Optimization of chickpea irrigation in a semi-arid climate based on morpho-physiological parameters

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ABSTRACT

Context: While the world population is steadily growing, the demand for plant-based protein in general, and chickpea in particular, is rising. Heatwaves and terminal drought are the main abiotic factors limiting chickpea yield worldwide.

Objective: Developing better irrigation management for the chickpea agro-system can promote higher and more sustainable yields. Supplemental irrigation at the right timing and dose may increase yield dramatically.

Methods: We studied the response of a modern Kabuli chickpea cultivar to irrigation during the pod-filling period over three growing seasons (2019-2021) in northern Negev, Israel, under semi-arid conditions. Six irrigation treatments were applied based on crop coefficients (Kc) of 0, 0.5, 0.7, 1.0, 1.25, and 1.4 of crop evapotranspiration (ET_c) as measured by a meteorological station on site. Morpho-physiological parameters and above-ground biomass accumulation were monitored throughout the cropping seasons, and the final grain yield was determined at maturation. Irrigation onset was determined based on the plants' water potential (> 15 bar).

Results: Our results indicate that optimal water status (as reflected by pressure chamber values) was in the range of 12-14 bar during the irrigation period. Irrigation according to evapotranspiration (ET_c) with a crop coefficient factor (Kc) of 1.25 resulted in the highest grain yields over the three years. To ensure optimal water supply during the reproductive phase, one that is compatible with the crop water requirements, maintaining values of 25 mm node length above the Last Fully Developed Pod (LFDP) and a 90 mm distance between LFDP to the stem apex is recommended.

Conclusions: Irrigation onset when the crop is already at mild drought stress, followed by sufficient irrigation while following the indicated morphology and water potential values, may help farmers optimize irrigation and maximize chickpea crop production.

Keywords: *Cicer arietinum*, crop evapotranspiration (ETc), crop coefficient (Kc), drip irrigation, water requirements

1. Introduction

World agriculture faces the challenge of feeding the growing global population under diminishing resources and changing climate, as reflected in the increasing frequency and intensity of extreme climatic phenomena such as droughts and heatwaves (Sade & Peleg, 2020). In the eastern Mediterranean, a significant reduction in the number of seasonal rain events is accompanied by an increase in rain intensity (per event) (Drori et al., 2021), resulting in lower soil water availability for rainfed crops.

Irrigated farmland is estimated at 20-25% of the world's cultivated land, producing ~40% of agricultural yield (Puy et al., 2021). Timely irrigation may enhance crop yield compared with rainfed farming (Mueller et al., 2012), but the availability and timing of water resources limit farmers' options. One way to improve global food security is to enlarge the area of irrigated staple crops, making them less reliant on precipitation and with higher potential yield. One such crop is the chickpea (*Cicer arietinum* L.), an important source of dietary protein (van der Maesen, 2007), which is getting more attention as a healthy and functional food. In parallel, there is an increasing demand for plant-based proteins (like chickpea) to replace animal proteins (Bar-El Dadon et al., 2017). This calls for agronomic research to develop advanced agro-techniques to promote yield (Singh et al., 2016).

The global chickpea production is about 14.2 million tons, harvested from ca. 13.7 million hectares (FAO stat 2021), mostly grown on marginal lands in semi-arid regions. Under traditional farming, chickpea is a post-rainy season crop (Kostrinski, 1974), a strategy adopted in antiquity to avoid the damage from ascochyta blight, a disease caused by the pathogen *Didymella rabiei* which spreads by raindrops (Abbo et al., 2003). Consequently, most chickpea cropping relies on residual soil moisture without adequate irrigation infrastructure and water resources. The gap between the high yield potential of chickpea (over 4000 kg/ha; Singh, 1990) and the average global is considered a combined result of biotic and abiotic stresses (Singh & Jana, 1993), with water availability during the reproductive phase as the most critical yield-limiting factor (Awasthi et al., 2014). Efficient and cost-effective irrigation is a key strategy to help close the gaps between yield potential and actual yields in semi-arid agro-systems.

Estimation of crop water requirement by calculating evapotranspiration (ET) from meteorological data relies on the reference ET (ET_0) (Doorenbos, 1977). ET_0 is a climatic parameter expressing the evaporative power of the atmosphere. Crop evapotranspiration (ETc)

refers to the evapotranspiration from crops grown in large fields with optimal soil water, excellent management, and environmental conditions that achieve full production potential under the given climatic conditions (Allen et al., 1998). Many factors affect the actual field evapotranspiration, Crop evapotranspiration- ETc. These include (but are not limited to) the crop species, crop cultivar, leaf area index (LAI), developmental stage, canopy height, crop roughness, a reflection of solar radiation and ground cover. Consequently, under identical environmental conditions, different ET levels are expected for diverse crops or growing stages and should be considered when evaluating the evapotranspiration from large, well-managed crops. One prevailing approach to determining crops' irrigation requirements is calculating the crop coefficient factor Kc (Allen et al., 1998), which is an experimentally determined ratio of ETc/ET_0. Differences in leaf anatomy, stomatal characteristics, aerodynamic properties, and even albedo cause crop evapotranspiration to differ from the reference crop evapotranspiration under similar meteorological conditions (Allen et al., 1998). Thus, The Kc factor for a given crop changes throughout the crop life cycle by the crop growth stages.

Due to its indeterminate growth habit, yield accumulation in chickpea depends upon continuing simultaneously vegetative and reproductive development since flowering commencement. Therefore, supplemental irrigation is essential to extend the reproductive period and support higher grain and total biomass yields. Yet, it is still unclear when to irrigate and what water cubature should be applied at each irrigation to ensure maximum grain yield. In other summer crops, such as cotton (*Gossypium hirsutum*), two morphological traits (number of nodes above the last white flower and the distance of the white flower from the plant apex) are used to monitor the crop development and make real-time decisions concerning irrigation, and management (Bourland et al., 1992; Waddle, 1982). Previously, Bosak et al. (1996) suggested morpho-developmental criteria as a tool to monitor the water status and adjust chickpea irrigation. These authors mentioned that chickpea Last Fully Developed Pod (LFDP) is correlative to the plant water pressure, yet, their research lacked actual evidence for that relationship, and the yield factor was overlocked.

