Industrial Crops and Products 71 (2015) 114–121

Industrial Crops and Products
journal homepage: www.elsevier.com/locate/indcrop

Intensification of dryland cropping systems for bio-feedstock production: Evaluation of agronomic and economic benefits of *Camelina sativa*

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ARTICLE INFO

Article history:
Received 19 December 2014
Received in revised form 20 February 2015
Accepted 27 February 2015
Available online 8 April 2015

Keywords:
Camelina
Cropping systems
Economics
Biofeedstock

ABSTRACT

Camelina (*Camelina sativa* L. Crantz) is a promising bioenergy crop, but a sustainable production system for this crop has not yet been well developed. There is also concern about competing land use between crop productions for bioenergy or food use. One approach to overcoming this concern and developing sustainable production systems for bioenergy crops is potentially replacing the fallow period in wheat-based cropping systems with bioenergy crops. The agronomic and economic benefits of growing camelina in rotation with winter wheat were evaluated in a replicated rotation study from 2008 to 2011 in the Northern Great Plains (NGP), focusing on the effects on wheat yield and overall profitability of the cropping system. Average winter wheat yields were 2401 and 1858 kg ha^{-1} following camelina and barley, respectively, representing a 13.2 and 32.8% winter wheat yield reduction compared to the fallow–winter wheat rotation (2766 kg ha^{-1}). Lower winter wheat yield in the alternative systems were offset by 907 kg ha^{-1} camelina and 1779 kg ha^{-1} barley yields. Economic analyses revealed that at existing market prices and production costs, the traditional fallow–winter wheat rotation provides greater net returns to growers due to substantially lower variable costs of the system. Scenario analyses that use more optimized, lower cost camelina production practices show that the net profits of camelina–wheat system could be closer to those in the fallow–wheat system. However, higher grain price and/or greater grain yield of camelina are essential to attract producers to include camelina in their cropping systems. Although the fallow–wheat system resulted in higher short-run net returns, the total biomass production and crop residue return to soil is much greater in camelina–wheat than fallow–wheat rotation, which is likely to improve soil quality and productivity in the long run.

1. Introduction

The traditional fallow–winter wheat rotation is the most widely used dryland cropping system in the NGP. A fallow period allows restocking of soil water recharge, thereby increasing yield stability and reducing the risk of crop failure in subsequent growing periods (Juergens et al., 2004; Nielsen et al., 2005). Land idling for extended periods (e.g., from 14 to 21 months depending on the type of wheat and planting and harvest dates), however, has been shown to be associated with numerous sustainability issues, including severe soil erosion, reduction of soil organic matter and soil fertility, and nitrate leaching (Peterson and Westfall, 2004; Machado, 2011). Furthermore, Farahani et al. (1998) and Nielsen et al. (2009) pointed out that fallowing is an extremely inefficient precipitation storage method, especially during the second summer fallow period (May through September).

The adverse effects of fallow–wheat systems have encouraged NGP producers to slowly replace this predominant cropping system with more intensive systems such as annual cropping without fallowing (Halvorson et al., 2004; Chen et al., 2012). Moreover, the adoption of no-till management practices has facilitated greater cropping diversification and intensification in this region (Nielsen et al., 2011; Halvorson et al., 2004). More diverse and intensive systems have been shown to provide Great Plains producers with

Abbreviations: BAR, barley; CAM, camelina; FAL, fallow; NGP, Northern Great Plains; WW, winter wheat.

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http://dx.doi.org/10.1016/j.indcrop.2015.02.065

enhanced economic benefits (Dhuyvetter et al., 1996), increased precipitation use efficiency (Farahani et al., 1998; Nielsen et al., 2005), and improved soil properties (Peterson and Westfall, 2004). Continued transition to more intensive cropping systems would not only result in improved production efficiency, but will also increase land availability. For example, in Montana, converting 30–50% of cropland from fallow–crop to crop–crop systems would add 0.7–1.1 million ha of productive farmland.

Crops used for biofuel production are one category of candidates for replacing fallow in winter wheat-based cropping systems. Increasing biofuel production has been a major effort by the U.S. government, which has directed programs such as the Advanced Energy Initiative (AEI) that proposes displacing 30% of petroleum use in the transportation sector with domestically produced renewable biofuels (Milliken et al., 2007). However, critics of such initiatives have argued that bioenergy feedstock crops may compete for farmland with food and feed crops, which is likely to increase food prices and potentially have significant economic destabilization effects. Therefore, the use of marginal land for bioenergy feedstock production has been recommended (Gelfand et al., 2013), and ideally, using a production system that can deliver feedstock crops with minimal disruption to the production of existing agricultural commodities.

