Irrigation response and water productivity of deficit to fully irrigated spring camelina

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1. Introduction

Production of biofuel crops created major interest with the passage of the Energy Policy Act of 2005 (http://www.afdc.energy.gov/laws/epact_2005.html) which was extended and expanded by the Energy Independence and Security Act of 2007 (<http://www.afdc.energy.gov/laws/eisa/>). The bulk of energy research has focused on oil-seed crops as a biomass source for biodiesel production. Camelina [*Camelina sativa* L. Crantz] is an ancient crop that has been produced for many years in different parts of the world (Knorzer, 1978; Putnam *et al.*, 1993). Recent interest in its potential as a biofuel (Bernardo *et al.*, 2003; Frohlich and Rice, 2005; Moser and Vaughn, 2010; Zaleckas *et al.*, 2012) and even as a jet fuel source (Shonnard *et al.*, 2010) have been reviewed. Life cycle analysis of camelina as a biodiesel source shows its greenhouse gas emissions are 75-80% less than common petroleum fuels (Shonnard *et al.*, 2010). Its high unsaturation levels of fatty acids result in poor oxidative stability which could limit camelina as a stand-alone biodiesel (Frohlich and Rice, 2005; Moser and Vaughn, 2010; Zaleckas *et al.*, 2012). Blended camelina esters may be similar to soybean esters (Moser, 2010) and may be comparable to soybean biodiesel (Soriano and Narani, 2012). Part of the attraction of using camelina as a biofuel source is that it is considered a non-food crop, although camelina meal can be used as an animal feed (Pilgeram *et al.*, 2007).

Camelina could be adapted for production in wheat-fallow rotations in the Great Plains of the USA (Aiken *et al.*, 2015; Allen *et al.*, 2014; Obour *et al.*, 2015; Pavlista *et al.*, 2011a; Schillinger *et al.*, 2012). Research on camelina irrigation requirements are limited, with much of the research from Arizona using surface irrigation to achieve different levels of soil water depletion (French *et al.*, 2009; Hunsaker *et al.*, 2013). Pavlista *et al.* (2012) compared growth patterns of camelina to canola (*Brassica napus*) and brown mustard (*Brassica juncea*) under low irrigation. One of the limitations with shallow seeded *camelina* is germination under unpredictable spring precipitation in the Great Plains. If necessary, light irrigations at seeding facilitated improved germination and stand and make it a good candidate for limited irrigation (Aiken *et al.*, 2015; Pavlista, *et al.*, 2016a).

Temperature effects during camelina flowering have not been researched extensively and this could be a constraint for spring *camelina* as much of the initial research was in Montana (Pilgeram *et al.*, 2007). Heat and moisture

effects on oil seed crops, however, have been known for many years (Canvin, 1965). The effect of higher temperatures on reducing seed yield are often accentuated by reduced rainfall; however, the effect of reduced rainfall might be minimized by timely irrigation similar to canola (Kamkar *et al.*, 2011).

Decreased ground water allocations (volumetric pumping restrictions) were initiated in 2004 for the northern High plains of western Nebraska (Bleed and Babbitt, 2015) and the need to determine water productivity response of potential biofuel crops was needed. Many areas of the High Plains have reduced irrigation amounts due to periodic drought (Basara *et al.*, 2013), ground water pumping allocations (Bleed and Babbitt, 2015) and reservoir supplies used for irrigation and aquifer recharge that are affected by a changing climate (Anderson and Woosley, 2005).

The concept of deficit irrigation has been known for many years (English, 1990) and has been researched as a production strategy on many conventional crops in Nebraska (Garrity *et al.*, 1982; Hergert *et al.*, 1993; Klocke, *et al.*, Payero, *et al.*, 2006; 1989; Schneekloth *et al.*, 1991) and more recently on canola (Hergert *et al.*, 2016; Pavlista *et al.*, 2016b), but not camelina. The goal of deficit irrigation is to manage irrigation timing so the resulting water stress has less of a negative impact on grain yield.

The objectives of this research were to determine the effects of deficit to full irrigation on the yield, oil content, soil water changes and water productivity of spring camelina.