We hypothesized that a gradient of irrigation treatments would result in a range of yield levels that would facilitate the determination of the agro-economic optima. Our underlying assumption was that crop morpho-physiological parameters would change alongside final grain yield with water availability treatments and their interaction with the seasonal weather conditions.

Accordingly, our primary goal was to establish a protocol for optimizing chickpea irrigation striving for maximum yield. In parallel, we calculated the water use efficiency (WUE) as grain yield divided by the amount of available water (precipitation and irrigation) of the different irrigation treatments. We seek to identify morphological indices that may help monitor the crop water status and to develop chickpea irrigation guidelines for a semi-arid Mediterranean climate.

2. Materials and methods

2.1 Plant materials and growing conditions

The Israeli cultivar "Zehavit" (Kabuli type, Hazera LTD), with an average weight of 370 mg/seed, was used for the field experiments because it is adapted to a semi-arid climate and is the most common in Israel.

A three-year study was conducted during the 2019-2021 seasons at Gilat Research Center, ARO, Israel (34°39' E; 31°20' N), located 160 meters above sea level (Fig. 1). This area is characterized by mild winters with average annual precipitation of 230 mm (Bonfil et al., 1999) while the spring and summer seasons are warm and dry (no rains at all). The soil at the location is sandy loam loess–Calcic Xerosol (Dan et al., 1982), with a pH of 7.9-8.3 and a bulk density of 1.45 g cm^{-3}. Daily meteorological data were collected from the Gilat meteorological station, located within 100-1500 meters of the experiment fields, provided by the Israeli Ministry of Agriculture (http://www.meteo.moag.gov.il). In all three years, the previous crop was bread wheat (*Triticum aestivum*). As wheat utilizes all available water (Bonfil et al., 1999), we assumed that no residual water in the soil from the previous season was available to the chickpea plants (especially in soil layers populated by chickpea roots).

Figure 1. **A**) Aerial image of the field experiment (Gilat 2020). **B**) Overview of the field plots (Gilat 2021). **C**) Image of the dripping line located between rows. **D)** Image of a representative main branch. The last fully developed pod (LFDP), node length above LFDP, and distance from LFDP to stem apex are indicated.

2.2 Experimental design

The experiments were conducted in a complete randomized block design with six replicates. Each plot was 5.79 meters in width (three 1.93 meters in width beds) and 25 meters in length. Sowing was held with a row planter in 15 seeds/meter-row density on two rows/bed with a 75 cm distance between them. The experiments were initiated on the last week of January (25, 30, and 22 for 2019, 2020, and 2021, respectively), and seeds emerged at the beginning of February (03, 16, and 02 for 2019, 2020, and 2021, respectively). Between seed emergence and the reproductive stage, rain and supplemental sprinkler uniform irrigations were applied to ensure proper development before the onset of the differential drip irrigation. Differential drip-irrigation was applied weekly with six treatments of 0, 0.5, 0.7, 1, 1.2, and 1.4 Kc values (Fig. S2) according to daily evapotranspiration data computed from the meteorological station (in 2019, there was no Kc=0 treatment). The differential irrigation was initiated only after leaf water potential passed values of 15 Bar. While facing heat waves (high temperatures and high evapotranspiration), irrigation was applied twice a week. For each irrigation treatment, we used a drip line with different dripping spaces (0.5-0.6 meters from dripper to dripper) and different flow capacities (0.7-1.2 liter per hour). With different combinations, we managed to irrigate each treatment simultaneously with different cubature but for the same duration of irrigation. The first irrigation (see below for timing determining) amounts were calculated by measuring evapotranspiration a week before starting irrigation. Irrigation cubature was calculated according to evapotranspiration (ET_c values) from

the previous irrigation until the date of application- multiplied by the specific coefficient factor (Kc) for every irrigation treatment.

2.3 Morpho-physiological characterization

Leaf water potential was measured weekly with a pressure chamber (Model 600D, PMS instrument company, OR, USA). One main stem from every plot was cut at the fifth or fourth node from the apex during the hottest part of the day (12:00-15:00) and quickly (<1 min) inserted into the chamber. The distance of the last fully developed pod (LFDP) from stem apices and node length above LFDP were measured once a week following the appearance of the first pods (2019 and 2020 seasons) or after the first irrigation (2021 season) until full maturity of each treatment (Fig. 1D). Plant samples of 0.5-meter row were harvested weekly at ground level, dried for 48 hours at 70°C, and weighed to obtain total dry matter (Tot. DM). Later, the samples were threshed using a laboratory threshing machine (LD 350, WinterSteiger, Reid, Austria), and reproductive DM (Rep. DM) was weighed. Vegetative DM was calculated as the difference between total DM to reproductive DM. At full maturity, plots were harvested by a conventional grain harvester to obtain the grain yield (GY). The harvest index (HI) was calculated as the ratio between Rep. DM and Tot. DM. Water-use efficiency (WUE) was calculated as the ratio between grain yield and water used (sum of irrigation and rainfall) for each irrigation treatment.

2.4 Statistical analyses and data visualization

The JMP® ver. 16 statistical package (SAS Institute, Cary, NC, USA) was used for statistical analyses unless specified otherwise. A factorial model was employed for the analysis of variance, with irrigation regimes as a fixed effect and years considered random effects. Descriptive statistics are graphically presented in the box plots: median value (horizontal short line), quartile range (25 and 75%), and data range (vertical long line).

