed size and lower energy content of soybean (Table 2). Field emissions from oilseed production ranged from 13 to 23% across the region. The contribution of camelina field emissions was different

than its oilseed peers due to low fertilizer use for production across the region and the disproportional contribution of diesel fuel consumption during farm activities relative to unit production output.

There was intraregional variability in the climate change impact among oilseed type (Fig. 6, SI Figs. 3–9). Canola performed appreciably better in the north and east in terms of a reduction in total climate change impact. In CMZ01 the canola impact remained relatively flat (655 g CO_2 eq per kg oilseed), while in CMZ02 and CMZ04 the impact to climate change (585 and 382 g CO_2 eq per kg oilseed) was reduced by 8 and 41%, respectively. The estimated results fall within the range found by Ukaew et al. (2016) of 242 to 713 g CO_2 eq per kg for canola production in North Dakota. Conversely, the impact of canola production in central Montana (CMZ18) was 57% greater than the NGP climate change impact average. These canola results were not surprising because this oilseed was originally developed for Canadian production; as a result areas agro-ecologically similar were most successful in producing canola. Advancements in crop management practices over time and the adoption of herbicide tolerant cultivars have led to an improved environmental profile. A recent study estimated the climate change impact of canola production at 525 g CO_2 eq per kg oilseed across various soil zones in western Canada, a 5% reduction in emissions from 1990 to 2010 has been reported (MacWilliam et al. 2016). Considering the comparatively large N fertilizer inputs required for canola production

(Table 2), further climate change impact reductions would be dependent upon the development of hybrid varieties more effectively minimizing inputs while increasing yields.

The climate change impact of soybean production across the NGP was minimized in eastern North and South Dakota (CMZ01, CMZ02, and CMZ04), where the average impact was 313 g CO_2 eq per kg production, representing a 37% reduction from the aggregated soybean NGP average. This was because the semi-arid climate of the western portion of the NGP study area was not agro-ecologically suitable for soybean production. This regional climatic variability was typified by northern Montana (CMZ06), where the climate change impact of soybean production was 3.5 times greater (2110 g CO_2 eq per kg oilseed) than the NGP average. As a basis of comparison, Norris et al. (2016) estimated that average soybean production across the US resulted in 421 g CO_2 eq per kg soybean and Kim and Dale (2003) estimated US production in the heartland to produce between 159 and 163 g CO_2 eq per kg of soybean produced. Domestic comparisons illustrate the weighted impact for the majority of soybean production in the US is located where inputs are minimized while the resulting yields are substantially higher given the agro-ecological benefits of geography. Globally, recent assessments of soybean production estimated greenhouse gas emissions in the State of Mato Grosso in central Brazil at 186 g CO_2 eq per kg soybean (Raucci et al. 2015), in Jilin province of China at 263 g CO_2 eq per kg soybean (Knudsen et al. 2010), and in the Golestan province in northern Iran at an average of 957 g CO_2 eq per kg of irrigated soybean (Mohammadi et al. 2013). The average yield among the international studies was 66% greater than that of the NGP, but with varying production inputs and methods relative to the NGP region. In Brazil, the application rate of N fertilizer and the diesel fuel consumed in the production process was less than one-third that of the NGP average. Soybean production in the Jilin province was most impacted by residue burned in field and had a 57% greater application rate of N fertilizer relative to the NGP. Irrigation substantially increased the impact of Iranian soybean production, creating a climate change impact three-times larger than the NGP.

Carinata tended to exhibit similar climate change impact characteristics across the NGP due to its tolerance to moisture variability and drought. Carinata and camelina often performed well where canola and soybeans performed poorly, and vice versa. Particularly, in the high soybean production area of the southeastern NGP (CMZ04), carinata and camelina underperformed their regional average by 6 and 24%, respectively. Much like canola, in general, carinata performed better in the northern areas of the NGP than in the southeastern region (261 versus 419 g CO_2 eq per kg carinata). This was likely due to the development of carinata cultivars for Canadian production, as a result they

are agro-ecologically adapted to cool, short-season northern climates. Northern North Dakota (CMZ02) exhibited the zone of lowest climate change influence for both carinata (234 g CO_2 eq per kg carinata) and canola (380 g CO_2 eq per kg canola), representing a 35 and 16% improvement relative to NGP averages. The northern trend continued for carinata across the region, where production in northern Montana (CMZ06) was reduced by 10%, and central Montana (CMZ18) showed a reduction of 4%, compared to the average across the region. The Canadian-sourced carinata cultivars included in this analysis performed better on average in the NGP (359 g CO_2 eq per kg carinata) than European documented varieties (430 to 890 g CO_2 eq per kg carinata) produced under conventional tillage (D'Avino et al. 2015). As new carinata cultivars are developed for different climates, these trends may change.

Camelina however, showed more inconsistent results than carinata despite similar overall NGP climate change impact trends. The current cultivars of camelina are prone to shatter, which can be exacerbated by the high winds and dry conditions common in the NGP during harvest (Sintim et al. 2016). In addition, the small seed size of camelina increases harvest loss. Camelina climate change impacts were 7% higher than the regional average (452 g CO_2 eq per kg camelina) in northern Montana (CMZ06, 485 g CO_2 eq per kg camelina) and 17% lower in central Montana (CMZ18, 376 g CO_2 eq per kg camelina). These results were within the range of Keshavarz-Afshar et al. (2015b) and Shonnard et al. (2010) findings for central Montana production of approximately 350 and 300–360 g CO_2 eq per kg camelina, respectively. The impact to climate change across the region was driven by camelina production yields which were geographically varied and often resulted in higher per kg impacts due to fertilizer application and field activities. These results were supported in existing literature, where climate change impacts was driven by nitrous oxide emissions to air from farm field activities, through the application of fertilizers, and to a lesser extent by emissions of carbon dioxide from the fuel combustion in farm equipment (Fazio and Monti 2011; Norris et al. 2016). These impacts were further magnified by low yield results in the drought-prone northwestern portion of the NGP relative to the higher moisture corn-belt region. The climate change impacts for the NGP were overall lower than production impacts for other areas of the US, such as the Pacific Northwest where Dangol et al. (2015) estimated camelina production impacts as 517 g CO_2 eq per kg camelina. Development of more shatter-resistant and/or larger seeded cultivars would improve harvestability and reduce climate change impacts of camelina production.

