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Responses of dry edible bean crop growth and water productivities under different irrigation scenarios in the U.S. high plains

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ABSTRACT

Dry edible bean is an important crop for protein sources worldwide. As freshwater resources become increasingly constrained, understanding how dry beans respond to different irrigation regimes and identifying optimal irrigation management strategies becomes crucial for maintaining adequate yields. This three-year (2021–2023) study investigated the impacts of irrigation treatments, ranging from rainfed to over-irrigated conditions, on soil water dynamics, canopy cover, leaf area index, yield, actual evapotranspiration, and water productivities for dry edible beans grown in western Nebraska, U.S. Although dry beans are often considered a shallow-rooted crop, our results demonstrated their ability to adapt to drought stress by extracting soil water from significantly deeper depths than previously expected. Results also revealed that reducing irrigation by 25 % did not significantly decrease yields across all three growing seasons. The pooled normalized biomass water productivity (WP_b) was 16.5 g m^{-2} with an R^2 of 0.68. This quantified WP_b can be valuable for future crop modeling simulations, such as those using FAO's AquaCrop model.

1. Introduction

Throughout human history, food production has been one of the most critical industries, driven by rapid population growth and the increasing demand for food. Production of food requires a large amount of freshwater resources. Agriculture accounts for approximately 75 % of global freshwater withdrawals and 90 % of consumptive water use. The irrigation demand for agriculture is projected to rise by 11 % by 2050 (Gonzalez-Porras et al., 2024; Puy et al., 2020). These pressures, coupled with the impacts of climate change on weather patterns and water availability, emphasize the need to improve water productivity, particularly in arid and semi-arid regions (McDermid et al., 2023).

Legumes, especially common beans (Phaseolus vulgaris L.), are among the most important food staples for human consumption (Beebe et al., 2013). Globally, around 30 million hectares are devoted to cultivating dry edible beans (DEB), valued for their high protein and nutritional content (Yonts et al., 2018). As the world's sixth-largest producer of DEB, the U.S. produced approximately 1.31 million tons in 2022, valued at 1.08 billion U.S. dollars (Davis et al., 2023). Among all DEB production states in the U.S., Nebraska (NE) contributes 10 % of the U.S.'s total production (Davis et al., 2022). Most of Nebraska's DEB production is located in the western part of the state, and over 90 % of the DEB cultivation in this semi-arid region requires supplemental irrigation due to evapotranspiration demands often exceeding seasonal precipitation (Yonts et al., 2018). Yet, restrictions on groundwater withdrawal and unstable surface water supplies in western NE are calling for better irrigation management strategies that can balance crop productivity and crop water use (Gonçalves et al., 2020; Scanlon et al., 2012).

Deficit irrigation (DI) strategies have proven to be effective in safeguarding yields while reducing the amount of irrigation, especially in arid and semi-arid regions (Fereres and Soriano, 2006). For instance, Ucar et al. (2009) found no significant difference in DEB yield when irrigation was reduced by 25 % compared to the full irrigation amount in a semi-arid region in Turkey. Sharma and Rai (2022) also reported similar results in Wyoming where no significant difference was observed

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when irrigation was reduced by 25 %. Yonts et al. (2018) concluded that by applying 75 % of the full irrigation requirement, the DEB yield was only reduced by 6 %, and on average the Gross Irrigation Water Productivity (GIWP) increased by 26 %. These studies suggest that introducing consistent, mild water stress can still achieve profitable yields, thereby improving water productivity and net income compared to full irrigation (Fernández 2020). However, the impacts of DI can vary significantly, depending on site-specific conditions, crops, and climatic variables (Jovanovic et al., 2020). Finding the responses of yield with crop water use is essential to understanding and identifying the best DI strategies.

The linear relationship of biomass and crop water use, first formalized by De Wit (1958), is essential in deriving crop water production functions (CWPF) and analyzing water use efficiency (WUE). This concept of WUE, introduced by (Viets, 1962), calculates crop yield relative to the water used for its production. Fernández (2023) and Fernández et al. (2020) suggested that WUE should be employed to assess the efficiency of converting irrigation plus precipitation into ET_c, while crop water productivity (WP_c) is more proper to quantify the yield generated by ET_c. Various equations have been developed to measure the water productivity of a crop, as described by Fernández et al. (2020). Depending on the parameters and associated equations, comparing WP can be challenging due to variations in calculation methods, resulting in significant differences in WP for the same crop. Even using the same calculation method, water productivities can vary by geographical location, climatic conditions, irrigation, and soil management (Yuan et al., 2013). For example, Spurgeon and Yonts (2013) found DEB gross irrigation water productivity (GIWP) values ranged from 0.46 kg m^{-3} to 0.91 kg m^{-3} in western Nebraska. Efetha et al. (2011) reported crop water productivity (WP_c) ranging from 0.76 to 1.54 kg m^{-3} for DEB grown in Alberta, Canada. Muñoz-Perea et al. (2007) recorded DEB GIWP of 0.68 kg m^{-3} under no water stress and 0.60 kg m^{-3} with intermittent water stress in south-central Idaho.

An alternative method to quantify crop water productivity is to calculate the normalized biomass water productivity (WP_b), which normalizes crop water productivity to local climate conditions. Steduto et al. (2007) provided the theoretical framework for the conservative behavior of WP_b, which was later used in the AquaCrop model developed by the Food and Agriculture Organization (FAO) (Raes et al., 2009; Steduto et al., 2009). The conservative behavior of WP_b also suggests good transferability between different production regions which can be beneficial to understand crop responses to water inputs (Steduto et al., 2007; Yuan et al., 2013). Besides biomass and yield, it is also important to understand the impact of DI on other parameters, such as canopy cover development expressed in the percentage of green canopy cover and leaf area index (LAI), as well as soil water dynamics and depletion. Therefore, experiments were conducted from 2021 – 2023 in western NE, and the objectives were: 1. Assess the effects of different irrigation regimes on DEB canopy cover percentage, LAI, soil water dynamics, and biomass; 2. Evaluate the impacts of irrigation regimes on different water productivity metrics; 3. Determine normalized biomass water productivity for DEB in western Nebraska of the U.S.

2. Materials and methods

2.1. Study location

The study was conducted in 2021, 2022, and 2023 at the University of Nebraska-Lincoln (UNL), Panhandle Research and Extension Center (PHREC) in Scottsbluff, Nebraska, U.S. (41°53’34.93"N, 103°41’2.04"W, 1189 m of elevation). The dominant soil in the study field is Tripp very fine sandy loam (coarse-silty, mixed, superactive, mesic Aridic Haplustolls) with an average bulk density of 1.32 g cm^{-3}. Soil texture, field capacity (FC), and permanent wilting point (PWP) up to 1 m are listed in Table 1. The field also has a 1–2 % downward slope from north to south. In all years, dry bean market class: Great Northern Beans with variety Virgo were planted at 55 cm spacing rows with a planting population of 230,796 plants per ha. Planting and harvest dates, varieties, and fertilizer application can be found in Table 2. Nitrogen was applied in the form of urea (46N-0P-K), while phosphorus was supplied as mono-ammonium phosphate (11N-52P-K0). Fertilizer, herbicide, and fungicide applications were applied based on UNL extension recommendations. The study area is considered a semi-arid climatic zone with an average annual precipitation of 398 mm. The meteorological data required for this study, including daily maximum and minimum air temperature (T_{max} *and* T_{min}), wind speed at 2 m height (u_2), incoming solar radiation (R_s), relative humidity (*RH*), and precipitation (*P*) were obtained from the Nebraska Mesonet network (https://hprcc.unl.edu/awdn/access/index.php). The weather station was located 0.25 km away from the study field.

Table 1
Soil texture, field capacity (FC) and permanent wilting point (PWP) at the study site.

Depth	Soil texture	Sand	Silt	Clay	FC	PWP
		%	%	%	$m^3\ m^{-3}$	$m^3\ m^{-3}$
0 – 60 cm	Sandy loam	58	34	8	0.27	0.12
60 – 100 cm	Sandy loam	66	27	7	0.25	0.10

2.2. Experimental design

The research plots were irrigated using a GPS-referenced four-span variable rate irrigation (VRI) linear-move sprinkler irrigation system (Zimmatic, Lindsay Corporation, Omaha, Nebraska, U.S.A.). During each growing season, 42 plots were established. Each plot measured 15.2 m in length and 13.4 m in width with 24 rows of dry beans. The middle eight rows of each plot were used for yield analysis, while the outer eight rows on each side served as borders. To minimize interferences when shifting irrigation rates, a 7.6-meter border was placed in the travel direction of the irrigation system. Plots were arranged using a Randomized Complete Block Design (RCBD) design with seven irrigation treatments, three blocks, and each treatment replicated twice within each block. The three blocks were strategically positioned from North (Block 1) to South (Block 3) to account for slight variations in field slopes. The seven irrigation treatments were designed to simulate dry bean production from rainfed conditions to over-irrigated conditions. The treatments varied in the amount of irrigation, and they were: 0 % (rainfed), 25 %, 50 %, 75 %, 100 % (FIT), 125 %, and 150 % of the full irrigation treatment (FIT). The full irrigation treatment (FIT) was designed to meet 100 % of the crop evapotranspiration needs to avoid any water stress. Irrigation was scheduled twice a week on Mondays and Wednesdays as necessary when root zone depletion was over the maximum allowable depletion (MAD), set at 40 % of the total available water of the root zone. Root zone depth was determined using the approach mentioned in Eisenhauer et al. (2021). The root zone depletion on day i was calculated using an equation in FAO56 (Allen et al., 1998).

$$D_{r,i} \quad = \quad D_{r,i-1} - (P - RO)_i - I_i - CR_i + ET_{c,i} + DP_i \tag{1}$$

Where, $D_{r,i}$ was root zone depletion at the end of day i (mm), $D_{r,i-1}$ was root zone depletion at the end of the previous day i-1 (mm), P_i was

Table 2
Agronomic management, planting and harvesting dates for the three growing seasons.

