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IRRIGATED COTTON IN THE TROPICAL DRY (WINTER) SEASON

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School of Agriculture and Food Sciences

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Statement of Contributions to Jointly Authored Works Contained in the Thesis

These publications are included in the thesis as Chapters 3, 4, 5 and 6 respectively:

1. Yeates, S.J., Constable, G.A., McCumstie, T., (2010). Irrigated cotton in the tropical dry season. I. Yield, its components and crop development. *Field Crops Res.* 116, 278-289
2. Yeates, S.J., Constable, G.A., McCumstie, T., (2010). Irrigated cotton in the tropical dry season. II. Biomass accumulation, partitioning and RUE. *Field Crops Res.* 116, 290-299.
3. Yeates, S.J., Constable, G.A., McCumstie, T., (2010). Irrigated cotton in the tropical dry season. III. Predicting the impact of temperature and cultivar on fibre quality. *Field Crops Res.* 116, 300-307.

Constable (thesis co supervisor) contributed to experimental design, measurements and reviewing of drafts (5%), McCumstie (technical officer) provided input into the layout of the experiments i.e. for irrigation management and spraying of defoliants to prevent movement between the sowing dates (2%). Yeates was responsible for the remainder of the work.

4. Yeates S.J, Kahl M., Dougall A.J., (2011). The impact of variable cold minimum temperatures on cotton flower retention, boll growth and yield recovery. Submitted to *Journal of Cotton Science* in January 2011.

Kahl and Dougall contributed to setting the glasshouse up for uniformity of temperature, timing of movement of plants inside and out and the irrigation system (10%). Yeates was responsible for the remainder of the work.

Statement of Contributions by Others to the Thesis as a Whole

Tony McCumstie CSIRO provided technical expertise and input into the layout of the field experiments, Stewart Addison, Geoff Strickland and their staff from Agriculture WA provided entomological assistance, Sally Philips, Natalie Nicolson, Diana Owens and farm staff from the Frank Wise Institute provided technical assistance, Warren Muller of CSIRO-MIS and Mark Hearden of NT Department of Resources provided statistical assistance and Kellie Cooper of CSIRO for HVI analysis, the NT Department of Resources for the provision of the glasshouse at Katherine Research Station and the assistance of Mike Kahl and Andrew Dougall in data collection and setting up the glasshouse .

Statement of Parts of the Thesis Submitted to Qualify for the Award of Another Degree

None.

Published Works by the Author Incorporated into the Thesis

These publications are included in the thesis as Chapters 3, 4, 5 and 6 respectively in their entirety except for parts of their Introductions which are included in Chapter 1 of this thesis. To avoid duplication, where appropriate the introductions of these chapters are referred to in the review of literature.

Yeates, S.J., Constable, G.A., McCumstie, T., (2010). Irrigated cotton in the tropical dry season. I. Yield, its components and crop development. *Field Crops Res.* 116, 278-289

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Additional Published Works by the Author Relevant to the Thesis but not Forming Part of it

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Abstract

The reintroduction of cotton to the Australian semi arid tropics (SAT) was prevented by insect pests that are dominant during the wet (summer) season and a perception that the crop could only be grown in the wet season. Growing cotton during the dry (winter) season could avoid these pests provided an integrated pest management system was adopted. However the photothermal pattern of the dry season is the reverse of the wet season and that of spring sown cotton in temperate latitudes. Cold night temperatures are possible mid season and high temperatures are likely early and late in the season. Solar radiation is 20% less than at temperate latitudes mid season and could also limit crop growth. It was not known what yield or fibre quality was possible or whether the crop could be reliably sown and picked within the confines of the dry season.

Over three seasons two Gossypium hirsutum *(upland) Bt transgenic cultivars and one* Gossypium barbadense *cultivar were sown from March to June in field experiments at the Ord River (15.5^{o}S) in Western Australia. A pot experiment was conducted at Katherine, Northern Territory (14.5^{o}S) where biotic stresses were removed and over two seasons: ambient and ambient plus 5 to 6 ^{o}C night thermal conditions were imposed from 1 wk prior to first flower to 2 wk after last effective flower. Day temperatures were the same. Average ambient minimum temperature for the treatment period was 2 to 4 ^{o}C less than the Ord River at the same growth stage. The OZCOT cotton simulation model was validated then applied to simulate gross margin, yield and quality, with enhancements to predict fibre length and colour grade developed in this thesis, at the Ord River using 53 years of historic climatic records for sowing dates from March 1st to May 25th.*

Experimental results at the Ord found for the upland cultivars, the highest lint yields of 1900 to 2300 kg/ha were for March and April sowings and were at the high end of Australian and international benchmarks. The lint yield of the Gossypium barbadense *cultivar was highest at a March sowing, at least 87% of the upland cultivars, which is comparable with temperate climates. For the March and April sowings both the lower temperatures and radiation during early boll growth reduced the crop growth rate during this phase compared with cotton grown at temperate latitudes. However, assimilate supply was adequate because boll demand was also lower due to early flowers having slower boll development, lower retention and smaller bolls. Increasing late season temperature and radiation permitted yield compensation via an extended flowering period and a greater contribution to yield from later pollinated flowers on the top and outside of the plant. The number of temperatures $>35^oC$ and or $<11^oC$ affected time to squaring, requiring modification of development models derived in temperate climates. Radiation use efficiency (RUE) was similar to* Gossypium hirsutum *grown at temperate latitudes. The RUE measured for the* Gossypium

barbadense *cultivar was the first reported for this species. The linear decline of RUE with average temperature up to first flower has not been reported previously in cotton and explains some of variation in RUE measured here and elsewhere. Due to cool temperatures during fibre development fibre length and strength at March and April sowings were low to marginal compared with market preference values. The cultivar differences observed here suggest wider screening may identify upland cultivars with suitable fibre length and strength in these conditions. The commercial prospects for* Gossypium barbadense *are doubtful unless longer and stronger fibre types are identified.*

The pot experiment confirmed that flowers were damaged by low ambient minimum temperatures near anthesis which led to shedding or reduced boll size due to lower seed number. The latter could be due to poor pollination and competition for assimilates. Importantly this experiment demonstrated that full yield recovery from minimums $<11^{o}C$ *during flowering and boll growth is possible provided they are episodic.*

The OZCOT cotton simulation model was validated for lint yield and average time-to-maturity in response to sowing date and N fertiliser rate. Further research was required to reduce the variability of maturity predictions. There was only a 14 day sowing period from March 19th where the simulated gross margin (GM) was maximised at $2378/ha. Poor trafficability combined with the Bt resistance sowing window, reduced the number of sowing days in the optimum period. Hence to reliably sow a commercial area it was likely sowing would extend beyond April 3 and reduce median GM by 9-15% due to lower fibre quality. Future research should apply this type of analysis throughout the Australian SAT.

Cotton management in the dry season should aim to increase the flowering period, to ensure yield compensation from later flowers and to adopt practices that can improve trafficability within the optimum window e.g. minimum tillage.

Keywords

Cotton, semi-arid tropics, *Gossypium barbadense,* minimum temperature, radiation, biomass, development.

Australian and New Zealand Standard Research Classifications (ANZSRC)

TO: Applied Research, FOR: 070301 (15%), 070302 (35%), 070303 (50%), SEO: 820301

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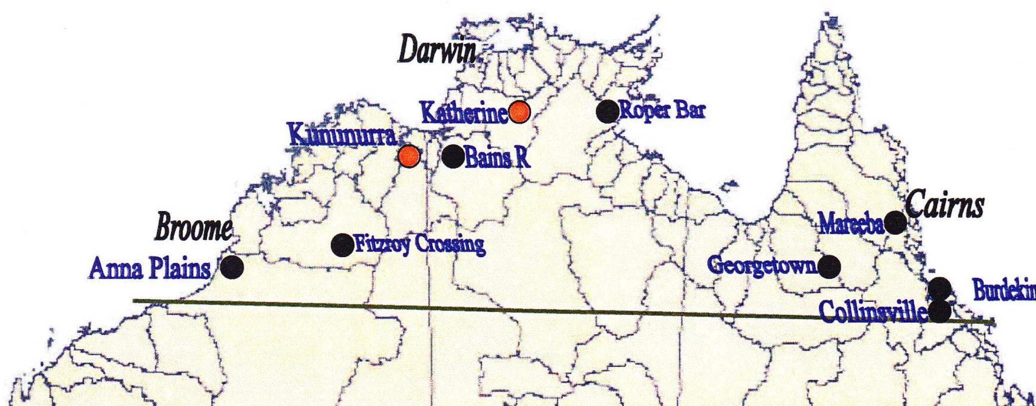
List of Abbreviations

Bn	boll number
CGR	crop of growth rate
CO	cut out
CSIRO	Commonwealth Scientific and Industrial Organisation
DAS	days after sowing
DDS_{12}	degree day sum with a base temperature 12°C
ELS	Egyptian Long Staple
F	flowering
NAWF	nodes above white flower
MP	monopodia fruit
MP+	fruit from monopodia + P4 + adventitious
ORIA	Ord River Irrigation Area
P1	1st fruiting position on a sympodial branch
P2	2nd fruiting position on a sympodial branch
P3	3rd fruiting position on a sympodial branch
P4	4th fruiting position on a sympodial branch
RI	radiation intercepted
RUE	radiation use efficiency
RMSD	root mean square deviation
SAT	semi arid tropics
Sc	seed cotton
Sn	seed number
Tav	average daily temperature
TO	gin turnout
WT	weighted temperature
WTmn	weighted minimum temperature

CHAPTER 1: Introduction and Justification for the Research

Improvements in regional infrastructure, opportunities to expand trade in nearby Asia, and reduced access to irrigation water in existing irrigated production regions of Australia has stimulated renewed interest in exploring the potential of irrigated cropping in tropical Australia north of 21°S (Map 1.1). Between 1990 and 2000 there had been considerable increase in the value and area planted to irrigated crops in the region, with the greatest increases (100 to 360%) occurring in the western half (Yeates et al. 2002a). The region is vast, approximately 30% of the Australian continent, and largely unutilised for cropping of any species. The climate for most of the region is defined as semi-arid tropics (SAT) and contains about 66 drainage basins or river catchments; these account for around 60% of Australia's surface water runoff, with significant ground water and arable soils (NLWRA 2001).



Map 1.1: Northern Australia, where expansion of irrigated cotton is being considered. Kununurra in the Ord River Irrigation Area and Katherine in the Daly Basin marked in orange were sites for the research reported here.

In the Australian SAT, broad acre mechanised farming over the wet (summer) season has always suffered operational challenges due to the rainfall pattern and soil limitations (Yeates et al. 1996). In response to these operational challenges and other factors such as market niches the production of many annual crop species has moved from the wet season to fully irrigated during the dry (winter) season (Bauer 1977; Done et al. 1985; Scholefield and Blackburn 1985; Mayers et al. 1991a; Chapman et al. 1996). Dry season production also alleviates many other constraints to cotton production in the wet season, such as water logging (Thomson and Basinski 1962) and flower abortion due to rain (Burke et al. 2002).

While cotton has been evaluated previously in many regions of the Australian SAT (Yeates 2001) other than some test-farming in the Ord River Irrigation Area (ORIA) and Burdekin Irrigation Area there is currently no commercial scale cotton production. The only significant commercial production of cotton in the region occurred at the ORIA between 1963 and 1974. Cotton was grown during the wet season (November to April) with irrigation supplementing rainfall to finish the crop early in the dry season (April to June) (Hearn 1975). Despite yields similar to south-eastern Australia during the same period, cotton production became uneconomic due to poor fibre quality and resistance of *Helicoverpa armigera* to insecticides, which resulted in excessive pesticide usage. (Hearn 1975).

The collapse of the ORIA cotton industry in the 1970's constitutes the most notable entomological catastrophe recorded in Australia and its legacy has hampered subsequent agricultural development in the region. Consequently it was paramount to identify the key factors which led to the failure of the pest management system so that errors are not repeated and strategies developed to overcome predictable problems for future development.

The reintroduction of cotton to the Australian SAT is being assessed via a multidisciplinary study that evaluates a novel production system designed to avoid the pest management problems of the previous cotton industry. The new system involves dry season cropping to avoid peak numbers of the key pests *Helicoverpa armigera, Helicoverpa punctigera, Spodoptera litura, Pectinophora gossypiella* and *Anomis spp*., which characterise the wet season, and incorporates Integrated Pest Management and Bt transgenic genotypes (Strickland et al. 1998). A comparison of the proposed system with the previous wet season system is shown in Table 1.1. Sowing of cotton crops from March 1st is desirable in the ORIA and much of the Australian SAT as they flower during the cooler months of May to August avoiding key insect pests (Strickland et al. 1998 & 2003). Once the first field is sown in a valley all cotton must be sown within five weeks of that date to minimise the number of generations of *Helicoverpa armigeria* exposed to Bt proteins (Monsanto and Cotton Australia 2010). Pest management research to date demonstrates effective insect management was achieved by adopting this system, requiring only 3.5 insecticide sprays per crop (Strickland et al. 1998; Annells and Strickland 2003) compared with 40 for the 1970's industry (Hearn 1975).

Table 1.1. Key elements of a novel cotton production system for the ORIA contrasted with the previously unsuccessful system of the 1970s (adapted from Strickland *et al* 1998).

1970s INDUSTRY	NEW INDUSTRY
Wet season planting window that was long – November to February.	Dry season (winter) cropping, with a narrow planting window (5 weeks) in March – April.
Flowering from wet season (February) to early dry season (May).	Flowering in low pest months of May to August.
Conventional cultivars	Bt transgenic cultivars
Broad spectrum insecticides	IPM systems
No pesticide resistance management	Pre-emptive Bt resistance management

The key agronomic change in this proposed production system is the requirement for a five week planting window that can commence on March 1st. Hence it is pertinent to ask why sowing after February was not practiced previously in the ORIA? Firstly, there was a perception that cotton growth and development during the coldest months of May-August would be poor, delaying boll set until temperatures increased and pushing harvest into the wet season. Results and recommendations on sowing date were contradictory (Toms 1963; Stern 1965; Thomson 1965; Hearn 1975) prompting the conclusion 'the possibility of March sowings warrants further investigation' (Thomson 1965). Secondly, larger modern pickers combined with all weather storage of seed cotton are now available and reduce the possibility of a long harvest and ginning season and UV light damage to fibre that occurred in the 1970's (Hearn 1975). Thirdly, prior to 1972, water storage capacity was insufficient to irrigate large areas of a fully irrigated dry season crop but the irrigation system capacity is now expanded.

Growing cotton in the dry season creates new challenges for crop growth and the timing of farming operations. A possible growing season in the ORIA of sowing in April, when trafficability is least affected by wet season rain, then picking in October is the reverse of temperate Australia in terms of temperature and daylength where cotton is usually sown in October and picked in April. Figure 1.1 compares the dry season in the ORIA (Kununurra, 15°S) with temperate summer cotton at Narrabri, NSW (30°S), for monthly rainfall, maximum and minimum temperature and solar radiation. Growing season rainfall is much less at Kununurra (Fig. 1.1A), although rainfall prior to sowing is

higher and may cause difficulties with land preparation and sowing operations. It will be important to pick promptly at Kununurra as rainfall increases significantly each month after October.

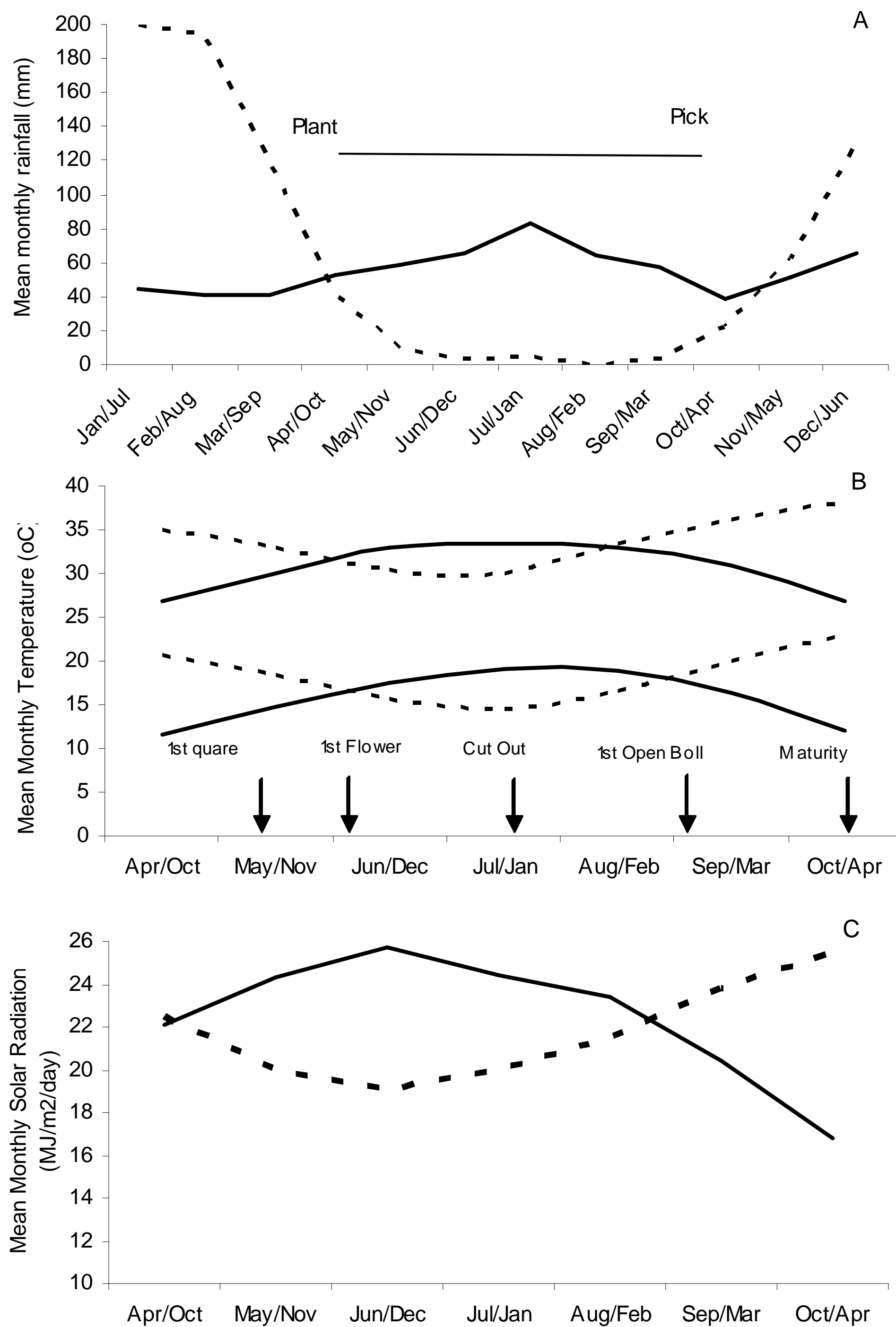


Fig. 1.1: Climatic comparison the proposed tropical dry or winter growing season in the Ord River (April to October) and the temperate summer growing season at Narrabri 30°S (October to April) A) Mean monthly rainfall; B) Average monthly temperatures, with possible development states shown for the Ord River based on degree day sums (Constable and Shaw 1988); C) mean daily radiation for each month. Where – Narrabri, --- Ord River.

Monthly temperatures (Fig. 1.1B) are higher early and late in the season, while mid season minimum temperatures are cooler averaging 14°C with extremes below 10°C (Cook and Russell 1983) which could be problematic for fibre quality and boll growth (Gipson and Ray 1969; Hearn 1994) and would delay crop development (Constable and Shaw 1988). High temperatures during September and October could also be detrimental to boll growth (Hearn 1994), but should enhance boll desiccation and improve defoliant efficacy.

Potential daily photosynthesis is lower during flowering and boll growth at Kununurra because daily radiation is about 80% of Narrabri during this phase (Fig. 1.1C) (Hearn 1994). However, it is not known whether reduced daily radiation will translate into lower yields as cooler temperatures may compensate via slower development rate and less night respiration. The effect of temperature and radiation on cotton growth and development is reviewed in more detail in Chapter 2.

There is very little literature reporting cotton grown during the dry season in the SAT worldwide. Cotton is known to be grown during the dry season in several tropical regions, such as eastern Asia, Central America, Colombia, Sudan, and Malawi. In most cases production is near the coast or large lakes where temperature extremes are minimised and these are developing countries which have lower economic yield expectations than Australia (Hearn 1995). Hence, there is a need to develop and evaluate the dry season production system outlined in Table 1.1 as a prerequisite to assessing the feasibility of reintroducing cotton into the Australian SAT. The ORIA is suitable for this evaluation as it is one of the few valleys north of 21°S developed for irrigation and expansion of the cropping area was planned for the near future (Yeates 2001; Yeates et al. 2002a).

While insect management and crop husbandry research was being conducted separately to this research (Strickland et al 1998; Annells and Strickland 2003; Yeates et al. 2002b, Moulden et al. 2006), the research reported here addresses the following important crop adaptation issues relevant to dry season cotton production:

1. Does the photothermal regime of the tropical dry season affect crop development or limit the conversion of radiation to dry matter and its partitioning.
2. What yield and quality is possible using modern genotypes and management given the potential limitations of temperature and radiation in the dry season?
3. What is the optimum sowing window for yield and quality given sowing must commence after March 1 to avoid insect pests and there must be sufficient time to pick by before the start of the wet season?

4. Can the above knowledge be integrated with other concurrent research and extrapolated to assess the impact of seasonal variability on crop yield, quality and timely farming operations on cotton production in tropical Australia?

CHAPTER 2: Review of Literature and Research Approach

The research questions identified above necessitate a ‘top down’ approach to the review of literature. Firstly, the reasons for the previous failure of wet season cotton in the ORIA plus international and Australian experience with dry season cropping are reviewed. Secondly, the likely climatic constraints of the tropical dry season compared to the temperate summer where all of Australia’s cotton is currently grown are examined. Thirdly, specific adaptation issues of cotton are reviewed, such as cotton morphology, yield components, and the effect of temperature extremes and radiation on growth, photosynthesis and development. Finally, the modelling tools that are available to extrapolate from field experiments to address operational and seasonal variability issues relevant to dry season cotton are reviewed.

2.1. The failure of previous wet season cotton industry in the ORIA

The history of the past Ord River cotton industry has been reviewed in detail (Hearn 1975; Wood and Hearn 1985). To summarise: Cotton was the first commercial crop in the ORIA and was grown between 1963 and 1974. Research that commenced in 1948 proceeded commercial production. The intention was to sow in November – December before wet season rains inhibited trafficability then pick in the early dry season (May-July). The area planted to cotton peaked at 4,795 ha in the 1966/67 season and produced 17,408 bales. Lint yields increased each year with the highest yield achieved in 1971 with 1082 kg/ha, which was equal to that from south-eastern Australia at that time. Yields were increased by extending the flowering period by delaying insect protection to February so flowering occurred in the climatically favourable months of March to May, ratooning about 30% of the crop, and increased N fertiliser usage. Due to machinery and trafficability limitations sowing extended from November-December to November-February. Hence, the calendar spraying of broad spectrum insecticides included more generations of *H. armigera* and this increased the quantity of pesticides used each season and the number of sprays applied per season doubled between 1971 and 1974 when an average of 40 insecticide applications were made per crop. By 1974 *H. armigera* resistance overshadowed all other pest problems and insect damage could not be prevented and yield declined to 660 kg/ha. In addition poor fibre quality may have caused the economic failure of the industry irrespective of the insecticide resistance. The fibre was severely weathered due to prolonged exposure to UV light and rainfall because insufficient picking capacity combined with the extension of the flowering period delayed picking until the high UV months of August to October.

It is important to recognise that the insecticide resistance of *Helicoverpa armigera* evolved from the treatment of *Spodoptera litura* (cluster caterpillar) and *Pectinophora gossypiella* (pink boll worm) which are in high numbers during the wet season (Strickland et al. 1998; Annells and Strickland 2003). In fact, during the first five years of commercial production insecticide protection was for the control of these pests and not *Helicoverpa armigera* (Hearn 1975). Resistance developed in the small populations exposed to insecticide treatment because there was no dilution of resistance genes from unsprayed populations, due to very little migration of *Helicoverpa armigera* from the surrounding native flora (Annells and Strickland 2003). Cluster caterpillar and pink boll worm numbers fall significantly during the dry season with the senescence of native flora hosts (Strickland et al. 2003). Hence, growing cotton in the dry season will avoid peak numbers of these pests and permit the implementation of an integrated pest management system that could focus on *Helicoverpa armigera.*

2.2. International experience with dry season cotton

As mentioned in the Introduction, there is very little literature reporting cotton grown during the dry season of the SAT. Cotton is known to be grown during the dry season in several tropical countries such as Thailand (Suriyapan et al. 1978; Saimaneerat et al. 1997), southern India, Burma, Luzon in the Philippines, Colombia, Lombok in Indonesia, Sinaloa State in Mexico, and Guatemala; while in Nicaragua the cotton cycle is prolonged by a double cycle that extends into the winter (Hearn 1995). In all these countries winter night temperatures are modulated by proximity to the coast and do not fall to the ORIA winter levels. The countries with climates and production most similar to the ORIA are the Sudan Gezira (14°N), the southern coast of Yemen (13°N) and northern Malawi (12°S). In the latter two, temperatures are buffered by proximity to water (Lake Malawi and the Ocean). The temperatures of Gezira are very similar to the ORIA (Hearn 1975), where the crop is sown in August (equivalent to February in the ORIA), which is 4 to 8 weeks earlier than what is proposed in ORIA. It is also important to recognise that the above are developing countries which have lower economic yield expectations than Australia (e.g. Saimaneerat et al. 1997).

2.3. Australian experience with dry season cropping

2.3.1. *Other crops*

As was stated in the Introduction there has been a trend for annual cropping in the Australian SAT to move away from wet season to irrigated dry season production for a range of crops including tobacco, sorghum, maize, vegetable crops, and rice (Chapman et al. 1996; Done et al. 1985; Scholefield and Blackburn 1985; Bauer 1977). The success of irrigated dry season tobacco in the

Atherton Tableland of north Queensland since the 1940's is of interest because it required recognition of the ecological limitations of the natural environment. Prior to the 1940's tobacco was grown rain fed during the wet season, production was unreliable due to variable water supply and radiation, while rain was an impediment to timely crop husbandry and the production of high quality leaf (Bauer 1977).

However the photothermal regime of dry season has been detrimental to soybean and peanut yields. Studies with soybean at the ORIA focused on the photoperiod and temperature adaptation of different genotypes when sown from mid - April to mid-June (Mayers et al 1991abcd). Inadequate biomass production was considered a major limitation to yield in dry season soybeans because of insufficient LAI and precocious flowering which were induced by the photothermal regime. Similarly, sowing date studies with peanut at the ORIA (Bell 1986) found yields were reduced as sowing progressed from the early wet season to the early dry season (November to March). Cool temperatures combined with falling radiation reduced canopy development and the interception of radiation at the March sowing date.

Muchow and Coates (1986) compared sorghum sown in April, May and June in the ORIA. Grain yields ranged from 7.4 t/ha to 9.5 t/ha with the lowest yield at the April sowing and the highest in May. Yield differences were attributed to partitioning and not the total amount photosynthetically active radiation intercepted, the RUE or the total biomass produced.

2.3.2. *Cotton*

Prior to 1961 sowing date studies in the ORIA for cotton only covered the wet season months of November to February. Yields of different sowing dates varied each year, the variation being associated with differences in water logging, disease incidence and rainfall pattern (Wood and Hearn 1985). Sowing in late October to early December was considered most desirable because land preparation and cultivation for weed control could occur before the high rainfall months of January and February (Thomson and Basinski 1962). The only studies to compare sowings after February were by Stern (1965) and Thomson (1965); their experiments being conducted concurrently in 1961 and 1962. These studies produced contradictory results. Stern (1965) compared 17 sowing dates from September to July on a sandy loam soil. The March, April and May sowings had most of their growth during the dry season and supported the belief that cotton was unsuited to the colder months. These sowings had lower yields due to inadequate dry weight of 500 to 600 g m^{-2} compared to 1100 to 1200 g m^{-2} for November and December sowings and a low portion of this dry weight as bolls (< 30%). However, it was acknowledged that insect damage to

the dry season sowings by *Spodoptera litura* had been very severe. Conversely the Thomson (1965) study, conducted on a heavy clay soil, compared monthly sowings from the early wet to early dry season that is November 22 to March 30. The March sowing date produced equivalent yields to the November to February sowings with 50% of this final dry weight as bolls and a canopy dry weight of 800 g m^{-2} which were higher than the Stern (1965) March sowing. It was concluded that March sowings warranted further investigation.

2.4. The growth and development of cotton

The climatic comparison with temperate Australia described Chapter 1 (Fig. 1.1), points to a need for a more detailed review of the growth and development of cotton including the effects of temperature and radiation.

Four species of cotton are cultivated worldwide with about 90% of production using genotypes of *Gossypium hirsutum* (upland cotton), 5% *Gossypium barbadense* (Pima cotton) with the remaining 5% *Gossypium herbaceum* and *Gossypium aboreum* (ICAC 2002). The former two species are grown in Australia with more than 95% *G. hirsutum* (Fitt 1994). Due to the dominance of *Gossypium hirsutum,* most published research covering the growth and development of cotton has been conducted using this species.

There have been many reviews on the growth and development of cotton, some with a physiological focus (Eaton 1955; Hearn and Constable 1984; Cothren 1999) and others covering morphological development (Mauney 1986; Oosterhuis and Jernstedt 1999). To summarise: In temperate or water limited tropical climates cotton is a perennial plant grown as an annual crop. The main-stem never terminates in an inflorescence hence the cotton plant is morphologically indeterminate. A new main-stem node can be produced every 2 to 4 days depending on temperature. Most fruit develop on sympodial branches that develop from the axis of main-stem leaves. Figure 2.1 shows the location of fruit on a cotton plant. A vegetative growth phase occurs until the first sympodia is initiated on the 4th to 9th node. The node of initiation is influenced by temperature, photoperiod and genotype, although modern genotypes grown in Australia and the USA are not considered sensitive to photoperiod. Sympodia also form on monopodial branches that grow out of the main-stem, and the initiation of these branches is increased as plant population is reduced and where there is damage to the main-stem. In cultivated cotton in 1m rows and 9.5 plants per m of row 3 to 9% of yield can occur on monopodial branches (Jenkins et al. 1990).

The first fruiting site on a sympodium is known as the first position (P1) and additional fruiting sites are produced at each node on the sympodia (P2, P3 etc) with the number of fruiting sites per sympodia rarely exceeding 4 in crops grown in 1m rows with 8 to 12 plants per m of row (Mauney 1986). Thus fruiting sites are generated vertically as the main stem produces new nodes and horizontally as each sympodia produce new nodes. Generally a P2 site will open its flower at the same time as the P1 flower 2 to 3 nodes above it, although this will vary with genotype (Hearn and Constable 1984). A leaf is produced adjacent to each fruiting site, and these leaves account for about 60% of total leaf area (Oosterhuis and Wullschleger 1988).

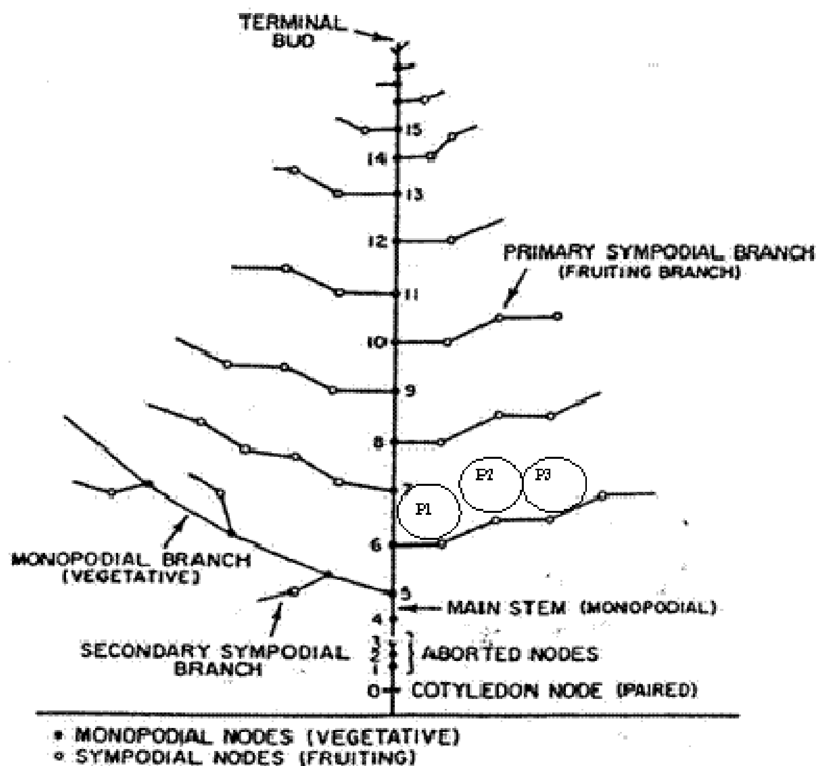


Fig. 2.1: A representation of a cotton plant showing the location of P1, P2, P3 bolls on a sympodial branch, a monopodial branch with secondary sympodial branch (vegetative branch) and the main stem with nodes numbered. Adapted from Oosterhuis (1990).

2.4.1. *The effect of temperature on cotton growth*

As was shown in Figure 1.1, the thermal regime of the tropical dry season is the reverse of the temperate growing season, being hot early in the season then cool mid season with temperatures rapidly rising late in the season. Cold night temperatures during June – August, (<10°C) can occur (Cook and Russell 1983) and, importantly, these temperatures are likely to coincide with cotton flowering. Because average monthly maximum temperatures of ≥ 35°C are observed early season (March – April) and late season (September – November), these temperatures may affect early growth and boll size (Hearn 1994).

Less is known about the impact of cold minimum temperatures during flowering and boll growth of cotton than on early growth (Mauney 1986; Cothren et al. 1999). Importantly the published research may not be completely transferable to the field grown crops in the tropical dry season because most studies have been conducted in controlled environments with fixed day or night temperature regimes (e.g. Gipson and Joham 1968; Hesketh and Low 1968; Reddy et al. 1991; Reddy et al. 1992; McDowell et al. 2007). The impact of temperature on boll growth is reviewed in more detail in Chapter 6.

Net photosynthesis in cotton is affected by temperature with the optimum between 20 and 30°C (Ludwig et al. 1965; Downton and Slaytor 1972) declining to zero between 4 and 12°C, and above 30°C there is a linear decline (Hearn and Constable 1984; Lu et al. 1997). However the response of photosynthesis to temperature is modulated by prior acclimation temperature (Downton and Slaytor 1972). Mild heat, that is a temperature increase from 30 to 40°C, reduced net photosynthesis by 30% in cotton when water was not limiting. Photosynthesis was limited by inhibition of the re-activation of the enzyme, Rubisco, as temperature increased (Salvucci and Crafts-Brander 2004).

Net photosynthesis in cotton is negatively correlated with leaf starch concentration with a 10% reduction for every 10 % increase in leaf starch concentration (Mauney et al. 1979). Photosynthesis was lower the day following cooler nights at the same day temperature. Reduced night respiration due to cooler temperatures was implicated in reducing the export of starch from leaves (Warner et al. 1995) although this response can be negated when acclimation to low temperatures occurs (Singh et al. 2005). Severe heat or cold will permanently damage photosynthetic apparatus preventing recovery (Berry and Bjorkman 1980). Controlled temperature studies on cotton found permanent injury to leaves depended on the temperature and its duration; e.g. fixed minimum temperatures from 5 to 10 ^{o}C for 2 and 20 nights respectively did not reduce photosynthetic capacity, but only a 2 ^{o}C minimum for 2 nights of 16 hours duration caused permanent damage to photosynthetic apparatus (McDowell et al. 2007). High night temperatures will reduce net photosysnthesis as maintenance respiration is doubled for each 10°C increase in temperature (Hearn and Constable 1984).

Low temperatures and humidity may inhibit pollen tube growth in the dry season if they coincide with anthesis. Kakani et al. (2004) found for 12 cotton genotypes that pollen germination was prevented between 11.1 and 20 ^{o}C and tube growth between 9.8 and 13.4 ^{o}C. Pollen tube growth was also reduced by low relative humidity (30%) (Stewart 1986).

Anthesis usually occurs in the morning (Bourke et al. 2002), but may be delayed following cool night temperatures. Root growth increases with temperature and is optimum at 30 – 35 ^{o}C (Pearson et al. 1970). Lint percentage is reduced at higher temperatures (Hesketh and Low 1968; Gipson and Ray 1976) although night temperatures of 13°C also reduced lint percentage (Gipson and Ray 1976).

2.4.2. *The effect of temperature on reproductive development*

Cotton is unlike many determinate crops because the timing of only some of the development stages is linearly related to temperature. The time to first square, first flower and the development of individual bolls (boll period) are all proportional to temperature (Hearn and Constable 1984) as is the production of main-stem nodes up to flowering (Hearn 1969). Hence all have a specific degree day requirement (Constable and Shaw 1988; Hearn 1994). However, the length of the flowering period and the time of maturity do not have a degree day requirement but are determined by the rate of fruit setting, which is influenced by the balance between nutrient supply from photosynthesis, the demand from developing fruit and the loss of fruit due to pests and other stresses (Hearn 1994). When the nutrient supply is less than the demand from developing bolls, the plant stops producing new leaves and fruiting sites, some fruit are shed, and this stage is called 'cut-out' (Hearn 1994). This is known as the nutritional hypothesis of fruit shedding (Eaton 1955). When fruit retention is reduced the demand for resources by bolls is also reduced, and the time of cut-out and maturity can be delayed (Munro 1971).

Modern cotton genotypes are not sensitive to photoperiod and the time to first square and first flower is proportional to temperature (Mauney 1986). Predicting first square and first flower is usually made using a heat sum (Hearn 1994; Viator et al. 2005). However, the minimum temperature for development or base temperature used in these calculations varies from 12°C in Australia (Constable and Shaw 1988, Hearn 1994), to 13 ^{o}C in South Africa (Dippenaar et al. 1990) while in the USA 15.5^{o}C is generally accepted (Mauney 1968), although there are regional variations (Viator et al. 2005). The methods of calculation also vary (see Constable and Shaw 1988; Birkasville and Emin 1969; Unruch and Silvertooth 1997). Presumably, the different regional prediction methods have become adopted on-farm due acceptable accuracy and simplicity of calculation.

The node of the first sympodia is lower at cooler temperatures (Hesketh et al. 1972; Mauney 1966), while high temperatures particularly at night and long day lengths can increase the node of the first

fruiting branch. These effects are greater in *Gossypium barbadense* genotypes (Hearn and Constable 1984).

It is assumed for all crop species that there is a unique upper threshold temperature for crop development (Ritchie 1991). For cotton an upper threshold is not commonly used to predict crop development, although Dippenaar et al. (1990) assumed an upper threshold of 35 ^{o}C.

Boll period, the time from anthesis to boll opening, is proportional to temperature (Mauney 1986) and has been predicted by heat sums, using similar base temperatures to squaring and first flower (Viator et al. 2005) and by integrating rate of progress (day^{-1}) as a function of mean daily temperature (Hearn 1994).

Predicting crop development and maturity is critical to assessing the likelihood that cotton with acceptable yields and quality can be grown within the confines of the tropical dry season. It is not known if current models that predict crop development are valid under this photothermal regime. Hence, the tropical dry season presents both an opportunity and challenge for predicting the reproductive development of cotton. Firstly because it will be possible in a field environment, by varying sowing date, to expose plants to a wide range of minimum and maximum temperatures without frost, and secondly, during the coolest months at the ORIA reproductive development will occur when minima are around 14°C (Cook and Russell 1983), which is near to the base temperatures derived for summer grown cotton in temperate climates (Mauney 1986, Constable 1976; Constable and Shaw 1988; Dippenaar et al. 1990; Hearn 1994; Viator et al. 2005).

2.4.3. *Solar radiation*

Photosynthesis in a cotton canopy increases in proportion to the radiation intercepted up to a maximum irradiance level (Hearn and Constable 1984). Hence radiation drives potential growth and yield. Cotton leaves acclimatise to the intensity of radiation with peak carbon fixation found to be up to 3.5 times higher per unit of leaf surface area in leaves grown in high radiation (photosynthetic flux density of 31.2 mol/m^2/d) compared with low (5.5 mol/m^2/d) radiation (Smith and Longstreth 1994). The amount of intercepted radiation is determined by leaf area development, which peaks about 3 to 5 weeks after the start of flowering when grown in temperate latitudes (Hearn and Constable 1984). Radiation interception is enhanced by the diaheliotropic leaf movement (Ehleringer and Hammond 1987), although the pattern of light interception into the canopy is also important as the earliest flowers open on lower nodes and canopy development continues in parallel with the growth of these lower bolls (Constable 1986).

Long sunny days in the absence of temperature extremes, moisture and nutrient stress are favourable to dry weight accumulation (Hearn 1994). Hence the reduced daily radiation in the tropical dry season (Fig. 1.1) should reduce daily dry weight accumulation in the absence of other stresses.

Radiation use efficiency (RUE) is the dry matter produced per unit of radiation intercepted and is used as a measure of net photosynthesis in estimation of biomass in crop simulation models (Sinclair and Muchow 1999). There has been no measurement of cotton RUE in the tropics, but temperature extremes and the reversed seasonal radiation pattern may also affect RUE for dry season cotton. Moreover, there appears to be no published RUE for *Gossypium barbadense*. A more detailed review is presented in Chapter 4.

2.5. Fibre growth and quality

Figure 1.1 suggested the extreme minimum temperatures (low and high) that can occur in the dry season could be detrimental to the important fibre properties of length, strength and micronaire. In addition, depending on the timing of boll opening, cotton fibre could be weathered by rainfall and high UV radiation. A review of relevant literature is presented in Chapters 5 and 7 which cover fibre quality and weathering respectively. The brief review that follows provides a background to cotton fibre development that is not included in the aforementioned chapters.

2.5.1. *Fibre growth and development*

Cotton fibres are highly elongated epidermal cells of the ovule with thickened secondary walls containing a high percentage of cellulose (Lang 1938). There are two main phases in the growth and development of the cotton fibre. Firstly, the fibre elongates (primary wall formation) for 15 to 27 days after anthesis or 25-40% of the boll period. Secondly, fibre thickening (secondary wall formation) occurs later, 15 to 55 days after anthesis or 25 to 75% of the boll period (Schubert et al. 1973). The rate of fibre elongation is proportional to temperature while the duration of elongation is inversely proportional to temperature (Gipson and Joham 1968 and 1969, Quisenberry and Kohel 1975, Xie et al 1993, Thaker et al. 1989). Consequently a slower rate of elongation as a result of cool temperatures can be compensated for by an extended elongation period.

2.5.2. *The effect of environment on fibre properties*

At crop maturity the properties of cotton fibre are determined by the combined effect of individual bolls developing under varying climatic conditions due the extended flowering period (Wanjura and Barker 1985; Bradow et al. 1997). Many studies have shown that the key fibre properties length, strength and micronair (fineness) are all affected by temperature extremes (Gipson and Joham 1968 and 1969; Gipson and Ray 1970; Hesketh and Low 1968; Quisenberry and Kohel 1975; Wanjura and Barker 1985; Liakatas et al. 1998; Xie et al. 1993); this is reviewed in more detail in Chapter 5.

2.5.3. *Weathering of fibre*

Rain and humidity combined with leaf trash after bolls have opened can discolour lint (Evenson 1967). Prolonged exposure to levels of ultra violet light at maturity will degrade fibres and reduce fibre strength and length (Basinski et al. 1973).

2.6. Genotype

Time-to-maturity, a capacity to produce acceptable vegetative and boll growth, and fibre properties under the temperature extremes of the tropical dry season are key traits required of a successful cultivar. All these traits are known to be at least partially heritable (Hearn and Constable 1984; Wells and Stewart 2010). Maturity is determined by the node of the first fruiting branch and the potential rate of fruiting site production, which are heritable (Moraghan et al. 1968) as well as the rate of survival of early fruit and boll period, which are more affected by environment and pests (Hearn 1994). The node of the first fruiting branch is considered to be the most reliable when breeding for earliness (Munro 1971). New cultivars which flower earlier are more in phase with vegetative development and have a higher partitioning to reproductive structures than older cultivars (Wells and Meridith 1984a). When there is sufficient growing season length, the rapid fruit setting associated with early maturity can result in lower yields than for later maturing cultivars due to assimilate demand exceeding supply leading to an early termination of flowering (Kohel and Benedict 1987). Rapid fruiting is negated when fruit are shed due to stress or pests as a result maturity is later. Cultivar differences in fibre quality in response to temperature extremes (high and low) have also been measured (Gipson and Ray 1970). Leaf morphology differences between genotypes, that is, okra and normal leaf, provide an opportunity to help balance the need for light interception for growth with greater air movement and light penetration into the lower canopy (Wells and Stewart 2010).

2.7. Optimum sowing date

In temperate climates, sowing date and growing season length is determined by temperature. That is, sowing can commence when soil temperatures warm and the size of the sowing window is determined by the length of the growing season. In temperate climates, the optimum planting date is usually the earliest permitted by soil temperatures as this will exploit the available growing season (Pettigrew 2002). However in tropical climates cotton growth is often not limited by cool temperatures and the growing season is determined by other factors such as water supply, avoidance of wet season cloud or rain at critical stages (flowering, picking) and avoidance of key insect or other pests (Hearn and constable 1984).

2.8. The application of modelling to assess the dry season production system

Sustaining a viable cotton industry in tropical Australia will require confidence from potential farmers and other infrastructure investors that economic returns can be sustained and past failures will not be repeated. Only a modelling analysis of the new production system, validated from field experiments and large scale trials, can incorporate seasonal variability in yield, fibre quality, the area sown, and the volume of production and its timing for costing of picking and ginning infrastructure.

The OZCOT model can simulate cotton yield, N uptake, fruiting dynamics, evapotranspiration and soil water extraction using climatic and agronomic inputs (Hearn 1994). OZCOT has been used in temperate Australia in decision support for cotton production (Carberry and Bange 1998) including optimisation of irrigation allocation (Hearn 1995). In addition OZCOT's capacity to simulate yield, fruiting dynamics, N uptake and water use has been validated at the Ord Valley for summer grown cotton during the 1960's and 70's (Hearn 1994). The OZCOT model is described in more detail in Chapter 7. The agricultural production systems simulation model (APSIM) has been linked to OZCOT, permitting simulation of production system scenarios involving a range of crops that are linked by a common soil module (McCown et al.1996; Probert et al. 1998). The APSIM-OZCOT model would be an excellent tool for the assessment of interaction of cotton with the cropping mix at the ORIA and elsewhere in the Australian SAT; however due to intellectual property arrangements the stand alone OZCOT model has to be enhanced and validated before it can be used in the APSIM model.

2.9. Conclusions and recommendations

The review of literature shows there is little knowledge on the performance of cotton in the tropical dry season. The dry season, while avoiding insect pests, presents new challenges at two levels for cotton production:

1. Climatically, what effect will the reverse season temperature and radiation pattern have on crop growth, biomass partitioning, lint yield and quality?
2. Operationally is there time to sow sufficient area near the end of the wet within the 5 week window required for the Bt resistance management plan, grow, pick and gin cotton reliably within the confines of the dry season?

Other crop species have been evaluated in the tropical dry season in Australia and many are now grown commercially during this season. The approach used to evaluate sorghum in the dry season (Muchow and Coats 1986), which is not sensitive to photoperiod like cotton, should be considered. That is to measure, the efficiency of conversion of radiation to biomass, the total dry weight accumulation, the radiation interception and the partitioning of dry weight to yield. Varying sowing date enabled an optimum to be identified and a wider range of temperatures at different growth stages, with only small variation in daily radiation. For cotton additional issues need to be considered; these are the time to maturity as this is determined by nutrient demand by bolls and not a heat unit requirement, and fibre quality as it is affected by temperature and rainfall. Moreover crop development models were not created in this photothermal regime and will require validation.

