Comparison of soil water extraction and yield of cotton planted using solid and single-skip row configurations

ABSTRACT

Australian growers plant crops using different skip row configurations to minimize production risk in water-limiting environments. Previous studies have focused on comparing the effect of row configuration on crop yield, and information on soil water is still lacking. The objective of this study was to compare the water use, soil water extraction, and yield of dryland cotton (*Gossypium hirsutum L.*) planted using solid and single-skip row configurations. An experiment comparing two row configuration treatments (solid and single-skip) was conducted in a cotton field with heavy-clay soil in the sub-tropical climatic environment of Queensland, Australia, during 2007-2008. Water content in the soil profile was measured about weekly using the neutron probe method. Measurements were taken from three positions from the crop row: within a row (P1), between two rows (P2), and skip or planted row (P3). The soil water measurements indicated that, in general, the solid treatment tended to extract more water from shallower depths earlier in the growing season. The single-skip treatment resulted in taller plants, which extracted more water from deeper in the soil profile later in the season. For the entire season, however, both treatments used around the same amount of soil water (128 mm), suggesting that both treatments were water-limited and used all the water available to the crop. The 128 mm added to the seasonal rainfall of 271 mm allowed us to estimate the seasonal crop water use at about 399 mm, which was around half of the seasonal grass-reference evapotranspiration (ETo = 804 mm) for the site. The lint yield was statistically the same for both treatments, although the taller plants from the single-skip treatment tended to have a greater yield per plant (but not significantly different). The estimated water use efficiency (WUE) for the solid and single-skip configuration were 3.5 and 3.3 kg lint/ha/mm water use, respectively.

Keywords: skip-row planting, cotton, soil water, neutron probe, water use

1. INTRODUCTION

Cotton production in Australia is concentrated in the eastern states of New South Wales (NSW) and Queensland and is distributed in several river valleys. The Australian cotton industry is among the world leaders in yield and fiber quality. In general, agricultural land tends to be relatively abundant in Australia, but water is a significant limitation for many cotton growers. This limitation is due to their reliance on capturing overland flow from rainstorms in on-farm storages as a substantial source of irrigation water in a semi-arid environment. Therefore, cotton production is practiced using combinations of full irrigation, limited/deficit irrigation, and rainfed production in different proportions depending on the availability of irrigation water.

Looking to adapt to water scarcity, Australian cotton farmers have adopted many water-efficient farming practices. One of the standard practices in the area is to reduce plant population to conserve water and reduce production risk. Cotton producers typically reduce plant population by using different planting row configurations, which consist of skipping the planting of some crop rows instead of just reducing the seeding rate [1]. Planting every crop row is the solid configuration, resulting in the normal 100% plant population. In addition to the solid configuration, several skip-row planting configurations, such as single-skip, double-skip, alternate-skip, and supper-single, are typically used. The single-skip configuration consists of planting two rows and skipping one row, resulting in 67% of the normal plant population. The double-skip configuration consists of planting two rows and skipping two rows, resulting in 50% of the normal plant population. The alternate-skip consists of planting one row and skipping one row, also resulting in 50% of the normal plant population. The super-single consists of planting one row and skipping two rows, resulting in 33% of the normal plant population.

These skip-row planting configurations are alternatively utilized depending on farmer's preference, farming equipment available, and how much water (irrigation + rainfall) is available or expected on the farm during the growing season. Although skip-row configurations, instead of solid configurations, are mainly used in dryland production, they are also being used in irrigated cotton in situations where water is limited to manage the cost of production [2]. It is assumed that the skip-row configurations provide additional water stored beneath the fallow rows compared to the planted rows [3].

Several studies have reviewed the results of previous research comparing yields of solid and skip cotton in Australia [4,5,6] and the following equations to estimate the yield of single-skip and double-skip compared to the yield of the solid configuration were suggested [5]:

$$Yss = 0.82Ys + 0.36 \qquad (1)$$

$$Yds = 0.58\ Ys + 0.79 \qquad (2)$$

where, Yss = single-skip yield, Yds = double-skip yield, Ys = solid yield, all in units of bales/ha. The equations were derived from over 30 irrigated and dryland experiments conducted during 1984-1993 in Central Queensland and the Darling Downs. Relationships obtained from other studies have also been reported [4, 7]. A plot of equations (1) and (2) would show that $Ys > Yss > Yds$, except for very low yield levels (i.e., Yields < 2.5 bales/ha). A study highlighted an increased yield difference between solid and single-skip cotton as the potential cotton lint yield increased above 1.6 bales/ha [6].

Although it is expected that skip row configurations would give up yield potential compared with solid planting when water is not limited, they may potentially reduce the risk of crop failure and provide insurance against poor fiber quality when water is severely limited [6]. Also, since skip row production costs can be significantly reduced, especially for Bollgard II varieties with high seed cost, it has been suggested that gross margins per unit area ($/ha) could increase with skip row compared to solid planting [5]. A study found that under dryland conditions, gross margins for single-skip and double-skip were respectively around 30% and 50% higher than for solid planting [7]. Additional potential income from skip row configurations under water limiting situations could also be derived from the premium price due to improved fiber quality compared to solid planting [7]. In contrast, others have reported that increased savings in seed, technology, and harvest costs for the skip row configurations were not enough to offset the lower yields on a total area basis compared with the solid planting) [8].

Although there has been much research comparing row configurations in Australia, the main focus has been on yield and fiber quality. Accurate comparisons of water use and soil water extraction pattern among cotton configurations are still lacking. For example, the effectiveness of skip row configurations in dryland conditions would be determined mainly by the amount of stored water in the soil profile, in-crop rainfall, and water extraction patterns by the relatively larger plants for the skip-row, compared with the solid-row configuration. An accurate understanding of soil water use and water extraction from different row configurations is essential for implementing suitable agronomic management practices for improving water use efficiency (WUE) in changing climatic conditions and for better economic and environmental sustainability. The objective of this study was to compare the water use, soil water extraction, and yield of dryland cotton planted using solid and single-skip row configurations.

2. MATERIAL AND METHODS

2.1 Site Description

The field experiment for this study was conducted at the Queensland Department of Agriculture and Fisheries Kingsthorpe research station during the 2007-2008 cotton growing season. The station is located within the Darling Downs area, in a sub-tropical climatic zone, about 20 km north-west of the city of Toowoomba, Queensland, Australia (27^{o}30'44.5" Latitude South, 151^{o}46'54.5" Longitude East, 431 m above mean sea level). The soil at the site is a Haplic, self-mulching, black, Vertosol. It has a heavy clay texture in the 1.5 m root zone profile, with a distinct change in soil color from brownish black in the top 90 cm to dark brown deeper in the profile. The soil is of alluvial fan and basalt rock origin, slowly permeable, with a surface slope of 0.5%.

2.2 Experimental Design

Two cotton planting configuration treatments (solid and single-skip) were compared as a split-plot within a larger irrigation experiment. The larger experiment included four irrigation treatments (including a dryland treatment) and three replications. Each main experimental plot was 13 m wide x 20 m long. A border (4-m wide) was allowed between plots, and a road (4-m wide) was located at the center of the research area. Six rows of a non-transgenic (conventional) cotton variety were planted as a refuge crop on the east and west sides of the research area to comply with local regulations related to growing genetically modified (GMO) cotton hybrids. The plots were irrigated individually with bore water using a hand-shift sprinkler system. Partial-circle sprinkler heads were used to avoid irrigating adjacent plots. The planting configuration comparisons reported here were conducted as a split-plot within the dryland treatment. The plots for the dryland treatment were divided into two, half of each plot was kept as a solid planting configuration and in the other half, plants in alternate crop rows were eliminated, and a single-skip planting configuration was established (Fig. 1).

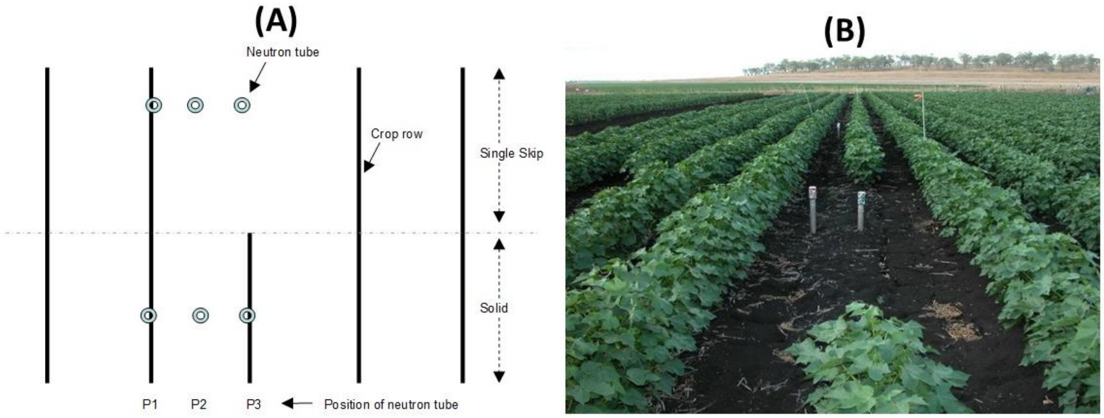

Fig. 1. (A) Positions of neutron tubes in the Solid and Single-skip cotton planting configurations compared at Kingsthorpe during 2007-2008, and (B) picture of the cotton crop showing the two planting configurations

2.3 Soil Water Measurements

For the planting configuration comparison, six neutron tubes were installed in each plot, three in the solid treatment and three in the single-skip. The three tubes were installed at three positions with respect to the crop row, two in the plant line (positions P1 and P3) and one in the middle of the crop row (position P2) (Fig. 1A). Neutron readings were taken about weekly (often twice a week) at 0.10 m depth increments to a depth of 1.4 m. Measurements were taken with a 503DR Hydroprobe (CPN International, Inc., Martinez, CA, USA), using integration periods of 16 seconds for normal counts and 240 seconds for standard counts. Standard counts were taken in water by lowering the neutron source on an access tube installed in the middle of a water drum (≈ 200 L). The neutron probe was calibrated to the site against gravimetric measurements of soil samples taken from dry and wet locations within the field, resulting in a good linear relationship between count ratios (CR, unitless) and volumetric soil water content (*swc*, fraction) [*swc* = 0.661CR, R^2 = 0.996]. Measured soil bulk densities (BD) for the site were used to convert from mass-based to volumetric *swc* (Fig. 2).