Year	Planting date	Harvest date	Nitrogen*	Phosphorus*
			kg/ha	kg/ha
2021	June 1st	September 27th	63	35
2022	June 6th	October 10th	56	60
2023	June 6th	October 18th	50	56

Note: Nitrogen was applied in the form of urea, while phosphorus was applied in the form of mono-ammonium phosphate.

precipitation on day i (mm), RO_i was runoff from the soil surface on day i (mm), I_i was net irrigation depth on day i that infiltrated the soil (mm), CR_i was capillary rise from the groundwater table on day i (mm), $ET_{c,i}$ was crop evapotranspiration on day i (mm), DP_i was water loss of the root zone due to deep percolation on day i (mm). Runoff in Eq. 1 was calculated using the NRCS Curve Number method (Moglen et al., 2022) where the curve number was set to 78 for well-drained soil with agricultural row crops. Deep percolation was calculated using:

$$DP_i = (P_i - RO_i) + I_i - ET_{c,i} - D_{r,i-1} \geq 0 \quad (2)$$

Eq. 2 is obtained from Eq. 1, and under the assumption that $D_{r,i}$ equals to zero following heavy rain or irrigation event (Allen et al., 1998). When $D_{r,I} > 0$, the soil will not drain and DP_i equals to 0. The groundwater table at the experimental site is approximately 14 meters (Yonts et al., 2018), while the root depth of dry edible beans is normally less than 1 m (Merrill et al., 2002). Therefore, CR was assumed to be 0 since the water table was more than 1 m below the bottom of the root zone (Allen et al., 1998). Crop evapotranspiration in Eq.1 was calculated using Eq. 2 below, where $K_{c,i}$ was the crop coefficients adopted from Liang et al. (2021). To calculate daily reference ET, the ASCE standardized reference evapotranspiration equation with alfalfa reference (ET_r) was utilized using the on-site weather data (ASCE, 2005).

$$ET_{c,i} = ET_{r,i} \times K_{c,i} \quad (3)$$

The crop coefficient was adjusted when water stress was present using the water stress coefficient, K_S. The water stress coefficients were calculated using the equation below:

$$K_{s,i} = \frac{TAW - D_{r,i}}{(1 - MAD) \times TAW} \quad (4)$$

Where, TAW was the total available water in the root zone (mm). Therefore, when water stress was present, the adjusted crop evapotranspiration became:

$$ET_{c\_adj,i} = ET_{r,i} \times K_{c,i} \times K_{s,i} \quad (5)$$

2.3. Data collection

2.3.1. Measured soil water content and depletion

Volumetric soil water content (θ_v) was measured on a weekly basis post each irrigation event using a neutron probe (CPN 503 ELITE Hydraprobe, Concord, CA, USA). A total of 21 access tubes (7 treatments x 3 replications) were installed in the middle 13th row of each plot down to 1.4 m depth. During each measurement, the neutron source was lowered down to a depth that would represent the soil moisture condition of that profile. Count readings were taken by placing the neutron probe at 0.30, 0.60, 0.90, and 1.2 m, respectively. The count readings were later converted to θ_v using a locally calibrated equation. Soil water depletion (SWD) at the entire measurement profile (0 – 1.2 m) was calculated using the following equation:

$$SWD_{ij} = \left(\left(\theta_{30cm,i} - \theta_{30cm,j}\right) + \left(\theta_{60cm,i} - \theta_{60cm,j}\right) + \left(\theta_{90cm,i} - \theta_{90cm,j}\right) + \left(\theta_{120cm,i} - \theta_{120cm,j}\right) \right) \times D \quad (6)$$

Where SWD_{ij} was the total soil water depletion (m) from 0 – 1.2 m between day i and day j, $\theta_{30\,cm,i}$, $\theta_{60\,cm,i}$, $\theta_{90\,cm,i}$, $\theta_{120\,cm,i}$ was the soil volumetric water content ($m^3\ m^{-3}$) measured at 30 cm, 60 cm, 90 cm, and 120 cm depths on day i, and $\theta_{30\,cm,j}$, $\theta_{60\,cm,j}$, $\theta_{90\,cm,j}$, $\theta_{120\,cm,j}$ was the soil volumetric water content ($m^3\ m^{-3}$) measured at 30 cm, 60 cm, 90 cm, and 120 cm depths on previous measurement day j, and D was the measurement depth which equals to 0.3 m. Then the cumulative seasonal soil water depletion SWD_{season} was the summation of n pairs of SWD_{ij}:

$$SWD_{season} = \sum_{n} SWD_{ij} \quad (7)$$

2.3.2. Canopy cover

Weekly canopy cover measurements were taken by capturing digital images from a downward, 90-degree angle at 2 m height above the DEB canopy. In each study year, three replicates (plots) of each treatment were selected for image capturing and analysis. Within each plot, three random images were taken at each sampling date. The images were then processed using the Crop Canopy Image Analyzer (CCIA) software to obtain the canopy cover percentage. For more information about the software, please refer to Liang et al. (2021) and Liang et al. (2023).

Weekly scouting and measurements of crop growth stage, leaf area index (LAI) and above-ground dry biomass were conducted in 2022 and 2023 years (not 2021). Leaf area index readings were obtained using a LAI 2200 C plant canopy analyzer (LI-COR Environmental, Lincoln, NE, USA). Five LAI readings were taken under clear sky using the 45° view cap, as recommended for heterogeneous row crops. The initial 1 m height reading served as a reference, and the remaining four were taken below and near the canopy following a diagonal transect from one row to the next. The above-ground dry biomass was obtained by randomly choosing three plants in 2022 and six plants in 2023. Biomass was not taken in 2021. Plant biomass weights were recorded after they were dried in the oven at 65°C for 48 hours. To convert from single plant biomass weight to area biomass ($g\ m^2$), the average weight was multiplied by plant population to obtain area-based above-ground dry biomass.

2.3.3. Yield, GIWP, WP_b, and ET_a

Like mentioned earlier, the middle rows of each plot were harvested for yield analysis using a commercial combine (9500 John Deere, Illinois, USA) equipped with a GPS reference yield monitor (Ag Leader Insight yield monitor, Ag Leader Technology, Inc., Iowa, USA). The yield monitor was calibrated against true weight using a weigh wagon (data not shown here). The yield map was later processed using ArcGIS Pro (Environmental Systems Research Institute, Inc., Redlands, California, USA). Yield values within the length of 11.5 m of each plot (total plot length 15.2 m) were averaged to get plot average yield.

As previously mentioned, various equations have been proposed to calculate WP. In some cases, the numerator (yield) remains constant, while the denominator varies, as seen in crop water productivity (WP_c) proposed by Kijne et al. (2003), Irrigation water productivity (WP_I) (Rodrigues and Pereira, 2009), or gross irrigation water productivity GIWP (Oweis and Hachum, 2006) which are represented by Eqs. 8, 9, and 10, respectively.

$$WP_c = \frac{Y}{ET_a} \quad (8)$$

$$WP_I = \frac{Y}{IWU} \quad (9)$$

$$GIWP = \frac{Y_i - Y_d}{IWU_i} \quad (10)$$

Where Y was the yield ($kg\ ha^{-1}$), ET_a was the actual crop evapotranspiration(mm), IWU was the total irrigation amount applied (mm), Y_i was the yield for irrigation treatment i ($kg\ ha^{-1}$), Y_d was the dryland yield under the same management (kg ha^{-1}) and IWU_i was the total irrigation water applied for treatment i (mm). WP_c, WP_I, and GIWP were calculated for each treatment using Eqs. 8, 9, and 10 in all years. Normalized biomass water productivity was calculated for each treatment using ET_a instead of T, as shown in Eq. 11:

$$WP_b = \frac{Biomass}{\sum_{i=1}^{n} \left(\frac{ET_a}{\overline{ET_r}}\right)_i} \quad (11)$$

Where Biomass was the gain in above-ground dry biomass (kg m^{-2}) from day i to day n, $\overline{ET_r}$ was the mean daily ET_r during i to n, and therefore the summation in the denominator represented normalized ET_a from day i to day n. As described in Steduto et al. (2007) and mentioned earlier, ET_a can be used instead of T in calculation of WP_b but needs to be clearly specified. It should also be noted that the unit of WP_b is kg/m^2 which is different from WP_c, WP_I, or GIWP which have units in kg/m^3. The actual evapotranspiration was calculated using water balance equation:

$$ET_a = P + I - DP - RO - \Delta SW \quad (12)$$

Where ET_a was the actual evapotranspiration (mm), P was the precipitation (mm), I was the irrigation applied (mm), DP was deep percolation (mm), RO was runoff (mm), and ΔSW was the change in soil water (mm). Since ΔSW was calculated based on neutron probe measurements, ET_a in Eq.12 represented cumulative ET_a between the measurement days. In the following context, WP_b refers to normalized biomass water productivity calculated using actual evapotranspiration with varying time durations. Normalized biomass water productivity was calculated for each treatment during the 2022 and 2023 growing seasons, as well as pooled value using the two years of data.