3. Results

3.1 Climatic conditions and irrigation pattern throughout the three growing seasons

The seasonal pattern of daily minimum and maximum temperatures during the vegetative stage before the application of differential drip irrigation shows that the 2019 season was characterized

by a relatively mild spring (range 9.4-21.8^{o}C) which allowed an onset of irrigation at 79 days after emergence (DAE) compared with 75 and 62 DAE in 2020 (range 10.1-23.4^{o}C) and 2021 (range 8.7-21.8^{o}C), respectively. This earlier irrigation onset in the 2021 season corresponded with the lower precipitation (140.7 mm) and sprinklers (60 mm). The evapotranspiration (ET_c) ranged from 263.1, 250.2, and 188.7 mm for 2019, 2020, and 2021 growing seasons, respectively (Fig. S1). In 2019, temperatures and evapotranspiration data showed mild conditions during the vegetative stage before the application of differential drip irrigation. This allowed the gradual development of plants without extreme stress episodes. As the season progressed, the crop faced several heat waves (Fig. S1A). The 2020 seasonal temperature and ETc pattern show an extreme 8-days ongoing heat wave (accompanied by high Etc values) less than two weeks after commencing irrigation (88 DAE). These extreme climatic conditions resulted in the restricted canopy and pod development - and grain set (Fig. S1B). In the 2021 season, the crop experienced several heat waves, two of which occurred before the onset of irrigation (62 DAE), followed by several events during the irrigation season until maturity (Fig. S1C). The average minimum temperatures were similar across the three growing seasons (11.3^{o}C), while the average maximum temperatures ranged from 25.7 (2019) to 26.1^{o}C (2020).

During the 2019 and 2021 growing seasons, the irrigation treatment of Kc=1 [302.0 and 389.5 mm (liters m^{-2}), respectively] was very close to measured evapotranspiration during the irrigation period (310.9 and 373.2 mm, respectively; Fig. S2). In the 2020 season, due to extreme heat waves (i.e., days with maximum temperature > 35°C, ETc> 6.5 mm/day), we had to apply a higher water cubature (277.5 mm irrigation compared with ET_c of 228.7; Fig. S1), trying to keep plants vital and functioning. The hostile evapotranspiration values during 2020 affected the plants' growth and development, resulting in a 28 days irrigation period, while the irrigation periods in the 2019 and 2021 seasons were 42 and 54 days, respectively (Table S1).

3.2 Physiological characterization

In general, analysis of variance (ANOVA) resulted in a significant effect of the irrigation treatment and year on productivity (rep. DM, total DM, and GY), physiological (water potential and water-use efficiency), and morphological (distance from apex to last inflated pod and length of node above the last inflated pod) parameters, except for harvest index (Table 1). A significant irrigation × year interaction effect was found for GY, WP, WUE, and the distance from apex to last inflated

pod and length of node above the last inflated pod (Table 1). Yearly analyses of variance to test the effect of differential irrigation treatment showed a significant effect for all parameters except harvest index, which was significant only during the 2021 season (Table S2).

Table 1. Analysis of variance (ANOVA) for total dry matter (Tot. DM), reproductive DM (Rep. DM), grain yield (GY), harvest index (HI), instantaneous water potential at median irrigation period (WP), water-use efficiency (WUE), the distance of the last fully developed pod (LFDP) from plant-apex and node length above LFDP at median irrigation period, under different irrigation regimes (0.5, 0.7, 1, 1.25, and 1.4 Kc values) over three experimental seasons (2019, 2020, and 2021).

Source	d.f.	Sum of square							
		Tot. DM	Rep. DM	GY	HI	WP	WUE	LFDP-stem apex	Node above LFDP
Irrigation (I)	4	363079356 0.0001	110228322 0.0001	51482379 0.0001	0.017021 0.1236	525.51 0.0001	0.0622889 0.0127	71996.1 0.0001	1508.18 0.0001
Year (Y)	2	67979614 0.0001	29865018 0.0001	8731135 0.0001	0.023848 0.0073	495.57 0.0001	0.6771756 0.0001	54215.6 0.0001	1729.8 0.0001
I×Y	8	20992203 0.2579	6673436 0.2814	6091376 0.0001	0.009 0.8562	63.76 0.0001	0.130 0.0015	17012.2 0.0001	508.42 0.0001
Error	75	151662642	49959031	7926023	0.170	80.26	0.342	7141.7	278.5

d.f., degree of freedom.

During the 2020 and 2021 seasons, instantaneous leaf water potential values at the onset of irrigation matched our pre-planned value (pressure-chamber values above 15 Bar). This value represents levels of water stress in farmers' fields that may impair the continuation of reproductive growth. The leaf water potential responded coherently to the irrigation treatments: high pressure-chamber values under deficit irrigation treatments compared with low values under optimal (well-irrigated) treatments. Under irrigation treatments of Kc>1, the pressure-chamber values during the irrigation period ranged around 12-13.5 bar, attesting to the plants' improved water status.