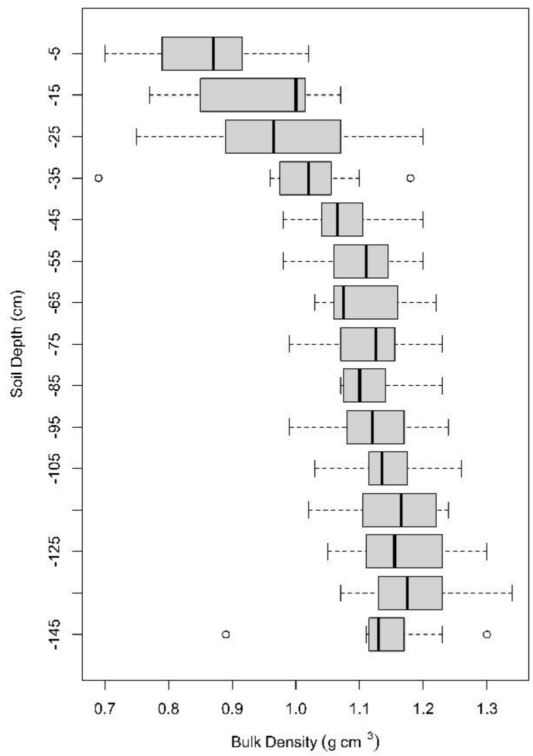

Fig. 2. Boxplot of the soil bulk density profile measured at Kingsthorpe

The measured *swc* for each depth was converted to mm of water as:

$$Twin = swc_i * d_i \quad (3)$$

$$TWto = swc_a * d_a \quad (4)$$

Where, *TWin* = total soil water in deph *i* (mm), swc_i = volumetric soil water content in depth *i* (fraction), d_i = depth increment (mm) for depth *i*, *TWto* = total soil water above soil deph d_a (mm), d_a = soil depth (mm), swc_a = average volumetric soil water content (fraction) above soil depth d_a. A 10-cm depth was considered for each soil depth increment. For *TWin*, volumetric soil water contents over the growing season were measured at four depths; 20-30, 50-60, 100-110 and 130-140 cm depths. Whereas, *TWto* represents the cumulative of available soil water above a given depth. For example, *TWto* 60 indicates the total available soil water to a depth of 60 cm and *TWto* 140 indicates the total available soil water to a depth of 140 cm. The water content in the top 0-15 cm soil profile was not presented due to large variations associated with neutron readings, severity of drying of the top soil layer and rainfall. However, this data was included in the total seasonal water use [3]. Total water use was calculated from the neutron readings taken at the start of the experiment and at the end of experiment, plus in-crop rainfall. Based on the prevailing dry conditions and the neutron readings it was assumed that no water movement as deep drainage or capillary rise occurred during the period of this study.

2.4 Cultural Practices

Originally, the crop was planted to a solid configuration, and the single-skip treatment was established by trimming the unneeded crop rows after the neutron tubes were installed (20 December 2007). Cotton was planted on 12 November 2007 after the soil received a few small rainfall events during the previous week. This planting date was still within the Bollgard® II cotton planting time window for the Darling Downs. The cotton hybrid Sicala 60 BRF was planted, which is a Bollgard® II Roundup Ready Flex® variety. The conventional (non-Bollgard) variety Sicot 43 RRF was planted as the refuge crop. Sicala 60 BRF was rated as a medium maturity variety with very good yield potential for late planting, excellent fiber quality characteristics, and with a long and strong fiber with mid-range micronaire [9]. Bollgard® II cotton varieties have been developed by genetically modifying cotton, adding two genes of the soil bacterium *Bacillus thuringiensis* (Bt). The addition of these genes produces two proteins that are toxic to the *Helicoverpa* caterpillar, the most important insect attacking conventional cotton varieties. Cotton seeds were planted at a density of 17 seeds/m, a depth of about 3.8 cm (1.5"), and a row spacing of 1 m. The aim was to get an established stand of 11-12 plants/m.

Lint yield was determined by hand harvesting a 2.5-m sample of two rows (14 May 2008). The seed cotton (lint + seeds) was collected from the open bolls. The green bolls were also collected separately. The number of open and green bolls in each plant of a 1-m length was determined. The seed cotton and green boll samples were oven-dried at 40°C for about a week. The green bolls opened after drying and the seed cotton was collected and kept separate from that harvested in the field. Seed cotton samples from the green balls and those harvested in the field were weighted separately. A 350 g subsample from the seed cotton harvested in the field was used to separate the lint from the seeds using a laboratory gin that was built in-house. Water use efficiency was estimated from the measured lint yield per hectare divided by the extracted amount of soil water plus in-crop rainfall.

2.5 Weather Data

An electronic weather station, model EnviroStation (ICT International Pty Ltd, Armidale, NSW, Australia), was installed at the research site. The station measured and recorded daily and hourly values of solar radiation, air temperature (maximum, minimum, and average), relative humidity, wind speed, and rainfall.

2.6 Statistical Analysis

Statistical analyses were conducted with GenStat (11th Edition, VSN International, Ltd), using the ANOVA and MANOVA procedures for comparing treatment means for datasets including one or more variables, respectively. Data plotting was conducted with R version 4.0.4 [10] and Microsoft Excel.

3. RESULTS AND DISCUSSION

3.1 Weather Conditions

A summary of the weather conditions at Kingsthorpe during the study is shown in Table 1. The growing season extended for about six months, from mid-November to mid-May. Air temperatures and water requirements peaked in January. For all months, the grass-reference evapotranspiration (ETo) far exceeded rainfall. February was the wettest month, accounting for almost half of the seasonal rainfall. Rainfall accounted for only about 1/3 of the seasonal ETo (271 mm vs 804 mm, Table 1), which explains the need for irrigation to be able to maximize crop yield. The monthly rainfall pattern indicated that the season was dry, except for exceptionally high rainfall occurring in Feb. The months of Nov, Dec, Jan, and Apr were drier than the long-term average. Rainfall was especially lacking in January, when ETo was at its peak.

Table 1. Weather conditions during the 2007-2008 cotton season at Kingsthorpe

Variable [a]	Month							Season Avg/total
	Nov	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	
Tmax (^{o}C)	27.0	29.0	30.7	29.2	28.0	25.4	25.0	*27.8*
Tmin (^{o}C)	14.7	17.5	17.5	16.1	12.6	7.3	3.7	*12.8*
Rs (MJ/m^{2}/d)	24.6	22.9	22.4	22.3	24.1	20.3	19.0	*22.2*
RH (%)	76.3	76.5	75.2	77.4	71.7	71.6	59.1	*72.5*
u (m/s)	2.9	2.9	3.4	2.9	3.0	2.2	1.5	*2.7*
Daily ETo (mm)	4.7	4.8	5.0	4.6	4.5	3.3	2.8	*4.3*
Monthly ETo (mm)	88.5[b]	149.6	156.1	132.5	140.5	100.1	36.7	*804.0*
Monthly Rain (mm)	26.0	44.0	16.0	126.0	37.0	22.0	0.0	*271.0*

[a]Tmax, Tmin = Maximum and minimum air temperatures, Rs = Solar radiation, RH= Relative humidity, u = Wind speed, ETo = Grass-reference evapotranspiration, [b] For Nov and May, only data within the cotton growing season were included.

3.2 Comparison of Total Soil Water (*TWin*) in Four Selected 10 cm Depths

The total water content (*TWin*) by cotton row configuration (single-skip and solid), measurement position (P1, P2, and P3) and days after sowing (DAS) in each of four selected 10-cm soil depths increments 20-30, 50-60, 100-110 and 130-140 cm are shown in Fig. 3. The midpoints of these soil depths are represented, respectively, in this and other figures as TWin25, TWin55, Twin105, and Twin135. Differences in *TWin* between the two configurations (single-skip minus solid) as a function of DAS for four selected depths (20-30, 50-60, 100-110 and 130-140 cm) are also shown in Fig. 4. Table 2 also shows the results of statistical analysis testing if the observed differences in *TWin* between configurations were statistically significant (shaded cells were statistically significant at α = 0.05). Positive differences in *TWin* in Table 2 and Fig. 4 indicate that slightly more water was available early in the growing season at all positions (P1, P2 and P3) for the skip compared with the solid configuration (Fig. 4).

Figure 3 shows that soil water was extracted from all depths at various magnitudes with no visible differences between configurations over the growing period. For each depth (20-30, 50-60, 100-110 and 130-140 cm), the difference in *TWin* between the initial and end sampling date tended to decrease with increasing depth. The greatest extraction of water occurred in the top two depths (20-30cm and 50-60 cm), where water was depleted from a maximum availability of about 45-50 mm early in the growing season to 30-35 mm at the end of the season for all positions (P1, P2 and P3). Whereas the minimal depletion occurred at the bottom depths (100-110 and 130-140 cm), water at these depths was depleted from a maximum availability of about 45 mm to only about 40 mm (Fig. 3). On an average, water extraction in the top 0-60 cm depth represented about 70% (90 mm) of the total extraction (about 128 mm), whereas only about 10% (about 20 mm) was extracted from the bottom depths, from 100-140 cm. Water extraction between 60 and 100 cm depth was about 18 mm (about 20% of the total extraction). About 85% water was extracted from the top 100 cm depth.

Differences in soil water (single-skip minus solid) at various depths in Figure 4 shows variability in the pattern of soil water extraction between row configurations, indicating that the Single-skip configuration tended to have just slightly (a few mm) more water at the shallower depths (20-30 and 50-60 cm depths), but slightly less than the solid configuration deeper in the profile (100-110 and 130-140 cm depths) for all the positions (P1, P2 and P3). However, greater water availability at the shallower depths for the single-skip was more pronounced earlier in the growing season, decreasing to less than the solid later in the season for most of the positions (Fig. 4). More detailed information on the differences in *TWin* for all depths and results of statistical analyses in Table 2 show that, on average, for all sampling dates, the skip configuration tended to have slightly more water in approximately the top 100 cm while the solid tended to have more water deeper in the profile.