2.4. Statistical analysis

Differences in yield, WP_c, WP_b, and ET_a across treatments and growing seasons were analyzed using Python (Jupyter Notebook, version 6.5.2, Project Jupyter USA). Two-way analysis of variance (ANOVA) was performed for WP_c, ET_a, yield, and WP_b with irrigation treatment and study year as factors. Following the ANOVA tests, if any significant differences were found in tested variables ($P < 0.05$), post-hoc analyses were conducted on the means using Tukey's test based on a 5 % significance level. For variables that were routinely sampled during the growing season, such as CC, LAI, SWD, and biomass, repeated measure ANOVA was performed with irrigation treatment and sampling date as factors. Lastly, yields were plotted against total water applied (I+P) and ET_a to derive crop water production functions (CWPF).

3. Results

3.1. Weather and irrigation

The dry bean growing season spans from June to October. By late September and early October, the crop should mature and there is minimum growth. Therefore, only weather data from June to September are presented below. During all three growing seasons, total precipitation from June to September was 142.1 mm, 100.3 mm, and 290.1 mm, respectively. Compared to the 30-yr average total rainfall from June to September (132.8 mm), the seasonal rainfall during the three study years was 22 % under, 31 % under, and 96 % over (Table 1, Fig. 1), and the three years were therefore normal, slightly dry, and wet years, respectively. In addition, 2023 exhibited the coolest temperatures, with seasonal averages 1.6°C and 1.5°C lower than in 2021 and 2022, respectively. Table 3 summarizes the monthly average weather conditions for the 2021, 2022, and 2023 growing seasons.

In 2021 and 2022, both the cumulative alfalfa-based crop reference evapotranspiration (ET_r) and cumulative crop evapotranspiration (ET_c) obtained from the single-crop coefficient method (Allen et al., 1998) were higher than in 2023, reaching 577 mm and 216 mm in 2021 and 589 mm and 268 mm in 2022, respectively (Fig. 2). In 2023, cumulative ET_r and ET_c were 465 mm and 197 mm, respectively. This trend can be attributed to the higher temperatures experienced during the 2021 and 2022 growing seasons, compared to the cooler weather conditions in 2023. Consequently, there were more irrigation events in 2021 and 2022 than in 2023. Total irrigation for the FIT treatment was 239.4 mm, 371.5 mm, and 181.7 mm for the 2021, 2022, and 2023 growing seasons, respectively (Table 3).

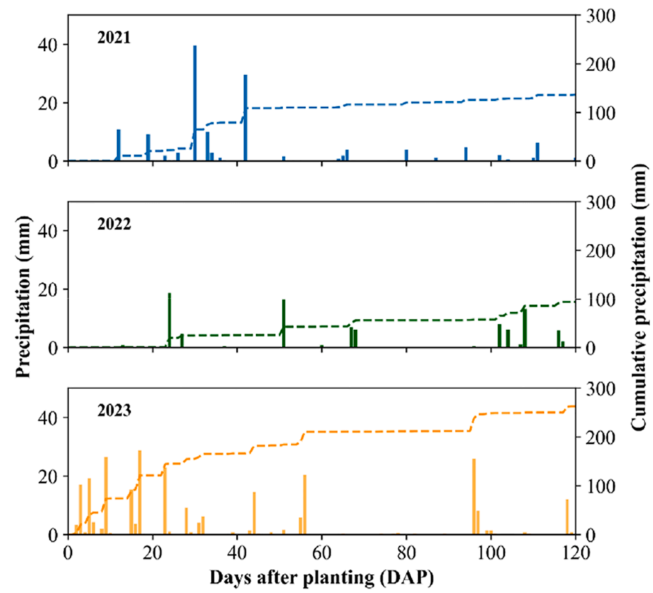

Fig. 1. Daily precipitation and cumulative precipitation over days after planting (DAP) during the 2021–2023 growing seasons at the study location.

3.2. Soil water dynamics and soil water depletion

Fig. 3 illustrates the variation in soil volumetric water content (VWC) at the 0–1.2 m soil profile over time during the three growing seasons for the seven irrigation treatments. In 2021, VWC was collected from three soil depths of 0 – 0.9 m, while in 2022 and 2023, VWC was collected from 0 – 1.2 m. During the 2021 growing season, VWC at all treatments was similar in the beginning around DAP 37. The variable rate irrigation treatments started on DAP 41. On DAP 50, VWC among treatments started to separate from each other. As the season progressed and irrigation treatments were applied on a weekly basis, the difference in VWC among treatments was more noticeable on DAP 65. Higher irrigation treatments, such as 150 %, 125 %, and 100 %, had higher VWC at all measurement depths than VWC of 0 %, 25 %, and 50 %. Crops at lower irrigation treatments were drawing soil water from deeper depths than the higher irrigation treatments. On DAP 72, clear differences in VWC at all depths can be seen among irrigation treatments, indicating successful applications of all irrigation treatments. It should be noted that the 0 % treatment drew soil water at even 1.2 m depth, suggesting an extended root system in response to drought stress. During the 2022 growing season, the initial VWC on DAP 23 of all treatments was lower compared to 2021. One irrigation (12.5 mm) was applied to all treatments on DAP 3 to allow plants at all plots to germinate. Irrigation treatments started on DAP 11, and differences in VWC at 0.3 m became noticeable on DAP 50. Similar to the pattern in 2021, the crop at lower irrigation treatments aggressively drew water from the entire soil profile. Especially for the 0 % irrigation treatment, the average VWC at 0.3 m was 14.1 % on DAP 67, and nearly exhausted all available water at the shallow soil profile. On DAP 94, the average VWC from 0 – 1.2 m of 0 % treatment was 16.5 %, indicating that the soil water at the whole soil profile was nearly at PWP. During the 2023 growing season, rainfall was 118.4 % over the

Table 3
Monthly average air temperature (T_{avg}), total precipitation (P), total irrigation for the 100 % or fully irrigated treatment (I), average relative humidity (RH), average 2-meter wind speed (U_{2_avg}), average daily short wave solar radiation (R_{s_avg}), cumulative alfalfa-based crop reference evapotranspiration (ET_r) in Scottsbluff, NE during 2021, 2022 and 2023 growing seasons.

Year	Months	T_{avg}	P	I	RH_{avg}	U_{2_avg}	R_{s_avg}	ET_r
		(°C)	(mm)	(mm)	(%)	(m s^{-1})	(MJ m^{-2} d^{-1})	(mm)
2021	June	22.8	50.2	29.5	47.2	3.5	52.1	246.0
	July	24.0	32.3	104.7	55.5	2.8	48.6	209.2
	August	21.8	11.8	105.2	52.5	2.5	44.0	178.6
	September	19.0	8.9	0	46.2	2.8	35.9	130.0
	Mean/Total	21.9	103.2	239.4	50.3	2.9	45.2	763.8
2022	June	20.9	20.1	57.2	41.9	2.8	25.0	239.0
	July	24.6	22.4	108.0	51.8	2.0	23.9	229.5
	August	23.3	14.0	206.3	53.0	1.6	22.3	185.4
	September	18.4	35.1	0	52.6	1.6	17.4	129.7
	Mean/Total	21.8	91.6	371.5	49.8	2.0	22.2	783.6
2023	June	18.8	155.7	0	69.5	2.0	22.5	159.3
	July	22.2	45.0	14.0	65.7	1.2	23.4	161.5
	August	22.2	21.8	133.4	62.0	1.0	21.1	137.6
	September	18.1	38.1	34.3	62.8	1.5	16.4	102.2
	Mean/Total	20.3	260.6	181.7	65.0	1.4	20.9	560.6

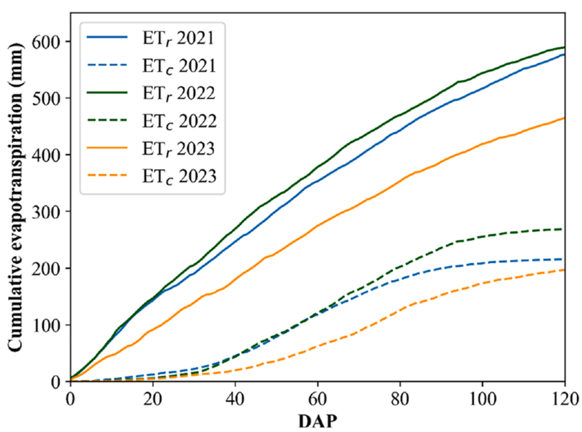

Fig. 2. Seasonal cumulative alfalfa-based crop reference evapotranspiration (ET_r) and cumulative crop evapotranspiration (ET_c) with day after planting (DAP) in Scottsbluff, Nebraska, USA during the years of 2021, 2022 and 2023. The crop evapotranspiration (ET_c) was calculated for 100 % or fully irrigated treatment (FIT).