Camelina is an annual oilseed crop belonging to the Brassicaceae family (Gesch, 2014). A shorter life cycle (60–90 days), higher seed oil content (35–45%), and greater water use efficiency compared to other oilseed crops such as canola make camelina a promising biofuel feedstock for dryland farming systems (McVay and Khan, 2011). Recent studies evaluating jet fuel performance in commercial airlines and military fighter jets have shown that camelina is a superior feedstock for biodiesel and jet fuel production (BioEnergy News, 2010). Previous studies in Montana, Wyoming, and Oregon showed that camelina is well-adapted to the semi-arid region of the NGP and Pacific Northwest regions (Schillinger et al., 2012 Wysocki et al., 2013). In Montana, camelina yields from 700 to 2000 kg seed ha^{-1} with 290 to 400 g kg^{-1} oil content, depending on precipitation and planting date (McVay and Lamb, 2008). However, little work has been done to evaluate the economic and environmental feasibility of growing camelina in the NGP's wheat dominated production region, especially because replacing fallow with camelina may adversely affect the yield of subsequent wheat crops.

In this study, we replaced fallow periods in the traditional dryland wheat–fallow cropping system in the NGP with camelina and barley. We then evaluated: (1) the impact of camelina and barley on winter wheat yield; (2) the performance of camelina in the dryland farming system of the region; and (3) differences in economic returns between the wheat–fallow cropping system and the alternative systems.

2. Materials and methods

2.1. Site description and experimental details

We compared the traditional fallow–winter wheat (FAL–WW) with alternative barley–winter wheat (BAR–WW) and camelina–winter wheat (CAM–WW) cropping systems. The study was conducted at the Central Agricultural Research Center (47°03′N, 109°57′W; 1400 m elevation) of Montana State University near Moccasin, MT from 2008 to 2012. The soil at this site is classified as a Judith clay loam (fine-loamy, carbonatic, frigid Typic Calciustolls) with the water holding capacity being limited by gravel content and a shallow soil profile (60 cm). Prior to the initiation of the study, the top soil (0–30 cm) has 31 g kg^{-1} organic matter content, pH 7.7 (1:2 soil to water ratio), 19.6 kg ha^{-1} NO_3-N, 8.3 ppm Olsen P, 185.3 ppm available K, and 35.0 meq per 100 g soil CEC. Soil samples were taken in the fall and spring every year to measure soil available N. Long term (l909–2013) average crop year (September–August) precipitation in this area is approximately 390 mm with mean air temperature of 5.8 °C. Table 1 presents the monthly precipitation and average temperature during the study and the 20-year long-term averages.

The operation practices details for each system were as follow: for the fallow period after winter wheat, one herbicide application was performed in the fall with 1.12 L ha^{-1} of glyphosate (*N*-[phosphonomethyl] glycine) to burn down the weeds. Additional two herbicide applications were sprayed with 1.12 L ha^{-1} glyphosate in the early spring and 1.12 L ha^{-1} of glyphosate plus 1.68 L ha^{-1} 2,4-D (2,4-dichlorophenoxyacetic acid) in early to mid-summer.

For winter wheat following fallow, glyphosate (1.12 L ha^{-1}) was sprayed in the fall before seeding in early September, and winter wheat (cv. Yellowstone) was direct-seeded using a ConservaPak no-till air-seeder (ConservaPak Indian Head, SK, Canada) at a seeding rate of 67 kg seed ha^{-1}. Starter fertilizer N–P_2O_5–K_2O–S (20–20–20–10) was applied at a rate of 112 kg ha^{-1} at the time of seeding as recommended by Jacobsen et al. (2003). In the following spring, additional 90 kg N ha^{-1} was broadcasted in the form of urea at late-tillering stage (Zadoks GS 30), and a broadleaf herbicide named bronate (Bromoxynil) was applied at 1.68 L ha^{-1}. Grain was harvested using a Wintersteiger plot combine (Wintersteiger Inc., Salt Lake City, UT) in late July to early August. The same operation procedures were also used for winter wheat following barley and winter wheat following camelina.

For barley following winter wheat, herbicide (glyphosate at 1.12 L ha^{-1}) was applied in the fall after winter wheat harvest and in the spring before barley planting. Barley (cv. Haxbey) was then planted in mid-April using a ConservaPak no-till air-seeder at a

Table 1
Monthly precipitation and average air temperature during the study and long term average (LTA) at Moccasin, Montana.