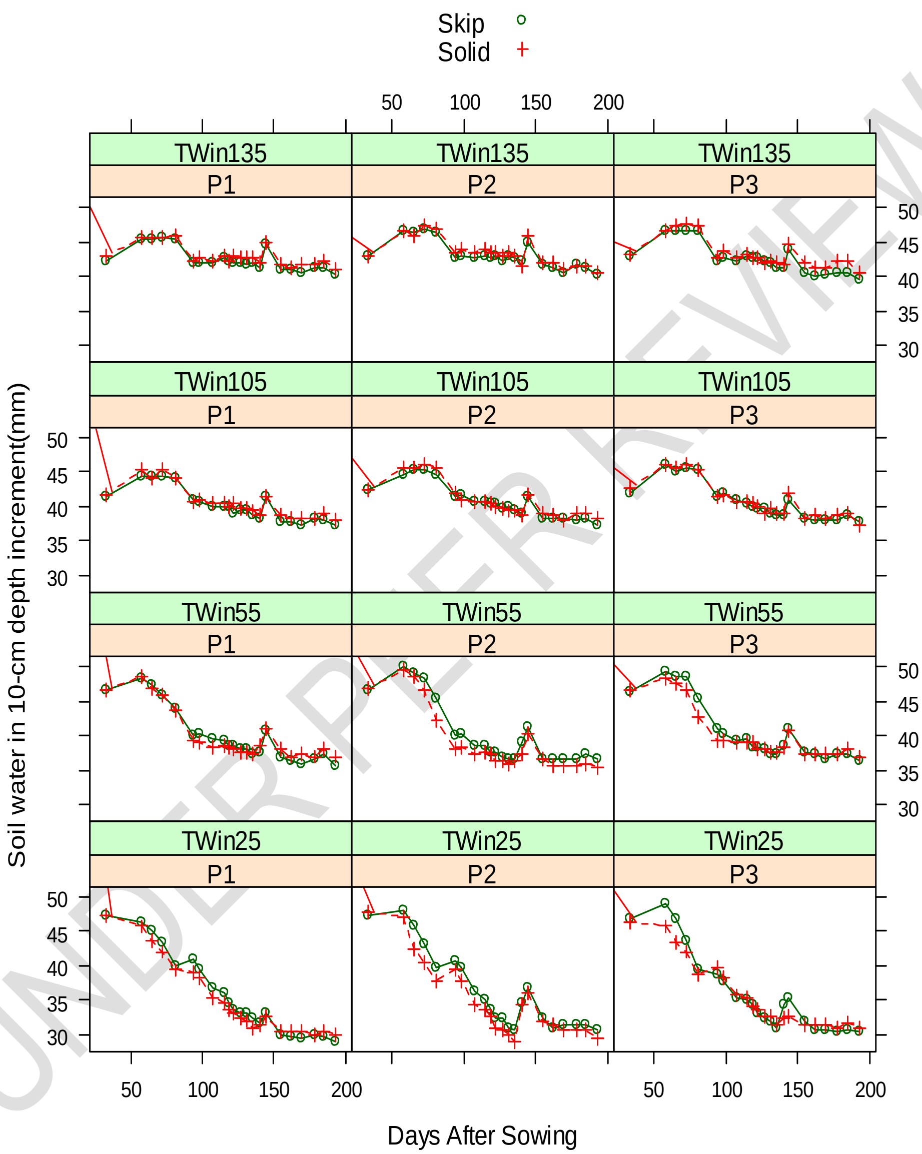

Fig. 3. Soil water content by cotton planting configuration (Skip and Solid), measurement position (P1, P2, P3) and days after sowing in each of 10-cm soil depths increments at 25, 55, 105 and 135 cm soil depths (TWin25, TWin55, TWin105, and TWin135) obtained at Kingsthorpe during 2007-2008

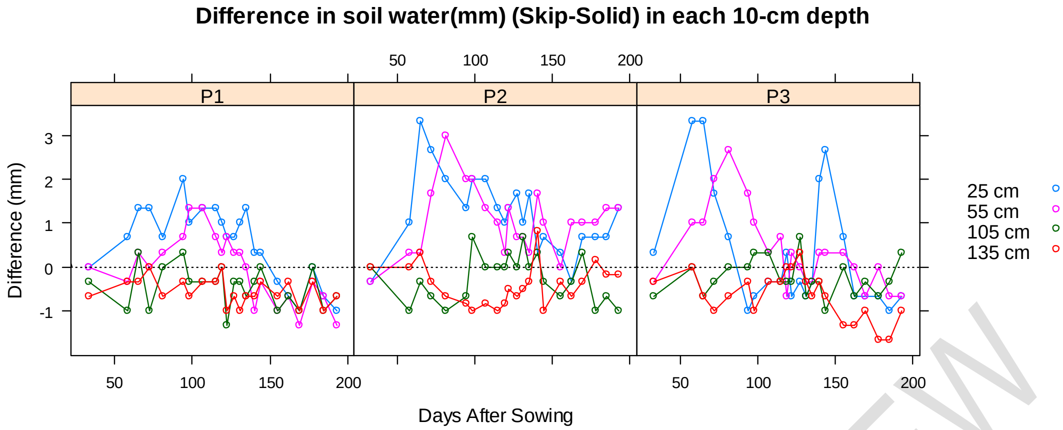

Fig. 4. Difference in soil water between Skip and Solid cotton configurations by days after sowing and measurement position (P1, P2, and P3) in each 10-cm depth increment at 25, 55, 105 and 135 cm soil depths obtained at Kingsthorpe during 2007-2008.

Table 2. Difference (single-skip minus solid) in soil water content (mm) in each 10-cm depth increment between single-skip and solid cotton configurations by days after sowing (DAS) and sampling positions (Pos = P1, P2, P3) obtained at Kingsthorpe during 2007-2008. Differences in shaded cells were statistically significant (α = 0.05)