30-year Average. Initial VWC at all measurement depths was at or beyond FC. First irrigation was not applied until DAP 43. Minimum differences in VWC among treatments were observed before DAP 57. During the later stages of the growing season, the lower water treatments started to utilize soil water at 0 – 0.6 m depths, and differences in VWC were observed mainly at those depths.

Soil water depletion (SWD) at all depths was calculated using VWC from neutron probe and FC (Eq. 6). Fig. 4 shows SWD for all depths over time under different irrigation treatments during the 2021, 2022, and 2023 growing seasons. The dashed line in Fig. 4 is the 40 % maximum allowable depletion (MAD) threshold. During the 2021 growing season, nearly all irrigation treatments maintained SWD above MAD. Except for the SWD of 0 % and 25 % went over MAD around DAP 72, when dry beans were at the pod elongation growth stage and were very sensitive to any water stress. In 2022, SWD exceeded the MAD threshold in most treatments after DAP 37, and 0 %, 25 %, and 50 % irrigation treatments were at MAD early in the season. It was also noted that the SWD of the higher water treatments, for example, 100 %, 125 %, and 150 %, were also below MAD during the middle of the growing season. This was mainly due to the irrigation system used in this study having a maximum capacity of applying 50 mm of irrigation per week. When weekly ET_c was as high as 65 mm, the irrigation system was not able to keep up with the ET demand of the crop. The lower initial VWC in 2022 also suggested that irrigators should be aware of their irrigation capacity and maybe consider applying more than the full rate to be able to keep up with the crop water use during the middle of the season. During the 2023 growing season, the SWD of all treatments was much lower than in 2022 and similar to 2021. Although the seasonal rainfall in 2023 was much higher than the 30-year average, 69 % of the rainfall (200 mm) was in the months of June and July. As a result, the SWD of all treatments remained above MAD prior to DAP 64. After DAP 64, SWD of 0 %, 25 %, and 50 % were below or close to MAD till the end.

3.3. Effect of irrigation treatments on canopy cover percentage, leaf area index, and biomass

The development of green canopy cover is a crucial visual indicator of crop health, reflecting water stress and having significant implications for yield (Liang et al., 2023; DeJonge et al., 2024). Fig. 5 presents the responses of canopy cover (CC) to different irrigation treatments across three growing seasons (2021, 2022, and 2023). The majority of the CC development happened in the early growth stages before DAP 50. Then the crop would maintain the same value of CC during the reproductive stage (DAP 50–80). At a later stage of pod filling (DAP 80 and after), DEB leaves started to yellow, and CC began to decrease. Right before harvest, DEB would begin to dry down to get ready for harvest, during which CC would decrease to zero.

In the 2021 growing season, CC measurements were collected from DAP 35–87. The canopy cover of 0 % treatment seemed lower than other treatments, although no statistically significant differences were observed among the treatments ($p = 0.233$). Canopy cover percentage was recorded from DAP 18–101 in the 2022 growing season, covering the dry bean development stages from VC to maturity. The 2022 growing season revealed significant differences in CC between treatments ($p < 0.001$). The impacts of water stress were evident from early crop stages to maturity, particularly in the 0 % irrigation treatment, which achieved a maximum canopy cover (CC_max) of only 52.8 % on DAP 59 at the R2-R3 stage, reflecting a 29.7 % reduction in comparison to the 100 % treatment. Higher irrigation levels (125 % and 150 %) resulted in CC_{max} values exceeding the 100 % FIT by 6.2 % and 11.2 %, respectively. During the 2023 growing season, no significant differences in CC were observed among treatments ($p = 0.496$), and all treatments showed similar values. By DAP 76, most treatments reached their CC_{max}, with the 100 % and 125 % treatments achieving values of 62.4 % and 63.3 %, respectively. Overall, CC values in 2023 were lower than in 2021 and 2022.

Fig. 6 illustrates the effects of various irrigation treatments on DEB above-ground dry biomass and LAI over time during the 2022 and 2023

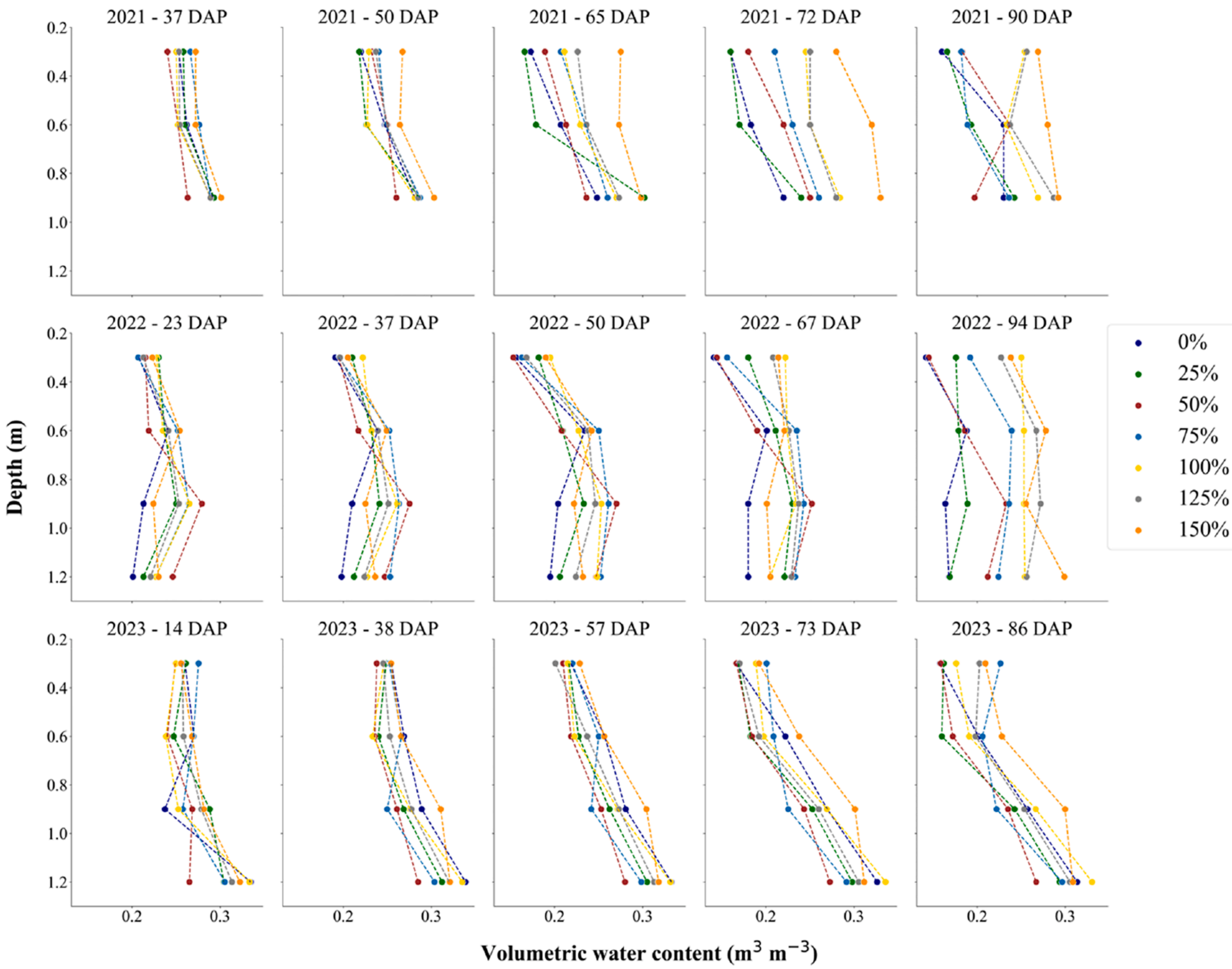

Fig. 3. Variations in volumetric water content (VWC) across the soil profile at different depths (0.3 m, 0.6 m, 0.9 m, and 1.2 m) measured on various days after planting (DAP) over three growing seasons (2021 – 2023) for the seven irrigation treatments in western Nebraska.

growing seasons. Due to a lack of data from the 2021 season, only results from the subsequent two years are presented. An overall increase in above-ground biomass was observed with increasing irrigation, consistent with the findings by Al-Kaisi et al. (1999), who reported similar trends in southwestern Colorado, where biomass increased with irrigation rates up to 1.33 ETc. No significant differences in biomass between treatments were observed ($p = 0.053$). However, an ANOVA performed on the final biomass measurement taken on DAP 99 showed the 125 % treatment had 85 % higher biomass than the 25 % treatment ($p = 0.046$). The 150 % irrigation treatment exhibited the highest biomass accumulation, reaching approximately 1390 g m^{-2} on DAP 67 during the R5 growth stage. All treatments reached peak biomass on DAP 67, followed by a decline as maturity approached. In contrast to the 2022 season, above-ground biomass in 2023 on DAP 115 ranged from 994 g m^{-2} for the 25 % treatment to 1570 g m^{-2} for the 125 % treatment, representing nearly double the biomass observed in 2022 ($p < 0.001$). This suggests a substantial difference in biomass production between the two growing seasons, potentially influenced by much higher precipitation during the vegetative stages.