Month	Precipitation (mm)					Month	Temperature (°C)				
	2008	2009	2010	2011	LTA		200	200	2010	2011	LTA
September	28.2	32.3	20.6	49.0	35.8	September	13.6	12.4	17.3	12.8	12.7
October	23.6	19.1	73.9	11.2	23.1	October	8.7	9.2	1.8	10.6	7.2
November	23.1	14.2	4.8	40.9	14.5	November	1.4	4.7	3.9	−2.2	0.5
December	0.5	8.9	8.6	17.0	13.7	December	−3.3	−8.8	−9.1	−3.3	−3.9
January	4.8	11.2	10.7	8.1	14.0	January	−5.6	−3.0	−3.0	−5.0	−5.8
February	5.3	5.1	5.1	15.0	11.4	February	−1.9	−1.5	−1.5	−8.3	−4.1
March	2.8	15.0	4.6	15.5	18.0	March	0.5	−0.6	4.8	−1.1	−4.1
April	11.2	36.6	27.9	59.9	30.5	April	2.8	4.2	5.3	3.3	5.0
May	109.7	14.2	85.3	186.7	65.5	May	9.8	10.2	7.6	8.3	10.1
June	74.7	23.9	66.3	107.4	79.5	June	13.6	13.7	13.6	13.3	14.3
July	11.4	54.9	37.3	20.8	42.4	July	19.3	18.6	17.6	19.4	18.8
August	22.6	39.6	96.0	18.0	41.7	August	19.4	18.3	18.1	20.0	18.3
Total	317.9	275.0	441.1	549.5	390.1	Average	6.5	6.5	6.4	5.7	5.8

Table 2
Input costs estimates for winter wheat, barley and camelina production (2009–2011) and projected 2015 input costs in Moccasin, MT region.

Materials and activities	Winter wheat costs ($/ha)				Barley costs ($/ha)			
	2009	2010	2011	2015	2009	2010	2011	2015
Seed and treatment (fungicide)	41.99	29.64	29.64	31.62	33.30	25.73	25.74	44.24
Herbicide cost	31.42	33.64	33.64	43.91	44.46	28.45	28.45	40.92
Fertilizer cost	182.30	146.71	144.73	187.13	129.57	108.53	108.53	132.28
Farm operations (seeding, spraying and harvesting)	94.98	95.25	95.58	95.84	94.98	95.25	95.58	95.84
Total costs	350.69	305.24	303.59	358.5	302.31	257.96	258.3	313.28
Materials and activities	Fallow costs ($/ha)				Camelina costs ($/ha)			
	2009	2010	2011	2015	2009	2010	2011	2015
Seed and treatment (fungicide)	0.00	0.00	0.00	0.00	14.82	14.82	14.82	14.82
Herbicide cost	46.68	21.59	21.59	35.14	54.88	42.76	42.73	18.98
Fertilizer cost	0.00	0.00	0.00	0.00	129.80	108.53	108.53	77.91
Farm operations (seeding, spraying and harvesting)	9.87	9.94	10.03	10.10	94.98	95.25	95.58	95.84
Total costs	56.55	31.53	31.62	45.24	294.48	261.36	261.66	207.55

seeding rate of 76 kg ha^{-1} with 30 cm row spacing. Starter fertilizer N–P_2O_5–K_2O–S (20–20–20–10) was applied at a rate of 112 kg ha^{-1} at seeding, and additional 52 kg N ha^{-1} was broadcasted in the form of urea in the spring. Bronate (1.68 L ha^{-1}) was applied in the spring at late tillering stage. Barley was harvested in late July using a Wintersteiger plot combine.

For camelina following winter wheat, one burn-down herbicide (1.12 L ha^{-1} glyphosate) was applied in the early September after harvesting winter wheat and another application (1.12 L ha^{-1}) in the spring prior to planting camelina. Camelina (cv. Blaine Creek) were sown in late March to early April using a ConservaPak no-till air-seeder at 3.4 kg ha^{-1} seeding rate with 30 cm row spacing. Starter fertilizer N–P_2O_5–K_2O–S (20–20–20–10) was applied at the time of seeding at the rate of 112 kg ha^{-1}. Additional 52 kg N ha^{-1} in the form of urea was broadcasted at rosette stage. A grassy herbicide, Poast (2-[1-(ethoxyimino) butyl]-5-[2-(ethylthio) propyl]-3-hydroxy-2-cycloxexen-1-one), was also applied in the spring at late rosette stage at 1.12 L ha^{-1} to control wheat volunteers and other grasses. Camelina seed was harvested in early to mid-July using a Wintersteiger plot combine.