Finally a means to assess the likely success of dry season cotton in the Australian semi-arid tropics is required. Hence modelling tools require validation and development and data from other relevant disciplines needs to be integrated.

CHAPTER 3: Irrigated Cotton in the Tropical dry Season - Yield, its components and crop development

3.1. Abstract

Growing cotton during the dry (winter) season avoids many insect pests endemic in the wet season (summer) and could permit the reintroduction of cotton to the semi-arid tropics in Australia. This research addressed the questions: 1) what yield is possible given the lower mid season radiation and temperature of the dry season, 2) the prediction and management of crop development using a range of sowing months to assess whether cotton can be grown and picked within the dry season. Over three seasons two *Gossypium hirsutum* L. (upland) cultivars and one *Gossypium barbadense* L. cultivar were sown from March, to June at the Ord River (15.5^{o}S) in Western Australia. For the upland cultivars, lint yields of 1900 to 2300 kg/ha for March and April sowings were at the high end of Australian and International benchmarks. High lint yields were linearly correlated with a greater proportion of bolls that were located on outer sites on fruiting branches than for high yielding crops in temperate climates (~ 30° lat.). The change in boll position increased the length of the growing season which was also linearly correlated with yield. Future research needs to confirm if low minimum temperatures early in flowering caused the change in boll position and to measure the impact of extreme temperature seasons on yield and time to maturity. The lint yield of the *Gossypium barbadense* cultivar was highest at a March sowing, at least 87% of the upland cultivars, which is comparable with temperate climates. The frequency of temperatures > 35 ^{o}C and < 11 ^{o}C affected time to squaring, requiring modification of existing development models derived in temperate climates. It was concluded sowing during March to April should achieve the dual objectives of high yields and avoidance of rain at maturity. The wide temperature range observed in these experiments improved the prediction of boll period from mean temperature; this function should be applicable outside the semi-arid tropics.

3.2. Introduction

As described in Chapter 1 little is known of the yield potential or length of growing season of cotton grown in the tropical dry season where the temperature and radiation patterns are the reverse of spring sown cotton at temperate latitudes (Fig. 1.1). That is higher temperatures early and late in the growing season but lower mid season.

Predicting crop development and maturity is critical to assessing the likelihood cotton can be successfully grown within the confines of the dry season. Modern cotton cultivars are not sensitive to photoperiod and the time to first square, first flower and the development of individual bolls (boll period) are all proportional to temperature (Hearn and Constable 1984; Mauney 1986; Chapman et al. 1996; Viator et al. 2005; Dippenaar et al. 1990). In Australia time to first square and first flower are commonly predicted for spring sown crops (lat. 24 to 36°S) using a degree day sum with a base temperature of 12 ^{o}C (Constable 1976; Constable and Shaw 1988; Hearn 1994). These relationships have not been assessed or calibrated for the winter dry season where temperatures are higher early in growth and cooler during flowering than where the relationships were developed (Fig. 1.1B).

The cotton plant is morphologically indeterminate and climatic conditions can determine the contribution to yield of different boll cohorts. In temperate climates, temperature and radiation are usually most favourable early in flowering (Fig. 1.1.). Hence, at least 80 % of yield is produced from early flowers, that is on the first (P1) and second (P2) positions of fruiting branches nearer the base of the plant (Mauney 1986; Heitholt 1993), with the P1 fruit having greatest probability of producing a harvestable boll (Kerby et al. 1987). Kerby and Hake (1996) found highest yields in California were associated with greater than 67% retention of P1 bolls. A similar P1 retention was reported by Constable (1991) at Narrabri in Australia and Jenkins et al. (1990) in Mississippi. Hence, monitoring of P1 boll retention is common in the USA and Australia. It is not known whether the lower radiation and temperatures early in flowering in the dry season (Fig. 1.1) will affect these relationships between yield and plant architecture.

Gossypium barbadense L. is best suited to irrigation in arid conditions and hence was not previously evaluated in the wet season in the Australian SAT. The change to dry season production, combined with a high market value justify comparing this species with *Gossypium hirsutum* L.

This chapter focuses on the questions of what yield is possible, the effect of sowing date on yield and the prediction of crop development to ensure that cotton can be reliably grown and picked within the dry season. Comparisons are made with benchmarks for yield components and fruit retention measurements used in high yielding temperate climates.

3.3. Materials and Methods

Experiments were conducted at the Frank Wise Institute, 13 km NW of Kununurra WA, Australia (Lat. 15°39'S, Long. 128°43'E) in the Ord River Irrigation Area during the 1995, 1996 and 1997 dry (winter) seasons. The soil was a Cununurra clay (Montmorillinitic Typic Haplustert, local classification Ug 5.34, (Northcote 1971)), a uniform dark medium to heavy clay with pronounced swelling and shrinking characteristics (Gunn 1969) and is the dominant soil in the area (Parberry et al. 1968).

The experiments used a split plot design, where main plots were the sowing date and sub plots were cultivars with four replications in randomised blocks. Four sowing dates were separated by 3 to 4 weeks with sowing commencing in late March and terminating in early June (Table 3.1). A buffer of 12 rows separated each sowing date to prevent drift of chemicals and to enable separate irrigation regimes. Two 'upland' *Gossypium hirsutum* L. cultivars were sown, Siokra L23 (Anon. 1992a) and CS50 (Anon. 1992b). These represent a range in plant growth habit leaf shape and maturity when grown in temperate areas. Siokra L23 is tall and is mid-late maturing, has large bolls and possesses the okra leaf shape; CS50 is medium maturing, has small bolls and a normal leaf shape. The Bt transgenic (producing the Monsanto Cry1Ac protein) equivalents of these cultivars were sown in the second and third seasons of this experiment Siokra L23i (Anon. 1997a) and Sicot 50i (Anon. 1997b). Where data is combined for the three seasons these cultivars are referred to as L23 and S50. Pima S7, a *Gossypium barbadense* L. cultivar, was also sown in each year. All the experiments were preceded by a summer fallow, although the previous winter crop varied, being sunflowers, wheat and maize in 1995, 1996 and 1997 respectively. Analysis of variance was made using Genstat (Lawes Agricultural Trust, IACR, Rothamsted, UK) and regression analysis using SAS (SAS 2001).

Table 3.1: Sowing dates for the three years of the study.

1995	1996	1997
March 29	March 28	March 27
April 24	April 29	April 21
May 18	May 23	May 14
June 9	June 14	June 10

A plant population of 14 and 18 plants/m^2 was established for the upland and Pima S7 cultivars respectively in 1995 and 11 plants/m^2 in 1996 and 1997 for all cultivars. The experiments were furrow-irrigated using a row configuration of two rows per bed separated by 90 cm with irrigation furrows between beds. Plots were 6 rows wide by 20m. Insect pests were managed by scouting twice weekly and insecticide spray decisions were made according to thresholds derived in temperate Australia (Dillon and Fitt 1995). Fertiliser, 150 kg/ha N as urea in 1995 and 200 kg/ha in subsequent years, plus 40 kg/ha P and 7 kg/ha S as double superphosphate, and 20 kg/ha of $ZnSO_4$.H2O, was banded one week prior to sowing, 15 cm below and 5cm outside the seed row. Weeds were controlled by 1.3 kg/ha of pendimethelin applied immediately post sowing. Mepiquat Chloride (Pix®) was applied to the *Gossypium hirsutum* cultivars according to the optimal rate and timing found for this location (Yeates et al. 2002b), that is 14 to 19 g ai /ha when the crop had between 7 and 12 mainstem nodes. There were two exceptions: the March 29 sowing in 1995 where 15.2 g ai / ha and 9.5g ai /ha were applied when the crop had 10 and 14 nodes respectively; and the June 15 sowing in 1996 where 19 g ai /ha was applied when the crop had 19 nodes.

3.3.1. *Measurements*

Date of first squaring was defined as when 50% of plants from 2m of a centre row per plot had one square, a square was considered ‘present’ when the subtending leaf was unfolded. Dates of first flower and first open boll were defined as when one per m of row per plot was present. The nodes above the uppermost first position white flower (NAWF) were counted on the same five plants per plot at approximately weekly intervals from first flower. Cut-out or last effective flower was defined as when NAWF < 4 (Bourland et al. 1992). Boll period was measured by tagging 30 recently pollinated (white or pink) first position flowers in each plot on 2 or 3 occasions with the date and node number recorded. The date of tagging was identified by different coloured tags. In the first season flowers were tagged early and late flowering. In the second and third seasons tagging occurred at early flowering, two weeks later and at late flowering which represented the

flowers on lower, middle and upper part of the main-stem. A total of 11,520 flowers were tagged over the three seasons. Bolls were hand picked on alternate days, the number of bolls and date picked was recorded and the boll period calculated as the time from tagging to the median open day. Seed cotton was machine harvested from 13m of a centre row of each plot. Lint yield was calculated by ginning a 1kg sub-sample with a 10 saw gin. In the first two seasons seed cotton was ginned at CSIRO Plant Industry at Narrabri, NSW, and in the third season the seed cotton was ginned locally. Because the gin turnout from a 10 saw gin is higher than a commercial scale gin, the gin turnout was adjusted to the commercial value using data from concurrent large scale pest management experiments (Strickland et al. 1998; Annells and Strickland 2003;). Adjustment to gin turnout was made relative to a commercial area of crop of one of the cultivars sown here on the same date; generally the gin turnout of the 10 saw gin was 2-3 percentage points higher than the commercial scale gin. The percentage of open bolls was determined by counting the number of open bolls in $2m^2$ per plot every 3-6 days from first open boll. At maturity plants were harvested from 1m of row per plot and mapped for fruit retention (Kerby and Hake1996).

3.4. Results

3.4.1. *Observed climate and pests*

For the growing months of March to November, rainfall was near the long term average (Figs. 1.1 and 3.1A) except April, which was well above average in 1995 and 1996, and delayed the April sowing to late in the month (Fig. 3.1A). For the months of May to August all monthly minimums were similar or 1 to 2^oC below their long term means only the June 1996 monthly minimum was 1^oC above (Figs. 1.1 and 3.1B). The number of minima below the Australian base temperature of 12^oC were also near the long term average of 18 with two fewer minima in 1995 and 1997 and three more minima in 1996 (Fig. 3.1B). The lowest minimums each season were between 7.3 and 8.5^oC and were recorded in June and July. Mean monthly maximum temperatures were near the long term average except June 1996, $2\,C^o$ hotter, and September in all seasons, 1 to $2\,C^o$ hotter. Daily radiation was near average except in April due to rain in 1995 and 1996 (Figs. 1.1 and 3.1C).

Mirids (*Creontiades dilutus, Campylomma* spp.), native boll worm (*Helicoverpa punctigera*), cotton boll worm (*Helicoverpa armigeria*) and rough boll worm (*Earias huegeli* and *E. vittella*) were the dominant pests, although their numbers varied between seasons. For the March and April sowings the non Bt transgenic *Gossypium hirsutum* cultivars (Siokra L23 and CS50) used in the 1995 season lost approximately two squares or early flowers per plant, due to one very high

infestation of *Helicoverpa punctigera* before being effectively controlled by insecticide. The *Gossypium barbadense* cultivar Pima S7 was less affected by *Helicoverpa punctigera*.

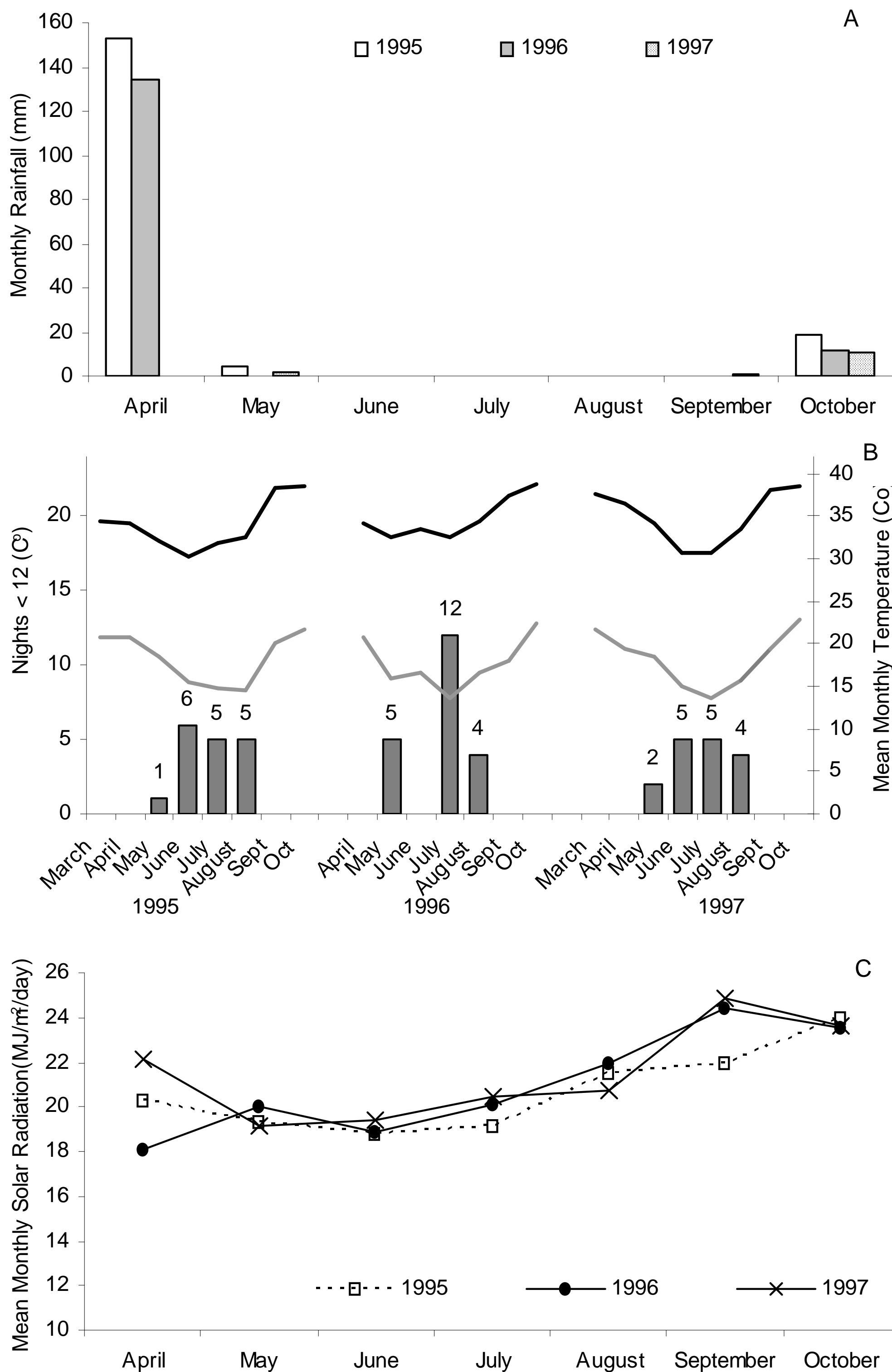


Fig. 3.1: Climatic data for the three seasons of the experiments reported A) monthly rainfall; B) Average monthly maximum and minimum temperature and number of minima < 12°C; C) Average daily solar radiation for each month of crop growth.

3.4.2. *Lint yield, plant mapping and yield components*

Lint yields ranged from 1079 to 2312 kg/ha depending on cultivar and month of sowing (Fig. 3.2). The main effect of month of sowing on lint yield was significant ($p<0.01$) in all years (Fig. 3.2A), with March sown yields higher than May or June in all years and April sown yields were not different from March in 1996 and 1997. Cultivar main effects were also significant ($p<0.01$) with Pima S7 less than the upland cultivars in all seasons. The cultivar by sowing month interaction was not significant in 1996 and 1997 (Fig. 3.2 C, D) and reflected the main effect, with a decline in yields for May and June sowings. In 1995 the cultivar yields responded differently to sowing month, due to a lower yield when April sown for Siokra L23 and Pima S7 and a higher May yield for Siokra L23 (Fig. 3.2B).

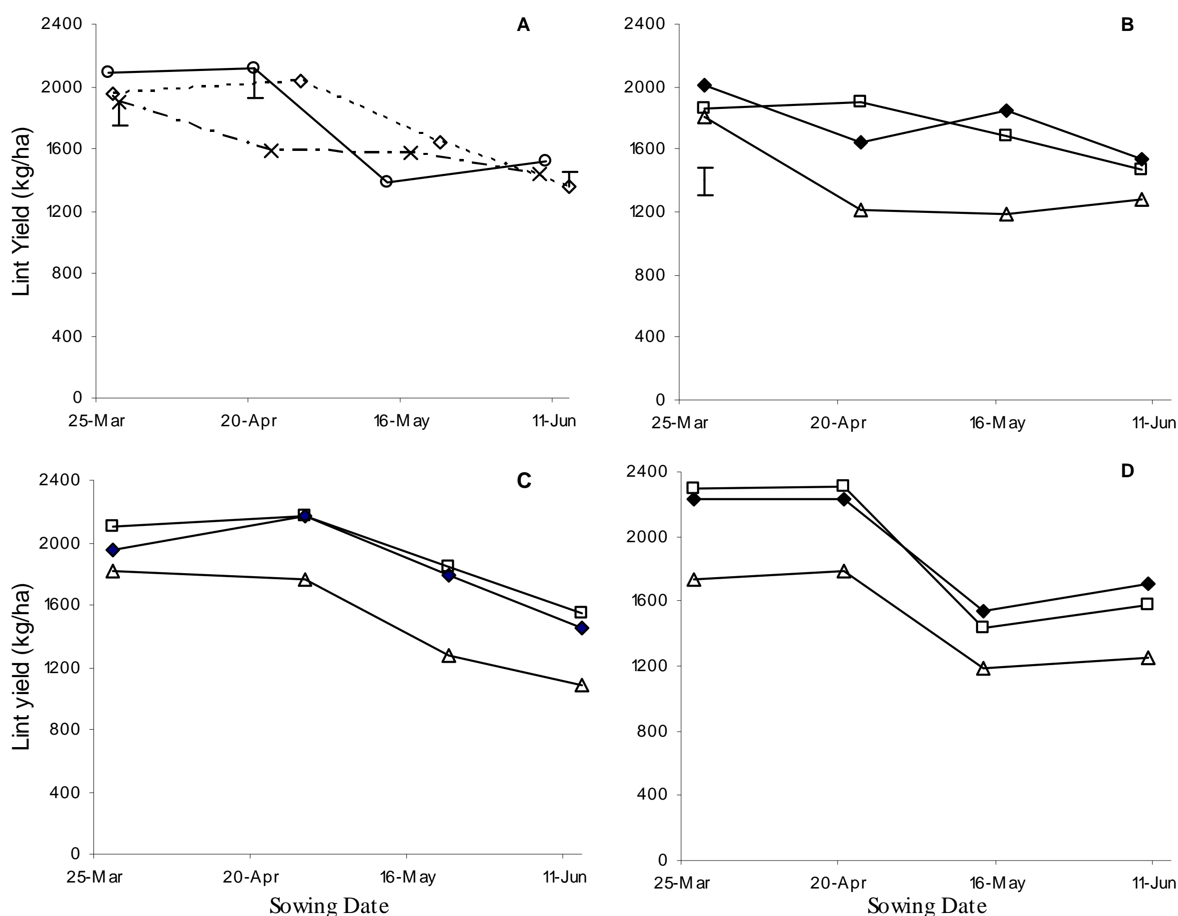


Fig. 3.2: The effect of sowing date on lint yield. A) The main effect of sowing date, where x = 1995, ◊=1996, ○=1997. The sowing date by cultivar interaction for B) 1995, C) 1996 and D) 1997, where ♦=L23 □ = S50, Δ= Pima S7. Bars are $Lsd_{0.05}$ when significant.

Lint yields of the upland cultivars when sown in March and April were high and ranged from 1864 kg/ha to 2312 kg/ha, the exception being Siokra L23 sown in April 1995, (Fig. 3.2 B, C, D). Lint

yields for these cultivars when sown in May or June never exceeded 1850 kg/ha and 1720 kg/ha respectively. The Pima S7 yields were consistently the highest at a March sowing being at least 1896 kg/ha. April sown Pima S7 exceeded 1750 kg/ha in two of three seasons but yields were less than 1300 kg/ha when sown in May or June (Fig. 3.2 B, C, D).

Lint yield was significantly ($p<0.05$) linearly correlated with time to maturity when all data was included, r^2 = 0.50, 0.47 and 0.80 for L23, S50 and Pima S7 respectively. Removal of the March and April sowings in 1995 for which maturity was delayed due to compensation from fruit removal by insects, improved correlations for the upland cultivars (Fig 3.3).

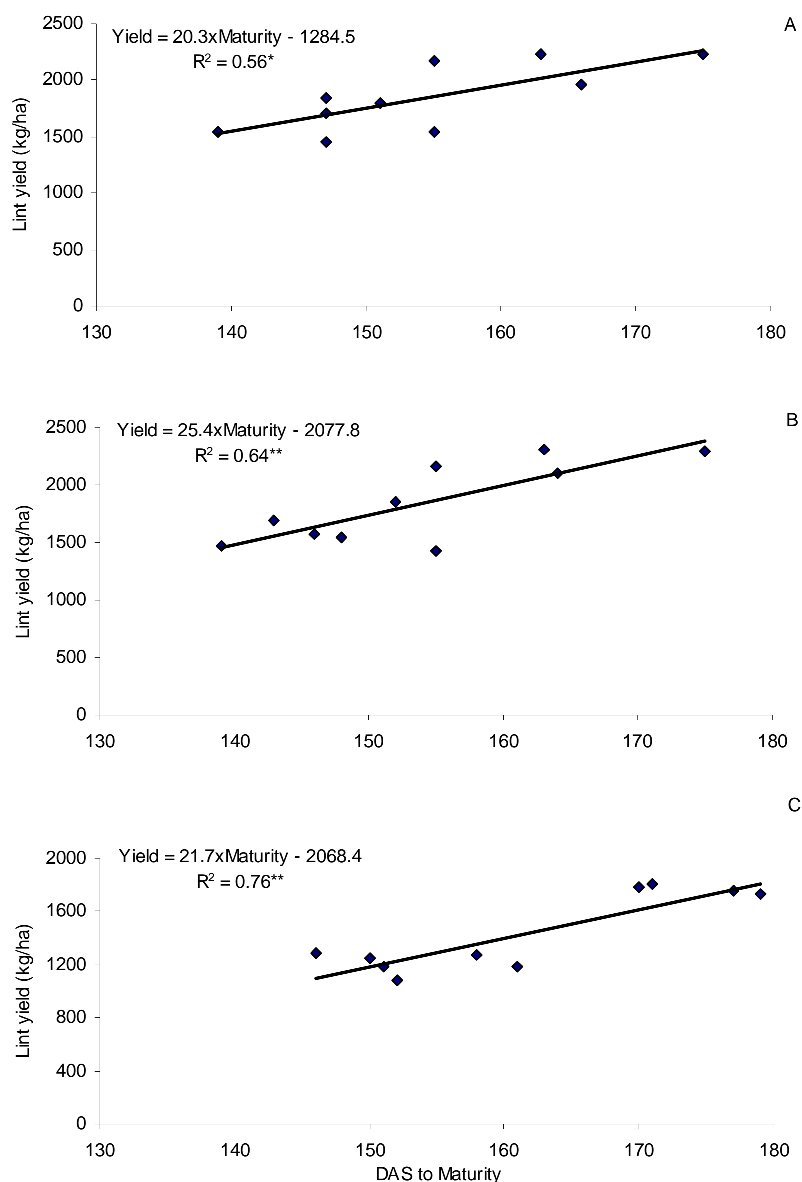


Fig. 3.3: The relationship between lint yield and days to maturity (sowing to 60% open bolls) for A) L23, B) S50 and C) Pima S7. Data points are the average of four replicates per treatment. Where * P< 0.05 and ** P< 0.01.

Sowing month affected gin turnout (P<0.01) in all years (Fig. 3.4A). Gin turnout was higher when sown in April followed by May with March and June sowing months generally the lowest. Cultivar differences were consistent over the three seasons with the gin turnout of Pima S7 less than the upland cultivars and a trend for S50 to be higher than L23 (Fig. 3.4 B, C, D). The interaction between sowing month and cultivar on gin turnout was significant in all years and was due to a different response in Pima S7 where gin turnout was relatively more stable across sowing months (Fig. 3.4 B, C, D).

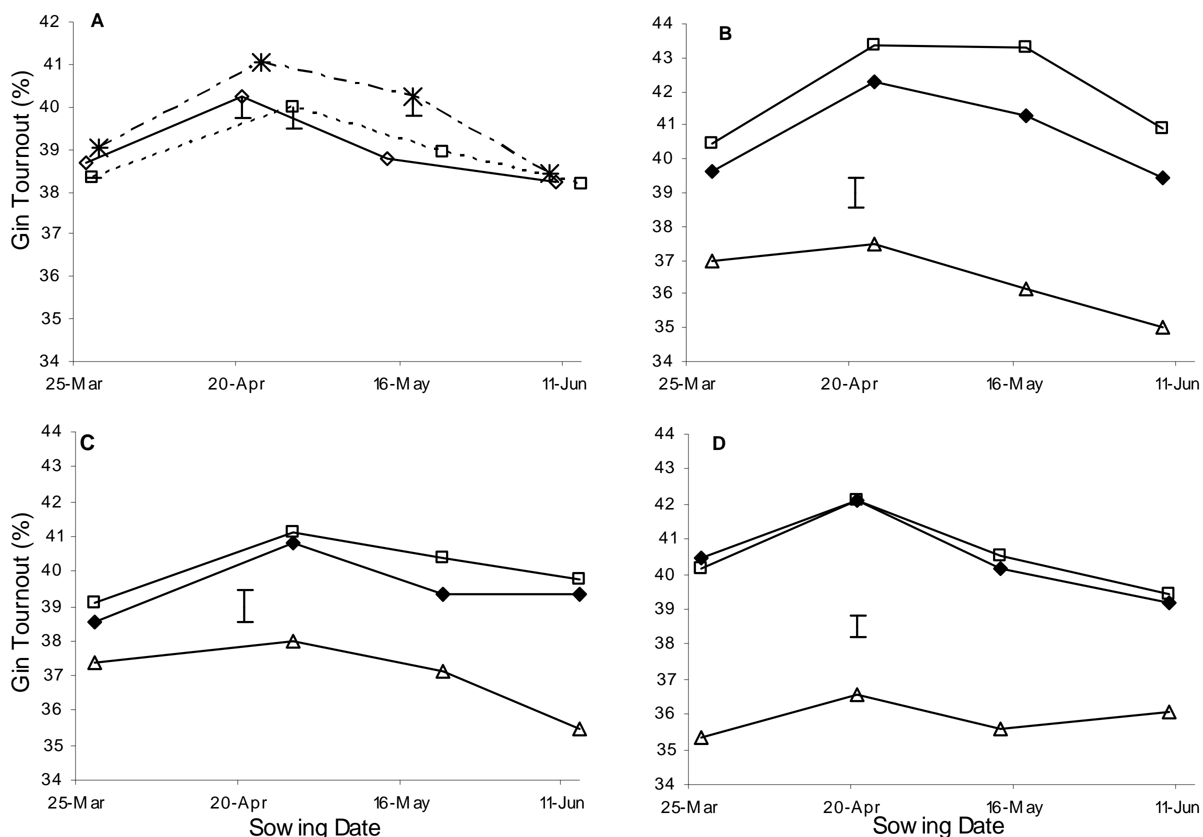


Fig. 3.4: The effect of sowing date on gin turnout. A) The main effect of sowing date, where x = 1995, ◊=1996, ○=1997. The sowing date by cultivar interaction for B) 1995, C) 1996 and D) 1997, where ♦=L23 □ = S50, Δ= Pima S7. Bars are Lsd0.05 when significant.

The proportion of all fruiting sites producing pickable bolls is a measure of fruiting efficiency. June sowings retained lowest proportion of bolls and May was generally lower than March and April sowings (Table 3.2). The cultivars were consistent in their relative retention with L23 < S50 < Pima

S7. Fruiting efficiency was less than 40% for L23 at all sowing months over the three years. Only in the May 1995 sowing did boll retention exceed 50% for CS50.

Table 3.2: Effect of sowing date and cultivar on fruiting efficiency (percentage of fruiting sites with pickable bolls) and the first position (P1) boll retention (bolls retained on P1 sites).

	Month of sowing					Analysis of variance	
Fruiting Efficiency (%)	March	April	May	June	Mean		Lsd $_{0.05}$
1995						*Main effects*	
Siokra L23	36.4	38.6	37.9	43.0	39.1	Month Sown	3.08
CS50	44.4	43.6	52.4	43.3	45.9	Cultivar	2.78
Pima S7	74.0	73.6	67.6	51.4	66.7	*Interaction*	ns
Mean	51.6	52.0	52.6	46.0			
1996						*Main effects*	
Siokra L23i	27.0	35.3	28.0	25.0	28.8	Month Sown	3.81
Sicot 50i	37.8	44.6	36.3	34.1	38.2	Cultivar	3.00
Pima S7	48.2	51.6	48.0	33.0	45.2	*Interaction*	5.92
Mean	37.7	43.8	37.4	30.7			
1997						*Main effects*	
Siokra L23i	33.7	32.2	37.5	26.1	32.4	Month Sown	2.12
Sicot 50i	44.7	43.2	29.6	35.1	38.2	Cultivar	1.83
Pima S7	71.4	61.0	65.0	57.2	63.7	*Interaction*	4.31
Mean	49.9	45.5	44.0	39.5			
P1 Retention (%)							
1995						*Main effects*	
Siokra L23	21.3	39.0	56.9	55.4	43.1	Month Sown	5.61
CS50	26.7	46.0	64.1	51.5	47.1	Cultivar	5.33
Pima S7	56.4	55.2	63.5	43.9	54.8	*Interaction*	11.81
Mean	34.8	46.7	61.5	50.3			
1996						*Main effects*	
Siokra L23i	25.6	44.4	40.0	45.2	38.8	Month Sown	ns
Sicot 50i	45.1	57.0	44.6	57.5	51.0	Cultivar	4.73
Pima S7	50.5	51.0	45.6	34.0	45.3	*Interaction*	11.15
Mean	40.4	50.8	43.4	45.6			
1997						*Main effects*	
Siokra L23i	47.1	47.3	56.1	46.8	49.3	Month Sown	ns
Sicot 50i	55.8	64.7	35.5	50.7	51.7	Cultivar	5.43
Pima S7	66.2	60.3	73.3	65.0	66.2	*Interaction*	12.45
Mean	56.3	57.4	55.0	54.2			

Sowing month did not affect first position (P1) boll retention in 1996 and 1997. In 1995 reduced retention was due to insect damage to early P1 squares and flowers in the March and April sowings (Table 3.2). The cultivar main effect was significant with L23 < S50 < Pima S7 in all seasons.

There was no consistent trend for the sowing month x cultivar interaction. P1 retention ranged between 21 and 65 % for the upland cultivars and 34 to 65% for Pima S7.

There were significantly more fruiting branches at a March sowing in all years and a trend for fewer fruiting branches at May and June sowings. Cultivar main effect was only significant in 1997 (Table 3.3). In contrast P1 retention on the first five fruiting branches was lower at a March sowing and generally greater at May and June sowings. L23 retained fewer lower fruit than the other cultivars (Table 3.3). The interaction between sowing date and cultivar was not significant for either variable (data not shown). The highest retention occurred in May and June 1997, and retention greater than 60% was only measured for Pima S7 in 1997.

Table 3.3: Effect of sowing month and cultivar on the number of fruiting branches per plant and the P1 retention on the first 5 fruiting branches.

Number of Fruiting branches	Month of Sowing					Cultivar			
	March	April	May	June	*$Lsd_{0.05}$*	L23	S50	Pima S7	*$Lsd_{0.05}$*
1995	12.3	10.9	10.8	10.2	*0.68*	10.9	10.8	10.6	*ns*
1996	15.6	13.6	14.1	15.2	*0.82*	15.1	14.1	15.0	*ns*
1997	16.4	14.0	13.5	13.3	*0.71*	14.6	13.7	14.5	*0.61*
Retention 1st 5 Fruiting Branches (%)									
1995	25.4	33.0	58.5	44.6	*7.5*	37.0	45.0	39.1	*ns*
1996	47.2	52.4	43.1	53.5	*7.7*	46.3	58.8	56.2	*8.78*
1997	40.5	56.9	60.4	60.4	*8.3*	48.7	53.7	61.2	*5.71*

The highest yielding sowing months of March and April had the most bolls for all cultivars (Table 3.4). The main effects of sowing date and cultivar were consistent over the three seasons with higher boll numbers at March and April sowing dates than May and June, while Pima S7 produced the most bolls and L23 the least. The sowing date main effect was influenced by the upland cultivars because boll number for Pima S7 responded differently to sowing month in 1995 and 1996, being lower in April and higher in June (Table 3.4). The month of sowing main effect was also significant for the number of fruiting sites, the number of first, second and third position and monopodial branch bolls, data not presented.

Table 3.4: Effect month of sowing and cultivar on final boll numbers (m^{-2}) for the years 1995, 1996, 1997.

	Month of sowing					Analysis of variance	
Year / Cultivar	March	April	May	June	Mean		Lsd $_{0.05}$
1995						*Main effects*	
Siokra L23	99	95	85	81	90	Month Sown	12.3
CS50	127	117	102	109	114	Cultivar	10.6
Pima S7	218	141	142	201	176	*Interaction*	21.3
Mean	148	130	118	110			
1996						*Main effects*	
Siokra L23i	98	96	90	76	90	Month Sown	10.1
Sicot 50i	114	121	115	98	112	Cultivar	8.8
Pima S7	195	179	180	119	168	*Interaction*	17.4
Mean	136	132	128	97			
1997						*Main effects*	
Siokra L23i	130	107	84	73	100	Month Sown	9.8
Sicot 50i	128	130	88	86	108	Cultivar	8.5
Pima S7	208	197	149	160	179	*Interaction*	ns
Mean	155	148	109	106			

3.4.3. *Correlation of lint yield and sowing date with mapping variables*

The number of pickable bolls per m^2 was significantly ($p < 0.01$) linearly correlated with lint yield for all cultivars, as were the number of second position (P2) and third and greater position ($P3^+$) bolls (Table 3.5). However, there was no correlation between lint yield and the number of P1 bolls, the total number of fruiting sites and all measures of boll retention taken (i.e. all fruiting sites, P1 bolls on all main-stem fruiting branches or the first five fruiting branches).

3.4.4. *The timing and prediction of reproductive development*

There was no significant difference between the upland cultivars in the time to each growth stage thus their data were combined. Figure 3.5 shows the average duration and the date of occurrence of each growth phase for each sowing month. The late March sowing matured in mid September and had the longest duration of growth of 170 days for upland cultivars and 172 days for Pima S7. Growth duration of was reduced with later sowing, the June sowing taking 144 days to reach maturity and occurred in mid November for the upland cultivars. Pima S7 was earlier to first-square, but had a longer flowering and boll growth phase than the upland cultivars (Fig. 3.5).

Table 3.5: Linear regression coefficients for the relationship between yield components or plant mapping variables and lint yield. Data for the three seasons combined. Where, ** $P<0.01$, * $P<0.05$ and ns = not significant, Position 3+ = (Position 3 + Position 4 + adventitious bolls). Analysis was made for the yield components and plant mapping variables where the analysis of variance was significantly different for sowing month ($p<0.05$).

Yield component / Plant mapping variable	Lint Yield (n=48 for each cultivar)		
	L23	S50	Pima S7
Pickable bolls (m^{-2})	0.37**	0.31**	0.46**
Position 1 bolls (m^{-2})	ns	ns	ns
Position 2 bolls (m^{-2})	0.41**	0.36**	0.38**
Position 3+ bolls (m^{-2})	0.34**	0.36**	0.45**
Monopodial Branch Bolls (m^{-2})	ns	ns	ns
Fruiting sites (m^{-2})	ns	ns	ns
Proportion of fruiting sites with bolls (%)	ns	ns	ns
Number of fruiting branches per plant	0.18*	ns	ns
Boll retention on P1 fruiting sites (%)	ns	ns	ns
P1 boll retention first 5 fruiting branches (%)	ns	ns	ns

The phase from first squaring to first flower was similar for all cultivars and sowing dates (Fig. 3.5). The effect of sowing date on the duration of other phases appeared to be related to temperature; being progressively cooler prior to squaring and warmer post cut-out as sowing progressed from March to June. The period of boll growth, that is from first flower to maturity, declined by 40 days as sowing moved from March to June. For the March and April sowings boll growth took 90 to 114 days and occurred during the cooler low radiation period from June to August (Fig. 3.5).

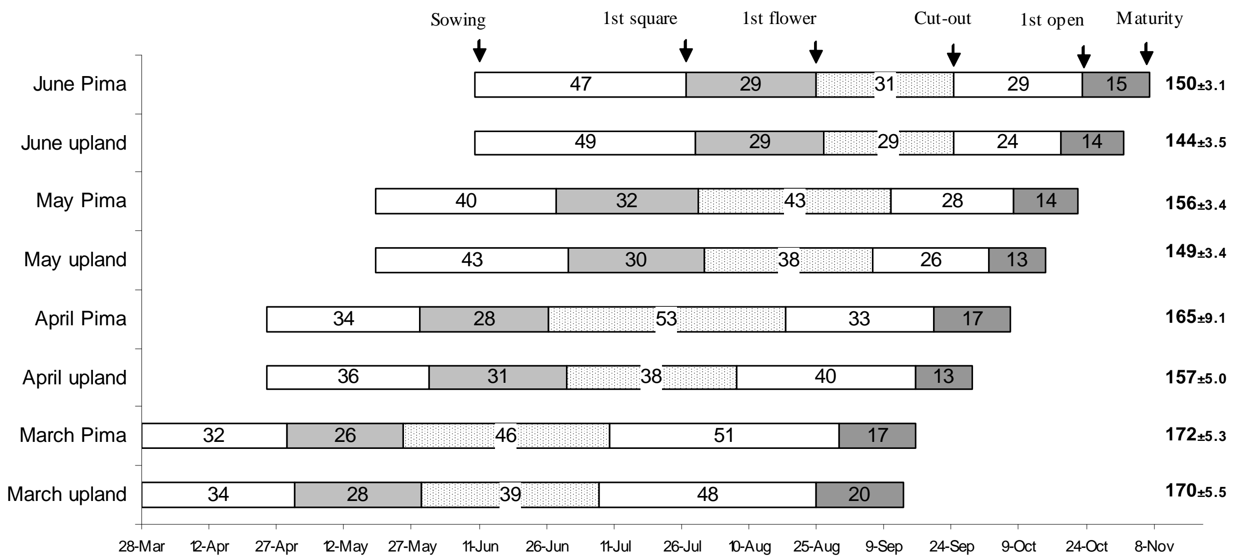


Fig. 3.5: The effect of sowing month on: the average duration of crop growth phases, shown inside bars as days; the date of occurrence of each growth phase for each month of sowing is shown on the x axis. The days from sowing to maturity (60% open bolls) is given to the right of each bar graph with its standard error. Data is the average for 3 seasons and the upland cultivars are combined.

The degree day sum using a base temperature of 12°C (DDS_{12}) calculated to first square and first flower for the upland cultivars was greater than the values of Constable and Shaw (1988), requiring approximately 40 and 120 DDS_{12} more thermal time to first square and to first flower respectively (Table 3.6). There was also considerable variability in these degree day sums.

Main-stem node number was linearly correlated ($p<0.001$) with DDS_{12} up to 18 nodes or 1000 DDS_{12} with $r^2 = 0.96$, and 0.95 for the upland cultivars and Pima S7 respectively. The slope of these relations was 56, and 57 DDS_{12} per node for the upland cultivars and Pima S7 respectively (Table 3.6).

Table 3.6: Degree day sums (DDS_{12}) using a 12 °C base temperature for these experiments ± se compared with the published values for temperate Australia (25 to 36 °S). The DDS_{12} / node were calculated up to node 19 from slope of linear regression, ± se of this slope.

Growth Stage (from planting)	Temperate Australia	Tropical winter season	
		Upland	Pima S7
Emergence	80#	67 ±14.8	67 ±14.8
Node	60*	56 ±4.0	57 ±3.7
1st square	505#	546 ±45.8	517 ±42.2
1st flower	777#	896 ±42.8	862 ±44.9
1st open boll	1537#	1906 ±94.8	1915 ±54.5
60% open	2060#	2147 ±130.5	2217 ±126.0

from Constable and Shaw (1988), and * from Hearn (1994).

Prior to squaring the March sowing was exposed to an average of 22 days or 67% of the square period above 35°C. Consistent with the average monthly temperatures the number of days > 35°C declined to 2 and 5 days by the May and June sowings. There was less variation in the number of days > 32 ^{o}C. The number of extreme minimum temperatures increased when sowing moved from March to June, hence only the May and June sowings were exposed to > 1 minima below the 12 ^{o}C base prior to first square. The frequency of temperatures below 12°C was much less than 15°C but followed the same pattern

Table 3.7 shows for the upland cultivars the coefficient of variation in the DDS to first square was not improved by increasing the threshold to 15°C or imposing an upper threshold of 35°C. For Pima S7 an upper and lower threshold of 35°C and 15°C produced a small reduction in the coefficient of variation of the DDS to first square.

Table 3.7: Coefficient of variation (CV) of degree day sums calculated from sowing to first square.

Threshold temperatures (^{o}C)	Upland		Pima	
	DDS	CV%	DDS	CV%
12	537	6.9	508	7.1
35 / 12#	531	6.7	469	7.2
32 / 12	505	7.7	469	7.0
35 / 15	421	6.9	391	6.5
15	425	7.4	397	7.5

NB for the calculation of DDS with and upper and or lower threshold it was assumed development stops above or below the threshold temperature.

The variation in the in the DDS_{12} to first square was better explained by the frequency of high maximum (>35°C) and low minimum temperature (<11°C) (Table 3.8). For the upland cultivars there were separate significant (P<0.01) linear correlations between DDS_{12} the number of minima < 11°C and the number of maxima > 35°C. A similar response was found for Pima S7, which had a smaller data set. The cumulative effect of these temperature thresholds was also a significant (P<0.05) linear increase in the number of nodes to the first fruiting branch (Table 3.8), the exception being the upland cultivars when maxima exceeded 35°C.

Table 3.8: Linear regression coefficients for the effect of the number of minima < 11°C and number of maxima > 35°C with no minima <11°C prior to first square on the accumulated degree days (DDS_{12}) to first square and the number of nodes to the first fruiting branch. Where ** = P< 0.01, * = P<0.05, ns = not significant

Threshold Temperature	DDS_{12}		Node of first fruiting branch	
	r^2	Slope ($DDS_{12}d^{-1}$)	r^2	Slope (node d^{-1})
Minima < 11°C				
Upland (n=14)	0.67**	13.2	0.71**	0.34
Pima S7 (n=8)	0.19ns	7.9	0.57*	0.21
Maxima > 35°C				
Upland (n=10)	0.73**	3.6	0.28ns	0.04
Pima S7 (n=4)	0.53*	3.3	0.86**	0.05

Rate of progress (1/days) to first square from sowing was linearly correlated (p<0.01) with average daily temperature for all cultivars (Table 3.9). However, the rate of progress from first square to first flower was weakly correlated with temperature (Table 3.9). Hence differences in the time to first flower were determined by the time from sowing to squaring. Table 3.9 also shows the boll period, expressed as the rate of progress from flowering to open boll (1/days) was linearly correlated (p < 0.01) with mean daily temperature with a separate function fitted for the upland cultivars and Pima S7.

Table 3.10 compares the predictions of reproductive development with from relations with mean daily temperature and degree day sums developed in this study with other published functions. The time to first square and the boll period by were most accurately predicted using the linear relation developed in this study between rate of progress to these growth stages and mean daily temperature.

Table 3.9: Rate of progress (d^{-1}) to reproductive development stages as a function of daily average temperature, linear regression coefficients and the slope of linear function. Where ** = p< 0.00 and ns = not significant. In brackets is se.

Phase	Mean daily temperature range (°C)		r2 (%)		Intercept		Slope (1/d) / C°	
	Upland	Pima S7	Upland	Pima S7	Upland	Pima S7	Upland	Pima S7
Sowing to First Square	22.1-28.1	21.9-28.1	87.3**	88.5**	-0.018 (0.005)	-0.020 (0.005)	0.0018 (0.0002)	0.0019 (0.0002)
Sowing to First Flower	22.9-27.5	22.9-27.6	82.5**	77.4**	-0.0053 (0.002)	-0.0066 (0.003)	0.0008 (0.0002)	0.0009 (0.0001)
First Square to First Flower	21.6-26.6	21.6-27.0	27.8	36.2	ns	ns	ns	ns
Boll Period (anthesis to open boll)	23.0-31.1	23.2-31.3	90.2**	90.0**	- 0.0165 (0.0014)	- 0.0181 (0.002)	0.00122 (0.00003)	0.00124 (0.00007)

Table 3.10: Comparison of crop development predictions between the relationships developed in this study and functions published elsewhere in Australia. Note the RMSD for the relations developed in this study was calculated with same data as used to derive functions. Where: na = not applicable and Tav = average daily temperature.

Function	Development Phase (RMSD)		
	Sowing to first square	Sowing to first flower	Boll period
DDS_{12} these experiments (Table 7)	3.7	3.0	4.5
1/d = fn Tav (Table 9)	3.1	3.4	4.3
Constable (1976)	4.8	na	na
Bange and Milroy (2003)	7.7	na	na
Constable and Shaw (1988)	4.8	8.3	25.4
Constable (1991)	Na	Na	10.3

3.5. Discussion

3.5.1. *Lint yields, plant mapping and yield components*

The lint yields measured here for the *Gossypium hirsutum* cultivars when sown in March and April (Fig. 3.2) should meet current commercial expectations if repeated reliably on a larger scale. These lint yields were at worst in line with recent Australian commercial irrigated yields (ABS 2006) and commonly reported research yields for irrigated cotton in temperate Australia and the USA, where lint yield was inflated by laboratory ginning, (e.g. Ayars et al. 1999; Grismer 2002; Wilson et al. 2003; Fritschi et al. 2003; Hutmacher et al. 2004; Bange and Milroy 2004) and at the top of international averages elsewhere (ICAC 2002). However, these lint yields still fall short of the highest research and commercial yields of 2700 to 3000 kg / ha for well managed crops occasionally reported in temperate Australia (Rochester 2007; The Australian Cottongrower 2003) and the 4040 kg/ha considered to be the theoretical maximum for temperate USA (Baker and Hesketh 1969). Suggesting the maximum potential yield for the tropical dry season may be lower than temperate latitudes.

It is not clear what effect extreme temperature seasons will have on lint yield. For the three seasons of this study large deviations from average temperatures were for short periods consequently mean monthly maximum and minimum temperatures were within 2 ^{o}C of the long term average (Figs. 1.1& 3.1). Prolonged temperature extremes, that is maxima > 35°C and minima either > 25°C or < 20°C during flowering can reduce boll size (Hearn 1994) and fruit retention (Powell 1969; Reddy et al. 1992) particularly if combined with low radiation (Christiansen 1986). While the likelihood of monthly temperatures in the damaging range is only 10% of seasons during flowering and boll growth that is mean monthly temperatures are ± 4 ^{o}C of the long term averages (BOM 2009). Further research is required to measure the effect of extreme temperature seasons on lint yield so a seasonal risk profile can be established.