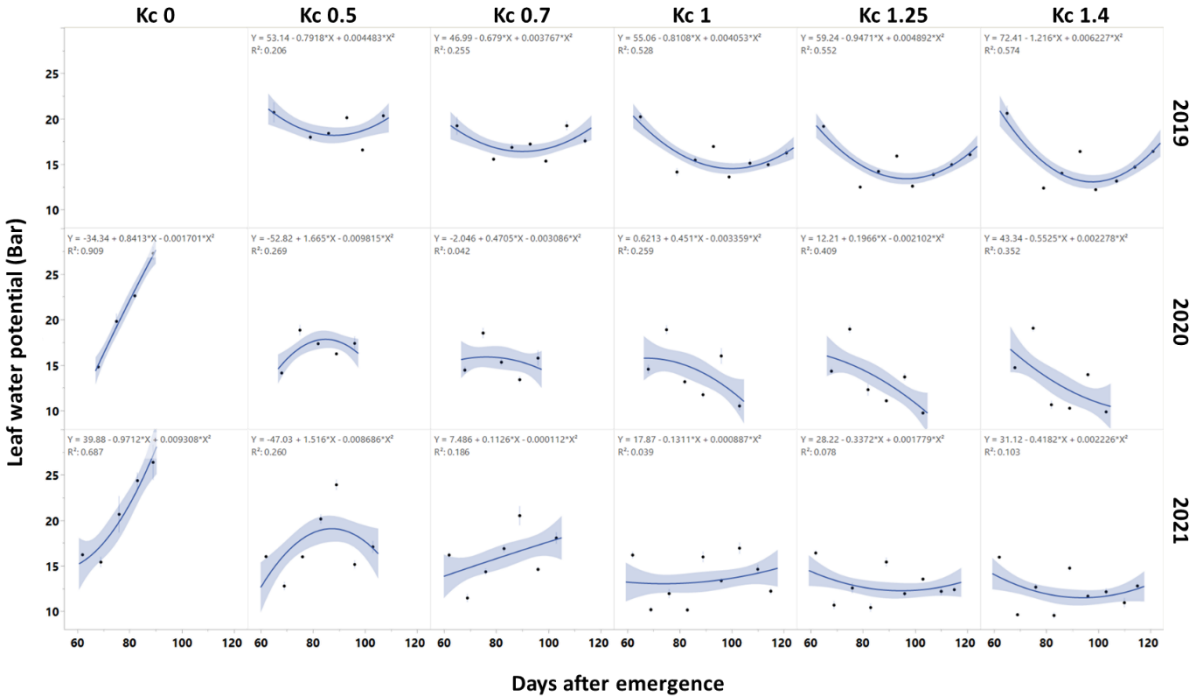

Figure 2. Instantaneous leaf water potential (pressure chamber values, Bar) along the irrigation period for each treatment (0, 0.5, 0.7, 1, 1.25, and 1.4 Kc values) over three experimental seasons (2019, 2020, and 2021). The curves represent the mean within the water treatment and year (*n*=6). Shading indicates the standard error.

3.2 Morphol-development parameters

The dynamics of the length of the stem node above the youngest fully inflated pod are presented in Figure 3A. For this morphometric parameter, the water treatments resulted in two responsiveness groups, one with irrigation Kc≥1, which showed increased values following irrigation throughout the irrigation period. The second response group comprised the irrigation treatments with Kc<1 and showed continuous growth decay.

The dynamic of the distance from the youngest fully inflated pod (LFDP-apex distance) to the stem apex over the crop reproductive periods are presented in Figure 3B. While all irrigation treatments start with a similar distance of LFDP-Top (around 70 mm), the irrigation treatments with Kc<1 responded with a shortening of LFDP-Top values dropping to 10-20 mm by the end of the season. Irrigation treatment with Kc>1 maintained the initial LFDP-Top value and even increased it slightly by the mid-season (70-100 mm). The Kc=1 treatment showed a constant decrease with a constant slope throughout the irrigation period (Fig. 3B).

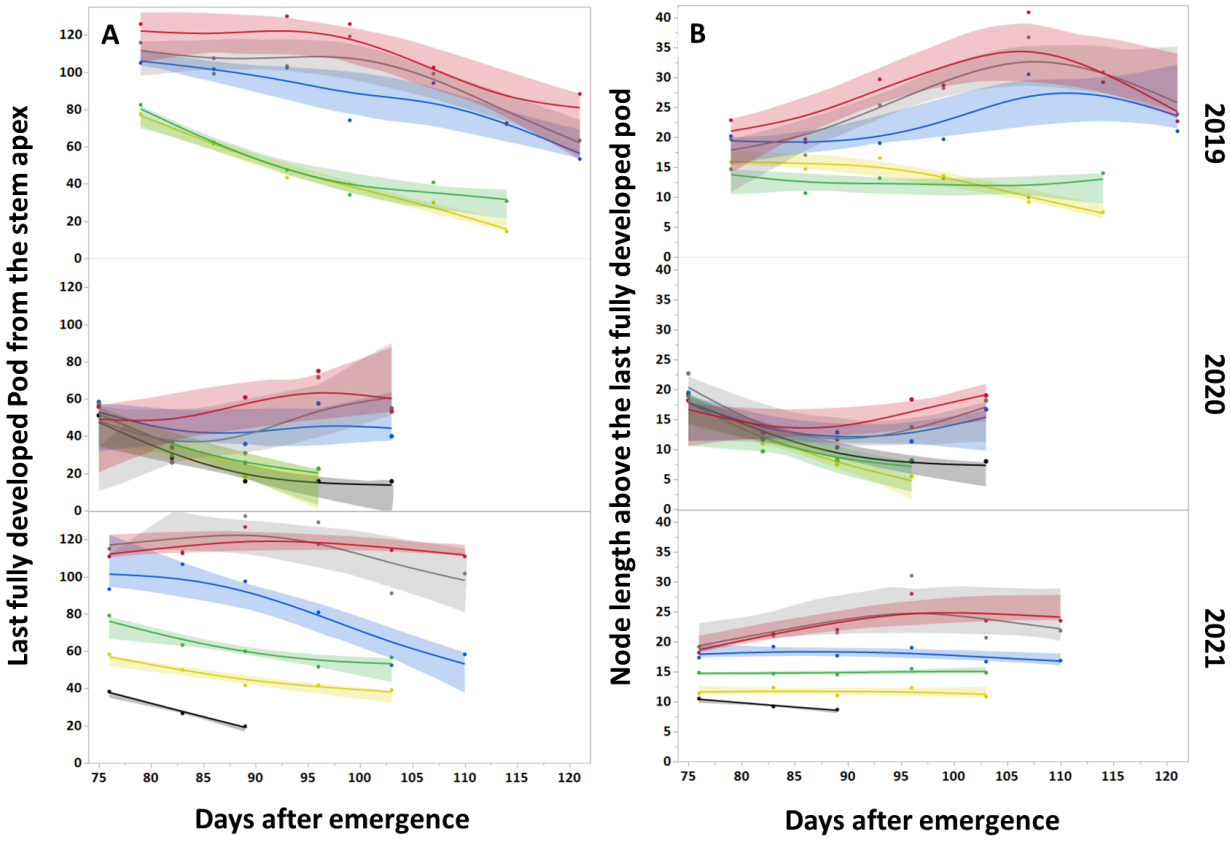

Figure 3. Distance of **A**) last fully developed Pod (LFDP) from the stem apex, and **B**) node length above the last fully developed pod by irrigation treatments along the three experimental seasons (Gilat 2019 – 2021). Irrigation treatments: 0 (black), 0.5 (Yellow), 0.7 (Green), 1 (blue), 1.25 (gray), and 1.4 (red) Kc values. The curves represent the mean (*n*=6). Shading indicates the standard error.