The rotation plots have dimensions of 3.7 m wide × 18.3 m long with four replications. To avoid the confounding effect of varying weather conditions on crop rotations, each phase of the crops was designed to appear in each rotation year. For the FAL–WW rotation, for example, each year had one plot in fallow and another plot in winter wheat, and was rotated in the following year. The experiment was conducted in a randomized complete block design with four replicates.

2.2. Data collection

Prior to grain harvesting, biomass samples were cut by hand from an area of 1 m^{-2} and air dried to determine dry biomass yield. Another sample was taken from the middle rows in each plot using a plot combine (with a 1.5 m wide header) to determine grain yield. Grain yield was then adjusted to 11% moisture content for wheat and barley and 6% for camelina. The straw yield was determined by subtracting grain yield from biomass yield. Harvested grains in each plot were thoroughly mixed and a sample of 200 g was separated for further analysis. The grain subsamples of wheat and barley were ground using a Wiley Mill grinder (Thomas Scientific, Swedesboro, NJ) and camelina seed was ground using a coffee grinder to pass through a 1 mm screen. Grain nitrogen content was measured based on the Dumas combustion method using a PerkinElmer 2410N analyzer (Waltham, MA). The nitrogen content was multiplied by 5.7 to determine grain protein content (Chen et al., 2011). Camelina seed oil concentrations were determined using the NIR method (Panford, 1990). Volumetric soil water contents in each plot were measured in the fall and spring using the gravimetric method.

2.3. Data analysis

Data were statistically analyzed using the GLM procedure in SAS (version 9.3). Means were compared according to Fisher's least significant difference test (LSD) at the $P = 0.05$ level.

2.4. Economic analysis

Discounted net present value returns for the three systems were determined by developing enterprise budgets, which included variable production costs and market returns during 2009–2011 (2008 data were considered as background and excluded in the analysis). Future values of net returns were discounted by 2.02%, which was the January 3, 2011 5-year U.S. Treasury bond rate. Fixed costs were assumed to be comparable and variable production and ownership costs were determined using the North Dakota State University and Idaho University production cost estimates for each year of the study. Table 2 provides the summaries of the nominal costs for winter wheat, barley, camelina and fallow. Further details about the costs of inputs and prices of outputs to calculate total costs, gross incomes, and net returns are described in Chen et al. (2012). Nominal winter wheat (by protein content level) and barley market prices were obtained from the Montana Wheat and Barley Committee (MWBC, 2015) (Table 3). Reasonable assumption about camelina price was made based on numerous market reports and personal communication with buyers and sellers about contracted prices. We used two approaches to determine market conditions under which there are sufficient incentives to use a camelina cropping system. In the first approach, we examined whether past market conditions were favorable for increasing camelina production. In the second approach, we evaluated the market conditions necessary for camelina production adoption and the likelihood that those conditions will occur.

3. Results and discussion

3.1. Winter wheat yield and protein content

Table 4 shows that winter wheat yield varied across study years due to the variation in precipitation. Three-year average winter wheat grain yields following camelina (CAM–WW) and barley (BAR–WW) were 2401 and 1858 kg ha^{-1}, respectively,

Table 3
Wheat, barley, and camelina grain prices in 2009–2011 and their projected prices in 2014–2015 marketing years in Moccasin, MT region (wheat price determined based on protein content).

Crop type		Grain price ($/kg)			
		2009	2010	2011	2015
Barley		0.110	0.164	0.221	0.220
Camelina		0.353	0.265	0.199	0.275
Winter wheat					
Protein	<11	0.160	0.148	0.21	0.232
con-	11	0.173	0.164	0.238	0.240
tent	12	0.184	0.179	0.263	0.242
(%)	13	0.194	0.190	0.283	0.243
	>13	0.215	0.214	0.321	0.245

Table 4
Yields of wheat, barley, and camelina in different cropping systems at Central Agricultural Research Center, Moccasin, MT (2009–2011).

