PHYSIOLOGICAL DETERMINANTS OF YIELD AND MATURITY IN ULTRA-NARROW ROW COTTON

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by

Rose Roche

BAppSc(Hons) Queensland University of Technology

BSc(Environmental Biology) University of Technology, Sydney

School of Land and Food Sciences

The University of Queensland

Australia

Declaration of originality

This thesis reports the original work of the author, except as otherwise stated. It has not been submitted previously for a degree at any university.

Declaration of contribution to jointly-published work

The following scientific papers, on which the author of this thesis is the senior author, have been published as a direct result of the work presented in this thesis:

Roche, R., Brown, E., Bange, M., Caton, J., and Milroy, S. (2005). Using Pix on UNR cotton. The Australian Cottongrower 26 (2) pp.53-55.

Roche, R., Bange, M., Milroy, S., Brown, E., Caton, J. and Hammer, G. (2004) Why aren't ultra-narrow rows earlier than conventionally spaced rows in Hillston? Proceedings 12th Australian Cotton Conference (Gold Coast, 10-12 August, 2004) CDROM.

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Roche, R., Bange, M., Milroy, S. and Hammer, G. (2003) Crop growth and maturity in ultra-narrow and conventionally space cotton. Proceedings 11th Australian Agronomy Conference (Geelong, 2-6 February, 2003) Website **http://www.regional.org.au/au/asa/2003/index.htm**

In the case of each paper, the senior author contributed the major intellectual component of the work. In the case of the above four papers, the text and figures of these papers were primarily produced by the senior author incorporating the comments and criticisms of the junior authors.

Declaration of contribution by others

R. Roche has been the primary author of all thesis chapters while gratefully acknowledging the suggestions and edits of her four supervisors, Prof. G. Hammer, Dr. M. Bange, Dr. S. Milroy and Prof. S. Fukai.

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Publications by the candidate relevant to the thesis

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Publications by the candidate relevant to the thesis but not forming part of it

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Roche, R. Bange, M. Milroy, S., and Hammer, G. (2004) How do cluster plants perform in UNR systems? The Australian Cottongrower. June-July pp 48-49.

Roche, R., Bange, M.P., Milroy, S.P., & Hammer, G.L. (2004). Does a different plant type enhance performance of UNR cotton production systems? In Proceedings of the Beltwide Cotton Conferences. Jan 5-9. San Antonio, Texas. National Cotton Council. Memphis, TN. pp 2009-2015.

Roche, R., Bange, M., Milroy, S., Roberts, G. & Constable, G. (2004) Management for ultra early cotton systems. "New directions for a diverse planet". Proceedings of the 4th International Crop Science Congress, 26 Sep – 1 Oct 2004, Brisbane, Australia. Published on CDROM. Website www.regional.org.au/au/cs

Abstract

Ultra-narrow row (UNR) cotton, a production system with rows spaced less than 40 cm apart, has been proposed as a system for earlier maturity without substantial yield loss. However, trials in the U.S.A. and Australia have found yield and maturity benefits difficult achieve consistently with UNR cotton production. This thesis aimed to improve the understanding of differences in the growth and development of cotton in conventionally spaced (1 m) and ultra-narrow rows (UNR) grown in high-input production systems in Australia. Six experiments from 2001-2004 investigated the yield and maturity response of UNR compared with conventionally spaced cotton. In three of these experiments more detailed investigations into the growth and development of UNR cotton were conducted to quantify differences in the growth and development of cotton in UNR compared with conventionally spaced cotton in high yielding, high-input systems. This study focussed on the physiological differences in growth and partitioning, differences in fruit development and retention, and identifying the importance of carbon supply on fruiting dynamics.

The UNR plants in all experiments in this study were smaller, set fewer bolls and maintained yield through a higher plant population, however a smaller plant with fewer fruiting branches did not cut-out earlier. Maturity was not influenced by differences in the time to reach crop development stages between row spacings or by loss of early bolls in the UNR plants. Node of first fruiting branch did not differ between row spacings. Time to first square, retention, time to last effective flower (last flower that was retained to boll maturity) and boll period were also not consistently different between row spacing treatments, which was consistent with maturity not occurring any earlier in the UNR crop.

This study has shown that the plants are smaller due to competition between plants restricting dry matter production per plant. As a result, site production in the UNR plants is slowed and the fewer fruit on the smaller plants are set over the same time period as the greater number of fruit on the larger, more vegetative plants in the conventionally spaced system. This response of slower growth occurred early during the plant's growth before anthesis and led to smaller boll size and lower retention in the UNR plants.

Yield was not significantly different between row spacings in any of the six experiments in this study. However, there was a trend to higher yield in the UNR crop in all of the experiments and a combined analysis found that the mean lint yield of the UNR treatments was 15.9% higher than the conventionally spaced treatments. While early season crop growth, fruit production and light interception tended to be higher in the UNR crop this did not translate into greater final crop biomass production. There was a trend to greater partitioning of carbohydrates to fruit in the UNR crop. Final boll numbers per m^2 *were higher in the UNR treatments compared to the conventionally spaced treatments. This was accompanied by a decrease in boll size. However, the 9% reduction in boll size in the UNR treatments was more than compensated for by the 21% increase in boll number.*

The major factors affecting crop growth and development of the UNR crop in this study were differences between the two row spacings in light interception and conversion efficiency. The UNR treatments had a higher crop light extinction coefficient (k), and hence, greater light capture at low LAI, but this did not lead to increased final total biomass production, most likely because of a compensating reduction in RUE. The higher k in UNR crops would be advantageous to light capture in early canopy development and generate greater earlier crop growth that supports early fruit production, leading to higher early fruit numbers at the crop level in the UNR crop. However, the associated

reduction in RUE would generate reduced crop growth at the higher LAI found after canopy closure, reducing retention of later fruit later in the UNR crop. Hence, the similar total final biomass of the two systems is a consequence of two compensating factors.

For UNR plants to mature earlier, early node production and fruiting site production must be produced at a similar rate to conventionally spaced crops. Further research is needed into whether increasing inputs early in the season will prevent slower growth and development in UNR system, or whether the plants are responding to other indicators such as root competition or changes in the light environment that might lead them to adjust their growth on detection of neighbouring plants. In the case of the latter, either genetic or environmental manipulations might be required to influence plant growth and development in UNR systems.

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List of abbreviations

Abbreviation	**Term Represented**
CLI_D	Accumulated intercepted radiation (MJ m^{-2})
DAS	Days after sowing
Exp.	Experiment
FFB	Node of first fruiting branch
k	Canopy extinction coefficient for total radiation
LAI	Leaf area index (m^2 m^{-2})
LI_I	Instantaneous light interception (%)
LI_D	Estimated daily light interception (%)
N	Nitrogen
NAWF	Nodes above last white flower
PAR	Photosynthetic active radiation (µmol m^{-2} s^{-1})
RH	Relative humidity (%)
RUE	Radiation use efficiency (g MJ^{-1})
SLA	Specific leaf area (cm^2 g^{-1})
SLN	Specific leaf nitrogen (g N m^{-2})
TDM	Total dry matter (g m^{-2})
UNR	Ultra-narrow row
VPD	Vapour pressure deficit (kPa)

Chapter 1

General introduction

1.1 Background

Cotton is a tropical perennial species that is grown as an annual crop for fibre and oil in many subtropical areas of the world. *Gossypium barbadense* L. and *Gossypium hirsutum* L. are the two main cotton species grown commercially. About 90% of cotton production uses cultivars of *G. hirsutum* (upland cotton) while *G. barbadense* (Pima cotton) accounts for 5% of cotton produced (Niles and Feaster 1984). The remaining 5% is made up of two other species that are grown commercially *Gossypium herbaceum* and *Gossypium aboreum* (Cotton Australia 2005).

Cotton growing regions in Australia extend from Emerald in Queensland through to Hay in southern New South Wales (Fitt 1994) (Figure 1.1). Although Australia accounts for only 12% of world cotton production, it is the third largest exporter of cotton and contributes $1.5 billion in exports to the Australian economy (Cotton Australia 2005). Nearly all cotton grown in Australia is *G. hirsutum* (Fitt 1994). Most of the cotton grown in Australia is irrigated and has high input management (fertilizer and insect control) (Hearn and Fitt 1992). This, combined with a suite of cultivars developed specifically for Australian growing conditions has led to Australian producers having the highest average yields in the world (Cotton Australia 2005).

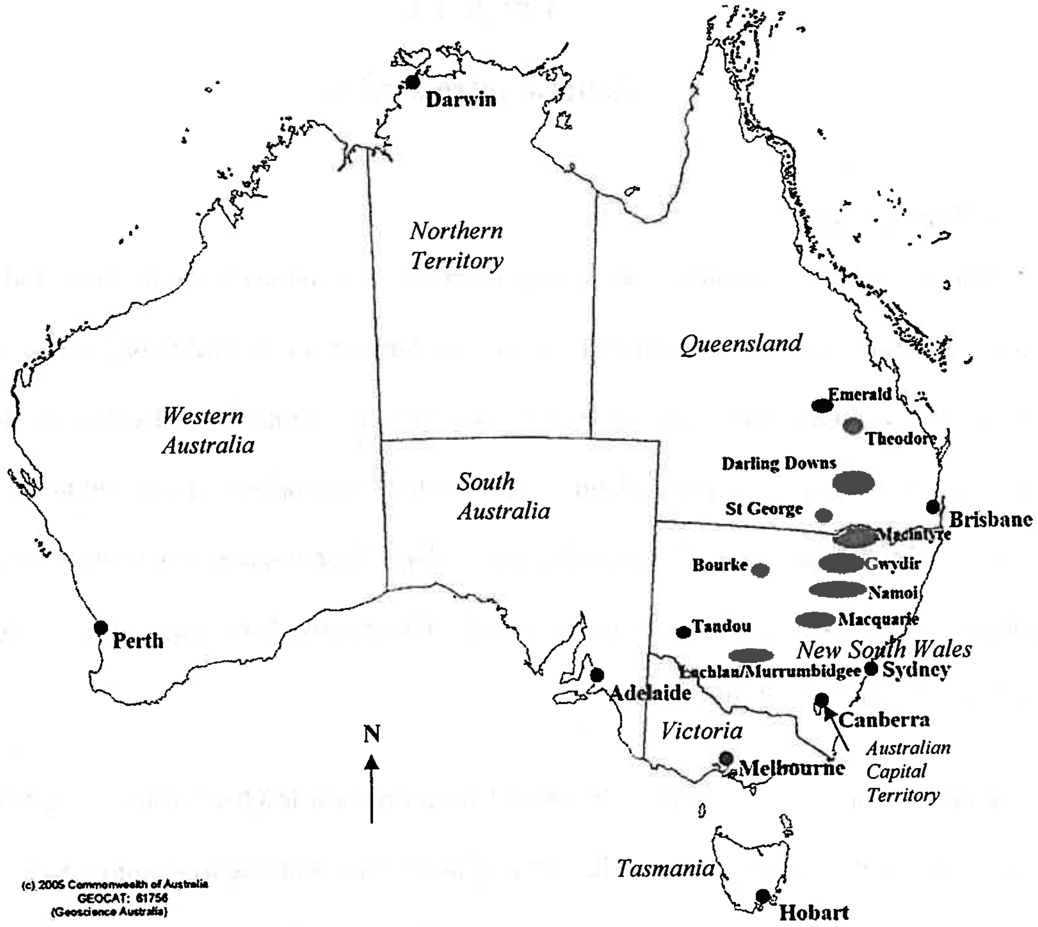

Figure 1.1 Map showing major cotton growing regions in Australia. (Source of base map: Geoscience Australia (2005)).

