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Water productivity, growth, and physiological assessment of deficit irrigated cotton on hyperarid desert-oases in northwest China

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ABSTRACT

Critical water shortage and hyperaridity are the principal reasons, limiting cotton cultivation on desert-oases in northwest China. However, if water dearth is effectively managed then these terrains can also add significant contribution in regional and country's total cotton production due to favorable climate. In that perspective, a 2-years (2015–2016) field study was conducted on cultivable southern periphery of Taklamakan desert to optimize water productivity of deficit drip irrigated cotton through evaluating its water use (ETc), growth, and physiology based water relations. Treatments included four drip irrigation regimes based on 100 (D_{100}), 80 (D_{80}), 60 (D_{60}), and 40% (D_{40}) replenishment of depleted water from field capacity. Results revealed that average ETc ranged from 510 mm at 40% to 1079 mm at 100% water replenishment. Crop growth and pre-dawn leaf water potential (ψ_{pd}) successively declined with reducing irrigation amount. Photosynthesis (*A*), and stomatal conductance (g_s) of D_{80} plants decreased by 15% at squaring and by only 8% at later stages while, this decline was more vigorous under 60 and 40% water replenishments. The 80% irrigated plants resulted in only 13% yield reduction from D_{100} whereas, the average seed cotton yield varied from 2433 kg ha^{-1} in 40% to 4376 kg ha^{-1} under 100% water replenishment. The maximum irrigation, and crop water use efficiencies (IWUE, WUE) were recorded 0.62 and, 0.48 kg m^{-3}, respectively, which reduced with increasing irrigation amounts. In addition, crop growth and physiological attributes showed linear correlations with ETc and irrigation regimes during yield formation. Following economic evaluation, these results suggested that, irrigating cotton up to 80% field capacity would provide the optimum yield and net income with 20% water saving while, D_{60} could save 40% water but, subject to major yield and profit loss. However, if water is sufficiently available then 100% irrigation can be practiced for maximizing cotton productivity and net gains on desert-oases.

1. Introduction

Rapidly growing world population and continuously depleting arable land resources due to urbanization are leading to serious food security threats worldwide while, affecting more seriously to densely populated developing countries (Li et al., 2017). Parallel to food, the world fiber demand is also increasing that needs more cultivable land and water resources to meet these challenges. Cotton (*Gossypium hirsutum* L.) is one of the most important food, feed, and fiber producing crop that is grown on widespread area in the world (Howell et al., 2004). Xinjiang Uyghur autonomous region in northwest China is an important agricultural zone, and the world leader in cotton production due to its promising climate and plentiful sunshine hours per day during crop season. In addition, by contributing 35% share in national, and about 11% in world's cotton production, the region highlights its significance for this crop (Tang et al., 2010). So far, due to higher yield per unit area, an increasing number of farming communities are engaged with cotton cultivation in the region for higher profit and better livelihood (Wang et al., 2014). As, the climate of Xinjiang is supportive for cotton, the total production of this region can be further enhanced by allocating more area to this crop but, limitation of arable land is concerned. In this scenario, the cultivated area in the region is intensively being expanded by continuous conversion of deserts into desert-oases. Nevertheless, the environmental threats to crops including water scarcity, high evaporative potential, negligible amount of rainfall, and persistent drought predominantly remained serious concerns

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within desert ecosystem (Guo et al., 2009; Zeng et al., 2006; Zhang et al., 2017).

Oases on the southern rim of Taklamakan desert, northwest China, is a new and fragile piece of cultivable land that also has great attraction for cotton cultivation due to suitable climate. This terrain can add a valuable contribution in total cotton production of Xinjiang but, its hyperaridity and an extreme shortage of irrigation water are the serious threats to ecological sustainability (Zeng et al., 2006), which forbid the widespread cultivation of cotton. However, the use of widely adopted deficit irrigation is the most feasible approach to be used for cotton production under such an extreme and water deficit conditions without disturbing ecosystem's stability (Fereres and Soriano, 2007; Howell et al., 2004; Oweis et al., 2011; Ünlü et al., 2011). In deficit irrigation practice, cotton is irrigated below 100% of its evapotranspirational requirement that optimizes yield within irrigation limits by limiting subsoil drainage and percolation (Fereres and Soriano, 2007; Oweis et al., 2011). Since, cotton grows in an indeterminate pattern (Quisenberry and Roark, 1976), its growth rate, biomass accumulation, leaf area, and gas exchange activities are adversely affected by deficit irrigation (Pettigrew, 2004). Photosynthesis is the most important physiological process that determines crop growth and final yield, is highly susceptible to water deficit stress (Deeba et al., 2012; Raines, 2011; Yi et al., 2016). Despite of that, numerous studies have reported the significance of deficit irrigation for cotton under water limited conditions. According to Zhang et al. (1999), a significant quantity of irrigation water can be saved under drought situation by limiting water use with a minimal influence on crop yield. Later, Fereres and Soriano (2007) also reported that deficit irrigation is potentially an efficient technique not only for enhancing water productivity, but also for profitable farm income.

