Yield, irrigation response, and water productivity of deficit to fully irrigated spring canola

G. W. Hergert\textsuperscript{a}, J.M. Margheim\textsuperscript{a}, A.D. Pavlista\textsuperscript{a},
D. L. Martin\textsuperscript{b}, R.J. Supalla\textsuperscript{b} and T.A. Isbell\textsuperscript{c}

\textsuperscript{a} University of Nebraska-Lincoln, PREC, Scottsbluff, NE 69361, USA
\textsuperscript{b} University of Nebraska-Lincoln, Lincoln, NE, 68583, USA
\textsuperscript{c} USDA-ARS, Peoria, IL 61604, USA

1. Introduction

Irrigation was introduced to provide more stability and profit to Great Plains agriculture and the High Plains aquifer is a primary source of irrigation water. Irrigation pumping began in the 1920’s and by the 1980’s had transformed 6.5 million ha of dryland crop production and rangeland into highly productive farmland (Supalla \textit{et al.}, 1982). The High Plains aquifer underlies 445 million ha in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. Water-level declines began in parts of the aquifer by 1950. Many areas of the High Plains region now face reduced irrigation amounts due to periodic drought (Basara \textit{et al.}, 2013), ground water pumping allocations (Bleed and Babbitt, 2015) and reservoir supplies that irrigate areas that recharge the aquifer but are affected by a changing climate (Anderson and Woosley, 2005).

The production of biofuel crops can compete for crop production area and irrigation water if there is an economic incentive to increase production. This incentive, and supporting research for biofuel crops, was realized with passage of the Energy Policy Act of 2005 (\url{http://www.afdc.energy.gov/laws/epact_2005.html}) which was extended and expanded by the Energy Independence and Security Act of 2007 (\url{http://www.afdc.energy.gov/laws/eisa/}). This legislation has been the driving force for the production of ethanol from maize (\textit{Zea mays} L.) and in Nebraska, alone, accounts for 30% of the crop being used for biofuel, which does not include 25% of the crop that is exported for both feed and ethanol production (\url{http://www.nebraskacorn.org/corn-production-uses/corn-usage/}).

The western portion of the Central Great Plains of the US is defined as the northern High Plains region and has lower rainfall, sandier soils and higher elevation than the eastern portion. In recent years, alternative energy research has focused on oil-seed crops as a biomass source for biodiesel production. Oil seed crops considered as biodiesel alternatives include brown mustard (\textit{Brassica juncea}), canola (\textit{Brassica napus}) (Pavlista \textit{et al.}, 2011b), camelina (\textit{Camelina sativa}) (Obour \textit{et al.}, 2015), safflower (\textit{Carthamus tinctorius} L.), and sunflower (\textit{Helianthus annuus}). These crops are well adapted to the northern High Plains region and, therefore, are potential biofuel crops under dryland or limited water conditions (Pavlista \textit{et al.}, 2011a.).

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Since canola can yield over 1030 l ha\(^{-1}\) of oil compared to 560 l ha\(^{-1}\) for soybean (CAST, 2008), it has become a crop of particular interest for biodiesel production in the northern Great Plains. Spring canola has traditionally been grown under rainfed conditions in the northern Great Plains, as well as in Canada, but has recently been shown to be a viable option in the central High Plains of western NE (Johnston et al., 2002; Pavlista et al., 2011b). Canola yields are affected by high temperatures during flowering (Gan et al., 2004) and this can be a greater constraint for areas south of traditional spring canola growing regions.

The effect of higher temperatures on reducing canola yield are often enhanced by reduced rainfall; however, the effect of reduced rainfall could be minimized by timely irrigation and adequate N (Kamkar et al., 2011). Because decreased ground water allocations were initiated in 2004 for the northern High plains area of western Nebraska (Bleed and Babbitt, 2015), determining water productivity response of potential biofuel crops was investigated.

Yield of canola in semi-arid climates under irrigation covers a wide range (Dogan et al., 2011; Faraji, et al., 2009; Gan et al., 2004; Gan et al., 2009; Hamzei, 2011; Kamkar et al., 2011; Nielsen, 1997). The western NE latitude and elevation are similar to Iranian research but other environmental parameters are different. This was new research for the US when initiated in 2007 as preliminary work was just being completed on initial studies of investigating the feasibility of growing irrigated canola in the northern High Plains region (Pavlista et al., 2011b).

