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Characterizing leaf gas exchange responses of cotton to full and limited irrigation conditions

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ABSTRACT

Plant responses to water deficit need to be monitored for producing a profitable crop as water deficit is a major constraint on crop yield. The objective of this study was to evaluate physiological responses of cotton (*Gossypium hirsutum*) to various environmental conditions under limited water availability using commercially available varieties grown in South Texas. Soil moisture and variables of leaf gas exchange were measured to monitor water deficit for various varieties under different irrigation treatments. Lint yield and growth variables were also measured and correlations among growth parameters of interest were investigated. Significant differences were found in soil moisture, leaf net assimilation (A_n), stomatal conductance (g), transpiration rate (T_r), and instantaneous water use efficiency (WUE_i) among irrigation treatments in 2006 while no significant differences were found in these parameters in 2007. Some leaf gas exchange parameters, e.g., T_r, and leaf temperature (T_L) have strong correlations with A_n and g. A_n and WUE were increased by 30–35% and 30–40%, respectively, at 600 μmol (CO_2) m^{-2} s^{-1} in comparison with 400 μmol (CO_2) m^{-2} s^{-1}. Lint yield was strongly correlated with g, T_r, WUE, and soil moisture at 60 cm depth. Relative A_n, T_r, and T_L started to decrease from FTSW 0.3 at 60 cm and FTSW 0.2 at 40 cm. The results demonstrate that plant water status under limited irrigation management can be qualitatively monitored using the measures of soil moisture as well as leaf gas exchange, which in turn can be useful for describing yield reduction due to water deficit. We found that using normalized A_n, T_r, and T_L is feasible to quantify plant water deficit.

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1. Introduction

Crop growth and yield are influenced by plant genetic factors as well as environmental factors such as weather conditions, water availability, and soil conditions. Plant water is one of the most important and readily manageable variables for producing a profitable crop (Kozlowski, 1972; Taylor et al., 1983). Stresses involving water deficiencies will adversely affect cell turgidity, resulting in reduced crop production. A solution to water shortages is irrigation, which has made agriculture possible in many nonproductive areas (Kramer and Boyer, 1995). In the Wintergarden area of Texas, irrigation is also one of the major limiting factors in producing cotton and other crops.

Quantifying plant sensitivity to water deficit remains a challenge. A number of different quantification methods have been sought from the traditional measure of volumetric available soil water (Martin, 1940; Ritchie, 1981) to thermodynamic measures, which include fraction of extractable soil water (Ritchie, 1981; Sinclair, 2005), plant or soil water potential (Comstock and Mencuccini, 1998; Lamhamedi et al., 1992), relative plant tissue water content (Ritchie et al., 1990), canopy temperature (Idso et al., 1982; Jackson et al., 1981), and leaf- and whole-canopy gas exchanges (Faver et al., 1996; Marani et al., 1985; Baker et al., 1997). However, characteristic functions using the thermodynamic measures were not found to describe plant responses to either plant or soil water potential. Many studies now show that a two-segment model based on available soil water thoroughly describes the changes in plant water using daily plant gas exchange rate (Sadras and Milory, 1996).

More than 90% of the water for urban and agricultural use in the Wintergarden and Lower Rio Grande Valley comes either from the Rio Grande itself or the Edwards aquifer. As the Texas Legislature placed water restrictions on the farming industry by limiting growers to a maximum use of 6100 m^3 ha^{-1} of water per year in the Edwards Aquifer region, maximization of agricultural production

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Abbreviations: A_n, leaf net assimilation; C_i, intracellular CO_2 concentration; ETc, crop evapotranspiration; ETo, reference evapotranspiration; FTSW, fraction of transpirable soil water; g, stomatal conductance; K_c, crop coefficient; LEPA, low energy precision application; LAI, leaf area index; PFD, photon flux density; SE, standard error; T_c, canopy temperature; T_r, transpiration rate; T_L, leaf temperature; VPD, vapor pressure deficit based on leaf temperature; WUE_i, instantaneous water use efficiency.

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efficiency has become a high priority for numerous studies in the Wintergarden area of Texas. Methods for improving water use efficiency described by some researchers (Taylor et al., 1983; Stewart and Nielsen, 1990) are (1) increasing the efficiency of water delivery and the timing of water application, (2) increasing the efficiency of water use by the plants, and (3) increasing the drought tolerance of the plants. The first method depends on mostly engineering and has been successful in improving productivity per unit of water delivered to the farm. The second and third methods depend on understanding physiological aspects and genetic characteristics of crops.

It is important to understand water requirement and physiological aspects of crops under limited irrigation management in order to achieve optimal production. The objectives of this research were to (1) investigate physiological responses of cotton based on leaf gas exchange measures under full and limited water availability using commercially available varieties at Uvalde, TX and (2) evaluate the feasibility to quantify plant sensitivity to water deficit with a measure of leaf canopy gas exchange. We also analyze factors affecting lint yield deduction.