The lower yield of the *Gossypium barbadense* cultivar Pima S7 compared to the *Gossypium hirsutum* cultivars (Fig. 3.2) was consistent with research and commercial experience with this species from temperate Australia (Buster 1994) and the USA (Kittock et al. 1981; Unruh and Silvertooth 1996; Fritschi et al. 2003). The relative yields of Pima S7 to the upland cultivars of 0.87 and 0.78 (Fig. 3.2) were within the range of 0.70 to 0.88 observed in temperate Australia (Buster 1994), 0.62 to 0.89 in Arizona (Kittock et al. 1981; Unruh and Silvertooth 1996) and 0.86 in California (Fritschi et al. 2003). Nevertheless the yields of the higher valued fibre from *Gossypium*

barbadense measured here (Fig. 3.2) would meet current commercial expectations provided quality standards are achieved.

Interpretation of plant mapping data provides insight into how lint yield was achieved for cotton grown in the dry season. An important finding from this study was the positive correlation between yield and greater horizontal fruiting, that is more 2nd position (P2) and ≥ 3rd position (P3+) bolls and the lack of correlation between the number of first position (P1) bolls and their retention and yield (Table 3.5). This is a departure from spring sown upland cotton in temperate climates where P1 bolls and their retention are regularly monitored due to their positive association with yield (Mauney 1986; Constable 1991; Kerby and Hake 1996). The relationship between yield and P1 retention found for temperate regions (Kerby and Hake 1996; Jenkins et al. 1990) is related to the need for earlier maturity due to a growing season length that is defined by cool temperature (Kerby and Hake 1996). In temperate climates the growth of bottom P1 bolls often coincides with favourable climatic conditions, which are the longest photoperiods and highest solar radiation for the growing season. Hence, P1 bolls were larger at each fruiting branch and had a greater chance of survival (Constable 1991). There is also greater likelihood of sub-optimal temperatures for later developing bolls making compensation from the loss of lower fruit risky. The tropical dry season is the reverse with the pollination of early flowers coinciding with less favourable climatic conditions, that is, cool to cold night temperatures and relatively low radiation, while later developing bolls were exposed to rising temperatures and radiation (Figs. 1.1, 3.1, 3.5).

It is possible the P1 retention of early flowers at some sowing dates (Table 3.3) was reduced by colder nights coinciding with anthesis (Figs. 3.1, 3.5). However it was difficult to differentiate physiological shedding possibly due to the colder nights from removal by insect pests. For the Bt transgenic cultivars fruit removal by insects not susceptible to the Bt protein prior to insecticide treatment was possible. While caterpillars would have contributed by removing some early fruit on the non *Bt* cultivars in 1995 (Table 3.3).

A lower retention of early P1 flowers (Table 3.3) may have had a positive impact on yield for the March and April sowings by reducing boll demand for assimilate early in flowering, a time when assimilate supply was limited by low solar radiation and cool night temperatures (Fig 3.1). Compensation for the loss of early flowers occurred due to a greater production of horizontal fruiting sites that flowered later when temperatures were warmer and radiation higher. The positive relation between yield and time-to-maturity supports this hypothesis (Fig. 3.3). While the lower yields for the May and June sowings could be explained by the combined impact of later flowering

(Fig. 3.5), a generally higher early flower retention (Table 3.3) which increased assimilate demand and reduced the flowering period (Fig 3.5), and very high temperatures late in boll growth (Figs. 3.1 and 3.5) inducing shedding and reducing boll size (Christiansen 1986; Hearn 1994).

The fruiting efficiency data presented in Table 3.2 also reflects the greater contribution of bolls set later in the season. For all sowing months the fruiting efficiency or total fruit retention was measured here was similar to that reported in temperate latitudes for upland cultivars having okra or normal leaf types (Kerby and Buxton 1976), hence was not affected by within season climatic differences. The lack of correlation with yield (Table 3.5) supports the observation that compensation for low early season retention was possible because of the more favourable climate later in the growing season.

The significant correlation between yield and boll number (Table 3.5) is consistent with other growing regions for upland (Hearn and Constable 1984) and Pima cotton (Buster 1994). Presumably individual boll weight accounted for the remainder of the variability. Although lint weight per boll was not measured, there was sufficient variation in boll number at similar yields to suggest this was the case (Table 3.4).

Gin turnout appeared to be affected by temperature, being highest when sown in April and May (Fig. 3.4) when temperatures were coolest during flowering (Figs. 1.1 and 3.5). The lower gin turnouts for the March and June sowings were associated with higher temperatures (Figs. 3.1B and 3.4). These observations are consistent with controlled environment studies, where high temperatures have been found to reduce gin turnout (Hesketh and Low 1968; Gipson and Ray 1970). The correlation between temperature and gin turnout is investigated further in Chapter 5.

The response of gin turnout in Pima S7 to sowing date differed slightly from the upland cultivars (Fig. 3.4). Pima S7 had a longer flowering period for the March and April sowings (Fig. 3.5) which may have exposed the developing bolls to different temperatures. Boll periods were also longer for Pima S7 (Table 3.6).

It is doubtful that early fruit damage by *Helicoverpa punctigera* observed on the non Bt cultivars in 1995 would have affected yield as in subsequent studies (Lei and Gaff 2003), dry season cotton has been found to compensate from this level of damage at early in flowering without yield loss. The *Gossypium barbadense* cultivar Pima S7 was less affected by *Helicoverpa punctigera,* which is consistent with studies in Sudan (Bindra 1985) and temperate Australia (Buster 1994). It is more

probable the lower nitrogen fertilizer rate used in 1995 may have contributed to slightly lower yields as concurrent studies found 200 kg N / ha increased yield by 10% at a late April sowing date (Yeates unpublished data), hence N rates were increased in 1996 and 1997.

3.5.2. *Implications of the timing and duration of crop development phases*

In addition to producing the highest lint yields, sowing in March and April made the best use of the dry season because maturity occurred by mid - October (Fig. 3.5) when the likelihood of early wet season rain is still low (Fig. 1.1). However, when grown in cooler seasons than observed here (Fig. 3.1) the growing period would be extended, increasing the risk of rain at maturity.

The April sowings were most likely to be affected by sub-optimal temperatures during flowering because flowering occurred between late June and early August when temperatures were lowest (Figs. 3.1 and 3.5). Cold nights could also impact on a March sowing late in flowering and during boll maturation (Fig. 3.5). May and June sowings were most likely to be exposed to cooler temperatures pre-flowering and high temperatures (> 35°C) from late in flowering to maturity (Figs. 3.1 and 3.5), the later may have contributed to lower yields at these sowing dates compared to March and April sowings (Fig. 3.2).

Of interest was the impact the reverse photothermal pattern of the dry season (Figs. 1.1 and 3.1) would have on lint yield and time to maturity compared with temperate latitudes. Season long effects were similar to temperature latitudes, that is, the seasonal heat unit accumulation (Table 3.6), the days from sowing to maturity (Fig. 3.5) (Bange and Milroy 2004) and the positive correlation between yield and days-to-maturity (Fig. 3.3) (Constable et al. 1976; Bange and Milroy 2004). However, within season photothermal differences may explain the lower the rate of yield increase with days-to-maturity of 20 to 25 kg/ha/d measured here (Fig. 3.3) compared with the 34 kg/d measured by Bange and Milroy (2004) in temperate Australia. When days-to-maturity was longest (180 days) the yield potential in the dry season was slightly lower compared to temperate latitudes (Bange and Milroy 2004) being the result of the mid season radiation and temperature limitations described previously (Figs. 1.1 and 3.1). When days-to-maturity was shortest (< 150 days), as was the case in the May and June sowings, yield during the dry season was higher compared with Bange and Milroy (2004), due to greater daily heat unit accumulation due to rising rather than falling temperatures combined with higher daily radiation during boll growth.

The longer boll filling period for the March and April sowings coincided with the low radiation and temperature months of July to August (Figs. 3.1C, 3.5) and assisted the reduced assimilate supply in

matching the demand from bolls. In this case boll filling was extended by a combination of lower temperatures (Figs. 3.1B, 3.5) and more bolls from later pollinated flowers on the top and outside of the plant (Table 3.5).

Of the sowing months compared in this study, March will have the greatest chance of receiving rain that could inhibit trafficability at sowing and potentially reduce the number of sowing opportunities (Fig. 1.1). To assess the likelihood of sowing commercial scale areas in March, future modelling analysis that combines historic climatic records with knowledge of the drying characteristics of the local soils is required.

3.5.3. *Prediction of crop development*

This study has highlighted the need for a common method of predicting the reproductive development of cotton. Internationally, there is no consistency in the threshold temperatures used to predict cotton reproductive development using degree day accumulation, with minimum thresholds being locally derived and ranging from 12 ^{o}C to 15.5 ^{o}C (Hearn and Constable 1984; Mauney 1986; Dippenaar et al. 1990; Viator et al. 2005) and upper thresholds some times used (e.g. Dippenaar et al. 1990). In addition Hearn and Constable (1984) reported a 'cold shock' minimum temperature of < 11°C increased the DDS_{12} to first square by 5.2 per minima. Perhaps then, it is not surprising the variation in the DDS to first square measured here (Table 3.6) was not improved by varying maximum or minimum thresholds of 35 ^{o}C or 32 ^{o}C in combination with 12 or 15 ^{o}C minimum thresholds (Table 3.7). At this location the variation in the DDS to first square could be explained by the frequency of supra (> 35 ^{o}C) and sub optimal (< 11°C) temperatures increasing the number of nodes to the first fruiting branch (Table 3.8). The observation that the node of the first fruiting branch was increased at sub and supra optimal temperatures is consistent with studies elsewhere where mean temperatures over the growth phase were compared (Mauney 1966; Hesketh et al. 1972; Hearn and Constable 1984). However there is no evidence that this knowledge has been applied to predict time of squaring. The increased DDS_{12} per minima < 11°C was 13.2 DDS_{12} /day (Table 3.8) was greater than the 5.2 DDS_{12} /day 'cold shock' reported by Hearn and Constable (1984). These maximum and minimum temperature extremes had a similar impact on Pima S7 (Table 3.8), although the sample size was small for this cultivar

The most accurate prediction of time to squaring was by the relationships developed here between rate of progress and mean daily temperature (Table 3.10). It is of note that the function tested here of Bange and Milroy (2003) is non linear and was derived in a controlled environment from a wide range of fixed temperatures. It is unclear why temperature did not affect duration of the phase from

first squaring to first flower in these experiments (Table 3.9). It is important to also note that these functions could not be tested with data independent of the data from which they were derived.

Improvement in prediction of boll period using temperature is possible using the function derived in Table 3.10. This function is based on a large data set with a wide average daily temperature (23-31°C) and boll period range (45 to 94 days) (Table 3.9), hence should be applicable to high input crops within the semi-arid tropics. Wider application of this boll period function could require incorporation of the impact of nitrogen and radiation (Li et al. 2009).

Rising end-of-season temperatures (Fig. 3.1) reduced the boll period of later flowers (Table 3.9) compressing the boll opening period and minimising cultivar and species differences. Hence, the *Gossypium hirsutum* cultivars grown in these experiments were of similar maturity in this environment (Fig. 3.5), which differed from their relative maturity when grown in temperate Australia where L23 is mid to late maturing while S50 has medium maturity (Anon. 1992ab, 1997ab). Similarly the *Gossypium barbadense* cultivar Pima S7 was at most 8 days later maturing than the upland cultivars (Fig. 3.5), which is 6 to 22 days less than the species difference measured in temperate Australia (Buster 1994) and the USA (Unruh and Silvertooth 1996). The interaction between cultivar maturity and sowing date should be the subject of future research when Bt cultivars with a greater range of maturities are available.

3.6. Conclusions

1. Sowing during March to April produced the highest lint yields and at a level at the higher end of Australian and International benchmarks. These sowing months are also likely to avoid rain at maturity. A March sowing would have the greatest likelihood of late wet season rain interrupting sowing operations.
2. High lint yields were associated with a greater proportion of bolls that were located on outer sites on fruiting branches than for high yielding crops in temperate climates (~ 30° lat.). This change in boll position increased the length of the growing season which was correlated with yield.
3. Further research is required to determine if low night temperatures caused the change in boll position and to measure the impact of extreme temperature seasons on yield.
4. A robust function was developed to predict boll period from a wide temperature range, however research is required to develop a more widely applicable method to predict reproductive development.

CHAPTER 4: Irrigated cotton in the tropical dry season - Biomass accumulation, partitioning and RUE

4.1. Abstract

Growing cotton during the tropical dry season avoids many insect pests endemic in the wet season. The impact of low mid season radiation and night temperature that characterise the dry season, on the conversion of radiation to biomass (RUE) and the partitioning of this biomass were measured as these were largely unknown. Over three seasons, two *Gossypium hirsutum* (upland) cultivars and a *Gossypium barbadense* cultivar were sown from March to June at the Ord River (15.5^{o}S), Western Australia. For the highest yielding March and April sowings, final biomass was similar to high yielding temperate grown cotton (~ 30° lat.) and was generally greater than May or June sowings. However, biomass was accumulated differently: maximum growth rate was 6 to 12 g/m^2/d for 78 to 134 days compared with 15 to 25 g/m^2/d for 25 to 60 days reported for temperate grown cotton. RUE changed significantly with ontogeny, peaking between squaring and early flowering. The range in RUE of 1.2 to 2.0 g/MJ throughout the crop lifecycle for the upland cultivars was similar to temperate climates where biomass was corrected to a glucose equivalent. The RUE of 1.2 to 2.3 g/MJ measured over the lifecycle of *Gossypium barbadense* cultivar was the first reported for this species. From first square to first flower the variation in RUE could be explained by a linear decline ($p<0.05$) with temperature, which may limit vegetative biomass in May and June sowings and in cooler than average seasons for March and April sowings. Due to favourable temperatures and water supply, sowing in March would have the greatest risk of rank growth. It was concluded the low temperature and radiation during flowering and boll growth combined to reduce crop growth rate but high yields were achieved when the crop boll filling phase was extended. Management must be tailored to ensure a high proportion of boll growth (60 to 80%) can occur after vegetative growth has terminated.

4.2. Introduction

Previous research found cotton lint yield when grown in the dry season was highest when sown in March and April and were most likely to achieve the dual objectives of maximum yield and avoidance of rain at maturity (Chapter 3). Yield was associated with the proportion of bolls located on outer nodes on each fruiting branch; which was higher than for high yielding crops grown in temperate climates (~ 30° lat.).

Little was know of the productivity of cotton grown in the dry season in terms of its conversion of radiation to biomass and the partitioning of this biomass between vegetative and reproductive organs. Dry season temperatures that can be high (> 37° C) early and late in the growing season and cool mid-season minima (< 10°C) (Cook and Russell 1983), combined with daily radiation that is 20% less during flowering and boll growth than for cotton at 30° latitude (Chapter 1), may affect radiation use efficiency (RUE) and biomass accumulation.

Inadequate biomass production was considered a major limitation to yield in dry season soybeans at the ORIA because insufficient leaf area and precocious flowering were induced by a photothermal regime of cool nights and short daylengths (Mayers et al. 1991a,b,c). In contrast, for sorghum grown in the dry season at Katherine, Australia (14.5^{o}S), inadequate partitioning of biomass into grain was found to limit yield not the production of biomass (Muchow and Coates 1986).

Only the sowing date studies of Stern (1965) and Thomson (1965) conducted during the wet season cropping era at the ORIA, included dry season sowing dates and measured biomass of cotton. These studies produced contradictory results. Stern (1965) found dry season sowings (March, April and May) had lower yields due to inadequate biomass and a low partitioning of this biomass into bolls (< 30%), although it was acknowledged yield was reduced by a build up of insect pests from earlier sowings. In contrast the Thomson (1965) study, conducted in the same year, produced equivalent yields for March 30 sowing as the wet season November to February sowings.

There has been no measurement of the RUE of cotton in the tropics. The RUE of upland cotton (*Gossypium hirsutum* L.) has been measured for spring sown crops in temperate Australia (30°S) (Constable 1986; Sadras 1996; Bange and Milroy 2000; Bange and Milroy 2004) and in the USA (31° N) (Rosenthal and Gerik 1991). The RUE values reported in these studies generally fall

within the range of 1.0 to 2.5 g / MJ of PAR and are comparable with reported values for other C3 crops when corrected to a glucose equivalent biomass (Kiniry et al. 1989; Sinclair and Muchow 1999; Wall et al. 1994). There appears to be no published RUE values for *Gossypium barbadense*.

Concurrent studies into the use of the growth regulator mepiquat chloride on dry season cotton found early growth was vigorous and without treatment could lead to rank growth at maturity (Yeates et al. 2002b, 2005). However these studies were only conducted on April sown cotton and the early vigour of plants sown at other times was not known.

As there is no known consistent measurement of the effects of the tropical dry season environment on cotton growth, the focus of this paper was to use sowing date experiments to measure the effect of the dry season photothermal regime on RUE, and subsequent crop biomass accumulation, partitioning, and plant height. Comparisons were made with benchmarks for these parameters measured for cotton grown in high yielding temperate regions and the tropical wet season. The aim was to use this information to determine any limitations to crop production in the tropical dry season system and to identify potential management options to address challenges.

4.3. Materials and Methods

Sowing date by cultivar experiments conducted over three seasons at the Frank Wise Institute, 13 km NW of Kununurra WA, Australia (15°39'S, 128°43'E) in the Ord River Irrigation Area were used to collect relevant data. These experiments are described in Chapter 3. To summarise, the *Gossypium barbadense* cultivar Pima S7 was compared with two Bt transgenic *Gossypium hirsutum* (upland) cultivars: Siokra L23i and Sicot 50i (producing the Monsanto Cry1Ac protein). In the first season, the non Bt transgenic equivalent of the upland cultivars (Siokra L23 and CS50) were sown. Where data are combined for the three seasons these cultivars are referred to as L23 and S50. In each of the 3 seasons these cultivars were sown on 4 occasions (main plots): 27 to 29 March, 21 to 29 April, 15 to 23 May and 9 to 14 June; there were 4 replications. The experiments were furrow-irrigated. The crop was sowing a at 90 cm row spacing on wide beds accommodating two rows per bed. Plots were 6 rows wide and 20m in length. Rows were in an east – west direction. Analysis of variance was made using Genstat (Lawes Agricultural Trust, IACR, Rothamsted, UK) and regression analysis using SAS (SAS 2001).

Plant height, defined as the distance from the soil surface to the top unfurled leaf, was measured weekly from 5 plants in each plot commencing 2 to 4 weeks after sowing. The same plants were measured on each occasion. If a plant was damaged, a plant of similar size was substituted.

Above ground biomass from $1m^2$ from each plot was partitioned into stems, leaves, squares, flowers and bolls prior to drying at 80^oC for 3 – 4 days in a fan forced oven. Biomass was partitioned at early squaring, at first flower, at approximately 30 and 60 days after first flower and when approximately 60% of the bolls were open. The final biomass sampling was made prior to chemical defoliation. Additional biomass were collected between first square and first flower in the 1996 and 1997 seasons and used for RUE calculations. For the March and April sowing dates, extra samples were also taken when the nodes above the first position white flower equalled four. Seed cotton was machine harvested from 13m of a centre row of each plot.

The proportion of light intercepted was measured at 10 to 20 day intervals from first squaring until a maximum was reached. A 0.9m line sensor (Licor industries, Nebraska USA) was placed across the centre of 1 row in each plot. Readings were taken at ground level and above the crop at two locations in each plot within 30min of solar noon. The proportion of radiation intercepted at noon was calculated as RI_n = (I above – I below)/ I above. Because noon measurements were taken, the proportion of intercepted radiation was adjusted for diurnal changes using the method of Charles-Edwards and Lawn (1984) i.e. $RI = 2RI_n/(1+ RI_n)$ where RI = the daily fraction of radiation intercepted. Incoming solar radiation was measured 500m from the field. The proportion of solar radiation that was photosynthetically active radiation (PAR) was assumed to be 50% (Monteith 1972). The cumulative intercepted PAR was calculated daily by multiplying RI by the total PAR received. The daily fraction of light intercepted was calculated from either the slope of highly significant linear correlations between light interception and days after sowing (DAS) up to maximum interception or when correlation coefficients were < 0.96 by interpolation between measurements. Senesced leaves were only observed near maturity at the March and April sowing dates in 1996 these leaves shed soon after colour change and were located at the bottom of the plant and therefore had minimal effect on light interception. Senesced leaves were measured as 6% of biomass in the upland cultivars and 9 % for Pima S7.

RUE was calculated in 1996 and 1997 for growth phases throughout the crop lifecycle for each variety using the methods of Trapani et al. (1992). That is, from the slope of the linear regression between accumulated intercepted PAR and biomass for each plot over the period of each growth phase for each variety. A two way analysis of variance was conducted for variety, growth stage

and their interaction. To determine the effect of temperature on RUE, the average RUE calculated for the different growth phases for each sowing month of each variety was plotted against the average minimum, maximum and mean temperature for the duration of the growth phase. Biomass was converted to a glucose equivalent using the method of Wall et al. (1994) e.g. dry weight multiplied by 1.4326, 1.3807 and 1.7636 for stems, leaves and fruit respectively.

4.4. Results

Temperature and radiation were near long term monthly averages except for lower radiation in April 1995 and 1996 due to above average rainfall (Chapter 3). Compared with spring sown cotton in temperate latitudes, temperatures were higher early in growth for the March and April sowings and cooler during early flowering and boll growth for these sowings. For the May and June sowings temperatures were cooler during early growth and hotter later in flowering and during boll growth. For all sowings the period from first square to first flower, that is May to August, there was a small range in the monthly average daily solar radiation, 18.9 to 22.0 $MJ/m^2/d$. There was no rain and the sky was almost cloud free during this period (Chapter 3).

4.4.1. *Biomass accumulation and partitioning at maturity*

The sowing date main effect on biomass at maturity was significant ($p < 0.05$) in all seasons with the biomass for a March sowing always significantly greater than for sowing in June (Table 4.1). The general trend was March ≥ April ≥ May ≥ June, only the March sowing exceeded 1000 g / m^2 for all cultivars in all years. The cultivar main effect on biomass was significant ($p < 0.05$) in each year with Pima S7 less than S50 in 1995 and 1996 and greater than S50 in 1997. The cultivars responded similarly to sowing date in 1995 and 1996 hence the sowing month by cultivar interaction was only significant in 1997, due to the higher biomass of Siokra L23i sown in March and Sicot 50i having a greater biomass when sown in June than in May.

For the proportion of biomass as bolls, sowing date and cultivar main effects were significant ($p < 0.05$) in all seasons (Table 4.1) with significant differences following the trend April ≥ March≥ May ≥ June. In 1996 and 1997 there were no consistent sowing date effects for the upland cultivars. Partitioning to bolls was lower in 1995 due to *Helicoverpa spp.* damage to flowers and bolls in March and April sowings, averaged across cultivars the proportion of biomass as bolls was June > March > April = May. Pima S7 had significantly higher partitioning to bolls than the upland

cultivars in all seasons. The significant sowing date by cultivar interaction was mainly due to the proportion biomass as bolls of Pima S7 having different response to sowing date than the upland cultivars.

Table 4.1: Total above ground biomass and the proportion of this biomass as bolls at maturity (approximately 60% open bolls). $Lsd_{0.05}$ = least significant difference = and ns = not significant.

	Month of sowing					Analysis of variance	
Final Crop Biomass (g/m^2)	March	April	May	June	Mean		Lsd $_{0.05}$
1995						*Main effects*	
Siokra L23	1016	865	1133	858	974	Month Sown	138.5
CS50	1147	915	1058	923	1011	Cultivar	78.1
Pima S7	1186	714	880	929	927	*Interaction*	ns
Mean	1116	831	1023	903			
1996						*Main effects*	
Siokra L23i	1132	1143	1008	1107	1098	Month Sown	81.2
Sicot 50i	1213	1209	1103	1112	1159	Cultivar	97.7
Pima S7	1010	1018	1041	813	971	*Interaction*	ns
Mean	1118	1123	1051	1011			
1997						*Main effects*	
Siokra L23i	1276	1049	775	809	977	Month Sown	69.9
Sicot 50i	1017	1057	867	754	924	Cultivar	58.1
Pima S7	1095	1057	869	955	994	*Interaction*	112.0
Mean	1129	1054	837	839			
Boll Proportion (%)							
1995						*Main effects*	
Siokra L23	38.0	43.7	37.7	54.2	43.4	Month Sown	1.75
CS50	40.9	41.9	38.9	53.3	43.8	Cultivar	1.52
Pima S7	55.3	42.3	48.6	54.7	50.2	*Interaction*	3.86
Mean	44.7	42.6	41.7	54.1			
1996						*Main effects*	
Siokra L23i	57.4	57.3	55.8	42.7	57.5	Month Sown	1.74
Sicot 50i	56.2	60.4	58.4	46.9	55.5	Cultivar	1.51
Pima S7	69.2	67.4	58.1	52.9	61.9	*Interaction*	3.39
Mean	60.9	61.9	57.4	47.5			
1997						*Main effects*	
Siokra L23i	55.9	61.0	57.3	55.6	57.5	Month Sown	1.86
Sicot 50i	58.1	61.0	58.3	58.0	58.9	Cultivar	1.61
Pima S7	66.8	67.3	66.7	62.2	65.8	*Interaction*	3.76
Mean	60.3	63.1	60.8	58.6			

For most sowing dates the proportion of leaf ranged between 9 and 12% of biomass at maturity (Table 4.2). Sowing date and cultivar main effects were significant in all seasons. The sowing date effect was the inverse of the boll percentage with June > May > March ≥ April. Generally the upland cultivars had a greater proportion of leaf than Pima S7, although bacterial blight (*Xanthomonas axonopodis*) late in the season in the March and April sowings of Pima S7 in 1996 caused some premature senescence of leaves and may have contributed to a lower percentage of leaf. The sowing month by cultivar interaction was significant in 1995 and 1997, due mainly to

Pima S7. The upland cultivars were not significantly different from each other for all but the April and May sowings in 1995.

Table 4.2: The proportion of total above ground biomass as stems and leaves at maturity (approximately 60% open bolls). $Lsd_{0.05}$ = least significant difference = and ns = not significant.

	Month of sowing					Analysis of variance	
Stem Proportion (%)	March	April	May	June	Mean		$Lsd_{0.05}$
1995						*Main effects*	
Siokra L23	51.5	51.3	53.1	32.3	47.1	Month Sown	2.11
CS50	50.2	50.2	48.1	32.1	45.2	Cultivar	1.84
Pima S7	38.1	52.8	42.4	32.4	41.4	*Interaction*	2.98
Mean	46.6	51.4	47.9	32.3			
1996						*Main effects*	
Siokra L23i	32.6	31.6	33.6	45.1	35.7	Month Sown	2.15
Sicot 50i	31.5	28.0	30.8	40.1	32.4	Cultivar	1.86
Pima S7	22.7	24.5	32.4	38.7	29.6	*Interaction*	2.72
Mean	28.9	28.0	32.0	41.3			
1997						*Main effects*	
Siokra L23i	35.1	29.7	30.3	30.1	31.3	Month Sown	2.32
Sicot 50i	32.9	28.0	30.8	27.4	29.8	Cultivar	2.00
Pima S7	26.2	24.6	21.4	22.9	23.8	*Interaction*	ns
Mean	31.4	27.4	27.5	26.8			
Leaf Proportion (%)							
1995						*Main effects*	
Siokra L23	10.6	5.0	9.2	13.5	9.6	Month Sown	0.98
CS50	8.9	7.9	12.0	14.6	11.0	Cultivar	0.85
Pima S7	6.6	4.9	9.0	12.9	8.4	*Interaction*	1.74
Mean	8.7	5.9	10.1	13.7			
1996						*Main effects*	
Siokra L23i	10.0	10.4	10.6	12.2	10.8	Month Sown	1.23
Sicot 50i	12.3	11.5	11.6	13.0	12.1	Cultivar	1.07
Pima S7	8.1	8.1	9.5	8.4	8.5	*Interaction*	ns
Mean	10.1	10.0	10.6	11.2			
1997						*Main effects*	
Siokra L23i	8.9	9.3	12.4	14.2	11.2	Month Sown	0.85
Sicot 50i	9.0	10.9	10.9	14.6	11.4	Cultivar	0.73
Pima S7	7.0	8.1	12.0	14.9	11.5	*Interaction*	1.49
Mean	8.3	9.4	11.8	14.6			

The proportion of stem was more variable than leaves or bolls and there was no consistent sowing month response (Table 4.2). In 1995 there was a greater proportion of stem than in 1996 and 1997. The cultivar main effect was significant with Pima S7 < upland. The stem proportion in upland cultivars was relatively consistent in 1996 and 1997, ranging from 27% to 35% except June 1996.

From sowing to first square, growth rates were low: 1 to 4 $g/m^2/d$ (data not presented). However, for most sowing months there was a highly significant ($p < 0.01$) linear increase in biomass from first square to maturity, hence a constant growth rate over this period (Table 4.3). Crop growth rates

in this phase ranged from 6.1 to 12.3 g/m^2/d. Generally the duration of the period of maximum growth rate decreased as sowing date moved from March (77 to 134 days) to June (69 to 105 days).

Table 4.3: The duration of maximum crop growth rate (CGR), the maximum crop growth rate and the regression coefficient for the linear relation between crop biomass and DAS for the maximum CGR period. Note CGR was calculated slope of this relation between crop biomass and DAS and all linear regressions were highly significant (P<0.001).

	L23			S50			Pima S7		
Year / Month Sown	Duration of maximum CGR (days)	Maximum CGR (g/m^2/d)	r^2	Duration of maximum CGR (days)	Maximum CGR (g/m^2/d)	r^2	Duration of maximum CGR (days)	Maximum CGR (g/m^2/d)	r^2
1995									
March	131	6.19	0.98	77	10.51	0.99	131	7.59	0.98
April	100	7.47	0.99	100	8.06	0.99	100	6.07	0.98
May	92	10.54	0.98	92	9.40	0.99	92	6.94	0.97
June	69	10.03	0.99	69	11.26	0.99	69	10.73	0.99
1996									
March	124	8.44	0.99	78	12.12	0.98	78	12.31	0.99
April	88	11.26	0.99	111	10.04	0.99	111	9.80	0.95
May	109	9.06	0.98	109	9.78	0.99	109	9.18	0.99
June	105	10.09	0.99	105	10.51	0.99	85	8.66	0.98
1997									
March	134	9.70	0.99	134	8.11	0.98	134	7.42	0.99
April	133	7.90	0.99	133	8.77	0.99	133	7.58	0.94
May	114	6.56	0.99	114	7.27	0.99	114	7.61	0.98
June	92	8.48	0.98	92	7.89	0.99	92	9.65	0.99

4.4.2. *Light interception and radiation use efficiency (RUE).*

Light interception increase was generally linear from first squaring to 75 to 106 DAS or 15 to 30 days after first flower (Fig. 4.1). In 1996 maximum light interception exceeded 90% for all sowing dates and cultivars. In 1997 maximum light interception was ≤ 85% for the May and June (Fig. 1GH) sowings and the April sowing of Pima S7 (Fig. 4.1B). For Pima S7, maximum light interceptions were lower than upland cultivars in 1997. The increase in light interception of Pima S7 was slower than the upland cultivars for when sown in April and May (Fig. 4.1 BCFG).

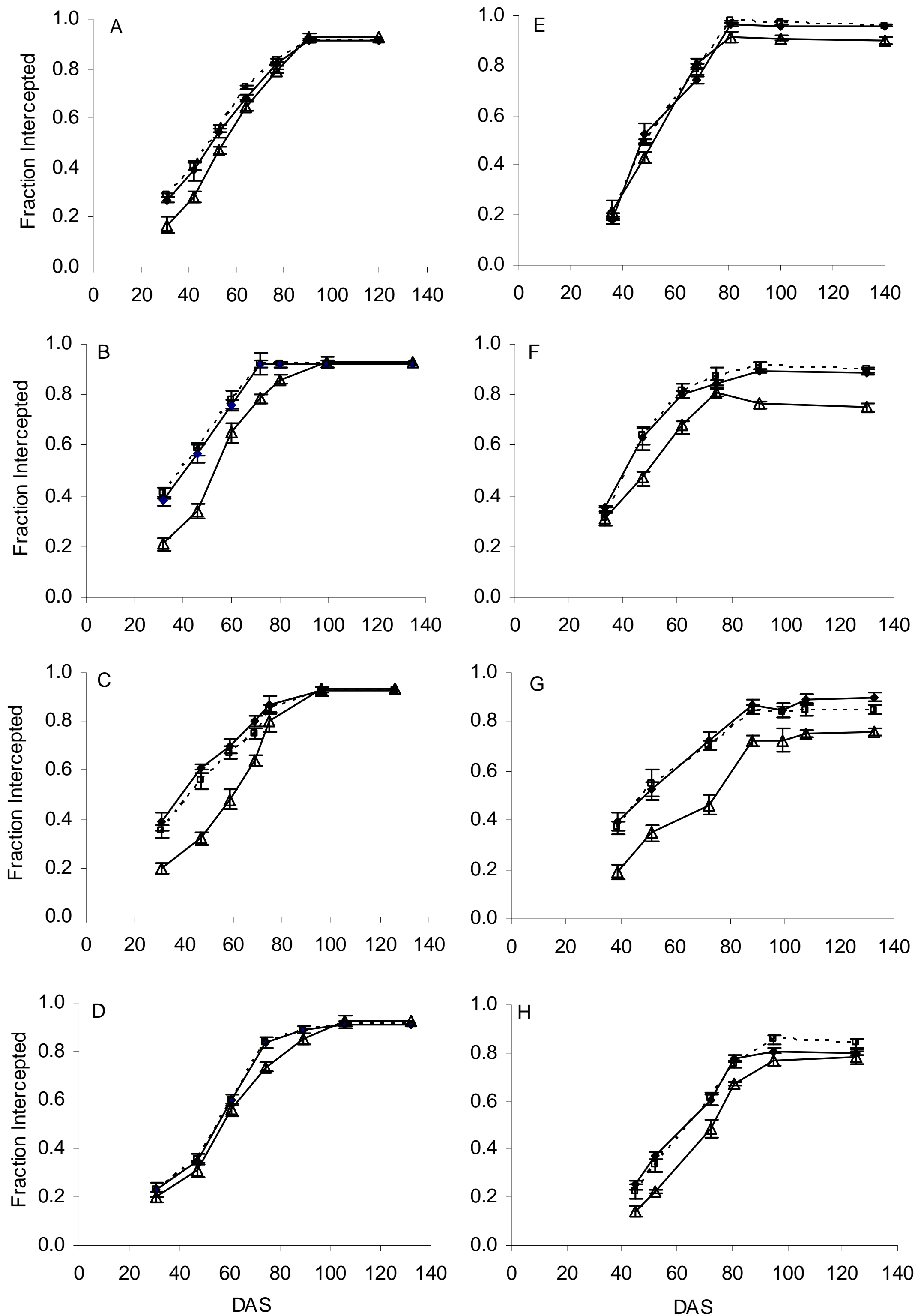


Fig. 4.1: The fraction of light intercepted with days after sowing (DAS). For 1996 sown in A) March, B) April, C) May , D) June and 1997 sown in E) March, F) April, G) May, H) June. Where ♦=Siokra L23i, □ = Sicot50i, △= Pima S7. Bars = ± 1 se from the mean.

For all varieties the glucose equivalent RUE changed significantly ($p<0.05$) with crop ontogeny (Fig. 4.2); being highest in the squaring to flowering period (1.88 to 2.34 g/MJ) then declining to a minimum late in boll growth of 1.2 to 1.4 g/MJ (Fig. 4.2). The variety main effect was not significant with the RUE averaged across growth stages being 1.54, 1.59 and 1.65 g/MJ for Siokra L23i, Sicot50i and Pima S7 respectively.

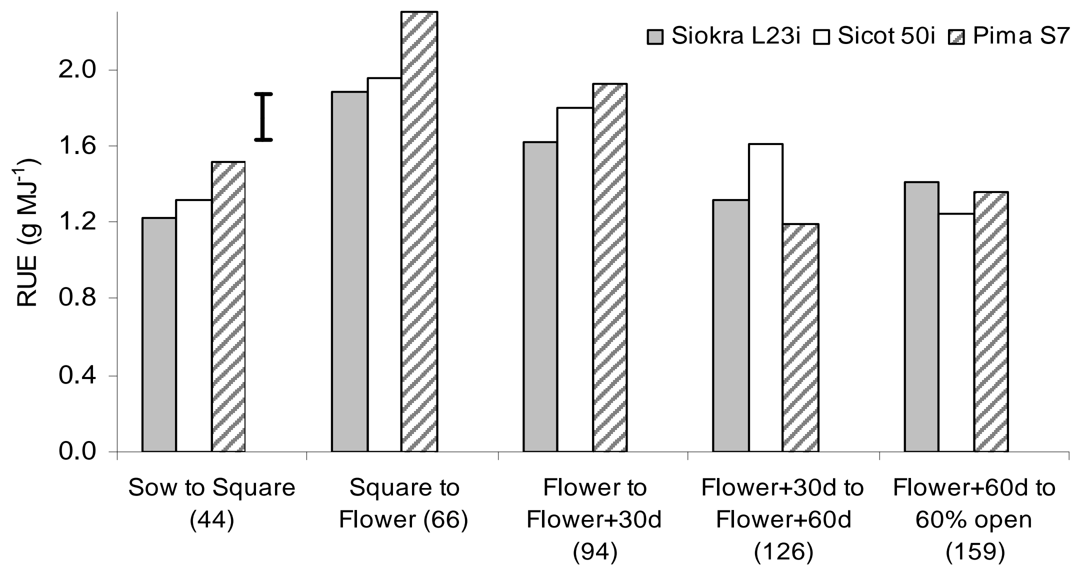


Fig. 4.2: The change in RUE with growth phase and genotype. Average DAS is in brackets. RUE was calculated as the average for each growth phase from the slope of the regression between biomass and accumulated intercepted PAR for each plot. The bar is the $lsd_{0.05}$ of the significant growth phase by variety interaction.

From first square to first flower the linear correlation between RUE and average temperature was highly significant ($p<0.01$) (Fig. 4.3A, B) as was minimum and maximum temperature. Correlation coefficients were 0.44 and 0.78 for minimum temperature and 0.43 and 0.68 for maximum temperature for the upland cultivars and Pima S7 respectively. The lines fitted for the upland cultivars Siokra L23i and Sicot 50i were not significantly different hence their responses were combined (Fig. 4.3A). The correlation between temperature and RUE after early flowering was not significant, although the temperature range was smaller (data not presented).

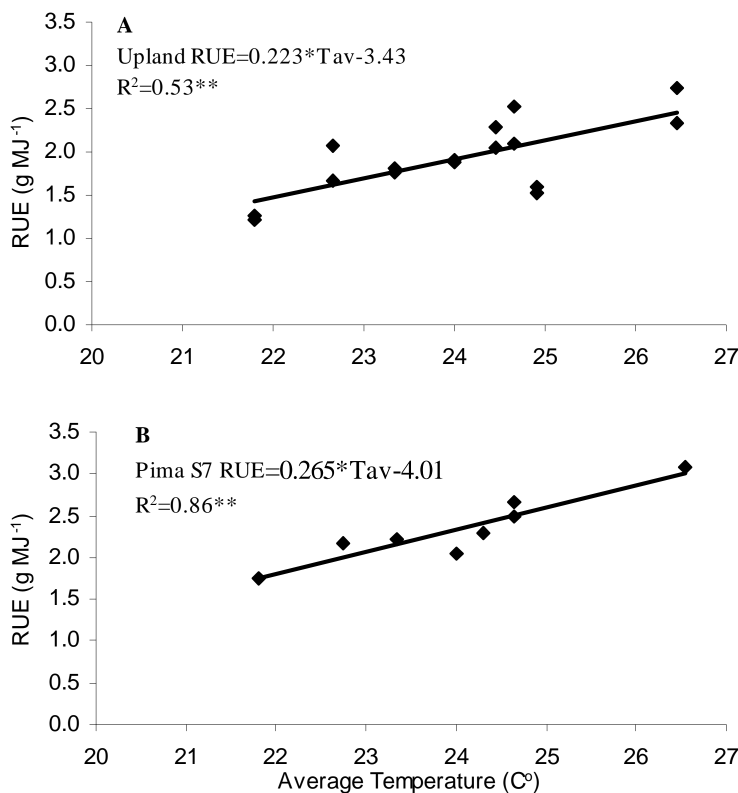


Fig. 4.3: The effect of average temperature on RUE for A) upland cultivars and B) Pima S7 between first square and first flower. RUE was calculated for each sowing date from the linear regression between accumulated biomass and intercepted PAR. Fitted lines, their equations and regression coefficients are shown. Where ** = $P < 0.01$, Tav = average temperature between first square and first flower.

4.4.3. *The partitioning of biomass with time*

Between first square (34 to 49 DAS) and maturity (144 to 172 DAS), there was a similar pattern of vegetative (stems, leaves) and reproductive (squares, flowers, bolls) biomass change among cultivars, hence only sowing date main effects for biomass components are shown in Fig. 4.4. The duration of the vegetative, concurrent and reproductive growth phases could be measured from Fig. 4.4. Up to early flowering 70 to 80 DAS vegetative growth accounted for > 90% was biomass accumulation, between 70 and 115 DAS growth vegetative and reproductive growth was concurrent and after 105 DAS (range 100 to 115 DAS) growth was only reproductive. Leaf senescence was responsible for slightly lower vegetative biomass between 100 DAS and maturity in March and April sowings in 1996 (Fig, 4.4).

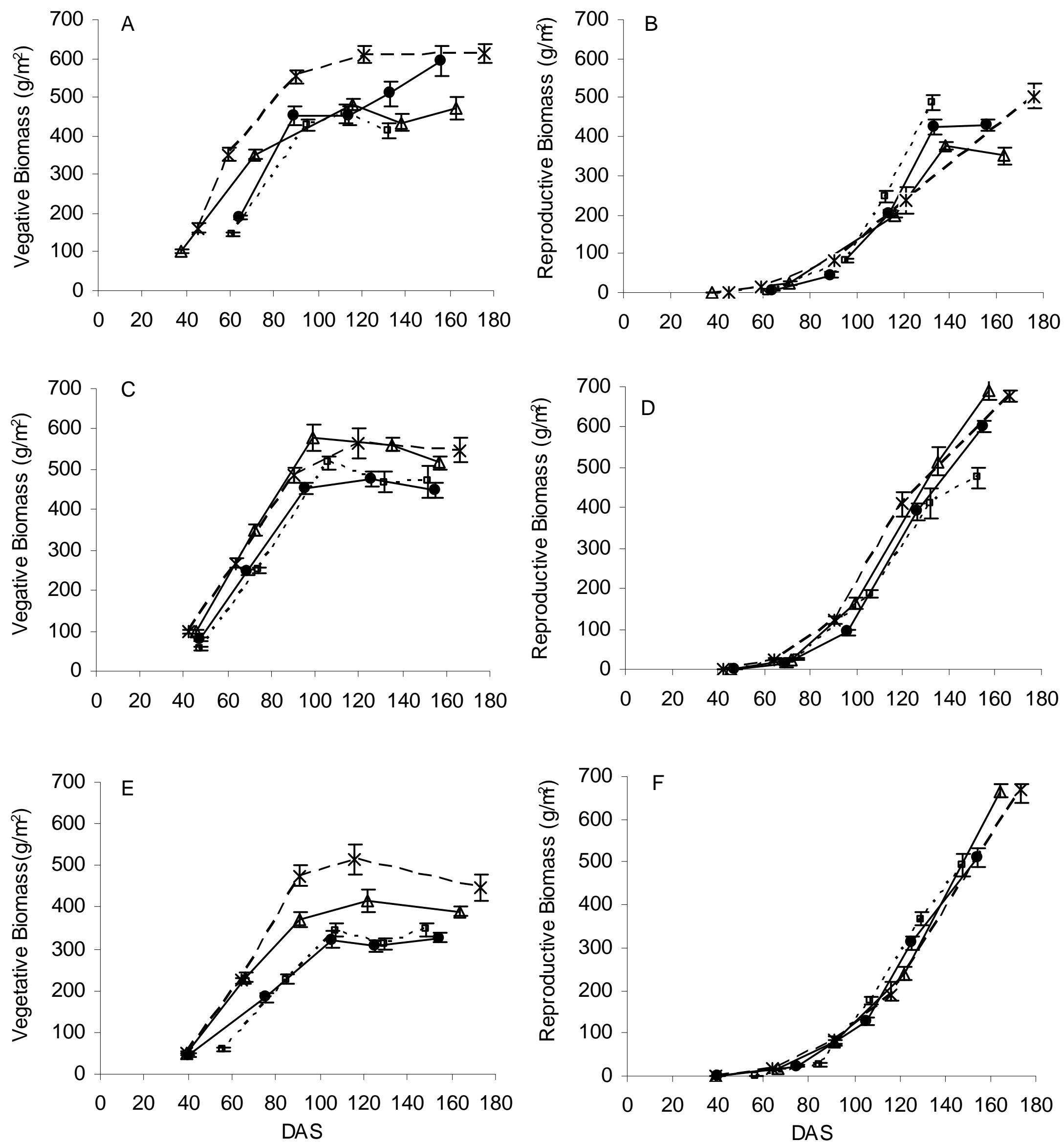


Fig. 4.4: Change in vegetative (stems and leaves) and reproductive biomass (squares, flowers, bolls) with DAS. Sowing date main effects for 1995 A) Vegetative, B) Reproductive; 1996 C) Vegetative and D) reproductive; 1997 E) Vegetative, F) Reproductive biomass. Where sowing months are - -x- - = March, Δ= April, ● = May, --□-- =June. Bars are ± one standard error.

Independent of years and sowing month the proportion of the total biomass as leaves, stems and bolls were each correlated ($p < 0.01$) with DAS (Fig. 4.5). The *Gossypium hirsutum* cultivars were combined because their responses were not significantly different ($p < 0.05$), (Kruskal and Wallis 1952). The proportion of leaves declined from early squaring until maturity. For the proportion of stems (including petioles) a parabolic relationship, which peaked at approximately 100 DAS, was fitted from first squaring (40 to 50 DAS) to 148 DAS. There was a linear increase in the proportion of bolls from 75 DAS (early flowering) until 148 DAS. The stem and boll proportions of total biomass were not correlated after 148 days from sowing (Fig. 4.5).