Deficit irrigation is defined as “the deliberate under-irrigation of the crop” by English (1990) and applies less water than is required to meet full evapotranspiration (ET). The goal is to manage irrigation timing such that the resulting water stress has less of a negative impact on grain yield. The strategy has been researched for many years. Previous NE research on limited irrigation (Garrity et al., 1982; Hergert et al., 1993; Klocke et al., 1989; Schneekloth et al., 1991) has looked at a range of crops, but not canola. Analytical tools (Water Optimizer) have been developed recently that can assist producers and water managers to assess reduced irrigation impacts on water balance and economic consequences for major crops of the Central Great Plains (Martin et al., 2010).

The objective of this research was to determine the effects of a range of water from no irrigation to full irrigation on the yield, oil content, soil water changes and water productivity of spring canola.

2. Methods and materials

The experiment was conducted in growing seasons 2007 through 2010. Spring canola (cv. Hyola 357 Magnum) 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). West of Alliance, NE (42.13° N, 103.20° W) canola was planted under a small center pivot irrigation system. The soil at Scottsbluff was a Tripp very fine sandy loam (coarse-silty, mixed, superactive, mesic Aridic Haplustolls); the soil at the Alliance location was a Creighton fine sandy loam (coarse-loamy, mixed, superactive, mesic Aridic Haplustolls); the soil at the Sidney location was a Keith silt loam (fine-silty, mixed, superactive, mesic Aridic Argiustolls). Other site characteristics are given in Table 1.

Plots were 7.6 m wide by 9.1 m long, with treatments replicated three times in a randomized complete block design. Rain gauges were placed within plot areas to record irrigation and rainfall. Soil water content from 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 canola emergence required 7 to 14 d depending on yearly climatic conditions. This allowed tube placement into similar stand uniformities and helped reduce spatial variability.

Throughout the study years, glyphosate tolerant canola was planted late March to early April at rates of 4 to 5 kg ha⁻¹ of pure live seed (PLS) in 20-cm row spacing with a no-till double-disc drill. A planting depth of 12 mm was targeted. Planting and harvest dates are shown in Table 2. Fertilizer was based on expected yield, soil organic matter and nitrate-N tests using fertilizer guidelines from Boyles, et al., 2006. The herbicide trifluralin (Treflan® HFP) at 1.2 l ha⁻¹ was soil incorporated for preemergence weed control. Canola seed was treated with thiamethoxam (Helix®-Xtra) for protection against flea beetle (Phyllotreta spp.). Canola plots were sprayed once with 1.1l ha⁻¹ glyphosate (Roundup) before the 6-leaf stage. Plots were hand weeded as necessary and routinely scouted during the summer for insect damage; however, no significant insect problems were observed. Azoxystrobin (Quadris®) was used as a fungicide for downy mildew (Peronosporaceae) control during periods of cool/wet weather during 2009 and 2010.

When producers have less water than is required to meet full crop ET, they must use a different application and timing strategy than traditional full irrigation scheduling. Each turn of the pivot 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. Irrigation application rates of 12.7 or 19.1 mm were used in this research to simulate producer practices. The highest rate of 19 mm was applied over 2 hours and did not exceed the infiltration capacity of the soils. With higher irrigation levels (e.g., 40 mm) biweekly irrigations were applied. 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.,...
Cumulative irrigation treatments had targeted amounts of 0, 100, 200, and 300 mm of water. The highest rate was set to be non-ET limiting and actual ET was used to calculate water use based on weather data from the High Plains Climate center (Changnon et al., 1990). Growing season water application for the highest irrigation level exceeded 300 mm in several instances due to high water demand. All treatments received light irrigations (5 mm) to enhance and ensure uniform seed germination and plant emergence.

Growing season rainfall at the three sites (Table 3) was dramatically different over the four years (NOAA, 2015). This provided an excellent range of conditions from drought to above average precipitation to determine plant growth and rooting depth from soil moisture extraction. Precipitation at Alliance and 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 all locations in 2009 and near average in 2010.