2. Materials and methods

2.1. Experimental field and irrigation

Studies were performed at a Texas AgriLife Research field in Uvalde, Texas (29° 13′ 03″, 99° 45′ 26″; 283 m) in 2006 and 2007. The field (~4.8 ha) bedded in a circle was irrigated by a center pivot with a low energy precision application, LEPA, system. Soil type was an Uvalde silty clay soil (fine-silty, mixed, hyperthermic Aridic Calciustolls with a pH of 8.1). In 2006, six commercial cotton varieties from Bayer CropScience (Research Triangle Park, NC): ST5599, ST4892, ST4664, ST4700, ST5007, and 989B2R were planted at 20,647 seed ha^{-1} on 1 m row spacings on 11 April and harvested on 7 September. Likewise, four varieties from Bayer CropScience (RTP, NC) and Delta and Pine Land Company (Scott, MS): ST4554, DP555, DP164, and FM9063 were planted on 23 April and harvested on 17 October in 2007. The varieties were selected among those best adaptable to this region from commercially available varieties for both years. After having narrow yield variations among the varieties in 2006, varieties were selected considering more various genetic pools in 2007. The experiments in both years were arranged in a split-block design with each main plot (irrigation) replicated two times and each subplot (variety) replicated three times. A 90° wedge of the center pivot field was divided equally into 15° sections, which were maintained at 100%, 75%, and 50% crop evapotranspiration (ETc) values. The varieties were randomly arranged within each main plot.

Irrigation scheduling and ET regimes for the field were imposed according to calculations of the standardized ASCE_PM equation (ASCE-EWRI, 2005). Actual crop water use requirements for cotton were determined based on the relation to a well-watered reference grass. The equation was as follows:

$$\mathrm{ETc} = K_c \times \mathrm{ETo} \quad (1)$$

where K_c is crop coefficient and ETo is reference evapotranspiration. We utilized the growth-stage-specific K_c values (Table 1), which were determined at the same study site (Piccinni et al., 2007). ET from a tall fescue grass (*Festuca arundinacea* Schreb.) with a height of 0.12 m and a surface resistance of 70 s m^{-1} was the ETo surface employed in K_c. The total amounts of irrigation from seeding to maturity (prior to defoliation) in 2006 and 2007 are presented with weather conditions in Table 2.

Table 1
Growth-stage-specific cotton crop coefficients (K_c) used.

Growth stage	Days after planting	K_c
Seeding	7	0.40
1st square	8–45	0.45
1st bloom	46–65	0.80
Max bloom	66–86	1.08
1st open	87–110	1.23
25% open	111–125	1.25
50% open	126–133	1.05
95% open	134–151	0.60
Pick	152–162	0.10

2.2. Data measurements and analysis

A neutron probe (530 DR Hydroprobe Probe Moisture Depth Gauge, Campbell Pacific Nuclear Corp. Int. Inc., Martinez, CA) was used to quantify soil moisture at various depths (20, 40, 60, 80, and 100 cm) during the crop growing season. Neutron probe data were obtained 13 times (8, 17, and 23 May; 1, 7, and 12 June; 20 and 28 July; and 4, 8, 10, 15, and 18 August) in 2006 and 10 times (6 and 22 June; 10 and 12 July; 2, 6, 10, 15, and 29 August; and 25 September) in 2007. After planting, neutron probe access tubes were installed at the center of each treatment plot. Volumetric water content, θ, was determined using a linear equation as follows:

$$\theta = a \times \mathrm{CR} + b \quad (2)$$

where a and b are coefficients and CR is the count ratio (count divided by standard count). The coefficients were determined for each soil depth by measuring soil moisture at different water contents with the neutron probe and by determining the gravimetric water content of soil samples. Fraction of transpirable soil water, FTSW, was calculated using the equation (Ritchie, 1981):

$$\mathrm{FTSW} = \frac{\theta_a - \theta_{ll}}{\theta_{ul} - \theta_{ll}} \quad (3)$$

where subscripts a, ul, and ll represent actual, lower limit, and upper limit of plant available water, respectively. The θ_{ll} and θ_{ul} used was 23.6% and 36.6%, respectively. The former was obtained from the NRCS soil survey (available at http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx), and the latter was determined using the method by Ratliff et al. (1983).

A LI-6400 (LI-COR, Lincoln, NE) with CO_2 injector and REDs (665 nm and 470 nm) light chamber were used to measure leaf gas exchange variables: leaf net assimilation, A_n (μmol (CO_2) m^{-2} s^{-1}); intracellular CO_2 concentration, C_i (μmol mol^{-1}); stomatal conductance, g (mol (H_2O) m^{-2} s^{-1}); transpiration rate, T_r (mmol (H_2O) m^{-2} s^{-1}); instantaneous water use efficiency, WUE_i; leaf temperature, T_L (°C); and vapor pressure deficit based on leaf temperature, VPD (kPa). Equations for calculating A_n, g, C_i, T_r, and

Table 2
Total irrigation applied and weather conditions during the cotton growing seasons in 2006 (11 April to 20 August) and 2007 (23 April to 10 September) in Uvalde, TX.

Year	Irrigation applied			Rainfall	Temperature	
	100% ETc	75% ETc	50% ETc		Max.	Min.
	mm				°C	
2006	487.7	382.3	291.6	71.4	35.0	21.3
2007	139.7	101.6	50.8	575.8	30.8	21.1
30 year[a]	–	–	–	315.2 (285.1)	34.5 (33.9)	20.7 (20.0)

[a] 30 year average (1971–2000): values in this row are seasonal averages from 23 April to 10 September while those in the parentheses are ones from 11 April to 20 August.