Cropping system	Grain yield Kg ha^{-1}	Straw yield Kg ha^{-1}	Grain protein g kg^{-1}	Oil g kg^{-1}
Winter wheat				
CAM–WW[A]	2401b	3286b	137a	–
BAR–WW[B]	1858c	2522c	135a	–
FAL–WW[C]	2766a	3876a	137a	–
SE[D]	101	148	4	–
2009	1934	2287	165	–
2010	3084	3618	119	–
2011	1998	3678	121	–
SE	88	129	3	–
Barley				
BAR–WW	1806	1573	135	–
2009	2107	1709	138	–
2010	2145	1753	108	–
2011	1168	1256	161	–
SE	144	128	4	–
Camelina				
CAM–WW	912	2510	271	370
2009	1087	2199	271	350
2010	1204	2335	255	373
2011	447	2995	286	385
SE	132	1012		5

Means within a column with a common letter are not statistically different at $P < 0.05$ by LSD test.
[A] Camelina–winter wheat.
[B] Barley–winter wheat rotation.
[C] Fallow–winter wheat rotation.
[D] Standard error.

representing 13.2 and 32.8% lower yield compared with the grain yield of wheat in the traditional fallow–winter wheat system (2766 kg ha^{-1}). Wheat grain protein content ranged from 135 to 137 g kg^{-1} implying that wheat quality levels were not affected by cropping system choice. Lower relative winter wheat grain yields in rotation with camelina and barley could mainly be attributed to lower stored water content in the soil compared to fallow, thus reducing moisture availability for winter wheat in the intensified cropping systems (Table 5). These results are consistent with previous reports by Aiken et al. (2013), Lyon et al. (2004), Miller et al. (2006), Nielsen and Vigil (2005), and Saseendran et al. (2004). The highest grain yields for all crops and lowest grain yield variability across systems occurred in 2010, when annual precipitation was the highest observed during the study period. This result is similar to Miller and Holmes (2005), who reported that replacing fallow with a spring broadleaf crop in the NGP resulted in modest (0–16%) yield reductions in normal years and greater yield reductions (21–41%) under drought conditions. The lowest wheat grain yield was observed in the barley–wheat rotation, which could be explained by a buildup of grassy weed and possible root disease in cereal–cereal annual cropping.

Table 5
The effect of crop rotation on soil moisture content (cm^3 cm^{-3}) in spring and fall from 2008–2010 at Central Agricultural Research Center, Moccasin, MT. The soil moisture is presented in this table is cumulative soil water stored in the top 0–0.6 m soil depth. Results are means for four replications.

Cropping system	Volumetric soil moisture content (cm^3 cm^{-3})				
	Spring 2008	Fall 2008	Spring 2009	Fall 2009	Spring 2010
CAM–WW[A]	0.18a	0.08b	0.17a	0.09b	0.15a
BAR–WW[B]	0.18a	0.07b	0.17a	0.09b	0.14a
FAL–WW[C]	0.18a	0.11a	0.19a	0.14a	0.15a

Means within a column with a common letter are not statistically different at $P < 0.05$ by LSD test. Data for fall 2010 were not available.
[A] Camelina–winter wheat rotation.
[B] Barley–winter wheat rotation.
[C] Fallow–winter wheat rotation.

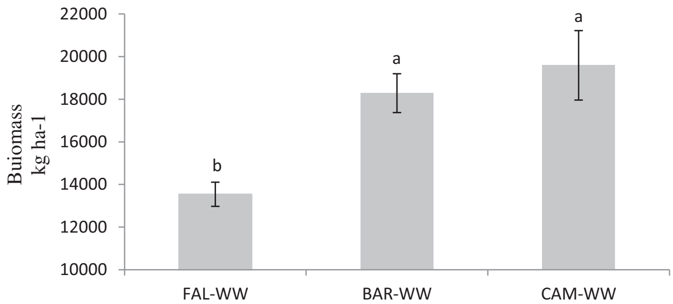

Fig. 1. Total biomass produced from 2008–2011 in different cropping systems at the Central Agricultural Research center, Moccasin, MT. Means were seprated using LSD at $P < 0.05$. Vertical bars represent standard error. BAR, barley; CAM, camelina; FAL, fallow; WW, winter wheat.

3.2. Camelina and barley yields following winter wheat

Similar to annual variability in winter wheat yields, camelina and barley yields also varied from year to year. The three-year average yield for camelina seed was 912 kg ha^{-1} with 271 g kg^{-1} protein and 370 g kg^{-1} oil (Table 4). Average barley grain yield was 1806 kg ha^{-1} with 135 g kg^{-1} protein. Camelina yield was significantly lower in 2011 than in the previous two years, which was due to excessive rainfall during May and June (the camelina blooming period) in this year. Excessive rainfall had detrimental effects on camelina pollination and adversely affected camelina seed formation and yield. High straw yield of camelina in 2011 also confirms this justification. Similarly, the Montana Agricultural Statistics (NASS, 2012) reported considerably lower yield for camelina and mustard across the state in 2011 compared to 2010. The camelina grain yield in this study was lower than the previously reported average yield of this crop (1280 kg ha^{-1}) in Southeastern Montana (McVay and Lamb, 2008), but comparable to camelina yields reported in Northeastern Oregon (351–1715 kg ha^{-1}), where annual precipitation averaged 421 mm (Schillinger et al., 2012).