Cotton is a long season crop taking an average 180 days from sowing to crop maturity (60% open bolls - when the crop is considered ready for defoliation). In Australia, the growing season extends from planting in September/October to harvesting in March/April. While most regions where cotton is grown in Australia have the climate to accommodate this long-season crop, there is significant variation in temperature from warmer areas in southern Queensland and northern NSW to cooler areas in southern NSW (Figure 1.1 and Table 1.1).

Temperature is a primary driver of growth and development in the cotton plant. Low temperatures after sowing increase the time to emergence and reduce seedling vigour, often affecting establishment and early growth. Cold temperatures at the end of the season can affect crop maturity, yield and fibre quality. Delaying planting can be used to avoid some of the cold temperature effects at the start of the season; however, the long time to crop maturity limits flexibility as delayed planting increases the chance of cooler temperatures while the crop is still maturing. Using cultivars or production systems that have a shorter crop cycle can help to avoid cold temperature effects.

Table 1.1 Days after sowing to cotton crop stages based on average day-degrees from 1 October for different cotton growing regions in Australia (Source data: SILO (2006a))

Crop Stage	Emerald	Goondiwindi (Macintyre)	Narrabri (lower Namoi)	Breeza (upper Namoi)	Hillston (Lachlan)
Emergence	6	9	10	12	13
5 true leaves	27	35	38	43	44
First square	39	50	54	61	61
First flower	58	71	76	84	84
Peak Flower	91	107	113	125	123
Open boll	105	122	128	142	139
60% open bolls	138	159	167	193	187
Day Degrees 1 Oct to 31 Mar	2689	2319	2208	1953	2007

There is strong interest in the Australian cotton industry to develop systems that reduce the time from planting to harvest without a yield penalty. In addition to avoiding cool temperatures, reducing the time to maturity may also lead to savings in irrigation water and spray costs. The main drawback of earlier crop maturity in current production systems is that there is generally a penalty in lint yield associated with gaining earlier maturity (Niles and Feaster 1984; Bange and Milroy 2004; Stiller *et al.* 2004). Recent research in Australia has found that there is an average lint yield loss of 34 kg ha^{-1} per day for each day that maturity is brought forward, equating to an approximately yield reduction of up to 1.0 bales ha^{-1} per week (Bange and Milroy 2004; Stiller *et al.* 2004).

Ultra-narrow row (UNR) cotton has been proposed as a system for earlier maturity without substantial yield loss (Low and McMahon 1973). The term ultra-narrow row (UNR) refers to cotton production systems with rows spaced less than 40 cm apart, compared with systems with conventionally spaced rows, which are usually 1 m apart. The rationale for ultra-narrow row production being earlier maturing and higher yielding than conventionally spaced cotton is relatively simple and based on general plant competition theory (Yoda *et al.* 1963). Plants grown in a high population should be smaller and set fewer fruit (bolls) per plant (Lewis 1971). Yield is maintained as a higher plant population compensates for smaller plants having fewer bolls per plant (Lewis 1971). A smaller plant, with fewer bolls should mature earlier than a larger, more vegetative plant as the bolls are set earlier on the lower parts of the plant (Lewis 1971). The closely spaced cotton closes the canopy faster than conventionally spaced cotton, leading to greater light interception earlier in the season (Kerby *et al.* 1996b; Kreig 1996).

These expectations, however, have not been consistently met in trials comparing UNR and conventionally spaced cotton in Australia and the United States of America (Constable 1977b; Constable 1977a; Jost and Cothren 2000b; Jost and Cothren 2000a; Jost and Cothren 2001). The inconsistent maturity and yield differences in research trials could be due to excessive competition for light and other resources in high population UNR cotton production (Baker 1976). Experiments comparing UNR and conventionally spaced production systems in Australia by Constable (1977a, b) found that higher early leaf area did not favour rapid crop setting, and the UNR systems had higher rates of fruit shedding than the conventionally spaced crop. Constable (1977a, b) suggested that competition for photoassimilates between fruit and vegetative growth both within and between plants in the UNR production system prevented the expected increase in boll growth associated with an increase in LAI.

Changes in production practices in Australia with better water and insect management and high-yielding cultivars (both transgenic and non-transgenic) mean these relationships need to be examined in current production systems to better understand what influences yield and maturity in UNR crops grown in high-input production systems.

1.2 UNR in high-input production systems

Most of the knowledge of the growth, development and yield of UNR systems has come from research conducted in the United States of America (Saleem and Buxton 1976; Kerby *et al.* 1990a; Kerby *et al.* 1990b; Heitholt *et al.* 1992; Williford 1992; Gwathmey 1996; Kerby *et al.* 1996b; Kreig 1996; Weir 1996; Cawley *et al.* 1998; Gerik *et al.* 1998; Prince *et al.* 1998; Cawley *et al.* 1999; Gerik *et al.* 1999; Prince *et al.* 1999; Gerik *et al.* 2000; Jost and Cothren 2000b; Weaver-Missick *et al.* 2000; Witten and Cothren 2000; Jost and Cothren 2001; McConnell *et al.* 2001; Vories *et al.* 2001; Bader and Culpepper 2002; McFarland *et al.* 2002; Nichols and Snipes 2002; Nichols *et al.* 2003). Many of these studies focussed on the agronomy and management of UNR cotton rather than detailed physiological studies. The agronomy and management of UNR cotton production in the USA is different to Australian production systems. UNR systems in the USA were initially conceived as low-input production systems on marginal soils where plant growth is limited. The aim was to improve yields by increasing plant density to compensate for the smaller plant size (Kerby *et al.* 1996b). In Australia UNR is being used commercially in high yielding, high-input systems in areas with a shorter growing season. There is limited understanding of cotton's growth response to different row configurations in the Australian production environment. Research into UNR in Australian cotton production systems has been limited with few studies into the detailed physiological responses of cotton to high plant population UNR production systems (Low and McMahon 1973; Hearn and Hughes 1975; Constable 1977b; Constable 1977a)

1.3 Objectives

The primary aim of this study was to evaluate the potential of ultra-narrow row (UNR) cotton as a production system in Australia that provides for earlier maturing crops while maintaining or improving yields using high inputs of nutrients, water and insecticides. Additionally, this study aimed to improve the understanding of, and quantify differences in, the growth and development of cotton in both conventionally spaced and UNR production.

Specific objectives were to:

i. Determine if there were any differences in yield and maturity between UNR and conventionally spaced cotton crops over a range of environments and years (Chapter 3).

ii. Establish the key aspects of growth and development that underlie differences in yield and maturity responses between high-input UNR systems and conventionally spaced cotton crops by:

   a) comparing differences in biomass accumulation and partitioning (Chapter 4);

   b) comparing dynamics of fruit development and retention (Chapter 5); and

   c) investigating the relationship between carbon supply and fruit production (Chapter 6).

iii. Highlight opportunities for optimising yield and maturity of UNR cotton compared to conventionally spaced cotton in high-input systems (Chapter 7).

The first step in understanding the performance of cotton in UNR production systems under high-input conditions in Australia is to determine whether UNR actually offers any maturity or yield benefits under such conditions. Previous studies have not compared these systems without confounding effects from differences in agronomic management used for each of the two systems. In order to further our understanding of how maturity and yield is influenced under UNR production systems a set of controlled experiments were conducted to compare rigorously the growth and development of cotton grown in UNR and conventionally spacings. Quantifying any differences in the way the crop grows in ultra-narrow rows and any influences on maturity and yield will help to better tailor cropping systems to desired outcomes, whether that is yield or crop maturity. A 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 systems.

Ultimately though, optimising UNR cropping systems may mean developing complete agronomic packages that differ from current practice. Only with a thorough understanding of how UNR crops grow, can agronomic practice be manipulated (e.g. cultivars, water, growth regulators and nutrition); to take better advantage of any benefits that UNR may confer.

In this thesis, firstly the physiological determinants of yield and maturity in conventionally spaced cotton and research into UNR production systems will be reviewed (Chapter 2). Secondly, the experimental program conducted to test the hypotheses on yield, maturity and fibre quality in UNR compared to conventionally spaced cotton under high input conditions will be reported. Analyses of data from six experiments conducted over three seasons and in three Australian cotton growing regions are considered (Chapter 3). Thirdly, a detailed growth analysis of conventionally spaced and UNR cotton from three of these experiments will be presented to explore the physiological determinants underpinning any differences (Chapter 4). Next, the dynamics of fruit development and retention of conventionally spaced and UNR production systems and how this relates to crop maturity will be discussed (Chapter 5). Next, fruit development and the relationship between carbon supply/demand of plants growing in the two systems will be examined (Chapter 6). The final chapter of this thesis will then discuss the potential to optimise yield and maturity in high input UNR cotton production systems based on the new knowledge gained from this study.

Chapter 2

Literature review

2.1 Introduction

There is strong interest in the Australian cotton industry to develop production systems that reduce the time from planting to harvest. Reducing the time to maturity means the crop can be grown in a shorter cycle with potential savings in irrigation water and insecticide spray costs. The need for a cotton crop that can be grown in a shorter period has become increasingly important as production in Australia expands into areas with shorter growing seasons. Having a shorter crop cycle allows cool temperatures to be avoided at the beginning and end of the season. Such temperatures can affect crop establishment and later yield and fibre quality. The main drawback in gaining earlier maturity is that there is generally a yield trade off (Niles and Feaster 1984; Bange and Milroy 2004; Stiller *et al.* 2004). Recent studies in Australia, have found that there is an average lint yield loss of 34 kg ha^{-1} per day for each day that maturity is brought forward, equating to a reduction of up to 1.0 bales ha^{-1} per week (Bange and Milroy 2004; Stiller *et al.* 2004). This is because a shorter crop cycle generally means a shorter fruiting period (earlier cut-out), resulting in fewer fruit per plant, and hence lower yield (Bange and Milroy 2004).

Interest in ultra-narrow row (UNR) cotton, a production system with rows spaced less than 40 cm apart, is increasing, as this system has shown potential for earlier maturity without substantial yield loss. Plants grown in a high population UNR production system should be smaller and set fewer fruit (bolls) per plant and hence have a shorter fruiting period (Lewis 1971). Yield is maintained as a higher plant population compensates for smaller plants having fewer bolls per plant (Lewis 1971). However, this potential has not been consistently achieved in experiments comparing UNR cotton with conventionally spaced cotton (1m row spacing) in Australia and the United States (Constable 1977b; Constable 1977a; Jost and Cothren 2000b; Jost and Cothren 2000a; Jost and Cothren 2001).

As little is known about what drives yield and maturity in UNR cotton production systems, it is important to understand the basic determinants of yield and maturity in conventionally spaced systems, to determine how these responses may differ in UNR spacings. This review will firstly consider the growth and development of the cotton plant and the physiological processes impacting yield and maturity. Research into how growth and development are influenced by light, water and nutrition in conventionally spaced production is then reviewed; finally, what is currently known about the determinants of yield and maturity in high plant populations, particularly UNR production systems, are reviewed.

2.2 Cotton growth and development

Cotton is a perennial plant that is grown as an annual crop. Because cotton is indeterminate, it fruits over time; therefore, both morphological development and biomass accumulation are important contributors to yield and maturity (Mason 1922; Hearn 1969a; Hearn 1969b; Baker *et al.* 1972; Hearn 1972c; Guinn 1974; Guinn 1982; Guinn and Mauney 1984b; Hearn and Constable 1984; Guinn 1985b). There have been a number of extensive reviews on the growth and development of cotton that focus on physiological (Eaton 1955; Brown and Osborn 1958; Benedict 1984; Hearn and Constable 1984; Cothren 1999) and morphological development (Brown and Osborn 1958; Mauney 1986; Oosterhuis 1990; Oosterhuis and Jernstedt 1999).