Fig. 6 also shows LAI development in the years 2022 and 2023. In 2022, the 0 % irrigation treatment consistently maintained the lowest LAI throughout the season, with values ranging from 2.9 to 3.9. The 25 % treatment showed a slightly higher range of 3.3–3.9, but neither exhibited a notable peak. The maximum LAI recorded was 8.2 for the 150 % treatment, which was 55 % higher than the maximum observed in the rainfed treatment ($P < 0.001$). In 2023, LAI was also significantly different across irrigation treatments ($P = 0.011$). The lowest LAI was recorded in the 25 % treatment, ranging from 2.2 to 6.2, while the highest was observed in the 100 % FIT treatment, ranging from 3.3 to 8.2. During early growth stages (DAP 45–64), minimal differences in LAI were noted, likely due to heavy precipitation events. More pronounced differences emerged after DAP 76, consistent with Rai et al. (2020), who found no significant differences in LAI during the early 2019 season in Powell, Wyoming, due to excessive precipitation. The final LAI measurement on DAP 113 showed minimal differences among the 50 %, 75 %, 125 %, and 150 % treatments, while the 25 % treatment remained significantly lower than other treatments.

3.4. Actual evapotranspiration, yield, and water production functions

The cumulative seasonal ET_a in 2021, 2022, and 2023 are shown in Fig. 7. Actual seasonal crop evapotranspiration increased with higher irrigation treatments. Significant differences in ET_a were observed across years ($p < 0.001$) and treatments ($p < 0.001$). Actual seasonal evapotranspiration ranged from 215 – 411 mm, 154 – 607 mm, and 310 – 480 mm in 2021, 2022, and 2023, respectively. In 2021, no significant differences in ET_a were observed among 0 %, 25 %, and 50 % treatments ($p = 0.611$). The ET_a of 0 % treatment was lower than ET_a of 75 %,

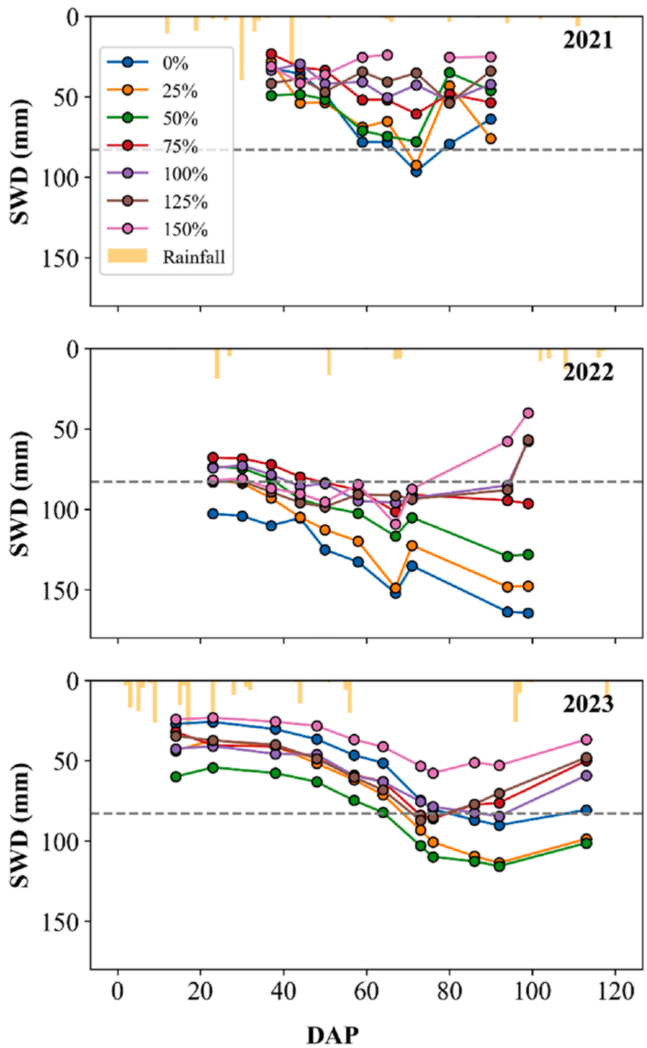

Fig. 4. Calculated seasonal soil water depletion (SWD) from the 0–1.2 m soil profile during the growing seasons of 2021 (top), 2022 (middle), and 2023 (bottom) for different irrigation treatments over days after planting (DAP). The dashed line represents 40 % of the maximum allowable depletion (MAD) threshold. Yellow bars indicate rainfall events.

100 %, 125 %, and 150 % treatments by 51.8 %, 71.1 %, 86 %, and 91.8 %, respectively ($p < 0.001$). Actual seasonal crop evapotranspiration of 75 % treatment was not significantly different than ET_a of 100 % or 125 % treatments but was 26.3 % less than ET_a of 150 % treatment ($P < 0.022$). Actual crop evapotranspiration of 75 % treatment was also 51.7 % higher than ET_a of 0 % treatment. During the 2022 growing season, the spread of ET_a amongst irrigation treatments was more obvious than in 2021. The average seasonal ET_a of 0 % treatment was only 146.9 mm, which was 61 % less than ET_a of 25 % treatment ($p = 0.008$) and 106 % less than the ET_a of 50 % treatment ($p < 0.001$). While applying 25 % less irrigation (75 % FIT) did not result in significantly lower ET_a compared to the 100 % treatment, it was 24.3 % and 26 % lower than the ET_a of 125 % and 150 % treatments, respectively. The ET_a of 100 %, 125 %, and 150 % treatments were not significantly different ($p = 0.183$). In 2023, ET_a exhibited less variability compared to 2022. The ET_a of 0 % treatment was 13 %, 21.3 %, and 21.3 % less than ET_a of 25 %, 50 %, and 75 % treatments, respectively ($p = 0.183$). The ET_a of 75 % treatment was 28 % less than the ET_a of 100 % treatment ($p < 0.001$). The ET_a of 100 %, 125 %, and 150 % were not significantly different ($p = 0.052$).

Fig. 8 shows the average DEB seed yields obtained for all the irrigation treatments during all three growing seasons. The DEB yields ranged from 2.5 – 4.1, 1.2 – 3.0, and 1.5 – 3.6 Mg ha^{-1} in 2021, 2022, and 2023, respectively. Yields in 2022 and 2023 were generally lower than yield in 2021 but possibly attributed to different reasons. In 2022, the lower yields might be caused by excessive water stress, as indicated by much lower seasonal ET_a (Fig. 6) and excessive SWD (Fig. 4). In 2023, the lower yields might be the result of excessive rainfall and much lower temperatures. In all three study years, the rainfed treatment (0 %) showed significantly lower yield than the fully irrigated treatment (100 %), regardless of seasonal rainfall amounts. Yields of the rainfed treatment were 34 %, 57 %, and 52 % lower than yields of the fully irrigated treatment in 2021, 2022, and 2023, respectively. Among all treatments, the 75 % treatment produced yields comparable to the 100 % treatment across all three seasons.

Table 4 summarizes the dry bean seed yields, irrigation, precipitation, seasonal ET_a, as well as water productivities (WP_c, WP_I, GIWP, and WP_b) from 2021 – 2023. In the 2021 growing season, WP_c, which is yield divided by crop evapotranspiration, ranged from 1.0 to 1.4 kg m^{-3}. The highest WP_c was found at 25 % and 50 % irrigation treatments with averages of 1.4 kg m^{-3}, but they were not statistically different than other treatments. While during the 2022 growing season, the range of WP_c was 0.6 – 0.8 kg m^{-3}, which was much lower than the range in 2021. This was possibly due to lower yields and higher ET_a in 2022. The

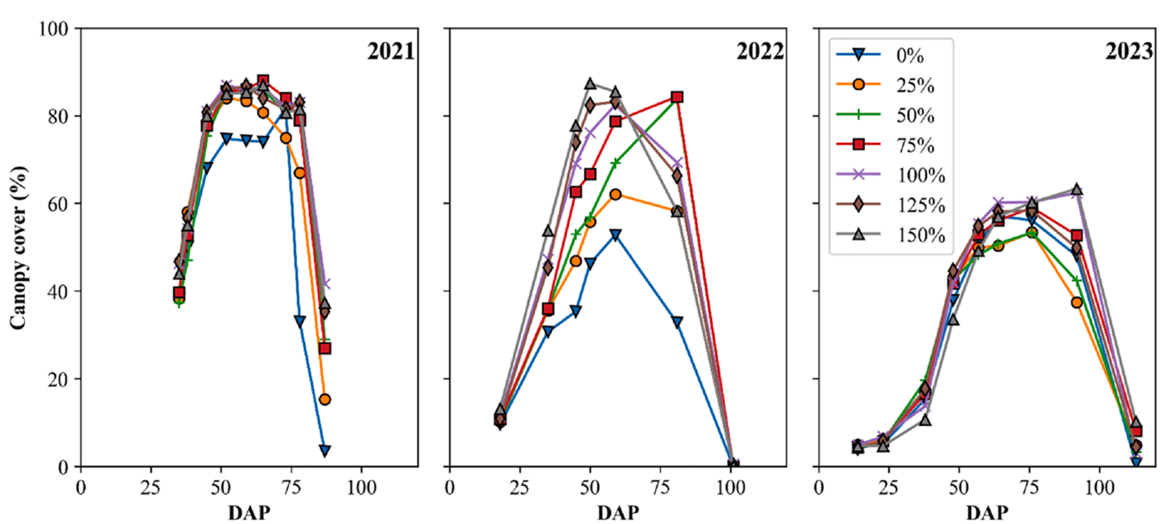

Fig. 5. Average dry bean canopy cover percentage for the seven irrigation treatments (0 %, 25 %, 50 %, 75 %, 100 % FIT, 125 %, and 150) over days after planting (DAP) across the 2021, 2022 and 2023 growing seasons.

