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Physiological determinants of high yielding ultra-narrow row cotton: Canopy development and radiation use efficiency

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ABSTRACT

Ultra-narrow row cotton (UNR, with rows spaced less than 40 cm apart) has long been proposed to have the potential to increase yields while reducing the time to crop maturity. Investigations have shown that biomass accumulation in high-input, high yielding UNR (25 cm spaced rows with yields greater than 1800 kg lint ha^{-1}) cotton is similar to conventionally spaced rows (100 cm) despite a three-fold increase in plant density, indicating a limitation on individual plant growth. This study investigates whether the increased plant density in UNR crops (36 plants m^{-2}) leads to differences in canopy development, radiation use efficiency (RUE) and light interception contributing to plant growth limitations. Three experiments over three years compared UNR treatments to conventionally spaced treatments in high-input production systems and found that early canopy development (leaf area index LAI) and consequently early interception was higher in the UNR crops in two of the three experiments. This resulted in a 17% higher seasonal canopy extinction coefficient (k) in UNR crops over the season. However, seasonal RUE of the UNR crop was 19% lower as increases in light interception were not accompanied by increased total dry matter. Light distribution through the canopy was poorer (higher k) in the UNR crop and LAI continued to increase in the UNR crop after maximum light interception was reached, which combined with a lower leaf nitrogen concentration may have reduced the photosynthetic efficiency of the UNR crop. We conclude that differences in canopy light interception and the efficiency of conversion of light to biomass were the primary factors responsible for differences in the pattern of biomass accumulation between UNR and conventionally spaced cotton.

1. Introduction

Ultra-narrow row cotton (UNR, with rows spaced less than 40 cm apart) has long been proposed to have the potential to increase yields while reducing the time to crop maturity (Nichols et al., 2003). This paper forms part of a detailed investigation into the growth and development of ultra-narrow row cotton in high-input production systems. We found that there was potential for higher yields when compared to conventionally spaced rows (100 cm row spacing) in high yielding, high-input productions systems in Australia, however there was no difference between row spacings in time to crop maturity (Brodrick et al., 2010).

A detailed growth analysis and physiological determinants framework (Charles-Edwards et al., 1986; Coleman et al., 1994) was used to identify key differences in the factors influencing yield and maturity of UNR and conventionally spaced cotton crops in high-input, high yielding production systems. Brodrick et al. (in press) found that the increased yield in UNR crops was not due to differences in final biomass accumulation but associated with more bolls per unit area and increased partitioning to reproductive growth in the UNR crops. Initially crop growth rate and biomass production was higher but crop growth rate slowed earlier in the UNR crop and final biomass was not different from the conventionally spaced crop despite a three-fold increase in plant density (Brodrick et al., in press). The UNR plants were smaller, with less biomass produced per plant indicating limitations in assimilates for growth due to the increased number of plants competing for resources in the UNR crop. If competition between plants in the UNR treatments reduced the availability of light, water and nutrients to individual plants, this would have limited their biomass production and growth, and as total crop water use and final nutrient uptake were not different (Brodrick et al., in press), it is likely that competition for light in the higher density UNR crop slowed biomass accumulation.

Few studies have compared the leaf area development and light interception characteristics of cotton grown in UNR and conventionally spaced rows in low-input systems, and none to our

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knowledge in high-input, high yielding (>1800 kg lint ha^{-1}) systems. In low-input UNR cotton systems the higher number of plants can lead to greater early leaf area index (LAI) accumulation compared to conventionally spaced cotton (Darawsheh et al., 2009; Gwathmey and Clement, 2010; Jost and Cothren, 2000; Kreig, 1996). Closer plant spacing means that plants do not need to be as large for the crop to achieve maximum light interception. An increase in light interception has been reported for narrower row spacings in cotton (Heitholt et al., 1992; Peng and Krieg, 1991) and other species such as corn (Andrade et al., 2002), chickpea (Leach and Beech, 1988), sorghum (Flenet et al., 1996), and soybean (Board and Harville, 1992; Savoy et al., 1992). This rapid canopy closure may also lead to reductions in weed competition (Forcella et al., 1992) and decreased soil evaporation (Kreig, 1996; Nunez and Kamprath, 1969). This increased early light interception has been thought by many researchers to be the primary reason for increases in yield in narrower row spacings in many indeterminate and determinate crops (Andrade et al., 2002; Flenet et al., 1996; Shibles and Weber, 1966).

Constable (1975) found a significant negative relationship between boll growth rate and LAI in UNR spaced cotton. Heitholt et al. (1992) found that narrow rows (0.5 m spaced rows) had a higher canopy extinction coefficient (k) compared to conventionally spaced rows and concluded that the optimal LAI for maximum light interception and yield for narrow rows was between 3 and 4 compared with an LAI of 4–5 for conventionally spaced rows. Other authors have hypothesized that the denser canopy in UNR spaced cotton could lead to reduced light penetration leading to increased shedding or smaller bolls (Baker, 1976; Constable, 1975; Jost and Cothren, 2001).

