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Deficit irrigation and surface residue cover effects on dry bean yield, in-season soil water content and irrigation water use efficiency in western Nebraska high plains

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ABSTRACT

Considering ground water pumping restrictions and unpredictable amount of water available for irrigation from year to year, Nebraska Panhandle producers are facing a challenge to reduce their irrigation water usage and practice deficit irrigation. Among irrigated crops in the region, dry bean (a major cash crop and critical to crop rotation systems) has relatively low water use and is capable to withstand periods of stress. Consequently, two experiments within six consecutive growing seasons (2010–2015) were conducted to determine the impacts of multiple irrigation scenarios (full irrigation, deficit irrigation, and rainfed) and two soil surface conditions (bare soil versus crop residue) on dry bean production, irrigation water use efficiency, and temporal soil water dynamic within the crop root zone. Dry bean yield ranged from 0.41 to 4.07 Mg ha^{-1} during the six years of the study (2010–2015). The results (2012–2015) indicated that reducing irrigation water by 25% on average increased irrigation water use efficiency (I_{WUE}) by 26% and only caused 6% yield reduction in relative to the full irrigation treatment scenario. However, applying only 50% crop evapotranspiration requirement (ETc) resulted in significant yield reduction (30% reduction on average) in 5 out of 6 years compared to the full irrigation treatment ($p < 0.05$). Our results indicate that temporal in-season rainfall and ETc demand variabilities along with the per-season soil water content status should be carefully analyzed in order to target the appropriate growth stage(s) for more severe deficit irrigation scenarios. When pre and early season rainfall was abundant deficit irrigation treatments imposed before flowering outperformed treatments targeting after flowering. However, under normal and dry conditions yield decline was more pronounced due to severe early season (before flowering) water stress compared to late season (after flowering) water stress. In two of three years plots with bare soil significantly ($p < 0.05$) outyielded plots covered with residue. Average yield across irrigation treatments was 14% lower for plots with residue cover (average yield: 2.15 Mg ha^{-1}) compared to bare soil plots (average yield: 2.51 Mg ha^{-1}). Overall, the dynamic of soil water content within root zone and I_{WUE} in plots covered with residue was similar to that in bare soil plots across irrigation treatments throughout the growing seasons.

1. Introduction

Water resources used for agriculture are becoming more restricted throughout the world and as a result the use of water for irrigated crop production must become more efficient. Across the US, Nebraska has the highest amount of irrigated land (over 3.5 million ha) wherein irrigated agriculture accounts for more than 90% of all groundwater consumption (Irmak et al., 2010; USGS, 2000). Since available fresh water resources are limited, irrigation water management has evolved into a top priority issue which is a critical element of the state's agricultural production and economy.

The Panhandle District is the most diverse region, in terms of Nebraska's agriculture production areas consisting of almost 62,000 km^2 of land area representing nearly 31 percent of Nebraska. There are more than 5900 farms in the district generating in excess of \$2.35 billion of revenue. The region is unlike any other in the state, due to its high elevation, low precipitation, limited water resources and crops grown. In the Panhandle of Nebraska,

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irrigation plays an essential role in crop production, since evapotranspiration (ET) almost always exceeds precipitation. The result being, that both surface, and groundwater, are used to fulfill crop water requirements. The surface irrigation network is supplied by snowpack that originates in the Rocky Mountains of Colorado and Wyoming. Groundwater management for irrigation and human use is controlled by the State's Natural Resource Districts (NRDs). Many NRDs have prescribed pumping limits for water applications and these limits are set in terms of an annual average pumping with no exceedance of a set value over three or five years. The recent drought cycle from 2002 to 2009 triggered more water allocation restrictions, thus pressuring farmers to enhance their irrigation water use efficiency (I_{WUE}). Recent deficit irrigation studies conducted in the region on multiple crops including sugarbeet, potato, camelina and canola indicate promising results on conserving water yet producing marketable yield (Haghverdi et al., 2017; Pavlista, 2015; Pavlista et al., 2016; Hergert et al., 2016).

Dry edible bean (Phaseolus vulgaris L.) is an important source of protein, fiber and nutrition and has been playing a critical role in human diet for a long time. Currently, dry bean is the largest pulse crop produced in the world, approximately 25 million tons produced over 30 million hectares each year (www.faostat3.fao.org/). In the United States, dry beans are produced in more than 17 states which makes this country the sixth-leading dry bean producer across the world with more than 5% of the total worldwide production. One of the highest producing edible dry bean regions in the Unites States is the central High Plains (i.e. Colorado, Wyoming and Nebraska) that produces approximately 20–25% of the U.S dry bean crop, approximately 0.25–0.30 million tons production annually from 12,000 to 16,000 ha planted. A majority of commercial land under dry beans (>90%) are irrigated in this region mainly by either center pivot or gravity systems. The average yield produced under irrigation (2 Mg ha^{-1}) is 3–6 times higher than that of rainfed condition (0.28–0.56 Mg ha^{-1}) (Schwartz and Brick, 2015).