Early growth of cotton is highly dependent on temperature. Cotton needs a minimum soil-temperature of 14°C to germinate and successfully establish (Constable and Shaw 1988). The relationship between cotton development and temperature has been used to estimate crop development in Australia. Results from early experiments investigating cotton growth in response to temperature (Constable 1976) were used to derive a day-degree function to estimate cotton development in Australia (Constable and Shaw 1988). This function used 12°C as a base air-temperature for day-degrees and is currently used in the Australian cotton industry to monitor and estimate crop development. The day-degree function is:

$$\text{Day-Degrees} = [(T_{max} - 12) + (T_{min} - 12)] / 2$$

where T_{max} is the maximum temperature and T_{min} is the minimum temperature. If T_{min} is less than 12°C, it is set at 12. For a crop to reach a certain stage of development, it requires a certain number of accumulated day-degrees (Table 2.1).

Table 2.1 Cumulative day-degrees required to reach key cotton crop stages (from Constable and Shaw (1988))

Crop Stage	Cumulative Day-degrees
Emergence	80
5 true leaves	330
First Square	505
First Flower	777
Peak Flower	1302
Open Boll	1527
60% Open Bolls	2050

The cotton plant can produce a new node every 2 to 4 days depending on temperature (Hearn and Constable 1984). Initially leaves arise from the main-stem (main-stem leaves) and are important for supplying assimilates for vegetative growth (Constable and Rawson 1980a; Oosterhuis and Urwiler 1988). The lower nodes usually remain vegetative and may later develop into a vegetative branch (monopodium), which is a replica of the main-stem (Hearn and Constable 1984). The vegetative growth of the plant is important in determining the rate of fruit (boll) production and number of bolls produced, as all sympodial branches arise from the axils of main-stem leaves (Mauney 1986).

Reproductive growth in cotton begins with the formation of flower buds (squares) and the expansion of the subtending sympodial leaf (Mauney 1986). In the major cotton growing regions in Australia this is usually about four to six weeks after sowing. Anthesis follows approximately two weeks later, with boll development beginning after fertilisation (Oosterhuis and Jernstedt 1999). All bolls on the plant are produced on sympodial branches. While most of the yield comes from primary sympodial branches, 3-9% of lint yield can be from bolls produced on secondary sympodial branches, which arise from monopodial branches not the main-stem (Jenkins *et al.* 1990a) (Figure 2.1).

Unlike many other plants grown as annual crops, vegetative growth stage and fruiting stages in cotton overlap, with the flower bud (square) initiating at the same time as the subtending leaf, which is the primary source of assimilates to the fruit (Benedict and Kohel 1975). This leaf expands before anthesis and senesces before boll maturity. This asynchronomy of leaf and boll development accentuates the importance of the plant producing enough assimilates to support developing bolls (Landivar 1987). Hearn (1976) describes assimilate production (based on leaf area) and demand (boll growth) in the plant as being out of phase: in the cotton plant, carbohydrate production from leaves is declining as demand for assimilates from growing bolls is increasing (Constable and Rawson 1980a; Constable 1981). It is important that the plant has sufficient assimilates to support the demand from the bolls (Hearn 1976; Hearn 1994). If assimilate demand by the bolls exceeds the supply, the plant may shed bolls that cannot be supported, which may lead to delayed maturity and yield loss (Mason 1922; Hearn 1972c; Hearn 1976; Hearn 1994; Guinn 1998).

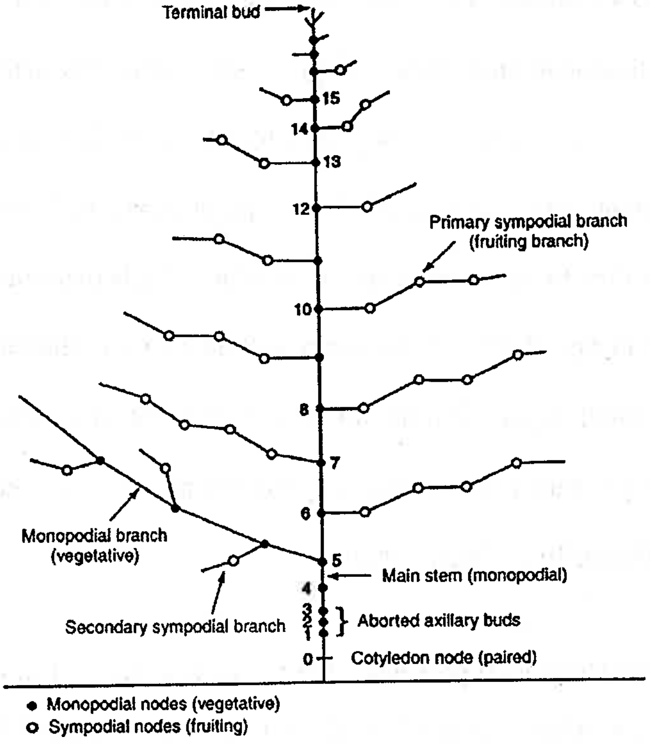

Figure 2.1 Representation of the cotton plant showing main-stem, monopodial and sympodial branch development (From Oosterhuis (1990)).

The next section will review research into carbohydrate supply and demand and how it influences yield and maturity in conventionally spaced cotton.

2.3 Determinants of yield and maturity

Yield of cotton is ultimately determined by the number of bolls per unit area and the amount of lint per boll (Hearn and Constable 1984). Similar yields can be reached via differing durations and development rates depending on the pattern of boll production and the capacity of the plant to retain those bolls. The number of fruiting sites and the rate of production of fruiting sites are primarily dependent on vegetative growth and the ratios and position of monopodial to sympodial branches (Mauney 1986). Unlike determinate crops these processes are not driven solely by temperature and day length, but also by the balance of supply and demand of resources to the developing bolls and growing points (Bange and Milroy 2000). The time for a crop to mature is variable and dependent on a range of factors, but is ultimately determined by the time to boll initiation (node of first fruiting branch and time to first square), the rate of boll production (main-stem and sympodial node production), boll growth (retention and boll size), the time to cessation of initiation of new bolls (cut-out) and the time from anthesis to maturity of those bolls retained (boll period) (Harland 1929; Richmond and Radwan 1962; Ray and Richmond 1966; Munro 1971). Essentially, lint yield and the time to crop maturity is determined by the balance of assimilates available for boll production (Mason 1922; Hearn 1994).

2.3.1 The Nutritional Hypothesis – fruit shedding and cut-out

As cotton is an indeterminate plant, there is no morphological limit to its size and development. As long as conditions are favourable, vegetative production of new main-stem and fruiting branches could continue indefinitely (Hearn and Constable 1984). However, the plant stops producing new leaves and fruiting sites (this stage is termed 'cut-out') due to the demand on the resource supply by developing bolls, leaving no surplus for the initiation of new fruiting sites (Mason 1922; Hearn 1994). This hypothesis was termed the nutritional hypothesis for fruit shedding (Eaton 1955) and many later studies investigating fruit dynamics in cotton support this hypothesis (Baker *et al.* 1972; Hearn 1972c; Ehlig and LeMert 1973; Mauney *et al.* 1978).

Eaton and Ergle (1954) found that not all shedding could be easily related to a supply-demand deficit and proposed an alternative hypothesis that the hormonal balance between auxin produced by the plant and auxin inhibitors produced by the developing bolls controlled shedding in cotton.

More recent work has integrated these hypotheses, with most authors agreeing that resource supply is the primary regulator of boll shedding and cut-out, with hormones playing an important role in this process (Guinn 1974; Mauney *et al.* 1978; Constable 1981; Bhatt *et al.* 1982; Guinn 1985b; Guinn 1985a; Guinn 1998). Hearn (1976) proposed that both the declining rate of boll production and the decreasing rate of boll growth were dependent on resource supply. Extensive work by Guinn *et al.* (Guinn 1974; Guinn and Mauney 1984a; Guinn and Mauney 1984b; Guinn 1985b; Guinn 1985a; Guinn and Brummett 1989; Guinn and Brummett 1993) led them to conclude that when demand for assimilates exceeded supply, boll growth and boll retention decreased leading to cut-out. Although, as Guinn (1998) points out, "the nutritional and hormonal theories of boll shedding are not contradictory or mutually exclusive; they just represent different parts of the overall control system". Consistent with this, investigations into the effects of radiation, nitrogen nutrition and water on shedding and cut-out indicate that these affect fruiting dynamics predominantly through their impact on assimilate supply (Guinn 1974; Turner *et al.* 1986).

2.3.2 The Nutritional Hypothesis – boll distribution and development

The way in which the cotton plant allocates assimilates is also important in determining boll distribution and development on a plant. In addition to resource supply regulating vegetative growth and the production of new fruiting sites, boll distribution and development is primarily dependent on the distribution and availability of adequate assimilates to support developing bolls (Jenkins *et al.* 1990b; Jenkins *et al.* 1990a; Constable 1991; Hearn 1994). If the demand by the bolls exceeds the supply, bolls that cannot be supported are abscised (Mason 1922; Hearn 1972c; Hearn 1994; Guinn 1998).

Although the abscission of squares and bolls is considered a natural process as the plant produces more fruit than it can support until maturity, whether an individual square or boll is retained is dependent on a number of physiological factors more complex than whole plant assimilate supply and demand (McMichael *et al.* 1973; Mutsaers 1976; Constable 1981; Kerby and Buxton 1981; Oosterhuis and Wullschleger 1988; Jenkins *et al.* 1990b; Jenkins *et al.* 1990a; Constable 1991; Zhu and Oosterhuis 1992; Hearn 1994; Cothren 1999; Oosterhuis and Jernstedt 1999). Many researchers have found that the timing of fruit initiation, position on the plant and the age of the fruit affects whether or not it will be abscised when there are insufficient assimilates to support all the fruit on the plant (Jenkins *et al.* 1990b; Jenkins *et al.* 1990a; Constable 1991; Hearn 1994).

Bolls on different fruiting sites have been found to have differing ability to compete for assimilates (Constable 1981; Wullschleger and Oosterhuis 1990b). Those bolls initiated later in plant development have lower retention rates because of limitations in assimilates to support their growth (Constable 1981). Bolls on the first position of a fruiting branch are stronger sinks of assimilates from nearby main-stem leaves compared to bolls further out on the branch (Constable 1981; Wullschleger and Oosterhuis 1990b). Assimilate supply is higher when the first position fruit develop because the main-stem leaf and subtending leaf have less shading from leaves higher in the canopy (Constable and Rawson 1980a). Second and third position fruit are less competitive for assimilates and develop later when leaves higher in the plant can shade the supporting leaves (Constable 1981; Kerby and Buxton 1981; Wullschleger and Oosterhuis 1990b; Cothren 1999).

Jenkins *et al.* (1990a, b) found that main-stem node position was related to fruit retention. They found that greater than 70% of the total yield was on the central part of the plant (in this case – main-stem nodes 9 to 14) (Jenkins *et al.* 1990a). The development of fruit on these nodes coincided with maximum leaf area in the canopy (Oosterhuis and Wullschleger 1988). These nodes also have the largest leaves and are the highest suppliers of assimilates to fruit, as leaves produced on lower nodes export a greater proportion of assimilates to root development (Constable 1981).