3.3 Longitudinal pattern of dry matter accumulation

The longitudinal pattern of total dry matter (DM, manual harvested) accumulation during the three growing seasons, from about four weeks before irrigation onset until full crop maturity, is presented in Figure 4A. The seasonal accumulation of total DM differed between the irrigation treatments

with the greater the amount of irrigation, the higher the DM accumulation. The seasonal patterns of the reproductive DM showed that in all treatments and during all seasons, there is a phase of about three weeks, starting from the formation of the first pods, in which pods are developing but with no appreciable reproductive DM accumulation (Fig. 4B). About two weeks after irrigation onset, this trend changes and each treatment enter a phase of rapid reproductive DM accumulation. While the water deficit treatments (Kc<1) result in a shorter crop cycle and stop accumulating reproductive DM, the well-irrigated treatments (Kc≥1) continue growing and set more pods (and DM) for extended periods as reflected in the respective DM dynamics (Fig. 4B). At the end of the experiment the plots were mechanically harvested. Generally, with the increased water availability, the grain yield increased till Kc=1.25 (Fig. 4C, Table S4). The Kc=1.4 treatment showed an inconsistent trend (either decrease, equally, or increased grain yield for the 2019, 2020, and 2021 seasons) compared with the Kc=1.25 treatment. Notably, these differences were below the significant threshold for all seasons. The extreme weather condition during the 2020 season (i.e., heat waves) resulted in two groups between the irrigation treatments, with Kc<1 and Kc≥1 clustering together. Notably, the non-irrigated treatment produced significantly lower yields in both the 2020 and 2021 seasons.

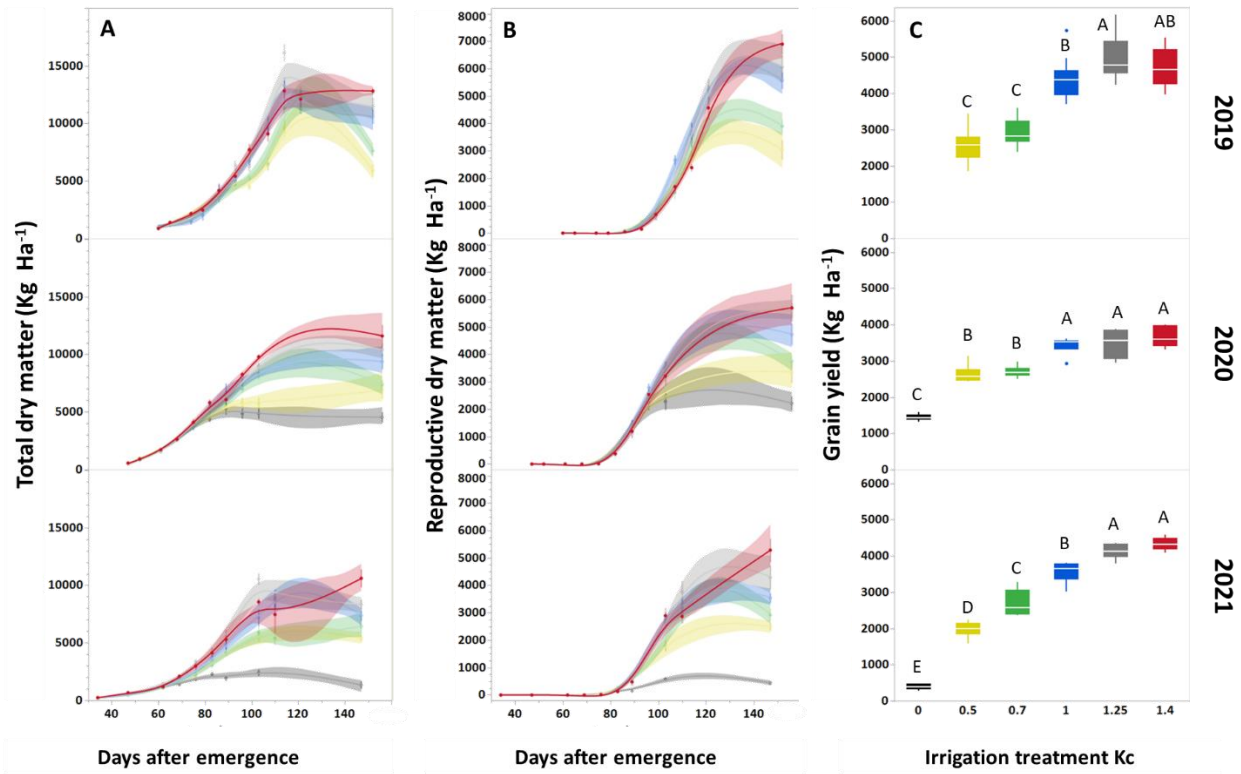

Figure 4. Seasonal accumulation of **A**) above-ground total dry matter (Tot. DM), **B**) reproductive DM (Rep. DM) and **C**) grain yield (GY). by irrigation treatment along the three growing seasons (Gilat 2019-2021). The curves represent the mean (n=6). Shading indicates the standard error. Irrigation treatments: 0 (black), 0.5 (Yellow), 0.7 (Green), 1 (blue), 1.25 (gray), and 1.4 (red) Kc values. Different letters indicate significant differences at $P \leq 0.05$.