Fig. 7 Summary of weighted NGP and crop management zone for freshwater eutrophication impact results based on specific activity and organized by feedstock type and crop management zone. The results are indicated by g P eq per 1 kg of product
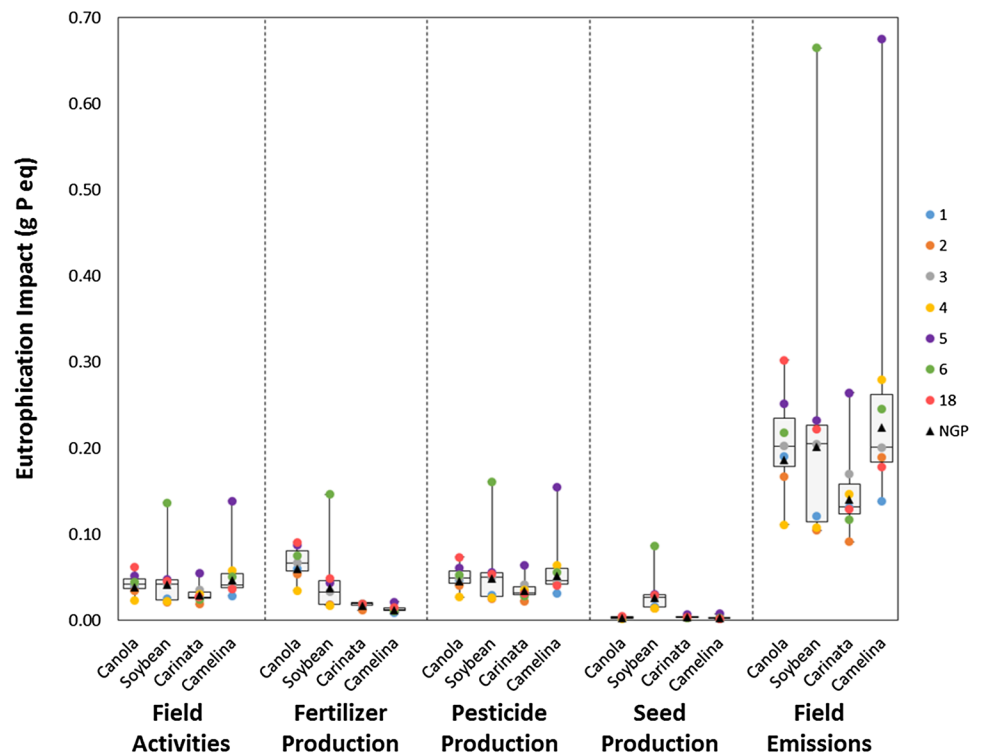
Fig. 8 Summary of weighted NGP and crop management zone for marine eutrophication impact results based on specific activity and organized by feedstock type and crop management zone. The results are indicated by g N eq per 1 kg of product
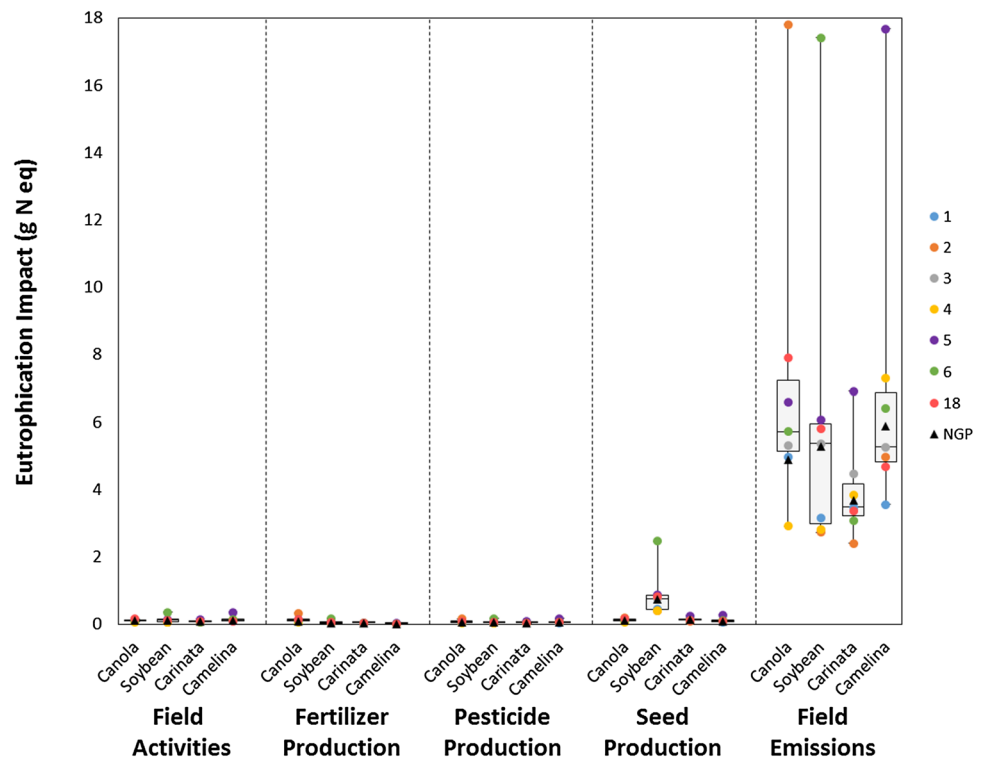
Eutrophication Impact