Pos	Depth	DAS																						*Avg*
		33	**58**	**65**	**72**	**81**	**94**	**98**	**107**	**115**	**119**	**122**	**127**	**131**	**135**	**140**	**144**	**155**	**162**	**169**	**178**	**185**	**193**	
P1	15	-0.3	-0.3	1.0	0.3	-0.3	2.0	1.3	1.7	1.3	0.3	-1.0	0.0	0.0	-0.3	-0.3	0.0	-0.7	-0.7	-1.7	-1.7	-1.3	-1.3	***-0.1***
	25	0.0	0.7	1.3	1.3	0.7	2.0	1.0	1.3	1.3	1.0	0.7	0.7	1.0	1.3	0.3	0.3	-0.3	-0.7	-1.0	0.0	-0.7	-1.0	***0.5***
	35	-0.7	0.7	0.7	0.3	0.3	0.7	1.0	1.3	1.0	0.7	0.7	0.7	0.3	0.7	-0.3	-0.7	-0.7	-0.3	-1.0	-0.7	-0.7	-1.0	***0.1***
	45	0.3	0.7	1.0	0.3	0.7	1.7	0.7	1.3	1.3	0.7	0.7	1.3	0.3	1.0	-0.7	-0.7	-0.7	-0.3	-1.0	-1.3	-0.3	-0.7	***0.3***
	55	0.0	-0.3	0.3	0.0	0.3	0.7	1.3	1.3	0.7	0.3	0.7	0.3	0.3	0.0	-1.0	-0.3	-1.0	-0.7	-1.3	-0.3	-0.7	-1.3	***0.0***
	65	-2.0	-1.3	-0.3	0.3	0.3	0.7	0.3	0.7	0.3	1.0	0.3	1.0	1.0	1.0	0.3	-0.3	0.0	0.0	0.7	0.3	-0.3	0.0	***0.2***
	75	-1.0	-0.7	0.0	0.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.7	1.0	1.0	0.3	0.3	0.3	0.0	0.0	0.0	0.3	***0.5***
	85	-1.0	-0.7	-0.3	-0.3	0.0	1.0	0.3	0.3	0.3	0.7	0.7	0.3	0.0	0.0	0.0	2.0	0.0	0.0	0.3	0.3	-0.7	-0.3	***0.1***
	95	-0.7	-0.7	-1.0	0.0	-1.0	0.7	0.7	0.0	0.3	-0.3	-1.0	0.7	0.3	-0.7	0.3	0.7	-0.3	-0.3	0.0	0.0	0.3	-0.7	***-0.1***
	105	-0.3	-1.0	0.3	-1.0	0.0	0.3	-0.3	-0.3	-0.3	0.0	-1.3	-0.3	-0.3	-0.7	-0.3	0.0	-1.0	-0.7	-1.0	0.0	-1.0	-0.7	***-0.5***
	115	-0.7	-0.7	0.3	-0.3	-0.3	0.0	-1.0	-0.7	-0.3	-0.3	-1.3	-1.0	-1.3	-1.3	-0.7	-0.7	-0.3	-1.3	-1.3	-0.7	-1.7	-1.0	***-0.8***
	125	-0.7	-1.0	-0.3	0.7	0.0	-0.3	-0.7	-0.3	0.0	0.3	-0.7	0.0	-0.3	-0.7	0.0	0.0	-0.7	-0.7	0.0	-2.0	-0.7	-0.3	***-0.4***
	135	-0.7	-0.3	-0.3	0.0	-0.7	-0.3	-0.7	-0.3	-0.3	0.0	-1.0	-0.7	-1.0	-0.7	-0.7	-0.3	-0.7	-0.3	-1.0	-0.3	-1.0	-0.7	***-0.5***
	Avg P1	***-0.6***	***-0.4***	***0.2***	***0.1***	***0.2***	***0.8***	***0.4***	***0.6***	***0.5***	***0.4***	***-0.1***	***0.3***	***0.1***	***0.1***	***-0.2***	***0.0***	***-0.5***	***-0.4***	***-0.6***	***-0.5***	***-0.7***	***-0.7***	***0.0***
P2	15	0.0	2.3	1.7	1.0	1.3	0.7	0.7	1.7	0.7	1.0	1.0	1.0	0.7	1.0	0.0	0.0	0.0	0.3	0.0	0.0	-0.7	-0.3	***0.6***
	25	-0.3	1.0	3.3	2.7	2.0	1.3	2.0	2.0	1.3	1.0	1.3	1.7	1.0	1.7	0.3	0.7	0.3	-0.3	0.7	0.7	0.7	1.3	***1.2***
	35	-0.3	0.7	2.0	3.7	2.3	2.3	2.3	1.7	1.7	1.0	1.0	0.7	1.0	1.3	0.7	0.3	1.0	0.3	1.7	1.0	0.7	1.0	***1.3***
	45	-0.7	0.0	1.0	1.7	2.3	2.7	2.3	1.7	2.0	0.7	1.3	0.7	1.3	1.7	1.0	0.7	1.0	1.3	1.0	0.7	1.3	0.3	***1.2***
	55	-0.3	0.3	0.3	1.7	3.0	2.0	2.0	1.3	1.0	0.3	1.3	0.7	0.7	0.3	1.7	1.0	0.0	1.0	1.0	1.0	1.3	1.3	***1.0***
	65	0.0	-0.3	0.7	1.0	2.3	2.0	2.0	1.0	1.0	1.0	1.0	0.3	0.0	0.0	1.7	1.7	1.3	0.7	0.0	0.7	0.7	1.0	***0.9***
	75	-1.3	-1.0	0.3	1.0	2.3	3.0	2.0	2.3	1.3	1.3	0.7	0.3	0.7	1.0	1.3	2.7	0.3	1.3	0.7	0.7	1.0	1.0	***1.0***
	85	0.0	-0.3	0.3	0.3	0.3	1.7	1.7	1.3	1.7	0.7	0.3	1.0	0.0	0.7	2.0	1.7	1.0	1.3	0.0	1.0	0.7	-0.3	***0.8***
	95	-0.3	0.0	0.3	0.0	-0.3	1.0	0.7	0.7	0.0	0.7	0.3	0.3	0.0	0.7	1.7	1.0	0.7	0.3	-0.3	0.7	0.3	0.0	***0.4***
	105	0.0	-1.0	-0.3	-0.7	-1.0	-0.7	0.7	0.0	0.0	0.0	0.3	0.0	0.7	0.0	0.3	-0.3	-0.7	-0.3	0.3	-1.0	-0.7	-1.0	***-0.2***
	115	-0.3	-1.7	-0.3	-1.0	-1.0	-0.3	-0.3	-0.3	0.0	0.0	0.0	0.0	-0.7	-0.7	0.3	0.3	-0.7	-0.3	-1.3	-1.0	-0.7	-0.3	***-0.5***
	125	0.0	-2.0	-0.3	-1.3	-1.3	-0.7	-1.0	-1.0	-0.7	0.0	-0.7	-0.3	-0.3	0.0	0.0	0.0	-0.7	-0.7	-1.0	-0.7	-0.3	-1.7	***-0.7***
	135	0.0	0.0	0.3	-0.3	-0.7	-0.8	-1.0	-0.8	-1.0	-0.8	-0.5	-0.7	-0.5	-0.3	0.8	-1.0	-0.3	-0.7	-0.3	0.2	-0.2	-0.2	***-0.4***
	Avg P2	***-0.3***	***-0.2***	***0.7***	***0.7***	***0.9***	***1.1***	***1.1***	***0.9***	***0.7***	***0.5***	***0.6***	***0.4***	***0.3***	***0.6***	***0.9***	***0.7***	***0.3***	***0.3***	***0.2***	***0.3***	***0.3***	***0.2***	***0.5***
P3	15	-0.7	4.7	3.3	0.3	0.0	-2.0	-0.3	-0.7	-0.3	-0.3	-1.3	-0.7	-1.7	-1.3	1.0	1.7	0.0	-0.7	0.0	-1.0	-1.7	-1.0	***-0.1***
	25	0.3	3.3	3.3	1.7	0.7	-1.0	-0.7	-0.3	-0.3	0.3	-0.7	-0.3	-0.7	-0.3	2.0	2.7	0.7	-0.7	-0.7	-0.7	-1.0	-0.7	***0.3***
	35	-0.7	2.3	2.3	2.0	1.0	0.0	0.0	0.0	-0.3	-0.3	-0.3	-0.3	-0.7	-0.3	2.0	2.0	0.3	-0.7	0.7	0.0	-0.3	0.3	***0.4***
	45	0.3	0.7	2.3	1.7	1.0	0.7	1.0	1.0	0.0	0.3	-0.3	0.3	-0.3	0.3	1.3	1.3	0.0	0.0	0.3	0.0	-0.3	0.0	***0.5***
	55	-0.3	1.0	1.0	2.0	2.7	1.7	1.0	0.3	0.7	-0.7	0.3	0.0	-0.3	-0.3	0.3	0.3	0.3	0.0	-0.7	0.0	-0.7	-0.7	***0.4***
	65	0.0	-0.7	0.7	1.3	3.3	2.0	2.0	1.0	1.0	0.7	0.7	-0.3	-0.3	1.3	1.0	0.7	0.0	0.7	0.0	0.0	-0.3	0.3	***0.7***
	75	-1.0	-0.3	0.3	1.0	2.0	2.7	1.7	0.7	1.0	0.3	0.7	0.3	0.3	1.0	0.7	0.7	0.3	0.7	-0.3	0.0	0.0	0.3	***0.6***
	85	0.0	0.0	0.0	1.0	1.7	2.0	2.0	1.3	0.7	0.3	0.3	0.0	1.0	0.3	0.7	0.3	0.7	1.0	0.0	0.0	0.7	0.7	***0.7***
	95	-1.0	0.0	-1.0	-0.3	0.3	0.7	1.0	0.7	0.3	0.3	0.0	0.0	0.0	0.0	0.3	0.3	0.0	-0.3	-0.3	0.3	0.0	0.3	***0.1***
	105	-0.7	0.0	-0.7	-0.3	0.0	0.0	0.3	0.3	-0.3	-0.3	-0.3	0.7	-0.7	-0.3	-0.3	-1.0	0.0	-0.7	-0.3	-0.7	-0.3	0.3	***-0.2***
	115	0.3	-1.0	-1.0	-0.3	0.0	0.0	0.0	-0.3	-0.3	-0.7	-0.3	-0.7	-0.7	-0.3	-0.7	-1.0	-1.0	-1.0	-1.0	-1.0	-0.3	-1.0	***-0.6***
	125	-0.3	-0.3	-0.7	-0.7	-0.7	0.0	-0.3	-0.3	0.0	-0.7	0.0	-0.3	-0.3	-0.7	-1.0	-1.3	-0.7	-1.3	-1.3	-1.0	-1.3	-1.7	***-0.7***
	135	-0.3	0.0	-0.7	-1.0	-0.7	-0.3	-1.0	-0.3	-0.3	0.0	0.0	0.3	-0.3	-0.7	-0.3	-0.7	-1.3	-1.3	-1.0	-1.7	-1.7	-1.0	***-0.7***
	Avg P3	***-0.3***	***0.7***	***0.7***	***0.6***	***0.9***	***0.5***	***0.5***	***0.3***	***0.1***	***-0.1***	***-0.1***	***-0.1***	***-0.4***	***-0.1***	***0.5***	***0.5***	***-0.1***	***-0.3***	***-0.4***	***-0.4***	***-0.6***	***-0.3***	***0.1***

3.3 Comparison of Total Soil Water Above a Given Soil Depth (*TWto*)

Plots of *TWto* by position, configuration, and DAS for four selected depths (20-30, 50-60, 100-110 and 130-140 cm) are shown in Fig. 5. Differences in *TWto* between configurations by position and DAS are plotted in Fig. 6. Differences in *TWto* between the two configurations above each depth increment, position and DAS are shown in Table 3. Table 3 also shows the results of statistical analysis testing if the observed differences in *TWto* between configurations were statistically significant (shaded cells were statistically significant at $\alpha = 0.05$). Again, positive differences in *TWto* in Table 3 and Fig. 6 indicate more water available for the single-skip compared with the solid configuration.

Figure 5 shows similar *TWto* pattern between configurations for position P1 at each of the four depths shown. At position P2, there was slightly more water available for the skip compared with the solid, especially in the early to mid-season. Position P3 shows the largest differences between the single-skip and solid, especially near the soil surface. However, the *TWto* above 135 cm shows that both configurations seem to have extracted about the same amount of soil water during the season.

Figure 6 suggests that the single-skip configuration tended to have more water available during the crop development stages at position P1, but less water late in the season. At position P2, it tended to have more water in the profile for practically the entire season. At position P3, it had more water early in the season and less water after about 100 DAS. Table 3 shows significant differences in *TWto* between configurations at the three positions. Significant differences resulted during 94 and 98 DAS at position P1, during 72, 94 and 98 DAS at position P2, and during 58 and 65 DAS at position P3. No significant differences were detected below 105 cm depth for any of the positions. These results indicate that overall, the single-skip configuration had more soil water available to it from about 58 to 98 DAS. Figure 6 shows that a maximum of about 15 mm more water was available to the single-skip configuration, which was mostly stored in the top 105 cm of soil. However, it should be noted that the significant differences were observed at 94 and 98 at P1 and P2 might be due to episodic rainfall event that occurred at day 85 with more than 100 mm rainfall.