3.4 Contribution of irrigation to grain yield

To test the grains yield contribution of additional water availability to grain yield, we plotted the GY along the three growing seasons based on the Kc irrigation treatments. While under rainfed conditions (Kc=0), yield is determined solely by climatic conditions (precipitation and ETc during grain filling period), under increasing irrigation treatments, we found linear responsiveness to added water across all years up to Kc≤1.25 (Fig. 5). The yield differences between years are the result of environmental conditions and especially heat wave events, their timing during the irrigation period and intensity. Under irrigation treatment of Kc=1.4, we found an inconsistent response that varied between years. In 2019 yield was lower than the irrigation treatment of Kc=1.25, whereas, in the 2020 and 2021 seasons, the additional water contributed to increased yield gain, but with different trends (slope of graph) and with a non-significant difference from irrigation treatment Kc=1.25.

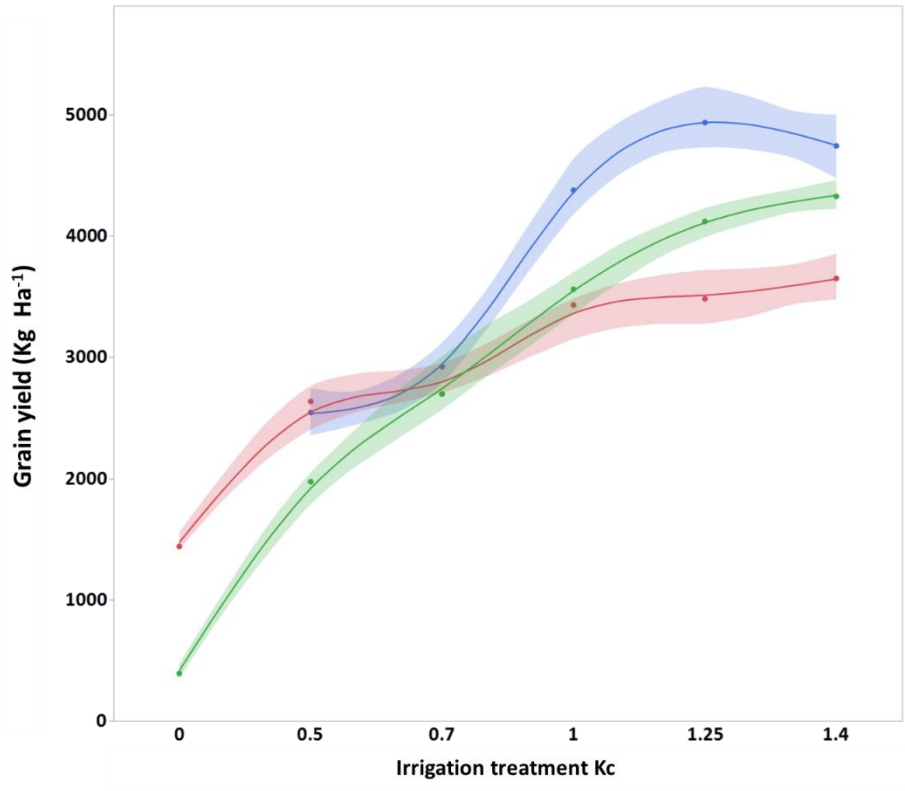

Figure 5. Grain yield (mechanical harvest) by irrigation treatment during the three growing seasons (2019, 2020, and 2021 (blue, red, and green, respectively) at Gilat). The curves represent the mean (*n*=6). Shading indicates the standard error.

To test the response of chickpea crop to water availability during the growing season (from sowing to maturity), we calculated for each treatment (Kc 0-1.4) in each growing season (2019-2021) the available amount throughout the season (i.e., rain and irrigation applied). The intersection point of the graph (X-axis=177 mm; Fig. 6A) implies the minimal amount of water that allows the development of plants in the field but limits the plant's ability to produce grains. The second parameter expresses the yield production potential of Israeli chickpea varieties under optimal growing conditions, as represented by the values above the saturation point (X-axis values >600). In semi-arid Mediterranean climate conditions, the value ranges around 4500 kg Ha^{-1}. The last parameter is the slope of the graph in its linear range of values, which expresses the water-use efficiency (WUE) of this chickpea variety under detailed climate and growing conditions (Fig. 6A).