Nutrient runoff from agricultural activities contributes to eutrophication of regional freshwater resources and coastal marine waters (Smith 2003). The single largest contributor

to eutrophication, both freshwater (g P eq per kg oilseed) and marine (g N eq per kg oilseed), was fertilizer runoff as measured by field emissions (Figs. 7, 8). Among the feedstocks considered, the average NGP freshwater eutrophication impact was 0.31 g P eq per kg of oilseed produced;

farm-level field emissions contributed 61% towards the total impact. Average marine eutrophication levels across the region were 5.38 g N eq per kg oilseed, with field emissions from production representing 92% of the total. Regional soybean production accounts for the highest freshwater eutrophication levels (0.36 g P eq per kg) which were between 6 and 7% higher than that of camelina and canola, and 59% greater than carinata. Within the NGP, the soybean application rate of phosphate fertilizer was nearly double that of canola, three-times greater than camelina, and six-times higher than carinata. Correspondingly, average marine eutrophication levels for soybean production across the NGP were 6.22 g N eq per kg soybean, nearly identical to camelina (6.14 g N eq per kg camelina) but 20 and 58% greater than canola and carinata, respectively. However, the proportional contribution of field emissions toward N eutrophication was consistently 10% lower for soybeans across the region due to lower average N application rates (27 kg/ha) and atmospheric nitrogen fixation (Ribeiro et al. 2015; Zimmer et al. 2016).

Oilseed production in northern North Dakota and northeastern Montana (CMZ02) showed a eutrophication impact reduction of approximately 27% in both P and N equivalent levels in comparison to the NGP average. The results were less impacted by the typical application of fertilizer within each CMZ, but more importantly related to the relatively tight distribution of application rates across the NGP specific to each crop type within the given geographies. For example, the average application rate of N for canola across the NGP was 118 kg/ha with a minimum application rate of 110 kg/ha in central Montana (CMZ018) and a maximum application rate of 130 kg/ha in northeastern Montana (CMZ06) (Table 2; Figs. 7, 8). The low resulting yields for canola within these regions suggested fertilizer use inefficiency relative to carinata and camelina. As a result, eutrophication benefits across the NGP were often greater for emerging oilseed feedstocks. Previous research estimated lower canola eutrophication impacts for North Dakota of 2.4 g N eq per kg using data from high-yielding (3000 + kg/ha), N efficient GMO canola varieties (Strange et al. 2008). Within higher canola yield areas (CMZ04; ~ 2400 kg/ha) of North Dakota, calculated eutrophication impacts (3.11 g N eq per kg canola) were within reasonable range of past estimates.

Among the oilseeds investigated, carinata exhibited the lowest eutrophication levels (0.15 g P eq per kg carinata and 2.56 g N eq per kg carinata); this was a 35% reduction relative to NGP averages and a benefit of approximately 42% compared to the zonal averages of other oilseeds. Soybean and camelina production showed a net benefit within CMZ01 of approximately 41 and 11% in comparison to regional averages, while carinata production eutrophication impacts increased by 17% relative to its NGP average. Soybean production in southeastern South Dakota (CMZ04), where historically the production of soybeans is highest throughout the region, resulted in the lowest eutrophication impact (0.19 g P eq per kg soybean and 3.31 g N eq per kg soybean) and unsurprisingly the highest comparative benefit (47% reduction of impact levels) to NGP average. Similarly, canola production (0.20 g P eq per kg canola and 3.11 g N eq per kg canola) eutrophication levels within the zone (CMZ04) were better (40% reduction) than NGP average. As seen with climate change impacts, northwesterly eutrophication impact improvements were observed for carinata production across the region. While the irregular canola, soybean, and camelina yields and comparatively high fertilizer inputs for canola and soybeans penalized production across north central Montana (CMZ06 and CMZ18). Irrespective of CMZ02 production, the average carinata eutrophication impact levels (0.20 g P eq per kg carinata and 3.46 g N eq per kg carinata) were minimized within these two zones. And, in comparison to their NGP average, resulted in a 10 and 11% reduction in P and N eutrophication levels, respectively.

Unlike climate change, there is not a de facto standardized unit for estimating eutrophication potential and impact levels can be directly tied to two fertilizer elements (N and P), and not just one. As a result, LCA literature values must be carefully interpreted. Among the feedstock included in this study, soybeans have the potential to have the lowest eutrophication levels because of the crop's leguminous nature. Many studies have assumed that for soybeans no N and minimal P were applied to fields (Ng et al. 2013). If no N and minimal P (~ 3 kg/ha) fertilizers were applied and if 'test' yields of over 3000 kg/ha (~ 45 bushels per acre) could be consistently achieved across the NGP, then the freshwater eutrophication impact would be similar to those reported in Brazil and in the range of 0.14 g P eq per kg soybean (Matsuura et al. 2016). However, according to NASS statistics this not the reality within the NGP (NASS 2017) because N fertilizer is used to stimulate soybean growth prior to mycorrhizal activity and P is necessary to sustain mycorrhizal activities and soybean plant growth (Bethlenfalvay et al. 1983). Widespread adoption of soil inoculants to stimulate mycorrhizal activity (Hoeksema et al. 2010) could potentially reduce soybean N fertilizer use in the future. As a result—camelina, carinata, and canola performed more sustainably than soybeans across most of the NGP with respect to eutrophication impacts. Fazio and Monti (2011) investigated the impact of fertilizer toward marine water eutrophication; their results indicated that halving fertilizer use would reduce eutrophication impacts by 28–32% while maintaining similar yield outputs. This recommendation may be applicable elsewhere, but based on this study's results, it would be more impactful if the field 'sweet spot' for fertilizer application was applied. Climate, crop and soil type, slope, and many factors affect NGP fertilization rates and fertilization needs can vary greatly from field to field.