2. Methods and materials

This experiment was conducted during the growing seasons of 2007 through 2010. Spring camelina (cv. Cheyenne) was planted under linear irrigation systems at the Panhandle Research and Extension Center, Scottsbluff, NE (41.89° N, 103.68° W) and the High Plains Ag Lab, Sidney, NE (41.23° N, 103.02° W). The soil at the Scottsbluff site was a Tripp very fine sandy loam (coarse-silty, mixed, superactive, mesic Aridic Haplustolls) whereas the soil at the Sidney location was a Keith silt loam (fine-silty, mixed, superactive, mesic Aridic Argiustolls). The slope at both sites ranged from 0.5% to 1%. Other site characteristics are given in Table 1. Soil characteristics are for the top 30 cm. Previous crops before camelina at Scottsbluff were dry beans (*Phaseolus vulgaris*) in 2006, 2007 and 2008 and potatoes (*Solanum tuberosum* L.) in 2009. Previous crops before camelina at the High Plains Ag Lab were proso millet (*Panicum miliaceum* L.) in 2006, 2007 and 2008 and winter wheat (*Triticum aestivum* L.) in 2009.

The plots were 7.6 m wide by 9.1 m long, with treatments replicated three times in a randomized complete block design. The irrigation system used was a Lockwood electric linear move with 5 spans 53 m in length with a Lindsay™

variable speed control panel. The system was plumbed with drops at 1.5 m spacing and nozzles located 1.4 to 1.5 m above ground level, each equipped with a manual turn off. The height of adjacent drops was varied (e.g., one at 1.4 m then the next at 1.5 m, etc.) to reduce overlap interference with the spray pattern. The nozzles used on each drop were 3000 series 3T #22 (Nelson Irrigation Corporation) that had maximum output of 10 l min⁻¹. The irrigation system was operated at 207 KPa. This arrangement provided a spray pattern diameter of 5.5 to 6 m which provided low instantaneous application rates that allowed maximum time for infiltration and no runoff. The combination of variable speed and the ability to turn off every other nozzle allowed water applications from 2.5 to 38 mm hr⁻¹, however, regardless of water application amount, the system applied 10 mm hr⁻¹ which was below the soil's infiltration capacity.

Rain gauges were placed within plot areas to record irrigation and rainfall. Soil water content in 0 to 15 cm was determined gravimetrically every week, while water content at soil depths of 30, 60, 90, 120 and 150 cm was determined from weekly neutron probe measurements in each plot (503 DR Hydroprobe®, CPN International, Inc.). Neutron access tubes were installed two weeks after planting to allow evaluation of stand uniformity as camelina emergence required 7 to 14 d depending on yearly weather conditions. This allowed tube placement into similar stand uniformities and helped reduce spatial variability.

Planting and harvest dates are shown in Table 2. Sowing was early to mid-April at rates of 3 to 3.5 kg ha⁻¹ of pure live seed (PLS) in 20-cm row spacing with a double-disc drill. A planting depth of 10 mm was targeted. Fertilization was based on expected yield, soil organic matter and nitrate-N tests using canola fertilizer guidelines (Boyles, *et al.*, 2006) but N rates were reduced 30% based on the literature (Putnam, *et al.*, 1993; Zubr, 1997). The residual nitrate level in most of the plots was high enough in most years that a preplant blanket application of 200 kg ha⁻¹ of ammonium sulfate (21-0-0 24S) provided sufficient N and S. P and K levels were also high (above critical level) and no fertilizer was required.

The herbicide trifluralin (Treflan® HFP) at 1.2 l ha⁻¹ was soil incorporated preemergence for weed control. Plots were hand weeded as necessary and routinely scouted during the summer for insect damage; however, no significant insect problems were observed. Azoxystrobin (Quadris®) at 0.73 l ha⁻¹ was used as a fungicide for downy mildew (*Peronosporaceae*) control during periods of cool/wet weather during 2009 and 2010. Disease was more severe at Sidney than Scottsbluff.

In many areas of the High Plains where ground water levels have declined or where pumping restrictions are enforced, producers who do not have enough water to meet full crop ET must use a different application and timing strategy than traditional full irrigation scheduling. Every rotation of a center pivot sprinkler increases cost, so if a producer can only apply 100 mm and they are not limited

by well capacity, they will apply 5 irrigations of 20 mm rather than applying 10 irrigations of 10 mm.