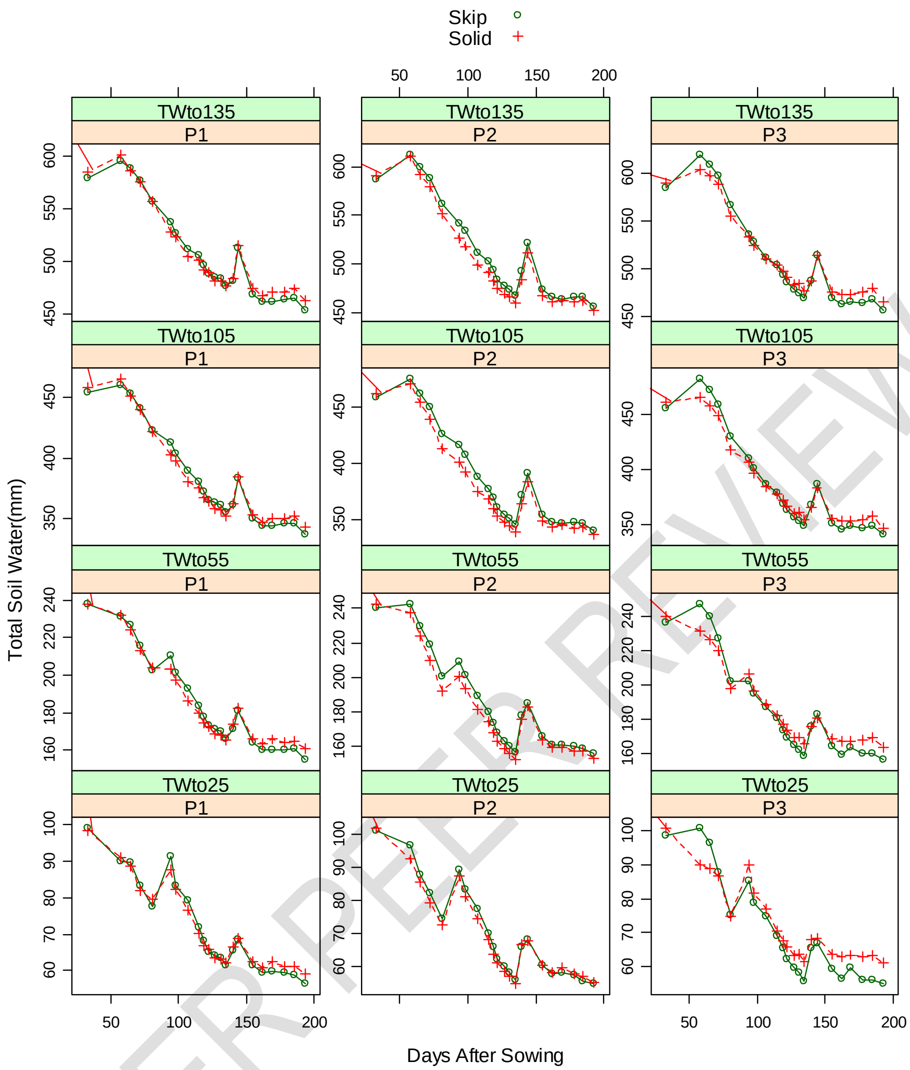

Fig. 5. Total soil water content by cotton row configuration (Skip and Solid), measurement positions (P1, P2, P3) and days after sowing in the top 25, 55, 105 and 135 cm soil depths (TWto25, TWto55, TWto105, and TWto135) obtained at Kingsthorpe during 2007-2008

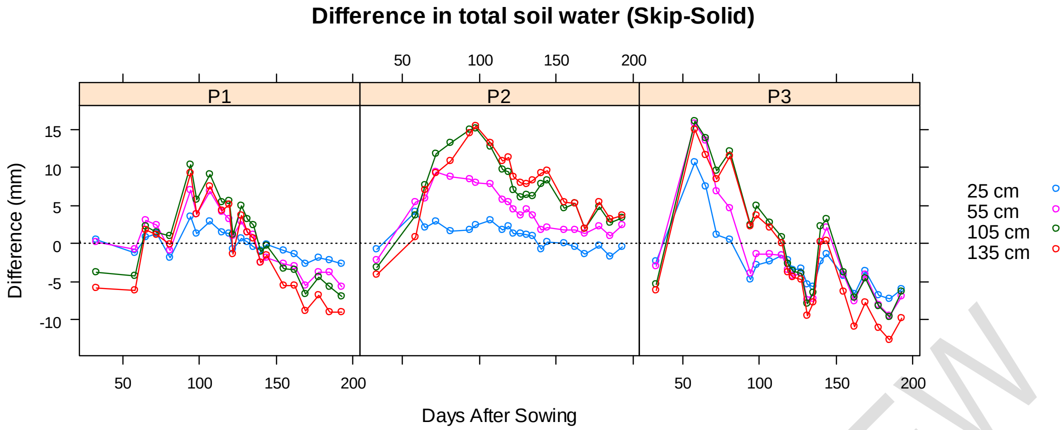

Fig. 6. Difference in total soil water content between Skip and Solid cotton configurations by days after sowing and measurement position (P1, P2, and P3) above the top 25, 55, 105 and 135 cm soil depths obtained at Kingsthorpe during 2007-2008

Table 3. Difference (single-skip minus solid) in total soil water content (mm) above each soil depth (cm) between single-skip and solid cotton configurations by days after sowing (DAS) and sampling positions (Pos = P1, P2, P3) obtained at Kingsthorpe during 2007-2008. Differences in shaded cells were statistically significant (α = 0.05)

Pos	Depth	DAS																						
		33	***58***	***65***	***72***	***81***	***94***	***98***	***107***	***115***	***119***	***122***	***127***	***131***	***135***	***140***	***144***	***155***	***162***	***169***	***178***	***185***	***193***	*Avg*
P1	15	0.6	-1.4	0.1	0.0	-2.2	2.0	0.4	1.3	0.3	0.1	-1.2	0.0	-0.6	-0.9	-0.7	-0.1	-0.6	-0.7	-1.6	-1.4	-1.4	-1.8	***-0.4***
	25	0.6	-1.3	0.9	1.3	-1.9	3.6	1.3	2.8	1.5	1.3	-0.7	0.7	0.2	-0.5	-0.9	-0.1	-1.0	-1.4	-2.6	-1.9	-2.1	-2.7	***-0.1***
	35	0.1	-0.9	1.5	1.7	-1.6	4.8	2.2	4.3	2.5	2.0	0.1	1.6	0.8	0.3	-1.3	-0.6	-1.5	-1.8	-3.5	-2.7	-2.8	-3.7	***0.1***
	45	0.4	-0.6	2.6	2.1	-1.3	6.1	2.8	5.8	3.6	2.9	0.5	2.5	1.2	1.0	-1.8	-1.1	-2.1	-2.3	-4.3	-3.6	-3.3	-4.7	***0.3***
	55	0.2	-0.7	3.1	2.4	-0.9	7.0	3.8	6.8	4.2	3.2	1.0	2.9	1.5	1.1	-2.5	-1.8	-2.6	-3.0	-5.6	-3.8	-3.8	-5.7	***0.3***
	65	-1.4	-1.7	2.7	3.1	-0.4	7.9	4.1	7.3	4.5	4.2	1.2	3.6	2.4	1.9	-2.3	-2.2	-2.7	-3.0	-5.3	-3.8	-4.2	-6.0	***0.4***
	75	-2.3	-2.3	2.5	3.1	1.3	8.8	5.1	8.4	5.2	5.4	2.2	4.5	3.1	3.0	-1.5	-1.8	-2.5	-2.9	-5.4	-3.8	-4.4	-5.5	***0.9***
	85	-2.9	-3.0	2.3	2.9	1.7	9.7	5.7	8.8	5.6	5.9	3.0	4.9	3.4	3.3	-1.2	-0.4	-2.2	-2.8	-5.4	-3.5	-4.9	-5.6	***1.2***
	95	-3.4	-3.5	1.9	2.6	1.0	9.9	6.1	9.1	5.7	5.8	2.2	5.3	3.5	2.8	-0.7	-0.2	-2.3	-3.0	-5.9	-3.9	-4.9	-6.2	***1.0***
	105	-3.7	-4.3	2.3	1.5	1.0	10.4	5.8	9.0	5.4	5.5	1.2	4.9	3.3	2.4	-1.1	-0.3	-3.2	-3.4	-6.6	-4.3	-5.7	-6.9	***0.6***
	115	-4.3	-4.9	2.5	0.9	0.8	10.2	5.2	8.4	5.0	5.4	0.0	3.9	2.5	1.5	-1.6	-1.4	-3.9	-4.5	-7.9	-5.0	-7.0	-7.5	***-0.1***
	125	-5.1	-5.8	1.9	1.0	0.3	9.6	4.5	8.1	4.8	5.2	-0.5	3.9	2.0	1.2	-1.8	-1.5	-4.8	-5.0	-8.0	-6.2	-7.7	-8.3	***-0.5***
	135	-5.8	-6.1	1.8	1.1	0.0	9.3	3.9	7.4	4.4	5.1	-1.4	3.6	1.4	0.7	-2.5	-1.6	-5.5	-5.4	-8.9	-6.8	-8.9	-9.0	***-1.1***
	Avg P1	***-2.1***	***-2.8***	***2.0***	***1.8***	***-0.2***	***7.6***	***3.9***	***6.7***	***4.1***	***4.0***	***0.6***	***3.3***	***1.9***	***1.4***	***-1.5***	***-1.0***	***-2.7***	***-3.0***	***-5.5***	***-3.9***	***-4.7***	***-5.7***	***0.2***
P2	15	-0.3	2.7	-0.2	0.8	0.4	0.3	0.7	1.5	0.7	1.2	0.4	0.2	0.1	-0.4	-0.7	-0.3	-0.3	-0.4	-1.4	-0.7	-1.6	-1.0	***0.1***
	25	-0.8	4.2	2.2	2.9	1.7	1.8	2.4	3.0	1.7	2.3	1.3	1.4	1.2	0.9	-0.7	0.1	0.0	-0.4	-1.3	-0.3	-1.7	-0.4	***1.0***
	35	-1.2	4.9	4.2	5.9	3.8	3.9	4.3	4.4	3.1	3.6	2.2	2.2	2.6	2.0	0.0	0.4	0.4	0.2	-0.4	0.7	-1.2	0.6	***2.1***
	45	-1.8	5.2	5.3	7.8	5.9	6.4	6.3	6.3	4.8	4.7	3.5	3.2	3.9	3.2	0.5	1.1	1.2	1.1	0.4	1.4	-0.2	1.2	***3.3***
	55	-2.1	5.5	6.0	9.5	8.7	8.4	8.0	7.8	5.8	5.4	4.5	3.7	4.5	3.8	1.8	2.1	1.7	1.9	1.3	2.2	1.0	2.4	***4.3***
	65	-2.3	5.1	6.8	10.7	11.1	10.5	9.6	8.6	6.7	6.4	5.1	4.2	4.9	4.2	3.0	3.8	2.9	2.5	1.6	3.1	1.5	3.3	***5.2***
	75	-3.0	4.6	7.1	11.7	13.2	13.0	11.7	10.2	7.9	7.3	5.8	5.0	5.5	5.0	4.4	5.8	3.4	3.7	2.3	4.2	2.4	4.2	***6.2***
	85	-3.1	4.3	7.5	11.9	13.6	14.5	13.4	11.8	9.1	8.4	6.3	5.6	6.0	5.5	6.4	7.3	4.4	5.1	2.1	4.9	3.2	4.3	***6.9***
	95	-3.1	4.3	7.7	11.9	13.8	15.2	14.6	12.6	9.6	9.0	6.6	5.9	5.9	6.3	7.5	8.5	5.0	5.4	2.0	5.4	3.3	4.5	***7.4***
	105	-3.2	3.7	7.7	11.7	13.3	14.9	15.2	12.7	9.7	9.4	7.0	6.0	6.4	6.2	7.9	8.2	4.7	5.2	1.9	4.9	2.8	3.4	***7.3***
	115	-3.3	2.6	7.3	10.9	12.5	14.5	15.2	12.7	9.5	9.2	6.7	6.3	5.8	6.1	7.9	8.5	4.3	4.7	0.8	4.1	2.2	3.2	***6.9***
	125	-3.6	1.0	6.7	9.9	11.6	13.8	14.6	11.9	9.1	9.5	6.5	5.6	5.7	5.8	7.4	8.1	3.7	3.8	0.4	3.4	1.5	1.9	***6.3***
	135	-4.1	0.9	7.1	9.2	10.8	14.4	15.5	13.2	10.8	11.3	8.8	8.0	7.8	8.3	9.2	9.6	5.4	5.3	1.9	5.4	3.3	3.7	***7.5***
	Avg P2	***-2.5***	***3.8***	***5.8***	***8.8***	***9.3***	***10.1***	***10.1***	***9.0***	***6.8***	***6.8***	***5.0***	***4.4***	***4.7***	***4.4***	***4.2***	***4.9***	***2.8***	***2.9***	***0.9***	***3.0***	***1.3***	***2.4***	***4.9***
P3	15	-2.0	6.9	4.3	0.1	-0.2	-3.2	-2.0	-1.7	-0.9	-1.8	-2.4	-2.7	-4.0	-4.7	-3.3	-2.8	-4.0	-5.2	-2.6	-5.2	-5.7	-4.7	***-2.2***
	25	-2.3	10.7	7.5	1.2	0.5	-4.8	-2.8	-2.4	-1.5	-2.2	-3.4	-3.3	-5.3	-5.7	-2.3	-1.4	-4.2	-6.6	-3.7	-6.8	-7.2	-6.0	***-2.4***
	35	-2.9	13.1	10.1	2.9	1.5	-5.2	-2.9	-2.3	-1.6	-2.8	-3.9	-3.9	-6.3	-6.6	-0.9	0.3	-4.2	-7.3	-3.6	-7.5	-8.2	-6.1	***-2.2***
	45	-2.9	14.4	12.3	4.7	2.5	-5.0	-2.1	-1.8	-1.7	-2.8	-4.4	-3.6	-7.0	-6.8	0.0	1.7	-4.3	-7.4	-3.4	-7.8	-9.0	-6.6	***-1.9***
	55	-3.0	15.8	13.5	6.8	4.7	-3.9	-1.4	-1.4	-1.5	-3.4	-4.3	-4.0	-7.4	-7.3	0.2	2.1	-4.0	-7.6	-4.0	-8.1	-9.4	-6.9	***-1.6***
	65	-3.5	15.5	14.1	8.2	7.8	-2.6	0.1	-0.4	-0.7	-3.0	-4.1	-4.2	-7.8	-6.8	1.0	2.5	-4.3	-7.4	-4.1	-8.0	-9.6	-6.8	***-1.1***
	75	-4.3	15.4	14.5	9.4	10.1	-0.3	1.8	0.4	0.2	-2.5	-4.0	-4.0	-7.6	-6.0	1.8	3.2	-3.8	-6.9	-4.2	-7.9	-9.7	-6.8	***-0.5***
	85	-4.5	15.9	14.6	10.2	11.7	1.6	3.4	1.4	0.7	-2.2	-3.5	-3.8	-7.1	-6.0	2.5	3.7	-3.6	-6.1	-4.0	-7.8	-9.3	-6.4	***0.1***
	95	-5.1	15.9	14.1	9.8	12.2	2.4	4.4	2.3	1.0	-2.1	-3.2	-4.0	-7.2	-6.1	2.7	4.0	-3.9	-6.4	-4.1	-7.5	-9.5	-6.2	***0.2***
	105	-5.4	16.1	13.8	9.5	12.1	2.4	5.0	2.8	0.9	-2.6	-3.6	-3.9	-7.8	-6.4	2.3	3.3	-3.8	-7.1	-4.5	-8.1	-9.6	-6.2	***0.0***
	115	-5.5	15.1	13.0	9.4	12.4	2.6	5.0	2.5	0.4	-3.1	-4.2	-4.5	-8.8	-6.8	1.7	2.4	-4.7	-8.1	-5.5	-9.2	-10.1	-7.0	***-0.6***
	125	-5.8	14.7	12.3	8.9	12.1	2.8	4.5	2.4	0.2	-3.6	-4.3	-4.6	-9.2	-7.2	0.7	1.3	-5.3	-9.5	-7.0	-9.9	-11.4	-8.5	***-1.2***
	135	-6.2	14.9	11.6	8.4	11.5	2.3	3.6	2.1	0.0	-3.7	-4.5	-4.7	-9.4	-7.7	0.1	0.4	-6.3	-10.9	-7.7	-11.1	-12.7	-9.7	***-1.8***
	Avg P3	***-4.1***	***14.2***	***12.0***	***6.9***	***7.6***	***-0.8***	***1.3***	***0.3***	***-0.3***	***-2.8***	***-3.8***	***-3.9***	***-7.3***	***-6.5***	***0.5***	***1.6***	***-4.3***	***-7.4***	***-4.5***	***-8.1***	***-9.3***	***-6.8***	***-1.2***