Ultimately, a standardized fertilization recommendation will not ensure sustainable crop production within the NGP. The rate of fertilization alone did not dictate life cycle impacts. If plants use the fertilizer applied to efficiently increase yield, then the life cycle nutrient load impacts of the feedstock and subsequent bioproducts will be reduced.

Cumulative Energy Demand and Net Energy Analysis

The efficient use of energetic inputs as a ratio of the energy produced, and a fundamental understanding of the farm-level impacts within the production process in relation to overall energy consumption is of primary importance for scientists and policy makers in the evaluation of biofuel feedstock alternatives. The best method to evaluate the energy efficiency of biofuel feedstocks has been hotly debated (Hall et al. 2011). The boundary of the farm-gate assessment alleviated co-production allocation issues often encountered in biofuel assessments. While the mass-balance allocation framework and the inclusion of embodied energy in the production process, supported through a systems approach, provided additional insight and incorporated all associated process inputs. Across the NGP, the energy analysis results were consistent with the environmental impact assessments. Based on average cumulative energy demand results, canola production (15.3 GJ/ha) was the most energy intensive feedstock alternative across the region; it was 47% greater than soybeans, 50% higher than carinata, and 107% more than that of camelina production (Fig. 9).

Chemical nitrogen fertilizer production is an energy intensive process (64 MG/kg) and phosphorous fertilizers are often mined from non-renewable resources. Fertilizer production accounted for 57% of the total cumulative energy demand for canola. Comparatively, the impact of fertilizer production was approximately 23% less for soybean and carinata production, while only representing 15% of the total cumulative energy demand for camelina. Conversely, farm-level field activities as a percentage of total energy demand contributed about half the energy demand of soybeans (48%) and carinata (50%) and the majority for camelina (69%) production. Corresponding to N fertilizer use across the region, the non-renewable fossil demand allocation for each feedstock ranged from 86% of the total cumulative energy demand for camelina to 93% for canola production. Reducing N fertilizer use improved EROIs, as shown in camelina results. Based on LHV, the average energetic content of feedstock biomass from production across the region was greatest for carinata (37.0 GJ/ha), followed by canola at 36.7 GJ/ha, soybeans at 34.4 GJ/ha, and finally camelina at 29.0 GJ/ha. The average net energy benefit was highest across the NGP for carinata production (26.8 GJ/ha), approximately 26% higher than canola and camelina, and 14% greater than the net energy returned for soybean production. Comparatively, the average EROIs for soybeans and canola were appreciably lower across the NGP (Fig. 9).

Intraregional energy statistics were dissimilar (SI Fig. 12). Intraregional cumulative energy demands varied geographically by CMZ, but were clustered by oilseed feedstock type. The production of canola and soybeans were most energy intensive across north central Montana (CMZ06). The corresponding net energy derived from canola (13 GJ/ha) and soybean (−5.13 GJ/ha) production, and resulting EROIs (1.82 and 0.58 for canola and soybeans, respectively) within CMZ06, illustrated the disparate values and impact of the spatial distribution of the average NGP yield values. From an energy efficiency perspective, canola performed well relative to its average in the southeastern NGP. Canola energy

		NGP	1	2	3	4	5	6	18	Zone Rank
Net Energy (GJ/ha)	Canola	21.30	18.26	22.52	16.15	41.99	9.31	13.05	6.31	1st
	Soybean	23.57	29.19	34.92	12.69	33.79	9.50	(5.13)	9.15	2nd
	Carinata	26.80	18.94	41.89	18.12	22.12	9.32	29.29	26.11	3rd
	Camelina	21.54	22.82	24.71	22.91	14.46	1.91	17.58	26.07	4th
Energy Ratio (EROI)	Canola	2.39	2.21	2.47	2.06	3.80	1.59	1.82	1.43	
	Soybean	3.18	3.86	4.26	2.21	4.25	1.86	0.58	1.75	
	Carinata	3.63	2.91	5.13	2.85	3.15	2.07	3.61	3.42	
	Camelina	3.91	3.98	4.35	4.12	2.98	1.27	3.45	4.27	