The irrigation timing used in this experiment was designed to prolong flowering and limit stress during seed fill. This strategy was patterned after canola (Faraji, et al., 2009; Gan et al., 2004; Hergert et al., 2016; Kamkar, et al., 2011). Previous research has shown that for most grain crops, applying limited water around flowering through early grain fill provides the greatest response to water (Anapalli et al., 2014; Hergert et al., 1993; Klocke et al., 1989). For the 100 mm treatment, irrigations were timed around early flowering through early grain fill. Depending on precipitation and the growing season, 60-70% of the total irrigation water was applied for each treatment during this time. The 200 mm treatment usually allowed irrigation from vegetative through mid- to late grain fill, depending on precipitation. The goal for this irrigation treatment was to apply 80% of the total water during this period. The 300 mm treatment allowed season-long irrigation that was based on weekly ET from water balance calculations. Irrigation application rates of 13 or 19 mm were used in this research to simulate expected producer practices. Our highest rate of 19 mm was applied over 2 hours and did not exceed the infiltration capacity of our soils. For higher weekly irrigation requirements (e.g., 40 mm) biweekly irrigations were used.

Crop evapotranspiration (ET) was calculated every week for all plots at the two locations using the standard water balance equation as

$ET = P + I - DP - R \pm \Delta S$ where ET is evapotranspiration, P is precipitation, I is applied irrigation, DP is deep percolation, R is surface runoff and ΔS is the weekly change in stored soil moisture. Values for precipitation, irrigation and changes in soil water content were measured or calculated for each replicate and averaged to compute a weekly water use (ET). No runoff was observed from plots after irrigation at either location. Adjustments were made for two precipitation events in 2009 and one in 2010 that did create runoff to calculate effective rainfall. Weekly water content at deeper soil depths did not show significant increases after the heavy rainfall events which indicated that deep percolation was negligible. Based on this, the equation was modified to $ET = P + I \pm \Delta S$ for soil water balance calculations.

Seed harvest occurred in mid- to late July, depending on crop maturity at the two locations. To minimize potential yield losses associated with delayed harvest (i.e., pod shattering due to wind, rain, hail, and bird feeding) and to assure a yield value, plots were either harvested by hand and/or with a small-plot combine. An area 1 m by 1.2 m was hand harvested by placing clipped plants in fine plastic mesh drying bags when the majority of seeds had a moisture content of 12-14% and were subsequently air dried and hand threshed when seed moisture was approximately 10%. Hand harvest occurred about a week to 10 d before combine harvest. Plots (1.2 m by 9 m area) were combine harvested when the majority of seeds had a moisture content of 8-10%. All harvested seed samples were weighed for yield and analyzed for moisture (Dickey-John® GAC 2100

Grain Analysis Computer).

Oil content was determined on samples for 2007 through 2010. Pulsed Nuclear Magnetic Resonance (pNMR) was used for total oil content. The analytical details are provided in Pavlista, *et al.*, 2011b.

Seed yield and oil content from all sites and years was analyzed using the SAS software program PROC GLIMMIX (SAS Inst., 2014). Individual sites were analyzed using PROC GLM (SAS Inst., 2014) and Duncan's Multiple Range Test.

3. Results

3.1. Soil water content and rooting depth

Rainfall during the growing seasons (Table 3) varied substantially over the 4 years ranging from 35% to 128% of the long term average (NOAA, 2015) at Scottsbluff and from 87% to 172% at Sidney. This variability provided a wide range of conditions to determine plant growth and rooting depth from soil moisture extraction. Precipitation at Scottsbluff during 2007 and 2008 was well below the long term average. At Sidney, 2007 precipitation was near average and 2008 was below average. Precipitation was well above average at both locations in 2009 and slightly above average in 2010.