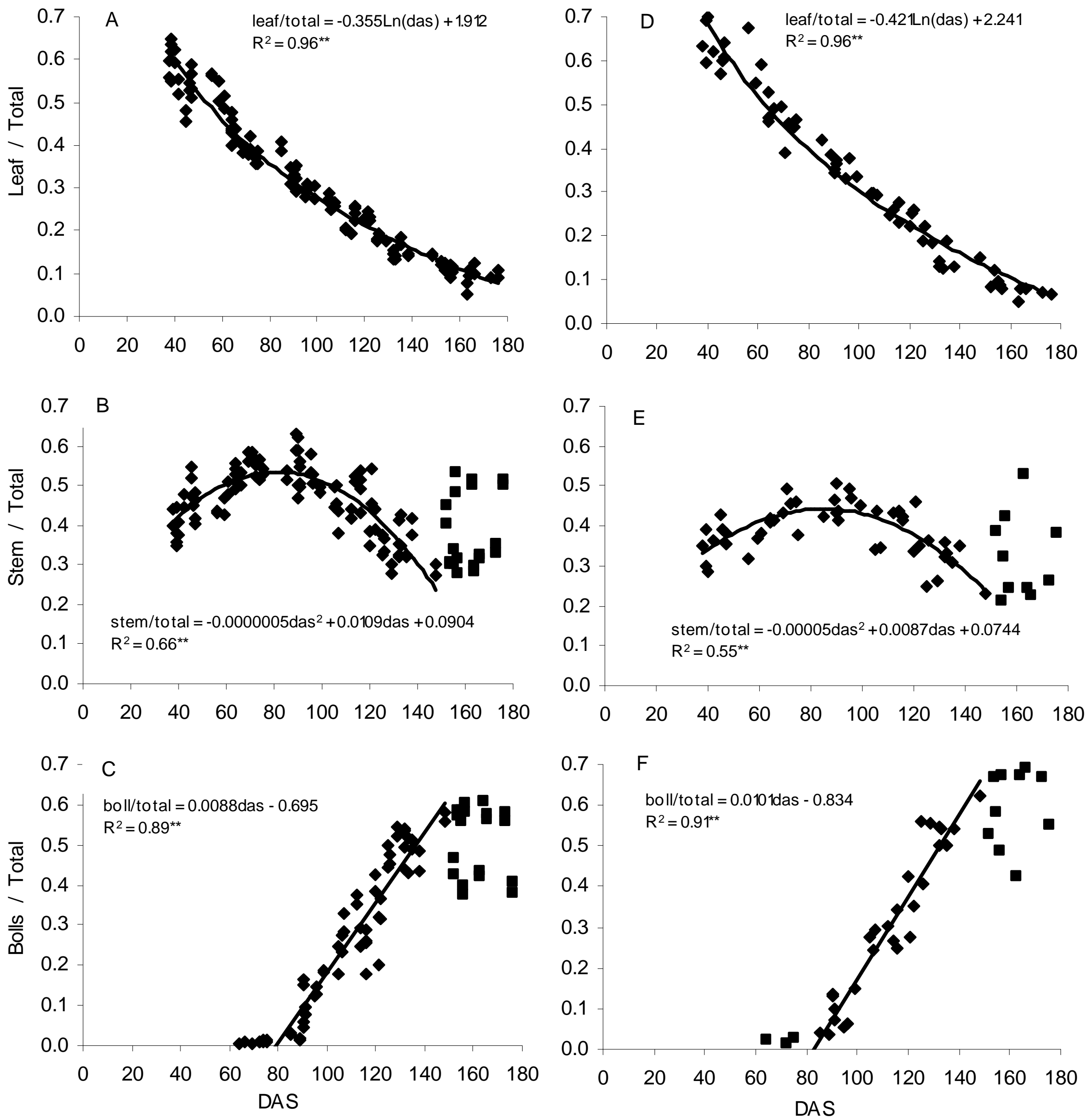


Fig. 4.5: The change in the proportion of total biomass as leaves, stems and bolls with DAS for the upland cultivars L23 and S50 A) leaves, B) stems, C) bolls and Pima S7 D) leaves, E) stems, F) bolls. Three seasons are combined. For Stems and bolls lines are fitted for < 149 DAS and 57 to 148 DAS respectively. Fitted lines are shown. n= 120 upland, n=60 Pima S7.

Allometric ratios were highly significant ($p<0.01$) and linear for the relations between boll or stem biomass and total biomass, where r^2 = 0.87, 0.86 and 0.94, 0.95 for the upland cultivars and Pima S7 respectively. The relationships between leaf biomass and total biomass was quadratic and highly significant for the upland cultivars r^2 = 0.85 and Pima S7 r^2 = 0.71 respectively.

4.4.4. *Plant height*

Early growth of the upland cultivars measured as plant height at 7.5 nodes was vigorous and not significantly effected by sowing month (Fig. 4.6). The analysis of variance was only significant ($P<0.05$) for the year main effect on plant height where 1995 = 43.3 cm, 1996 = 31.5 cm and 997 = 29.8 cm ($lsd_{0.05}$ = 7.3). The height at 7.5 nodes of tropical dry season cotton was double that expected for spring sown temperate cotton (Fig. 4.6). Treatment with mepiquat chloride occurred at or after 7.5 nodes (Chapter 3) and could not have affected plant height prior to this growth stage.

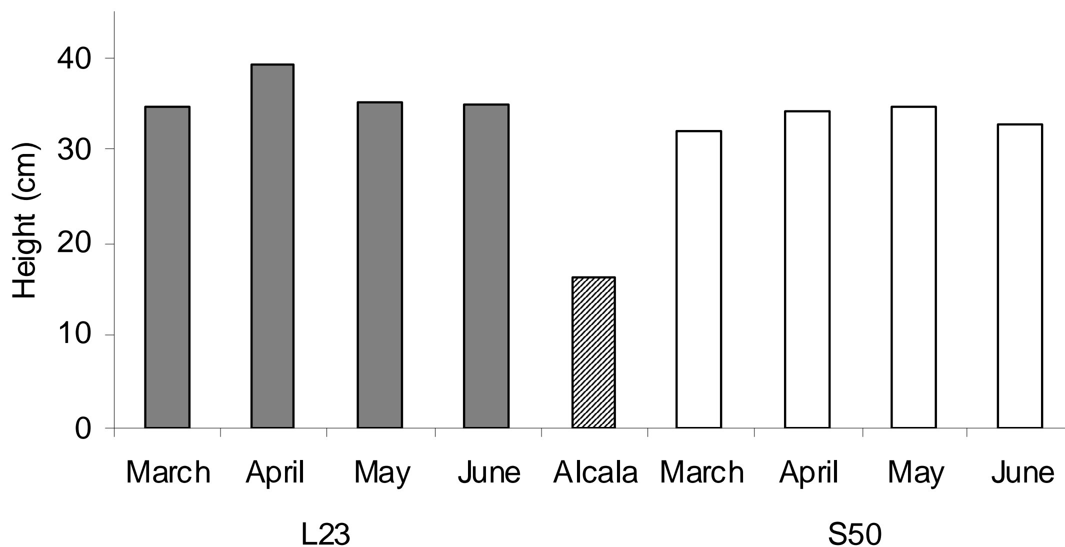


Fig. 4.6: The effect of sowing month on early plant height at 7.5 nodes, average of 3 years for L23 and S50. The standard Acala height at 7.5 nodes for spring sown cotton in temperate USA is adapted from Constable (1995). Where the analysis of variance for variety x sowing month was not significant ($p<0.05$).

At maturity March sowings were the tallest ($P<0.01$) for all cultivars in all years (Table 4). April and May sowings were the shortest although cultivar interactions ($P< 0.05$) were due to differences in the May sowing in 1995 and 1997. Cultivar main effects were significant ($P<0.01$) with L23 > S50 > Pima S7 in all years.

Table 4.4: Effect of month sown and cultivar on final height (cm).

Year / Month sown	Cultivar L23	S50	Pima S7	Mean	Analysis of variance	$Lsd_{0.05}$
1995					*Main effects*	
March	141.5	122.2	104.2	122.6	Month Sown	3.48
April	114.5	108.4	90.1	104.3	Cultivar	3.01
May	132.9	113.6	99.3	115.3	*Interaction*	5.91
June	110.8	101.7	97.8	103.4		
Mean	124.9	111.5	97.8			
1996					*Main effects*	
March	135.6	124.8	111.8	124.1	Month Sown	4.95
April	125.7	111.7	107.9	115.1	Cultivar	4.28
May	115.8	110.0	106.7	110.8	*Interaction*	ns
June	140.4	126.5	116.7	127.8		
Mean	129.3	118.3	110.8			
1997					*Main effects*	
March	127.3	118.6	102.3	116.0	Month Sown	4.20
April	109.8	97.6	85.7	97.7	Cultivar	3.65
May	97.6	100.0	76.9	91.5	*Interaction*	6.89
June	104.8	97.9	91.9	98.2		
Mean	109.9	103.5	89.2			

4.5. Discussion

4.5.1. *Biomass accumulation and partitioning at maturity*

Final crop biomass did not limit yield. For the highest yielding March and April sowings (Chapter 3) final crop biomass was mostly > 1000 g /m^2 (Table 4.1), which was similar to the maximum values reported for irrigated cotton in temperate Australia (Constable and Hearn 1981; Constable et al. 1990; Sadras 1996; Bange and Milroy 2004) and the USA (Wells and Meriedith1984a; Fritschi et al. 2003). These biomasses were also 25 to 60 % higher than for dry season cotton but similar to wet season cotton grown in the 1960's at this location (Stern 1965; Thomson 1965).

An important finding was that biomass was accumulated differently in the tropical dry season than in temperate (~ 30° lat.) and tropical wet season grown cotton. In the highest yielding March and April sowings in 1996 and 1997 (Chapter 3), final biomass was accumulated by sustaining a modest growth rate of 7.4 to 12.1 g/m^2/d for a long period (78 to 134 days) between first squaring and boll opening (Table 4.3). This contrasts with similar yielding crops in temperate climates where growth was characterised by shorter period (25 to 60 days) with a greater maximum growth rate of 15 to 20 g/m^2/d (Baker and Hesketh 1969; Hearn and Constable 1984; Mauney 1986; Kennedy and Hutchison 2001; Bange and Milroy 2004) and lower yielding wet season cotton, with a similar

vegetative biomass to this study, where a maximum growth rate of 7 to 16 g/m^2/d was maintained for 50 to 60 days (Stern 1965; Thomson 1965). However, the accumulation of biomass measured here was similar to that reported for a dry season sowing (March 30) at this location in the 1960's, where a maximum growth rate of 7.5 g/m^2/d was maintained for 101 days, although partitioning to bolls was lower than measured here (Thomson 1965).

The analysis of biomass accumulation shows that while the low mid-season temperature and radiation of the dry season combined to reduce growth rate, assimilate supply was able to meet the boll demand in the March and April sowings due an extended crop boll filling period (Chapter 3). The boll filling period was extended by the survival more bolls in distil positions on the sympodia. These flowers were produced later when temperature and radiation had increased; the outcome being that yields were highest for sowings in March and April (Chapter 3). The May and June sowings generally maintained their maximum growth rates for shorter periods than March and April sowings thereby often accumulating less biomass (Tables 4.1 and 4.3). The combination of lower biomass and or reduced partitioning to bolls (Table 4.1), a boll growth period that was 14 to 48 days shorter due to high early flower retention (Chapter 3) and supra optimal temperatures during boll growth (Hearn 1994) would explain the lower lint yields when sown in May or June.

For the upland cultivars, the proportion of final biomass as bolls in 1996 and 1997 (Table 4.1) was similar to temperate USA and Australia (Bassett 1970; Fritschi et al. 2003; Sadras et al. 1997) and 17 to 100% higher, than past dry season research at the ORIA (Stern 1965; Thomson 1965). Interestingly when only the vegetative biomass is calculated for these early 1960's studies, the values are similar to the March sowings in 1996 and 1997 (Fig. 4.4). It is possible modern cultivars, higher inputs of N fertiliser and superior insect control contributed to the higher partitioning to bolls measured in these experiments (Wells and Meredith 1984b; Hearn 1975). The lower proportion of total biomass as bolls in the first three sowings of 1995 (Table 4.1) could be attributed to less effective control of *Helicoverpa* larvae by the non Bt transgenic cultivars grown in that season (Chapter 3). This damage was unlikely to reduce yields in this environment due to rising end-of-season temperatures providing sufficient heat units for compensatory growth via new fruiting sites (Lei and Gaff 2003). It is possible in this environment, where bolls on distal sympodia contributed more to yield, to grow new fruiting sites required additional vegetative biomass thus reducing the proportion of dry weight as bolls.

The proportion of leaves at maturity (Table 4.2) was at the lower end of the range reported for summer grown crops in Australia and the USA (Bassett 1970; Constable and Hearn 1981; Fritschi

et al. 2003) and for a March sowing at this location (Thomson 1965). However, timing of sampling will affect final proportion of leaves. The proportion of final biomass as stems (Table 4.2) was in the higher end of the range reported elsewhere (Bassett 1970; Constable and Hearn 1981; Fritschi et al. 2003) and reflected the taller plants observed in this environment (Table 4.4).

4.5.2. *RUE and light interception*

The reduction of RUE with average temperature up to first flower (Fig. 4.3) has not been reported previously in cotton and explains some of variation in RUE observed here (Figs. 4.2 and 4.3) and elsewhere (e.g. Sadras 1996; Bange and Milroy 2004). The development of this relationship was possible because the temperature range observed for these sowing months was greater than could be generated reliably over the first square to first flower phase in temperate latitudes (~30°) or in the tropical wet season (Chapter 3). Low temperatures have reduced RUE in peanut (Bell et al. 1992), sorghum (Hammer and Vanderlip 1989) and maize (Andrade et al. 1993). The effect of lower temperatures on RUE would be expected to occur in cotton via their effect on photosynthesis (Peng and Krieg 1991). A similar reduction in photosynthesis due to temperature extremes occurs in grain legumes and has been incorporated in growth models via changes to RUE (Robertson et al. 2002).

Low temperatures are more likely to reduce RUE when cotton is sown in May or June because the greatest proportion of growth up to early flowering at these sowing dates coincides with the cooler months of June and July (Chapter 3). This observation appears to be supported by the generally lower biomass (flowering and maturity) of the May and June sowings (Fig. 4.4, Table 4.11). For these experiments, monthly temperatures were near (± 2°C) the long-term average (Chapter 3), hence the RUE for cotton sown in April could also be reduced in seasons with lower than average minima during flowering (May and June).

The change of RUE with ontogeny (Fig. 4.2) is consistent with studies in temperate climates. Sadras (1996) found for well grown cotton RUE increased from 73 to 90 DAS then declined until maturity. A similar response was found by Milroy and Bange (2003) when specific leaf nitrogen was moderate or low. The response of RUE to ontogeny appears to reflect the effect of leaf age on photosynthesis measured for cotton (Constable and Rawson 1980; Wells et al. 1986; Peng and Kreig 1991).

For the upland cultivars the range in RUE reported in Figs. 4.2 and 4.3 was similar to elsewhere using the glucose equivalent (GE) and dry weight only methods of calculating biomass (Sadras 1996; Bange and Milroy 2000; Bange and Milroy 2004; Constable et al. 1990; Rosenthal and Gerik

1991) but lower than the peak values of 3 g/MJ/m^2 reported by Milroy and Bange (2003), where leaf nitrogen concentration was high. The RUE for Pima S7 (*Gossypium barbadense*) of 1.2 to 2.3 g (GE) / MJ (Fig. 4.2) is the first for this species.

The days from sowing to reach maximum light interception was similar to that reported for temperate areas (Rosenthal and Gerik 1991; Milroy et al. 2001; Bange and Milroy 2004).

4.5.3. *Partitioning of biomass over time*

Cotton growth is concurrent where vegetative and reproductive growth competes for some of the crop life cycle (Hearn and Constable 1984; Mauney 1986; Bange and Milroy 2000). It is important to understand this competition to ensure effective management practices in the unique growing conditions of the tropical dry season. It was found for cotton grown in tropical dry season, the period when vegetative and reproductive competition occurred between 70 and 115 DAS or less than 30% of the life of the crop (Fig. 4.4). Importantly when vegetative biomass terminated, boll weight was only 20 to 40% of the boll weight at maturity, with the March and April sowings having the lowest proportions (Fig. 4.4). Hence, 60 to 80% of the final boll weight was accumulated after the termination of vegetative growth which is consistent with a high proportion of yield coming from later pollinated flowers (Chapter 3). This finding has important ramifications for crop management as it will be necessary to ensure that there is sufficient vegetative growth to produce the additional fruiting sites on the out side of the plant and leaf integrity will need to be maintained long after the last effective flower has been pollinated to grow a greater proportion of yield at this time. Hence pest, disease and nutrition management must ensure healthy leaves.

The pattern of partitioning over time (DAS) of biomass to leaves, stems and bolls observed here (Fig. 4.5) was similar to the pattern reported for temperate USA (Wells and Meredith 1984 a,b; Fritschi et al. 2003), although the change in the proportion of boll and stem weight was shifted to later in growth than reported in these studies, reflecting the greater fruiting on the outside of the plant (Chapter 3). However, the pattern of biomass partitioning differed from cotton grown during the wet season at this location (Thomson 1965), but was similar to the one dry season sowing (March) in the Thomson (1965) study.

The linear increase in the proportion of total biomass that was bolls (including walls, Fig. 4.5 C, F) with DAS is similar to that reported for temperate cotton by Sadras et al. (1997) and consistent with linear increase in harvest index observed in soybean (Sinclair 1986). Hence this response could be incorporated in a cotton growth model to simulate yields in a similar manner to soybean (Sinclair et

al. 1987) and other grain legumes (Robertson et al. 2002). The application of linear increase in harvest index to cotton yield simulation will also require a mechanism to adjust the slope and to terminate harvest index accumulation as these are affected by fruit survival and the balance between source supply and sink demand for assimilate (Hearn 1994). This is why the relationships fitted for the proportion biomass as bolls and stem (Fig 4.5: B, C, E, F) appeared to have different slopes than other studies and could only be applied up to 148 DAS.

Similarly allometric ratios are used to simulate biomass partitioning of a range of organs in many crop simulation models e.g. pearl millet (van Oosterom et al. 2002). The allometric ratios from this study can not be applied to simulate the partitioning of biomass of cotton until the timing of reproductive development can be accurately predicted over a greater climatic range (Chapter 3).

4.5.4. *Plant height*

Vigorous early growth (Fig. 4.6) was due to favourable temperatures and abundant nutrient and water supply. This was reflected in the plant height at 7.5 nodes of the upland cultivars that was double that reported for spring sown cotton in temperate regions (Fig. 4.6) but similar to other experiments at ORIA that were sown in April (Yeates et al. 2002b and 2005).

Sowing date differences in final height (Table 4.4) were due to a combination of temperature and early boll retention differences. Milder temperatures and higher early retention in May and June sowings preventing excessive vegetative growth, while the March sowing was exposed to longer periods of high temperatures during vegetative growth (Chapter 3). Due to taller plants, the March sowing would have the greatest risk of rank growth which can reduce picking and spraying efficiency. Growth suppression via early application of growth regulators (Yeates et al. 2002b) and optimised management of early season water and nutrient supply are options for management (Yeates unpublished data) of excess vegetative growth.

4.5.5. *Species differences*

A limitation of growing the *Gossypium barbadense* cultivar Pima S7 in the dry season could be greater susceptibility to cold early season temperatures if sown in April or May, as RUE was more sensitive to cool temperatures (Fig. 4.3) and canopy development was slower than the *Gossypium hirsutum* cultivars (Fig. 4.1). An advantage would be a reduced likelihood of rank growth due to Pima S7 being significantly shorter than the upland cultivars (Table 4.4).

4.6. Conclusions

1. Cotton grown in the tropical dry season accumulated biomass differently compared to temperate grown cotton (~30°S), the lower temperature and radiation during flowering and early boll growth combined to reduce growth rate but high yields were achieved because of an extended crop boll filling phase.
2. RUE was reduced in proportion to average temperature prior to flowering with the *Gossypium barbadense* cultivar more sensitive than the *Gossypium hirsutum* cultivars, which for both species, may limit vegetative biomass in May and June sowings and in cooler than average seasons for March and April sowings.
3. Crop management needs to be tailored to account for the production of a high proportion of yield (60 to 80%) after the termination of leaf growth.
4. Due to favourable early season temperatures and abundant nutrient supply, sowing in March produced the tallest plants and would have the greatest risk of rank growth.

Chapter 5: Irrigated cotton in the tropical dry season - Impact of temperature, cultivar and sowing date on fibre quality

5.1. Abstract

Depending on sowing month, temperatures during boll growth in the tropical dry season are potentially sub or supra optimal for the fibre quality parameters length and strength. The aims of this research were to: 1) measure the effect of sowing date on the quality of fibre from cotton grown during the dry season as this was not known; 2) use the range in temperature created by varying sowing date in the dry season, to derive relationships with gin turnout, the fibre quality parameters length, strength and micronaire. Over three seasons, two *Gossypium hirsutum* (upland) cultivars and one *Gossypium barbadense* cultivar were sown from March to June at the Ord River (15.5^{o}S), Western Australia. For the highest yielding sowing months of March and April, fibre length and strength were at or below market preference due to relatively low temperatures and solar radiation during early fibre development. Fibre micronaire achieved market preference at all sowing months due to favourable late season temperatures and radiation. It is likely that current *Gossypium barbadense* cultivars will have short fibre when grown in the dry season. For fibre length and gin turnout quadratic responses ($p < 0.05$) to weighted minimum temperature were fitted for each cultivar, where the optimum minimum temperature was 18 to 20°C and 16 to 17°C respectively. The cultivar differences in fibre properties observed here suggest wider screening may identify *Gossypium hirsutum* cultivars with suitable fibre length and strength in the dry season. It was demonstrated by weighting of temperatures for the contribution of the cohort of bolls pollinated each day the variation in crop fibre quality and gin turnout in the field due to temperature can be predicted.

5.2. Introduction

Cotton is primarily grown for its fibre and the research reported here forms part of a broader research effort to evaluate the potential to grow cotton as an irrigated dry (winter) season crop in the Ord River Irrigation Area in Western Australia (15°S) and potentially more widely within the semi-arid tropics. This Chapter assesses the effect of cultivar, sowing month and temperature on fibre quality as the fibre quality of irrigated cotton grown in the tropical dry season was largely unknown.

Previous research (Chapters 3 and 4) found sowing in March and April produced the highest cotton lint yields which were comparable to the upper end of Australian and international benchmarks for irrigated cotton. However, high yield was correlated with bolls on the outside fruiting sites on the plant, which differed from temperate climates (approximately 30° lat.). Gin turnout was also affected by sowing date and possibly temperature. For the highest yielding March and April sowing months, biomass and canopy development were not limiting to yield, although the final biomass was accumulated via a slower maximum growth rate that was maintained for a longer period than occurs in temperate regions. Radiation use efficiency from first square to first flower was reduced in proportion to temperature which may limit dry weight accumulation in cooler than average seasons.

In Chapters 3 and 4 the daily minimum temperatures during boll growth for the March and April sowing months averaged 13 to 16°C with the lowest individual minimum being 7.1^{o}C. Maxima and minima greater than 37°C and 22°C occurred during boll growth of the May and June sowings. These temperatures were consistent with the long term average (Cook and Russell 1983) and could be problematic for fibre growth and development as fibre length, strength and micronaire are all affected by extremes of temperature (Gipson and Joham 1968 and 1969; Hesketh and Low 1968; Gipson and Ray 1970; Quisenberry and Kohel 1975, Wanjura and Barker 1985; Xie et al. 1993; Liakatas et al. 1998). The range of temperatures observed in the sowing dates used in these experiments also provide an opportunity to measure the effect of temperature on fibre quality for field grown cotton in an environment where average monthly radiation, although lower than temperate latitudes at the same growth stage, is reasonably constant during flowering, 19 to 22 MJ/m^2 (Chapter 3).

The reported responses of fibre length to temperature have varied, being parabolic or linear to night or mean or daily range of temperature (Gipson and Joham 1968 and 1969; Hesketh and Low 1968;

Gipson and Ray 1970; Wanjura and Barker 1985; Liakatas et al. 1998). Large cultivar differences in the type of response and sensitivity of fibre length to temperature have been measured (Hesketh and Low 1968; Kohel et al. 1974). Fibre strength and micronaire are also reduced by cool temperatures (Gipson and Joham 1968 and 1969; Hesketh and Low 1968; Gipson and Ray 1970; Quisenberry and Kohel 1975; Wanjura and Barker 1985; Liakatas et al. 1998).

Fibre length is determined during the fibre elongation phase which occurs during the first 25 to 40% of the boll period (Schubert et al. 1973; Kohel et al. 1974; Thaker et al. 1989). Fibre strength and micronaire are determined toward the end of the fibre elongation phase and into the secondary wall formation phase, with most fibre weight increase occurring between 25 to 75% of the boll period (Schubert et al. 1973).

Due to cotton's prolonged flowering period, the final quality of a crop of cotton, in the absence of water and nutrient stress, is the sum of the contribution of cohorts of bolls that flowered on each day, thus have grown under different temperatures (Wanjura and Barker 1985; Bradow et al. 1997). Hence, the prediction (simulation) of the effect temperature on fibre quality for a crop of cotton requires a model that can predict the timing of the temperature sensitive boll development stages, the fibre quality and the proportion of lint yield contributed by each cohort of bolls.

Therefore, the aims of this paper are: First, to measure the quality of fibre from cotton cultivars grown during the tropical dry season. Second, to use the variation in temperature created by varying sowing date in the dry season, to derive relationships with gin turnout and the fibre quality parameters length, strength and micronaire.

5.3. Materials and Methods

Sowing date by cultivar experiments conducted over three seasons at the Frank Wise Institute, 13 km NW of Kununurra, WA, Australia (15°39'S, 128°43'E) in the Ord River Irrigation Area were used to collect relevant data. These experiments are described in greater detail in Chapter 3. To summarise, the *Gossypium barbadense* L. cultivar Pima S7 was compared with two Bt transgenic *Gossypium hirsutum* L. (upland) cultivars Siokra L23i and Sicot 50i (producing the Monsanto Cry1Ac protein). In the first season the non Bt transgenic equivalent (Siokra L23 and CS50) of the upland cultivars were sown. Where data is combined for the three seasons these cultivars are referred to as L23 and S50. In each of the 3 seasons these cultivars were sown on 4 occasions (main plots): 27 to 29 March, 21 to 29 April, 15 to 23 May and 9 to 14 June; there were 4

replications. The experiments were furrow-irrigated. The crop was sown at a 90 cm row spacing on wide beds accommodating two rows per bed. Plots were 6 rows wide and 20m in length. Analysis of variance was made using Genstat (Lawes Agricultural Trust, IACR, Rothamsted, UK) and regression analysis using SAS (SAS 2001).

Fibre quality was tested on a 300 g sub-sample of lint from each plot, with High Volume Instrumentation at CSIRO Plant Industry at Narrabri, NSW. Flower and boll counts were made from 1m^2 in each plot at 10 to 14 day intervals from first flower to when 60% of bolls were open. A flower was defined as a boll when the petal was red. Gin turnout was measured as described in Chapter 3. Because different gins were used over the three seasons the gin turnout relative to the maximum for each season was calculated for each cultivar and used in regressions with temperature. Temperatures were collected in a standard Stevenson screen 500m from the experiment site.

5.3.1. *Prediction of fibre quality from temperature*

The objective of this analysis was to find out wether crop fibre length, strength, micronaire and gin turnout could be related to temperature for a field grown crop via the sum of contribution to the fibre properties of the bolls set each day of the flowering period. Where the number of bolls set each day is a cohort. Because the quality of each cohort was not measured (cost) the crop fibre quality (all cohorts combined) was related to a weighted temperature derived for each cultivar based on the proportional contribution to final boll number from each cohort. The method of calculation of weighted temperature was similar to that used by Yeates et al. (2000) to weight the effect of rainfall and humidity to predict seed quality of mungbean (*Vigna radiata*) using daily cohorts of ripe pods.

<u>5.3.1.1. Steps in calculation of weighted temperature</u>

1. *The proportion of final boll number (pollinated) per cohort.* This equals the daily increase in boll numbers (m^{-2}) divided by the total number of bolls set (m^{-2}) and was calculated from Fig. 5.1 for each cultivar and sowing month. For most of the treatments the increase in boll numbers from first flowering to the final value was linear (Fig. 5.1) and reflects the increase in boll dry weight, which was also linear from first flower (Yeates et al. 2010b). The last effective flower date occurred when final cohort of bolls pollinated, which was defined as the date when the boll count first reached the total at maturity. As Fig. 5.1 shows the count often increased after this date only

to fall by crop maturity, hence it was assumed these additional bolls had been shed due to insufficient assimilate supply (see Hearn 1994).

2. *The boll period for each cohort.* The functions developed in Chapter 3 were used:

Upland cultivars $1/bp = 0.00122Tav – 0.0165$

Pima S7 $1/bp = 0.00124Tav-0.0181$

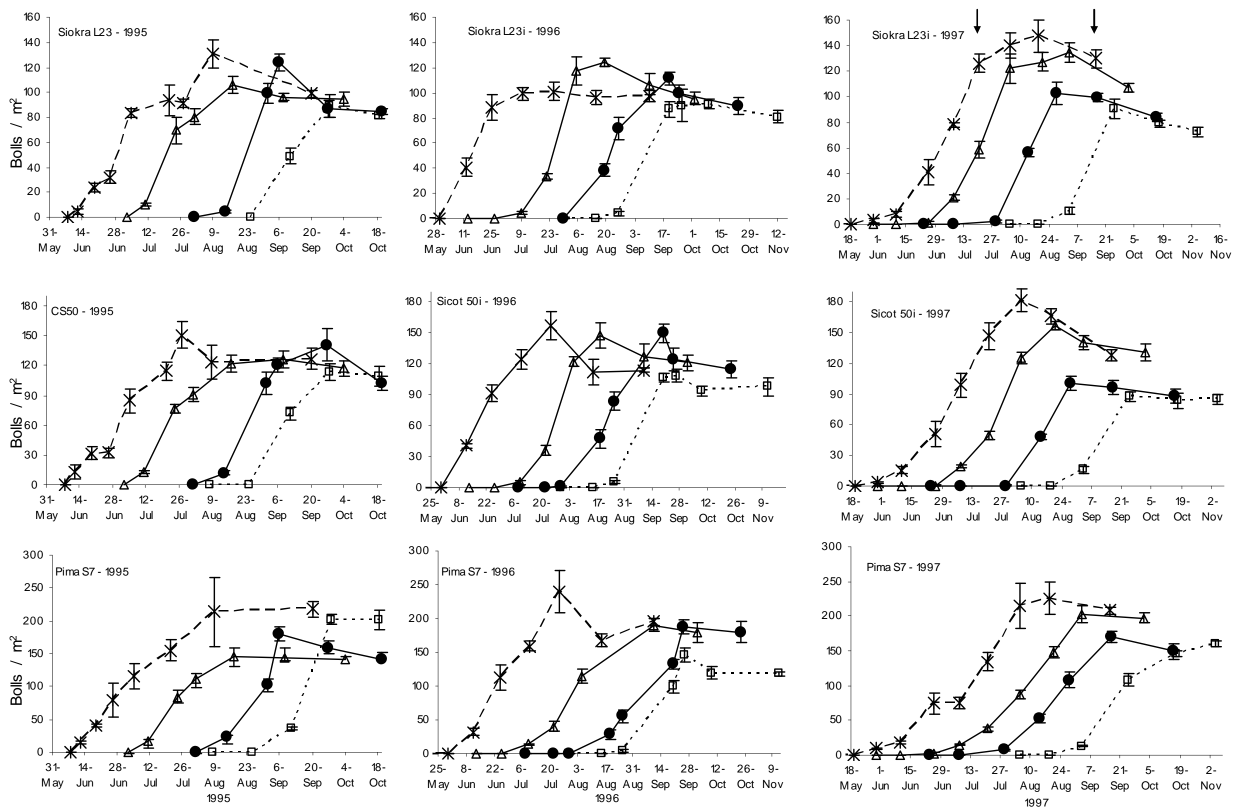
Where boll period (bp) is calculated by integrating the daily rate of progress to boll maturity (1/dp) due to average daily temperature (Tav).

3. *The average temperature for different proportions of the boll period for each cohort.* The average minimum, mean and maximum daily temperatures for 30%, 30 to 75%, 75% and 100% of the boll period were calculated for each day of the flowering period.

4. *The weighted temperature.* This was calculated from first flower to last effective flower and incorporated the proportional contribution of each cohort as shown:

$$WT = {}^{CO}{}_{F}\Sigma \text{ (T* boll number of each cohort / total boll number).}$$

Where: WT = weighed temperature; T = average temperature (maximum or minimum or mean) over the boll period, or proportions of, calculated for each cohort; F = first flower; CO = last effective flower. The weighted temperature was calculated for 30, 30-75, 75 and 100% of the boll period.



5.1: The change in boll numbers used to determine the daily cohort of bolls that was set. Using the March 1997 sowing of Siokra L23 as an example of how this calculation was made. Each daily cohort is calculated between the start of boll number increase and the first arrow. This arrow shows the first date when the boll number equalled boll number at maturity, that is, the date when the last cohort of bolls was pollinated. The second arrow marks the final boll number at maturity. Any bolls pollinated between the arrows were assumed to have shed. Where x = March, Δ= April, ● = May and □ = June sowing months. Bars are ±se.

5.4. Results

5.4.1. *Climate details*

Daily maximum and minimum temperatures for the experiments are shown in Fig. 5.2. Daily minima varied widely during the flowering period of May to August and minima below 10°C were observed in June, July and early August. Monthly rainfall and radiation were near the long term average for the flowering period at all sowing dates (Chapter 3). There was a small range in the average daily solar radiation per month during the flowering period, 18.9 to 22.0 MJ/m^2 and post flowering period (August to October), 20 to 24 MJ/m^2 (Chapter 3).

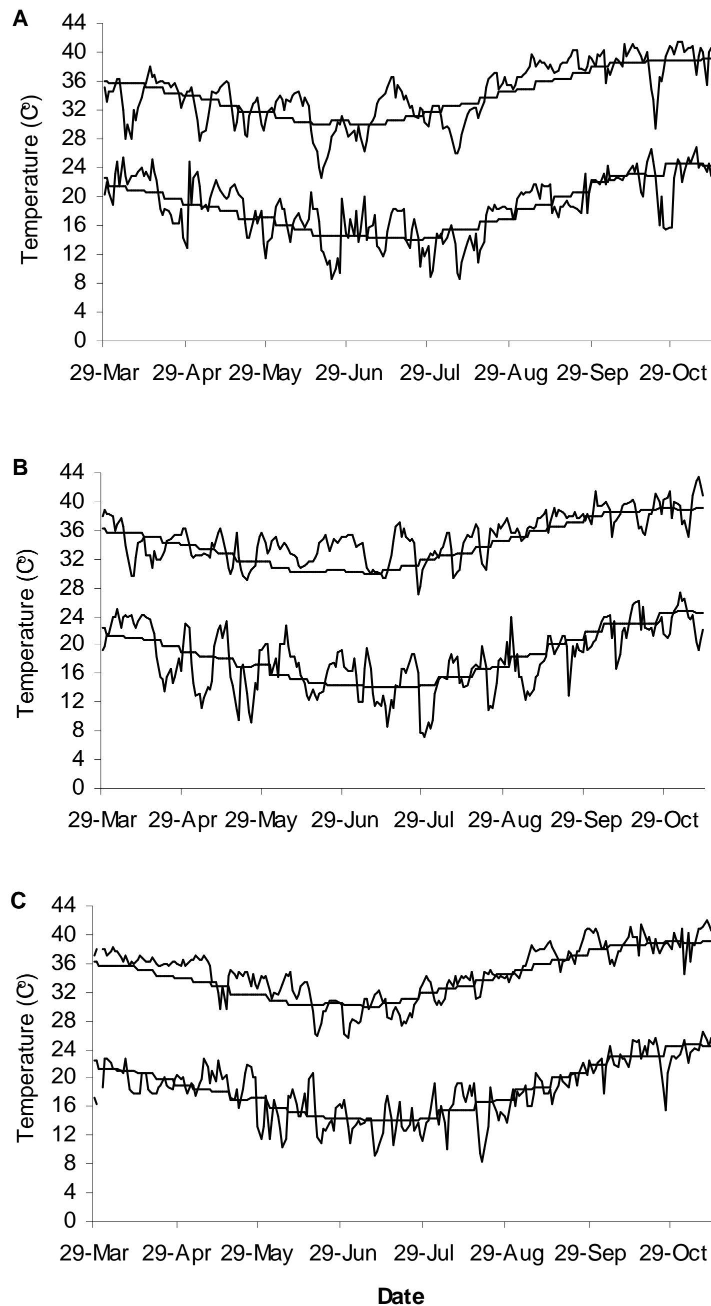


Fig. 5.2: Daily maximums and minimum temperatures for A) 1995, B) 1996, C) 1997. Solid line is long term average.

5.4.2. *The effect of sowing month on fibre length, strength and micronaire*

Fibre length was significantly ($p<0.05$) affected by month of sowing in all years (Fig. 5.3A). April sowings consistently had the shortest fibre with May and June sowings producing the longest fibre in all cultivars over the three seasons (Fig. 5.3 BCD). Cultivar main effects were also significant ($p<0.05$) for the three seasons with Pima S7 > L23 > S50 (Fig. 3 BCD). The cultivars responded similarly to sowing month with a significant cultivar by sowing date interaction only observed in

1995, which was due to Pima S7, when sown in April, having relatively longer fibre and Siokra L23, when sown in June, having relatively shorter fibre

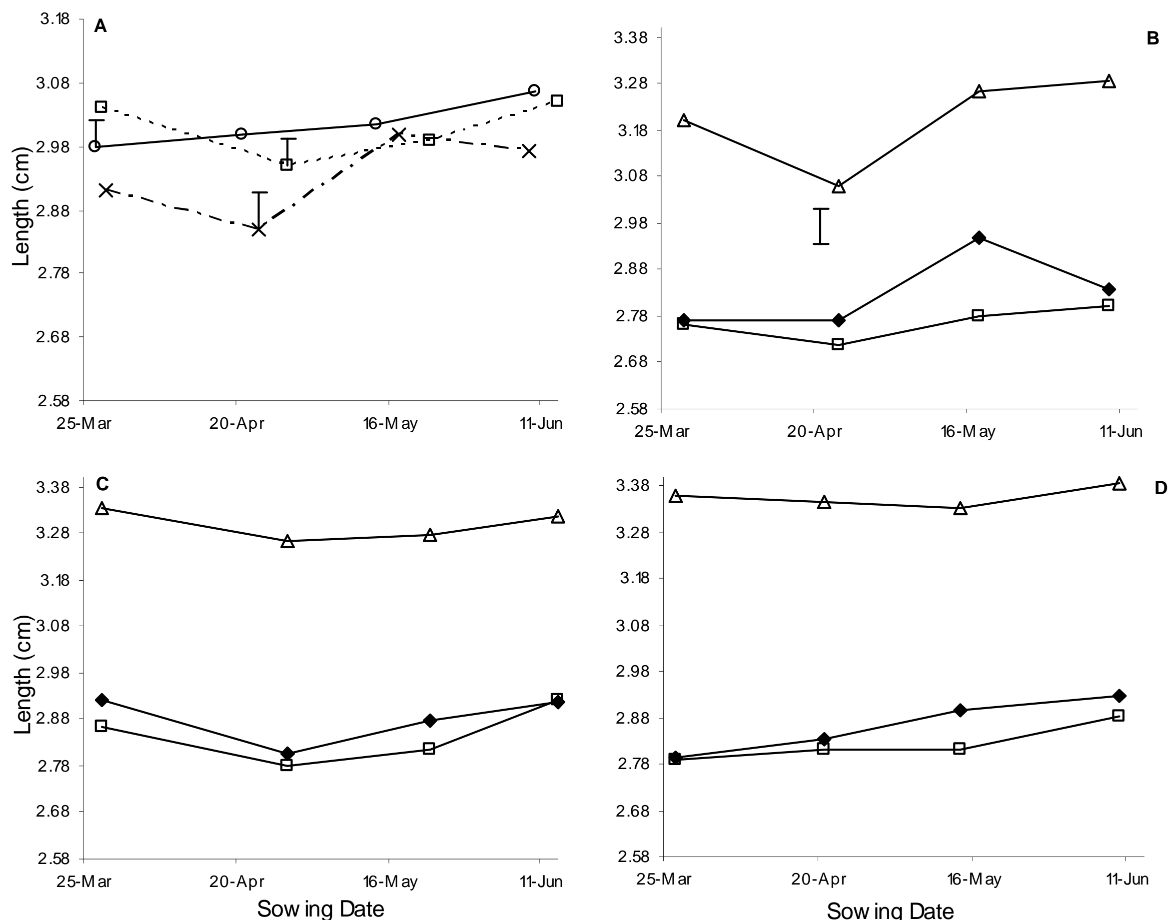


Fig. 5.3: Effect of sowing date and cultivar on fibre length (cm). A) shows the sowing month main effect where: x = 1995, ◊ = 1996, ○=1997. B), C), D), show the sowing date by cultivar interaction for 1995, 1996 and 1997 respectively. Where: ♦ = L23, □ = S50, Δ = Pima S7. Bars are $Lsd_{0.05}$ when significant.

The fibre length of Pima S7 was below the Egyptian Long Staple (ELS) or the Supima preference lengths for *Gossypium barbadense* of 3.66 and 3.51 cm (Supima 2009) for all sowings in all years. S50 was near or below the Australian preference length for *Gossypium hirsutum* of 2.78 cm (Bange et al. 2009) in all April and 1995 and 1997 March sowings. L23, although having longer fibre than S50, was also near or below the preference length for most March and April sowings (Fig. 5.3BCD).

The sowing month main effect on fibre strength was significant ($p<0.05$) in all years (Fig. 5.4A). Strength was generally lower at March sowings, April sowings were variable and fibre was

consistently strongest at May and June sowings. Cultivar main effects were also significant ($p<0.05$) in all years and similar to their length properties with Pima S7 > L23 > S50 (Fig. 5.4 BCD). The upland cultivars were below the Australian preference of 28 g/tex (Bange et al. 2009) at all March and April sowing dates except Siokra L23i sown in March 1997 and April 1996. The strength of S50 was below 26 g/tex in most sowings over the three years, which would incur the maximum price discount. The sowing month by cultivar interaction was significant due to higher strength of Pima S7 in April 1996 and May 1995 (Fig. 5.4BC).

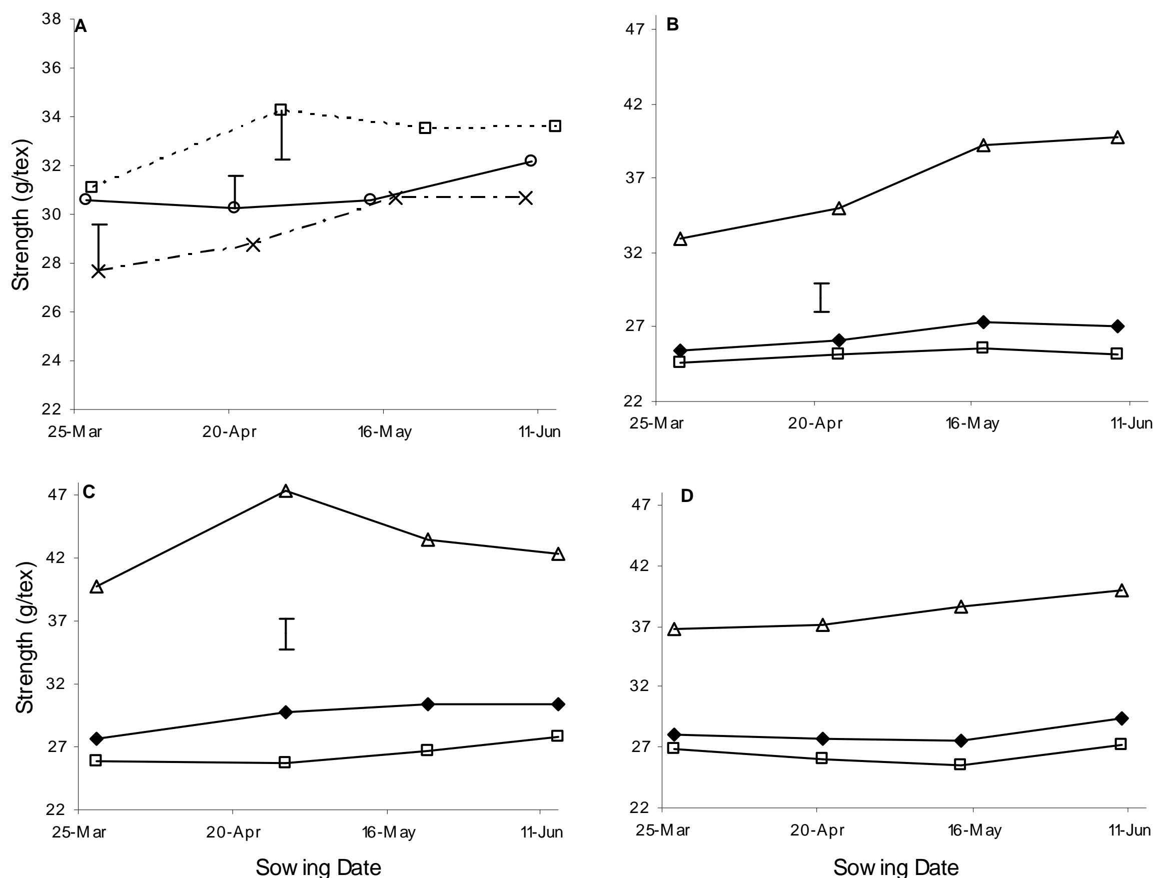


Fig. 5.4: Effect of sowing date and cultivar on fibre strength. A) shows the sowing month main effect where: x = 1995, ◊ = 1996, ○=1997. B), C), D), show the sowing date by cultivar interaction interactions for 1995, 1996 and 1997 respectively. Where: ♦ = L23, □ = S50, Δ = Pima S7. Bars are $Lsd_{0.05}$ when significant.

The fibre strength of Pima S7was below preference for ELS and Supima of 38 and 41 g/tex (Supima 2009) respectively for March and April sowings in 1995 and 1997. Given these are the best months for yield (Chapter 3) it means two-thirds of the years had low strength.

For the upland cultivars (*Gossypium hirsutum)* micronaire was within the Australian preference range of 3.5 to 4.9 (Bange et al. 2009) for all sowing months in all years (Table 5.1). The sowing date main effect was significant ($p<0.05$) in 1995 and 1997 with March sowings lower than other months. The upland cultivars had greater micronaire than Pima S7. The sowing month by cultivar interaction was also significant in all years due mainly to the upland cultivars increasing micronaire between March and April sowings and micronaire of Pima S7 decreasing between these months. The Pima S7 micronaire was within the preferred range of 3.5 to 4.1 (Supima 2009) for all except March and June sowings in 1997 when micronaire was higher.

Table 5.1: Effect of sowing date and cultivar on fibre micronaire for each year.

	Month of sowing						
Micronaire	March	April	May	June	Mean	$Lsd_{0.05}$	
1995							
Siokra L23	3.9	4.3	4.1	4.0	4.1	Month Sown	0.22
CS50	3.6	4.1	4.1	4.2	4.0	Cultivar	0.11
Pima S7	3.8	3.8	3.5	3.5	3.6	Interaction	0.27
Mean	3.8	4.1	3.9	3.9			
1996							
Siokra L23i	4.3	4.3	4.1	3.8	4.1	Month Sown	Ns
Sicot 50i	4.1	4.2	4.3	3.9	4.1	Cultivar	0.14
Pima S7	3.8	3.6	3.8	4.1	3.8	Interaction	0.27
Mean	4.0	4.0	4.1	3.9			
1997							
Siokra L23i	4.2	4.7	4.4	4.5	4.4	Month Sown	0.21
Sicot 50i	4.2	4.8	4.3	4.7	4.5	Cultivar	0.12
Pima S7	4.2	4.1	4.1	4.3	4.2	Interaction	0.27
Mean	4.2	4.5	4.3	4.5			

5.4.3. *Prediction of fibre quality from temperature and boll cohorts*

Crop fibre length was most significantly correlated with weighted minimum temperature (WTmn) calculated for the first 30% of the boll period for each day's cohort of bolls (Table 5.2). Fibre length was most sensitive to WTmn for the cultivar L23 (Table 5.2). The response to WTmn was quadratic for all cultivars and fibre length was greatest were WTmn was between 17 and 19°C for the first 30% of the boll period (Fig. 5.5). Similar responses were found for weighted average and maximum temperature but the regression coefficients were less than for minimum temperature (data not presented). For example the correlation coefficients for the quadratic relationship between weighted minimum, average or maximum temperature and fibre length for L23 were r^2 = 0.82, 0.78 and 0.66 respectively.