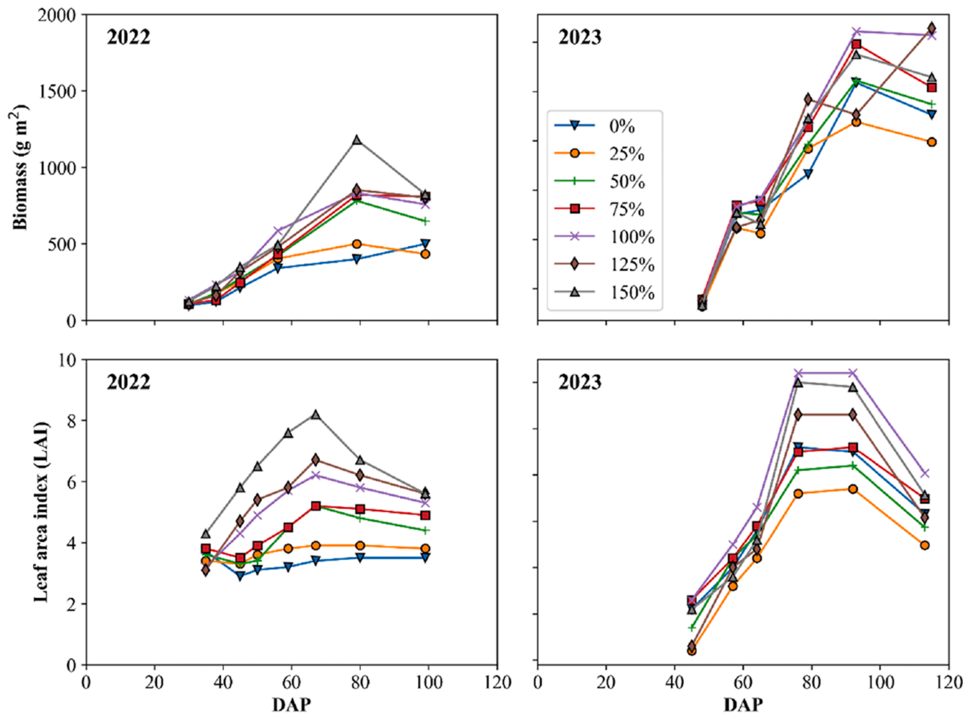

Fig. 6. Average dry bean above-ground dry biomass and leaf area index (LAI) of seven irrigation treatments over days after planting (DAP) during 2022 and 2023 growing seasons in western Nebraska.

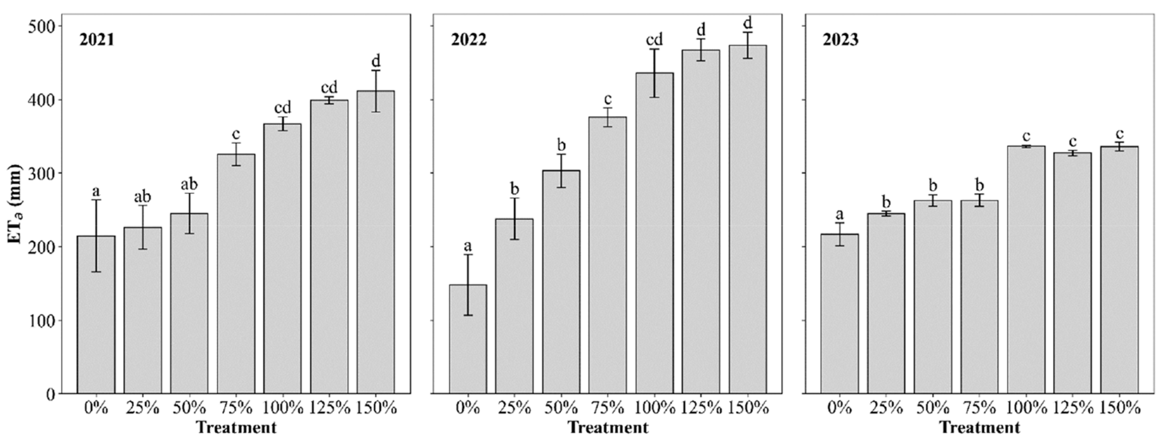

Fig. 7. Dry bean seasonal actual evapotranspiration (ET_a) for the seven irrigation treatments in western NE.

range of WP_c was 0.7 – 1.2 kg m^{-3} in the 2023 growing season and they were not statistically different among treatments. The 75 % irrigation treatment in 2023 appeared to have the highest WP_c among treatments. Across all years, WP_c tended to increase with the amount of irrigation, reaching a maximum before decreasing as additional irrigation was applied.

The irrigation water productivity, or WP_I, showed different patterns than WP_c. Due to the way it was calculated, WP_I decreased as the amount of irrigation increased, and the rainfed treatment tended to have the highest value. The value of WP_I also varied significantly across years, as evidenced by the ranges 1.4–4.4, 0.5–1.7, and 1.3–2.8 kg m^{-3} during the years 2021, 2022, and 2023, respectively. The gross irrigation water productivity (GIWP) exhibited mixed patterns compared to WP_I or WP_c. It decreased with added irrigation in 2021 and 2022, ranging from 0.6–1.1 and 0.3–0.9 kg m^{-3}, respectively. In 2023, GIWP increased with added irrigation up to the 75 % irrigation treatment level, then decreased with further irrigation, ranging from 0.4–0.7 kg m^{-3}. Not only did GIWP values vary significantly across years, but it was also noted that GIWP showed very large standard deviations in some cases. For example, the GIWP of the 25 % treatment in 2021 was 1.1 $\pm$ 1.8 kg m^{-3}, while WP_I was 4.4 $\pm$ 0.9 kg m^{-3}, and WP_c was 1.4 $\pm$ 0.4 kg m^{-3}. Across all three growing seasons, WP_c varies significantly between years ($P < 0.001$). The mean difference of WP_c of 2021–2022 was 0.519 kg m^{-3}, with 2021 having a significantly higher WP_c value than 2022 ($P < 0.001$). The mean difference of WP_c of 2023–2022 was 0.273 kg m^{-3}, indicating that 2023 had a significantly higher WP_c value than 2022 ($P = 0.002$). Yet, the GIWP didn't change significantly between years ($P = 0.417$). Lastly, WP_I varied significantly between years, with WP_I in 2023 larger than the WP_I of 2022 by a mean difference of 0.974 kg m^{-3}, and WP_I in 2022 less than the WP_I of 2021 by a mean difference of 1.40 kg m^{-3}.

The relationship between ET_a and yield, also known as crop water production function (CWPF) for the 2021–2023 seasons is shown in Fig. 9. Second-degree polynomial regression curves were used to fit the

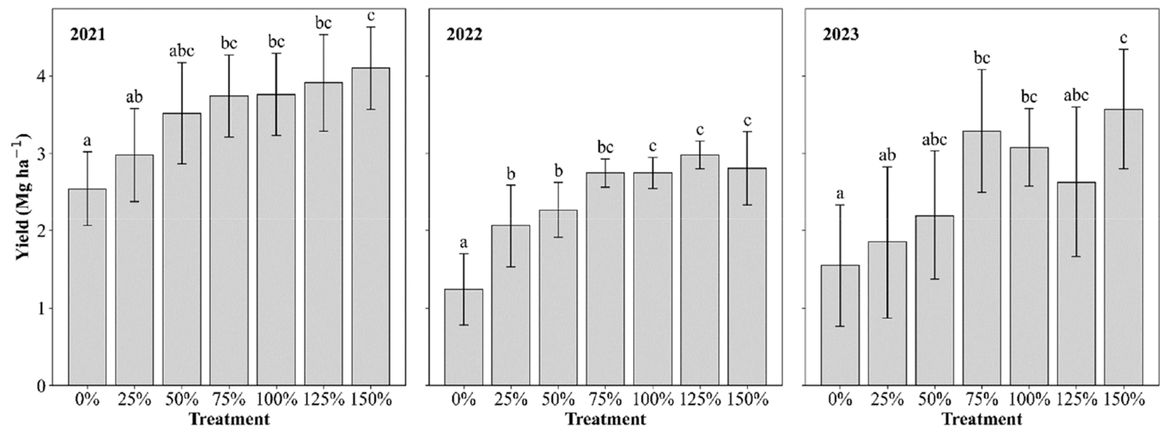

Fig. 8. Dry bean yield (Mg ha^{-1}) for the seven irrigation treatments during three growing seasons (2021–2023) in western NE. Letters indicate significance differences.

Table 4
Dry bean seed yield, irrigation plus precipitation (I+P), seasonal actual evapotranspiration (ET_a), crop water productivity (WP_c), irrigation water productivity (WP_I), gross irrigation water productivity (GIWP), and normalized water productivity (WP_b) for seven irrigation treatments from 2021, 2023 and 2023 growing seasons.