Fig. 9 Summary of net energy and energy ratio results for weighted NGP and crop management zone. The summary compares and ranks each feedstock type by average across the NGP and for each individual crop management zone

efficiency performance decreased as production moved west and north across the region. The highest energy efficiency ratio of 3.80 (MJ/MJ) for canola across the region was in southeast South Dakota (CMZ04), a 59% improvement from its NGP average. The lowest energy efficiency ratio was 1.59 MJ/MJ (33% lower than average across the NGP), located in south central South Dakota (CMZ05). From an energy efficiency perspective, relative to its oilseed peers, canola underperformed the studied alternatives on average across the NGP, and within each CMZ. Intraregional soybean energy efficiency was 34% greater than its regional average in northern North Dakota northeastern Montana (CMZ02) (4.26 MJ/MJ) and southeastern South Dakota (CMZ04) (4.25 MJ/MJ). However, within CMZ02, soybean production ranked second to carinata (5.18 MJ/MJ). Comparatively, domestic assessments for canola and soybeans served as benchmark and pointed to regional results leveraged by geographic location. Fore et al. (2011) assessed US domestic production of canola and soybeans, and found the net energy benefits for canola and soybeans to be 29 GJ/ha and 45 GJ/ha, respectively. These net energy values correspond to energy efficiency ratios (EROIs) of 4 and 11. These national values were consistent with NGP values for canola but not for soybeans. The canola consistency was likely because North Dakota ranks as the largest producer of canola within the US (NASS 2017). The national average inconsistency for soybeans was likely a result of the higher NGP fertilizer use and lower yields.

Both carinata and camelina had high cumulative energy demands across north central (CMZ06) and central Montana (CMZ18) (11 and 8 GJ/ha), but the resulting net energy values were 9% and 21% higher than the regional average of each feedstock. Further, the calculated energy efficiency ratio for carinata (3.61 MJ/MJ) was nearly double that of canola and more than six-time higher that of soybean production in north central Montana (CMZ06). Camelina production energy efficiency was 90% higher than canola and over five-times that of soybeans within the crop management zone. A farm-gate boundary energy analysis provides the first step to insight toward the evaluation of sustainability for the biofuel production system. Murphy et al. (2011a) and Mourad and Walter (2011) found that feedstock production accounted for between 11% and 36% of the total energy inputs in biofuel production where approximately 12% was variable based on geographic location.

Uncertainty Analysis

The uncertainty results indicated that on average across the NGP region, the climate change and freshwater eutrophication impacts of soybean production was volatile throughout the region with a coefficient variation of 54% and 103%, respectively (SI Fig. 10). This variation reflected the uncertainly associated with producing soybeans without irrigation in semi-arid areas and the issues with generalizing crop production across broad climates and geographies (Kim and Dale 2003). The intraregional comparisons of climate change impact uncertainly for soybean production across CMZs remained consistent (SI Fig. 14–20). Conversely, the more climactically acclimated oilseeds exhibited significantly lower variation across all environmental impact measures.

Regional Variability and its Impacts on Sustainability

Incorporating newer oilseed feedstocks such as camelina and carinata into semi-arid NGP agronomic production would likely improve system-level sustainability. In this context, sustainability was defined as the mitigation of environmental impact while maximizing the energy return of production. Within North Dakota and South Dakota, the Missouri River marks the bifurcation between the moisture-rich glaciated plains to the east the semi-arid northwestern Great Plains to the west. The results were markedly different across this gradient. The optimal feedstock(s) were the crop(s) most suitable to the agro-ecoregion. The energy assessment results were often complimentary of the environmental impact results and supported intraregional production which leveraged agronomic and ecological efficiencies. Within the NGP, despite relatively high fertilizer input values, feedstock sustainability improved within zones of higher yields. For example, canola on average had the highest climate change impact values across the region, mediocre eutrophication impacts, and provided the smallest net energy and energy efficiency ratio benefits. In southeastern South Dakota (CMZ04), the environmental impact of canola was reduced by 40% while N application within the region was 3% less than the NGP average (Fig. 6). The resulting large yield improvement relative to a modest reduction in N fertilizer lead to a higher net energy benefit and efficiency ratio (42 GJ/ha and 3.8 MJ/MJ) of zonal canola production. The opposite impact was observed for camelina and carinata, where positive average impact results of production was observed in the northern and western portions of the NGP, or as the production region became less optimal (marginalization increases), these oilseed alternatives outperformed their regional average and traditional food oilseeds. The results illustrate that a regional perspective is necessary to better understand the environmental and energetic trade-offs associated with the agro-ecological impacts of oilseed production. Planting the right crop in the right area focuses on geographic location which leverages the underlying ecoregion, leading to increased sustainability of agricultural crops

as viable feedstock alternatives for utilization in biofuel and bio-based products.

Conclusion

For biofuel production to meet domestic and global demands, appropriate feedstock selection is imperative in minimizing the environmental impact while maximizing the net energy delivery. The presented results underscore the strategic role that crop selection farm management practices have towards future bioenergy production sustainability and viability. The task of minimizing the environmental burden while maximizing energy efficiency is of primary import. Given the results across the NGP, the 'one-size-fits-all' model of feedstock selection was proven to be insufficient. The study results indicated that on average carinata and camelina were beneficial alternatives to canola and soybean production in terms of climate change impacts, eutrophication impacts, and energy efficiency. However, intraregional variability indicated that irrespective of the food versus fuel debate, the food-based feedstocks of soybean and canola performed well in their traditional and highly productive agroecoregions. Until carinata and camelina are commercially introduced, the superior choice for feedstock selection will likely remain inconclusive. This research represents a first step in understanding the complexities of second generation bioenergy production within the NGP.