3.4 Seasonal change in soil water and estimate of crop water use

Table 4 shows a summary of *TWto* for the entire soil profile (to 135 cm soil depth), the total soil water difference (*TD)* and daily soil water difference (*DD*) between consecutive sampling dates, for each configuration, position and DAS. *TD* and *DD* provide an indication of soil water extraction (positive) or water gain (negative) during consecutive sampling periods. Figure 7 shows the seasonal change in *TWto* for the entire soil profile (to 135 cm soil depth) by configurations and positions. It shows that although there were small differences among positions, when all positions were averaged the seasonal change in *TWto* was the same for both configurations (128 mm). Therefore, since there was 271 mm of seasonal rain and 128 mm of water extracted from the soil, a rough estimate of seasonal water use for the crop was about 399 mm for both planting configurations, assuming that all the rain was effective and that there was no deep percolation, which are reasonable assumptions under the conditions of this study.

Fig. 7. Comparison of seasonal change in soil water in the whole soil profile (to 135 cm) between configurations (single-skip and solid) and positions (P1, P2, P3) first and last sampling dates (days after sowing 33 to 193)

Table 4. Total soil water in the soil profile (*TWto*, mm, for 135 cm soil depth), total soil water difference (*TD*, mm) and daily soil water difference (*DD*, mm/d) between consecutive sampling dates, for each configuration (single-skip and solid), sampling position (P1, P2, P3) and days after sowing (DAS) obtained at Kingsthorpe during 2007-2008

			DAS																					
			33	**58**	**65**	**72**	**81**	**94**	**98**	**107**	**115**	**119**	**122**	**127**	**131**	**135**	**140**	**144**	**155**	**162**	**169**	**178**	**185**	**193**
Skip	P1	*TWto*	578.5	594.6	587.6	576.3	557.0	537.0	527.1	511.7	505.4	496.6	488.3	485.6	483.5	477.4	481.4	513.4	468.9	462.2	462.0	464.2	465.2	453.6
		TD		-16.1	7.0	11.3	19.3	20.0	9.9	15.4	6.3	8.8	8.3	2.7	2.1	6.1	-4.0	-32.0	44.5	6.7	0.2	-2.3	-1.0	11.6
		DD		-0.6	1.0	1.6	2.1	1.5	2.5	1.7	0.8	2.2	2.8	0.5	0.5	1.5	-0.8	-8.0	4.0	1.0	0.0	-0.3	-0.1	1.4
	P2	*TWto*	586.6	612.0	599.2	588.5	562.2	541.6	534.0	512.3	502.9	494.0	484.5	477.5	474.0	468.1	493.2	521.8	473.6	466.3	464.5	466.3	466.0	456.1
		TD		-25.3	12.8	10.7	26.3	20.6	7.6	21.7	9.4	8.9	9.5	7.0	3.5	5.9	-25.1	-28.6	48.2	7.4	1.8	-1.8	0.3	10.0
		DD		-1.0	1.8	1.5	2.9	1.6	1.9	2.4	1.2	2.2	3.2	1.4	0.9	1.5	-5.0	-7.2	4.4	1.1	0.3	-0.2	0.0	1.2
	P3	*TWto*	584.3	619.2	608.7	597.1	567.0	535.9	528.4	512.1	504.2	493.6	486.4	478.6	474.9	469.3	487.1	514.6	469.6	462.8	465.8	464.4	467.7	456.5
		TD		-34.8	10.4	11.6	30.1	31.2	7.5	16.3	7.9	10.6	7.2	7.8	3.7	5.6	-17.8	-27.5	45.0	6.8	-3.0	1.4	-3.3	11.3
		DD		-1.4	1.5	1.7	3.3	2.4	1.9	1.8	1.0	2.6	2.4	1.6	0.9	1.4	-3.6	-6.9	4.1	1.0	-0.4	0.2	-0.5	1.4
Avg Skip		***TWto***	***583.2***	***608.6***	***598.5***	***587.3***	***562.1***	***538.2***	***529.8***	***512.0***	***504.2***	***494.7***	***486.4***	***480.6***	***477.5***	***471.6***	***487.2***	***516.6***	***470.7***	***463.8***	***464.1***	***465.0***	***466.3***	***455.4***
		TD		***-25.4***	***10.1***	***11.2***	***25.2***	***23.9***	***8.3***	***17.8***	***7.9***	***9.4***	***8.3***	***5.8***	***3.1***	***5.9***	***-15.6***	***-29.4***	***45.9***	***7.0***	***-0.3***	***-0.9***	***-1.4***	***10.9***
		DD		***-1.0***	***1.4***	***1.6***	***2.8***	***1.8***	***2.1***	***2.0***	***1.0***	***2.4***	***2.8***	***1.2***	***0.8***	***1.5***	***-3.1***	***-7.3***	***4.2***	***1.0***	***0.0***	***-0.1***	***-0.2***	***1.4***
Solid	P1	*TWto*	584.3	600.7	585.8	575.2	557.1	527.7	523.2	504.3	501.1	491.5	489.7	482.0	482.1	476.7	484.0	515.0	474.5	467.6	470.8	471.0	474.2	462.7
		TD		-16.4	14.9	10.6	18.1	29.3	4.6	18.9	3.2	9.6	1.8	7.7	-0.1	5.4	-7.3	-31.0	40.5	6.8	-3.2	-0.2	-3.1	11.5
		DD		-0.7	2.1	1.5	2.0	2.3	1.1	2.1	0.4	2.4	0.6	1.5	0.0	1.4	-1.5	-7.8	3.7	1.0	-0.5	0.0	-0.4	1.4
	P2	*TWto*	590.7	611.1	592.1	579.3	551.4	527.2	518.5	499.0	492.1	482.7	475.7	469.6	466.2	459.8	484.0	512.2	468.2	461.0	462.6	460.9	462.7	452.4
		TD		-20.4	19.0	12.8	27.8	24.3	8.6	19.5	6.9	9.4	7.0	6.1	3.4	6.3	-24.1	-28.2	43.9	7.2	-1.6	1.7	-1.9	10.4
		DD		-0.8	2.7	1.8	3.1	1.9	2.2	2.2	0.9	2.4	2.3	1.2	0.8	1.6	-4.8	-7.0	4.0	1.0	-0.2	0.2	-0.3	1.3
	P3	*TWto*	590.5	604.3	597.1	588.7	555.5	533.5	524.8	510.0	504.1	497.3	490.9	483.3	484.3	477.0	487.0	514.2	476.0	473.7	473.5	475.5	480.4	466.2
		TD		-13.8	7.1	8.4	33.2	22.0	8.8	14.8	5.8	6.8	6.5	7.6	-1.0	7.3	-10.0	-27.3	38.3	2.2	0.2	-2.0	-4.9	14.2
		DD		-0.6	1.0	1.2	3.7	1.7	2.2	1.6	0.7	1.7	2.2	1.5	-0.3	1.8	-2.0	-6.8	3.5	0.3	0.0	-0.2	-0.7	1.8
Avg Solid		***TWto***	***588.5***	***605.4***	***591.7***	***581.1***	***554.7***	***529.5***	***522.2***	***504.4***	***499.1***	***490.5***	***485.4***	***478.3***	***477.5***	***471.2***	***485.0***	***513.8***	***472.9***	***467.5***	***469.0***	***469.1***	***472.4***	***460.4***
		TD		***-16.8***	***13.7***	***10.6***	***26.4***	***25.2***	***7.3***	***17.7***	***5.3***	***8.6***	***5.1***	***7.1***	***0.8***	***6.3***	***-13.8***	***-28.8***	***40.9***	***5.4***	***-1.5***	***-0.2***	***-3.3***	***12.0***
		DD		***-0.7***	***2.0***	***1.5***	***2.9***	***1.9***	***1.8***	***2.0***	***0.7***	***2.1***	***1.7***	***1.4***	***0.2***	***1.6***	***-2.8***	***-7.2***	***3.7***	***0.8***	***-0.2***	***0.0***	***-0.5***	***1.5***