Year	Irrigation Treatment	Seed Yield (Mg ha^{-1})	I+P (mm)	Seasonal ET_a (mm)	WP_c (kg m^{-3})	WP_I (kg m^{-3})	GIWP (kg m^{-3})	WP_b (kg m^{-2})
2021	0 %	2.5 ± 0.5^{a}	149.1	214.5 ± 49.0^{a}	1.1 ± 0.1	/	/	/
	25 %	3.0 ± 0.6^{ab}	207.1	226.1 ± 29.7^{ab}	1.4 ± 0.4	4.4 ± 0.9	1.1 ± 1.8	/
	50 %	3.5 ± 0.6^{abc}	250.2	245.2 ± 27.4^{ab}	1.4 ± 0.3	3.1 ± 0.8	1.0 ± 1.0	/
	75 %	3.7 ± 0.5^{bc}	317.7	325.6 ± 15.4^{c}	1.2 ± 0.2	2.2 ± 0.4	0.9 ± 0.2	/
	100 %	3.8 ± 0.5^{bc}	375.7	367.0 ± 9.5^{cd}	1.1 ± 0.2	1.7 ± 0.3	0.7 ± 0.2	/
	125 %	3.9 ± 0.6^{bc}	421.8	398.9 ± 4.7^{cd}	1.0 ± 0.2	1.4 ± 0.2	0.6 ± 0.3	/
	150 %	4.1 ± 0.5^{c}	445.6	411.4 ± 28.2^{d}	1.0 ± 0.1	1.4 ± 0.2	0.6 ± 0.2	/
2022	0 %	1.2 ± 0.5^{a}	115.0	148.0 ± 41.4^{a}	0.6 ± 0.2	/	/	14.1 ± 15.3
	25 %	2.1 ± 0.5^{b}	197.9	237.8 ± 28.3^{b}	0.8 ± 0.2	1.7 ± 0.6^{a}	0.9 ± 0.8	12.5 ± 4.2
	50 %	2.3 ± 0.4^{b}	286.8	303.2 ± 9.4^{b}	0.8 ± 0.1	1.2 ± 0.2	0.7 ± 0.1	16.7 ± 2.6
	75 %	2.8 ± 0.2^{bc}	375.7	375.8 ± 13.0^{c}	0.7 ± 0.1	1.0 ± 0.1	0.7 ± 0.1	16.3 ± 0.5
	100 %	2.8 ± 0.2^{c}	464.6	435.8 ± 32.8^{cd}	0.6 ± 0.1	0.7 ± 0.1	0.5 ± 0.1	12.9 ± 2.9
	125 %	3.0 ± 0.2^{c}	553.5	467.3 ± 14.6^{d}	0.6 ± 0.0	0.6 ± 0.0	0.4 ± 0.1	12.4 ± 2.3
	150 %	2.8 ± 0.5^{c}	642.4	473.6 ± 17.9^{d}	0.6 ± 0.1	0.5 ± 0.1	0.3 ± 0.1	14.2 ± 0.8
2023	0 %	1.5 ± 0.8^{a}	288.0	216.9 ± 15.7^{a}	0.9 ± 0.2	/	/	20.8 ± 1.6
	25 %	1.8 ± 1.0^{ab}	327.1	244.9 ± 3.4^{b}	0.7 ± 0.4	2.8 ± 1.6	0.5 ± 1.1	17.1 ± 3.9
	50 %	2.2 ± 0.8^{abc}	366.1	262.9 ± 8.0^{b}	0.9 ± 0.2	2.3 ± 0.6	0.4 ± 0.8	18.8 ± 4.1
	75 %	3.3 ± 0.8^{bc}	405.2	263.0 ± 8.3^{b}	1.2 ± 0.5	2.1 ± 0.8	0.7 ± 0.6	20.6 ± 0.0
	100 %	3.1 ± 0.5^{bc}	444.3	336.6 ± 1.7^{c}	0.9 ± 0.2	1.6 ± 0.3	0.5 ± 0.3	20.8 ± 2.3
	125 %	2.6 ± 1.0^{abc}	483.3	327.4 ± 3.4^{c}	0.9 ± 0.3	1.4 ± 0.5	0.5 ± 0.5	18.9 ± 1.8
	150 %	3.6 ± 0.8^{c}	522.4	336.0 ± 4.8^{c}	1.0 ± 0.2	1.3 ± 0.3	0.5 ± 0.4	17.0 ± 4.0

*Letters indicate significant differences between the treatments. The WP_b for 2021 was not calculated and indicated as "/".

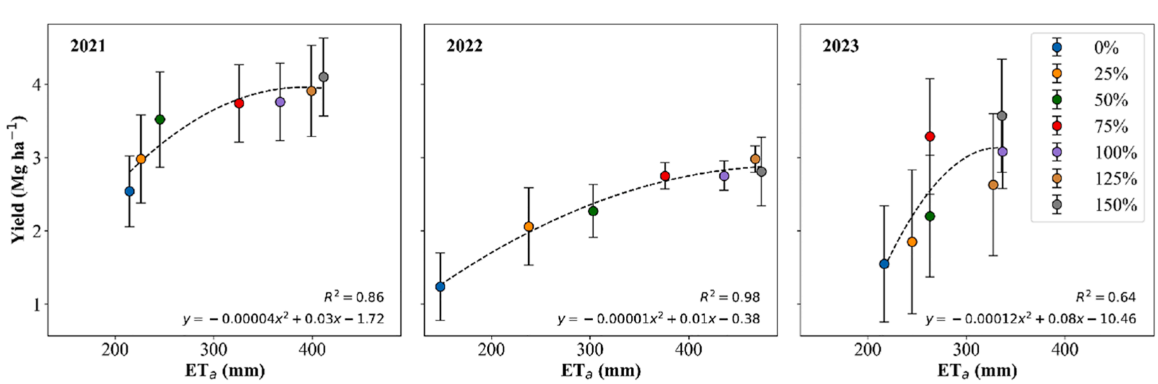

Fig. 9. Seasonal actual evapotranspiration (ET_a) and dry bean seed yield relationship for the seven irrigation treatments during three growing seasons (2021–2023).

data points. The R^2 for all three years showed high correlations between ET_a and yield, ranging from 0.78 to 0.97, with 2022 exhibiting the highest R^2 of 0.97. The CWPFs were very different among all study years in terms of the range of yields and the slope of the curves. To address the variations in CWPFs, researchers have tried to normalize yield and ET_a by dividing the yield and ET_a by the maximum yield and ET_a of that year

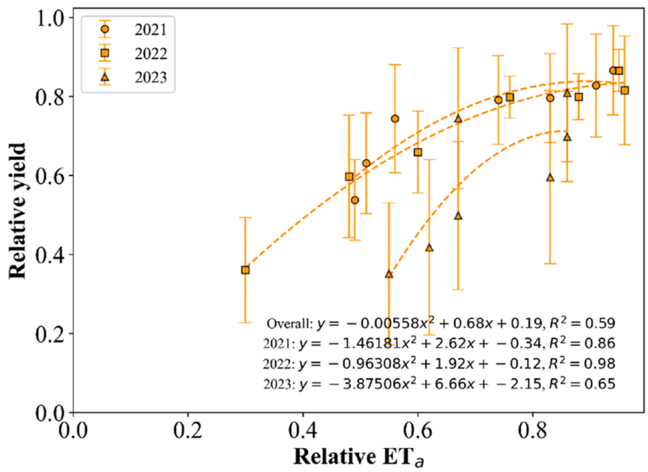

Fig. 10. Dry bean normalized crop water production functions (CWPF) for the three growing seasons using relative yield and relative actual evapotranspiration (ET_a).

to get relative yield and ET_a (Trout and DeJonge, 2017). We followed a similar approach and the normalized CWPFs are presented in Fig. 10. The normalization yielded similar normalized CWPFs in the years 2021 and 2022, while in 2023 the slope of the CWPF was sharper. We suspect that this was possibly due to the way that water stress was applied to lower water treatments. In 2021 and 2022, the lower water treatments (0 %, 25 %, 50 %, and 75 %) experienced water stress during the majority of the growing season, yet the lower water treatments didn't experience water stress during the early season in 2023. In all years, approximately 0.85 – 0.9 relative ET_a would achieve optimal yields.

3.5. Normalized biomass water productivity - WP_b

The average biomass water productivity (WP_b) for the seven irrigation treatments was 11.5 g m^{-2} in 2022 and 16.4 g m^{-2} in 2023, and pooled WP_b for the two years was 16.5 g m^{-2} (Fig. 11). Good correlations between accumulated biomass and normalized ET_a were obtained in 2022 ($R^2 = 0.77$) and 2023 ($R^2 = 0.76$). The biomass water productivity was also calculated for each treatment in both years (Table 4). No significant difference was found among treatments in 2022 ($p = 0.894$) or 2023 ($p = 0.674$), but a yearly difference was present ($P < 0.001$). In both years, WP_b seemed to decrease as irrigation levels increased, similar to patterns of other water productivities (Table 4). Moreover, the rainfed treatment had a relatively higher WP_b of 14.1 kg m^{-2} and 20.8 kg m^{-2} in 2022, and 2023, respectively.