Compliance with Ethical Standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

AAFC (2014) Carinata production: a guide to best management practices. Agriculture and Agri-Food Canada (AAFC), Ottawa, pp 1–14

Agrisoma (2015) Resonance carinata 2015 production manual: a guide to best management practices US Northern Plains. Agrisoma, Gatineau, Quebec, pp 1–22

Ajanovic A (2011) Biofuels versus food production: does biofuels production increase food prices? Energy 36(4):2070–7076. doi:10.1016/j.energy.2010.05.019

Bentivoglio D, Finco A, Bacchi M.R.P., Spedicato G (2014) European biodiesel market and rapeseed oil: what impact on agricultural food prices? Int J Glob Energy Issues 37(5–6):220–235. doi:10.1504/IJGEI.2014.067667

Bethlenfalvay GJ, Bayne HG, Pacovsky RS (1983) Parasitic and mutualistic associations between a mycorrhizal fungus and soybean: the effect of phosphorous on host plant-endophyte interactions. Physiol Plant 57:543–548. doi:10.1111/j.1399-3054.1983.tb02783.x

Bouaid A, Martinez M, Aracil J (2009) Production of biodiesel from bioethanol and *Brassica carinata* oil: oxidation stability study. Bioresour Technol 100(7):2234–2239. doi:10.1016/j.biortech.2008.10.045

D'Avino L, Dainelli R, Lazzeri L, Spugnoli P (2015) The role of co-products in biorefinery sustainability: energy allocation versus substitution method in rapeseed and carinata biodiesel chains. J Clean Prod 94:108–115. doi:10.1016/j.jclepro.2015.01.088

Dale BE, Anderson JE, Brown RC, Csonka S, Dale VH, Herwick G et al (2014) Take a closer look: Biofuels can support environmental, economic and social goals. Environ Sci Technol 48(13):7200–7203. doi:10.1021/es5025433

Dangol N, Shrestha DS, Duffield JA (2015) Life cycle analysis and production potential of camelina biodiesel in the Pacific Northwest. Trans ASABE 58(2):465–475. doi:10.13031/trans.58.10771

De Domenico S, Strafella L, D'Amico L, Mastrorilli M, Ficarella A, Carlucci P et al (2016) Biodiesel production from *Cynara cardunculus* L. and *Brassica carinata*. A. Braun seeds and their suitability as fuels in compression ignition engines. Ital J Agron 11(1):47–56. doi:10.4081/ija.2016.685

EIA (2016) Monthly biodiesel production report with data for November 2015. EIA, Washington, D.C.

EIA (2017) April 2017 monthly energy review: Table 10.4 Biodiesel and other renewable fuels overview. EIA, DOE, Washington, D.C.

El Bassam N (2010) Handbook of bioenergy crops: a complete reference to species, development and applications. Routledge, Abingdon, ISBN 978–1844078547

EPA (2003) Ecoregions of Montana, North Dakota, and South Dakota. US Environmental Protection Agency (EPA), US Geological Survey, USDA Natural Resources Conservation Service, and US Forest Service, Washington, D.C.

EPA (2011) Ecoregions Level III and IV, US, 2011. US EPA, SEGS. US Environmental Protection Agency (EPA), US Geological Survey, USDA Natural Resources Conservation Service, and US Forest Service, Washington, D.C.

EPA (2016) Renewable fuel standard program: final renewable fuel standards for 2017, and the biomass-based diesel volume for 2018. US Environmental Protection Agency (EPA), Washington, D.C.

ERS (2016) Fertilizer use and price. Economic Research Service (ERS), US Department of Agriculture, Washington, D.C.

Escobar JC, Lora ES, Venturini OJ, Edgar EY, Almazan O (2009) Biofuels: environment, technology and food security. Renew Sustain Energy Rev 13(6–7):1275–1287. doi:10.1016/j.rser.2008.08.014

Fazio S, Monti A (2011) Life cycle assessment of different bioenergy production systems including perennial and annual crops. Biomass Bioenergy 35(12):4868–4878. doi:10.1016/j.biombioe.2011.10.014

Fore SR, Porter P, Lazarus W (2011) Net energy balance of small-scale on-farm biodiesel production from canola and soybean. Biomass Bioenergy 35(5):2234–2244. doi:10.1016/j.biombioe.2011.02.037

Geyer R, Stoms DM, Lindner JP, Davis FW, Wittstock B (2010) Coupling GIS and LCA for biodiversity assessments of land use. Int J Life Cycle Assess 15:454–467. doi:10.1007/s11367-010-0170-9

Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R (2009) ReCiPe 2008: a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Ruimte en Milieu: Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, The Hague

Grady K, Nleya T (2010) Camelina production. South Dakota State University (SDSU) Extension Service, Brookings. http://igrow.org

Gui MM, Lee K, Bhatia S (2008) Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock. Energy 33(11):1646–1653. doi:10.1016/j.energy.2008.06.002

Hall C.A.S., Dale BE, Pimentel D (2011) Seeking to understand the reasons for different energy return on investment (EROI) estimates for biofuels. Sustainability 3(12):2413–2432. doi:10.3390/su3122413

Hill J, Nelson E, Tilman D, Polasky S, Tiffany D (2006) Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. PNAS 103(30):11206–112010. doi: 10.1073/pnas.0604600103

Hoeksema JD, Chaudhary Bala, Gehering V, Johnson CA, Karst NC, Koide J, R.T., et al (2010) A meta-analysis of context-dependency in plant response to inoculation with mycorrhizal fungi. Ecol Lett 13:394–407. doi:10.1111/j.1461-0248.2009.01430.x

Hull CH, Loveridge EJ, Donnison IS, Kelly DE, Kelly SL (2014) Co-production of bioethanol and probiotic yeast biomass from agricultural feedstock: application of the rural biorefinery concept. AMB Express 4(64):2–8. doi:10.1186/s13568-014-0064-5

Jacobson M (2009) Review of solutions to global warming, air pollution, and energy security. Energy Environ Sci 2(2):148–173. doi:10.1039/b809990c