Table 5.2: Regression coefficients (quadratic) between fibre quality parameters or gin turnout and weighted temperature averaged for the different proportions of the boll period. Fibre length and gin turnout are correlated with weighted minimum temperature and fibre strength and micronaire are correlated with weighted average temperature. The weighted temperature was calculated from anthesis for each daily cohort of bolls. Where, *=p<0.05, ** = p<0.01.

	Proportion of boll period (r^2%)			
Cultivar	30%	30 to 75%	75%	100%
		Fibre Length		
L23	81.4**	74.4**	43.0*	45.6*
S50	36.4*	31.6	33.1	25.1
Pima S7	38.5*	9.7	16.7	22.7
		Fibre strength		
L23	25.0	17.8	21.0	25.8
S50	12.7	30.4	26.5	36.3*
Pima S7	39.7*	16.5	27.6	17.9
		Micronaire		
L23	6.2	4.4	3.5	11.0
S50	2.3	4.2	5.3	2.0
Pima S7	1.7	3.5	1.5	1.0
		Gin turnout		
L23	33.8	35.1*	35.4*	11.2
S50	14.0	50.5*	55.2*	35.6
Pima S7	34.1	25.2	44.0*	25.2

Fibre strength was most strongly correlated with weighted average daily temperature (Table 5.2), the highest correlation coefficients, although significant ($p < 0.05$), explained at best only 40% of the variation in fibre strength due to temperature. There was no consistent proportion of the boll period where temperature had a greater influence on fibre strength. Micronaire was not correlated (r^2 <10%) with weighted temperature calculated for any proportion of the boll period.

For all cultivars, WTmn for the first 75% of the boll period had the highest correlation gin turnout, although it was difficult to identify a critical proportion of the boll period when gin turnout was most sensitive to temperature, as correlation coefficients were similar for between 30% to 75% of the boll period (Table 5.2). The response gin turnout to WTmn for the first 75% of the boll period was quadratic, significant ($p<0.05$) and accounted for 35, 44 and 54% of the variation in gin turnout for L23, S50 and Pima S7 respectively (Fig. 5.6). Gin turnout was greatest when weighted minimum temperature was between 16 and 17°C for all cultivars (Fig. 5.6).

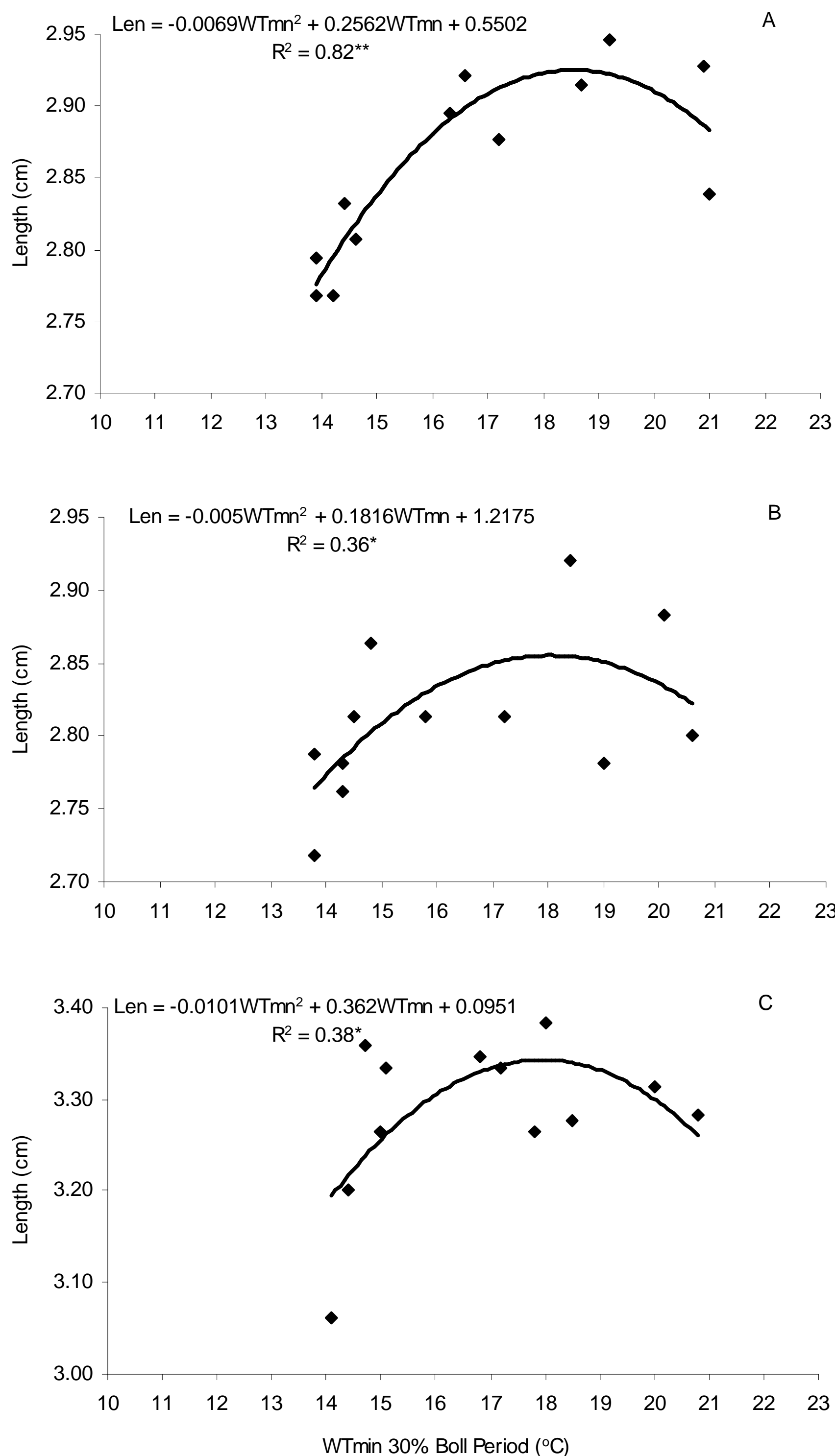


Fig. 5.5: Significant quadratic relations fitted for the effect on fibre length (cm) of minimum temperature weighted (WTmn) for daily contribution of boll cohorts and calculated for the first 30% of the boll period for each cohort. A) L23, B) S50 and C) Pima S7. Fitted equations are shown. *=$p<0.05$, ** = $p<0.01$.

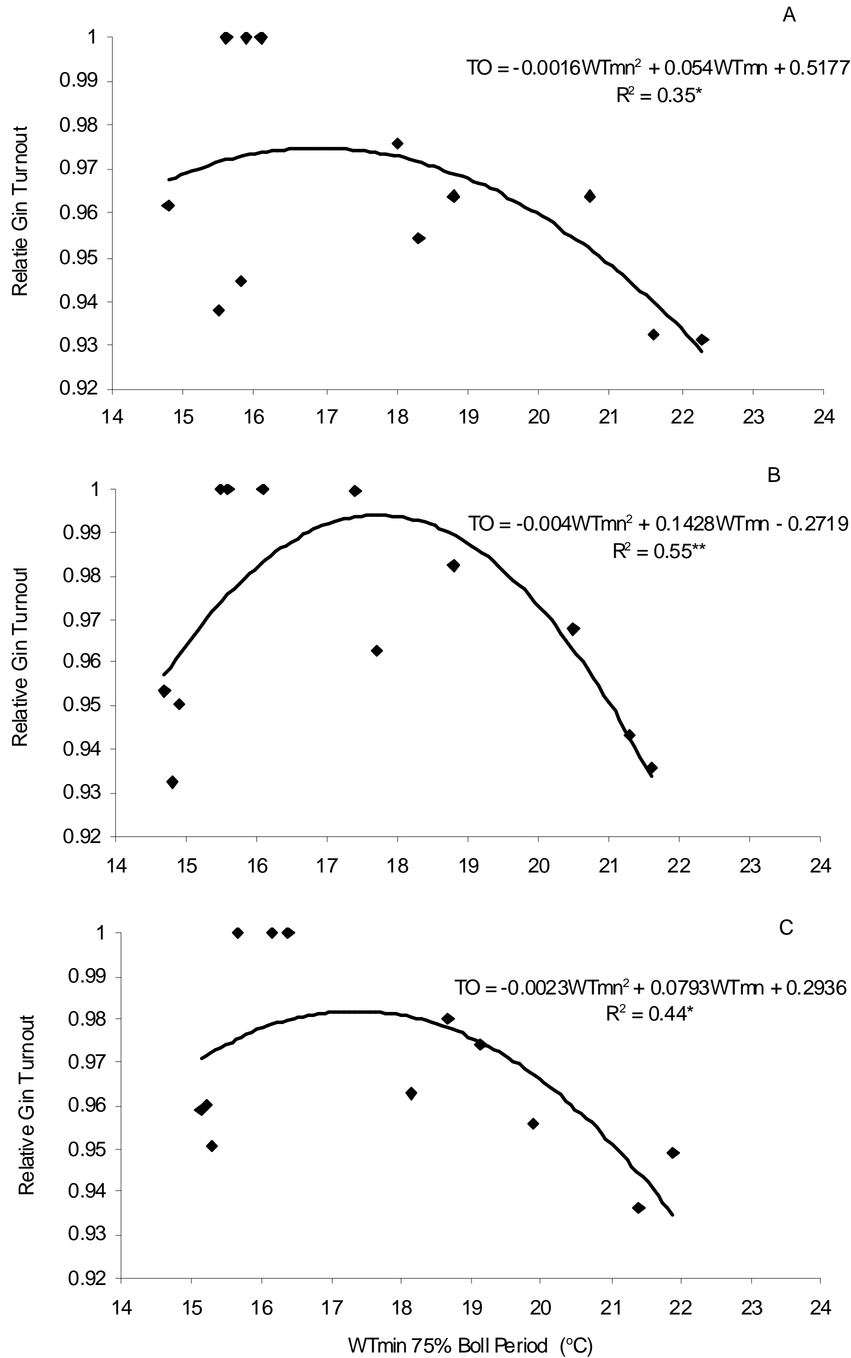


Fig. 5.6: Significant quadratic relations for the effect on relative gin turnout (TO) of minimum temperature weighted (WTmn) for daily contribution of boll cohorts and calculated for the first 30% of the boll period for each cohort. A) L23, B) S50 and C) Pima S7. Fitted equations are shown. *=$p<0.05$, ** = $p<0.01$.

5.5. Discussion

5.5.1. *The effect of sowing month and cultivar on fibre quality*

Producing fibre with a length and strength that is acceptable to the market at the sowing months most favourable for yield and time to maturity, that is March and April (Chapter 3), appears to be a limitation to producing cotton in the dry season (Figs. 5.3 and 5.4). Flowering for the March and April sowing months coincided with the coolest temperatures in June and July (Chapter 3). Cool temperatures, particularly minima, are known to reduce fibre length and strength (Hesketh and Low 1968; Gipson and Ray 1970; Wanjura and Barker 1985; Liakatas et al. 1998). However, the range in fibre length and strength observed here for the upland cultivars (Figs. 5.3 and 5.4), was sufficiently encouraging that wider screening may identify cultivars that can reliably produce suitable fibre in these conditions.

The *Gossypium barbadense* cultivar Pima S7 produced fibre shorter than the current market preference in all sowing months in these experiments and other fibre properties were also frequently below preference (Supima 2009), so it was unsuitable on the basis of quality (Fig. 5.3). Concurrent screening of eight *Gossypium barbadense* lines released by the USDA-ARS breeding program in Arizona (Turcotte et al.1991), failed to find any lines with suitable fibre length under cool nights (Yeates S.J. and Constable G.A. unpublished data). The commercial prospects for *Gossypium barbadense* are doubtful unless longer and stronger fibre types are identified.

Interestingly the maximum fibre length measured here of 2.95, 2.92, 3.38 cm for L23, S50 and Pima S7 respectively (Figs 5.3 and 5.5) was lower than for the same cultivar when grown in temperate Australia of 3.05, 3.07 and 3.58 cm respectively (Constable, G.A. unpublished data). Similarly the maximum strength of L23 and S50 of 30.4 and 27.9 g/tex were below their averages in temperate Australia of 31.5 and 30.2 g/tex. Temperatures in southern Australia were similar to the optimums reported here. It is possible that the lower radiation during boll growth (Chapter 3) may have limited assimilate supply increasing competition between bolls during elongation and secondary wall formation. Competition between bolls has reduced boll size in temperate regions (Kerby and Buxton 1981; Jenkins et al 1990; Constable 1991; Pettigrew 1995; Boquet and Moser 2003). A higher proportion of second and third position bolls on fruiting branches contributed more to yield here compared to temperate climates (Chapter 3), and bolls from these positions usually have lower fibre length and strength in temperate climates (Heitholt 1997; Davidonis et al. 2004).

Micronaire was largely unaffected by sowing date and achieved current market benchmarks for all cultivars. This result reflects the rising temperature and radiation late in the season, August to October (Fig. 5.2) (Chapter 3), and is consistent with the micronaire measured in similar temperatures late in boll development in other studies (Gipson and Ray 1970; Wanjura and Barker 1985). The slightly lower micronaire at the March sowing reflects cooler temperatures late in boll development (Chapter 3).

5.5.2. *Prediction of fibre parameters from temperature*

The boll cohort approach was successful in explaining a significant proportion of the variation in fibre length due to temperature in the field (Table 5.2, Fig. 5.5). This approach also demonstrates the effect of temperature on crop fibre length can be simulated provided the proportion of final yield produced from the daily boll set can be predicted. This is possible using the cotton simulation model OZCOT (Hearn 1994).

The quadratic response of fibre length to weighted minimum temperature in these field experiments (Fig. 5.5) was similar to the response to fixed minima measured elsewhere (Gipson and Joham 1968; Gipson and Ray 1970). Moreover, the relations fitted in Fig. 5.5 had regression coefficients at worst similar to the r^2 of 0.43 to 0.20 for the five cultivars compared by Gipson and Ray (1970) or the r^2 of 0.12 and 0.74 for the two cultivars compared by Gipson and Joham (1968). As was the case in their experiments, the cultivars in our field experiment responded differently to minimum temperature (Fig. 5.5). These quadratic responses to minimum temperature differed from the negative linear relation fitted by Hesketh and Low (1968), where fixed day and night temperatures were compared in a controlled environment.

The positive correlation of fibre strength with temperature (Table 5.2) was consistent with other studies (Hesketh and Low 1968; Wanjura and Barker 1985; Liakatas et al. 1998). The correlation of fibre strength with temperature was generally poor (Table 5.2) and could be in part due to the method of testing a bundle of fibres of fixed volume. A sample dominated by fine fibres will have more fibres that are individually weaker but have an acceptable strength (Gipson and Joham 1968). Unfortunately fibre fineness was not measured in these experiments. There were only small variations micronaire across the sowing dates and seasons (Table 5.2), hence it was not surprising that there was no correlation with temperature.

The boll cohort approach also identified a significant correlation between gin turnout and minimum temperature for a field grown crop (Table 5.2, Fig 5.6). The reduction in gin turnout as minimum

temperature exceeded 18°C was consistent with controlled environment studies (Hesketh and Low 1968; Liatatas et al. 1998). The greater variability in gin turnout at lower minimum temperatures is more difficult to explain (Fig. 5.6). The growth rate of seed is known to exceed cellulose at low night temperatures (Stewart 1986) suggesting that gin turnout should be lower. Heitholt (1997) found gin turnout increased along the fruiting branch from first to third position bolls. It is possible that a high proportion of second and third position bolls may have increased the gin turnout for the April sowings which were also exposed to the coolest night temperatures (Chapter 3).

There are three possible sources of error in the simulation fibre quality by the boll cohort approach used here. First, is the assumption that fibre quality is not affected by competition for assimilates between reproductive and vegetative organs. It is known competition for assimilate between bolls and vegetative organs can reduce boll size and fibre quality (Jenkins et al 1990; Constable 1991; Pettigrew 1995; Heitholt 1997; Davidonis et al. 2004). Second, the assumption that all bolls are shed after the maximum boll number is first reached may be further source of error as some replacement of bolls could occur. The maximum boll number was reduced 0 to 25 % by maturity in these experiments (Fig. 5.1) unless a high proportion of the early pollinated bolls were replaced during this time this error is likely to be small. Third, measurement of fibre quality from individual cohorts could improve the robustness of this analysis. Further research is required to quantify the impact of these assumptions.

5.6. Conclusions

1. For the highest yielding March and April sowings, fibre length and strength were low to marginal due to cool temperatures during fibre development. The cultivar differences observed here suggest wider screening may identify *Gossypium hirsutum* cultivars with suitable fibre length and strength in these conditions.
2. Using the large temperature range observed here it was demonstrated that by the weighting of temperatures for the contribution of the cohort of bolls pollinated each day the variation in crop fibre quality and gin turnout in the field due to temperature can be predicted.

Chapter 6: The impact of variable cold minimum temperatures on boll retention, boll growth and yield recovery of cotton

6.1. Abstract

A previous field experiment grown in the tropical dry season, where minimum temperatures during flowering were variable but occasionally cold (<10 ^{o}C) found a greater proportion of cotton yield was from bolls that pollinated when minimums were warmer. The retention and growth of flowers was postulated to be reduced by cold night temperatures. However biotic stresses (e.g. pests) may have confounded this response. Reported is a pot experiment where biotic stresses were effectively removed. Over two seasons: (i) ambient and (ii) ambient plus 5 to 6 ^{o}C (range 10 to 24 ^{o}C) night thermal conditions were imposed from 1 wk prior to first flower to 2 wk after last effective flower. Day temperatures were the same. Average ambient minimum temperature for the treatment period was 12.6 ^{o}C (range 5.9-21.1 ^{o}C) and 10.2 ^{o}C (range 2.6-21.0 ^{o}C) in 2003 and 2004. Flowers were damaged by low ambient minimum temperatures near anthesis which lead to shedding or reduced boll size due to lower seed number. The later could be due to poor pollination and competition for assimilates. Shedding was correlated ($p < 0.01$) with minimum temperature at anthesis with < 40% survival when minimums were < 6 ^{o}C. Seed cotton yield was the same. It was concluded the recovery from variable low minimum temperatures during flowering: (1) was similar to where damage to fruit was biotic with compensation occurring on later flowering fruiting sites provided temperatures were warm; (2) was unlikely to be impacted by damage to photosynthetic apparatus due to the minimum temperatures observed here.

6.2. Introduction

Minimum temperatures below the lowest reported base temperature for cotton development of 12°C (Constable and Shaw 1988) that coincide with flowering may be detrimental to boll retention and growth. An evaluation of cotton grown in the tropical dry or winter season (lat. 15°S), found a reduced retention of bolls and a lower contribution to yield from flowers when anthesis coincided with the greatest frequency of cool minimums (< 12°C) (Chapter 3). In these experiments cool minimums occurred early in flowering hence flowers on the first position on sympodia nearer the bottom of the plant were most affected. However, these crops also produced high lint yields (2064 kg lint /ha) due to greater contribution from later flowers which occur on upper and outer fruiting sites of the plant when temperatures warmed combined with a greater biomass (Chapters 3 and 4). In a field environment it was difficult to determine whether cool minimum temperatures were a factor in the early fruit loss as other possible causes such as insect pests, water logging, nutrient stress can all occur. Moreover in the field there was no 'warm night' control to compare with.

Less is known about the impact of cold minimum temperatures during flowering and boll growth of cotton than on early growth (Mauney 1986; Cothren et al. 1999). In controlled environment studies, where fixed temperatures were used, there was a quadratic response of boll weight to temperature with the optimum occurring at a minimum of around 22°C or mean of 25°C with a rapid fall in boll weight when night temperature was below 16°C or above 25°C (Gipson and Ray 1970; Hesketh and Low 1968). Hesketh and Low (1968) also found boll retention was correlated with minimum temperature, although square retention was more tolerant to cooler temperatures than bolls.

Controlled environment research may not be completely transferable to field grown crops because most published studies of cotton have been conducted with fixed day and or night temperature regimes (e.g. Gipson and Joham 1968; Hesketh and Low 1968; Reddy et al. 1991; Reddy et al. 1992; McDowell et al. 2007). Moreover many of these studies have been run for a set calendar day period and hence have not allowed for developmental thermal time differences between treatments when measuring boll weights in response to temperature. For example Gipson and Joham (1968) measured the effect of night temperatures from 10°C to 26.5°C on boll growth for the first 45 days of boll growth. While Reddy et al. (1991) using five different fixed maximum and minimum temperatures, the coldest being 20/10°C, measured boll weight 49 d after flowering. Not surprisingly boll weights under cool temperatures were less at the time of measurement in both studies.

Low minimum temperatures can reduce boll growth and retention due to: (1) lower net photosynthesis following reduced night growth and respiration that suppresses sink demand and so inhibits the export of starch from leaves (Warner et al. 1995), although this response can be negated when acclimation to low temperatures occurs (Singh et al. 2005); (2) permanent injury to photosynthetic apparatus (Berry and Bjokman 1980); (3) prevention of pollen germination and tube growth, where the minimum that stops growth or germination depended on genotype and ranged from 9.8 and 20.1^{o}C (Stewart 1986; Kakani et al. 2004).

The climate of the tropical dry season adds a further dimension to mid season cold temperature effects because temperatures at sowing are hot then fall until flowering when the coldest minimums occur, temperatures then rise rapidly during late boll fill as the days become longer (Chapter 3). The positive correlation between yield and fruit on the upper and outer fruiting sites of the plant measured in field experiments (Chapter 3) suggest climatic conditions were more favourable later in crop growth. This poses the question of how reliably can yield compensation from later developing fruit (after the cold) occur? Fruit removal studies elsewhere have found that yield compensation may occur in cotton when climatic conditions become more favourable following removal (Pettigrew et al 1992; Kennedy et al. 1986; Wilson et al. 2003). Minimum temperatures are also variable during the dry season and so there are not extended periods of extreme cold (Cook and Russell 1983), hence it is possible greater boll retention and growth may occur during periods were minimums are warm, which can also occur early in flowering.

The objective of these experiments was to measure the effects of variable cold minimum temperatures (averaging 10°C to 12°C) during flowering on cotton fruit growth, fruit retention, fruiting dynamics (compensation) and yield, while minimising confounding effects such as insects and disease.

6.3. Materials and Methods

The experiments were located at the Katherine Research Station, 4 km east of Katherine (14°28' S, 132°18' E), Northern Territory, Australia. Due to greater distance from the ocean Katherine has a greater probability of cooler dry season minimums than the Ord River, Western Australia (15°39’S, 128°43’E), where the previous field experiments were located (Chapter 3), with similar maximum temperatures, photoperiod and monthly radiation (Cook and Russell 1983). Minimum temperature was manipulated by protecting plants in a glasshouse at night during flowering (‘warm’ plants) and comparing these with plants grown at ambient temperatures at night (‘cool’ plants). Glasshouse temperatures were maintained approximately 5°C above ambient to ensure similar daily variation in

minimum temperature to plants grown at ambient temperatures. The only exceptions were when ambient temperatures were < 6°C, on these nights glasshouse temperatures were not permitted to fall below 10.3^{o}C and when ambient temperatures were warm, glasshouse minimum temperatures did not exceed 24°C. The glasshouse was not artificially heated but used adjustable roof vents to regulate night temperatures. The experiment was run over two seasons with sowing occurring on April 28, 2003 and April 30, 2004.

Cotton was grown in 17 L square pots containing one plant per pot. There were three replicates of each treatment with eight plants per treatment per replicate. The replicates were aligned in an east to west direction to account for a dry easterly breeze that is common during the day during June to September.

Four seeds were sown per pot and thinned to one per plot 15 days later. There was only room in the glasshouse for one cultivar, hence the Bt transgenic cultivar Siokra V-16B was grown (containing the Monsanto Cry1Ac and Cry2Ab proteins). This cultivar had produced consistently high yields in cultivar comparisons made over the previous six years in the dry season at the ORIA (S. J. Yeates unpublished data).

For the 'warm' plants there was one trolley per replicate containing the eight pots arranged in two rows of four. Movement in and out of the glasshouse was timed so plants were exposed to a temperature change of at most 2°C. Accordingly plants were moved outside on the coldest mornings approximately 45 minutes after sunrise and returned 30 minutes prior to sun set. The same east – west direction of the replicates was maintained at night. For the period when plants were inside after sunrise 50% of ambient photosynthetically active radiation passed through the glasshouse. Using a model of potential photosynthesis (Constable 1986), it was calculated that the average conditions of each treatment (Figure 1) the additional time inside the glasshouse would account for less than 3% of daily photosynthesis, because of cooler temperatures after sunrise. The 'cool' plants were grown outside night and day with the base of the pots at the same height above the ground (15 cm) and arrangement of the 8 plants per replicate as the 'warm' plants on trolleys. Temperature treatments were randomised within replicates. Pots were rotated clockwise weekly from 15 days after sowing until approximately one month prior to picking as there was risk of damaging the plants and large bolls when moved. Temperatures were logged (Tinytag Plus™, TGP-0050, Gemini Data Loggers, www.geminidataloggers.com) half hourly at canopy height inside and outside the glasshouse with a logger also placed on a trolley. The glasshouse and trolley loggers

were placed in an ACS50 Stevenson Screen (www.geminidataloggers.com) while the outside logger was placed inside a standard Stevenson Screen.

Each pot was irrigated at 10 am by a single 2 L/h emitter until the drainage occurred from exit holes at the base. From 14 days after first flower the plants were watered twice daily, at 10 am and 3 pm. The potting mix consisted of a mixture of sand, peat and vermiculite at a ratio by volume of 6:5:1 respectively. Slow release fertiliser 45 g Ozmocote™ + Moeco™ 10 g /pot (i.e. 8.4 g N, 1.8 g P, 5.1 g K, 1.1 g S, 0.5 g Mg, 0.1 g Ca, 0.2 g Fe, 9 mg Zn, 1 mg each of Cu, B, Mn, Mo) was incorporated with the potting mix. Aquasol™ liquid fertiliser 0.8 g was applied to the soil surface of each pot in 250 ml of water on three occasions 14 days apart in June and July each year (i.e., 184 mg N, 32 mg P, 144 mg K, 0.4 mg Zn, 0.48 mg Cu, 0.01 mg Mo, 1.2 mg Mn, 0.5 mg Fe, and 0.1 mg B per application).

The timing of plant growth stages and the treatment period are shown in Table 6.1. To ensure plants were exposed to the same minimum temperatures prior to flowering all plants were grown outside until 6 and 7 days prior to first flower in 2003 and 2004 respectively. When the temperature treatments commenced the warm night plants were moved inside at night for the next 60 and 53 days in 2003 and 2004 respectively; that is at least 15 days after flowering was completed. Plants were scouted twice weekly for insect pests and protected with insecticide when required; there was minimal insect damage. The plants were mapped for fruit retention weekly from early squaring to the start of the treatment period then bi weekly from first flower to the end of flowering then weekly to maturity. Fruit were characterised in to squares, white flowers, pink flowers and bolls. Fruit position on the plant was also recorded, where for each sympodia P1, P2 and P3 are first, second and third fruiting positions laterally from the main-stem respectively. Monopodia fruit were recoded for each node when such fruit were present. The anthesis date was recorded for each fruit from the mapping data, where a white flower = anthesis today, red flower = anthesis one day ago and a small boll (< 5 mm) with a withered petal = anthesis two days ago. It was observed that when minimum temperatures were < 10°C for at least 3 nights the red flower stage lasted one day longer (2 days) than when minimum temperatures were > 10°C, hence in estimating the day of anthesis for red flowers a two day period and withered petals three days was recorded. At maturity fruit retention, seed cotton weights, seed cotton weight per boll, the number of bolls and seeds were measured for each fruiting position on all plants. Analysis of variance and regression analysis was made using SAS (SAS 2001).

Table 6.1: Dates of plant growth stages and the timing of the treatment period.

Growth Stage	2003	2004
Sow	30 April	30 April
1st Square	5 June	3 June
Start treatment period	***23 June***	***21 June***
1st Flower	29 June	28 June
Last effective flower		
Warm	24 July	22 July
Cool	29 July	29 July
End treatment period	***20 August***	***13 August***
Maturity		
Warm	26 September	21 September
Cool	30 September	7 October

To have a sufficient number of flowers to calculate survival at each position, three day mean was used, hence minimum temperature was averaged over the corresponding days.

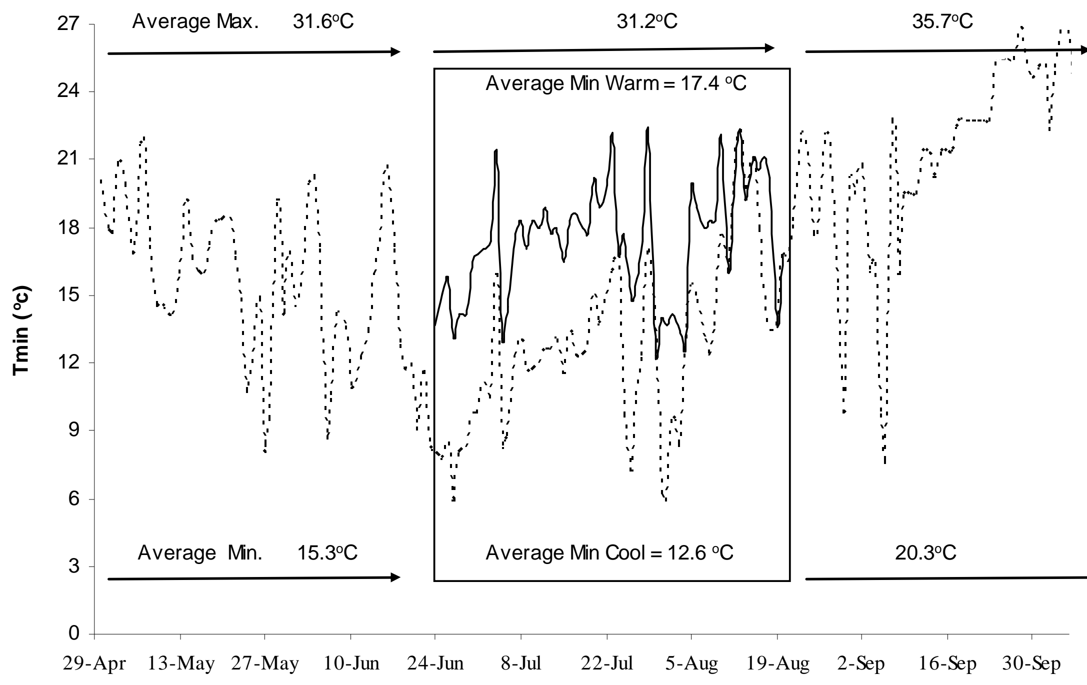
6.4. Results

6.4.1. *Observed Temperatures*

During the treatment period ambient minimum temperatures averaged 12.6 °C (range 5.9 to 21.1 °C) and 10.2 °C (range 2.6 to 20.1 °C) for the 'cool' plants and glasshouse minimums for the 'warm' plants averaged 17.4°C (range 12.3 to 23.4 °C) and 16.0 °C (range 10.3 to 23.4 °C) in 2003 and 2004 (Fig. 6.1). The number of ambient minima below 12 °C during the treatment period was 22 and 38 in 2003 and 2004. For the 'warm' plants there were 0 and 8 minima below 12°C in 2003 and 2004 respectively. Temperatures increased following the treatment period.

In 2003 temperatures prior to the treatment period were cooler and more variable after May 23 with 5 minimums < 10 °C during the period. The average minimum for the 10 days prior to the treatment period was 13.7 °C. The average minimum for the 10 days after the start of the treatment period was 8.8 °C and 15.4 °C for the cool and warm plants respectively.

Prior to the treatment period in 2004 minimums were warm and only fell below 15 °C on one occasion from plant establishment to June 10. From June 11 to start of the experiment all minimums were < 13 °C with lowest 3.9°C and the average 7.8°C. Cold minimums continued for 10 days after start of the treatment period that is to July 1 and averaged 6.8°C for the cool plants and 13.4°C for the warm plants.



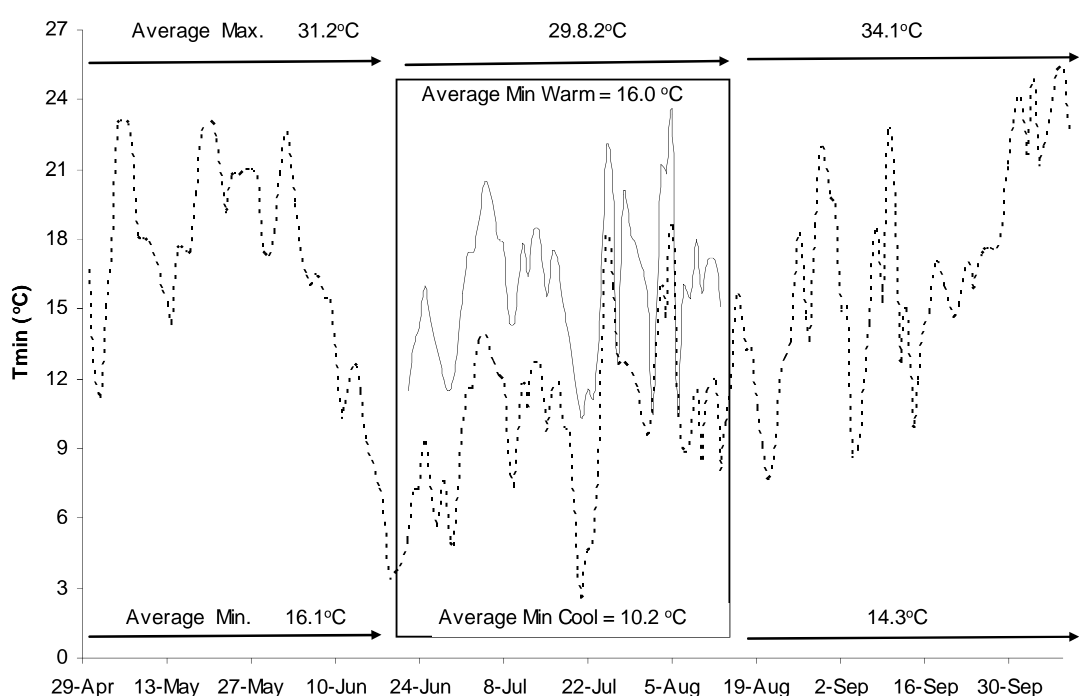


Fig. 6.1: Observed daily minimum and average maximum temperatures; where the box shows the period when the temperature treatments were imposed and the average minimum for this period. Broken line = ambient minimum temperature and solid line = glasshouse minimum temperature. Arrows show the period before, during and after the temperature treatments were imposed, average maximum and minimum temperature for each period is shown above the arrows.

6.4.2. *Fruit retention at start of experiment*

At the start of the treatment period square retention was very high for all treatments being 98.3% and 98.8% in 2003 and 2004 respectively and there were no significant differences between treatments. There was also no significant difference in total square number, or their location on the plant. The average node number for the uppermost fruiting branch P1, P2 and P3 squares was 12, 10 and 7 respectively for both treatments.

6.4.3. *Yield and boll position on the plant*

Surprisingly there was no seed cotton yield difference ($p<0.05$) between the 'cool' and 'warm' plants in both seasons. Fig. 2 shows this was because the 'cool' plants compensated by producing yield on different parts of the plant to the 'warm' plants. For the 'warm' plants 51 and 41 % of seed cotton yield was from P1 bolls while for 'cool' plants 36 and 24% seed cotton yield was from P1 bolls. Figure 6.2 shows the 'cool' plants produced a greater proportion of yield on fruiting positions other than P1 or P2 that is P3, and MP+ (monopodia + fourth position + adventitious bolls) which accounted for 40 and 53% of seed cotton yield compared with 23 and 33% for the warm plants. The majority of the MP+ yield comprised monopodia bolls with the proportion of total seed cotton yield as adventitious and P4 bolls being 2 to 3% in the warm treatment and 6% in the cool treatment.

6.4.4. *Anthesis date for different fruit positions and yield accumulation*

As expected due to the temperature difference between the treatments the median anthesis date at the same fruiting position became greater as the treatment period progressed. Approximately 14 days after minimum temperature differences were imposed (July 6) the delay in flowering was small, hence there was only a 0 to 2 day delay in flowering of P1 bolls on the lowest 4 nodes (Fig. 6.3). By late in July the same fruiting position flowered 4 to 7 days later on the 'cool' treatment. Figure 3 also shows for the 'cool' treatment many of the P3+ bolls (P3 + monopodia + P4 + adventitious) flowered after July 18 and at least 45% of the monopodia yield was produced on bolls that flowered after July 26 compared with no monopodia yield after this date on the 'warm' treatments.

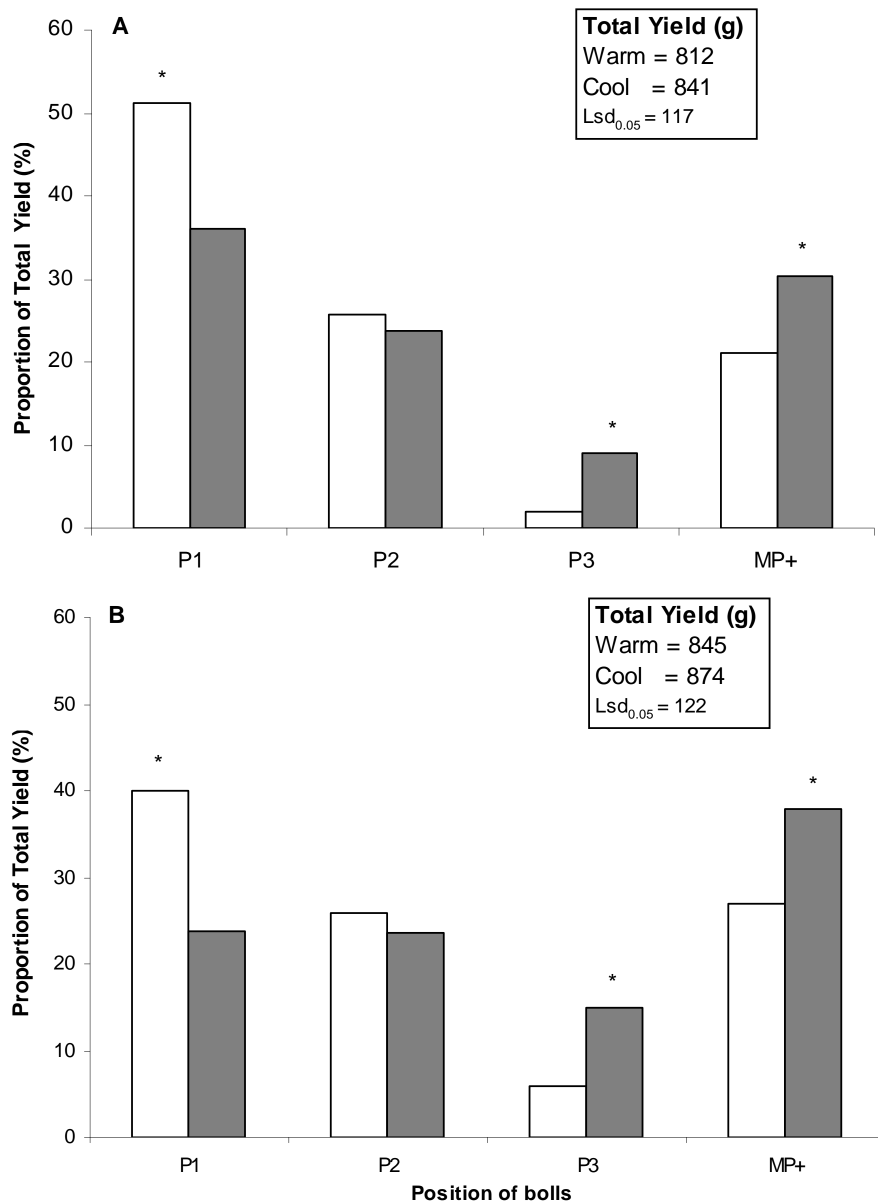


Fig. 6.2: Total seed cotton yield (g / 8 plants) and the proportion of seed cotton yield on P1 = first position bolls, P2 = second position bolls, P3 = third position bolls and MP+ = monopodia + adventitious + P4 bolls for A) 2003 and B) 2004. Open bars is warm treatment, filled bars is cool regime. Where, * = significantly different for a boll position ($p<0.05$). Note: total seed cotton yield was not significantly ($P<0.05$) different for the two treatments in each season.

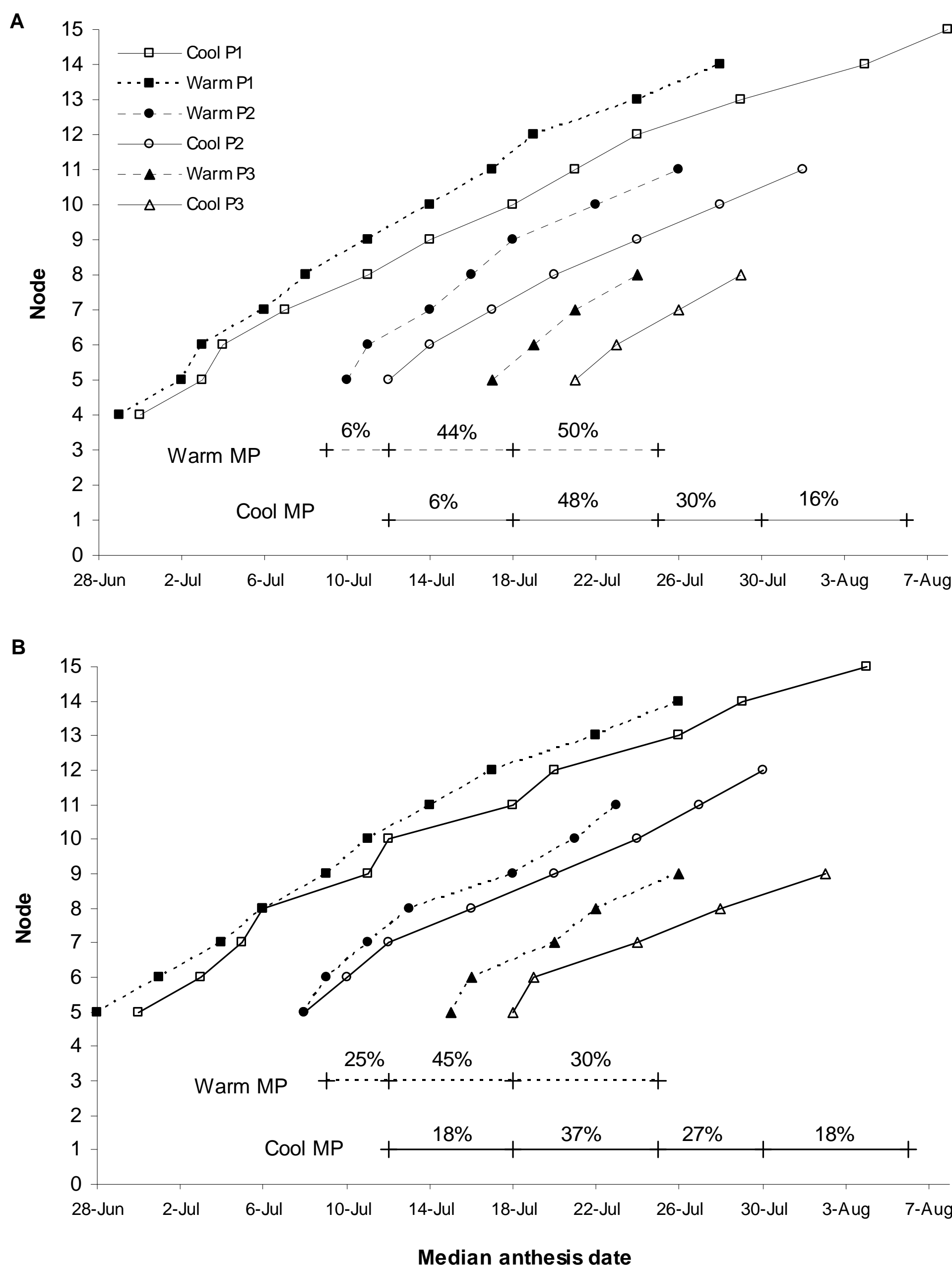


Fig. 6.3: The median anthesis date for P1, P2 and P3 flowers on main-stem nodes. Horizontal lines show the range of anthesis dates for monopodial bolls (MP) and the percentage of the total mature MP bolls that flowered within these dates. For: A) 2003 and B) 2004. Note: all adventitious bolls that produced seed cotton were located on nodes 8 to 11 and flowered on the same day as the P2 boll at that node. Mature P4 bolls were only produced on the 'cool' treatment on nodes 5 to 7 with anthesis coinciding with anthesis of the P1 flower 7 nodes above. NB the range in anthesis dates for any fruiting position was ± 2 to 8 days from the median.

Figure 6.4 shows flowers that pollinated after July 18 contributed 60 to 70% of yield in the 'cool' treatment compared with 15 to 30% of yield for the warm treatment and these flowers were on fruiting sites on the out side of the plant (Fig. 6.3). The slower accumulation of yield on the 'cool' plants between July 18 and July 25 in 2004 than in 2003 coincided with much lower minimums

over the period, 7.8°C compared with 14.2°C respectively (Fig. 6.4), despite similar fruiting positions flowering at this time in both seasons (Fig. 6.3).

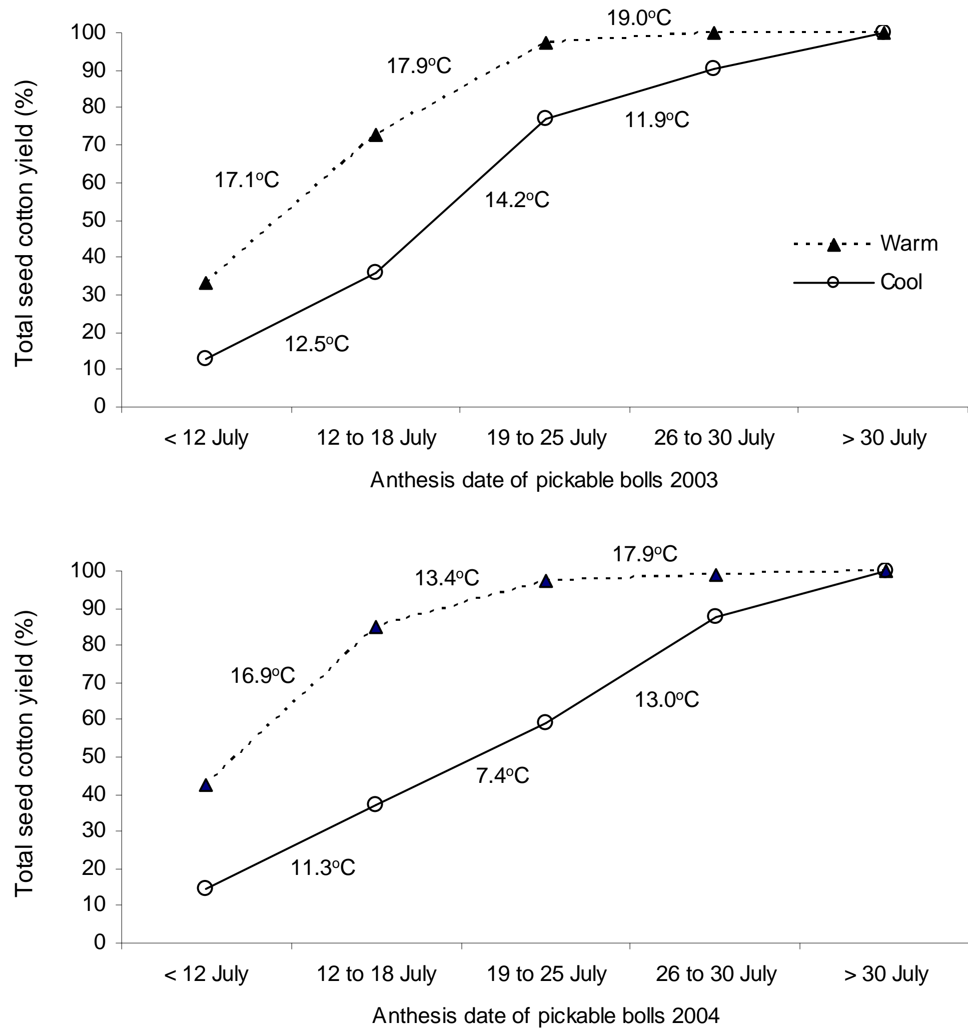


Fig 6.4: The accumulation of seed cotton yield by the anthesis date of pickable bolls. Average minimum temperatures for each range of anthesis dates up to 30 July is also shown.