Young squares and bolls are more likely to be shed than older squares and bolls, which is thought to be a hormonal response due to local assimilate shortage (Mutsaers 1976; Constable 1981; Cothren 1999). Constable (1981) found that a reduction in whole plant assimilate supply (through shading) caused higher shedding of young squares from the lower nodes than the rest of the plant. Even when total plant supply is adequate, abscission can occur if local assimilate supply is reduced. Constable (1981) showed that transport of assimilate through the developing peduncle was inadequate to support young squares if local assimilate production was reduced. Large squares, flowers and bolls older than 10 days are less likely to be shed. In the case of older squares and flowers this is most likely because up to 50% of their assimilate requirements can be produced from the bracts of the flower bud, so they are less reliant on assimilates from nearby leaves (Constable 1981) (Figure 2.2). As bolls develop, cell wall thickening helps prevent abscission. McMichael *et al.* (1973) found that young bolls (< 14 days old) are also the most sensitive to water stress. This may also be due to inadequate vascular transport to the young boll. Young bolls can produce only 8% of their assimilate requirements (Constable 1981) and initially the demand of young bolls is quite high, but becomes less as the boll matures (Mutsaers 1976; Constable 1981) (Figure 2.2).

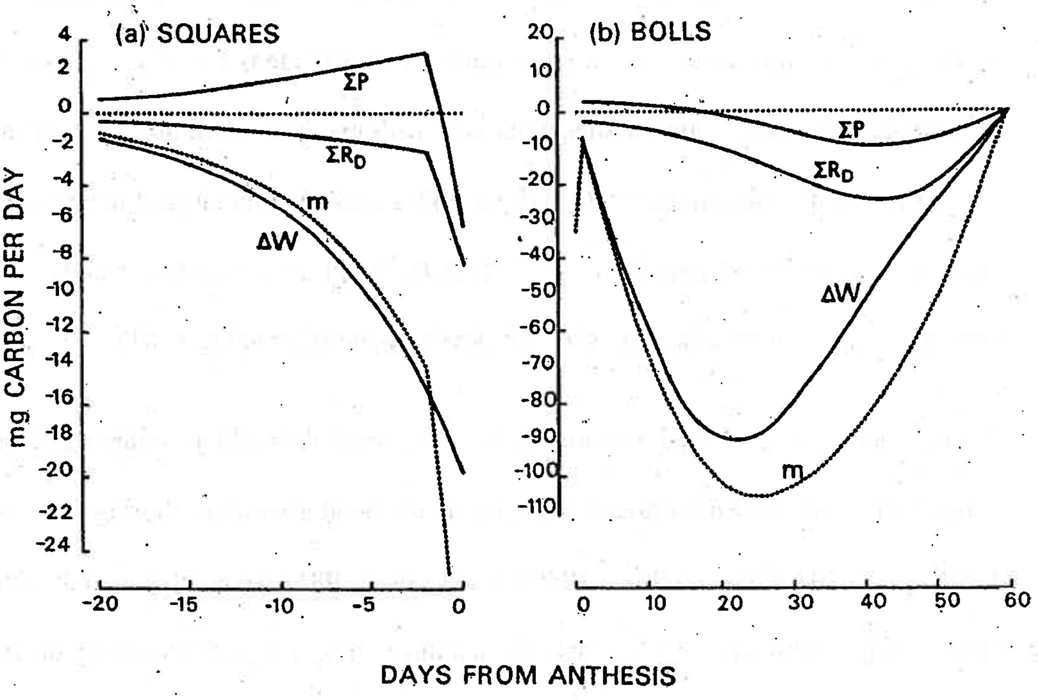

Figure 2.2 Calculated daily dark respiration ($\sum R_D$), net CO_2 exchange during the day ($\sum P$), growth (ΔW) and the resulting import (m) for (a) squares and (b) bolls. Negative values denote respiration, growth requirement or import to the fruit. (From Constable (1981)).

Even if the fruit is not abscised, boll size can be significantly reduced if assimilate supply to the developing boll is below optimum. Changes in boll size are closely correlated to those processes already discussed affecting fruit retention (Jenkins *et al.* 1990b; Jenkins *et al.* 1990a). The patterns of boll size distribution on the plant are dependent on sink strength and assimilate supply. The largest bolls are generally first position fruit in the middle section of the plant as these are the positions that often have the greatest assimilate supply (Jenkins *et al.* 1990b; Jenkins *et al.* 1990a).

2.4 Factors affecting assimilate supply

Factors affecting assimilate supply or causing direct damage to the fruit can also lead to abscission. Temperature and the amount of light available to the leaves are key factors influencing assimilate production and hence fruit retention and development (Mason 1922; Eaton and Ergle 1954; Guinn 1974; Guinn 1982). Along with light stress, water stress is one of the key reasons for delayed growth and early shedding of fruit. Adequate nitrogen is also critical for assimilate production and hence fruit retention and boll development (Hearn 1975a; Hearn 1975b; Longstreth and Nobel 1980; Jackson and Gerik 1990; Gerik *et al.* 1994). If retention is low, cut-out and hence maturity can be delayed, and yield may be reduced (Harland 1929; Munro 1971). Slowed or reduced boll development can also lead to delays in maturity and yield loss.

2.4.1 Radiation

A major determinant of crop growth and yield is radiation interception (Monteith 1977). Production of assimilates by the leaves is the primary determinant of yield. Adequate carbohydrate production by the leaves is essential to support both vegetative and reproductive growth. While the pattern of light penetration and light interception by the canopy is important in most crops, it is particularly important in cotton because the earliest fruit are produced on lower branches of the plant in the bottom half of the canopy (Constable 1986). Cotton leaves can acclimate to different radiation levels within the crop (Cothren 1999). Smith and Longstreth (1994) found that a leaf grown under good light conditions is able to assimilate 3.5 times more CO_2 than a leaf grown under low light condition. Although cotton leaves are diaheliotropic to ensure maximum exposure of the leaf surface to the sun (Lang 1973; Ehleringer and Hammond 1987), canopy structure is also important to maximise light interception and assimilate production.

The ability of the crop to intercept radiation is largely determined by leaf area (Hay and Walker 1989). Leaf area index (LAI) is a commonly used measure to estimate crop leaf area (Hay and Walker 1989). LAI values greater than 3 have been reported to intercept the maximum amount of radiation and maximise crop growth rate (Ashley *et al.* 1965; Hearn 1969b; Hearn 1972b; Constable and Gleeson 1977). LAI levels in irrigated production can reach values up to 5 (Ashley *et al.* 1965; Basinski *et al.* 1975; Constable and Gleeson 1977; Heitholt 1994). Heitholt (1994) reported the optimum LAI for cotton was between 4 and 5 where 90% of incident radiation is usually intercepted. Higher levels of LAI do not necessarily increase yields (Ashley *et al.* 1965; Basinski *et al.* 1975). Constable and Gleeson (1977) found that a high LAI was not needed for maximum boll growth and that low light conditions caused by shading could lead to reduced retention of lower bolls. As the crop grows and new leaves higher in the canopy shade older leaves, lower radiation levels in the lower part of the canopy reduce the level of assimilates available from subtending leaves, bracts and nearby leaves needed to support boll growth (Constable and Rawson 1980b; Constable and Rawson 1982; Cothren 1999). Experiments by Brown (1971) found that shedding of squares and young bolls was increased by closer row spacing and total fruiting positions decreased with increased plant populations. The adverse effects of crowding were especially severe in the lower third of the plant canopy, where light intensity was low.

Radiation levels can be influenced by climatic conditions. Cloudy conditions during flowering and fruit development can cause significant reductions in yield and fibre quality (Pettigrew 1994; Zhao and Oosterhuis 2000). In low light conditions the carbohydrate production of the whole plant is reduced (Zhao and Oosterhuis 1998c). Studies by Zhao and Oosterhuis (1998a, b) found that photosynthesis was much lower in shaded plants compared to control plants. They also found that leaf nitrogen and chlorophyll content increased under shaded conditions as is often the case with shaded leaves in C_3 plants (Evans 1989). Reduced radiation levels reduce the capacity of the crop to maintain maximum photosynthesis and can lead to delayed development or fruit shedding. A number of experiments have shown increases in shedding rates in cloudy conditions (Mason 1922; Goodman 1955; Guinn 1974). Controlled experiments by Guinn (1974) showed that light is a key factor in fruit shedding because of the importance of adequate assimilate supply to support boll growth even though cloudy conditions can be accompanied by other factors that contribute to boll shedding, such as cool temperatures and rain. In these experiments, young bolls were more responsive to low-light levels, shedding almost immediately, with square abscission occurring a few days later. Returning the plants to full light conditions did not stop shedding. Guinn (1974) hypothesised that ethylene production increased in response to reduced photosynthate production. Shedding due to increased ethylene was delayed and continued even though light levels had since increased. Constable (1981) showed that shedding of young fruit can occur when light available to nearby leaves is reduced, even if total plant carbohydrate production is adequate to support those bolls. Goodman (1955) found that plants with the heaviest boll loads were most likely to shed after cloudy weather.

The efficiency of a crop to convert intercepted solar radiation into biomass is considered to be a key determinant of crop yield in many crops (Sinclair and Muchow 1999). Biomass production of the crop, and hence yield, is often linearly related to the photosynthetically active radiation (PAR) absorbed or intercepted by a crop and this relationship or radiation use efficiency (RUE) is a useful method to quantify canopy photosynthesis (Monteith 1977). The RUE of cotton is reported to be within the range of 0.71 – 2.71 g MJ^{-1} (Constable *et al.* 1990; Rosenthal and Gerik 1991; Heitholt *et al.* 1992; Sadras and Wilson 1997; Sinclair and Muchow 1999; Milroy and Bange 2003; Bange and Milroy 2004). This RUE value can be affected by pest damage (Sadras and Wilson 1997), water and nutrient availability (Constable *et al.* 1990; Milroy and Bange 2003), cultivars (Rosenthal and Gerik 1991), row spacing (Heitholt *et al.* 1992) and other factors which affect photosynthesis of the crop canopy (Sinclair and Muchow 1999; Bange and Milroy 2004).

2.4.2 Water

Water availability is a key determinant of yield and maturity in cotton due to its importance in the physiological processes of a plant. Cotton is often grown in areas where water stress due to high temperatures or limited rainfall occurs frequently (Kreig and Sung 1979). In most high yielding cotton production systems, supplemental water is required. Leaf expansion and transpiration slows at much higher soil-water status in cotton compared with most other crops, with a plant available water threshold (PAW_t) from 0.25 to 1.0 (Sadras and Milroy 1996). Along with light stress, water stress is one of the key reasons for delayed growth and early shedding of fruit (McMichael *et al.* 1973; Jordan 1979; McMichael 1979; Guinn 1982; Guinn and Mauney 1984b; Turner *et al.* 1986; Bondada *et al.* 1996).

Limitations in growth because of water stress can induce cut-out much more rapidly than caused by nutritional demand (Jordan 1979). Frequent rainfall or irrigations through the growing season can lead to rapid vegetative growth, often delaying fruit production, which can delay maturity (Hearn 1975a). A lush canopy can also increase the crop's attractiveness to pest species, leading to fruit loss (Hake and Kerby 1996). If rainfall occurs at anthesis before pollination, it can rupture pollen and the poorly pollinated flowers may be shed (Peng 1984). Timing irrigations to prevent water stress while minimising excessive vegetative growth and waterlogging can optimise growth, biomass partitioning of reproductive to vegetative structures, and minimise fruit loss to maintain yields while avoiding delays in maturity.