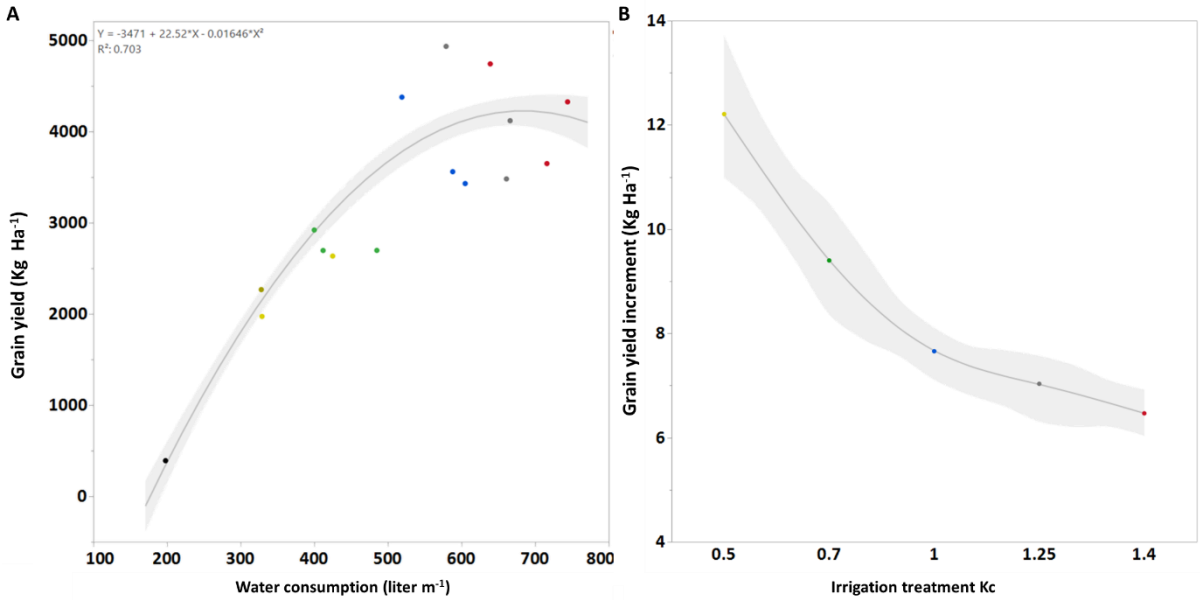

Figure 6. A) Grain yield (mechanical harvest) response to water consumption over 2019, 2020, and 2021 growing seasons at Gilat, Israel. **B**) Grain yield (average of 2020 and 2021 growing seasons) contribution to mm (liter m^{-1}) irrigation by irrigation treatment (Kc factor). The curves represent the mean (*n*=6). Shading indicates the standard error.

The contribution of additional water to grain yield accumulation under each irrigation treatment is presented in Figure 6B. Under the lowest water availability (i.e., lower Kc), there was the highest contribution to yield, 8-12 kg grain ha^{-1} mm^{-1} of irrigation. With increasing water availability (kc≥1), the contribution to yield per mm irrigation water decreased to 6-8 kg grain ha^{-1} mm^{-1}. However, it still allows additional yield accumulation and offers an approach for achieving the maximum grain yield potential of the field.

4. Discussion

The unpredictable and fluctuating climatic conditions associated with present and projected climate change have become the primary constraint for chickpea production worldwide and jeopardize future food security. This study's primary objective was to develop an optimal strategy for chickpea irrigation based on meteorological data and supported by morpho-physiological parameters to promote maximizing grain yields under the semi-arid Mediterranean basin. We have used the measured ET_c values to design differential irrigation regimes well reflected in differential crop physiology and morphological parameters (Tables 1, S2; Figs. 2-3). Eventually, these irrigation

treatments resulted in a range of biomass and grain yield values (Fig. 4) which may assist in formulating chickpea drip-irrigation protocols for semi-arid Mediterranean growing regions.

4.1. Morphological- rather than physiological- traits easily capture the crop water status dynamics

Assessing the crop water status during the growing season is expensive, cumbersome, and time-consuming, which poses a challenge for plant physiologists and farmers. Various strategies have been suggested, including direct sensors (e.g., soil tensiometers, stem diameters, pressure chamber, etc.) or remote sensing (e.g., multi-spectral and thermal imaging) to assess this trait (Zhou et al., 2021; Ezenne et al., 2019; Avneri et al., 2023). In the current study, we used a pressure chamber to measure directly the crop water potential in the field (Fig. 2). This strategy was used to understand the plant-water relationships (Turner, 1988). However, this technology does not enable many measurements during any sampling day. The need for real-time knowledge of the crop water status emphasizes the necessity to identify objective morph-physiological indices to determine the plant water status (Cohen et al., 2015). Our irrigation protocol and the documented morpho-developmental indices of node-length above the last fully developed pod (LFDP) and distance between LFDP to plant apex can help by providing irrigation control feedback which enables monitoring the crop water status without sophisticated equipment. When considering the overall results of node-length above LFDP and distance LFDP-plant apex between years and irrigation treatments, it seems that node length shorter than 20 mm indicates that the plant experiences water stress.

In comparison, LFDP-plant apex values above 30 mm may hint at excess irrigation. It seems that under Mediterranean-basin climatic conditions for Kabuli varieties, node length above LFDP around 25 mm is required to maximize grain yield. Higher values of our morpho-developmental parameters may serve as an indication to decrease the amount of irrigation in the following application, while lower values are an indication of water stress, and higher irrigation cubature should be considered. In addition, a farmer may monitor these parameters on his chickpea crop over several seasons and varieties and, if need be, make required local adjustments. In our view, the morphological indices best reflected the crop water status since plant development in effect (and by definition) integrates all environmental determinants over the growing period. Therefore, monitoring the ET_c and growth parameters may assist in determining the precise water dose before

each irrigation pulse, thereby ensuring uninterrupted yield accumulation and preventing yield losses from lodging, pod shading, and/or leaf diseases.

The distance between the LFDP to the plant apex reflects, in our opinion, the long-term water status throughout the podding period. This parameter shows a similar trend between years in which distance shortens as the water availability to the plant decreases and as irrigation season approaches its end (Fig. 3). The values of this parameter were statistically different between irrigation treatments in all growing seasons (Table S2), thereby providing an essential and easy measure to assess the crop water status. While irrigation treatments with Kc≥1 can maintain this distance (even for 1-2 weeks) or even increase it, irrigation treatments with Kc<1 are characterized by decreasing values of this parameter. This fact implies that the crop water requirements during podding are higher than the ET_c (Kc=1), and the field should be irrigated above this value to extend the irrigation period as long as the crop is capable. Likewise, the node length above LFDP is also a reliable indicator of plant water status. This is the last stem node that ended its elongation and reflects the plant's water availability during the period between node formation and measurement day- final length. Unlike pressure chamber measurements that provide instantaneous (day-time) information, this node length may be considered as an integrator of the conditions experienced by the plant ever since its formation to the day of measurement. No less important, it is easy to measure, requires no expensive equipment, and it is not affected by extreme climate conditions that may occur on the measurement day or hour. However, it is necessary to consider that desired values may change between cultivars, growth conditions, and their interactions. This parameter is proportional to the applied water cubature, with the highest amount of irrigation, the longest the nodes. From the irrigation onset date, values are decreasing under irrigation treatments with Kc <1 while irrigation treatments with Kc>1 show increased length to desired values (above 20 mm). This corroborates our claim that the irrigation water demand by the crop during the podding phase (mid-season) is greater than Kc.