6.4.5. *Yield and its components by fruiting position*

6.4.5.1. Seed cotton yield, boll number and weight per boll

The P1 seed cotton yield at each sympodia was significantly less on the 'cool' plants up to nodes 11 or 12, which flowered earliest and was due to fewer and smaller bolls (Fig. 6.5). However, the contribution of these yield components to P1 yield could be different between nodes (Fig. 6.5). In 2003 P1 boll weight was significantly reduced by cool nights at flowering on nodes 6, 10 and 11 while P1 boll number and weight were significantly reduced in the 'cool' treatment on nodes 7 to 9. After node 13 greater boll number and weight contributed to a higher P1 seed cotton yield in the 'cool' treatment. In 2004 boll number explained P1 seed cotton yield differences on node 10 and

above with a mixture of boll number and boll weight contributing to P1 seed cotton yield on nodes 5 to 9.

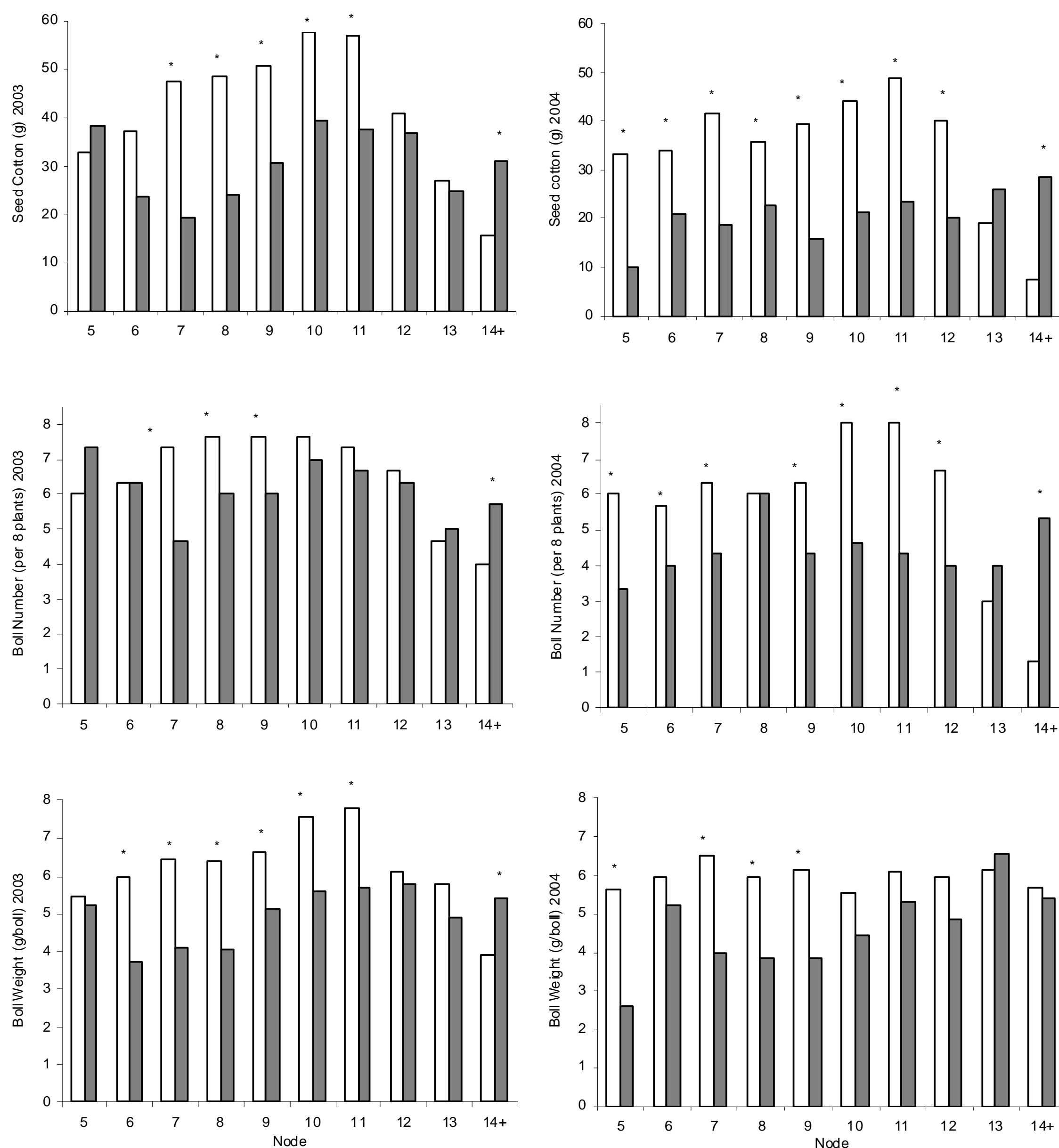


Fig. 6.5: Seed cotton weight, boll number and average boll weight on the first position (P1) sympodium flower at each main-stem node. Where open bars are warm nights, filled bars are cool nights and * indicates a significant difference ($p<0.05$) at a boll position.

Fig. 6.6 shows the seed cotton yield, boll number and boll weight for the non P1 fruiting positions. Significantly higher seed cotton yield on P3 and MP+ sites for the ‘cool’ treatment were due to greater boll number. Boll weight was generally less for the ‘cool’ treatment at all fruiting positions. Although the P2 yields were the same the distribution of P2 bolls within the plant was changed by

minimum temperature in a similar manner to the P1 bolls. The ‘warm’ plants had greater seed cotton yield on the earliest flowering nodes 5 to 7 in 2003 and nodes 5 to 8 in 2004 while seed cotton yield was greater on the ‘cool’ plants for the later flowering nodes 9 to 13 in both seasons (data not presented). Plates 1 and 2 show the differences in P1 boll size due to ambient minimum temperature. Plate 3 shows when minimum temperatures were ‘warm’ P1 bolls where larger in the lower canopy.

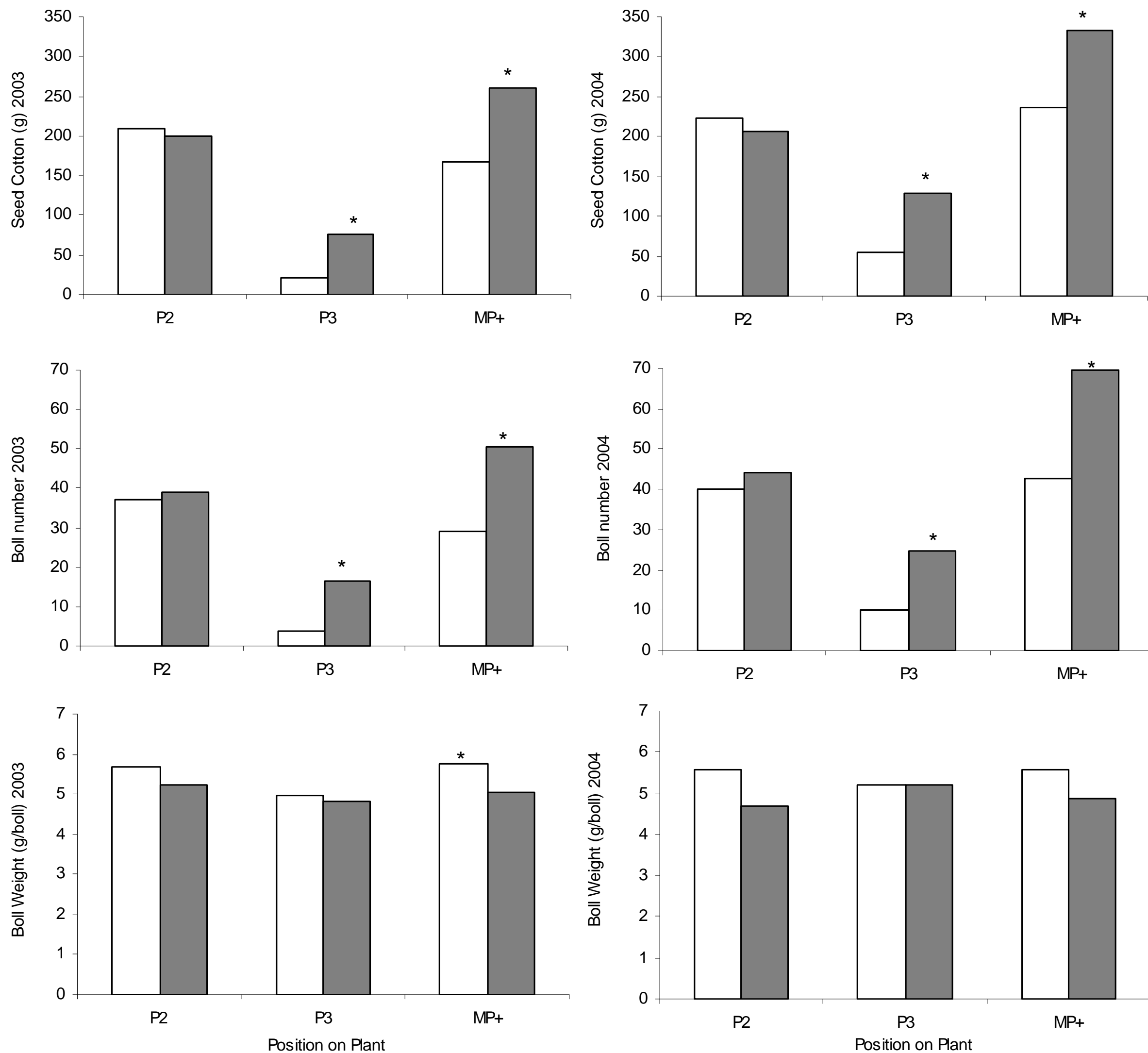
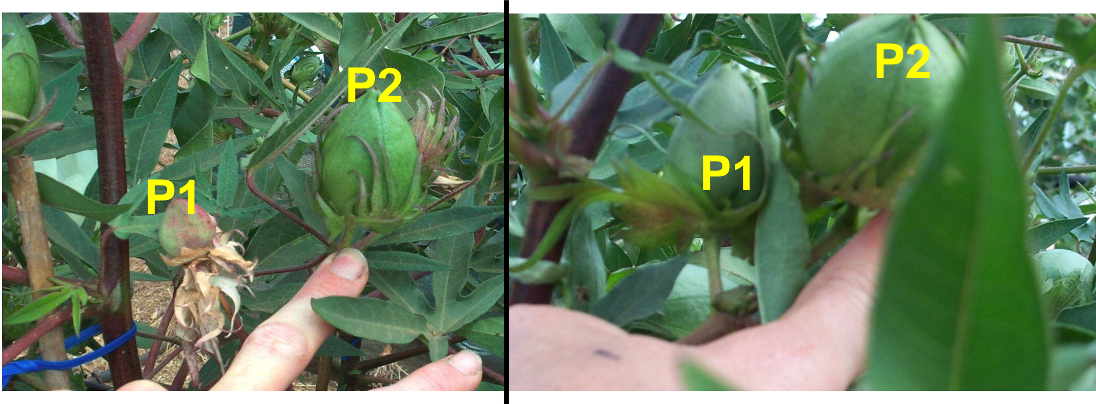


Fig 6.6: Combined seed cotton, boll number and weight per boll for P2, P3 and MP+ (monopodia+P4+adventitious) bolls. Where open bars are warm nights, filled bars are cool nights and * indicates a significant difference ($p<0.05$) at a boll position.



Plates 6.1 and 6.2: A P1 boll damaged by low ambient minimum temperature, the adjacent P2 boll flowered in warmer temperatures.

Plate 6.3: Warm treatment plants showing large P1 bolls in the lower canopy.

6.4.5.2. Comparison for early flowers when treatments overlapped for the date of flowering

As there was little difference in the median flowering date between the temperature treatments for P1 bolls on nodes 5 to 7 and 5 to 8 in 2003 and 2004 (Fig. 6.3), these bolls were exposed to the same daily pattern of temperature changes early in growth for the 'warm' and 'cool' treatments. In addition flowering occurred prior to distal position flowers on these nodes thus minimising competition for assimilate soon after flowering. Figure 6.5 shows that the P1 seed cotton yield at these nodes was significantly reduced on the 'cool' plants in both years the only exception was node 5 in 2003. In 2004 the weight per boll and boll number was reduced while in 2003 lower weight per boll contributed most to yield differences at node 6 and boll number and weight per boll were significantly lower on the cool plants at node 7.

Comparing Fig. 6.5 with Figs 6.1 and 6.3, the differences in P1 seed cotton yield on each node could be explained by the minimum temperature at flowering. In 2003 there was no P1 yield difference between the 'warm' and 'cool' treatments at node 5 as flowering coincided with higher ambient minimum temperatures on July 4. The lower P1 yield on the 'cool' treatment on nodes 6 and 7 was associated with lower temperatures near anthesis, that is < 10°C on the 5th and 6th July. These temperatures occurred soon after anthesis at node 6 and boll weight was reduced in the 'cool' treatment, while for node 7 the median anthesis date coincided with these cold temperatures and boll number and weight were reduced. In 2004 P1 flowering of the 'cool' treatment on nodes 5, 6 and 7 coincided with minimum temperatures ≤ 9 ^{o}C and boll number was significantly less than the warm treatment at these nodes. Warmer temperatures on the later flowering bolls > 12 ^{o}C from July 4 to 7 would explain the greater boll weight at node 6. These warmer temperatures also coincided with pollination of most surviving P1 flowers at node 8 and boll survival was equal to the warm treatment. After July 7 minimum temperatures cooled to < 8°C which combined with competition for assimilate later in boll growth significantly reduced boll size at node 8 compared with the 'warm' treatment.

6.4.5.3. Seed number

Table 6.2 shows seed cotton yield was best explained by seed number. For seed number there was no difference in the linear regression between the P1 bolls exposed to warm or cool minimum temperatures ($r^2 \geq 0.97$), which contrasted with boll number where the regression with seed cotton yield was lower when minimums were cool. Not surprisingly the regression between boll number and seed number was less than the relationship either component had with seed cotton yield. The inclusion of seed cotton yield from non P1 positions (e.g. P2 and P3) was also highly correlated

($p<0.001$) with seed number and did not change the regression coefficient (Table 6.2) or relationship (data not presented) between seed number and seed cotton yield.

Table 6.2: The linear regression between seed cotton weight (Sc) and seed number (Sn) or boll number (Bn), boll number and seed number for P1 bolls and all fruiting positions. Where the Sc, Sn, and Bn are from the combined bolls harvested at each node for each position were used in the correlation. All regression coefficients were highly significant ($P<0.001$): n = the sample number.

Treatment	Regression coefficient (r^2)		
	Sc v Bn	Sc v Sn	Bn v Sn
All - P1 (n=49)	0.89	0.98	0.84
Cool – P1 (n=26)	0.86	0.97	0.79
Warm – P1 (n=23)	0.94	0.98	0.84
All fruiting positions (n=117)	0.90	0.98	0.85

6.4.6. *The effect of minimum temperature on flower survival*

The survival of flowers to become harvestable bolls was significantly ($P<0.01$) correlated with minimum temperature near anthesis (Fig. 6.7). The relationship was curvilinear with a rapid fall in flower survival when minimums were < 11 ^{o}C with survival of between 20 and 40% of flowers when minimum temperatures were < 6 ^{o}C.

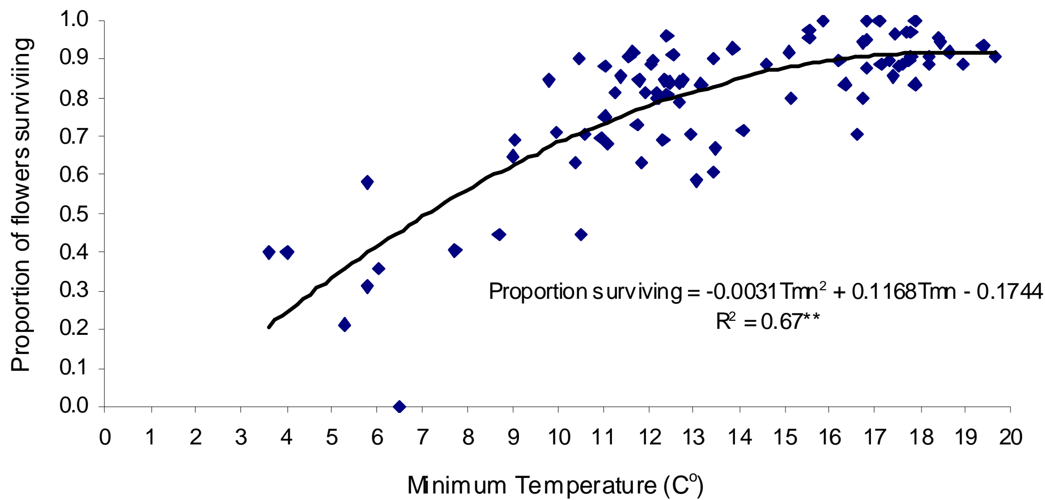


Fig. 6.7: The effect of minimum temperature (Tmn) near anthesis on the proportion of flowers from all fruiting sites surviving to produce pickable bolls. Where minimum temperature was calculated as the average for the day of anthesis plus two days. Anthesis dates after the P1 flower on node 11 were not included to avoid natural shedding due to competition from older bolls.

6.5. Discussion

These experiments explained the reduced contribution to yield from early first position flowers in the tropical dry season (Chapter 3) was due to low minimum temperatures near anthesis and not biotic causes such as pests. Moreover the ambient minimum temperatures observed here during flowering that averaged 10°C and 12°C were below that observed in the experiments described in Chapter 3 and demonstrate that full yield recovery from low minimums is possible provided low minimums are episodic.

Yield compensation from cold minimums during flowering occurred via two processes. Firstly, these experiments found for all fruiting positions boll survival was significantly correlated with minimum temperature near anthesis (Fig. 6.7). Because minimum temperatures in the field were variable, greater boll retention occurred when anthesis coincided with periods of warmer minimums. Secondly, the greater contribution to yield from later pollinated flowers reflected the general increase in temperature and radiation later in flowering that typifies the tropical dry season (Chapter 3). These climatic conditions meant yield compensation was via the retention of fruiting sites that in circumstances where temperatures were warmer during flowering would have shed due to competition from earlier pollinated bolls (Hearn 1994).

The full yield recovery from low minimum temperatures was similar to the recovery reported where fruit removal was biotic (i.e. insect pests, real and simulated) (Kletter and Wallach 1982; Lei and Gaff 2003; Pettigrew et al 1992; Kennedy et al. 1986; Jones et al. 1996; Holman and Oosterhuis 1999; Wilson et al. 2003). As was the case in this study, in the above studies lost fruit were replaced with later flowering fruit from other sites, with recovery greatest where temperatures remained favourable for boll growth later in the growing season. However a key difference between these experiments and the aforementioned studies was that damage to fruit was abiotic and vegetative organs were also exposed to the low minimum temperatures.

The full yield recovery suggests that any damage to photosynthetic apparatus by the low minimum temperatures observed here was minor. This is consistent with controlled temperature studies by McDowell et al. (2007) where fixed minimum temperatures from 5 to 10 ^{o}C for 2 and 20 nights respectively did not reduce photosynthetic capacity, only a 2 ^{o}C minimum for 2 nights of 16 hours duration caused permanent damage to photosysthetic apparatus. In my experiments the lowest recorded temperature was 2.6 ^{o}C, however, being an ambient temperature this minimum was only sustained for the hour prior to sunrise.

For the ‘warm’ treatment it was possible to generate minimum temperatures during flowering that were less detrimental to early fruit retention or growth than where temperatures were ambient. During the experimental period the warm plants were exposed to average minimum temperature above the reported base for cotton development of 12 to 15.5 ^{o}C (Hearn and Constable 1984; Mauney 1986; Dippenaar et al. 1990; Viator et al. 2005). For the warmest season (2003), were the average minimum temperature in the ‘warm’ treatment was 17.4 ^{o}C during the experimental period (Fig. 6.1), the partitioning of yield within the plant (Fig. 6.2) was similar to that reported in temperate summer grown crops with similar average minimums where 80% of yield was from P1 and P2 bolls (Mauney 1986; Heitholt 1993).

Seed number reflects the number of ovules and their fertilization efficiency (Stewart 1986) as both can be lessened by low temperatures so it was not surprising that seed number was most highly correlated with seed cotton yield. Many of the minimum temperatures observed here during flowering were below 11.1 and 9.8 ^{o}C, the lowest temperatures where pollen germination and tube growth was prevented in *in vitro* studies (Kakani et al. 2005), suggesting the fertilisation of ovules may have been prevented which would have also reduced the likelihood of boll survival (Fig. 6.7). In addition biomass accumulation and net photosynthesis would have been reduced by the low minimum temperatures observed here (Reddy et al. 1992; Burke et al. 1988; Hearn and Constable

1984; Lu et al. 1997) and combined with competition from other bolls the number of ovules per boll would have been reduced. For example the lower weight per boll from the flowers on distal positions and monopodia in the cool treatment despite greater boll numbers (Fig. 6.6) reflects this competition for assimilate supply.

6.6. Conclusions

This study confirmed that flowers were damaged by low ambient minimum temperatures near anthesis which lead to shedding or reduced boll size due to lower seed number. The later could be due to poor pollination and competition for assimilates. In the field temperatures were variable, hence yield recovery from damaged to flowers and bolls caused by low minimum temperatures occurred during periods of warmer temperatures. The yield recovery from cool minimum temperatures was similar to where damage to fruit was biotic with compensation occurring as bolls on later flowering fruiting sites when temperatures warmed. This suggests that the photosynthetic capacity of the plants was retained after the cold nights.

CHAPTER 7 – Extrapolation beyond field experiments to evaluate the impact of climatic variability on sowing opportunities and crop performance

7.1. Abstract

Despite high experimental yields the commercial adoption of dry (winter) season cotton to the Australian semi-arid tropics was constrained by uncertainties in selecting the optimum sowing window due to a complex trade-off between yield, the number of sowing days within the optimal window due to rain and insect pest resistance management regulations, fibre length and pre-picking weathering. This trade-off was investigated by validating then applying the OZCOT cotton simulation model using 53 years of historic climatic records at the Ord River and sowing dates commencing at March 1st and terminating on May 25th with enhancements to predict fibre length and colour grade. OZCOT was successfully validated for the simulation of lint yield and maturity in response to sowing date and N fertiliser rate. Future improvements to OZCOT are discussed.

Simulated lint yield peaked at sowing dates between March 19 and April 26. However, there was only a 14 day sowing period from March 19 to April 3 when the yield and quality of cotton could be optimised. Poor trafficability combined with the 35 day Bt insect resistance sowing window, reduced the number of sowing days in the optimum period. Hence to reliably sow a commercial area it was likely sowing would extend beyond April 3 and reduce median gross margin by 9 to 15% due to lower fibre quality. This trade-off was considered acceptable provided picking was prompt because the gross margins were still about $2000 / ha. Delaying the start of the sowing window until mid March was recommended to reduce yield variability and increase the number of sowing days when yield would be maximised and fibre quality near optimal. The importance of minimum tillage to improve sowing opportunities combined with prompt picking to minimise discolouration due to weathering was demonstrated. Future research should: 1) evaluate options for the extension of the Bt insect resistance window when rain interrupts sowing after a small area is sown and a significant proportion of the 35 day window is not available for sowing; 2) Expand this type of analysis throughout the Australian SAT to assist in identification of new cotton growing regions, providing focus for sustainable natural resource management and the location and provision of infrastructure.

7.2. Introduction

The previous chapters addressed potential abiotic (climatic) constraints to cotton growth, development, yield and quality when grown in the tropical dry season. This chapter will use a modelling approach to extrapolate beyond these experiments and address operational and seasonal variability issues associated with sowing and picking transgenic Bt cotton at commercial scale within the tropical dry season.

Growing cotton in the dry or winter season is new to the Australian semi-arid tropics (SAT) where insect pests are a problem during the wet season. If successful, cotton would be a new crop to a new region in a new growing season. Critical to the commercial success of dry season cotton is being able to sow sufficient area soon after the end of the wet season (March / April) and pick this area before the dry season ends (October) to avoid pre-picking weathering (Chapter 3). Low night temperatures can occur during flowering in June and July and will delay maturity (Chapter 3) particularly when prolonged cold nights cause a significant proportion of flowers to shed (Chapter 6) and reduce fibre length (Chapter 5). Therefore the decision to grow cotton in the dry season will require knowledge of the impact of seasonal variability on likely yield, fibre quality and the area of cotton that can be sown and picked each season.

The field research described in Chapters 3, 4 and 5 was conducted in seasons where monthly temperatures were near long term averages as was end-of-season rainfall. Hence it was concluded that crop performance over a greater seasonal range was required to adequately assess the prospects for dry season cotton. This is a situation where modelling combined with historic climatic records can be applied to provide this knowledge; although the availability of validated models is a prerequisite to successfully using this approach.

The OZCOT cotton growth model can simulate the yield, fruiting dynamics and time-to-maturity of upland cotton (*Gossypium hirsutum* L.) in response to climate (temperature, rainfall, radiation) and management inputs (nitrogen, water, plant population, genotype). It has been validated for spring sown crops at temperate latitudes and wet season crops in the tropics. The model is described in detail by Hearn (1994). Potential lint yield is simulated in the absence of disease, weed infestations and nutrient deficiencies other than N. It has a dynamic fruiting routine capable of integrating fruit initiation, growth and development with the plants carbon and nitrogen supply. OZCOT does not simulate fibre quality although the simulation of length, micronaire, strength and neps could be

incorporated in the near future (Dr M. Bange, CSIRO Cotton Research Unit, Narrabri NSW, personal communication, 2010). To adequately assess the sowing date and pre-picking weathering risks associated with dry season production OZCOT will require validation of yield, time of maturity simulations and enhancement to simulate fibre length and colour. Chapters 5 and 6 have provided functions to simulate fibre length, gin turnout and cold induced fruit shedding from temperature, with the latter delaying time-to-maturity in cold seasons (Chapter 6). However to predict the effect of post-maturity, pre-picking weather on fibre quality required additional field data.

Rain and humidity combined with leaf trash after bolls have opened can discolour lint (Evenson 1967). Prolonged exposure of cotton fibre to ultra violet radiation after maturity can degrade fibres and reduce fibre strength and length (Basinski et al. 1973). In Chapter 3 it was found that dry season cotton matures during September to November, which is also the transition from the dry to the wet season (Yeates et al. 1996). This period is characterised by the yearly peaks of ultra violet radiation and temperature combined with increasing frequency of rainfall (Cook and Russell 1983). Hence there is a real risk that fibre quality could be reduced by weathering caused by moisture and ultra violet light. The extent of any weathering would depend on the timing of boll opening relative to rainfall and the duration of exposure to ultraviolet radiation prior to picking.

The sowing window and the number of available sowing days to establish a dry season cotton crop will be tight for two reasons: 1) Chapter 3 found for maximum yield and avoidance of rain at picking cotton should be sown in March or April. With March being the transition from the wet to the dry season trafficability could be impeded by a combination of late wet season rain and high soil moisture due to rain during the preceding months; 2) The insect pest resistance management plan for Bt cotton in WA stipulates a 5 week sowing window in order to minimise the number of generations of *Helicoverpa* exposed to the Bt proteins (Monsanto and Cotton Australia 2010). That is once the first field is sown in a valley all cotton must be sown within five weeks of that date. Moreover, in order to avoid high insect numbers during flowering, the sowing window cannot commence before March 1st (Chapter 3). These constraints will reduce the number of days available to sow the crop at the optimum time. The obvious risks being rain interrupting sowing after the sowing window has started, making fewer sowing days within the 5 week window, or a late finish to the wet pushing sowing into May when lower yield and later picking are possible (Chapter 3). The impact of rainfall during this defined planting window on the area that can be sown and the date the crop is sown needs to be determined.

The adoption of tillage and crop establishment practices that can maximise the number of sowing opportunities soon after March 1 is critical. Concurrent research (Yeates et al. 2006) has shown minimum tillage combined with permanent beds, the shallow placement of starter fertiliser and watering up after sowing, will permit sowing 10 to 18 days earlier than the conventional tillage system traditionally used for non cotton crops that are sown in May. That is full cultivation, bed preparation and fertiliser banding, pre-irrigation (if soil too dry) then sowing up to 10 days later when the soil has dried.

In this Chapter described are the enhancements to OZCOT developed in Chapters 3, 5 and 6 to predict fibre length, gin turnout, and fruit shedding due to cold minimum temperature. The OZCOT model was validated for yield and maturity predictions for cotton grown in the tropical dry season. Additional experiments were included that relate weather damage to fibre (discoloration and UV damage) due to pre-picking rainfall and high solar radiation. The enhanced model was then applied using historic climatic records to evaluate the trade-off between the likely sowing dates, the number of sowing days, yield and fibre length and pre-picking weathering.

7.3. OZCOT Model Enhancement

7.3.1. *Materials, methods and results*

OZCOT (version 2007-10-1-0) was used in this analysis. Table 7.1 shows the potential changes to the OZCOT model due to the research in Chapters 3 to 6. The cultivar specific changes were relatively easy to make to via their parameter files. However the other enhancements required a programmer to change model code and check the changes did not influence the broader performance of the model. Shedding due to low night temperatures could not be incorporated in time for this analysis. The main impact of this omission is to under predict time-to-maturity in cold seasons due to the replacement of shed bolls extending the flowering period. Changes to boll period due to temperature are accounted for already. Therefore significant delays in maturity are only likely to occur in seasons were there are prolonged periods of cold nights (<11°C) during flowering. For example, in Chapter 6 it was shown that an average minimum temperature for the flowering period of 10°C (or coldest 10% of seasons) did not affect final yield, but the measured delay to maturity of 16 days compared with a 12.6^{o} C average temperature was due to combined effect of longer boll periods for surviving bolls and the replacement of shed bolls.

Table 7.1: Summary of potential OZCOT changes due to research in Chapters 3, 5 and 6. Where TO = gin turnout, Tmn = minimum temperature, bp = boll period

Parameter	Source of change	Cultivar			
		L23		S50	
		Old OZCOT	New OZCOT	Old OZCOT	New OZCOT
Seed cotton per boll (g)	Chapter 3	4.7	6.3	3.8	5.8
GinTurnout (%)	Chapter 3	Fixed at 43%	Relative TO= $-0.0016Tmn^2+0.054Tmn+0.58$ Maximum TO = 42%	Fixed at 43%	Relative TO= $-0.004Tmn^2+0.148Tmn-0.2719$ Maximum TO = 42%
Fibre length	Chapter 5	Not simulated	Length (cm) = $-0.0069Tmn^2+0.256Tmn+0.5502$	Not simulated	Length (cm) = $-0.005Tmn^2+0.182Tmn+1.218$
Shedding due to minimum temperature	Chapter 6	Not simulated	Fraction shed = $-0.003Tmn^2+0.1116*Tmn-0.1744$	Not simulated	As for L23
Boll period	Chapter 3	Constable 1991	1/bp= 0.00122*Tav-0.0165	As for L23	As for L23

7.3.1.1. The cultivar specific parameters changed

When grown in the tropical dry season some of the cultivar specific parameters differed from observed values and the following changes were made:

Seed cotton weight per boll is an empirical constant in the OZCOT model and is used to calculate potential growth rate per boll (Hearn 1994). This potential is discounted when temperature extremes and or water, nitrogen and carbon are limiting to boll growth. The maximum seed cotton per boll measured here (shown in Appendix 1) was greater than the weight parameterised for these varieties in the model (Table 7.1). Hence the upper values measured, that is L23 = 6.3 g/ boll and CS50 = 5.8 g/boll were used for simulations at this location.

Gin turnout is also an empirical constant where for L23 and S50 a turnout of 43% was used by OZCOT. In Chapters 3 and 5 it was found that gin turnout changed with minimum temperature and ranged between 39% and 42% for these cultivars. The adjustment for minimum temperature is shown in Table 7.1. In order to test this function it was not necessary to change model code as gin turnout was be calculated using a spreadsheet and lint yield calculated after seed cotton yield was simulated.

7.3.1.2. General parameters

Except for fibre colour the following enhancements were incorporated:

Since the comparison of functions to predict time to first square and first flower was made in Chapter 3, (Table 3.10), in late 2008 a new function was incorporated into OZCOT (M. Bange CSIRO unpublished data 2010). Hence was OZCOT was not changed to include the locally derived time to squaring function from Chapter 3, but instead the new function was validated using the same independent data as yield and time-to-maturity predictions (see section 2). The boll period function was changed to the locally derived function in Table 7.1.

The relationship between fibre length and minimum temperature (Table 7.1) was included for the cultivar L23 and linked to the existing functions that simulate the daily change in boll numbers and their growth. The simulation of boll numbers and dry weight accumulation by OZCOT is described in detail by Hearn (1994).

7.4. OZCOT validation for the simulation of yield and time-to-maturity

7.4.1. Methods

Except for the minor changes to the cultivar parameters and boll period prediction described above, dry season experiments conducted at the Ord River Irrigation Area could be used as independent data to validate the simulation of yield and time to maturity.

The OZCOT model was validated from two types of replicated experiments conducted at Kununurra over 3 years 1995 to 1997. The first was three separate sowing time experiments (Chapter 3), which compared four sowing dates (late March, late April, mid May and early June), with two cultivars (L23 and S50). In total 24 treatments were simulated. The second was three nitrogen rate experiments (Yeates unpublished data), which compared five rates of nitrogen fertilizer (0, 75, 150, 225, 300 kg N / ha) sown to the cultivar S50 in late April, a total of 15 treatments simulated over three seasons 1995 to 1997. For all experiments relevant climatic data was collected within 500 m of the field, established plant population, starting soil NO_3 to a depth 1.3 m, and date and duration of furrow irrigation applications were also recorded. Measurements were lint yield, time of 60% open bolls and pick maturity. The soil was a Cununurra clay (Gunn 1969; Parberry et al. 1969), which is common to the valley. The plant available soil water for cotton for the 0 to 130 cm profile was measured as 205 mm and the characterisation for cotton by soil layer is shown in Appendix 2.

7.4.2. Results

OZCOT accurately predicted the effect of sowing month and nitrogen nutrition on lint yields over three seasons (Fig. 7.1). The only major deviations from observed occurred for a June sowing, which is highly unlikely to be used commercially due to lower yield and lateness of maturity (Chapter 3). When simulations of individual treatments were compared with observed, there was highly significant linear regression ($P < 0.01$) between observed and predicted values, where r^2=0.59 and r^2=0.64 for the cultivars L23 and S50 respectively in time of sowing experiments and r^2=0.78 for the nitrogen response experiments.

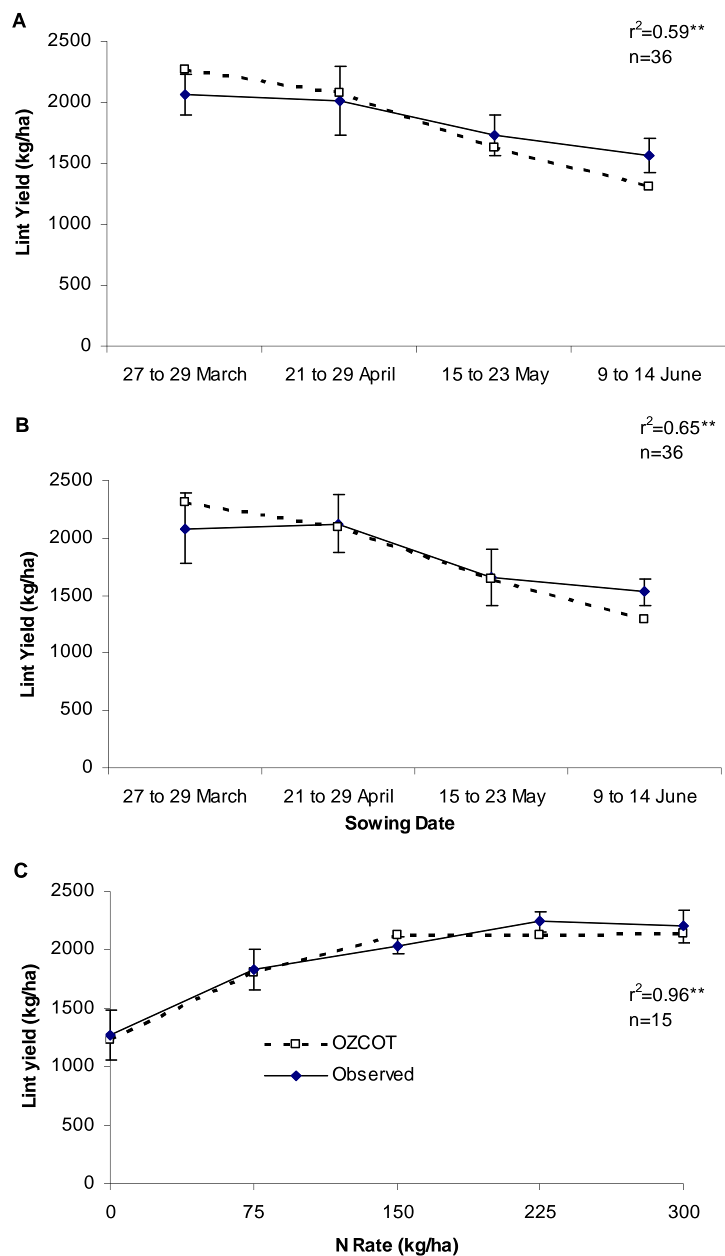


Fig. 7.1: Mean observed and OZCOT predicted yields for sowing date and nitrogen experiments conducted at the ORIA. Where: (A) Sowing date response for the cultivar L23; (B) Sowing date response for the cultivar S50; (C) Response to N fertiliser. Bars = standard errors of observed data.

Time to first square and first flower was predicted with similar accuracy to the locally derived functions in Chapter 3 (Table 3.10), RMSD = 4 (data not presented), while time to maturity was not as accurately predicted (Fig. 7.2). Deviations from the observed maturity date were as much as 20 days, with the larger deviations for May and June sowings. However the simulated average time-to-maturity for the combined sowings was very close to the observed (Fig. 7.2).

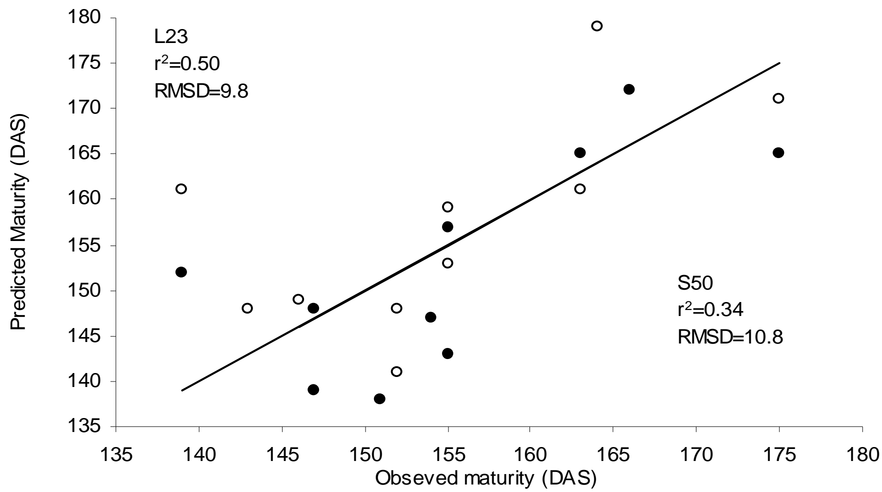


Fig. 7.2: Prediction of days after sowing (DAS) to maturity (60% open bolls) compared with observed. Where solid circles are L23 and open circles are S50 and solid line is 1:1, RMSD = root mean square deviation. Average time to maturity for L23 observed = 154 DAS, predicted = 150 DAS; for S50 observed = 154 DAS, predicted = 154 DAS.

7.5. Prediction of fibre colour grade and degradation due to pre-picking weather

7.5.1. *Materials and methods*

Data collected from the experiments described in Chapter 3 were used to measure the post-maturity colour grade of lint following rainfall and any degradation of fibre length, strength and micronaire due to exposure to pre-picking weather (solar radiation, temperature and rainfall). The crops were exposed to pre-picking weather by leaving 10m of three rows in each replication unpicked. Due to the Bt cotton not being registered for commercial use in tropical Australia at the time and being grown under a permit (by the Genetic Manipulation Advisory Committee, later the Office of the Gene Technology Regulator) it was not possible to leave unpicked plants in the field after late November. Unfortunately pre-picking rainfall did not exceed 60mm in these experiments hence the only option was to collect pre-picking colour data from cotton grown in a subsequent season. Data exceeding 60mm of cumulative pre-picking in was collected for the same varieties in 2001 (Dr. A. Annells, Dept, Agriculture & Food, WA, unpublished) at 2 sowing dates April 8 and May 17. Rainfall was measured at the experiment sites, while temperature and solar radiation were measured within 500m of the experiments.

Colour was defined in terms of its reflectance (Rd) and yellowness (+b), which are measured by a photoelectric cell (Perkins et al. 1984). Trash content is also included in the subjective interpretation of colour grade (Bange et al. 2010). Australian cotton is classed into the white colour group for which there are seven grades where Middling is the base grade (Table 7.2). Grades above middling attract a premium provided other fibre properties are above their base values, e.g. fibre length (Coulton 1991):

Commencing at picking maturity (> 95% bolls open) one m^2 was hand picked from the centre row following rainfall and when possible prior to rainfall, dried at 40^oC in a fan forced oven for 24 hours then stored in an air conditioned laboratory at constant temperature and humidity. Four weeks after the last sample was picked samples were weighed, ginned and sent for quality testing. The samples were classed for colour grade by Namoi Cotton, Wee Waa, NSW, and fibre length, strength and micronaire measured with High Volume Instrumentation (HVI) at CSIRO Plant Industry, Narrabri, NSW. To remove any confounding effect due to lint being knocked off plants due to storm wind, an analysis of variance of seed cotton weights was made and fibre quality after the date when seed cotton was significantly lower ($p<0.05$) was not used in the quality analysis.

In order to test for relationships between colour grade and exposure to weather after maturity, a modification of the standard colour grading system was used to simplify statistical analysis. Where the colour grade was given a numerical value i.e. 3.1 = 31 and trash was not included as plants were hand picked (Table 7.2).

Table 7.2: Colour grades the simplified code used in regression analysis and their relative price (adapted from Edminston 1997).

	Colour Grade	Simplified grade (white)	Price relative* to Middling
1.	Good Middling	11	101
2.	Strict Middling	21	101
3.	Middling	31	100
4.	Strict Low Middling	41	91
5.	Low Middling	51	87
6.	Strict Good Ordinary	61	75
7.	Good Ordinary	71	70

*based on prices October 2010, R. Jones, Queensland Cotton Ltd, Emerald, Qld.

The objective for the length, strength or micronaire data was to measure the minimum pre-picking exposure time before these fibre properties were significantly degraded. Therefore for each pick, the days since pick maturity was recorded and the time to a significant change identified by an analysis of variance.

7.5.2. *Results*

7.5.2.1. Fibre colour grade

Simplified colour grade was linearly correlated ($p<0.01$) with cumulative rainfall up to 58mm (Fig. 7.3), when the colour grade reached about 61 or Strict Good Ordinary (Table 7.2), after which there was little change in grade up to an exposure of 275 mm of precipitation.

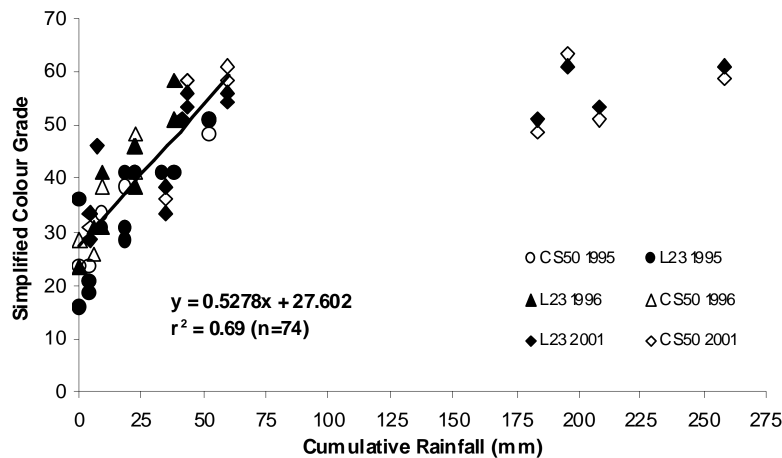


Fig. 7.3: The relationship between pre-picking weathering measured as modified lint colour grade and cumulative rainfall. Regression fitted for cultivars L23 and S50 combined up to 58 mm of cumulative rainfall ($p<0.01$).

7.5.2.2. Pre-picking degradation of fibre

Fibre strength was significantly ($p<0.05$) reduced by pre-picking exposure weather for both cultivars in the majority of sowing dates (Table 7.3). The number of days of pre-picking exposure to weather required to significantly reduce fibre strength varied with sowing date and season the shortest exposure 19 days when L23 was sown in April 2001 and the longest 47 days for S50 when sown in March 1996 (Table 7.3).

Fibre length and micronaire were not changed by exposure to weather. The only exceptions were a significant reduction in the fibre length of L23 when sown May 1995 and an increase in micronaire of S50 when sown in April 2001 (data presented in Appendix 3).

Table 7.3: Maximum duration of exposure of fibre to pre-picking weather and the exposure time required to significantly ($p<0.05$) reduce fibre strength, ns = not significant.

Sowing date	Earliest picking date L23/S50	Duration of exposure to pre-picking weather (days)		Pre-picking exposure required to reduce ($p<0.05$) fibre strength (days)	
		L23	S50	L23	S50
March 1995	Sept-23	45	45	45	45
April 1995	Oct-2/1	47	47	35	35
May 1995	Oct-15	36	36	24	ns
June 1995	Nov-11	19	19	ns	ns
March 1996	Sept-22	47	47	33	47
April 1996	Oct-1	38	38	38	38
May 1996	Oct-18	21	21	ns	n
April 2001	Sept-30/25	37	37	19	37
May 2001	Oct-31/26	27	27	20	ns

7.6. Model application studies of sowing date options

7.6.1. *Materials and methods*

All simulations were carried out with historical weather records from the Frank Wise Institute at Kununurra, WA (Lat. 15°39'S, Long. 128°43'E) in the ORIA for the years 1957 to 2009. These years were used because the measurement of radiation, temperature and evaporation commenced in 1957.

7.6.1.1. The likely sowing dates and number of sowing days as effected by the Bt sowing window and tillage method

Two comparisons were made: 1) Using minimum tillage permanent beds (MTPB) the impact of the Bt sowing window on the likely sowing date and the number of sowing days was measured; 2) MTPB was compared with conventional tillage (CT) and their likely sowing date and number of sowing days calculated assuming the Bt sowing window is applied. The tillage systems are described below.