A soil water balance was calculated weekly for all plots at all locations. 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 (Allen, et al., 1998). The standard water balance equation is

\[
\text{ET} = P + I - \text{DP} - R + \Delta S
\]

where ET is evapotranspiration, P is precipitation, I is applied irrigation, DP is deep percolation, R is surface runoff and \(\Delta S\) is the weekly change in stored soil moisture. Since excessive runoff was not observed from plot areas after irrigation or precipitation events and deep percolation was negligible based on measurements of water content at deeper soil depths, the equation was modified to

\[
\text{ET} = P + I + \Delta S
\]

for soil water balance calculations.

Harvest occurred during late July to early August, depending on crop maturity at the different locations. To assure a yield value and to minimize potential yield losses associated with delayed harvest (i.e., pod shattering due to wind, hail, and bird feeding), plots were either harvested by hand and/or with a small-plot combine. Plots (1 m by 1.2 m area) were hand harvested by placing clipped plants in fine plastic mesh drying bags when the majority of seeds had a moisture content of 14-16% and, subsequently, air drying and hand threshing the
respective clippings 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 10-12%. All harvested seed samples were oven-dried at 100-105° C (1
wk) and, subsequently, weighed for yield and analyzed for moisture and test
weight (Dickey-John® GAC 2100 Grain Analysis Computer).

Oil content was determined on samples for 2007 through 2009. Pulsed
Nuclear Magnetic Resonance (pNMR) was used for total oil content. The
analytical details are provided in Pavlista, et al., 2011b.

Seed yield data 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 moisture extraction and rooting depth

Soil water use patterns were developed by comparing soil water contents at
the beginning and end of a crop growing season at the various, respective soil
depths. These patterns helped determine the degree and depth of rooting
development within the soil. The 2008 growing season was drier than normal at
Scottsbluff and Alliance. Scottsbluff data was used to show soil water content
changes/rooting, but similar data were collected for the other two sites 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). The no irrigation treatment
received two light irrigations of 6 mm each to assure uniform emergence. The
non-irrigated canola (Fig 1a.), was able to extract soil water from depths greater
than 1.2 m. The data show that water extraction and rooting may have occurred
below this depth but 1.2 m was the limit of measurement. At the Scottsbluff and
Sidney, NE locations, 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.

A similar moisture extraction pattern was shown for the low and medium
irrigation treatments that received 100 and 200 mm of water (Fig 1b and 1c). For
the three lower water levels, soil water content was near the permanent wilting
point at a volumetric water content of 0.10. At the highest irrigation level, there
was soil water use at deeper depths but, in comparison to other treatments at the
end of the growing season, volumetric water contents at these depths were
higher due to additional irrigations (Fig 1d). Due to high ET demand, the “high
irrigation” treatment received 355 mm of irrigation plus 135 mm of rainfall at
Scottsbluff during 2008. Data from the Alliance and Sidney sights showed
moisture extraction/rooting depths of 1.2 to 1.5 m.
3.2. Seed yield

Seed yield (Table 4) showed a wide range during different years and locations. Because all main and interaction effects were significant (Table 5), seed yield data is shown by individual sites and years (Table 4). Yield increases of fully irrigated treatments were five to six-fold higher than the non-irrigated treatment during dry years. During wetter years, there was no response to irrigation. Non-ET limited yields during 2007 through 2009 were excellent except for the Sidney location in 2008 which suffered hail damage. Yields in 2010 were also reduced significantly by weather. Freezing temperatures across the region on April 24 reached -4.5ºC when canola was about 4 to 6 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. The reduced yields show these effects. Without significant weather problems, the data do show that spring canola has good yield potential for producers in this area but also shows the degree of reductions from adverse weather.

3.3 Yield versus irrigation response

Irrigation versus seed yield over all years and locations fell into two groups: wet years and dry years, based on comparison to the long-term average precipitation (Table 3, Figure 2). Data for Sidney canola in 2008 are not included due to significant crop losses from adverse harvesting conditions. Data for Alliance canola (2009) is not reported due to complete crop loss from hail. Seed yield for yields during above average precipitation years showed a curvilinear response to increasing irrigation. The quadratic model had a significantly better fit ($R^2 = 0.67$) versus a linear model ($R^2 = 0.57$). The regressions exhibited a plateau showing that full evapotranspiration crop demand was attained at or near the respective maximums of cumulative irrigation water.