The results of this study indicated that the total water extraction from the soil profile was similar for both row-configurations (solid and single-skip) over the growing period. However, patterns of water extraction from individual depths were different. The single-skip configuration extracted more water from deeper depths, whereas the solid configuration used more water from the shallower depths. This behavior may be possible with differential root growth and development for the tested configurations. Closer row spacing for the solid is likely to result in more concentration of roots in the topsoil layers/depths. On the other hand, wider row spacing for the single-skip configuration, resulting in about 10 cm taller plants, might have also resulted in greater rooting depth and greater water extraction from deeper depth than the solid configuration. In this context, others have reported a greater cotton root length density (RLD) in the top 0-15 cm soil depth for the solid compared with the 2x1 skip row planting configuration (similar to the single-skip configuration in our study) [3]. They also reported that the skip-row configuration resulted in greater water extraction from deeper depths due to greater RLD deeper in the soil profile [3]. Furthermore, they noted that more than 80% of the RLD and a more significant proportion of the water extraction came from the top 75-cm soil depth and a negligible water extraction occurred below a depth of 100 cm [3].

We also noted that more than 85% of the soil water was extracted from the top 100 cm depth and only about 15% from below 100 cm depth (Fig. 3). Similarly, another study reported a maximum extractable depth of about 70-80 cm for cotton crops in similar soil and climatic conditions [11]. The same study also found that the top 50 cm soil layer accounted for 75% of the seasonal extraction, and the top 80 cm profile accounted for 90% [11]. The study also pointed out that substantial water may be available at the lower depths, but this water extraction would be limited due to limited roots at deeper depths.

The magnitude of water extraction for the single-skip treatment was expected to be more than the solid, especially at positions P1 and P2, which were closer to the plant, due to bigger plants and, consequently, more extensive and deeper root system than the solid configuration. This effect was, however, not pronounced as expected. Figure 3 did not show any visible differences between the row configuration for water extraction due to larger values at the y-axis. However, the differences in water availability at a specific depth (Fig. 4) and above that specific depth (Fig. 6) clearly showed that the single-skip configuration tended to have just slightly (a few mm) more water at the shallower depths during early and mid-growth stages. In contrast, the solid configuration tended to have more water deeper in the profile later in the season (Fig. 4). In other words, more water was available in the shallower and deeper depths for the single-skip and solid configurations, respectively. It was also expected that water extraction from the farthest position from the plant line (P3 for the single-skip) would be significantly less than at the P1 position due to the absence of growing plants at P3. Still, a similar amount of water was extracted from those two positions (P1 and P3) as observed in the selected depths (Fig. 4).

These results could be due to two likely reasons, firstly, more soil evaporation taking place from the bare soil at position P3 for the single-skip configuration, and secondly, through the potential development of deep cracks in the soil profile in the absence of any plant shade at position P3 compared with plant shade at P1. Shade of plant cover can reduce surface evaporation and water loss. It may also be possible that there was directional water movement along the developed water potential gradient between P1 and P3 (towards P1) due to greater extraction capacity by larger plants for the single-skip configuration. Another study also reported similar water extraction from 1 m solid and 2x1 single skip-row but relatively less water extraction from double-skip (2x2) than solid or single-skip [3]. The impact of deep cracks was also evident from the water availability for all depths and positions, *TWin* for the two configurations tended to follow each other very closely throughout the entire season (Fig. 3). When there were increases in *TWin*, these increases tended to occur at all depths. This could be explained by preferential water flow through the side of the neutron access tubes and/or the cracking nature of the soil type. These black expanding clay soils tend to form big cracks when dry. Water fills the cracks, and the soil starts filling from the bottom up rather than from the top as is typical of most soils.

The total water use, including soil evaporation and crop transpiration, was 399 mm for both configurations as estimated from the neutron probe measurements and in-crop rainfall in this study. A previous study reported that the total water use (ET, evapotranspiration), while recording changes in soil moisture (using neutron probe measurements and in-crop rainfall) varied from about 430 mm to 530 mm for various okra and normal leave varieties, with the normal leave variety Sicot having the highest water use [12]. However, seasonal differences in rainfall and weather conditions can impact considerable on dryland cotton water use (ET). Another study using neutron probe measurements [13] reported seasonal evapotranspiration between 560 and 815 mm over a two-year period in similar regions of New South Wales (NSW), showing significantly higher ET in comparison with our study. But, in the above study [13], yield varied between 1000 kg and 2300 kg lint/ha, averaging more than 1700 kg lint/ha, whereas in our study, the mean yield was around 1400 kg lint/ha for the solid treatment. In contrast, another study [3] reported seasonal water use between 170 mm to 300 mm for dryland cotton crops, with significantly reduced yield (between 400 kg and 600 kg lint/ha). Another study [6] reported dryland cotton lint yield between 450 kg lint/ha (2 bales/ha) and 1900 kg lint/ha (8.5 bales/ha) from northern NSW and southern Queensland from various row configurations. In comparison to dryland cotton production, on average, high yielding irrigated cotton crops utilise 6-7 ML/ha (600-700 mm) irrigation water in the northern NSW regions of Australia [14].

3.5 Crop Height and Yield

Figure 8 shows the maximum canopy height for the solid and single-skip configurations. Cotton plants in the single-skip configuration grew more than 10 cm taller than those in the solid. This difference in canopy height was statistically significant ($\alpha = 0.05$). Crop lint yields are shown in Table 5. When comparing single-skip and solid configurations, it is necessary to compare yields both per unit area (g m^{-2}, kg ha^{-1}, bales ha^{-1}) and yield per linear meter (g m^{-1}, which provides an indication of yield per plant). Table 5 shows no significant differences in lint yield when expressed per unit area or linear meter. Significant differences were not detected mainly due to high yield variability among replications. Although yields were not significantly different in statistical terms, in numeric terms, the yield for the single-skip treatment was 27% greater when calculated on a linear basis but 5% lower on a per-area basis than the solid treatment. Table 5 also shows that the lint fraction (LF = lint mass/seed cotton mass) was 0.42 (42%) for both configurations, with no significant difference between them. Also, there were no significant differences in the fraction of lint from green balls (FLGB) between the two configurations.

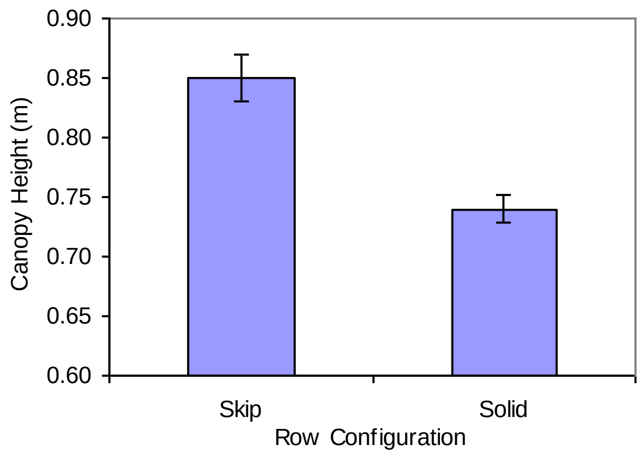

Fig. 8. Maximum canopy height for cotton at Kingsthorpe during 2007-2008. Error bars are standard error of the means.