It is worth noting that there is always a yield gap between the small plot variety trials and producers fields or cropping systems trials. In some variety trials, camelina cultivars were grown in a fallowed field which has more soil stored moisture, and therefore camelina yielded higher than those grown in a re-cropped field, such as the field in this crop rotation study. Moreover, several recently developed camelina cultivars have shown to have considerable yield advantages over existing cultivars (Chen unpublished data). Using the new cultivars will likely improve the camelina yields in the cropping systems. The oil content of camelina seed was also within the range reported in southwestern Montana (McVay and Khan, 2011) and west central Minnesota (Gesch, 2014), but slightly lower than that reported by Gugel and Falk (2006) for western Canada (38–43% content).

3.3. Total biomass production

Considerably more plant biomass was produced in the intensified cropping systems compared with the FAL–WW system (Fig. 1). The biomass yields of the CAM–WW and BAR–WW systems were 44 and 35% more than the biomass produced by the FAL–WW system, respectively, indicating that precipitation was more efficiently used in those systems (on the biomass basis). Greater biomass production is one important advantage of intensified cropping systems because more plant residues will return to the soil, which will improve soil quality. Machado (2011) reported that only continuous cropping systems increased soil organic carbon in a long-term study. Increased soil organic matter and C sequestration in the soil, improved soil infiltration, enhanced soil health, and reduced soil degradation are important benefits of more plant residuals added to the soil (Shaver et al., 2002; Peterson and Westfall, 2004). Peterson and Westfall (2004) also point out that intensifying cropping rotations, by shortening the summer fallow period and using the precipitation nearer to the time it is received, would increase the overall system precipitation use efficiency. Greater precipitation use efficiency will ultimately increase soil productivity via the increased annual amounts of residue added to the soil. However, further studies are needed to confirm the potential long-term effects of the camelina–wheat cropping system on soil health and quality.

Table 6
Total net profit of the studied cropping systems at the Central Agricultural Research Center, Moccasin, MT using actual input costs and grain prices (2009–2011).

Cropping system	($/ha)		
	Market revenues	Total costs	Net return
CAM–WW[a]	1059	838	221
BAR–WW[b]	918	838	80
FAL–WW[c]	822	509	313

[a] Camelina–winter wheat rotation.
[b] Barley–winter wheat rotation.
[c] Fallow–winter wheat rotation.

3.4. Input costs and net economic returns

Despite potential agronomic benefits of the CAM–WW cropping system, widespread adoption of this system depends on its economic incentives compared to the traditional rotations. The economic analysis showed that CAM–WW and BAR–WW cropping systems had higher production costs compared to FAL–WW (Table 6), which was due to considerably lower variable costs in fallow period (Table 2). The major added cost for camelina production were the application of 112 kg ha^{-1} starter fertilizer and an in-crop application of the herbicide Poast.

The CAM–WW rotation resulted in the highest gross returns, while the FAL–WW had the lowest 3-year gross returns (Table 6). The high gross returns for the camelina system were primarily driven by the atypically high camelina prices during the 2009–2011 period, which were boosted by increased demand associated with several U.S. government sponsored projects. However, the high gross returns were not large enough to outweigh the high production costs for the CAM–WW system. Under the 2009–2011 market conditions, the FAL–WW provided the highest three-year discounted net present value of returns. BAR–WW was by far the least profitable system, which was primarily due to unusually low barley market prices in 2010 and 2011.

3.5. Economic returns scenario analyses

We conducted several different scenario analyses to characterize production and market conditions under which camelina production would and would not be favorable. First, we considered a very short-run scenario in which production practices, costs, and market prices of all commodities do not change and compared net returns under alternative camelina prices. The assumptions underlying this short-run scenario are reasonable because camelina production represents a small proportion of the overall U.S. agricultural sector and small changes in its price are unlikely to significantly affect the agricultural sector. Under each camelina price alternative, we determined net returns ratios of the camelina system relative to the other systems. When the ratio is less (greater) than one, then the net return of the CAM–WW system would be higher (lower) than an alternative system. For example, using actual 2009–2011 market prices (Table 7), for every dollar of net

Table 7
Net returns advantage of CAM–WW cropping system over FAL–WW and BAR–WW rotations based on real market price (2009–2011) and different price scenarios for camelina (assuming barley and winter wheat prices were fixed).