2.4.3 Nutrition

Optimising crop nutrition is important when aiming for high yields or early maturity. Nitrogen is essential for photosynthesis and hence very important for leaf development and boll production. Nitrogen supply along with carbohydrate supply are considered by many authors to be the limiting factors to crop growth (Sinclair and Horie 1989; Sinclair and Vadez 2002). The nutritional hypothesis of Mason (1922) and subsequent work considered carbohydrate and nitrogen supply as the critical resources needed by developing bolls, and it was the availability of these two factors that controlled fruit shedding and cut-out (Eaton 1955; Hearn 1981; Landivar 1987). Leaf area in cotton is reduced under low nitrogen conditions (Basinski *et al.* 1975; Radin and Parker 1979; Radin and Eidenbock 1986; Gerik *et al.* 1994; Bondada *et al.* 1996). This reduction in leaf area and reduced photosynthesis can lead to early cut-out and decreased boll numbers (Jackson and Gerik 1990; Wullschleger and Oosterhuis 1990a). Nitrogen availability can affect fruiting patterns and maturity. Boll retention is higher at higher nitrogen application rates and maturity can be delayed due to greater vegetative growth (Weir *et al.* 1996). While reducing nitrogen can lead to earlier maturity and cut-out, it can also reduce yield (Hearn 1975a; Hearn 1975b; Leffler 1979; Hearn 1981; Bondada *et al.* 1996). High nitrogen application rates can delay crop maturity due to high early season vegetative growth, delayed boll set, and regrowth of the plant at the end of the season (Basinski *et al.* 1975; Hearn 1975a; Leffler 1979; Constable *et al.* 1992; McConnell *et al.* 1993; Bondada *et al.* 1996; Rochester *et al.* 2001). In Australia, Rochester *et al.* (2001) found that for each 50 kg N ha^{-1} of nitrogen fertiliser that is applied, maturity is delayed by two days. Good nutrition management with monitoring to identify problems and timely nutrient applications to correct deficiencies can help optimise yield and maturity.

2.5 Plant populations and ultra-narrow row cotton

The focus of this study is to determine whether yield and maturity of cotton can be manipulated through different plant populations by altering inter-row plant spacing. The optimum plant population for any crop is the population that maximises yield while optimising resource use (Willey and Heath 1969). By changing the spacing between plants, competition for light, water and nutrients is altered, which can change fruit number and retention per plant and the size of the plant (Bednarz *et al.* 2000). Changing row spacing and plant population has been used to increase yield in many other crops both determinate (Flenet *et al.* 1996; Andrade *et al.* 2002; Ozer 2003), and indeterminate crops (Taylor 1980; Putman *et al.* 1992; Board and Harville 1993; Noffsinger and van Santen 1995; Andrade *et al.* 2002). Due to the influence of environmental conditions on plant growth and development, specific row spacing and population recommendations for crops vary due to regional and management differences in the areas of study.

2.5.1 Intra-row population

The indeterminate habit of the cotton plant allows it to compensate its fruiting patterns in response to plant populations allowing it to be grown successfully at a wide range of populations depending on soil, climate and cultivar (Silvertooth *et al.* 1999). Numerous studies have investigated optimum plant populations for cotton in conventionally spaced systems (1 m row spacing); some with conflicting reports of the influence of intra-row spacing on yield (Bridge *et al.* 1973; Hawkins and Peacock 1973; Leigh *et al.* 1974; Koli and Morrill 1976a; Koli and Morrill 1976b; Rao and Weaver 1976; Kerby and Buxton 1978; Kostopoulos and Chlichlias 1979; Galanopoulou-Sendouka *et al.* 1980; Guinn *et al.* 1981; Burch 1988; Heitholt 1994; Jones and Wells 1997; Bednarz *et al.* 1998; Jones and Wells 1998; Bednarz *et al.* 2000; Lewis 2001)

In Australia the optimum population for 1 m row spacing was found to be around 8-12 plants per metre of row. In the 1970s, studies investigating the optimum population in different cotton growing regions in the U.S.A. found that there was a fairly small yield response across a broad range of populations (from 2 – 22 plants m^{-2}) and ideal populations were similar to those in Australia. These optimum populations were: 7-12 plants m^{-2} for Mississippi (Bridge *et al.* 1973), 8-15 plants m^{-2} in Texas and 9.5-14.5 plants m^{-2} in Georgia (Buxton *et al.* 1977). Research in the early 1980s in the San Joaquin Valley, California found that around 10 plants per metre of row had the highest yield (Kerby *et al.* 1996a) (Figure 2.3).

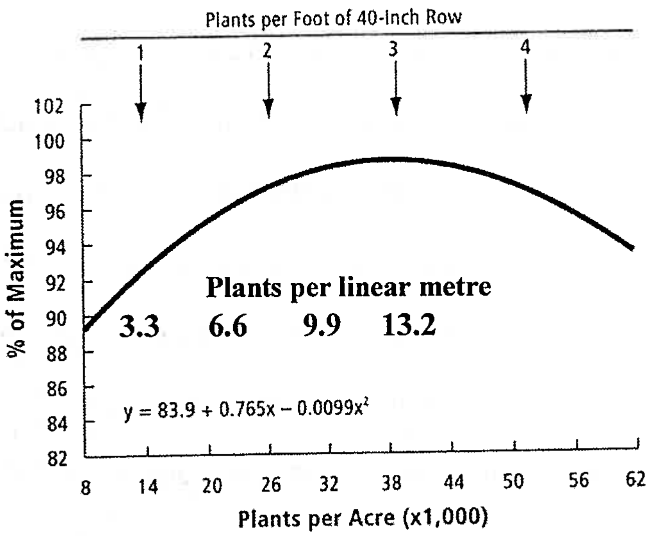

Figure 2.3 Plant population and percentage of relative yield: nine tests, 1983-1985, in the San Joaquin Valley (From Kerby *et al.* (1996a)).

This stability of yield response to plant population in cotton and most other crops, relies on uniform plant population within the crop to ensure uniform plant growth and development (Yoda *et al.* 1963; Constable 1976). Constable (1976) found that good establishment was more important than average plant population. An even plant stand allows the crop to mature evenly and yield and fibre quality is more uniform across a field. A 'gappy' or uneven plant stand can mean some plants in the crop grow very large with delayed maturity while the rest of the crop matures normally. A poor plant stand can increase the availability of resources to the plants allowing them to grow larger with more vegetative growth leading to lower harvest index. In areas with a long growing season a poor plant stand does not necessarily cause a yield penalty but can delay maturity. In areas with a shorter growing season, a delay in maturity could lead to poor yield and fibre quality.

At conventional row spacings, the yield and maturity response of cotton is not as responsive to intra-row plant spacing as to other factors (Brown 1971; Leigh *et al.*

1974; Koli and Morrill 1976a; Koli and Morrill 1976b; Rao and Weaver 1976; Fowler and Ray 1977; Galanopoulou-Sendouka *et al.* 1980; Guinn *et al.* 1981; Burch 1988; Heitholt 1994; Heitholt 1995; Hernandez-Jasso and Gutierrez-Zamoran 2000; Lewis 2001). Bednarz *et al.* (2000) found that plant population (from 2.5 – 23.0 plants m^{-2}) did not influence total yield and fruit numbers in a conventionally spaced system. Hearn (1972a) showed that the optimum plant population decreased in unfavourable conditions. When population is low and conditions permit ideal growth, plants are bigger with longer fruiting branches and more vegetative branches (Kerby *et al.* 1996a; Bednarz *et al.* 1998; Bednarz *et al.* 2000). At high populations plants, are generally smaller with short fruiting branches and few vegetative branches (Eaton 1955; Hearn 1969a; Buxton *et al.* 1977; Fowler and Ray 1977; Kerby *et al.* 1996a; Jones and Wells 1997).

2.5.2 High plant populations

Although crop yield is often not affected by high plant populations in cotton, the growth and development of individual plants within the crop can be altered. A high plant population limits the resources available to the individual plant, which may restrict growth leading to smaller plants with fewer fruit (Yoda *et al.* 1963; Hearn 1969a; Jones and Wells 1997; Bednarz *et al.* 2000). This can be compensated for by the greater number of plants per unit area compensating for or increasing yield potential (Bednarz *et al.* 2000).

A number of researchers have reported that increasing plant population in cotton led to more rapid LAI accumulation and increased dry matter production per unit area (Fowler and Ray 1977; Makki and Briggs 1979; Bednarz *et al.* 1998). They also found that increased plant population in cotton reduced individual plant dry matter production, plant height and node numbers (Fowler and Ray 1977; Makki and Briggs 1979; Bednarz *et al.* 1998). Fruit to vegetative ratio decreased with increased plant populations and retention was much lower in some studies (Fowler and Ray 1977; Bednarz *et al.* 1998). If the plant population is too high, competition for light and other resources can lead to low fruit retention and a higher number of barren plants (Constable 1977b; Galanopoulou-Sendouka *et al.* 1980; Bednarz *et al.* 2000). Fowler and Ray (1977) hypothesised that the higher LAI in the higher plant populations may have caused mutual shading of leaves and decreased net photosynthesis per plant leading to increased fruit shedding. Cotton normally intercepts 90% of light at LAI of 4 to 5, but higher LAI has been reported for high plant populations when environmental conditions led to increased vegetative growth (Heitholt 1994). Higher populations have been associated with reductions in boll size, which is often compensated for by an increase in boll number per unit area (Bridge *et al.* 1973; Hawkins and Peacock 1973; Baker 1976; Rao and Weaver 1976; Fowler and Ray 1977; Buxton *et al.* 1979; Smith *et al.* 1979; Galanopoulou-Sendouka *et al.* 1980; Jones and Wells 1997; Bednarz *et al.* 2000).

In some cases increasing plant population has reduced the time to crop maturity (Rao and Weaver 1976; Smith *et al.* 1979; Bednarz *et al.* 1998; Bednarz *et al.* 2000). However, this relationship is not always realized with other authors finding no relationship between plant population and crop maturity (Baker 1976; Kostopoulos and Chlichlias 1979). An intermediate population has been recommended for more consistent early maturity (Fowler and Ray 1977; Galanopoulou-Sendouka *et al.* 1980; Bednarz *et al.* 2000) Eaton (1955) describes the effect of high population on cotton crop maturity as having two opposite effects. The first is increased earliness, because most branches only bear first position fruit and the time between fruit development on successive fruiting branches is shorter than time to develop fruit along a fruiting branch. However, if increased plant population leads to a delay in fruit initiation and the first boll appears later and is higher up in the plant, maturity can be delayed (Eaton 1955). This increase in the node of first fruiting branch (FFB) with increased plant population has been reported by a number of authors (Buxton *et al.* 1977; Fowler and Ray 1977; Kerby *et al.* 1990b; Jones and Wells 1997), although not in all studies (Galanopoulou-Sendouka *et al.* 1980; Bednarz *et al.* 2000).

A change in fruit distribution is also common in cotton grown at higher plant populations (Jenkins *et al.* 1990a; Bednarz *et al.* 2000). The lack of second and third position fruit is commonly reported in high populations (Jenkins *et al.* 1990a; Bednarz *et al.* 2000). Bednarz *et al.* (2000) reported that at high population densities (20-23 plants m^{-2}) 94% of lint came from first position bolls, with maximum yield on node 9 from the middle part of the canopy. In contrast, at the lowest populations (2.5-4.5 plants m^{-2}) only 29% of lint came from first position bolls, with maximum yield from node seven in the lower part of the canopy (the cotyledonary node was counted as node one).

While most studies on the effect of plant population in cotton have concentrated on intra-row competition, there have been numerous studies that have investigated the effects of changing inter-row spacing to alter plant population.

2.5.3 Inter-row populations

Conventionally spaced cotton is planted in rows 1 m apart. Increasing or decreasing this row spacing can give a more equidistant spacing between individual plants for the same plant population per unit area. Fowler and Ray (1977) examined cotton growth in five equidistant spacings, where the intra- and inter-row spacing was the same.

Their results were consistent with plant population studies on 1m row spacings, with maximum yield and earliest maturity at intermediate plant populations. Hearn (1972a) in similar experiments in Uganda, found that the optimum planting density varied according to environmental conditions and pest pressure but recommended 0.45 m x 0.25 m spacing of plants (7.4 plants m^{-2}) as a suitable compromise.