Seed yields in the dry years’ group showed an almost linear response to irrigation. A quadratic model had a higher $R^2$ (0.87) but was not statistically different than a simple linear model ($R^2 = 0.84$). Maximum seed yields near 3,300 kg ha$^{-1}$ were produced at the respective maximums of cumulative irrigation water for each response function.

3.4 Yield versus evapotranspiration

Figure 3 presents total evapotranspiration versus seed yield for canola. The function is described by a linear regression with the slope and x-intercept corresponding to a water use efficiency and threshold water use value.

The water use/seed yield production function for canola predicted a water use efficiency of 7.6 kg of seed for each mm of cumulative water use, with a threshold water use value of 123 mm. Canola seed yields ranged from 440 to 3,280 kg ha$^{-1}$ with 165 and 582 mm of cumulative water use.
3.5 Weekly and seasonal water use

The effect of different irrigation levels on maximum crop ET, the length of crop water use and effects on crop maturity were highlighted during the very dry 2008 growing season. Figure 4 shows the effect of different irrigation levels on the extent and duration of crop ET, as affected by water stress at Scottsbluff, NE.

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 8 to 9 weeks after planting. Thereafter, “peak” water use for each irrigation treatment continued for approximately 14-21 d before declining. Phenology data collected from canola plots in Scottsbluff during 2007, indicate that observed “peak” values in water use are associated with maximum vegetative growth and flowering (Pavlista et al., 2012). Continued water use was related to pod and seed development. Maximum water use approached values for maize (Payero et al., 2006) during the hot and dry conditions of 2007 and 2008.

Maturity dates were also significantly affected by different irrigation treatments. Figure 4 shows that there was about 3 weeks difference between the maturity of the non-irrigated treatment and the 300 mm irrigation level. The crop adapted to the water deficits by reducing ET and maturing more rapidly. In contrast to 2008, the growing season of 2009 had above average rainfall and there was no significant difference between any of the irrigation levels for water use, crop development, maturity and yield (data not shown). Downy mildew (Peronosporaceae) limited yields even though fungicide was applied as a control measure. Weekly water use was maximized near 43 mm per week in 2009, compared to a maximum value near 63 mm per week in 2008.

3.6 Oil Content

The analysis showed that all main and interaction effects were significant (Table 6), so data is shown by individual sites and years (Table 7).

During the drier and warmer years of 2007 and 2008, oil content was quite low. Yield and oil content were both increased by irrigation which provides a significant economic benefit. In 2009 and 2010 when rainfall was above average and temperatures were cooler, oil content was higher. These results are similar to those of Hamzi (2011) and Kamkar et al. (2011).

4. Discussion

4.1 Rooting Depth
Canola withdrew soil water to 1.2 to 1.5 meters usually reaching those depths about midway through flowering. Similar rooting depths have been shown for canola in the Great Plains (Gan, et al., 2009; Merrill, et al., 2002; Nielsen, 1997). Soil moisture extraction was similar for both fine textured and sandy soils. Deep rooting is essential in deficit irrigated areas to tap into deeper soil moisture to supplement the limited amount of water available. If canola were grown in current irrigated rotations in the High Plains that include dry beans (Phaseolus vulgaris), sugar beet (Beta vulgaris) and maize, there would normally be sufficient deeper soil moisture from the previous crop that would allow deficit irrigated canola production.

4.2 Water Productivity

In drier years, canola showed significant response to irrigation. Yield potential under our environment was between 3000 to 3300 ha⁻¹. The response in semi-arid climates under irrigation shows a wide range (Dogan et al., 2011; Hamzei, 2011; Kamkar et al., 2011; Nielsen, 1997). Our yields were significantly higher than those in Saskatchewan (Gan et al., 2009). During years with near average precipitation, irrigation of 150 to 170 mm produced near maximum yields. In drier years, irrigation response was almost linear with maximum irrigation of 300 mm or more required for full yield. In the wettest year (2009) there was no response to irrigation.