		Camelina prices scenarios ($/kg)			
	2009–2011 Prices	0.132	0.220	0.309	0.397
CAM–WW[a]	1.00	1.00	1.00	1.00	1.00
BAR–WW[b]	0.36	3.32	0.58	0.33	0.22
FAL–WW[c]	1.42	13.11	2.28	1.25	0.86

[a] Camelina–winter wheat rotation.
[b] Barley–winter wheat rotation.
[c] Fallow–winter wheat rotation.

returns in the CAM–WW rotation, using the BAR–WW system would have resulted in net returns of $0.36 and in net returns of $1.42 for the FAL–WW system, implying that the CAM–WW system provided nearly three times as much net returns than the BAR–WW rotation but substantially lower returns relative to FAL–WW rotation. The scenario analysis indicates that the CAM–WW system does not become preferable to the FAL–WW system until camelina prices exceed the breakeven price $0.358 kg^{-1}.

These scenario analyses provide insights about market conditions when camelina can be part of a profitable winter wheat system. But what is the likelihood that camelina market prices would be sufficiently high for at least the breakeven scenario, market prices of $0.358 kg^{-1}, to occur in the future if the markets (i.e., demand) for camelina remained the same? To answer this question requires access to historical camelina market prices, which would enable the computation of an empirical market price distribution. However, there is limited information about historical camelina market prices because most transactions are forward contracted and are not made publicly available. Therefore, we used historical prices of canola futures contracts (2000–2014) traded on the Intercontinental Exchange (ICE) to get an appropriate proxy for the distribution of camelina prices because canola and camelina prices are likely highly correlated. Fig. 2 shows the fitted density from the empirical histogram of canola futures prices (in 2014 U.S. dollars) and a rescaled fitted density to represent a likely camelina distribution. That is, after comparing the mean canola price to the mean camelina price, the canola price distribution location parameter was rescaled such that central tendency of the approximate camelina distribution reflected the relationship between the mean canola and camelina prices, under the assumption that the dispersion characteristics of the two crop prices were relatively similar. The camelina distribution makes evident that in existing market conditions, the likelihood of camelina prices being above $0.358 kg^{-1} is approximately 0.94%.

These results imply that if no structural market shifts occur and/or production practices and camelina yields remain similar to those in the trials, there is a low likelihood that camelina market prices would be sufficiently high to incentivize widespread adoption. However, there is a potential to reduce camelina production costs by refining agronomic practices. In fact, extensive research efforts have been made in recent years to optimize the agronomic practices in this crop especially in regard to fertilization and weed control (Chen unpublished data). For example, our experiences show that the application of a starter fertilizer (20–20–20–10) for camelina following winter wheat may not be essential as sufficient N, P, and S carry over from the previous crop. Furthermore, the application of grassy herbicides (such as Poast) may also be skipped for camelina if the field is clean of weeds. These optimizations would reduce camelina production costs and, thus, the overall production costs of the CAM–WW rotation. Therefore, we examine how future production and market changes could affect the potential for camelina adoption. We consider whether a more optimized production approach and more recent market conditions provide new insights relative to the 2009–2011 period analysis.

Assuming the optimized production approach, input and output prices for the 2012–2014 production and marketing years