Changes in biomass production can also be a result of differences in a crop's ability to convert solar radiation into biomass, as represented by the radiation use efficiency (RUE) of the crop (Monteith, 1977). No studies have compared radiation use efficiency in UNR to conventionally spaced rows in cotton. Savoy et al. (1992) found that narrower rows in soybean (0.36 m spaced rows) had higher light interception, greater biomass accumulation and higher radiation-use-efficiency compared to wide rows (1.02 m spaced rows).

Understanding how decreasing row spacing in high-yielding, high-input cotton systems affects the physiological determinants of biomass production is important in realizing any benefits of these systems. In this paper we will test the following hypotheses, (i) the increased plant population in the UNR crop increases light interception in the UNR crop; (ii) canopy development leads to a higher canopy extinction coefficient in the UNR crop and (iii) radiation use efficiency is lower resulting in no differences in final biomass production in the UNR crop.

2. Methods

2.1. Site and climate description

UNR and conventionally spaced cotton crops were compared in three experiments grown near Narrabri, in a semi-arid environment of north-west New South Wales, Australia. The experiments are described in detail in Brodrick et al. (in press). Briefly, three experiments were sown using the cultivar Sicala V-3RRi (Reid, 2001). Exp. 1 was sown 16 November 2001, Exp. 2 was sown 10 October 2002, and Exp. 3 was sown 23 October 2003. These experiments correspond with Exps. 1, 2 and 5 in Brodrick et al. (2010). In the 25 cm UNR treatment, the row configuration was six rows spaced 25 cm apart on a 2 m bed sown with 36 plants m^{-2}. In the conventionally spaced treatment, the row configuration was two rows spaced 1 m apart on a 2 m bed sown with 12 plants m^{-2}. A randomized complete block design with four replicates was used. Experiments were fully irrigated according to crop requirements. Management followed current commercial practices for high-input management, irrigation and insect control as described by Hearn and Fitt (1992). Crop water use and nitrogen uptake details are reported in Brodrick et al. (in press).

2.2. Measurements

2.2.1. Leaf area index

On approximately 12 occasions in each experiment, biomass, leaf area, specific leaf area (SLA) and LAI were measured by destructive sampling (see Brodrick et al., in press). Leaf area was determined by measuring the leaf area of the sub-sample with a LiCor planimeter (Model LI-3100, LiCor Inc., Lincoln, NB, USA). This sample was dried and weighed and specific leaf area determined ($m^2\,g^{-1}$). LAI was calculated as the product of specific leaf area and amount of leaf dry matter ($g\,m^{-2}$).

2.2.2. Light interception

Total daily incoming radiation was measured using a calibrated pyranometer at the Australian Cotton Research Institute weather station less than 2 km from the experimental fields. In Exp. 1, solar radiation intercepted by the canopies was measured using tube solarimeters (Model TSL Delta-T Devices Ltd, Cambridge, UK). A single tube solarimeter was placed across one bed in each plot (in a north–south orientation) to measure transmitted radiation. One tube solarimeter was placed above the crop in the middle of the experiment to measure incident solar radiation. The solarimeters were calibrated against the solarimeter positioned above the crop before and after each experiment. The solarimeters were programmed to scan at 5-min intervals, recording average hourly readings on a programmable datalogger (Model DL Delta-T Devices Ltd, Cambridge, UK).

In Exps. 2 and 3 solarimeter data were not collected for the full season or for all plots due to problems with dataloggers. For these experiments intercepted solar radiation was calculated from weekly measurements of intercepted photosynthetically active radiation (PAR) using a sunfle0ck ceptometer (SF-80, Delta-T Devices Ltd, Cambridge, UK). Incident radiation was recorded between 11:00 and 13:00 h (Australian Eastern Standard Time) above each plot averaging three readings. Transmitted radiation was recorded by average readings taken at ground level in three random areas in each plot from the center of the furrow to the center of the bed. Solarimeter data from experiment 1 was converted to PAR.

To estimate canopy closure, the proportion of PAR intercepted by the crop at midday (LI_I) was calculated as:

$$LI_I = \frac{(\text{incident radiation} - \text{transmitted radiation})}{\text{incident radiation}}$$

An exponential function was fitted to LI_I over DAS to allow interpolation between measurement dates:

$$LI_I = a\left(1 - e^{(-b\text{DAS})}\right) + c$$

where a, b and c are fitted coefficients (Charles-Edwards and Lawn, 1984).

To calculate cumulative intercepted daily radiation and the light extinction coefficient (k), total daily intercepted radiation (LI_D) was calculated from instantaneous measurements by adjusting the measurements using the relationship (Charles-Edwards et al., 1986):

$$LI_D = \frac{2LI_I}{1 + LI_I}$$

To allow interpolation between dates of measurement LI_D was also regressed over DAS using the same equation as for LI_I.