For these comparisons sowing can commence on March 1 provided the soil has dried sufficiently. The Bt sowing window requires that sowing ends 35 days after the first field is sown. Using a sowing rule for each tillage system the first day when sowing was possible was calculated for each season as was the number of sowing days within the Bt window. For the MTPB system the number of sowing days was also calculated assuming there was no Bt window. A combination of this research, experience from other research that compared tillage systems (Yeates et. al 2006), commercial paddocks used for concurrent IPM research between 2003 and 2007 (A. Annells and J. Moulden, AGWA, Kununurra, WA, unpublished data) and farmer experience (Spike Desert, Desert Seeds, Kununurra, WA, personal communication) were used to develop sowing rules for each tillage system.

For minimum tillage with permanent beds (MTPB) the cumulative net evaporation (evaporation – rainfall) must be greater than 65mm with no daily falls > 10mm (i.e. 9 to 14 days) for sowing to commence. The accumulation of net evaporation commences when there are 2 consecutive days of ≤ 1mm rainfall and subsequent daily falls ≤ 10mm are subtracted from the cumulative total. When daily falls are >10mm but < 50mm the Ritchie (1972) two stage soil drying model is used to calculate soil evaporation, which is accumulated until 75% of the rainfall volume has evaporated

with the other 25% assumed to have runoff from the beds to evaporate as free water in the furrows or tail drains. When daily precipitation or multiday totals exceed 50mm then the cumulative net evaporation is re set to zero with sowing commencing when cumulative net evaporation is > 65mm.

The calculation of cumulative net evaporation commences prior to March 1 and must be greater than 65mm for sowing to commence on this date. It is assumed that if it is dry (< 50mm) in mid February pre irrigation will occur at this time so sowing can commence on March 1. Cumulative net evaporation is calculated from the time of pre irrigation and rainfall between pre-irrigation and sowing is accounted for as described above.

For conventional tillage (CT), cultivation and bed forming commences when cumulative net evaporation > 65mm and is assumed these operations will take two days. Because cultivation and bed preparation dries the soil, rainfall or irrigation is required before sowing can occur. If there is < 30mm of rainfall on the third day the field is pre irrigated. The MTPB sowing rules are then applied to calculate the sowing date.

7.6.1.2. Simulation of the effect of sowing date on yield, fibre length and time-to-maturity

The modified OZCOT model was run for cotton grown on a Cununurra clay soil characterised for cotton (see Appendix 2 for the available volumetric water and bulk density for each profile layer). Yield, time of first flower, fibre length and time-to-maturity (1st picking date) was simulated for the sowing dates identified for each season using the MTPB sowing rule commencing on March 1 with and with out the Bt resistance window. The model simulates maturity as the time when defoliation commences (i.e. 60% of bolls are open), picking cannot commence until the leaves are removed and all bolls are open. Because climatic conditions affect the time between defoliation and picking the model does not predict the time of picking maturity. To calculate picking maturity the average time from defoliation to picking measured in the experiments conducted in Chapter 3 was added to the simulated time-to-defoliation. The average time from defoliation to picking was dependent on month of defoliation being 14, 10 and 8 days prior for September, early October, and late October or later defoliation dates respectively.

The crop management used for the simulations reflected that used in Chapter 3. The variety L23 was grown as it produced the same yield as S50 (Chapter 3) but had more acceptable fibre length and strength (Chapter 5). Row spacing was 0.9 m with 8 plants per m of row. The crop was furrow

irrigated with irrigation commencing 21 days after sowing then scheduled when 90mm plant available water was extracted from the soil until 40% of bolls were open. Soil NO_3 at sowing was set at 115 kg/ha and fertiliser N was applied as 50 kg N/ha at sowing and 150 kg N /ha one month after sowing.

7.6.1.3. The risk of pre-picking weathering

Using a relationship developed from the data collected in Section 3, colour grade was predicted for two week periods of exposure commencing on September 1st and terminating on November 16th. The rational for using a two week of pre-picking exposure to weather was based on 300 ha of cotton being an economic area with 20 ha picked per day, requiring 15 days to pick assuming there are no delays due to weather or breakdowns. To evaluate the impact of an extended picking period e.g. due to insufficient picking capacity, breakdowns or wet fields, colour grade was also predicted for monthly periods of exposure to pre-picking weather commencing on October 1. Fibre colour grade was predicted in two steps: 1) The grade at the start of picking was calculated from the simulated date of 60% open bolls and a weighted average grade calculated for each daily cohort of bolls that opened until the date picking would commence; 2) The final average grade at the end of each picking period, where the colour grade was recalculated for each day of picking and a weighted average grade used to calculate the bale price discount.

7.6.1.4. *Gross margin analysis*

To quantify the economic impact of sowing date gross margins were calculated by combining simulated yields and fibre quality. Due to a reliable water supply cotton produced in the Ord River can usually be forward sold at higher prices than the daily trade price. Hence based on cotton futures prices for the past 15 years (R. Jones, Queensland Cotton Ltd, Emerald, Qld, Pers. Com.) and 66% of the yield being forward sold an average bale price of $480 was used in this analysis. Variable costs were $2300 /ha and a per bale cost of $35 (transport to gin and research levy). The returns from seed sales were assumed to equal ginning costs. Discounting of the bale price for colour grade and fibre length was calculated from the relative values shown in Table 7.2 and Fig. 7.7. For each year of sowing the simulated lint yield was used to calculate the total income from lint sales at each sowing date. Similarly the simulated fibre length and fibre colour values were used to calculate any price discount for each season and sowing date.

7.6.2. *Results*

7.6.2.1. The impact of the Bt sowing window on the likelihood of sowing at different dates

Figure 7.4 shows the impact of the 35 day Bt resistance management sowing window (Bt window) on the proportion of seasons when sowing was possible using MTPB to establish the crop. Where sowing was attempted within the Bt window the proportion of seasons when sowing was possible peaked between March 19 and April 11. Sowing before March 19 was often prevented by wet soil, while for each week after April 11 the opportunities to sow declined because there was a greater likelihood the Bt window had passed. Without the Bt window sowing was possible after April 11 in at least 89% of seasons and 100% of season after May 3.

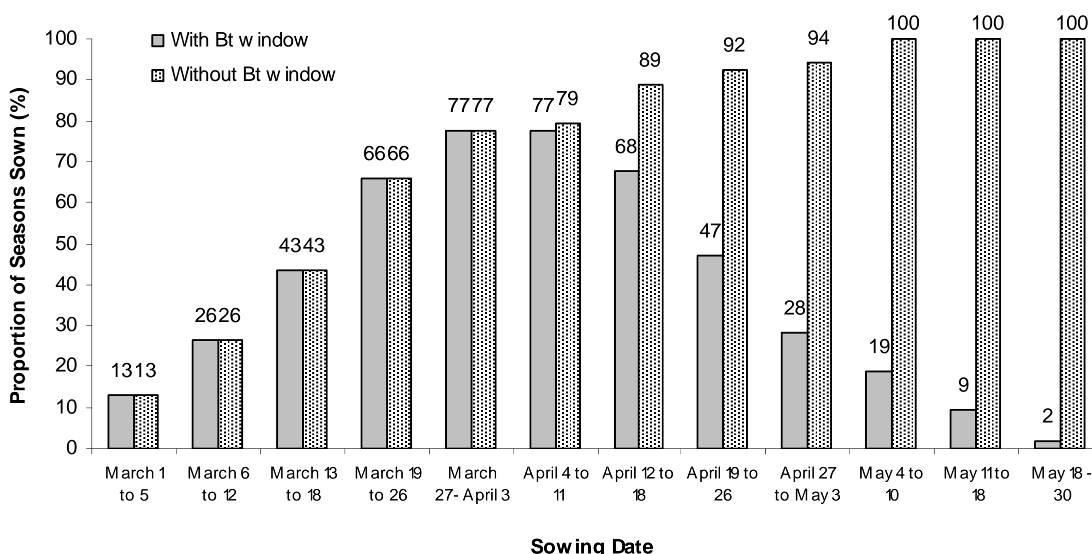


Fig. 7.4: The percentage of seasons (1957 to 2009) when soil moisture permitted at least 1 sowing day at different dates with and without the Bt resistance management window. It was assumed that the crop was established using minimum tillage and permanent beds.

7.6.2.2. The effect of tillage system on sowing opportunities

CT delayed sowing by approximately two weeks compared with the MTPB system (Fig. 7.5A). Importantly, using the MTPB system in 50% of seasons, 7 planting days could be expected in late March and 9 planting days between April 1 and 15 (Fig 7.5B). Between March 15 and April 30 the MTPB system would permit sowing on all available planting days for each two weeks in at least 10% of seasons, while sowing would not be possible at this time in 10 to 30% of seasons using this system. If the CT system was adopted, the majority of sowing opportunities would occur in April.

The number of planting days available to the MTPB system after April 15 was reduced by the Bt window.

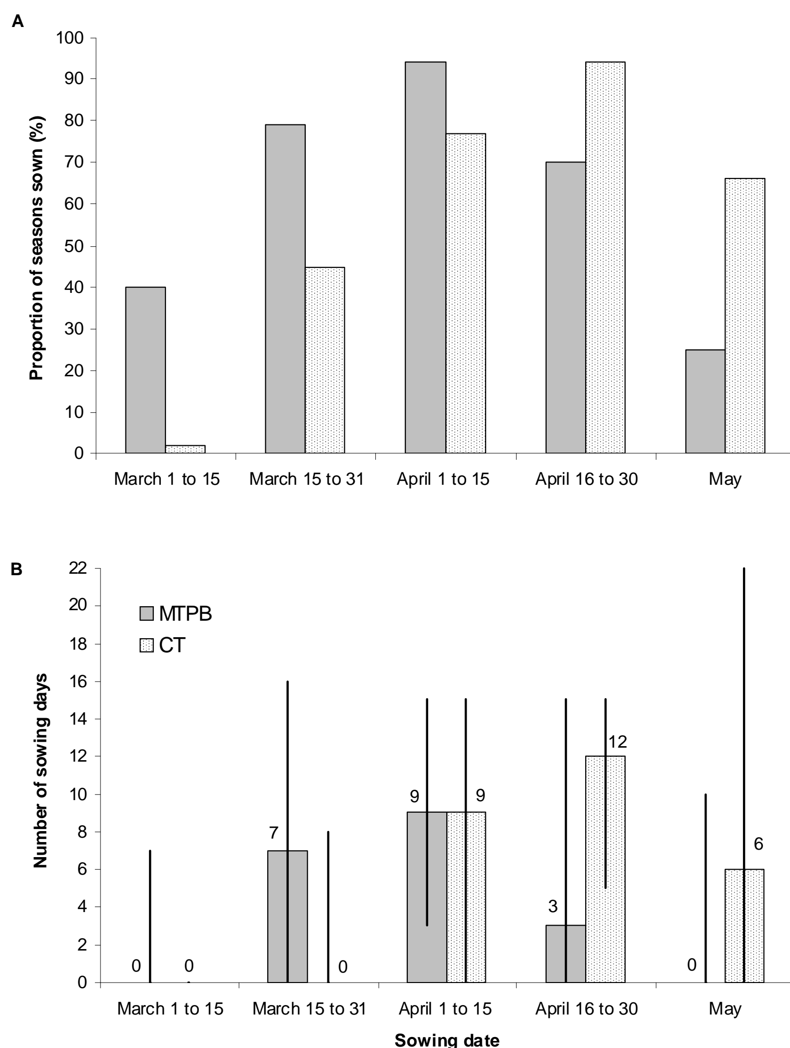


Fig. 7.5: Comparison of minimum tillage + permanent beds (MTPB) and conventional tillage (CT) for different fortnights commencing at March 1 over the 53 years 1957 to 2009 for: A) the proportion of seasons when sowing was possible; B) the median number of sowing days within the Bt window. Bars = 10 to 90% of seasons. The Bt window was enforced for both tillage systems. The median starting date for the Bt window was March 18 for MTPB and April 2 for CT.

7.6.2.3. The effect of sowing date on the simulated yield, start date of picking and fibre length

Fig. 7.6 shows effect of sowing from early March to late May on simulated lint yield for the period 1957 to 2009. Consistent with the field experiments in Chapter 3, the highest yields were from sowing between March 18 and April 26. This sowing period also had the least variable yields. Yields declined for each week after an April 26 sowing date, with a 23% reduction in median yield

when sown after May 10. Moreover there was a 40% reduction in average yield when sown between March 1 and 6.

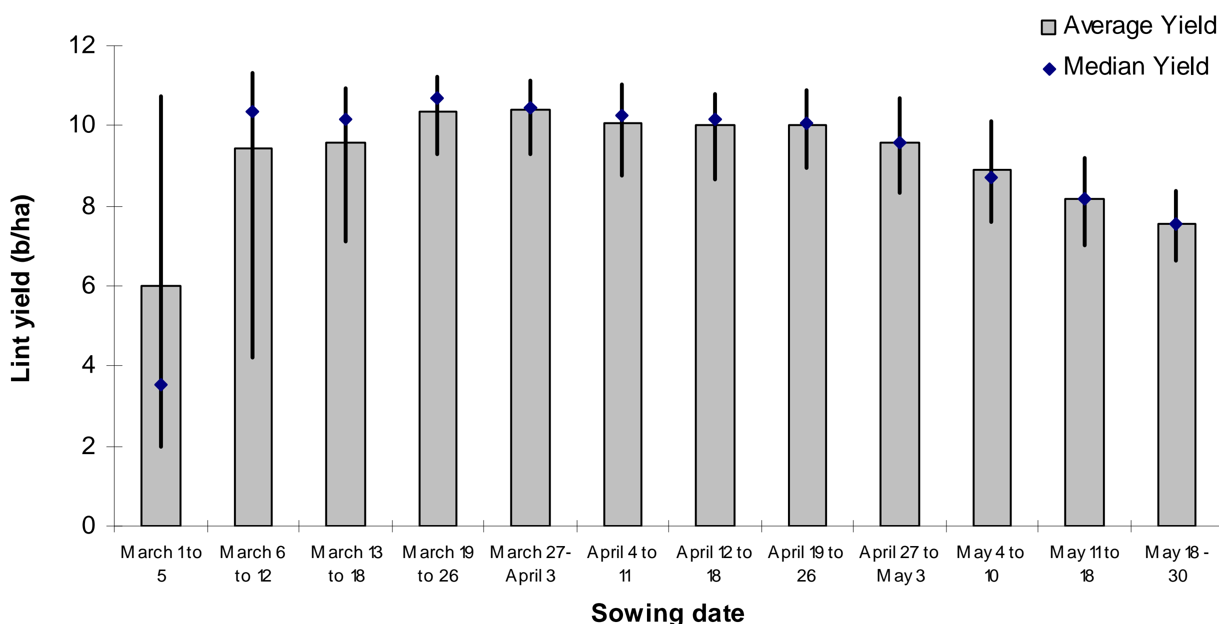


Fig. 7.6: The simulated average and median lint yield (bales/ha) for weekly sowing periods for seasons when the MTPB sowing rule was met: Error bar shows yield for 10 to 90% of seasons. One bale = 227 kg of lint.

There were only small changes in the simulated lint yields and their variability by the inclusion of the Bt window (Appendix 4). The only exception was sowing between May 18 and 30 due to sowing only being possible in one season between 1957 and 2009 when the BT window was applied (Fig. 7.3). It is likely over a greater number of seasons than was available in this analysis there would be more sowing opportunities between May 18 and 30 and the yield response would reflect that shown in Fig. 7.6.

Simulation of fibre length showed it was moderately below the preference length, incurring discounts of 2 or 8% in at most 31% and 11% of seasons respectively (Fig. 7.7). Fibre length was most likely to be below preference when sowing occurred between March 19 and April 26 with the greater reduction in fibre length at April 4 to 18 sowing dates.

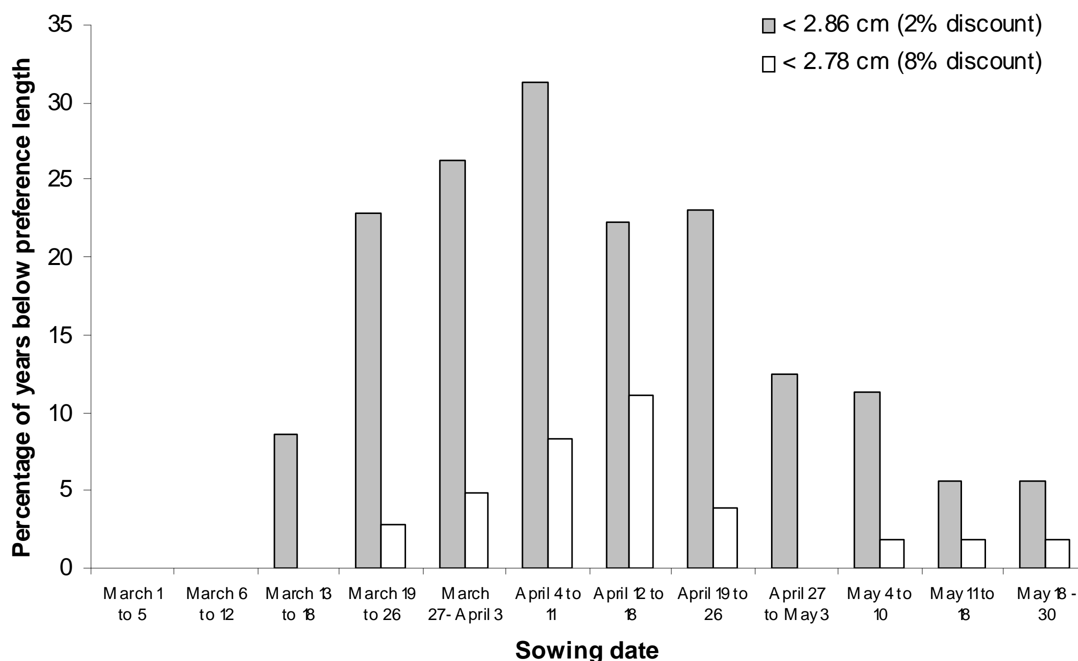


Fig 7.7: The percentage of seasons when the simulated fibre length would have been below preference due to temperature extremes during fibre elongation for sowing dates from March 1 to May 30.

Fig. 7.8 shows the effect of sowing date on the simulated date when picking would commence. The median picking dates were in agreement with the late-March, late-April and mid-May sowing dates used in Chapter 3. To commencing picking by early October in 50% of seasons sowing would have to occur by April 3. To commence picking by mid October sowing would have to be completed by April 26. Picking could not start before late October in 50% of seasons when sowing occurred in May.

7.6.2.4. The risk of pick date and promptness on pre-picking weathering of mature lint

Figure 7.9 shows the prospect for pre-picking rainfall downgrading fibre colour is low provided the crop is picked by the 15th of October. Exposure of mature fibre to rain in the last two weeks of October will incur a price discount in 23% of seasons while for the first two weeks of November in only 51% of seasons will a discount be avoided (Fig. 7.9A). The importance of prompt picking is shown in Fig. 7.9B where a delay of one month after a mid October maturity date is likely to incur a discolouration in 66% of seasons with 36% of the lint being severely down graded.

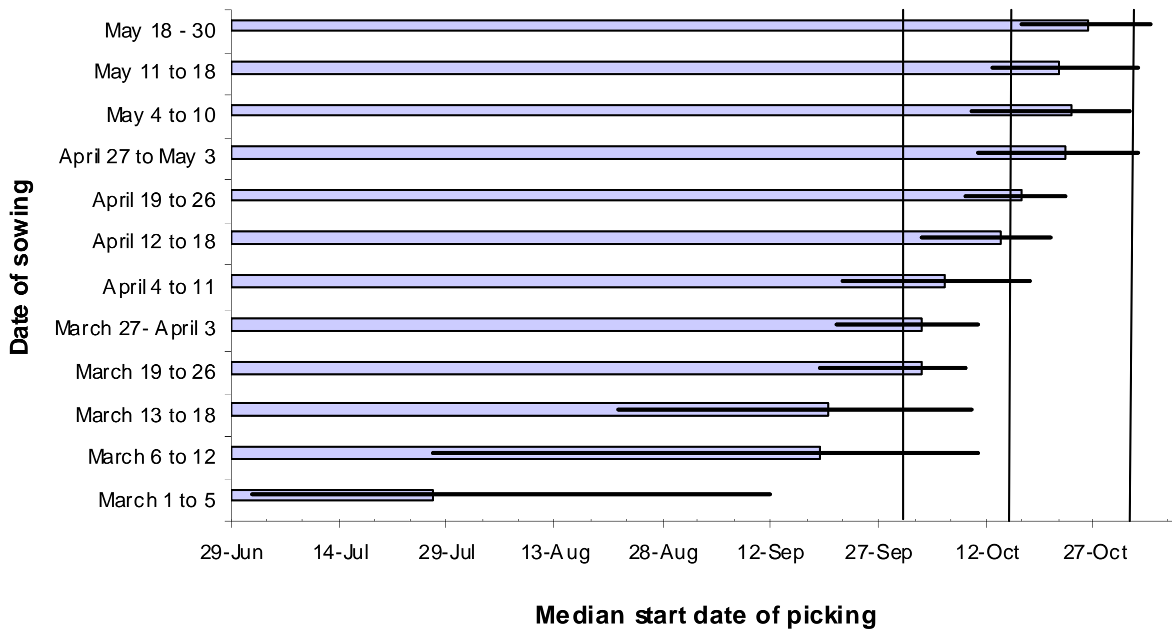


Fig. 7.8: The effect of sowing date on the median date for the start of picking. The time from sowing to picking was simulated by OZCOT. Bars show 10 to 90% of seasons. Vertical lines indicate 1st October, 15th October and 1st November.

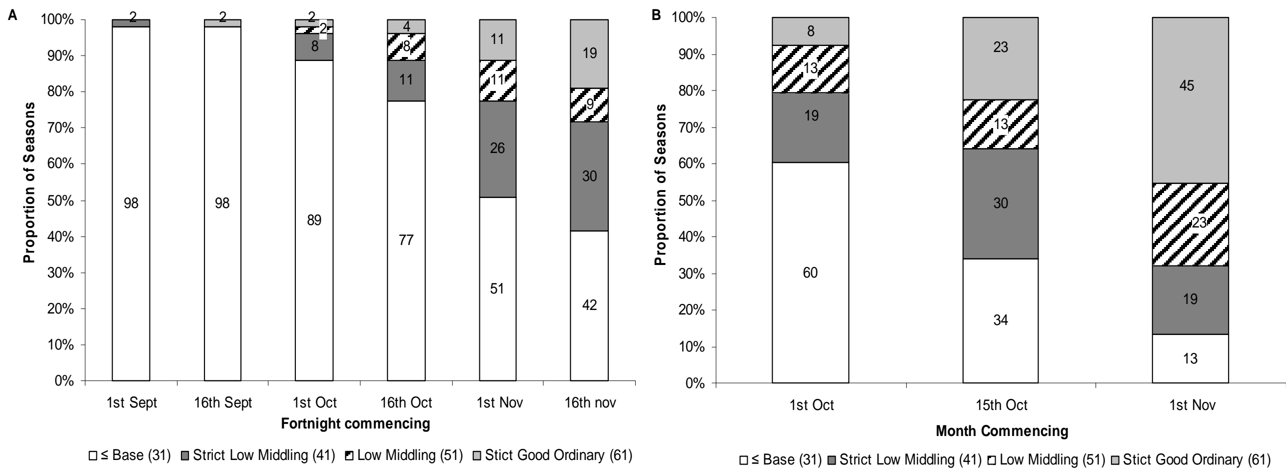


Fig. 7.9: The impact of prompt picking on the simulated percentage of seasons (1957 to 2009) when fibre of different colour grade is produced. Where A) is a two week and B) a month delay after the first picking date.

7.6.2.5. Effect of sowing date on gross margin

When picking was prompt (Fig. 7.10A) gross margin was highest and least variable when sowing occurred between March 19 and April 3. After April 11 median gross margin was 85% of a March 19 sowing due mainly to fibre length discounts. Gross margin declined rapidly when sowing occurred after April 26 due to lower yield and weathering. Sowing in May reduced median gross margin to 35 to 58% of sowing in March 19 to 26. There was a large penalty for delaying picking when sowing occurred after April 3 (Fig. 7.10B).

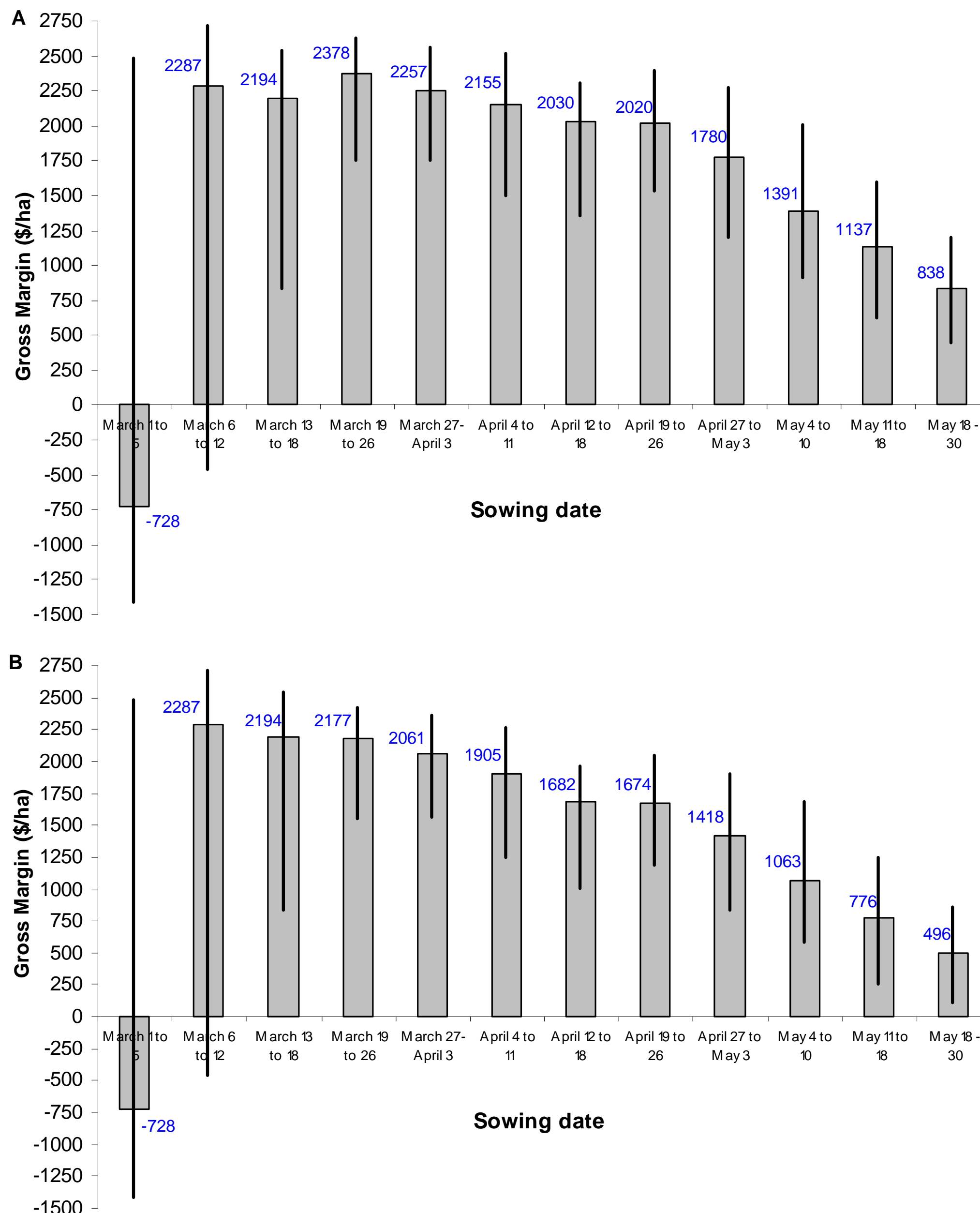


Fig. 7.10: The effect of sowing date on median gross margin calculated from simulated yields, fibre length and colour grade. Where A) is for a 14 day picking period and B) is for a 30 day picking period.

7.7. General Discussion

Management of the dry season cropping system researched here has novel challenges because optimum sowing date for cotton is determined by a combination of biotic (insect pest management) and abiotic (temperature, radiation and rainfall pattern) limitations. This analysis demonstrates how operational research based on a modelling approach can assist in extrapolating from field experiments in a variable climate to assess risks and optimise sowing date for lint yield and quality. It was shown that there is a complex trade off between sowing early to avoid pre-picking weathering, when there is potential for water logging, fibre length discounts and reduced sowing opportunities due to rainfall, and sowing later to increase sowing opportunities and to avoid fibre length discounts when the risk of pre-picking weathering and lower yields are higher.

By integrating the results from the modelling analysis these sowing date trade-offs could be quantified. While lint yield was greatest when sown between March 19 and April 26 (Fig. 7.6), for the least risk of fibre length and colour grade discounts (Figs 7.7, 7.8, 7.9) sowing would have to occur between March 19 and April 3 to maximise gross margin (Fig. 10A). However, even with the adoption of MTPB (with the Bt window), sowing will need to extend beyond these dates as the number of available sowing days to establish a commercial area (e.g. 300 ha sown at 40ha / day) is likely to be insufficient with a median of 7 sowing days and no opportunities in about 20% of seasons during this optimum period (Fig 7.5). Sowing in April would provide the greatest number of additional sowing opportunities with the least disruption to income, because gross margin was more stable than sowing prior to March 19 (Fig. 7.10A) and provided sowing occurs prior to April 27 the reduction in median gross margin would be 9 to 15% compared with the optimum period (Fig. 7.10A).

Operationally the importance of prompt picking can not be overstated in this cropping system (Table 7.3, Figs. 7.9B & 7.10B). Cotton can only be picked at half the rate that the crop can be sown i.e. about 20 ha/day compared with 40 ha/day (A. Keely, contractor, Ayr Qld, pers communication). Moreover large pickers require dry soil to operate so rainfall can easily cause delays. Leaving mature cotton exposed to weather for a month is unacceptable (Figs. 7.9B&7.10B, Table 7.3) and there will need to be sufficient picking capacity to ensure mature cotton remains in the field for at most a two weeks. Picking capacity will be most critical in seasons when a large proportion of the cotton area is sown in late April to May, not only because the risk of rainfall will be higher but later sown crops also mature faster due to higher temperatures (Chapter 3), which will mean synchronous maturity of the different sowing dates (Fig. 7.8).

Sowing prior to March 13 appears questionable based on the modelling analysis. Sowing opportunities were very limited (Figs 7.4 and 7.5) and simulated yields and gross margins could be low and highly variable (Figs. 7.6 & 7.10). This is an important finding as it was not possible to sow prior to March 26 due to wet soil in the field experiments (Chapter 3). In clay textured soils, lint yield is reduced in proportion to the duration of water logging during reproductive growth with lower N uptake the primary cause (Hodgson 1984). The OZCOT model simulates water logging, which occurs when plant available water is within 87% of saturation (Hearn 1994). Water logging suppressed simulated yields in some seasons when sowing occurred in early March.

There would be two advantages in delaying the start of the sowing window until mid March. First, there should be more sowing days per season which, due to later sowing, will occur after mid April, when gross margins are likely to be higher and less variable than in early March and weathering manageable provided picking capacity is adequate. Second, it should reduce the chance of a 'false start' to the Bt window, that is when a small area is sown early and rain prevents the majority of the area being sown until much later, when the available sowing days could be reduced due to the termination of Bt sowing window.

This analysis used rainfall collected at one location so does not account for spatial variability in rainfall within the valley. For this reason 'false starts' are likely to occur more frequently than measured in this analysis and the number of sowing opportunities after early April are likely to be less than predicted here. Unfortunately there are insufficient sites with long term meteorological records within the Ord Valley to adequately assess the impact spatial variability on sowing opportunities. Instead future research should evaluate options for the extension of the Bt window when 'false starts' occur. For example can larger areas of refuge crops generate sufficient numbers of *Helicoverpa spp.* to compensate for exposure of an additional generation of the pest to Bt proteins created by a small proportion of the cotton area being sown early?

Cultivar selection offers the best long term solution to short fibre as concurrent screening has identified potential cultivars that can produce market preference fibre length in the dry season when exposed to cool nights during fibre elongation (G.A., Constable and S.J., Yeates, CSIRO plant industry, unpublished data). The simulation of fibre length can be improved by incorporating the greater range of cultivar responses to night temperature that are known to exist (Gipson and Ray 1970). Longer fibre cultivars will improve the gross margin for sowings made between April 4 and

18 in the Ord valley because discounts for short fibre were most likely with existing cultivars when sown at this time (Fig. 7.7).

The need for unified international method of predicting the time of reproductive development for cotton was identified in Chapter 3. While the prediction of time to first flower was accurately predicted in this location, the lack of unified method of prediction will inhibit the extrapolation of the OZCOT model to a wider climatic range.

Prediction of the time to maturity was the least accurate of all the model parameters validated (Fig. 7.2). This will require a significant research effort to improve as time-to-maturity is a growth and development process being determined by the rate of fruit setting and the effectiveness of photosynthesis in meeting fruit demand for assimilate (Hearn and Constable 1984; Hearn 1994). Because predictions of time-to-maturity when averaged for all data were near observed (Fig. 7.2), it is likely that where simulations are run for a large number of seasons (Fig. 7.8) the model will predict the average time to maturity accurately.

The simple relationship developed here between cumulative rainfall and fibre colour grade (Fig, 7.3) is location specific and would require further development to be applied in climatic conditions that differ from those observed here. At maturity in the Ord River, day and night temperatures are high and rainfall events are most frequent in the late afternoon and early evening (Tupper et al. 1996). This means following precipitation, open bolls remain wet overnight, which combined with warm temperatures is favourable for the growth of the microbes that cause discolouration of lint (Allen et al. 1995). It is likely that this function can be applied to much of the Australian SAT because climatic conditions late in the dry season are similar to those observed here (Williams et al. 1985). However in temperate growing areas, where the time of day of rainfall events is variable and temperatures are usually much cooler this will not be the case. Extrapolation of fibre colour grade simulation to other environments will require simulation of the factors correlated with fungal / bacterial growth. That is temperature, humidity and the duration wetness of the host media (Allen et al. 1995).

Expansion of this type of analysis throughout the Australian SAT is a future research need as it would assist in identification of new cotton growing regions, provide focus for sustainable natural resource management, the location and provision of infrastructure. It would also assist farming investment decisions and tactical and strategic decision making for new growers. However,

diversity of climate and different irrigation delivery systems will require additional model validation.

7.8. Conclusions

This study demonstrated the value in applying a locally validated and enhanced simulation model to extrapolate temporally beyond field experiments to address complex crop management questions that were limiting the adoption of a new crop in a new growing region. This analysis showed for a potential cotton sowing window from March 1 to May 25, there was only a 14 day period (late March) when simulated yield and quality could maximise the gross margin. Poor trafficability combined with the Bt resistance management sowing window, reduced the number of sowing days, hence it was likely sowing would extend beyond the optimum dates. Sowing in April was most likely to increase the number of sowing days with the least impact on gross margin. Delaying the start of the sowing window from March 1 until mid March to reduce yield variability and increase the number of sowing days when yield and fibre quality would be near optimal was recommended.

CHAPTER 8: General Conclusions and Future Research

This thesis is the author's contribution to a multidisciplinary study that evaluated the potential for reintroduction of cotton to the Ord River Irrigation Area and more widely within the semi-arid tropics using a novel dry season production system designed to avoid the pest management problems of the previous cotton industry.

8.1. Conclusions

The stated objectives of this thesis have largely been met. Firstly at the Ord River the effect of the dry season photothermal pattern, which is the reverse of temperate or tropical wet season growing regions, on cotton development, growth, biomass partitioning, RUE, fruit retention, lint yield and quality was measured and options for crop management identified. Secondly, following validation and enhancement of the OZCOT cotton simulation model, application studies demonstrated the impact of sowing date, seasonal variability and timely farming operations on potential economic return.

For growing seasons with near long term average temperatures and radiation, lint yields were at the high end of Australian and international benchmarks for *G. hirsutum* and *G. barbadense* when sown in March and April. Importantly the field experiments described in Chapters 3 and 4 were able to explain how these yields were achieved despite the photothemal constraints identified in Chapters 1 and 2. At maturity, heat unit accumulation, the days from sowing to maturity, total biomass, partitioning of this biomass and the positive correlation between yield and days-to-maturity were similar to crops grown in temperate latitudes. However, dry season cotton had a different within-season pattern of fruit retention, biomass accumulation, and biomass partitioning.

The lower temperature and radiation during flowering and early boll growth for the March and April sowings combined to reduce the crop growth rate during this phase compared with cotton grown at temperate latitudes. However, assimilate supply was adequate because boll demand was also lower at this time due to early flowers having slower development, lower retention and smaller bolls. Increasing late season temperature and radiation permitted yield compensation via an extended flowering period and a greater contribution to yield from later pollinated flowers on the top and outside of the plant.

The lower yields for the May and June sowings could also be explained by the photothemal conditions. For these sowings temperatures were usually coolest from sowing to flowering which was found to lower RUE. During flowering temperatures were warmer favouring higher early flower retention than the March and April sowings, hence there was a greater boll demand for assimilates and earlier termination of flowering. After flowering supra optimal temperatures induced boll shedding and reduced boll size. The impact of these factors was a lower final biomass and or a reduced partitioning to bolls than the March or April sowing dates.

Chapter 6 confirmed reduced contribution to yield from early first position flowers observed in the field experiments was due to low minimum temperatures near anthesis and not biotic causes such as pests. Importantly in this experiment plants were exposed to colder ambient minimum temperatures than observed in the field experiments. That is an average of 4°C below the long term mean for the flowering period, demonstrating that full yield recovery from low minimums is possible provided they are episodic. The yield recovery from cool minimum temperatures was similar to where damage to fruit was biotic with compensation occurring as bolls on later flowering fruiting sites when temperatures warmed. Flowers were damaged by low ambient minimum temperatures near anthesis which led to shedding or reduced boll size due to lower seed number; inhibition of pollen germination and tube growth was implicated in this response. However, photosynthetic capacity was not permanently reduced by the cold minimum temperatures observed here.

Over the crop life cycle radiation was converted to biomass with similar efficacy (RUE) to cotton (*Gossypium hirsutum*) grown at temperate latitudes. The RUE measured for the *Gossypium barbadense* cultivar was the first reported for this species. The linear decline of RUE with average temperature up to first flower has not been reported previously in cotton and explains some of variation in RUE measured here (Chapter 4) and elsewhere. The development of this relationship was possible because the temperature range observed for these sowing months was greater than could be generated reliably over the first square to first flower phase in temperate latitudes or in the tropical wet season (Chapter 3). Temperature may limit vegetative biomass accumulation in May and June sowings and in cooler than average seasons for March and April sowings.

Fibre length and strength at the highest yielding March and April sowings were low to marginal compared with market preference values (Chapter 5). This was due to cool temperatures during fibre development. The cultivar differences observed here suggest wider screening may identify *Gossypium hirsutum* cultivars with suitable fibre length and strength in these conditions. The

commercial prospects for *Gossypium barbadense* are doubtful unless longer and stronger fibre types are identified.

Predicting crop development and maturity was critical to assessing the likelihood cotton can be successfully grown within the confines of the dry season. A robust function was developed to predict boll period from a wide temperature range (Chapter 3), however further research was required to develop more widely applicable methods to predict reproductive development and time-to-maturity. Internationally, there is no consistency in the threshold temperatures used, with minimum thresholds being locally derived and ranging from 12 ^{o}C to 15.5 ^{o}C. Moreover, there has been no attempt to incorporate the impact of supra (> 35 ^{o}C) and sub optimal (< 11°C) temperatures observed in this study and elsewhere on the node of first fruiting branch. Prediction of the time-to-maturity was the least accurate of all the model parameters validated in Chapter 7. This was because time-to-maturity is a growth and development process being determined by the rate of fruit setting, the boll period of each surviving cohort of flowers, and the effectiveness of photosynthesis in meeting fruit demand for assimilates.

Growth regulator treatment is more likely to be required early in growth. High early season temperatures were reflected in plant height at 7.5 nodes of the upland cultivars that was double that reported for spring sown cotton in temperate regions. Rank growth at maturity was most likely for a March sowing due to longer periods of high temperatures during vegetative growth.

The assessment of climate variability conducted in Chapter 7 demonstrated the value in applying a locally validated and enhanced simulation model to extrapolate temporally beyond field experiments to measure yield and quality variability and to address complex crop management questions that were limiting the adoption of dry season cotton into a new growing region.

Enhancements to the OZCOT cotton simulation model were made using the data collected from the field experiments conducted in this study. Gin turnout and fibre length were predicted from temperature and the relative contribution of daily boll cohorts as described in Chapter 5. Boll period was predicted from temperature (Chapter 3) and fibre colour grade from accumulated rainfall (Chapter 7). Maximum boll weight was cultivar specific and was different to temperate Australia so local values were used (Chapter 7). Insufficient programming time prevented the inclusion of the function to predict flower survival from minimum temperature (Chapter 6). The model accurately simulated lint yield and the average time-to-maturity, however, for the latter there was high variability between the crops that were simulated.

The modelling analysis (Chapter 7) showed for a potential cotton sowing window at the ORIA from March 1 to May 25, there was only a 14 day period (commencing March 19) when simulated yield and quality could maximise the gross margin ($2257 to $2378 /ha). Poor trafficability combined with the 35 day Bt resistance management sowing window reduced the number of sowing days, hence it was likely sowing would need to extend beyond the optimum dates. Sowing in April was most likely to increase the number of sowing days with the least impact on gross margin that was 9 to 15% lower due to below preference fibre quality. This trade-off was considered acceptable provided picking was prompt because the lower gross margins still exceeded a median of $2000 / ha, which was acceptable for profitable production using benchmarks from temperate Australia. Delaying the start of the sowing window until mid March was recommended to reduce yield variability and increase the number of sowing days when yield would be maximised and fibre quality was near optimal. The importance of minimum tillage to improve sowing opportunities and prompt picking to minimise fibre discolouration due to weathering was demonstrated.

8.2. Recommendations for crop management and future research

8.2.1. *Crop management*

Likely changes to crop management can be identified from this research which was located at the Ord River and Katherine (Map 1.1) these changes could be expected to be broadly applicable to other regions in the SAT with a similar climate and pest life cycles (Strickland et al. 2003) e.g. Bains River, Roper River and Anna Plains. However for cooler and or wetter regions in the south east (e.g. Burdekin, Collinsville) further research is required.

8.2.1.1. Tactical management

Compared with cotton grown in temperate latitudes, Chapters, 3, 4 and 6 found growing high yielding cotton in the tropical dry season requires an extended flowering period, a greater contribution to yield from later pollinated flowers and 60 to 80% of boll growth occurring after the termination of vegetative growth. Hence within season crop monitoring and management will require adaption to account for these changes in growth:

1. The emphasis in crop monitoring will need to shift from measuring and ensuring high P1 boll retention and then protecting these bolls because of their high contribution to yield in temperate climates, to monitoring all fruiting positions to ensure the production of new fruiting sites is sufficient to permit yield compensation when needed.

2. Achieving a balance between yield compensation via fruiting sites toward the top and outside of the plant and appropriate vegetative growth will require careful management. Over use of growth regulators or insufficient irrigation or nutrient deficiency will inhibit compensatory growth and reduce yield. On the other hand a luxurious supply of water and or nutrients combined with an insufficient amount of growth regulator could lead to excessive or 'rank' vegetative growth. Concurrent growth regulator research has shown that avoidance of high doses during fruiting site production is essential to permit compensation via the production of additional fruiting sites (Yeates et al. 2002b). Concurrent studies (S.J. Yeates; J. Moulden, AGWA unpublished data) found lowering of plant density to assist the growth of these fruiting sites is unlikely to be an option because it only increased the ratio of out side bolls to top bolls.

3. To grow a high proportion of yield after the termination of vegetative growth, leaf integrity will need to be maintained long after the last effective flower has been pollinated hence pest, disease and nutrition management must ensure healthy leaves.

8.2.1.2. Strategic management

Common to growing cotton in the dry season is the need to sow late in the wet season when rainfall can prevent trafficability with the risk of rainfall at picking increasing as sowing becomes later. The analysis for the Ord River in Chapter 7 clearly shows that the optimum planting widow is tight on clay soils. This will also be the case in higher rainfall regions with lighter textured soils, hence minimum tillage systems will be essential to establish the crop on time. In addition in seasons when a significant area is sown after the optimum widow, options for increased picking capacity should be considered as should sowing an early maturing cultivar (if available) or not sowing cotton.

8.2.2. *Future research*

The future research identified from this study falls into two categories 1) contributions to the wider cotton knowledge and 2) knowledge gaps in the production of cotton in the dry season in the SAT.

8.2.2.1. Contributions to the wider cotton knowledge

The need for unified international method of predicting the rate of development for cotton growth stages proportion to temperature was identified in Chapter 3. This will require a larger data set than collected here and will need to incorporate sub and supra optimal temperature effects. Similarly Chapter 7 demonstrated the need for improvement in time-to-maturity prediction that in addition

accounting for temperature incorporates the impact of assimilate supply and abiotic stresses on boll period, fruit retention, boll size and fruiting site production.

Chapters 5 and 7 found the simulation of fibre properties and colour grade required further research. In addition to expanding the climatic and genotype range available in this study the simulation of the fibre properties length, strength and micronaie requires further testing of the assumptions in the daily boll cohort method developed in Chapter 5. That is, boll size and fibre quality per boll were not changed by competition for assimilates and that all bolls are shed after the maximum boll number is first reached. Extrapolation of the simple function to predict fibre colour grade from rainfall (Chapter 7) to other environments will require simulation of the factors correlated with fungal / bacterial growth. That is temperature, humidity and the duration wetness of the host media. The impact of average minimum temperatures $< 18^{o}C$ on gin turnout (Chapter 5) also requires further research.

8.2.2.2. Knowledge gaps in the production of cotton in the dry season in the SAT

Although the field experiments conducted in this study were at one location, the monthly rainfall and temperature cycle is similar throughout the Australian SAT with regional differences in the total rainfall, soil texture and extremes of temperature (Williams et al. 1985). For example Katherine, Kununurra and Anna Plains (see Map 1.1) average 975, 750 and 387mm of rainfall per year respectively but the monthly rainfall pattern is the same as shown for Kununurra in Fig 1.1, with the January and February the wettest months and rainfall declining rapidly after March to June then increasing from October to January. The difference between the locations being the monthly rainfall totals. Due to lower totals at Anna Plains sowing and picking operations are less likely to be affected by rainfall. Whereas at Katherine the optimum sowing widow will be earlier and smaller than Kununurra if weathering is to be avoided as rainfall is greater in October and November.

An analysis similar to that shown in Chapter 7 applied throughout the Australian SAT is a future research need as it would assist in identification of climatic and operational risks for other potential cotton growing regions (Map 1.1) provide focus for sustainable natural resource management, the evaluation of crop rotation options, the location and provision of infrastructure. It would also assist farming investment decisions and tactical and strategic decision making for new growers. However, further model enhancement as described above is required before this analysis can occur. Extrapolation to regions with a significantly different climate, soil or irrigation delivery systems

than the ORIA will require additional field research (agronomy, entomology), model validation and enhancement.

Because Bt transgenic cultivars had only been recently released the when this study was conducted there was only a small number of cultivars available for evaluation. This study identified the need for further genotype screening for high fibre quality under these conditions and to measure the interaction between cultivar maturity and sowing date.

Bibliography

ABS, 2006. The Australian Bureau of Statistics, Agricultural Commodities Australia – 7121.0 - 2004-05, p19. www.abs.gov.au

Allen, S.J., Auer, P.D., Pailthorpe, M.T., 1995. Microbial damage to cotton. Textile Res. J. 65, 379-385.

Andrade, F.H., Uhart, S.A., Cirilo, A., 1993. Temperature affects radiation use efficiency in maize. Field Crops Res. 32, 17-25.