The weekly soil moisture measurements were used to develop soil water use patterns. Soil water contents at the beginning and end of a crop growing season at the various soil depths helped determine the degree and depth of rooting development within the soil. The 2008 growing season was drier than normal at Scottsbluff and the data was used to show soil water content changes/rooting. Similar data were collected for the Sidney location but not shown. The initial soil water content of the Scottsbluff soil in 2008 was just slightly below field capacity soon after planting (Fig 1). All treatments received two small irrigations of 6 mm each to assure uniform emergence. The non-irrigated camelina (Fig 1a.), was able to extract soil water to about 1.0 m. The data show no significant water extraction below this depth. At both Scottsbluff and Sidney, a calcium carbonate/caliche layer at 1.2 to 1.5 m was dense enough that we could not install neutron access tubes any deeper.

Similar moisture extraction patterns were shown for the low and medium irrigation treatments that received 100 and 200 mm of water (Fig 1b and 1c). Most of the moisture extraction was from the top 60 cm. For all irrigation treatments, soil water content was near permanent wilting point at a volumetric water content of $0.10 \text{ m}^3 \text{ m}^{-3}$ in the surface 15 cm layer. There was little change in soil water content below 60 cm in all irrigation levels. Volumetric water contents at depths below 60 cm were similar to preplant levels. Due to high ET demand, the "high irrigation" treatment received 356 mm of irrigation plus 135

mm of rainfall at Scottsbluff during 2008. Sidney also showed moisture extraction/rooting depths near 1.0 m.

3.2. Seed yield

Seed yield analysis (Table 4) showed that all main and interaction effects were significant, so seed yield data is shown by individual sites and years (Table 5). Yield of fully irrigated treatments were three to four-fold higher than the non-irrigated treatment during dry years of 2007 and 2008. During the wetter years (2009 and 2010 at Scottsbluff) there was no response to irrigation, however, other factors also influenced final yield.

Non-ET limited yields during 2007 and 2008 were good except for the Sidney location in 2008 which suffered hail damage. Yields in 2009 and 2010 were reduced significantly by weather and disease. Freezing temperatures across the region in 2010 on April 24 reached -4.5°C when camelina was about 4 to 5 cm tall. Snow and cold temperature on May 11 and 12 also affected the crop. During June, all locations had moderate hail and hard rain. Downy mildew (*Peronosporaceae*) caused significant damage during the cool and wet weather during 2009 and 2010 (Harveson *et al.*, 2011). Azoxystrobin (Quadris®) applications helped somewhat at Scottsbluff, but disease severity at Sidney in 2009 may have required earlier and repeated fungicide application. In 2010 yield levels at Scottsbluff and Sidney were similar and there was a significant irrigation effect at Sidney.

3.3 Yield response to irrigation and evapotranspiration.

Seed yield as affected by irrigation for all years and locations differed by seasonal precipitation amounts. Data was divided into wet years and dry years, based on comparison to the long-term average precipitation (Table 3, Fig. 2). Yield versus irrigation for 2009 and 2010 did not show any relationship. Data for both locations during 2007 and 2008 showed a curvilinear response to increasing irrigation (Fig. 2). A quadratic model had a higher R^2 (0.84) but was not statistically different than a simple linear model ($R^2 = 0.82$). Maximum seed yields near $2,900 \text{ kg ha}^{-1}$ were reached.

ETc data for the growing season are shown in Table 6. Seed yield versus ET for spring camelina is shown in Fig. 3. The 2009 Sidney data were not included due to severe disease pressure and very low ETc and seed yields. The function is described by a linear regression with the slope and x-intercept corresponding to water productivity and a threshold water use value. The water production function for camelina predicted a yield increase of 7.0 kg ha^{-1} of seed for each mm of water use above the threshold amount required to produce the first unit of seed yield (125 mm). Camelina seed yields ranged from 578 to $2,865 \text{ kg ha}^{-1}$ with 200 to 526 mm of cumulative water use.