One of the limitations with spring canola is that the shallow seeding depth and 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). In our sandy soils and semiarid climate, rainfall most years may not be sufficient to produce a good stand. As noted here, one or two light irrigations of 5 to 7 mm was usually sufficient to insure a good stand. It can be the difference between near full yield and 30% yield if a good stand is not established. If a good stand is established and with average precipitation, spring canola would be a good deficit irrigation choice as applying 50 to 70% of full irrigation would provide good yields. The irrigation timing used in this experiment was designed to prolong flowering and limit stress during pod-fill. This is the most sensitive stage for stress (Faraji, et al., 2009; Gan et al., 2004; Kamkar, et al., 2011). Irrigation from the 100 mm irrigation level was held off until flowering to maximize efficiency. A different irrigation strategy e.g., uniform application through most of the season, would not produce similar results (Payero et al., 2009).

The yield versus evapotranspiration data showed 7.6 kg⁻¹ mm⁻¹ of cumulative water use, with a threshold value of 123 mm. These values are similar to those reported by Nielsen (1997) of 7.7 kg⁻¹ mm⁻¹ with a threshold of 157 mm. A much wider range of values (2.3 to 11.7 kg ha⁻¹ mm⁻¹) was shown in Turkey, depending on planting date (Faraji et al., 2009). The Mediterranean climate is much different than that of the High Plains, however. The significant effect of deficit irrigation on crop response in terms of maximum
water use and maturity in Fig. 4 show that deficit irrigation definitely reduced maximum ET and also hastened maturity. The additional ET from the fully irrigated treatment versus lower irrigation amounts allowed additional biomass production which ultimately led to more yield (Pavlista et al., 2016).

Oil content showed an extremely wide range during this experiment and was significantly influenced by yearly weather. This effect has been known for many years in Canadian production areas (Canvin, 1965). The low oil content during hot and drier years is something that growers must be aware of when considering canola production in the High Plains. In drier years when temperatures during seed filling were also higher, oil content was increased by irrigation but not to levels above 40%. Alleviation of water stress can compensate somewhat for higher temperatures, but not totally. The irrigation effect on oil content did not always occur at the lowest level of irrigation (100 mm) but was fairly consistent at the 200 mm level. Economically, this is an important fact as producers consider deficit irrigation of canola. 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. Because this research was conducted over 4 years, it encompasses a wide range of weather conditions that shows the effects of not only deficit irrigation but weather on the production potential of canola in the High Plains.

5. Conclusions

Canola rooting depth in both fine textured and sandy soils in western NE is sufficiently deep to make it a viable alternative for deficit irrigation. Because most of the rainfall in the northern High Plains occurs in spring (May and June), natural precipitation plus limited irrigation at critical times provides an opportunity for canola to use moisture stored in the lower part of the soil later in its growth cycle. Deep rooting is essential in deficit irrigated areas to tap into deeper soil moisture to supplement the limited amount of water available. If canola were grown in current irrigated rotations in the High Plains that include dry beans, sugar beet and maize, there would normally be sufficient deeper soil moisture that would encourage deficit irrigated canola production.

Seed yield of canola was sufficiently high during the varied precipitation conditions throughout the four years of this study to produce a profitable crop. Even with deficit irrigation, the yield potential was significantly higher than most rainfed areas in the northern Great Plains and Canada (Gan et al., 2004; Gan et al., 2009; Johnston et al., 2002). Applying 150 to 200 mm of irrigation which would be 50% to 67% of fully irrigated conditions in most years, yields were 93% and 100% of maximum in wetter years and 60% to 75% in very dry years. At these irrigation levels in drier years the additional water also increased oil content. Deficit irrigation affects growth by decreasing peak water use compared to non-ET limiting conditions and by also hastening 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.

One of the production concerns would be the effects of above average
temperatures on oil content. Irrigation did increase yield and oil content during
the dry years of 2007 and 2008, but oil content did not reach levels above 40%.
This may not be as much of an issue if spring canola were grown as a biofuel
crop versus being grown as a food oil. Because there is no established canola
market in this region, this is an unknown.

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
canola 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 canola an attractive alternative
production and biofuel crop for this region.

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