Skip-row patterns of cotton planting, where one or more rows normally planted in a conventionally spaced system are left fallow, have been shown to have yield advantages in long season rain-fed cotton production systems as the cotton plant has access to a wider soil water profile (Hons and McMichael 1986; Milroy *et al.* 2004; Bange *et al.* 2005). However, in seasons with adequate rainfall, crops planted at conventional row spacings usually out-yield those with skipped rows (Bange *et al.* 2005).

Reducing the inter-row spacing with the same or higher population has long been seen as a way of optimising use of light, water and nutrients earlier in the season, with higher initial growth, light interception and smaller plants that partition more to fruit than vegetative structures (Lewis 1971). Plants are more evenly spaced when sown in narrower row spacings and the efficiency of light interception can be improved, which has been found in corn, sorghum, soybean and sunflowers (Fernandez *et al.* 1996).

Ultra-narrow Row (UNR) cotton production is an alternative production system that may have the potential for earlier crop maturity than traditional cotton production systems. In this study the term “UNR cotton” will be used to refer to cotton production systems where rows of cotton are spaced less than 40 cm apart. The next section will discuss the history and research into the potential of UNR cotton as a system to optimise yield and maturity.

2.5.4 Definition of ultra-narrow row

One of the difficulties in reviewing work on UNR cotton is the discrepancies in definition of ultra-narrow row cotton; some authors define all cotton grown in less than 1m row spacings as narrow row and assume the yield or maturity benefits are equal across all row spacings (Kerby *et al.* 1996b). Early research termed all narrower row research "narrow row" (Niles 1970; Lewis 1971; Taylor 1971; Wiese and Smith 1971; Niles 1972; Parish and Waddle 1972; Low and McMahon 1973; Onken and Sunderman 1973; Parish *et al.* 1973; Leigh *et al.* 1974; Hearn and Hughes 1975; Wanjura and Baker 1975; Saleem and Buxton 1976; Walker *et al.* 1976; Whiteley *et al.* 1976a; Whiteley *et al.* 1976b; Constable 1977b; Constable 1977a; Pustejovsky 1979). In recent years the term ultra-narrow row has been used to make distinctions between row spacings; with narrow row cotton being 75 cm row spacings and UNR those spacing less than 50 cm (Gwathmey 1996; Gerik *et al.* 1998; Gerik *et al.* 1999; Gerik *et al.* 2000) or 40 cm (Jost and Cothren 1999b; Jost and Cothren 1999a; Vories *et al.* 2001; Nichols and Snipes 2002; Nichols *et al.* 2003). Some authors have a narrow definition of what are UNR spacings confining it to rows spaced less than 25 cm apart (Atwell 1996; Burmester 1996; Jost *et al.* 1998; Bednarz *et al.* 1999; Mayfield 1999; Marois *et al.* 2004; Boquet 2005). UNR and narrow row should not be treated the same. Although the basic rationale for the benefits of narrower rows holds true, UNR cotton often has an increase in plant population as well as a decrease in row spacing, though not necessarily an increase in intra-row population (Jost *et al.* 1998). Narrow row cotton, with fewer rows per unit area than UNR, does not necessarily have an accompanying increase in plant population. UNR cotton plant densities are usually >24.7 plants m^2 (Snipes 1996; Jost *et al.* 1998; Jost and Cothren 2000b; Jost and Cothren 2001). Narrow row cotton can also be spindle picked with a modified spindle picker. This review will focus on research into row spacings less than 40 cm apart. The term UNR will be used to refer to cotton crops with row spacings less than 40 cm apart and the term narrow row to cotton crops with row spacings between 40 and 99 cm (Nichols *et al.* 2003; Nichols *et al.* 2004). When referring to different row spacings in other crops the term "narrower rows" will be used as what is considered narrow or wide rows varies considerably between crops, where possible the row spacings being discussed will be specified.

2.5.5 History of ultra-narrow row cotton

Despite limited popular support due to resistance to changing traditional row spacings, research into narrower row spacings for cotton production dates from the 1940s in the U.S.A. (Prince *et al.* 1998). UNR cotton has long been seen as a potential alternative system for Australian cotton, especially in regions with shorter growing seasons (Low and McMahon 1973).

UNR cotton was initially conceived in the U.S.A. as a low-input production system to improve yield or profit margin to compensate for small plant size on marginal soils (Kerby *et al.* 1996b). The main emphasis was on reduced harvesting and input costs without substantial yield loss (Kerby *et al.* 1996b). Kerby *et al.* (1996b) reports that research into narrower row spacings in the early 1970s found that the potential of narrower row spacings was greatest in areas where growth was limited while keeping similar populations to conventional spacings. He also emphasised that research had shown that good management was more important for narrower row spacings, maturity was not necessarily earlier and fibre quality was generally reduced because of the need to stripper harvest compared to spindle picking.

This focus has shifted to high-input UNR cotton production systems to maintain yields while reducing the time to crop maturity. UNR production systems that increase plant population while providing a more equidistant spacing around the plants than conventionally spaced rows, have long been seen as ideal systems for optimising yield and maturity (Low and McMahon 1973). In Australia, cotton is high yielding, usually irrigated and has high input management (fertilizer and insect control) (Hearn and Fitt 1992). High input, high plant population UNR cotton contrasts with earlier work into narrower row spacings which aimed to maximise yield without significant delays in maturity by using narrower row spacings to give more equidistant spacings between plants at the same plant populations as conventionally spaced cotton (Kerby *et al.* 1996b).

Another suggested benefit of UNR production is that a shorter fruiting period with fruit of similar age could also give more consistent fibre quality (Jost and Cothren 2001). This idea is supported by research into higher plant populations (13.5 – 372 plants m^{-2}) in rapeseed found that higher plant population led to earlier, more synchronous maturity and more uniform seed maturity due to differences in pod distribution with most pods at the top of the canopy in the high plant population (Leach *et al.* 1999). This synchronicity of crop maturity in response to high plant populations has also been reported for indeterminate crops such as lupins (Noffsinger and van Santen 1995).

Conceptually, in high-input systems, high plant populations using UNR spacings reduces the time to crop maturity, as fewer bolls are needed for maturation per plant to achieve yields comparable to conventionally spaced cotton crops (Lewis 1971). In practice, this earliness has been difficult to achieve consistently in UNR trials in both

Australia and the U.S.A., irrespective of the level of crop inputs (Constable 1977b; Constable 1977a; Jost and Cothren 2000b; Jost and Cothren 2000a; Jost and Cothren 2001).

2.5.6 Potential for earliness in ultra-narrow row cotton

The rationale behind ultra-narrow row production being earlier and higher yielding is relatively simple:

- plants in a high population would be smaller and set fewer bolls per plant;
- yield is maintained as a higher number of plants m^{-2} compensates for smaller plants having fewer bolls per plant;
- a smaller plant would have fewer fruiting branches and should cut-out earlier;

therefore, the fruit on the smaller plants should be set and mature over a shorter period than a larger more vegetative plant (Lewis 1971). The focus of most studies into row spacing responses in other crops has been on the potential for yield increases rather than reducing time to crop maturity (Costa *et al.* 1980; Taylor 1980; Leach and Beech 1988; Graterol *et al.* 1996; Andrade *et al.* 2002). This may be because cotton, a perennial species grown as an annual row crop, has a longer crop cycle compared to other annual indeterminate crops.

This rationale for earlier maturity while maintaining yield under ultra-narrow rows in cotton relies on a few assumptions: that cotton's response to higher populations is similar to other crops where intraspecific competition leads to smaller individual plant size; that the competition for resources between plants is not so high that it leads to plant mortality or fruit loss (Yoda *et al.* 1963); and that crop growth rate is maintained but cut-out is earlier.

2.5.7 Yield and maturity in ultra-narrow row cotton

Reports of higher yield and/or earlier maturity in cotton are inconsistent. Differences in yield and maturity in experiments comparing cotton grown in UNR spacings and conventionally spacings are not always consistent across years (Constable 1977b; Constable 1977a; Cawley *et al.* 1998; Cawley *et al.* 1999; Jost and Cothren 2001; Vories *et al.* 2001; Bader and Culpepper 2002; Nichols *et al.* 2004). The higher yield potential of UNR cotton production has been reported by a number of researchers (Hawkins and Peacock 1973; Koli and Morrill 1976b; Heitholt *et al.* 1992; Atwell *et al.* 1996; Gwathmey 1996; Gerik *et al.* 1998; Gwathmey 1998; Cawley *et al.* 1999; Gerik *et al.* 1999; Gwathmey *et al.* 1999; Gerik *et al.* 2000; Vories *et al.* 2001; Bader and Culpepper 2002; Nichols *et al.* 2003; Nichols *et al.* 2004). Some reports are of substantial yield increases, with a 15-113% increase in yield in UNR cotton in one set of experiments (Gerik *et al.* 1999). Vories *et al.* (2001) found that seed cotton yield was higher in UNR treatments two of the three years of their study; however, the UNR cotton had lower gin turnout, averaging 4% lower over the three years, and hence lint yield was only higher in one year. Yield increases in UNR cotton compared to conventionally spaced cotton are often associated with higher boll numbers per unit area in UNR crops (Heitholt *et al.* 1992; Gerik *et al.* 1998; Bednarz *et al.* 1999; Gerik *et al.* 1999; Gerik *et al.* 2000).

Some researchers report no yield benefit in UNR cotton (Baker 1976; Bednarz *et al.* 1999; Clawson and Cothren 2002; Marois *et al.* 2004; Nichols *et al.* 2004). In some studies yield has been lower in the UNR cotton than conventionally spaced cotton (Boquet 2005). Hearn and Hughes (1975) in their study of narrow row spacings from 0.2 m – 1.0 m in northern Australia found an increase in yield as row spacing decreased. However, they pointed out that agronomic management of the conventionally spaced system was tailored for the narrower rows and this may have reduced the yield potential of the conventionally spaced system. They suggested that there was no yield advantage in UNR spacings over the current conventionally spaced system when managed differently as the same variety grown adjacent to the experiment as a conventionally spaced system had higher yields than the narrower rows in their experiment.

Maturity benefits in UNR systems compared to conventionally spaced systems have also been inconsistent with some reports of significantly earlier maturity (Hearn and Hughes 1975; Young *et al.* 1980; Cawley *et al.* 1998; Cawley *et al.* 1999) and others of little difference in maturity between row spacings (Hawkins and Peacock 1973; Gerik *et al.* 1998). Where earlier maturity in UNR cotton has been reported these differences ranges from as little 3 days earlier (Clawson and Cothren 2002) to one or two weeks earlier maturity (Cawley *et al.* 1998; Cawley *et al.* 1999; Jost and Cothren 2001). Research into UNR spacing in Australia gained earlier maturity in one season of a three year study (Constable 1977b). Jost (2000) found UNR spacings were up to 10 days earlier than conventionally spaced rows in one year and not different in the other year of his two-year study.

As most of the research into cotton's response to UNR production systems has been in low-input systems, it may be that competition for resources has led to the inconsistent yield and maturity responses. Cotton grown under high-input UNR production systems will have increased resource availability and this may reduce the variability in yield and maturity between years and across different environments.