Detailed plant growth data were taken from these plots (Pavlista *et al.*, 2016a). Camelina seed was considered mature and ready for harvest when the pods desiccated and hardened, and the seed color changed from green to cinnamon orange. During the very dry 2008 growing season, the effect of different irrigation levels on maximum crop ET, the length of crop water use and effects on crop maturity were significant (Fig. 4). The physiological maturity dates for the different water levels were: 0 mm: 14 weeks after planting (WAP); 100 mm: 15 WAP; 200 mm: 16 WAP and 300 mm: 17 WAP. Although the maximum and total crop ET are directly related to increased levels of irrigation, each water use function exhibited “peak values” in water use at 9 to 11 weeks after planting. Thereafter, “peak” water use for each irrigation treatment continued for approximately 12 to 18 d before declining. Phenology data collected from camelina plots in Scottsbluff during 2007 and 2008, indicate that observed “peak” values in water use are associated with maximum vegetative growth and flowering (Pavlista *et al.*, 2016a). Continued water use was related to pod and seed development. Maximum water use approached values for canola (Hergert *et al.*, 2016) and maize (Payero *et al.*, 2006) during the hot and dry conditions of 2007 and 2008.

Different irrigation treatments also significantly affected maturity dates (Fig. 4). There was about a 3 week difference between the maturity of the non-irrigated treatment and the 300 mm irrigation level. Camelina adapted to water deficits by reducing ET and maturing more rapidly. In contrast to 2008, the growing season of 2009 had above average rainfall, however, Downy mildew (*Peronosporaceae*) limited yields even though fungicide was applied as a control measure. Consequently, there was no significant difference between any of the irrigation levels for water use, crop development, maturity and yield. Maximum weekly water use was only 44 mm in 2009 due to limited growth from disease compared to 63 mm in 2008 when conditions were very favorable for growth.

3.4 Oil Content

Statistical analysis showed that all main and interaction effects were significant except for site by irrigation (Table 7), so data is shown by individual sites and years (Table 8). Oil content was low during the drier and warmer years of 2007 and 2008 compared to expected values of 32 to 38%. Yield and oil content were increased by irrigation at all sites in 2007 and 2008 and oil was increased at all sites except Sidney. The total oil production (data not shown) increased with irrigation amount at both sites for both years. In 2009 and 2010 when rainfall was above average and temperatures were cooler, oil content was higher except at Sidney where there was significant disease.

4. Discussion

4.1 Camelina Management

Camelina is a recently cultivated crop in the High Plains and has not had the advantage of years of plant breeding improvement similar to spring canola (Obour *et al.*, 2014). Yield potential of spring camelina with our climatic conditions was between 2600 to 2900 kg ha⁻¹. This is significantly higher than rainfed or dryland production in semi-arid climates (Getch and Johnson, 2015; Sintim *et al.*, 2016b) or under irrigation in Arizona (French *et al.*, 2009; Hunsaker *et al.*, 2011; Hunsaker *et al.*, 2013). Similar yields have been reported in Eastern Europe (Vollmann *et al.*, 2007) and in Washington (Schillinger *et al.*, 2012). Yield potential during above average precipitation years may be a problem because of disease. The 2009 growing season precipitation was exceptionally high and there were many cloudy, high relative humidity days which is uncommon for our semi-arid climate. We also experienced some hail and freezing temperatures in 2010 that limited yield when precipitation was only 15 to 17% above the long-term average.

A management difficulty with spring camelina is shallow seeding depth. The very small seed requires adequate soil moisture for about two weeks after planting to insure uniform germination and a good stand (Aiken *et al.*, 2015; Obour *et al.*, 2015; Pavlista *et al.*, 2011a). In our sandy soils and semiarid climate, rainfall most years may not be sufficient to produce a good stand. One or two small irrigations of 5 to 7 mm was usually sufficient to insure a good stand.

Pod shattering was a problem when direct combine harvest was used. Comparison of early hand harvest with combine harvest ranged from 10% to 15% grain loss due to shattering which is similar to other research in this region (Sintim *et al.*, 2016a). Genetic improvement could overcome this problem, but there is currently limited funding and biodiesel production has lagged from lack of US government action. If recent alternative oilseed crops are to compete for crop acreage, innovative and faster breeding improvement will be required (Runck *et al.*, 2014) as well as research into weed control options. Disease severity (downey mildew) during 2009 and 2010 was more pronounced on camelina than canola at our locations (Hergert *et al.*, 2016). For canola, years of genetic improvement have created cultivars that have resistance to a number of diseases. Camelina has also shown resistance to a number of diseases (Eynck *et al.*, 2013), but it has not been grown widely enough to test that natural resistance. Camelina showed more resistance to flea beetle (*Phyllotreta* sp.) than canola in our research (Hergert *et al.*, 2016). The complete package of supporting agronomic traits and practices are still being developed for camelina.