Annells, A.J., Strickland, G.A., 2003. Assessing the Feasibility for Cotton Production in Tropical Australia: Systems for *Helicoverpa spp*. Management. In: Swanepoel A., (Ed.), Proceedings of the World Cotton Research Conference-3: Cotton Production for the new millennium. 9-13 March 2003, Cape Town, South Africa, pp. 905-912.

Anon., 1992a. Siokra L23. Plant Varieties J. 5, 13.

Anon., 1992b. CS50. Plant Varieties J. 5, 12.

Anon., 1997a. Siokra L23i. Plant Varieties J. 10(3), 20.

Anon., 1997b. Sicot 50i. Plant Varieties J. 10(3), 19.

Ayars, J.E., Phene, C.J., Hutmacher, R.B., Davis, K.R., Schoneman, R.A., Vail, S.S., Mead, R.M., 1999. Subsurface Irrigation of row crops: a review of 15 years of research at the Water Management Research Laboratory. Agric. Water Manage. 42 (1), 227-244.

Baker, D.N., Hesketh, J.D., 1969. Respiration and the carbon balance in cotton (*Gossypium hirsutum*, L). In: Proc. Beltwide Cotton Physiology Conference, National Cotton Council, Memphis, 7-8 January 1969, New Orleans, LA, pp60-64.

Bange, M.P., Milroy, S.P., 2000. Timing of crop maturity in cotton: Impact of dry matter partitioning. Field Crops Res. 68, 143-155.

Bange, M.P., Milroy, S.P, 2003. Effect of temperature on the rate of early fruiting developmental processes of cotton. In: Proc. 10th Aust. Agron. Conf., Horbart, 2001, The Australian Society of Agronomy, http://www.regional.org.au/au/asa/2001/.

Bange, M.P., Milroy, S.P., 2004. Growth and partitioning of diverse cotton cultivars. Field Crops Res. 87, 73-87.

Bange, M.P., Constable, G.A., Gordon, S.G., Naylor, G.R.S., Van der Sluijs, M.H.J., 2009. FIBREpak A guide to improving Australian cotton fibre quality. CSIRO and the Cotton Catchment Communities Cooperative Research Centre. ISBN 978-0-9775317-1-4, Narrabri, NSW, Australia.

Baskerville, G., Emin, P., 1969. Rapid estimation of heat accumulation from maximum and minimum temperatures. Ecology, 50, 514-515.

Basinski, J.J, Robinson, G., Thomson, N.J., 1973. Pre-harvest weathering of cotton under mechanised production in a tropical area. Cotton Growing Review. 50, 193-217.

Bassett, D.M., Anderson, W.D., Werkhoven, C.H.E., 1970. Dry matter production and nutrient uptake in irrigated cotton (*Gossypium hirsutum*). Agron. J. 62, 299-303.

Bauer, F.H., 1977. Cropping in North Australia: Anatomy of Success and Failure. Australian National University, North Australia Research Unit, 25-27 August 1977, Darwin NT, Australian National University, Canberra.

Bell, MJ, 1986. Effect of sowing date on growth and development of irrigated peanuts. Arachis hypogaea L cv. Early Bunch, on a monsoonal tropical environment. Aust J. Agric. Res. 37, 361-373.

Bell, M.J., Wright, G.C., Hammer, G.L., 1992. Night temperature affects radiation-use efficiency in peanut. Crop Sci. 32, 1329-1335.

Berry, J., Bjorkman, O., 1980. Photosynthetic response and adaptation to temperature in higher plants. Ann. Rev. Plant Physiol. 31:491-543.

Bindra, O.S., 1985. Relation of cotton cultivars to the cotton-pest problem in the Sudan Gezira. Euphytica 34, 849-856.

BOM, 2009. Australian Government Bureau of Meteorology, Climatic statistic for Australian locations, www.bom.gov.au/climate/averages.

Boquet, D.J., Moser, E.B., 2003. Boll retention and boll size among intrassympodial fruiting sites in cotton. Crop Sci. 43, 195-201.

Bourland, F.M., Oosterhuis. D.M., Tugwell, N.P., 1992. Concept for monitoring the growth and development of cotton plants using main-stem node counts. J. Prod. Agric. 5, 532-538.

Bradow, J.M., Bauer, P.J., Hinojosa,O., Sassenrath-Cole, G.F., 1997. Quantification of cotton fiber-quality variations arising from boll and plant growth environments. Eur. J. Agron. 6, 191-204.

Burke, J.J., 2002. Moisture sensitivity of cotton pollen: An emasculation tool for hybrid production. Agron. J. 94, 883-888.

Burke, J.J., Hatfield, J.L., Mahan J.R., 1988. Cotton specific thermal kinetic windows in relation to wheat and cotton biomass production. Agron J. 80, 553-556.

Buster, S.H., 1994. An evaluation of the nitrogen requirements and agronomic potential of Pima cotton (*Gossypium barbedense*) in western New South Wales, Australia. M. Rural Sc. Thesis, Department of Agronomy and soil Science, University of New England, Armidale, NSW, Australia.

Carberry, P.S., Bange, M.P., 1998. Using systems models in farm management. In: Proceedings of the 9th Australian Cotton conference. Broadbeach, Qld, The Australian Cotton Growers Research Association, p 309-56.

Chapman, A.L., Sturtz, J.D., Cogle, A.L., Mollah, W.S., Bateman, R.J., 1996. Farming systems in the Australian semi-arid tropics – a recent history. Aust. J. Exp. Agric. 36, 915-28.

Charles-Edwards, D.A., Lawn, R.J., 1984. Light interception by grain legume row crops. Plant Cell Environ. 7, 247-251.

Christiansen, M.N., 1986. Influence of atmospheric parameters on growth and development. In: Mauney, J.R., Stewart, J.McD., (eds) 'Cotton physiology'. The Cotton Foundation, Memphis, p. 45.

Constable, G.A., 1976. Temperature effects on early field development of cotton. Aust. J. Exp. Agric. An. Husb. 16, 905-910.

Constable, G.A., 1986. Growth and light receipt of mainstem cotton leaves in relation to plant density in the field. Agric. For. Meterol. 37, 279-292.

Constable, G.A., 1991. Mapping the production and survival of fruit on field grown cotton. Agron. J. 83, 374-378

Constable, G.A., 1995. Predicting yield responses of cotton to growth regulators. In: Constable, G.A., Forrester, N.W., (Eds.), Challenging the Future: Proceedings of the World Cotton Research Conference-1. Brisbane Australia, February 14-17, 1994, CSIRO, Melbourne, pp 3-5.

Constable, G.A., Rawson, H.M., 1980. Effect of leaf position, expansion and age on photosynthesis, transpiration and water use efficiency of cotton. Aust. J. Plant Physiol. 7, 89-100.

Constable, G.A., Hearn, A.B., 1981. Irrigation for crops in a sub-humid environment. VI. Effect of irrigation and nitrogen fertilizer on growth, yield and quality of cotton. Irrig. Sci. 3, 17 – 28.

Constable, G.A., Shaw, A.J., 1988. Temperature requirements for cotton. Agfact P5.3.5, Department of Agriculture NSW, Australia.

Constable, G.A., Harris, N.V., Paull, R.E., 1976. The effect of planting date on the yield and some fibre properties of cotton in the Namoi Valley. Aust. J. Exp. Agric. An. Husb. 16, 265-271.

Constable, G.A., Rochester, I.J., Hodgson, A.S., 1990. A comparison of drip and furrow irrigated cotton on a cracking clay soil. 1. Growth and nitrogen uptake. Irrig. Sci. 11,137-142.

Cook, L.J., Russell, J.S., 1983. The climate of seven CSIRO field stations in northern Australia. Division of Tropical Crops and Pastures, Technical Paper No. 25, CSIRO, Australia.

Cothren, J.T., 1999. Physiology of the cotton plant. p. 207-268 In: W.C. Smith and J.T. Cothren (ed.) Cotton: Origin, History, Technology and production. John Wiley & sons, Inc, New York.

Coulton, RT., 1991. Cotton fibre quality. NSW Agriculture, Agfact, P5.3.7, Agdex 151/25, ISSN-7759.

Davidonis, G.H., Johnson, A.S., Landivar, J.A., Fernandez, C.J., 2004. Cotton fiber quality is related to boll location and planting date. Agron. J. 96, 42-47.

Dillon, G.E., Fitt, G.P., 1995. Reassessment of sampling relationships for Helicoverpa spp. (Lepidoptera: Noctuidae) in Australian cotton. Bul. Entomol. Res. 85(3), 321-329.

Dippenaar, M.C., Nolte, C.R., Barnard, C., 1990. Controlling excessive growth in cotton by multiple applications of low concentrations of mepiquat chloride. S.-Afr. Tydskr. Plant Grond. 7(1), 50-54.

Done, A.A., Muchow, R.C., Warren, J.D., Kernot, I.I., 1985. Maize and Sorghum. In: Muchow, R.C. (Ed.), Agroresearch for the semi-arid tropics: North-west Australia. University of Queensland Press: St Lucia, Qld, pp. 115-132.

Eaton, F.M., 1955. The physiology of the cotton plant. Ann. Rev. Plant Phys. 6, 299-328.

Edminsten, K., 1997. Cotton classification. In: 1997 North Carolina Cotton production Guide. Hppt://ipmwww.ncsu.sdu/production_Duides_Cotton/chptr4.html

Ehleringer, J.R., Hammond, S.D., 1987. Solar tracking and photosynthesis in cotton leaves. Agric. Forest Meteor. 39, 25-35.

Evenson, J.P., 1967. Effect of atmospheric humidity on grade of cotton lint in the Ord Valley, North-Western Australia. Cotton Grow. Rev. 44, 29-38.

Fitt, G.P., 1994. Cotton pest management: Part 3. An Australian perspective. Ann. Rev. Entomology 39, 543-562.

Fritschi, F.B., Roberts, B.A., Travis, R.L., Rains, D.W., Hutmacher, R.B., 2003. Response of irrigated Acala and Pima S7 Cotton to Nitrogen Fertilisation: Growth, Dry Matter Partitioning, and yield. Agron. J. 95, 133-146.

Gipson, J.R., Joham, H.E., 1968. Influence of night temperature on growth and development of cotton (*Gossypium hirsutum* L.). II. Fiber Properties. Agron. J. 60, 296-298.

Gipson, J.R., Joham, H.E., 1969. Influence of night temperature on growth and development of cotton (*Gossypium hirsutum* L.).III. Fiber Elongation. Crop Sci. 9, 127-129.

Gipson, J.R., Ray, L.L., 1970. Temperature-cultivar interrelationships in cotton. 1. Boll and fiber development. Cotton Grow. Rev. 47, 257-271.

Grismer, M.E., 2002. Regional cotton lint yield, ET_c and water value in Arizona and California. Agric. Water Manage. 54, 227-242.

Gunn, R.H., 1969. Soils of the Kimberley Research Station, Kununurra, WA. CSIRO, Australia, Division of Land Research, Technical Memorandum, 69/12.

Hammer, G.L., Vanderlip, R.L., 1989. Genotype-by-environment interaction in grain sorghum. I. Effects of temperature on radiation use efficiency. Crop Sci. 29, 370-376.

Hearn, AB, 1969. The growth and development of cotton in a desert environment II. Dry matter production. J Agric. Sci. Camb. 73, 75-86.

Hearn, A.B., 1975. Ord Valley Cotton Crop: Development of a Technology. Cotton Grow. Rev. 52, 77-102.

Hearn, A.B., 1994. OZCOT: A simulation model for cotton crop management. Agric. Sys. 44, 257 – 299.

Hearn, A.B., 1995. Cotton in the Kimberley: A note on varieties for tropical winter production. Unpublished report for The Australian Cotton CRC, 'Myall Vale' Wee Waa Rd Narrabri NSW, Australia, 2p.

Hearn, A.B., Constable GA, 1984. Cotton, Ch 14, In: Goldsworthy, P.R., Fisher, N.M., (eds). The Physiology of tropical food crops. John Wiley & Sons, Chichester, pp 495-527.

Heitholt, J.J., 1993. Cotton boll retention and its relationship to lint yield. Crop Sci. 33, 486-490.

Heitholt, J.J., 1997. Floral removal from specific fruiting positions in cotton: Yield and fiber quality. Crop Sci. 37, 826-832.

Hesketh, J.D., Low, A., 1968. Effect of temperature on components of yield and fibre quality of cotton varieties of diverse origin. Cotton Grow. Rev. 45, 243-257.

Hesketh, J.D., Baker, D.N., Duncan, W.G., 1972. Simulation of growth and yield in cotton II. Environmental control of morphogenesis. Crop Sci. 12:436-439.

Hodgson, A.S., Chan, K.Y., 1982. The effect of short term waterlogging during furrow irrigation on cotton in a cracking clay. Aust. J. Agric. Res. 33, 109-116.

Holman, E.M., Oosterhuis, D.M., 1999. Cotton photosynthesis and carbon partitioning in response to floral bud loss due to insect damage. Crop Sci. 39, 1347-1351.

Hutmacher, R.B., Travis, R.L., Rains, D.W., Vargas, R.N., Roberts, B.A., Weir, B.L., Wright, S.D., Munk, D.S., Marsh, B.H., Keely, M.P., Fritschi, F.B., Munier, D.J., Nichols, R.L., Delgado, R., 2004. Response of recent acala cotton cultivars to variable nitrogen rates in the San Joaquin Valley of California. Agron. J. 96, 48-62.

ICAC, 2002. Cotton world statistics. Bulletin of the International Cotton Advisory Committee, September 2002. www.icac.org.com.

Jenkins, J.N., McCarty, J.C., Parrott, W.L., 1990. Effectiveness of fruiting sites in cotton: Yield. Crop Sci. 30, 365-369.

Jones, M.A., Wells, R., Guthrie, D.S., 1996. Cotton response to seasonal patterns of flower removal: I Yield and fibre quality. Crop Sci. 36, 633-638.

Kakani ,V.G., Reddy, K.R., Kotti, S., Wallace, T.P. Prasad, V.V., Reddy, V.R., Zhao, D., 2005. Differences in in-vitro Pollen Germination and Pollen Tube Growth of Cotton Cultivars in Response to High Temperature. Ann. Bot. 96, 59–67.

Kennedy, C.W., Hutchinson, R.L., 2001. Cotton growth and development under different tillage systems. Crop Sci. 41, 1162-1168.

Kennedy, C.W., Smith, W.C. Jr, Jones J.E., 1986. Effect of early season square removal on three leaf types of cotton. Crop Sci. 26, 139-145.

Kerby, T.A., Buxton, D.R., 1976.fruiting in cotton as affected by leaf type and population density. Beltwide Cotton Prod. Res. Conf. Las Vegas, Nev., National Cotton research Council, Memphis, Tennessee. P.67-70.

Kerby, T.A., Buxton, D.R., 1981. Competition between adjacent fruiting forms in cotton. Agron. J. 73, 867-871.

Kerby, T.A., Hake, K. D., 1996. Monitoring Cotton's Growth. In: Hake, S.J., Kerby, T.A., Hake, K.D., (Eds), Cotton Production Manual. University of California, Oakland, pp. 335-355.

Kerby, T.A., Keely, M., Johnson, S. 1987. Growth and development of Acala cotton. Califonia Agric Exp. Sta Bull. 1921.

Kiniry, J.R., Jones, C.A., O'Toole, J.C., Blanchet, R., Cabelgunne, M., Spanel, D.A., 1989. Radiation-use efficiency in biomass accumulation prior to grain filling for five grain crop species. Field Crops Res. 20, 51-64.

Kittock, D.L., Henneberry, T.J., Bariola, L.A., 1981. Fruiting of upland and Pima cotton with different planting dates. Agron. J. 73,711-715.

Kletter, E., Wallach, D., 1982 Effects of fruiting form removal on cotton reproductive development. Field Crops Res. 5, 69-84.

Kohel, R.J., Benedict, C.R., 1987. Growth analysis of cotton with different maturities. Agron. J. 79, 31-34.

Kohel, R.J., Quiesenberry, J.E., Benedict, C.R., 1974. Fiber elongation and dry weight changes in mutant lines of cotton. Crop Sci. 14, 471-474.

Kruskal, W.H., Wallis, W.A., 1952. Use of ranks in one-criterion variance analysis. J. Amer. Statist. Ass. 47: 583-621.

Lang, A.G., 1938. The origin of lint and fuzz hairs of cotton. J. Agr. Res. 56, 507-521

Lei, T.T., Gaff, N., 2003. Recovery from terminal and fruit damage by dry season cotton crops in tropical Australia. J. Econ. Entomol. 96(3), 730-736.

Li, W., Zhou, Z., Meng, Y., Xu, N., Fok, M., 2009. Modeling boll maturation period, seed growth, protein, and oil content of cotton (*Gossypium hirsutum* L.) in China. Field Crops Res. 112, 131-140.

Liakatas, A., Roussopoulos, D., Whittington, W.J., 1998. Controlled-temperature effects on cotton yield and fibre properties. J. Agric. Sci. Camb. 130, 463-471.

Ludwig, L.J., Saeki T., Evans, L.T., 1965. Photosynthesis in artificial communities of cotton plants in relation to leaf area. I experiments with progressive defoliation of mature plants. Aust. J. Biol. Sci. 18, 1103-1117.

Lu, Z.J., Chen, J., Percy, R.G., Zeiger, E., 1997. Photosynthetic rate, stomatial conductance and leaf area in two cotton species (*Gossypium barbadense* and *Gossypium hirsuitum*) and their relation with heat resistance and yield. Aust. J. Plant Physiol. 24, 693-700.

Mauney, J.R., 1966. Floral initiation of upland cotton Gossypium hirsutum L. in response to temperatures. J. Exp. Bot. 17, 452-459.

Mauney, J.R., 1986. Vegetative growth and development of fruiting sites. In: Mauney, J.R., Stewart J.McD., (Eds) Cotton physiology, The Cotton Foundation, Memphis, p11-28.

Mauney, J.R., Guinn, G., Fry, K.E., Hesketh, J.D., 1979. Correlation of photosynthetic carbon dioxide uptake and carbohydrate accumulation in, cotton, soybean, sunflower and sorghum. Crop Sci., 13, 260-266.

Mayers, J.D., Lawn, R.J., Byth, D.E., 1991a. Agronomic studies on soybean [*Glycine max* (L.) Merrill] in the dry season of the tropics. I. Limits to yield imposed by phenology. Aust. J. Agric. Res. 42, 1075-1092.

Mayers, J.D., Lawn, R.J., Byth, D.E., 1991b. Agronomic studies on soybean [*Glycine max* (L.) Merrill] in the dry season of the tropics. II. Interaction of sowing date and sowing density. Aust. J. Agric. Res. 42, 1093-1107.

Mayers, J.D., Lawn, R.J., Byth, D.E., 1991c. Agronomic studies on soybean [*Glycine max* (L.) Merrill] in the dry season of the tropics. III.Effect of artificial photoperiod extension on phenology, growth and seed yield. Aust. J. Agric. Res. 42, 1109-1121.

Mayers, J.D., Lawn, R.J., Byth, D.E., 1991d. Adaption of soybean [*Glycine max* (L.) Merrill] to the dry season of the tropics. II. Effects of genotype and environment on biomass and seed yield. *Aust. J. Agric. Res*. 42, 1075-1092.

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P., Freebairn, D.M., 1996. APSIM: a novel software system for model development, model testing and simulation in Agricultural systems research. Agric Sys 50, 255-271.

McDowell, A. J., Bange, M.P., Tan, D.K.Y., 2007. Cold temperature exposure at 10 degrees C for 10 and 20 nights does not reduce tissue viability in vegetative and early flowering cotton plants. Aust. J. Exp. Agric. 47(2), 198-207.

Milroy, S.P., Bange, M.P., 2003. Nitrogen and light responses for cotton photosynthesis and implications for crop growth. Crop Sci. 43, 904-913

Milroy, S.P., Bange, M.P., Sadras, V.O., 2001. Profiles of leaf nitrogen and light in reproductive canopies of cotton (*Gossypium hirsutum*). Ann. Bot. 87, 325-333.

Monteith, J.L., 1972. Solar radiation and productivity in tropical ecosystems. J. Appl. Ecol. 9, 747-766.

Monsanto Australia and Cotton Australia, 2010. Schedule A – Resistance Management Plan for BollgardII cotton 2010/2011. Ord River Irrigation and Burdekin Bowen Basin Areas. In: Cotton Pest management Guide 2010-2011 (eds) Cotton CRC Development and Delivery Team, p80-81. http://www.cottoncrc.org.au/content/Industry/Publications/Pests_and_Beneficials/Cotton_Pest_Management_Guide_2010__11.aspx

Moragon, B.J., Hesketh, J.D., Low, A. 1968. Effects of temperature and photoperiod on floral initiation amoung strains of cotton. Cotton Grow. Rev. 45, 91-100.

Moulden, J.H., Yeates, S.J., Strickland, G.R., Plunkett, G.M., 2006. Developing an environmentally responsible irrigation system for cotton in the Ord River Irrigation Area. *In:* Proceedings of ANCID 2006, 16 - 19 October, Darwin, NT. The Australian National Committee on Irrigation and Drainage.

Muchow, R.C., Coates, D.B., 1986. An analysis of the environmental limitation to yield of irrigated grain sorghum during the dry season in tropical Australia using a radiation interception model. Aust. J. Agric. Res. 37, 135-48.

Munro, JM, 1971. An Analysis of earliness in cotton. Cotton Grow. Rev. 48, 28-41.

NLWRA, 2001. National Heritage Trust, Australian Agriculture Assessment 2001, Volume 1. National Land and Water Resources Audit, p 8-9, Commonwealth of Australia. ISBN 0 624 37129 6, (www.nlwra.gov.au/atlas).

Northcote, K.H., 1971. A factual key for the recognition of Australian Soils. 3rd Edition. Rellim Technical Publications, Glenside, South Australia.

Oosterhuis, D.M., 1990. Growth and development of a cotton plant. In: Miley, W.N., and Oosterhuis, D.M., (eds.). Nitrogen nutrition of cotton: Practical issues. ASA, CSSA, and SSSA, Madison, WI, pp 1-24.

Oosterhuis, D.M., Wallschledger, S.D., 1988. Cotton leaf area distribution in relation to yield development. In: Proc. Beltwide Cotton Conferences, pp. 82-84

Parbery, D.B., Rose, C.W., Stern, W.R., 1968. Characteristics of the three main soils in the lower Ord River Valley, Western Australia. CSIRO, Australia, Division of Land Research, Technical Memorandum, 68/7.

Pearson, R.W., Ratliff, L.F., Taylor, H.M., 1970. Effect of soil temperature, strength, and pH on cotton seedling root growth. Agron. J. 62, 243-246.

Peng, S., Krieg, D.R., 1991. Single leaf and crop photosynthesis response to leaf age in cotton. Agron. J. 83, 704-708.

Perkins, H.H. Jr, Ethridge, D.E., Bragg, C.K., 1984. Fibre. In: Kohel, R.J., and Lewis, C.F., (eds), Cotton, American Soc. Agron., Madison. WI, p 437 – 509.

Pettigrew, W.T., 1995. Source-to-sink manipulation effects on cotton fiber quality. Agron. J. 87, 947-952.

Pettigrew, W.T., 2002. Improved yield potential with an early planting cotton production system. Agron. J. 86, 731-735.

Pettigrew, W.T., Heitholt, J.J., Meredith, W.R.Jr, 1992. Early season floral bud removal and cotton growth, yield and fibre quality. Agron. J. 84, 209-214.

Powell, R.D., 1969. Effect of temperature on boll set and development of *Gossypium hirsutum*. Cotton Grow. Rev. 46, 29-36.

Probert, M.E., Dimes, J.P., Keating, B.A., Dahl, R.C., 1998. APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agric. Sys. 56, 1-28.

Quisenberry, J.E., Kohel, R.J., 1975. Growth and development of fiber and seed in upland cotton. Crop Sci. 15, 463-467.

Reddy, V.R., Reddy, K.R., Baker, D.N., 1991. Temperature effect on growth and development of cotton during the fruiting period. Agron. J. 83, 211-217.

Reddy, K.R., Reddy, V.R., Hodges, H.F., 1992. Temperature effects on early season growth and development. Agron. J. 84, 229-237.

Reddy, K.R., Hodges, H.F., Reddy, V.R., 1992. Temperature effects on cotton fruit retention. Agron. J. 84, 26-30.

Ritchie, J.T., 1991. Specificaions of the ideal model for predicting crop yields. In: Muchow, R.C., and Bellamy, J.A., (eds), Climatic risk in crop production: models and management for the semiarid tropics and subtropics. CAB International, Wallingford, Oxfordshire, UK.p 99-120.

Ritchie, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Res. Research, 8, 1204-13.

Robertson, M.J., Carberry, P.S., Huth, N.I., Turpin, J.E., Probert, M.E., Poulton, P.L., Bell, M., Wright, G.C., Yeates, S.J., Brinsmead, R.B., 2002. Simulation of growth and development of diverse legume species in APSIM. Aust. J. Agric. Res. 53, 429-446

Rochester, I.J., 2007. Nutrient uptake and export from an Australian cotton field. Nutr. Cycl. Agroecosyst. 77, 213-223.

Rosenthal, W.D., Gerik, T.J., 1991. Radiation use efficiency among cotton cultivars. Agron. J. 83, 655-658.

Sadras, V.O., 1996. Cotton response to simulated insect damage: radiation-use efficiency, crop architecture and leaf nitrogen content as affected by loss of reproductive organs. Field Crops Res. 48, 199-208.

Sadras, V.O., Bange, M.P., Milroy, S.P., 1997. Reproductive allocation in cotton in response to plant and environmental factors. Ann. Bot. 80, 75-81.

Saimaneerat, A., Pookpakdi, A., Crozat., Y., Kasemsap., P., 1997. Effects of water deficit on cultivar Sri Sumrong 60. Kasetsart J. (Nat Sci.) 31, 93-100.

Salvucci, M.E., Crafts-Brandner, S.J., 2004. Inhibition of photosynthesis by heat stress: the activation state of Rubisco as a limiting factor in photosynthesis. Physiologia Plantarum 120,179-186.

SAS, 2001. The SAS system for windows. Release 8.0. SAS Inst., Cary, NC, USA.

Scholefield, P.B., Blackburn, K.J., 1985. Horticultural Crops. In: Muchow, R.C. (Ed.), Agroresearch for the semi-arid tropics: North-west Australia. University of Queensland Press: St Lucia, Qld, pp. 192-208.

Schubert, A.M., Benedict, C.R., Berlin, J.D., Kohel, R.J., 1973. Cotton fiber development – kinetics of cell elongation and secondary wall thickening. Crop Sci. 13, 704-709.

Sinclair, T.R., 1986. Water and nitrogen limitations in soybean grain production. I. Model development. Field Crops Res. 15, 125-41.

Sinclair, T.R., Muchow, R.C., 1999. Radiation Use Efficiency. Adv. Agron. 65, 215-265.

Sinclair, T.R., Muchow, R.C., Ludlow, M.M., Leach, G.J., Lawn, R.J., Foal, M.A., 1987. Field and model analysis of the effect of water deficits on carbon and nitrogen accumulation by soybean, cowpea and black gram. Field Crops Res. 17, 121-40.

Singh, B., L. Haley, J. Nightingale, W.H. Kan, C.H. Haigler, and A.S. Holaday. 2005. Long-term night chilling of cotton (*Gossypium hirsutum*) does not result in reduced CO_2 assimilation. Functional Plant Biology. 32, 655-666.

Smith, J.E., Longstreth, D.T., 1994. Leaf expansion and carbon assimilation in cotton leaves grown at two photosynthetic photon flux densities. Amer. J. Bot. 18, 711-717.

Stern, W.R., 1965. The seasonal growth characteristics of irrigated cotton in a dry monsoonal environment. Aust. J. Agric. Res., 16, 347-66.

Stewart, J.M., 1986. Integrated events in the flower and fruit. In: Mauney, J.R., and Stewart J.McD., (eds) Cotton physiology. The Cotton Foundation, Memphis, TN, p297.

Stewart, S.D., Layton, M.B., Williams, M.R., Ingram, D., Maily, W., 2001. Response of cotton to prebloom square loss. J. Econ. Entomol. 94, 388-396.

Strickland, G.R., Yeates, S.J., Fitt, G.P., Constable, G.A., Addision, S.J., 1998. Prospects for a sustainable cotton industry in tropical Australia using novel crop and pest management. In: Gilliam F.M., Kechagia, U., Xanthopoulos, F. Tsaliki E. (Eds). Proceedings, World Cotton Conference-2, New Frontiers in Cotton Research, Athens, Greece, September 7-11, 1998, pp850-857.

Strickland, G.R., Annells, A.J., Ward, A.L., 2003. Assessing the feasibility for cotton in tropical Australia: Research for the development of sustainable pest management systems. In: Swanepoel, A. (Ed.), Proceedings of the World Cotton Research Conference-3: Cotton Production for the new millennium. 9-13 March 2003, Cape Town, South Africa, pp. 975-986.

Supima, 2009. Supima – World’s Finest Cottons, http://www.supima.com/whats-supima/faq/

Suriyapan, P., Boonyong, B., Somnus, P., 1978. The influence of nitrogen and phosphorus on growth, yield and fibre quality of irrigated cotton in the dry season. Thai J. Agr. Sci. 11, 11-14.

The Australian Cottongrower 2003. Cotton Year Book 2003, Greenmount Press, Toowoomba, Qld, Australia, p67.

Thomson, N.J., 1965. Cotton cultivar trials in the Ord Valley north western Australia. 3. The effect of time of sowing on cultivars of different maturity. Empire Cotton Grow. Rev. 42, 263-278.

Thomson, N.J., Basinski, J.J., 1962. Cotton in the Ord Valley of Northern Australia. Empire Cotton Grow. Rev. 39, 81-92.

Toms, W.J., 1963. Commercial cotton growing in the Ord River Project. J. Dept. Agric. West Aust. 4(4), 754.

Trapani, N., Hall, A.J., Sadras, V.O., Vilella, F., 1992. Ontogenic changes in radiation use efficiency of sunflower (*Helianthus annuus* L.) crops. Field Crops Res. 29, 301-316.

Thacker, V.R., Saroop, S., Vaishnav, P.P., Singh, Y.D., 1989. Genotypic variations and influence of diurnal temperature on cotton fibre development. Field Crops Res. 22, 129-141.

Turcotte, E.L., Feaster, C.V., Young, E.F.Jr$_4$, 1991. Registration of six American Pima cotton germplasm lines. Crop Sci. 31, 495.

Unruh, B.L., Silvertooth, J.C., 1996. Comparisons between an upland and a Pima cotton cultivar: I Growth and Yield. Agron. J. 88, 583-589.

Viator, R.P., Nuti, R.C., Edminsten, K.L., Wells, R, 2005. Predicting cotton boll maturation period using degree days and other climatic factors. Agron. J. 97, 494-499.

van Oosterom, E.J., O'Leary, G.J., Carberry, P.S., Craufurd, P.Q., 2002. Simulating growth, development, and yield of tillering pearl millet. III. Biomass accumulation and partitioning. Field Crops Res. 79, 85-106.

Wall, G.W., Amthor, J.S., Kimball, B.A., 1994. COTCO2: a cotton growth simulation model for global change. Agric. For. Meteorol. 70, 289-342.

Wanjura, D.F., Barker, G.L., 1985. Cotton lint yield accumulation rate and quality development. Field Crops Res. 10, 205-218.

Warner, D.A., Holaday, A.S., Burke J.J., 1995. Response of carbon metabolism to night temperature in cotton. Agron. J. 87:1193-1197.

Wells, R., Meredith, W.R., 1984a. Comparative growth of obsolete and modern cotton cultivars. I. Vegetative dry matter partitioning. Crop Sci. 24, 858-862.

Wells, R., Meredith, W.R., 1984b. Comparative growth of obsolete and modern cotton cultivars. II. Reproductive dry matter partitioning. Crop Sci. 24, 863-868.

Wells, R., Stewart, A.M., 2010. Morphological alterations in response to management and environment. In: Stewart, J.M., Oosterhuis, D.M., Heitholt, J.J., Mauney, J.R., (eds), Physiology of Cotton. Springer Science + Business Media B.V. pp 24-32.

Wells, R., Meredith, W.R., Willford, J.R., 1986. Crop photosynthesis and its relationship to plant productivity in near-isogenic cotton lines differing in leaf morphology. Plant Physiol. 82, 635-640.

Wilson, L.J., Sadras, V.O., Heimoana, S.C., Gibb, D., 2003. How to succeed by doing nothing: cotton competition after simulated early season pest damage. Crop Sci. 43, 2125-2134.

Williams, J., Day, K.J., Isbell, R.F., Reddy, S.J., 1985. Soils and Climate. In: Muchow, R.C. (Ed.), Agroresearch for the semi-arid tropics: North-west Australia. University of Queensland Press: St Lucia, Qld, pp. 31 – 92.

Wood, I.M., Hearn, A.B., 1985. Fibre Crops. . In: Muchow, R.C. (Ed.), Agroresearch for the semi-arid tropics: North-west Australia. University of Queensland Press: St Lucia, Qld, pp. 149-164.

Xie, W., Trolinder, N.L., Haigler, C.H., 1993. Cool temperature effects on cotton fiber initiation and elongation clarified using in vitro cultures. Crop Sci. 33, 1258-1264.

Yeates, S.J. 2001. Cotton Research and Development Issues in Northern Australia: a review and scoping strudy. The Australian Cotton CRC, 'Myall Vale' Wee Waa Rd Narrabri NSW, Australia, August 2001, p6-11, http://www.cotton.crc.org.au/Publicat/NthIssue.htm.

Yeates S.J., Lawn R.J., Adkins, S.A., 2000. Predicting Weather Damage of Mungbean Seed in Tropical Australia. I. Relation between seed quality, weather and reproductive development. Aust. J. Agric. Res. 51, 637-48.

Yeates S., Strickland, G., Murti, S., Wood, B., Mcleod, I., 2002a. Is There a Future for Cotton in Northern Australia? Invited paper In: Field to Fashion, Proceedings 11th Australian Cotton Conference, Brisbane, 13-15 August, 2002 12 pp. Australian Cotton Growers Research Association.

Yeates, S.J., Constable, G.A., McCumstie, T., 2002b. Developing management options for mepiquat chloride in tropical winter season cotton. Field Crops Res. 74, 217-230.

Yeates, S.J., Constable, G.A. and McCumstie, T. 2005**.** Cotton growth and yield after seed treatment with mepiquat chloride in the tropical winter season. Field Crops Res. 93, 122-131.

Yeates, S.J., Abrecht, D.G., Price, T.P., Mollah, W.S., Hausler, P., 1996. Operational aspects of ley farming systems in the semi-arid tropics of northern Australia: a review. Aust. J. Exp. Agric., 36, 1025-1035.

Yeates, S.J., Moulden, J.H., Plunkett, G.M., and Strickland, G.R., 2006. Assessing the feasibility of GM cotton in the Ord River Irrigation Area: tillage systems for late wet season sowing. In: Ground Breaking Stuff, Turner, N., Acuna, T., Johnson, R., (eds), Proceedings 13th Australian Agronomy Conference, Perth, 10-14 September, 2006, 5 pp (www.agronomy.org.au)

Appendix 1: Average boll weights for OZCOT calibration

Average boll weights (seed cotton g / boll) measured from the experiments in Ch3. Where weighted average for L23 = 5.6 g/boll and S50 = 5.1 g/boll.

Cultivar	Sowing month	Position on the plant		
		Lower	Mid	Upper
Siokra L23	March	**6.3** ± 0.23	5.4 ± 0.59	5.5 ± 0.36
	April	5.5 ± 0.30	5.1 ± 0.12	6.1 ± 0.26
	May	4.9 ± 0.29	5.5 ± 0.39	5.3 ± 0.18
	June	5.6 ± 0.08	6.1 ± 0.26	5.3 ± 0.20
Sicot 50	March	**5.8** ± 0.13	5.2 ± 0.22	4.5 ± 0.21
	April	5.1 ± 0.34	4.9 ± 0.22	5.3 ± 0.11
	May	4.5 ± 0.30	5.6 ± 0.33	4.5 ± 0.17
	June	5.0 ± 0.15	5.0 ± 0.25	4.5 ± 0.14

Appendix 2: Soil characterisation data for Cununurra clay

Drained upper limit (DUL) and crop lower limit (CLL) volumetric moisture contents, bulk density and plant available water-holding capacity (PAWC) measured for dry season cotton grown on a Cununurra clay (Yeates unpublished data). For VMC mean and standard error of 8 samples per depth increment are presented.

Layer (cm)	Bulk density	CLL (mm mm^{-1} ±se)	DUL (mm mm^{-1} ±se)	PAWC# / layer (mm)	PAWC mm mm^{-1}
0-10*	1.25	0.203	0.425	22.2	0.22
10-25	1.38	0.140±0.056	0.408±0.009	40.0	0.27
25-35	1.43	0.209±0.065	0.391±0.007	18.2	0.18
35-45	1.43	0.223±0.070	0.394±0.006	17.1	0.17
45-60	1.43	0.233±0.066	0.387±0.005	23.1	0.15
60-70	1.43	0.255±0.043	0.388±0.009	13.3	0.13
70-90	1.58	0.280±0.021	0.384±0.007	20.9	0.11
90-110	1.58	0.283±0.038	0.385±0.010	20.4	0.10
110-130	1.60	0.316±0.037	0.431±0.009	22.9	0.12

* from average of Ivanhoe Plain soils by Plunkett and Muchow (2003)

calculated from highest VMC and CLL.

Appendix 3: Fibre properties after exposure to pre-picking weather in the field

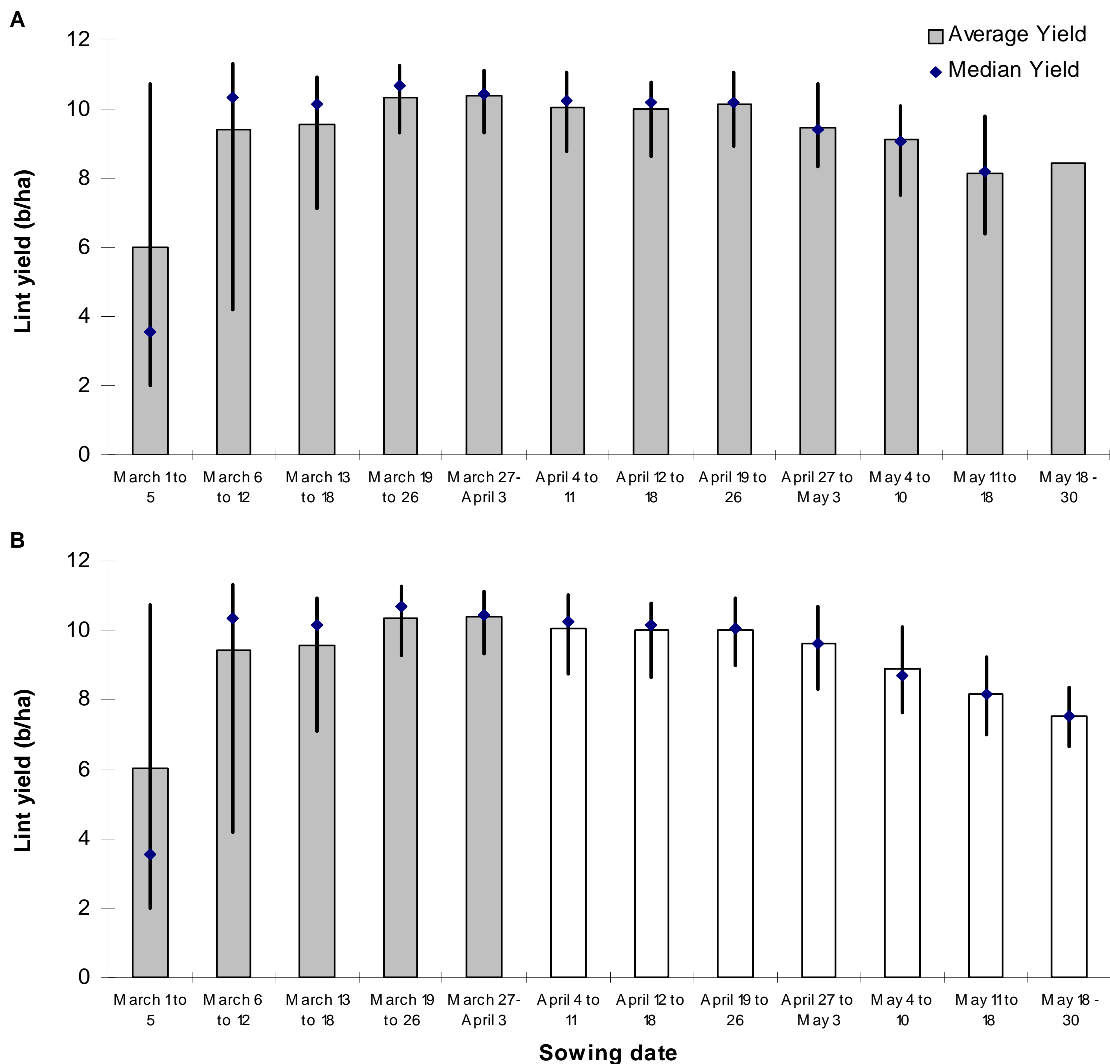
Fibre length (in), strength (g/tex), and nicronaire after pre-pick exposure to weather in field experiments. Lsd = least significant difference p<0.05, in brackets is value where not significant or ns. DAHM = days after pick maturity.

Sowing date	Cultivar	Sample date	DAHM	Length	Strength	Micronaire
Mar-95	L23	25-Sep-95	2	1.10	27.0	4.20
		18-Oct-95	25	1.08	27.2	4.28
		25-Oct-95	32	1.10	26.3	4.03
		08-Nov-95	45	1.08	24.9	4.43
		lsd		ns (0.031)	1.82	ns (0.40)
		25-Sep-95	2	1.10	27.0	4.08
	S50	18-Oct-95	25	1.09	27.1	4.00
		25-Oct-95	32	1.09	26.3	4.00
		08-Nov-95	45	1.08	24.9	4.05
		lsd		ns (0.374)	1.47	ns (0.40)
Apr-95	L23	06-Oct-95	4	1.07	29.0	4.78
		25-Oct-95	21	1.07	26.7	4.83
		08-Nov-95	35	1.07	26.7	4.48
		20-Nov-95	47	1.05	25.1	4.65
		lsd		ns (0.026)	2.22	ns (0.42)
	S50	06-Oct-95	4	1.07	27.3	4.48
		25-Oct-95	21	1.07	26.1	4.53
		08-Nov-95	35	1.08	25.4	4.25
		20-Nov-95	47	1.07	26.9	4.15
		lsd		ns (0.03)	ns (2.3)	ns (0.39)
May-95	L23	20-Oct-95	5	1.18	31.6	3.93
		08-Nov-95	24	1.16	30.5	3.98
		20-Nov-95	36	1.15	30.3	4.03
		lsd		0.0222	0.86	ns (0.32)
	S50	20-Oct-95	5	1.13	27.5	4.20
		08-Nov-95	24	1.09	28.4	4.05
		20-Nov-95	36	1.10	29.0	3.85
		lsd		ns (0.04)	ns (2.13)	ns (0.19)
Jun-95	L23	01-Nov-95	0	1.14	29.6	4.23
		08-Nov-95	7	1.12	30.5	4.20
		20-Nov-95	19	1.0975	29.2	4.08
		lsd		ns (0.074)	ns (1.73)	ns (0.26)
	S50	01-Nov-95	0	1.10	27.9	4.45
		08-Nov-95	7	1.11	29.6	4.23
		20-Nov-95	19	1.09	28.3	4.53
		lsd		ns (0.047)	ns (3.12)	ns (0.33)
Mar-96	L23	23-Sep-96	1	1.16	27.8	4.18
		08-Oct-96	16	1.14	26.1	4.50
		25-Oct-96	33	1.13	24.2	4.43
		08-Nov-96	47	1.12	23.7	4.38
		lsd		ns (0.035)	1.79	ns (0.31)
	S50	23-Sep-96	1	1.11	23.58	4.30
		08-Oct-96	16	1.12	24.90	4.23
		25-Oct-96	33	1.12	23.50	4.18
		08-Nov-96	47	1.11	21.10	4.08
		lsd		ns (0.03)	2.0887	ns (0.51)

Sowing date	Cultivar	Sample date	DAHM	Length	Stength	Micronaire
Apr-96	L23	08-Oct-96	7	1.13	29.08	4.28
		25-Oct-96	24	1.10	26.65	4.45
		08-Nov-96	38	1.11	25.98	4.10
		lsd		ns (.044)	2.66	ns (0.47)
	S50	08-Oct-96	7	1.11	26.1	4.43
		25-Oct-96	24	1.09	24.5	4.50
		08-Nov-96	38	1.09	22.8	4.45
		lsd		ns (0.037)	1.64	ns (0.27)
May-96	L23	25-Oct-96	7	1.13	30.4	4.10
		01-Nov-96	14	1.14	30.1	3.88
		08-Nov-96	21	1.15	29.0	4.10
		lsd		ns (0.031)	ns (1.5)	ns (0.33)
	S50	25-Oct-96	7	1.11	26.6	4.30
		01-Nov-96	14	1.13	26.4	4.35
		08-Nov-96	21	1.12	25.1	4.33
		lsd		ns (0.029)	ns (1.7)	ns (0.24)
Apr-01	L23	03-Oct-01	3	1.16	31.0	3.75
		09-Oct-01	9	1.17	30.9	3.88
		16-Oct-01	16	1.15	29.9	3.90
		19-Oct-01	19	1.15	28.8	3.70
		23-Oct-01	23	1.15	29.4	3.93
		30-Oct-01	30	1.14	29.8	3.95
		02-Nov-01	33	1.15	28.9	3.73
		06-Nov-01	37	1.14	29.8	3.70
		lsd		ns (0.035)	1.149	ns (0.32)
	S50	03-Oct-01	3	1.12	29.3	3.58
		09-Oct-01	9	1.12	29.0	3.58
		16-Oct-01	16	1.12	28.5	3.58
		19-Oct-01	19	1.12	29.1	3.58
		23-Oct-01	23	1.12	28.0	3.48
		30-Oct-01	30	1.12	28.4	3.35
		02-Nov-01	33	1.14	28.8	3.33
		06-Nov-01	37	1.11	27.3	3.80
		lsd		ns (0.33)	1.20	0.34
May-01	L23	02-Nov-01	2	1.13	31.9	4.35
		06-Nov-01	6	1.13	30.0	4.28
		13-Nov-01	13	1.13	31.7	4.15
		20-Nov-01	20	1.10	29.2	4.15
		27-Nov-01	27	1.13	30.4	4.68
		lsd	0	ns (0.043)	1.95	ns (0.51)
	S50	02-Nov-01		1.09	30.3	3.73
		06-Nov-01	6	1.10	30.0	4.00
		13-Nov-01	13	1.10	31.1	3.78
		20-Nov-01	20	1.08	28.8	3.80
		27-Nov-01	27	1.10	30.0	3.90
		lsd		ns (0.034)	ns (1.83)	ns (0.36)

Appendix 4: The expanded Fig. 7.6 showing simulated lint yields for weekly sowing periods with and without the Bt sowing window

The expanded Fig. 7.6 showing the simulated average and median lint yield (bales/ha) for weekly sowing periods for seasons when the MTPB sowing rule was met: A) with the Bt window (grey bars); B) without the Bt window (white bars). Error bar shows yield for 10 to 90% of seasons. One bale = 227 kg of lint.



Appendix 5: Plates showing field experiments at the ORIA

Picking the high yielding April sowing

One replicate showing from left to right Buffer of the March sowing, April sowing and May sowing just emerged