Our results indicate a close match between the seasonal pattern of the two morphometric parameters (as an indication of the crop water status) and the reproductive DM accumulation across irrigation treatments and years (Fig. 4). The reliability of our morphological parameters and their usefulness in general irrigation design (and ad-hoc decision making) is evident from the close match between the dynamics of the seasonal water potential values and the longitudinal patterns of the LFDP and the length of the node above the LFDP.

4.2 Extentending the reproductive phase is essential for grain yield improvement under semi-arid conditions

Oweis et al. (2004) suggested that 2-3 additional irrigations per season during the reproductive phase enable higher chickpea grain yield in the Mediterranean basin. We have used a different approach of more frequent irrigations to maintain a constant soil moisture content to stabilize the crop water status for extended periods. We suggest that to achieve high grain yields (>4 Ton Ha^{-1}), the irrigation period must be extended by keeping the crop vital and functioning. Davies et al. (1999) showed a correlation between plant water potential and net photosynthesis (Davies et al., 1999). Thus, by maintaining a desirable plant's water status, the plant can support a high level of net photosynthesis that contributes to appropriate partitioning and redistribution of dry matter from vegetative organs (stems and leaves) to reproductive organs (flowers and pods). Indeed, this is one of the main physiological determinants of high grain yield in chickpeas growing under Mediterranean-type conditions (Leport et al., 1999). Extending reproductive growth in crops with indeterminate growth patterns (Bonfil & Pinthus, 1995), which support high grain yield, can only be achieved by careful tuning of drip irrigations at high frequency. Such an approach may enable farmers to match crops' water demand via quick response during extreme weather conditions. Adequate water status allows evaporative cooling of the foliage during extreme weather conditions, thereby keeping plants active and functional. Indeed, our Kc 1.25 and 1.4 treatments were capable of preventing crop collapse and growth cessation during heat waves with days above 40°C (Fig. S1). In other words, maintaining crop growth is likely to result in large and well-developed plants that can bear more main and secondary branches carrying flowers and pods (Pushpavalli et al., 2015).

4.3 Kc=1.25 provides the most productive regime for chickpea in Mediterranean conditions

The contribution of the amount of irrigation to grain yield was defined only in 2020 and 2021 (with rainfed treatment) by calculating the yield differences between specific irrigation treatment and the rainfed treatment, divided by the amount of supplied water (Fig. 6A). Notably, under low Kc (e.g., 0.5 and 0.7) irrigation treatments, additional water had a relatively large contribution to the grain yield (~10 kg grains Ha^{-1} mm^{-1} irrigation water). Under high Kc≥1 irrigation levels (1, 1.25, and 1.4), water contribution to yield decreased to about 7.0 kg grains Ha^{-1} mm^{-1} irrigation. We suggest

that using a crop coefficient (Kc) of ca. 1.1-1.25 may support relatively high grain yield levels (>4 t/ha) even in years with high intensity of extreme heat waves, such as the 2020 season (Fig. S1), albeit at the cost of low water-use-efficiency.

The current chickpea irrigation protocol (Allen et al., 1998), recommends irrigation using a crop coefficient (Kc) of 1 during the median irrigation period and 0.35 during the late-season irrigations to supply the crop its water demand. Our findings point at a greater Kc of 1.25 from the onset of irrigation until the end of the growing season, with parallel monitoring of the morphological parameters as feedback for fine-tuning the irrigation's cubature. These recommendations are even higher relative to published results that suggested a Kc of 0.97 over mid-season and Kc of 0.54 at late-season for Desi-type chickpea (Rinaldi et al. 2008). A possible explanation for our high Kc compared with the works of Rinaldi et al. (2008) and (Allen et al., 1998) is probably due to the different types of cultivars (Kabuli *vs*. Desi) and the more xeric conditions in the southern Levant.

4.4 Conclusion and future perspective

Extending the reproductive period from the beginning of the spring to early summer is essential for producing high yields in the Mediterranean basin (i.e., rising temperatures and extremely hot days) (Fig. S3A). The intensity and duration of heat waves can result in dramatic yield reduction due to the shortening of the reproductive period, as happened in the 2020 season (Fig. 4). Such high-evaporative requirement days decrease the plant's turgor, which may cause crop lodging (see Fig. S3B). This phenomenon is irreversible, and plants do not resurrect, making the continuation of irrigation ineffective. Thus, maintaining the crop fully turgid throughout the irrigation period will enable plants to cope with extreme heat waves. The morphological traits are a feedback tool for examining the applied irrigation water and allow a fine adjustment under changing growing conditions such as crop rotation, field patchiness, and different locations. The morphological traits reflect the effects of a two weeks period, unlike single time-point physiological characteristics, and therefore offer a more reliable tool for plant water status evaluation.

Our new irrigation guidelines for semi-arid environments for chickpea were already adopted by farmers in commercial fields in southern Israel (2021 and 2022 rainfall 200-450 mm) during the 2021 and 2022 growing seasons, resulting in high yields ranging from 4.5-5.5 Ton ha^{-1} (Fig. S3C). Notably, this irrigation practice efficiently coped with extremely high daily temperatures (> 40°C)

during the irrigation periods. While this protocol resulted in increased yields, it is important to point out that application of our guidelines to other cultivars and environmental conditions requires adjusting the use of the morphological parameters. Moreover, this experimental approach of differential irrigation method, while each irrigation treatment receives the desired amount of water accurately for the same irrigation duration, could also be implemented for other crops for a better understanding of their irrigation requirements. Importantly, our findings, and the increased frequency of extreme weather events, call for an urgent re-evaluation of current irrigation protocols to cope with the current and projected climatic conditions and enhance yields to ensure food security.

Author contributions

AA, RNL, ZP Conceptualization; AA, RS, OP, DB Data curation; AA, ZP, SA, RNL Formal analysis; SA, ZP, RNL, IH Funding acquisition; SA, RNL Project administration; SA, RNL Supervision; AA, SA, ZP, RNL Writing - original draft; All authors read and approved the final version of the manuscript.

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