2.5.8 Physiology of UNR cotton

While many researchers report yield and maturity differences between UNR and conventionally spaced cotton crops, few report on other differences between row spacings (e.g. fertilizer and water use) and even fewer investigate differences in growth and development of the plant to indicate the reasons for the differences reported. Despite the inconsistency in maturity or yield benefits of UNR spacings many of the changes reported about the growth of the plant have been fairly consistent. Many of the characteristics reported for UNR plants are analogous with those reported for high plant populations in conventionally spaced cotton and other indeterminate crops. Generally, because of the high number of plants and greater LAI accumulation, canopy closure is earlier in UNR cotton than conventionally spaced cotton (Kreig 1996; Cawley *et al.* 1999; Jost and Cothren 2000b). An increase in light interception has been reported for narrower row spacings in cotton (Peng and Krieg 1991; Heitholt *et al.* 1992), corn (Andrade *et al.* 2002; Widdicombe and Thelen 2002), chickpea (Leach and Beech 1988), sorghum (Flenet *et al.* 1996), and soybean (Boquet *et al.* 1982; Hiebsch *et al.* 1990; Board and Harville 1992; Savoy *et al.* 1992).

Changes in plant architecture in response to UNR spacings in cotton can be different to the responses to narrower spacings reported in other crops. For example, in narrower row spacings soybean plants can be taller {Hiebsch, 1990 #992} and have increased pod numbers per plant (Herbert and Litchfield 1984), whereas in cotton UNR plants tend to be shorter, with fewer nodes and fewer vegetative branches than conventionally spaced cotton (Jost and Cothren 2001; Vories *et al.* 2001; Marois *et al.* 2004; Nichols *et al.* 2004). These differences in height and node number can vary from season to season (Jost and Cothren 2001; Marois *et al.* 2004). UNR plants have a higher number of mature bolls on first positions, with few second or third positions fruiting sites being initiated (Cawley *et al.* 1998). There are fewer mature bolls per plant, but the higher number of plants per unit area compensate for this so that total boll number is usually the same or slightly higher (Witten and Cothren 2000). In situations where there have been yield increases, these are often related to increased boll numbers but not any increase in boll retention (Heitholt *et al.* 1992).

The architecture of a UNR plant fits the theoretical understanding of how a plant in a high population UNR cotton system should grow; however, earlier maturity is not consistently found. A number of researchers have studied the reasons why UNR cotton crop does not consistently mature earlier or yield higher than a conventionally spaced crop, even though the characteristics fit the concept of earlier maturity proposed by Lewis (1971).

Increase in yield ultimately occurs through an increase in the number of bolls per unit area or the amount of lint per boll (Hearn and Constable 1984). Increased biomass production or partitioning to reproductive growth even with the same dry matter production can lead to higher yields (Charles-Edwards *et al.* 1986). Few studies have examined biomass production and partitioning in UNR cotton. Constable (1975) found that biomass accumulation was more rapid in UNR compared to conventionally spaced cotton, but final crop biomass was the same. If crop biomass is the same then partitioning to fruit must be higher to gain higher yields. Increased partitioning to reproductive growth in UNR cotton has been reported (Best *et al.* 1997; Jost 2000). Best *et al.* (1997) found that as row spacing decreased biomass production increased and partitioning to fruit increased. However, these changes in biomass production and partitioning are not always consistent year to year. Jost (2000) found increased biomass production in high population UNR treatments in both years of his study, but increased partitioning in only the first year. LAI exceeded 8 in the UNR crop that year, whereas in the previous year there were no differences in LAI between row spacings. Jost (2000) concluded that soil type differences between the experiments led to higher vegetative growth in UNR in the second year of his study. Jost (2000) found that crop maturity was earlier and yield was higher in UNR cotton crop in the year that less vegetative growth occurred. He concluded that UNR crops perform better when grown on a soil type (in this case heavy clay) and under conditions that do not lead to high vegetative growth. They are also more likely to mature earlier than conventionally spaced cotton, and these factors were more important than final plant population, which was the other treatment in his study.

Smaller boll size is commonly reported in UNR studies (Baker 1976; Constable 1977a; Bednarz *et al.* 1999; Witten and Cothren 2000; Boquet 2005) although not always (Hawkins and Peacock 1973; Gerik *et al.* 1999). High rates of shedding in UNR cotton production have often been reported in studies comparing UNR fruit production to conventionally spaced cotton (Constable 1975; Baker 1976). Smaller or fewer bolls in UNR cotton production would limit the potential yield of UNR cotton and may delay maturity. As Constable and Gleeson (1977) stated, "the success of narrow row spacing and other forms of crop manipulation aimed at rapid crop setting depends on the retention and rapid growth of early bolls". A smaller boll size or increased shedding of bolls may indicate a restriction in assimilate supply.

Increased early light interception has been thought by many researchers as the primary reason for increases in yield in narrower row spacings in many indeterminate and determinate crops (Shibles and Weber 1966; Taylor *et al.* 1982; Flenet *et al.* 1996; Andrade *et al.* 2002). Closer plant spacing means that plants do not need to be as large to achieve maximum light interception. Savoy *et al.* (1992) found that narrower rows in soybean (0.36 m spaced rows) had higher light interception, greater biomass accumulation and high radiation-use-efficiency compared to wide rows (1.02 m spaced rows).

Cotton spaced closer together can lead to earlier canopy closure compared with conventionally spaced cotton, due to increased LAI leading to greater light interception earlier in the season (Peng and Krieg 1991). This rapid canopy closure may also lead to reductions in weed competition (Forcella *et al.* 1992; Teasdale 1994; Snipes 1996) and decrease soil evaporation (Nunez and Kamprath 1969; Kreig 1996).

Constable (1975) found that higher early leaf area did not favour rapid crop setting and that control of vegetative growth might be necessary to achieve earliness. He also found a significant negative relationship between boll growth rate and LAI in UNR spaced cotton. He hypothesised that this negative relationship could have been due to shading of the lower canopy, disease (increased boll rot), inadequate insecticide penetration or simply because lower reproductive demand for assimilates due to boll shedding led to higher vegetative growth and hence, higher LAI. Baker (1976) found that UNR cotton produced more flowers per unit area than conventionally spaced cotton; however, this higher yield potential was lost through increased shedding of flowers and young bolls and the production of smaller bolls in the UNR crop. He concluded that canopy closure and competition from other plants was the cause of shedding, primarily because of reduced light penetration, although this relationship was not specifically tested in that study.

These results are in agreement with the findings from research into high populations in conventional row spacings, which showed that an increase in LAI did not necessarily result in a proportional increase in yield (Galanopoulou-Sendouka *et al.* 1980). Increases in LAI and light interception has not always led to increased yield in narrower row spacings in soybeans and has in some cases led to abortion of pods under high plant populations (Hiebsch *et al.* 1990). In contrast, Taylor (1980) and Taylor *et al.* (1982) found that LAI development and dry matter production was not different between row spacings but attributed yield increases to increased late season light interception reducing pod abortion in narrower rows. Board and Harville (1994) attribute greater yield in soybean grown in narrower row spacings to increased pod number through greater light interception and crop growth rate between first flowering and seed initiation.

While there are conflicting reports of the importance and timing of increased light interception for increased yield in narrower row spacings in soybean, higher light interception is only of benefit if it translates into increases in yield. If increased light interception leads to increases in fruit production (number or size) either through higher partitioning of dry matter production to the crop or increased dry matter production, yield will be higher. Duncan (1986) found that increased crop dry matter production was a good indicator of increased yield in narrower row spacings in soybean and that increases due to narrower row spacings tended to be in systems where dry matter production in wider rows was limited. They suggest that total dry matter production would be a more reliable criteria to judge the success of narrower rows in a region, agreeing with other authors that the benefits of narrower rows in soy bean are greatest where total dry matter production is limited in wider rows (Elgi *et al.* 1987; Board *et al.* 1990).

Marois *et al.* (2004), in a study examining canopy microclimate differences between UNR and conventionally spaced cotton, found that differences in canopy structure resulting from differences in plant height had a greater impact on microclimate (RH, VPD and temperature) than row spacing. Marois *et al.* (2004) agree with other authors who suggest that managing vegetative growth in UNR crops is critical to prevent increased shading of the lower part of the canopy. They hypothesised that early canopy closure may lead to early senescence of leaves lower in the canopy, which has been found in conventionally spaced crops (Wullschleger and Oosterhuis 1992). Once the canopy has closed, fewer new leaves are produced and plants can no longer offset leaf aging in the crop (Wells and Meredith Jr 1984; Wullschleger and Oosterhuis 1992). The average leaf age of the canopy becomes older, photosynthesis decreases and canopy senescence is earlier than in a crop where canopy closure is later (Wullschleger and Oosterhuis 1992). Elevated LAI can be detrimental if it leads to excessive shading of the lower canopy and reduces assimilate production needed to support boll development (Hake *et al.* 1996).

Few studies have focussed on the difference in the light distribution in UNR cotton crops and the relationship to poor fruit retention of cotton grown in UNR spacings. Studies of light interception in narrower row spacings in other crops (maize, soybean and sunflower) have found that the light extinction coefficient (Thornley 1976) increases with reduction in row spacing (Flenet *et al.* 1996).

Steglich *et al.* (2000) compared the light extinction coefficient of UNR crops to conventionally spaced crops and found that as row spacing decreased the light extinction coefficient increased in the UNR spaced crops and the UNR crop had higher lint yield. However, whether the higher yields were due to greater biomass production or a higher ratio of fruit to dry matter production was not reported in their study. Steglich *et al.* (2000) stated that the higher yield was due to greater light interception, primarily due to a more evenly distributed canopy in the UNR crop, which allowed a greater percentage of leaves to receive and photosynthesise incoming radiation. A higher light extinction coefficient implies changes in canopy architecture such that there is more light interception per unit area of leaf. Hence, Baker's (1976) suggestion that reduced light penetration to bottom of the canopy may be due to more effective light interception in the top part of the canopy in UNR crops is plausible.

To gain earlier maturity in UNR production systems it is imperative that most of the bolls that are set are on lower branches, as these mature first (Constable and Gleeson 1977; Kerby *et al.* 1996b). Clawson and Cothren (2002) found a higher percentage of bolls were on nodes 6-10 and a significantly lower proportion of bolls were on higher fruiting branches in UNR cotton compared to conventionally spaced cotton. Gerik *et al.* (1998) found that UNR cotton set a higher percentage of bolls on the lower branches in one year of their study but not in the other. Constable (1975) in his studies on UNR cotton found that peak LAI and boll growth rate were best aligned in time with, and hence conditions were better for, fruit set on the middle fruiting branches than on lower or higher fruiting branches. While light availability to support bolls and prevent shedding of early bolls is considered a key factor in the yield and maturity of UNR cotton, other agronomic factors may influence carbohydrate availability for biomass production and boll development in UNR cotton crops.

It is difficult to determine what influences yield and maturity responses with so few studies reporting more than just yield and maturity, and most of these studies with only a few exceptions investigating cotton's response to UNR spacings under low-input production. The response of cotton and other row crops to narrower row spacings appears to be highly variable across regions, climates and resource availability. Understanding how growth and development is altered under UNR spacings in high-input production will allow an evaluation of how important different growth determinants such as biomass accumulation, light interception and fruit retention and development influence yield and maturity in UNR cotton in Australia.

2.5.9 Agronomic considerations for UNR cotton

As with other crops, limitations in light, nutrient or water availability may be key determinants of yield and maturity in high-input UNR cotton production systems. In a high-input environment, growth of a cotton plant is usually only limited by season length (temperature and radiation). Cultivar choice and the level of inputs usually determine plant size. Increasing the plant population may increase resource demand per unit area and limit growth, fruit development or maturity. Gerik *et al.* (1999) found that a 15% to 113% increase in yield resulted from UNR systems when compared to narrow row systems. However, this increase was dependent on water availability and the length of the growing season. This is important as most Australian cotton is grown under fully irrigated conditions so yield responses may be different from many U.S.A. trials, which have been grown in rain-fed systems.