4.2 Soil Water Use

Camelina showed soil water withdrawal to 0.9 to 1.0 m usually reaching those depths midway through flowering. Most of the soil water depletion was in the top 60 cm. These are somewhat shallower than rooting depths shown for canola in the Great Plains (Gan, *et al.*, 2009; Hergert *et al.*, 2016; Merrill, *et al.*, 2002; Nielsen, 1997) or Arizona (Hunsaker *et al.*, 2013) but similar to winter

camelina (Gesch and Johnson, 2015). Camelina also did not deplete soil water during the season as much as spring canola (Hergert, *et al.*, 2016) throughout the soil profile. This may again be a reflection of less vigor from limited genetic improvement.

The soil moisture extraction pattern was similar for both locations. Deep rooting and effective use of stored soil water are essential in deficit irrigated areas to extract deeper soil moisture to supplement seasonal precipitation and irrigation. Rotations in the High Plains that include dry beans, winter wheat, sugar beet (*Beta vulgaris*) and maize would usually provide sufficient deeper soil moisture from the previous crop to allow deficit irrigated production with a crop that can effectively extract that moisture from below 0.8 to 1 m.

4.3 Water Productivity

Camelina showed significant response to irrigation in drier years. During higher rainfall years there was no response to irrigation. During 2009 and 2010, response was affected not only by additional precipitation but freezing late spring temperatures and disease. In drier years, irrigation response was almost linear with maximum irrigation of 300 to 350 mm required for highest yield

Cumulative water use under non-limiting conditions showed maximum ET_c of 450 - 500 mm. This is about 100 mm less than for canola at this site (Hergert *et al.*, 2016), however, canola yields were higher than camelina yields. The slope for the yield-ET line for camelina was 7.0 kg mm⁻¹ whereas canola was 10% higher (7.7 kg mm⁻¹). Hunsaker *et al.*, (2013) showed values that were about half of this, but their air temperature during mid-season were much higher than the High Plains during the heat of our summer. Threshold water use for both crops was near 125 mm. The ET values are similar to other published work on canola in this region (Nielsen, 1997).

There was a significant effect of deficit irrigation on crop response in terms of maximum water use and maturity (Fig. 4). Deficit irrigation significantly reduced maximum ET and also accelerated maturity. The additional ET from the fully irrigated treatment versus lower irrigation amounts allowed additional biomass production which ultimately resulted in more yield (Pavlista *et al.*, 2016). With good stand establishment and with average precipitation in this region, spring camelina could be an option for deficit irrigation as applying 60 to 70% of full irrigation would provide good yields.

There was a wide range in oil content during this experiment and it was significantly influenced by yearly weather and disease. This effect has been known for many years in Canadian canola production areas (Canvin, 1965). The range of oil content is consistent with other US research (French *et al.*, 2009; Hunsaker *et al.*, 2013) and other areas of the world (Berti *et al.*, 2011; Vollmann *et al.*, 2007). Because we experienced a wide range of weather conditions over

the four years of the study, we were able to observe the impact of different conditions on camelina oil production in the High Plains. In drier years when temperatures during seed filling were higher, oil content was increased by irrigation but not to levels above 30%. Alleviation of water stress can compensate somewhat for higher temperatures, but not totally. The economic benefit of the increased oil production compared to the increased cost of the irrigation could be calculated to determine break even irrigation values. The impact of disease at Sidney in 2009 shows its damaging effects on oil content. Economically, this is an important fact as producers consider deficit irrigation of camelina. During the very wet year of 2009, which also had cooler summer temperatures, there was no effect of irrigation and oil content was high. In 2010, temperatures during grain fill were ideal and oil content was very high.