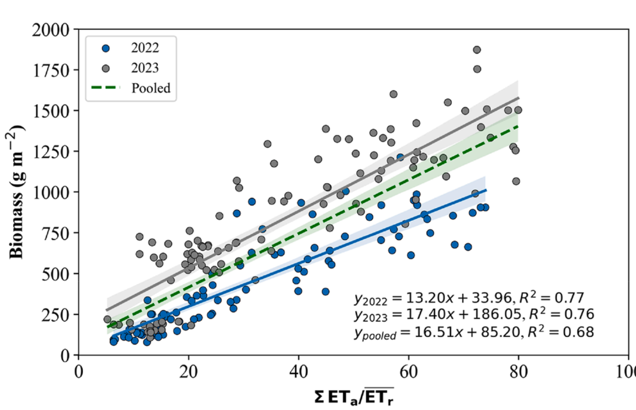

Fig. 11. Relationships between above ground dry biomass (g m^{-2}) and normalized cumulative crop evapotranspiration ($\sum ET_a/\overline{ET}_r$, unitless) in 2022 and 2023 growing seasons as well as pooled data.

4. Discussion

4.1. Dry bean responses to irrigation treatments

The root depths of dry edible beans are normally considered less than 1 m (Merrill et al., 2002), and 85 % of soil water extraction happens at the top 0.4 m (Yonts and Nuland, 1997). Our study showed that dry bean root depths were very adaptable to drought stress. They can aggressively draw water at deeper root depths (~1.2 m) when plants are severely stressed in early growth stages. For example, 0 %, 25 %, and 50 % irrigation treatments showed declining in VWC at a depth of 1.2 m from DAP 65 and onward in 2021. In 2022 when rainfall was much less, even 75 % irrigation treatment showed signs of water use at 0.9 m depth. The capability to develop deep root depth which can extract deeper soil moisture is essential for the success of deficit irrigation strategies (Hergert et al., 2016). It should be noted that in 2023, the abundance of rainfall in the early growth stage didn't promote deep root development in lower water treatments as they did in 2021 or 2022.

In two out of three years of our study (2021 and 2023), canopy cover was not significantly different among treatments, and therefore failed to reflect different treatment levels. However, the leaf area index was able to detect the differences among canopies of treatments in 2023. DeJonge et al. (2024) reported that CC could vary throughout the day for corn. Especially for water-stressed treatments, the curling of corn leaves would reduce CC during noon of the day. It is evident that the CC might need more frequent sampling than what was possible in this study to obtain more accurate CC readings. One possibility is to use edge-computing camera devices with telemetry to continuously monitor CC (Liang et al., 2023).

Dry bean yields in our study ranged from 1.2 to 4.1 Mg ha^{-1} during all three growing seasons (2021–2023). A similar range was reported by Yonts et al. (2018) with dry bean yields ranging from 0.41 to 4.07 Mg ha^{-1} during a six-year experiment (2010–2015) conducted in western Nebraska. In another study, Spurgeon and Yonts (2013) applied four irrigation treatments from 0.5 ET_c to 1.25 ET_c using a subsurface drip irrigation system and obtained dry bean yields from 1.44 to 3.63 Mg ha^{-1} from 2005 to 2008. In our study, the level of water stress, indicated by soil water depletion (SWD) appeared to have a strong correlation with the final yield. For example, many treatments in 2022 experienced water stress by depleting soil water below MAD, especially 0 % and 25 % almost depleting the entire soil water at 0 – 1.2 m. As a result, yields of treatments in 2022 were much lower than in 2021 and 2023.

Across all three study years, applying 25 % less water than the 100 % irrigation treatment didn't cause a significant yield decrease. These results align with the findings by Sharma and Rai (2022), in which they found that applying 25 % less water of full crop water needs did not affect DEB yield in Wyoming, U.S. This implies viable DI strategies for dry bean growers in the High Plains of U.S. Many studies also suggest that dry bean can be quite sensitive to drought stress in early season (before flowering), and applying late stress would be better DI strategy without much yield penalty (Efetha et al., 2011; Yonts et al., 2018). In addition, out of all three growing seasons, over irrigation treatments (125 % and 150 %) didn't result in statistically higher yields. Actual seasonal evapotranspiration was the same for 100 %, 125 %, and 150 % treatments in 2021, 2022, and 2023, indicating the added water didn't translate into crop water use. Extra irrigation can cause nutrient leaching. For dry beans, extra irrigation can also increase the risk of white mold disease (Efetha et al., 2011).

4.2. Water production functions and water productivities

Water production functions were developed in this study as Yield ~ f (ET_a). Similar to Yonts et al. (2018), seasonal WPFs were different across years. In this study, relative WPFs using normalized yield and ET_a were also developed. All WPFs showed a concave downward curvilinear pattern, and yield gain started to level off at a certain irrigation amount or when relative ET_a was close to 1. Using normalized yield and ET_a yielded similar WPFs in 2021 and 2022. However, the WPFs in 2023 had a distinct shape. This was possibly due to water stress in 2023 was not evenly distributed during the season as it was in 2022 or 2021 due to abundant precipitation in the early growth stages. As dry bean responds differently to water stress that happens during pre- or post-growth stages (Efetha et al., 2011; Yonts et al., 2018), WPFs can be different for growing seasons with different patterns of water stress (Geerts and Raes, 2009).

Different water productivities were calculated in this study, including WP_c, WP_I, GIWP, and WP_b. Spurgeon and Yonts (2013) presented the GIWP of DEB ranging from 0.26 to 1.77 kg m^{-3}. Whereas in our study, GIWP ranged from 0.3 – 1.1 kg m^{-3}. The higher GIWP in Spurgeon and Yonts (2013) could be attributed to the use of subsurface drip irrigation system in which water loss through soil evaporation was reduced (Geerts and Raes, 2009). In all years, WP_c appeared to be higher at lower water treatments. For example, in 2021, the highest WP_c was 1.4 kg m^{-3} for 25 % and 50 % treatments, and the highest WP_c was 0.8 kg m^{-3} for 25 % and 50 % treatments in 2022. The 75 % treatment had the highest WP_c of 1.2 kg m^{-3}. Efetha et al. (2011) reported a WP_c range of 0.74–1.9 kg m^{-3} for Othello dry bean (Pinto bean market class) and they found higher WP_c was associated with frequently irrigated treatments. The differences in water productivity values highlight the challenge of comparing WP across different locations, and caution should be taken when doing so (Fernández et al., 2023). Fernández et al. (2020) also suggested that not only biophysical WP but also economic WP indicators should be taken into account for best irrigation strategies.

The normalized biomass water productivities in 2022, 2023, and pooled values were 13.2, 17.4, and 16.5 g m^{-2}, respectively. Typically, the WP_b values for C3 crops range from 15 to 20 g m^{-2}. Leguminous crops, however, may have values below 15 g m^{-2} as a result of their nitrogen biological fixation process (Raes et al., 2023). Yuan et al. (2013) obtained WP_b for five different C3 crops in Mongolia over the 2009–2011 growing seasons, concluding that WP_b remained constant over the years and across the crops, obtaining an average WP_b of 14 ± 0.3 g m^{-2} with an R^2 of 0.91. Similarly, DEB WP_b values were presented in a study conducted in Belgrade, which showed WP_b of 12.2 g m^{-2} for late sowing date treatment with FIT and 15.6 g m^{-2} for early sowing date treatment with FIT (Lipovac et al., 2022). Some studies (Albrizio and Steduto, 2005; Steduto et al., 2007) suggest that WP_b should be calculated for vegetative and reproductive stages separately, especially for crops that have high protein, lipids, and lignin contents, as the biosynthesis of these products require more energy per unit dry weight. Although DEB is a high-protein content crop, we didn't find a clear separation of WP_b during vegetative and reproductive growth stages.

5. Conclusions

A three-year study was conducted in western Nebraska, U.S., to evaluate the responses of dry beans to different irrigation treatments. Results showed that the dry bean root system was adaptable to drought stress, and capable of extracting water from deep soil depths (> 0.6 m). It was also found that applying 25 % less than the full irrigation requirement did not reduce yield or actual crop evapotranspiration, providing viable deficit irrigation options for dry bean growers when water is limited. Normalized biomass water productivity (WP_b) was found to be 16.5 g m^{-2} using two years of data. WP_b is a valuable parameter for crop models, particularly AquaCrop. Unlike GIWP, which relies on end-season measurements like yield and applied irrigation, WP_b can be determined during the growing season using available biomass and ET data. Conversely, WP_b could also be used to estimate crop ET by sampling dry matter and dividing it by WP_b to obtain the normalized cumulative crop transpiration at the sampling time. However, this approach requires further validation through field experiments before it can be adopted by growers. Canopy cover indicated differences in water stress in one of the three years. In the future, it is recommended to use devices that enable continuous monitoring of canopy cover and possibly other spectral-index-enabled tools to better monitor crop responses to water stress.

CRediT authorship contribution statement

Xin Qiao: Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Angie Gradiz:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Swathi Palle:** Conceptualization. **Jun Wang:** Writing – review & editing, Funding acquisition. **Saleh Taghvaeian:** Writing – review & editing, Supervision. **Wei-zhen Liang:** Writing – review & editing, Validation, Supervision, Software, Formal analysis. **Abia Katimbo:** Writing – review & editing, Supervision. **Daran Rudnick:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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