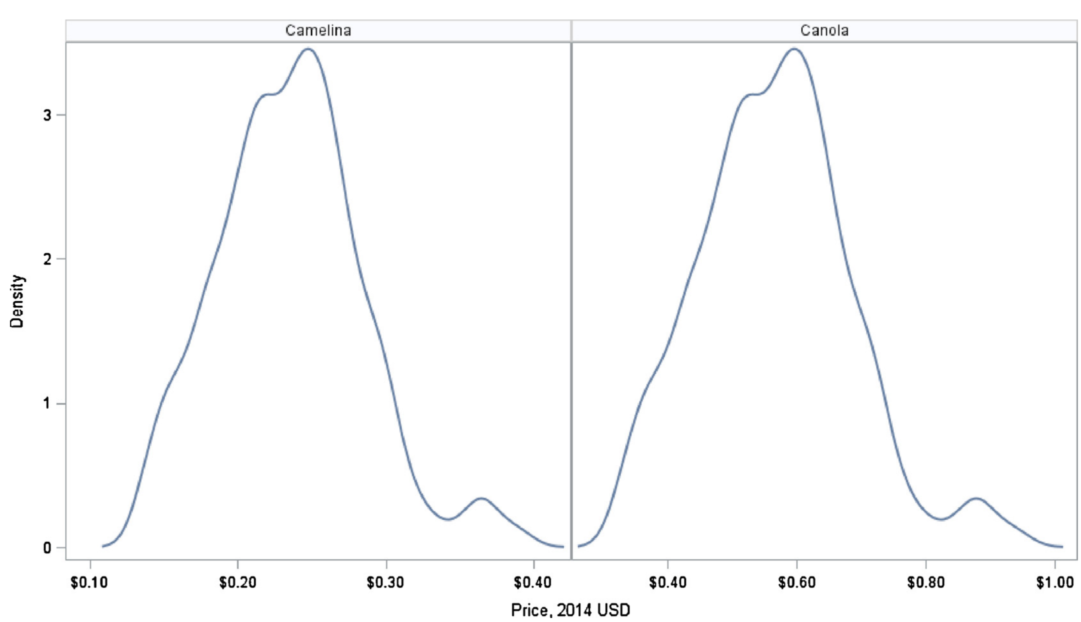

Fig. 2. Estimated density of historical canola futures prices (2000–2014, in 2014 U.S. dollars per kg) and location parameter re-scaled approximated density of camelina prices.

Table 8
Total net profit of the studied cropping systems at the Central Agricultural Research Center, Moccasin, MT using 2009–2011 trial average yields and 2012–2014 average inputs and grain market prices.

Cropping system	($/ha)			
	Market revenues	Total costs	Net return	Net return[d]
CAM–WW[a]	838	576	263	475
BAR–WW[b]	852	672	180	180
FAL–WW[c]	678	404	274	274

[a] Camelina–winter wheat rotation.
[b] Barley–winter wheat rotation.
[c] Fallow–winter wheat rotation.
[d] Net return estimated based on 1500 kg ha^{-1} camelina yield.

(assumed to be representative of likely 2015 market conditions; Tables 2 and 3), and average yields from the three-year trials, we re-calculate the 2-year discounted net present value of returns. Table 8 shows that under these conditions, the returns for FAL–WW and CAM–WW are closer than during the 2009–2011 period primarily due to the lower production costs. However, the FAL–WW system still outperforms CAM–WW by approximately $9 ha^{-1}. This implies that even with substantially lower costs, an increase in camelina demand, and subsequently price, is required. Alternatively, increases in camelina yields are needed to sufficiently increase gross returns at existing market prices. For example, achieving typical camelina yields of 1500 kg ha^{-1} (an achievable yield target during variety trials), along with using optimized low input production practices, the net return of CAM–WW rotation would be $475 ha^{-1} compared to $274 ha^{-1} in FAL–WW rotation (Table 8).

It is necessary to note that longer-term research is necessary to capture the potential indirect economic benefits of camelina. As explained previously, repeated implementation of FAL–WW rotation has been associated with soil degradation (nutrient depletion, erosion, organic matter reduction, etc.) and can hinder crop diversification and production system sustainability. Furthermore, due to the shallow soil profile in central Montana, the fallow period not only did not conserve much precipitation (Table 5), but could also result in nitrogen and salt leaching down to the ground water. Therefore, along with direct economic revenue, the long-term ecological and environmental impacts and sustainability of cropping systems should be taken into account when determining the suitability of a cropping system.

4. Conclusions

The results of this study indicate that the current fallow–winter wheat cropping system is economically more profitable than the two alternative systems, primarily because market prices for barley and camelina were not sufficiently high to offset the additional production costs. With optimization of crop management practices, the net revenue for camelina–wheat rotation would be closer to the fallow–wheat rotation. To attract producers to include camelina in their cropping system, higher market prices and/or higher seed yields are necessary. Releasing high yielding cultivars and more research efforts in cropping systems to improve the crop yield, and down-stream bio-products development to increase camelina value are necessary to achieve the above-mentioned objectives. An additional consideration is that although the fallow–winter wheat cropping system results in short-term favorable net returns, its long-term ecological sustainability as well as its long-term agronomic-economic benefits still remains ambiguous.

Acknowledgements

The authors would like to thank Johnna Heser for the field and laboratory technical support. The funding support for this project was provided by USDA Western SARE, USDA-BRDI, and Montana Agricultural Experiment Station.

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