5. Conclusions

The rooting depth of camelina in both fine textured and sandy soils in western NE is sufficient to make it a viable alternative for deficit irrigation. Most of the rainfall in the northern High Plains occurs in spring (May and June). Precipitation plus limited irrigation at critical times provides an opportunity for camelina to use moisture stored in the lower part of the soil, but it does not root as deeply as canola. This is somewhat of a limitation that will need to be overcome by genetic improvement if commercial production is developed.

Camelina seed yield was sufficiently high during the varied precipitation conditions throughout the four years of this study to show its production potential which match that of other regions in the world. The yield potential in this region with irrigation was significantly higher than has been reported in most rainfed areas in the US (Gesch and Johnson, 2015; Hunsaker et al, 2013; Sintim et al, 2016a, 2016b). Applying 210 to 250 mm of irrigation in drier years which would be 60% to 70% of fully irrigated conditions produced yields of 78% and 87% of maximum. At these irrigation levels in drier years the additional water also increased oil content. Deficit irrigation decreased peak water use compared to non-ET limiting conditions and also hastened maturity. However, proper timing of deficit irrigation during flowering to early grain fill during severe moisture stress years produced significantly more yield than the non-irrigated treatment.

Natural Resource Districts in western NE are currently allowing yearly allocations of between 300 and 350 mm of irrigation (Bleed and Babbitt, 2015). Applying only 50% to 70% of the irrigation allotment would make deficit irrigated camelina an attractive lower water use cropping option when grown in rotation with higher water requiring crops. The additional benefits of not only higher yield, but also higher oil content makes deficit irrigated camelina a possible biofuel crop for this region.

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Table 1. Site characteristics for the two camelina locations for the top 20 cm.

Location	Elevation	Annual Precipitation	pH	Organic Matter	Θ_v Field Capacity*	Θ_v Wilting Point*
Scottsbluff	1189 m	394 mm	8.2	1.5%	0.23 - 0.28 m ³ m ⁻³	0.11 m ³ m ⁻³
Sidney	1247 m	404 mm	7.5	2.2%	0.25 - 0.31 m ³ m ⁻³	0.13 m ³ m ⁻³

* National Cooperative Soil Survey
National Cooperative Soil Survey Characterization Database
<http://ncsslabsdatamart.sc.egov.usda.gov/>
Accessed Thursday, June 02, 2016

Table 2. Camelina planting and harvest dates.

Site		Years			
		2007	2008	2009	2010
Scottsbluff	Sowing	15 Apr	8 Apr	10 Apr	9 Apr
	Harvest	24 Jul	24 Jul	20 Jul	8 Jul
Sidney	Sowing	18 Apr	16 Apr	8 Apr	12 Apr
	Harvest	18 Jul	25 Jul	13 Jul	14 Jul

Table 3. Growing season precipitation* at the two plot locations (April to harvest).

Site	Years					
	2007	2008	2009	2010	30 y avg.	
		----- mm -----				
Scottsbluff	Apr	29	17	65	66	43
	May	30	57	47	83	84
	Jun	8	38	149	110	71
	Jul	12	23	31	9	30
	Total	79	135	292	268	228
Sidney	Apr	94	35	96	63	36
	May	75	66	41	59	71
	Jun	50	76	252	102	74
	Jul	11	32	21	50	58
	Total	230	209	410	274	239

* NOAA, 2015. <http://www.ncdc.noaa.gov/cdo-web/>.

Table 4. Analysis of variance of camelina yield over all years.

Effect	Prob >F
Site	<0.01
Irrigation	<0.01
Site x irrigation	0.01
Year	<0.01
Site x year	<0.01
Irrigation x year	<0.01

Table 5. Camelina seed yield (kg ha⁻¹) at different irrigation treatments for different locations 2007 through 2010.

		2007	2008	2009	2010
Site	Irrigation-mm				
Scottsbluff	0	833d	768d	1574a	1036a
	100	1356c	1495c	1481a	1159a
	200	2004b	2139b	1575a	1144a
	300	2587a	2867a	1608a	1146a
Irrg effect					
Pr>F		0.01	0.01	0.29	0.35
CV		6.5%	10.8%	7.1%	6.6%
Sidney	0	1147c	578c	428a†	644c
	100	1952b	1330b	446a	741c
	200	2521a	1661a	449a	937b
	300	2671a	1931a	457a	1120a
Irrg effect					
Pr>F		0.01	0.01	0.57	0.01
CV		6.0%	11.7%	5.2%	8.6%

*Values followed by the same letter are not significantly different at the P<0.05 level based on least significant differences;
 NS = non-significant at P<0.05.