In Xinjiang, mulched drip micro irrigation is commonly used on large scale for cotton cultivation, as, it saves enough water and enhances water productivity (Ibragimov et al., 2007; Wang et al., 2013). Yet, in those regions where aridity and water scarcity issues are more challenging, there, water saving, and use efficiency can be further improved by switching from full to the deficit drip scheme. In that perspective, Thind et al. (2008) found that deficit drip irrigated cotton ensures 25% more water saving with better yield than normal practices. Besides, Dağdelen et al. (2009) and Ünlü et al. (2011) evaluated water use efficiency and yield of cotton using deficit drip irrigation regimes and proposed 75% and 70% levels as optimum for arid and semiarid Mediterranean regions, respectively. Singh et al. (2010) reported that reduced irrigation is the best alternative under water shortage conditions while, 100% water supply gives the maximum net returns, if water availability is of no concern. Later on, Oweis et al. (2011) concluded that, though a negligible yield loss has to be sacrificed but, deficit drip irrigation proved to be an appropriate technique for cotton in water limited regions. Even, several other similar crop water management studies from Xinjiang northwest arid region of China have also reported the improved water use efficiency and profitability of cotton with more water saving under deficit drip irrigation technique (Guan et al., 2013; Kang et al., 2012; Wang et al., 2014; Wang et al., 2013; Yang et al., 2015). As, it is obvious from earlier studies that water limitation in arid regions is a critical issue against profitable cotton production, thus, in desert ecosystem, the situation could be more challenging. However, it was needed to optimize yield and water use efficiency of cotton on a very important cultivable southern rim of the Taklamakan desert through evaluating its growth and physiological based water relations. Since, despite of favorable climate, none of the literature has reported cotton cultivation and agricultural water management studies from this terrain.

The particular objectives were to; (1) examine physiological traits including rate of photosynthesis, stomatal conductance, leaf water potential, and growth response such as leaf area index, crop growth rate, and biomass accumulation, and (2) determine seed cotton yield, yield response factor (k_y), consumptive water demand (ETc), water use efficiencies (WUEs), and yield-ETc relations of deficit drip irrigated cotton under desert ambiance. The outcome of this study would provide necessary information that would help in successful and sustainable cotton production on cultivable terrains of desert ecosystems and in those regions where extreme water scarcity and high evapotranspiration persist due to global climate change.

Table 1
Long term and experimental year's monthly climate data of study site.

Years	Months	T_{max} (°C)	T_{min} (°C)	$T_{avg.}$ (°C)	Rainfall (mm)	R.H (%)
2000–2014	April	24.33	8.09	16.21	0.0	27.0
	May	29.79	12.91	21.35	4.4	32.2
	June	33.92	17.08	25.50	3.7	39.4
	July	38.05	19.42	28.74	1.9	44.7
	August	35.12	18.33	26.73	9.6	55.3
	September	26.83	9.86	18.35	20.8	53.8
	October	20.18	2.92	11.55	0.0	47.1
2015	April	25.89	7.31	16.60	0.0	25.3
	May	30.35	12.76	21.56	5.6	33.1
	June	31.90	15.19	23.55	7.2	38.7
	July	36.90	18.37	27.64	3.8	41.6
	August	32.75	18.39	25.57	0.2	44.1
	September	27.72	10.37	19.05	17.4	52.9
	October	23.22	3.24	13.23	0.0	46.2
2016	April	26.70	10.51	18.61	0.0	26.4
	May	30.14	14.03	22.09	3.4	34.8
	June	34.73	18.35	26.54	1.8	33.2
	July	35.26	18.54	26.90	1.2	41.6
	August	32.07	16.83	24.45	21.8	59.5
	September	28.17	10.91	19.54	29.1	51.7
	October	22.72	3.88	13.30	0.0	44.0

T_{max}, T_{min} and T_{avg}: maximum, minimum, and average temperature, R.H: relative humidity.

2. Materials and methods

This field experiment was carried out on Cele National Station of Scientific Observation for Desert-Grassland Ecosystem (36°51′30″N, 80°44′28″E), Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, during growing seasons of 2015 and 2016. The study area is located on southern rim of the Taklamakan desert, northwest China, which is a warm temperate zone with a continental desert climate. Its mean annual temperature and the maximum evaporative potential are 11.9 °C and 2595 mm, respectively, while, the long term and experimental year's monthly data for climate are provided in Table 1, which were obtained from a metrological unit of the Cele Desert Research Station. The soil type of experimental site was classified as loamy sand/Aeolian sand, and its physical and chemical properties are listed in Table 2.

2.1. Plant material and experimental layout

Cotton crop was planted on 20th and 15th of April during 2015 and 2016, respectively, under super high density planting technique, in which the cotton plants are raised in narrow spaces in order to maintain high population density (approx. 200,000 plants ha^{-1}). To check the sideways seepage losses, plastic sheets were installed around each trial unit up to 1.2 m depth. Plants were grown in 30 and 60 cm alternate row spacing with 10 cm planting distance (Fig. 1). Drip lines with inter-emitters distance of 10 cm, were placed between the narrow rows (30 cm) under thin plastic film. The quantities of N:P:K fertilizers used in this trial were 240:120:60 kg ha^{-1}, respectively. All phosphorus (P_2O_5) as di-ammonium phosphate (DAP) and potassium as K_2SO_4 were mixed in soil just before plantation, while nitrogen in the form of urea was dressed at four intervals (¼ at sowing, ¼ at first irrigation, ¼ at squaring, and ¼ at boll formation). Weeds were controlled manually on