Several studies in the literature have reported yield reduction for bean due to increasing water deficits (Bourgault et al., 2010; Nielsen and Nelson 1998; Dapaah et al., 2000; Boutraa and Sanders 2001; Calvache and Reichardt 1999; Wakrim et al., 2005). It is important to determine what magnitude of stress dry bean is capable to withstand without significant yield reduction and how deficit irrigation strategies impact I_{WUE}. Bourgault et al. (2013) reported insignificant and significant yield reductions for moderate (depletion fraction of 0.6) and severe (depletion fraction of 0.7) stress levels, respectively compared to recommended irrigation application (depletion fraction of 0.45, Allen et al., 1998). In a long-term simulation study, de Faria et al. (1997) found out that maximum economic benefits are achieved when depletion fraction is below 0.4. Webber et al. (2006, 2008) studied the impact of regulated deficit irrigation and alternate furrow irrigation on dry bean in Uzbekistan and found reduction in crop consumptive water use for both strategies, but observed no change in the WUE of bean over several irrigation treatments because any water use reduction resulted in a corresponding yield reduction. Efetha et al. (2011) noticed significant increase in average dry bean seed yield and in WUE for higher frequently irrigated treatments compared to less frequently irrigated treatments, therefore recommended keeping the majority of roots moist to optimize yield and WUE. Efficient practicing of deficit irrigation depends on farmers' knowledge about how much of a reduction in applied water can be tolerated and when that reduction can occur throughout the growing season. Simsek et al. (2011) observed sensitivity of bean yield to the water stress was more pronounced in the vegetation stage (from seed germination to beginning of flowering) than reproductive stage (from the first flowering to the end of harvesting) over the course of a three-year experiment conducted in southern Turkey. Findings of Efetha et al. (2011) also showed dry bean to be more sensitive to drought during vegetative growth stages.

In addition, it is critical to find the best agronomic practices to reduce evaporation from soil surface, runoff, and deep percolation hence maximizing readily available water for crop per unit of applied irrigation water. The general belief is that planting directly into crop residue, allows moisture retention at the soil surface for seedling development, while preventing stand reduction due to wind and heavy rain damage. A covered soil surface with residue is expected to have lower evaporation rate mainly because it gets protected from solar radiation and air movement above the soil surface is diminished. This may have a positive impact on yield when deficit irrigation is practiced. On the other hand, crop residue may cause wet soil surface and lower temperature delaying planting date (Van Donk et al., 2010). Baumhardt et al. (2013a, 2013b) studied residue management effects on water use and yield of corn and cotton under deficit irrigation at Bushland, Texas. They reported higher corn and cotton yield with conservation tillage and attributed that to likely higher transpiration caused by lower early season evaporation. Van Donk et al. (2010, 2012) reported higher corn and soybean yield for residue covered plots compared to bare soil plots under deficit irrigation in central Nebraska.

The main goal of this study was to develop water conservation and deficit irrigation strategies for dry bean production in western Nebraska High Plains. The specific objectives were to determine the effects of (i) a variety of irrigation scenarios (full irrigation, deficit irrigation, rainfed) and (ii) surface residue conditions (bare soil versus residue-covered) on yield, soil water dynamics and irrigation water use efficiency of dry bean.

2. Material and methods

Two sprinkler irrigated deficit irrigation experiments were conducted within six consecutive growing seasons on dry edible bean crop in western Nebraska at the University of Nebraska Panhandle Research and Extension Center (PREC; 41.89 ∘N, 103.68 ∘W, elevation: 1189 m). The soil was a coarse-textured Tripp very fine sandy loam at pH = 8 with an organic matter content of 1%, soil bulk density of 1.32 (Mg m^{-3}), and plant water holding capacity of 0.15–0.17 m m^{-1} (Yonts et al., 2003). The groundwater depth was approximately 14 m.

The climate at Scottsbluff is semi-arid, with a long-term average (1982–2016) relative humidity of about 60%, a high and low daily temperature of 17 °C and 1 °C, respectively and an accumulative annual precipitation and reference ET (calculated for reference crop alfalfa using Penman ET model, Penman, 1948) of approximately 297 mm and 1656 mm, respectively (http://www.hprcc.unl.edu/). Fig. 1 depicts the long term average (1982–2016) and variabilities of ETo and precipitation data throughout the experiments (2010–2015). The precipitation was remarkably different among years with 2011 and 2015 being considerably above the long term average and 2012 being well below the long term average (∼300–350 mm). The year-round ETo demand was highest in 2012 (20% above the long term average) and lowest in 2015 (10% below the long term average).

Table 1 summarizes the in-season monthly irrigation and rainfall data over the course of the experiments. The highest amount of in-season rainfall (151 mm) occurred in 2015 growing season. Driest year was 2012 with precipitation equal to 67 mm. Irrigation followed the crop evapotranspiration (ETc) requirements, obtained from the High Plains Climate Center (Changnon et al., 1990), where site and emergence date were input to obtain the daily ETc values using available local crop coefficients for dry bean (https://hprcc.unl.edu/images/awdn/crop_drybean.txt). The highest irrigation rate was set to be non-ETc limiting and deficit irrigation