A major limitation to the wide-spread adoption of UNR cotton production is difficulty in harvesting (Curley 1982; Williford 1992; Kerby *et al.* 1996b; Weir 1996; Weaver-Missick *et al.* 2000; Vories *et al.* 2001). The spindle picker used for conventionally spaced harvesting plucks the cotton from the bracts minimising trash content of the lint. However, the brush or finger stripper that has to be used for UNR cotton also strips sticks and leaves from the plant leading to higher trash content, ginning difficulties and quality penalties (Weaver-Missick *et al.* 2000). It is important that the plant stand is even and plants are columnar for stripper harvesting to avoid branches clogging the stripper and hindering harvesting (Curley 1982; Mayfield 1999). Despite these disadvantages, using stripper harvesters is much cheaper compared to spindle pickers, and this is also listed as one of the major advantages of UNR production in areas where it is grown commercially (Mayfield 1999; Jones 2001). Differences in harvest efficiencies between UNR brush stripped cotton and conventionally spaced spindle picked cotton can sometimes negate any yield advantages (Jones 2001). However, new advances in picker technology allowing 38 cm UNR cotton to be spindle picked (John Deere 9996 PRO-12 Vari-Row System Picking Units) may allow further development of these systems without the limitations of stripper harvesting.

Plant population and stand establishment is more critical in UNR than conventionally spaced cotton, primarily because of the requirement for small, upright and columnar plants with few vegetative branches for efficient harvesting (Atwell *et al.* 1996; Allen *et al.* 1998; Vories *et al.* 2001). A high population also increases costs and may lead to high inter-plant competition. Like conventionally spaced cotton, UNR cotton does not have a large yield response to a wide range in plant population (Hawkins and Peacock 1973; Koli and Morrill 1976a; Allen *et al.* 1998; Jost and Cothren 2001). However, there are some conflicting reports of the influence of plant population on yield and maturity in UNR cotton. Delaney and Monks (2002) reported an interaction between different plant populations (198 000- 494 000 plants ha^{-1}) and planting dates on the yield of UNR cotton. They found that lower plant populations had the highest yield when sown late but these populations had the lowest yield when sown earlier. Gerik *et al.* (1998) found yield of UNR cotton increased in higher plant populations

(200 0000 plants ha^{-1}) in 1 yr of a 2 yr study. Boquet (2005) found that increasing plant population (128 000 to 385 000 plants ha^{-1}) under irrigated conditions slightly decreased yield of UNR cotton. Jost (2000) found that increasing plant population in UNR from 12.2 to 45 plants m^{-2} resulted in earlier maturity but did not affect yield. Smith *et al.* (1979) also found that higher plant populations matured earlier. In contrast, Mohamad *et al.* (1982) found that increased plant population in UNR cotton led to later maturity.

Another concern about UNR cotton production is that fibre quality may be inferior to that of conventionally spaced cotton production systems. In addition to higher trash content through the use of stripper harvesters, earlier canopy closure and early fruit set, along with reduced boll size, could negatively affect fibre quality in UNR systems (Marois *et al.* 2004). The effect of UNR on HVI fibre quality is inconsistent with several studies reporting no effect on fibre quality (Hawkins and Peacock 1973; Heitholt *et al.* 1993; Gwathmey 1996; Gerik *et al.* 1998; Gerik *et al.* 2000; Jost and Cothren 2001; Nichols *et al.* 2004; Boquet 2005). Jost (2000) reported that fibre length was shorter in UNR cotton compared to conventionally spaced cotton. Some researchers have reported lower micronaire in UNR production systems (Hearn and Hughes 1975; Vories *et al.* 2001). This may be due to stripper harvesting of immature cotton that would not be picked by a spindle picker (Vories *et al.* 2001).

Cultivar choice may be important in the success of UNR production systems. Although cotton has high phenotypic plasticity some authors suggest that varieties with different morphological traits (such as determinate varieties that are compact with short fruiting branches and few or no vegetative branches) or cultivars less prone to high vegetative growth may perform better in UNR production systems (Fowler and Ray 1977; Heitholt and Stewart 1999). Many studies of UNR cotton in the past were conducted with older cultivars that had lower partitioning to reproductive biomass than current cultivars (Jost and Cothren 2001). The use of high retention, earlier maturing cultivars may help avoid the problems found in UNR production systems associated with high vegetative growth. Kerby *et al.* (1980) found in a study of narrow-row cotton comparing normal, okra and super-okra cultivars that normal leaf cotton favoured vegetative growth over reproductive growth due to the high LAI of the canopy when grown in narrow-row (0.51 m spacing) production systems. The availability of transgenic herbicide-resistant cotton varieties has reduced weed control problems in UNR cotton production that were encountered in the past, and has been a major influence of renewed interest in UNR cotton production (Atwell *et al.* 1996; Gerik *et al.* 1999; Hayes *et al.* 1999; Bader and Culpepper 2002).

Fertilizer demand, particularly nitrogen, in UNR cotton production could be a critical determinant of yield and maturity. Most studies into agronomic management of UNR cotton systems have found that nitrogen requirements are similar to that of conventionally spaced cotton (Weaver-Missick *et al.* 2000; Clawson and Cothren 2002; Marois *et al.* 2004; Boquet 2005). Some studies have, found however, that the nitrogen requirements of UNR have been higher (Rinehardt *et al.* 2004) or lower (McConnell *et al.* 2001) than conventionally spaced cotton. The high plant populations in UNR production systems may require higher rates of nitrogen than normal plant populations (Rinehardt *et al.* 2004; Boquet 2005). Conversely, UNR production systems require less growth per plant to give similar yields so nitrogen uptake per unit area may be similar to conventionally spaced cotton production (McConnell *et al.* 2001). High nitrogen rates may lead to higher vegetative growth in UNR production systems reducing yield and delaying maturity (Koli and Morrill

1976b) as is often the case in conventionally spaced cotton production (Bell *et al.* 2003). A dense canopy in UNR production systems through increased nitrogen application may also lead to boll rot, poor insecticide penetration and low light conditions in the canopy (Marois *et al.* 2004).

The use of growth regulators is considered important to the success of a UNR crop due to the need to prevent high vegetative growth (Atwell *et al.* 1996; Gwathmey 1996; Nichols *et al.* 2003; Wright *et al.* 2004). Early and frequent use of mepiquat chloride is often considered as part of a UNR systems package (Wright *et al.* 2004). However, the effects of mepiquat chloride on UNR have rarely been compared with the same treatments on conventionally spaced cotton. Kerby (1998) recommended that early applications of mepiquat chloride in UNR cotton are more important than application rate. Ensuring efficient harvesting through controlling vegetative growth is one of the major reasons for mepiquat chloride applications in UNR cotton (Wright *et al.* 2004). It is also important to limit crop height when harvesting with a stripper harvester used for UNR cotton (Atwell *et al.* 1996; Allen *et al.* 1998; Vories *et al.* 2001). The effect of mepiquat chloride on yield in UNR cotton is inconsistent. Prince *et al.* (1998) found that application rate of mepiquat chloride did not affect lint yield in UNR or conventional row spacing, but the study was hampered by severe water stress, and so was not experiencing increased vegetative growth. Jones (2001) in a two-year study of 19 cm, 38 cm and 76 cm row spacings reported no response in lint yield to four different mepiquat chloride application rates. Nichols *et al.* (2003) reported a yield increase in UNR to mepiquat chloride application in only one year of their three-year study. Gwathmey (1996 and 1998) reported a 7% increase in lint yield in UNR treatments with mepiquat chloride applications compared to untreated treatments. Allen *et al.* (1998) found that mepiquat chloride reduced yields in UNR.

Inconsistent responses to mepiquat chloride are also found in conventional row spacings, due to environmental variables, including temperature, moisture and nutrient status (Briggs 1980; Kerby 1985; Kerby *et al.* 1986; Cathey and Meredith Jr 1988). Wright *et al.* (2004) recommended monitoring and applying mepiquat chloride in UNR systems following the guidelines developed for conventionally spaced systems. In Australia, the most commonly used indicator of when growth is excessive and the application of mepiquat chloride may be needed is when average internode length exceeds 5.5 cm.

2.6 Summary

Most early experiments investigating UNR crop growth, maturity and yield were in low-input systems. These early studies and some more recent ones have suggested that the potential of UNR production systems is greatest in conditions where growth is limited and high vegetative growth is unlikely to occur (Constable 1977a; Kerby *et al.* 1996b; Jost and Cothren 2001). Many of the studies comparing UNR and conventionally spaced cotton report only on yield and maturity. Of those that report the differences in more detail many have focussed on the agronomy and management of UNR cotton rather than detailed physiological studies. The agronomy and management of UNR cotton production in the USA is different to Australian production systems. UNR systems in the USA were initially conceived as low-input production systems on marginal soils where plant growth is limited. The aim was to improve yields by increasing plant density to compensate for the smaller plant size (Kerby *et al.* 1996b). In Australia, UNR cotton is grown commercially in high yielding, high-input systems on fertile soils in areas with a shorter growing season.

In the last 30 years, nutrition, pesticide and weed control have been improved and hence crop growth and yield have improved dramatically. Most recent studies in the U.S.A. into UNR production systems have been under rain-fed conditions with little additional irrigation (Vories *et al.* 2001). These systems are very different to the current high yielding, high-input systems in Australia where 83% of cotton is grown under fully irrigated conditions (Dowling 2002). There is limited understanding of cotton's growth response to different row configurations in the Australian production environment. Research into UNR in Australian cotton production systems has been limited with few studies into the detailed physiological responses of cotton to high plant population UNR production systems (Low and McMahon 1973; Hearn and Hughes 1975; Constable 1977b; Constable 1977a). The first step in understanding the performance and growth of cotton in UNR production systems in high-input systems in Australia is to determine whether UNR actually offers any maturity or yield benefits under high-input production systems.

The yield and maturity of cotton is either directly or indirectly affected by all the factors influencing assimilate supply presented in this review. As lint yield and the time to crop maturity in cotton are essentially determined by the balance of assimilates available for boll production, understanding the differences in biomass production and fruit development and retention in high-input UNR crops compared to conventionally spaced cotton is critical to unravelling the key determinants of yield and maturity in high-input UNR cotton.

There is little information on the physiology of UNR cotton in terms of biomass production and fruit retention and how this relates to yield and maturity in high yielding, high-input systems, particularly in Australia. In order to tailor management to optimise any system it is important to understand the differences in the way the crop responds to its environment. Measuring the growth of UNR cotton in comparison with conventionally spaced cotton in these environments is the first step in gaining this understanding.

Chapter 3

Yield and maturity of UNR cotton

3.1 Introduction

UNR, a production system with rows spaced less than 40 cm apart, has shown potential for earlier maturity in low-input systems in the U.S.A. Conceptually, the high density planting of UNR reduces the time to crop maturity, as fewer bolls per plant need to be produced to achieve comparable yields to conventionally spaced cotton crops (Lewis 1971). In practice, this earliness has been difficult to achieve consistently in UNR trials in Australia and the U.S. (Constable 1977a; Kerby *et al.* 1990a). Cotton in Australia is primarily grown in high-yielding, high-input productions systems compared with the lower input production systems in the U.S.A. To date, most trials in Australia comparing UNR to conventionally spaced systems include different management strategies for each system thus confounding comparisons and failing to clearly identify any possible advantages of UNR.

The first step in understanding the performance and growth of UNR cotton production systems using high-inputs in Australia is to determine if they confer maturity or yield benefits. The studies reported in this chapter compare crop maturity, lint yield, yield components, fibre quality, final fruit distribution and plant architecture characteristics for UNR and conventionally spaced cotton grown using high inputs of nutrient, water and insecticides.

The results of six experiments conducted over three years and across a range of environments are presented. One experiment included an additional row spacing treatment (twin row) to UNR and conventionally spaced cotton. Two experiments also compared the effect of the growth regulator - mepiquat chloride (Pix®) on UNR and