† Plot had severe disease.

Table 6. Soil water balance data (ETc) for the Scottsbluff (SB) and Sidney (HP) locations.

Year	Site	Rainfall	Irrigation	Δ Soil water	ETc
----- mm -----					
2007	SB	66	15	-99	180
2007	SB	66	102	-109	277
2007	SB	66	203	-102	371
2007	SB	66	305	-89	460
2007	HP	221	15	-64	300
2007	HP	221	89	-51	361
2007	HP	221	203	-51	475
2007	HP	221	262	-3	485
2008	SB	112	15	-86	213
2008	SB	112	107	-64	282
2008	SB	135	216	-51	401
2008	SB	137	356	-33	526
2008	HP	145	15	-41	201
2008	HP	145	114	-41	300

2008	HP	145	203	-28	376
2008	HP	145	267	-30	442
2009	SB	292	20	-33	345
2009	SB	292	33	-3	328
2009	SB	292	43	-5	340
2009	SB	292	43	-3	338
2009	HP	318	18	69	267
2009	HP	325	38	94	269
2009	HP	325	51	86	290
2009	HP	325	51	94	282
2010	SB	218	13	-76	307
2010	SB	218	58	-51	328
2010	SB	218	94	-30	343
2010	SB	218	94	-30	343
2010	HP	244	38	3	279
2010	HP	244	38	-13	295
2010	HP	244	74	3	315
2010	HP	244	74	-3	320

Table 7. Analysis of variance of camelina oil content over all sites.

Effect	Prob >F
Site	0.01
Irrigation	0.01
Site x irrigation	0.38
Year	<0.01
Site x year	<0.01
Irrigation x year	<0.05

Table 8. Camelina oil content (%) for different locations 2007 through 2010.

Year		2007	2008	2009	2010
Site	Irrigation-mm				
Scottsbluff	0	29.7ab	25.7c	38.6a	41.1a
	100	28.1c	26.9b	40.3a	42.8a
	200	28.9bc	27.4b	38.7a	43.9a
	300	30.1a	28.6a	38.8a	44.2a
Irrg effect					
Pr>F		0.02	0.01	0.19	0.57
CV		1.9%	1.4%	2.4%	6.7%
Sidney	0	29.4a	25.4c	29.3a	47.9a
	100	29.9a	25.7c	29.2a	47.2a
	200	29.8a	27.1b	29.2a	49.8a
	300	30.0a	27.6a	29.1a	47.8a
Irrg effect					
Pr>F		0.41	0.01	0.99	0.30
CV		1.4%	1.0%	3.7%	3.3%

*Values followed by the same letter are not significantly different at the
P<0.05 level based on least significant differences; NS = non-significant at P<0.05.

List of Figures

Figure 1. Seasonal soil water content change at Scottsbluff, Nebraska during the dry year of 2008.

Error bars show $\pm$ standard error of the mean.

Figure 2: Irrigation effect on camelina seed yield (2007-2008).

HP-07 and HP-08 were Sidney, NE locations in 2007 and 2008.

SB-07 and SB-08 were Scottsbluff, NE locations in 2007 and 2008.

Figure 3: Water use and seed yield for camelina (2007-2010).

HP-07, HP-08 and HP-10 were Sidney, NE locations in 2007, 2008 and 2010.

SB-07, SB-08, SB-09 and SB-10 were Scottsbluff, NE locations in 2007, 2008, 2009 and 2010.

Figure 4. Weekly crop water use for camelina at different irrigation levels at Scottsbluff, Nebraska in 2008.

■ HP-07 ● SB-07 □ HP-08 ○ SB-08 ● SB-09 ■ HP-10 ● SB-10

Graphical Abstract caption Rev3

Camelina is on the left and canola on the right side of the photo. The highest irrigation level is in the middle of the plant grouping with no irrigation on the ends.