Joly CA, Huntley B, Dale V, Mace G, Muok B, Ravindranath N (2015) Biofuel impacts on biodiversity and ecosystem services. In:Huntley BJ, Sluys M-AV (eds) Bioenergy and sustainability. Scientific Committee on problems of the environment (SCOPE) rapid assessment process on bioenergy and sustainability, Paris, pp 555–580

Keshavarz-Afshar R, Chen C (2015) Intensification of dryland cropping systems for bio-feedstock production: energy analysis of camelina. BioEnergy Res 8(4):1877–1884. doi:10.1016/j.indcrop.2015.02.065

Keshavarz-Afshar R, Mohammed YA, Chen C (2015a) Energy balance and greenhouse gas emissions from dryland camelina as influenced by tillage and nitrogen. Energy 91:1057–1063. doi:10.1016/j.energy.2015.07.136

Keshavarz-Afshar R, Mohammed YA, Chen C (2015b) Energy balance and greenhouse gas emissions of dryland camelina as influenced by tillage and nitrogen. Energy 91:1057–1063. doi:10.1016/j.energy.2015.07.136

Kim S, Dale BE (2003) Cumulative energy and global warming impact from the production of biomass for biobased products. J Ind Ecol 7(3):147–162. doi:10.1162/108819803323059442

Kim S, Dale BE (2005) Life cycle assessment of various cropping systems utilized for producing biofuels: bioethanol and biodiesel. Biomass Bioenergy 29(6):426–439. doi:10.1016/j.biombioe.2005.06.004

Kim H, Kim S, Dale BE (2009) Biofuels, land use change, and greenhouse gas emissions: some unexplored variables. Environ Sci Technol 43(3):961–967. doi:10.1021/es802681k

Knudsen MT, Yu-Hui Q, Yan L, Halberg N (2010) Environmental assessment of organic soybean (*Glycine max.*) imported from China to Denmark: a case study. J Clean Prod 18(14):1431–1439. doi:10.1016/j.jclepro.2010.05.022

Li X, Mupondwa E (2014) Life cycle assessment of camelina oil derived biodiesel and jet fuel in the Canadian Prairies. Sci Total Environ 481:17–26. doi:10.1016/j.scitotenv.2014.02.003

MacWilliam S, Sanscartier D, Lemke R, Wismer M, Baron V (2016) Environmental benefits of canola production in 2010 compared to 1990: a life cycle perspective. Agric Syst 145:106–115. doi:10.1016/j.agsy.2016.03.006

MAES (2017) Montana Agricultural Research Station. Montana State University, Bozeman. http://agresearch.montana.edu/

Matsuura M.I.F., Dias FR, Picoli JF, Lucas K.R.G., de Castro C, Hirakuri MH (2016) Life-cycle assessment of the soybean-sunflower production system in the Brazilian Cerrado. Int J Life Cycle Assess. doi:10.1007/s11367-016-1089-6

Mohammadi A, Rafiee S, Jafari A, Dalgaard T, Knudsen MT, Keyhani A et al (2013) Potential greenhouse gas emission reductions in soybean farming: a combined use of life cycle assessment and data envelopment analysis. J Clean Prod 54:89–100. doi:10.1016/j.jclepro.2013.05.019

Moser BR (2010) Camelina (*Camelina sativa* L) oil as a biofuels feedstock: Golden opportunity or false hope. Lipid Technol 22(12):270–273. doi:10.1002/lite.201000068

Mourad AL, Walter A (2011) The energy balance of soybean biodiesel in Brazil: a case study. Biofuels Bioprod Biorefin 5(2):185–197. doi:10.1002/bbb.278

Mousavi-Avval SH, Rafiee S, Jafari A, Mohammadi A (2011) Energy flow modeling and sensitivity analysis of inputs for canola production in Iran. J Clean Prod 19(13):1464–1470. doi:10.1016/j.jclepro.2011.04.013

Murphy DJ, Hall CA, Dale M, Cleveland C (2011a) Order from chaos: a preliminary protocol for determining the EROI of fuels. Sustainability 3(10):1888–1907. doi:10.3390/su3101888

Murphy DJ, Hall CA, Powers B (2011b) New perspectives on the energy return on (energy) investment (EROI) of corn ethanol. Environ Dev Sustain 13(1):179–202. doi:10.1007/s10668-010-9255-7

Murphy DJ, Carbajales-Dale M, Moeller D (2016) Comparing apples to apples: why the net energy analysis community needs to adopt the life-cycle analysis framework. Energies 9(11):917. doi:10.3390/en9110917

NASS (2017) National Agricultural Statistics Service (NASS), Quick Stats. United States Department of Agriculture, Washington, D.C.. https://quickstats.nass.usda.gov

NDSU (2017) North Dakota State University (NDSU) variety trial results. North Dakota State Research Extention Center, Fargo. https://www.ag.ndsu.edu/varietytrials

Ng TL, Wayland Eheart J, Cai X, Braden JB, Czapar GF (2013) Agronomic and stream nitrate load responses to incentives for bioenergy crop cultivation and reductions of carbon emissions and fertilizer use. J Water Resour Plan Manag 140(1):112–120. doi:10.1061/(ASCE)WR.1943-5452.0000320

Nitschelm L, Aubin J, Corson MS, Viaud V, Walter C (2016) Spatial differentiation in life cycle assessment LCA applied to an agricultural territory: current practices and method development. J Clean Prod 112:2472–2482. doi:10.1016/j.jclepro.2015.09.138

Norris CB, Parent J, Groupe AGÉCO (2016) Update of soybean life cycle analysis

NRCS (2017) Crop management zones for the continental United States. Natural Resources Conservation Service (NRCS), US Department of Agriculture, Washington, D.C.. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/tools/rusle2/?cid=stelprdb1247555