Table 5. Treatment means and Analysis of Variance (ANOVA) of cotton lint yields obtained at Kingsthorpe during the 2007-2008 season

			Lint from open bolls				Total lint (open + green bolls)			
Treat	LF	FLGB	(g m^{-1})	(g m^{-2})	(kg ha^{-1})	(ba ha^{-1})	(g m^{-1})	(g m^{-2})	(kg ha^{-1})	(ba ha^{-1})
Solid	0.42	0.014	138.17	138.17	1381.75	6.09	140.07	140.07	1400.70	6.17
Skip	0.42	0.040	170.70	128.34	1283.42	5.65	177.56	133.50	1335.04	5.88
Pr > F	0.979	0.097	0.22	0.62	0.62	0.62	0.15	0.73	0.73	0.73
LSD	0.028	0.038	61.26	51.26	512.65	2.25	58.95	49.27	492.77	2.17
SEM	0.005	0.006	12.26	8.54	85.45	0.38	12.67	8.07	80.72	0.36

LF = Lint fraction = (lint mass)/(seed cotton mass), FLGB = Fraction of lint from green bolls = (lint yield from green bolls)/ (Total lint yield), Lint yields per unit area (g m^{-2}, kg ha^{-1}, bales ha^{-1}) took into account that plants in the single-skip treatment had access to an area 1.33 times larger than plants in the solid treatment, while yields per unit length (g m^{-1}) did not take this into account, SEM = standard errors of means, LSD = least significant difference at the 0.05 level, ba = bales.

The solid treatment had slightly greater cotton lint yield on a total land area basis than the single-skip, although this small difference was not statistically significant (Table 5). Other studies have found higher yield for the solid treatments [2,3,15,16]. At a commercial scale, the fact that the skip had the same yield as the solid is significant because the single-skip would need only 67% of the seeds compared to the solid, which would save on planting cost. The single-skip treatment was able to compensate for the reduction in plant population by producing taller plants that tended to produce more yield per plant. Increased plant height with the single-skip configuration is consistent with findings in other studies [2,17]. Taller plants, however, could be prone to lodging with high winds, leading to likely adverse impact on the yield and profitability [2]. Yield increases per plant due to wider row spacing was just enough to overcome yield reductions due to decreased plant population in a per hectare basis for the single-skip configuration compared to the solid in this study.

Although the impact of early maturity on crop yield was not evaluated in the study, it is likely that earlier maturity by the solid configuration may also have an impact on lint yield. A study reported that a greater percentage of total yield was harvested at the first picking from the solid than from the single-skip [15], indicating that the solid configuration was able to mature earlier than the single-skip [16], whereas the skip row treatment had a greater yield than the solid configuration during the mid and late picking. In contrast, another study reported a strong positive relationship between maturity and lint yield, where lint yield increased more than 34 kg/ha with every day of delay in maturity [12]. In addition to the effects of row configuration on yield, another study found that the solid planting tended to close the canopy earlier and suppressed weed population better than the skip row planting [2]. That study also noted that plant density was the most influential component for yield under dryland conditions. Cotton grown at higher plant densities accumulated more dry matter leading to higher yield [18], whereas less densely planted cotton plant population resulted in significant reductions in boll retention and yield [19].

A greater interception of radiation and radiation use efficiency (RUE) with dense plant population in the solid configuration could be one of the main contributing factors for the slight yield increase compared with skip-row [20,21]. Many recent studies have shown that plant density and row spacing pattern influence canopy structure, light interception, and RUE, influencing cotton yield [22,23,24,25]. One of these studies also found that uniform row spacing (like solid planting) enhanced the RUE which had more significant positive effects on boll number and lint yield [25]. The same study also showed shorter plants in higher, than in lower plant population, like our results with the single-skip population. Similarly, another study reported poor canopy photosynthetic capacity in low density population [23].

Lint quality and fraction are expected to be modified by planting density, but in our study lint fraction did not differ between the solid and single-skip configurations (Table 5). Other studies also reported no difference in the fiber quality due to variable planting density [18, 26,27]. However, one of these studies found that the cotton fiber micronaire value was reduced by increasing planting density [28]. The influence of dense cotton population on lint percentage and fiber quality may not be that important compared with the significant increases in yield for economic profitability. For example, researchers compared 25, 76 and 101 cm row spacing in skip-row configuration for irrigated and dryland conditions [8]. They found that the effects of planting configuration on fibre quality were not significant relative to row spacing effects, and skip- row cotton had a lower net return than the solid-row cotton.

Based on the measured lint yield and seasonal water use, the estimated water use efficiency (WUE, Yield/total water use) for the solid and single-skip row configuration respectively were 3.5 and 3.3 kg lint/ha/mm water use. A previous study compared cotton soil water use in solid and 'one-in-one-out' skip-row configuration in the Gwydir Valley of NSW [29]. Their results indicated that more cotton was produced per megalitre of water applied for the solid compared to the skip. Similarly, another study reported higher water use efficiency from ultra-narrow row cotton (25 cm) than 76 or 102 cm row spacings and skip row configurations [30]. Another study reported that later maturing cotton varieties had higher WUE than the earlier maturing variety [12].

In this study, only a slight increase in WUE was found for the solid configuration compared to the single-skip. The WUE values obtained in this study for both treatments were greater than those reported by [12], who found WUE values in the range between 2.6 and 3.2 kg lint/ha/mm for various conventional and okra leave varieties. The slight decrease in WUE for the single-skip could have resulted from less canopy cover and likely more soil evaporation losses, which did not contribute to increase crop yield. As discussed before, the dense canopy system with solid planting tends to have improved radiation use efficiency (RUE), which is also linked to the WUE. Recent studies have proposed that RUE could explain 52% of the variance in WUE across C3 and C4 agricultural row crops, including maize, soybean, sorghum, and winter wheat [31,32]. They suggested that the WUE vs RUE relationship was subject to change with VPD conditions and crop specific features such as photosynthetic pathways, canopy architecture, leaf angle, leaf morphology and plant density.

3.6 Role of skip-row planting and seasonal conditions in Queensland

Skip row has been arguably regarded as a sort of insurance against complete crop failures in dry seasons. In this study, monthly rainfall pattern indicated that the growing season was dry to average, except that an exceptional rainfall occurred in February. The long-term rainfall average during the cotton growing season (Oct to Mar) for Queensland cotton growing regions varies between 380 mm and 450 mm [6], indicating that the growing period for this study was significantly drier than normal. On average, the months of Nov, Dec, Jan, and Apr were drier than the long-term rainfall average. Rainfall accounted for only about 1/3 of the seasonal ETo (271 mm vs 804 mm, Table 1). Insufficient rain early in the growing season was expected to significantly reduce the vegetative growth and, therefore, to have a negative impact on cotton lint yield, particularly for the solid configuration. In contrast, cotton lint yield from the solid configuration (1400 kg lint/ha [> 6.0 ba/ha]) was not only slightly greater than the single-skip, but was similar or higher to yields reported by others for dryland cotton crops [6,12].

It is important to note that several studies reported that under relatively drier conditions (the threshold between 1.6 to 2.5 ba/ha) the skip row could show greater yield than the solid in this region [2,6,7]. However, the season was considerably drier in our study, but both configurations yielded around 6 ba/ha. This poses the question on the reliability of a better economic return from the skip-row over solid planted for an unpredicted drier season in this region. Cotton is a summer crop, and the Darling Downs region has summer dominant rainfall. Long-term rainfall average indicates that only 1 year out of 10 years would have a chance to receive less than 250 mm of rainfall during the cotton growing season. It seems that 90% of the time there will be rainfall between 400-450 mm during the season in the summer months [6]. It is better not to plant if the seasonal rainfall pattern indicates very dry conditions, which is very hard to predict (only 10% of the years). Growers can miss out 90% of the year if they stick to skip-row planting every year for the sake of saving the crop from an unpredictable extremely dry conditions rather planting solid. A study using a cotton model (CSIRO OZCOT) simulated cotton crop water use and water use efficiency in a changing climate for various scenarios in Australian regions [33]. The study found that for rain-fed cotton, a solid planting configuration had the greatest positive response to future climate scenarios at Emerald, Dalby and Moree, while double skip planting generated positive response in Narrabri.

4. CONCLUSION

This study compared single-skip and solid cotton configurations under dryland conditions in a sub-tropical climatic zone. Soil water measurements indicated that in general, the solid configuration tended to extract more water from shallower depths, earlier in the season, whereas the single-skip configuration extracted more water from deeper in the soil profile later in the season. This difference in the water extraction pattern reflected abundance of greater root concentration in the shallower soil profile with closer row spacing for the solid-row configuration, whereas for the single-skip configuration with wider row spacing and larger plants had greater rooting depth and water extraction later in the season. Although larger plant from the single-skip configuration had slightly greater (but not significantly different) lint yield per plant, but 33% less plant density resulted in statistically the same lint yield per unit area (kg/ha) between the single-skip and solid treatment. Since the two configurations had statistically the same yield and seasonal water use, the estimated water use efficiency (WUE) was also very similar, averaging 3.4 kg lint/ha/mm between the two treatments. There was no apparent yield advantage from the skip row configuration over the solid planted cotton in relatively drier years of the study period. This highlights that there is a need of careful consideration for type of row-configuration in this region, where growers can miss out 90% of the year with normal rainfall if they stick to skip-row planting for the sake of saving the crop from an unpredictable extremely dry condition.

COMPETING INTERESTS DISCLAIMER:

AUTHORS HAVE DECLARED THAT NO COMPETING INTERESTS EXIST. THE PRODUCTS USED FOR THIS RESEARCH ARE COMMONLY AND PREDOMINANTLY USE PRODUCTS IN OUR AREA OF RESEARCH AND COUNTRY. THERE IS ABSOLUTELY NO CONFLICT OF INTEREST BETWEEN THE AUTHORS AND PRODUCERS OF THE PRODUCTS BECAUSE WE DO NOT INTEND TO USE THESE PRODUCTS AS AN AVENUE FOR ANY LITIGATION BUT FOR THE ADVANCEMENT OF KNOWLEDGE. ALSO, THE RESEARCH WAS NOT FUNDED BY THE PRODUCING COMPANY RATHER IT WAS FUNDED BY PERSONAL EFFORTS OF THE AUTHORS.

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