OECD-FAO (2017) Organisation for economic co-operation and development (OECD). United Nations Food and Agriculture Organization (FAO) Agricultural Outlook 2016–2025, Rome

Owsianiak M, Laurent A, Bjørn A, Hauschild MZ (2014) IMPACT 2002+, ReCiPe 2008 and ILCD's recommended practice for characterization modelling in life cycle impact assessment: a case study-based comparison. Int J Life Cycle Assess 19(5):1007–1021. doi:10.1007/s11367-014-0708-3

Petre S, Jurcoane Ş., Dobre P, Petcu R, Dimitriu D (2012) Life cycle assessment: by-products in biofuels production battle; rapeseed vs. *Camelina sativa* L. AgroLife Sci J 2(1):58–65

Pimentel D, Patzek TW (2005) Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. Nat Resour Res 14(1):65–76. doi:10.1007/s11053-005-4679-8

PRéConsultants (2016) SimaPro (v8.0), PRé Consultants, PRéConsultants, Amersfoort

Raucci GS, Moreira CS, Alves PA, Mello FF, de Almeida Frazão L, Cerri C.E.P. et al (2015) Greenhouse gas assessment of Brazilian soybean production: a case study of Mato Grosso State. J Clean Prod 96:418–425. doi:10.1016/j.jclepro.2014.02.064

Ribeiro CW, Alloing G, Mandon K, Frendo P (2015) Redox regulation of differentiation in symbiotic nitrogen fixation. Biochim Biophys Acta 1850(8):1469–1478. doi:10.1016/j.bbagen.2014.11.018

Rulli MC, Bellomi D, Cazzoli A, De Carolis G, D'Odorico P (2016) The water-land-food nexus of first-generation biofuels. Sci Rep 6:22521. doi:10.1038/srep22521

Seepaul R, Bliss CM, Wright DL, Marois JJ, Leon R, Dufault N et al (2015) Carinata, the jet fuel cover crop: 2015 production manual for the southeastern United States. The University of Florida/Institute of Food and Agricultural Sciences (UF/IFAS) and North Florida Research and Education Center (NFREC), Quincy

Shonnard DR, Williams L, Kalnes TN (2010) Camelina-derived jet fuel and diesel: Sustainable advanced biofuels. Environ Prog Sustain Energy 29(3):382–392. doi:10.1002/ep.10461

Sieverding HL, Bailey LM, Hengen TJ, Clay DE, Stone JJ (2015) Meta-analysis of soybean-based biodiesel. J Environ Qual 44(4):1038–1048. doi:10.2134/jeq2014.07.0320

Sieverding HL, Zhao X, Wei L, Stone JJ (2016a) Life-cycle assessment of oilseeds for biojet production using localized cold-press extraction. J Envrion Qual 45(3):967–976. doi:10.2134/jeq2015.06.0313

Sieverding HL, Zhao X, Wei L, Stone JJ (2016b) Life-cycle assessment of oilseeds for biojet production using localized cold-press extraction. J Environ Qual 45(3):967–976. doi:10.2134/jeq2015.06.0313

Sintim HY, Zheljazkov VD, Obour AK, Garcia y Garcia A, Foulke TK (2016) Evaluating argoniomic responses of camelina to seeding date under rain-fed conditions. Agron J 108:349–357. doi:10.2134/agronj2015.0153

Smith VH (2003) Eutrophication of freshwater and coastal marine ecosystems a global problem. Environ Sci Pollut Res 10(2):126–139. doi:10.1065/espr2002.12.142

Strange A, Park J, Bennett R, Phipps R (2008) The use of life-cycle assessment to evaluate the environmental impacts of growing genetically modified, nitrogen use-efficient canola. Plant Biotechnol J 6(4):337–345. doi:10.1111/j.1467-7652.2008.00323.x

Tabatabaie S.M.H., Murthy GS (2017) Effects of geographical location and stochastic weather variation on life cycle assessment of biodiesel production from camelina in the northwestern USA. Int J Life Cycle Assess 22(6):867–882. doi:10.1007/s11367-016-1191-9

Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L et al (2009) Beneficial biofuels—the food, energy, and environment trilemma. Science 325(5938):270–271. doi:10.1126/science.1177970

Ukaew S, Shi R, Lee JH, Archer DW, Pearlson M, Lewis KC et al (2016) Full chain life cycle assessment of greenhouse gases and energy demand for canola-derived jet fuel in North Dakota, United States. ACS Sustain Chem Eng 4(5):2771–2779. doi:10.1021/acssuschemeng.6b00276

Youngs H, Somerville C (2014) Best practices for biofuels. Science 344:1095–1096. doi:10.1126/science.1255812

Zgola M, Reinhard J, Liao X, Simonnin G, Gmuender S, Dettling J et al (2016) Update of soybean life cycle analysis, United Soybean Board, Chesterfield

Zimmer S, Messmer M, Haase T, Piepho H-P, Mindermann A, Schulz H et al (2016) Effects of soybean variety and *Bradyrhizobium* strains on yield, protein content and biological nitrogen fixation under cool growing conditions in Germany. Eur J Agron 72:38–46. doi:10.1016/j.eja.2015.09.008

Zollinger R, Christoffers M, Endres G, Gramig G, Howatt K, Jenks B et al. (2016) North Dakota weed control guide. North Dakota State University (NDSU) Extension Service, Fargo. https://www.ag.ndsu.edu/weeds/weed-control-guides, p 111