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Review

Can sustainable cotton production systems be developed for tropical northern Australia?

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Abstract. This article reviews research coordinated by the Australian Cotton Cooperative Research Centre (CRC) that investigated production issues for irrigated cotton at five targeted sites in tropical northern Australia, north of 21°S from Broome in Western Australia to the Burdekin in Queensland. The biotic and abiotic issues for cotton production were investigated with the aim of defining the potential limitations and, where appropriate, building a sustainable technical foundation for a future industry if it were to follow.

Key lessons from the Cotton CRC research effort were: (*1*) limitations thought to be associated with cotton production in northern Australia can be overcome by developing a deep understanding of biotic and environmental constraints, then tailoring and validating production practices; and (*2*) transplanting of southern farming practices without consideration of local pest, soil and climatic factors is unlikely to succeed. Two grower guides were published which synthesised the research for new growers into a rational blueprint for sustainable cotton production in each region. In addition to crop production and environmental impact issues, the project identified the following as key elements needed to establish new cropping regions in tropical Australia: rigorous quantification of suitable land and sustainable water yields; support from governments; a long-term funding model for locally based research; the inclusion of traditional owners; and development of human capacity.

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Introduction

This paper reviews published research and development by successive Australian Cotton Cooperative Research Centres (CRC) and their partners between 1995 and 2012 that assessed the feasibility of irrigated cotton production in Australia's tropical north while building a technical foundation for a sustainable future industry should it be established. Potential availability of land and water resources combined with excellent market prospects in nearby Asia, and the availability of a suite of new technologies, were believed to enhance prospects for sustainable cotton farming systems in the region. Various parts of northern Australia were chosen for thorough feasibility assessment (Fig. 1) because the climate was possibly suitable, water and land resources were considered adequate, and there was grower or investor interest.

Capturing the agricultural 'opportunities' in Australia's tropical north has been desired by Europeans since they first explored and settled the continent. However, northern Australia has always presented challenges for crop production; hence, extensive beef production remains the dominant land use. Despite apparently huge supplies of water and large tracts of land, most crop production is confined to near the coast in tropical Queensland (except Cape York), small irrigated areas in the Northern Territory and the first stage of the Ord River Irrigation Area in Western Australia.

There have been many attempts at broadacre crop production (dryland and irrigated) in tropical Australia, often supported by research, but with only a few successes (Bauer 1977, 1985; Cox and Chapman 1985; McCown *et al*. 1985; Robertson and Chapman 1985; Chapman *et al*. 1996; McCown 1996*a*). These past efforts have shown clearly that conventional farming practices cannot simply be transferred from traditional agricultural areas to northern Australia. They are mostly unsuitable, and contributed to failures. However, technology and our understanding of complex biological issues in agriculture have advanced enormously over the last 20 years. These advances have provided the opportunity for northern agricultural practices to be developed that are also sensitive to environmental concerns.

Bauer (1985) gave three reasons for failure of large-scale commercial agriculture in northern Australia at the time: (*i*) distance, (*ii*) ignorance of the physical environment, and (*iii*) 'a reprehensible aversion to learning by experience'. Bauer's review was written when the Ord River was tagged 'a white elephant'. However, since 1985 there has been considerable improvement in knowledge and infrastructure such that, in some regions, the limitations of distance and ignorance of the physical environment have diminished significantly, for example, soil surface management and soil nitrogen (N) dynamics, road transport development and

Fig. 1. Cotton research sites in northern Australia: Ord River Irrigation Area, Katherine (Daly Basin), Broome area (La Grange basin), Richmond (Flinders River) and the Lower Burdekin. Marked is the boundary between likely dry-season (north of black line) and wet-season (south of dashed line) production areas with the production season unknown between the lines (adapted from Yeates and Bange 2003).

increased labour availability—the latter two due to expanded tourism and other industries. Hence, it is point (*iii*), ‘a reprehensible aversion to learning by experience’, that has the most relevance today. Virtually all crop species currently grown or under evaluation in northern Australia have been trialled previously, with many well-documented commercial failures (Bauer 1985; Chapman *et al*. 1996). Cotton is no exception, being evaluated at many locations since the late 1800s (Yeates 2001).

The ‘northern challenge’ for crop development was perhaps best summarised by Chapman *et al*. (1996):

> ‘*Nowhere else in Australia has it proved more difficult to devise agricultural systems that are flexible enough to accommodate climate and market fluctuations, while maintaining or enhancing productivity over time and avoiding adverse impacts on the resource base.*’

Successful new crops in northern Australia have market advantages (e.g. out-of-season horticulture crops), and many of the climatic limitations have been avoided by moving production from the wet season to the dry season and using irrigation (Chapman *et al*. 1996). It was hoped that dryland grain production could be established via synergies with extensive grazing of beef cattle and by using legume-ley pastures and conservation tillage to overcome limitations of poor soil nutrition, variable rainfall and high soil temperature (McCown *et al*. 1985). This has not eventuated due to insufficient returns from the grain crops (McCown 1996*a*).

The decade since 1990 was the most successful in the history of agriculture in northern Australia, measured by percentage increases in the value of production. In particular, crop production in the Northern Territory and the Kimberley region of Western Australia increased in value by 366 and 157%, respectively, albeit from a small base; in northern Queensland, the increase in the value of crop production was a more modest 38% due to the dominance of the existing sugar industry (Yeates *et al*. 2002*a*). Virtually all of the increase in crop production in the Kimberley and Northern Territory has been irrigated. In the Northern Territory, horticultural crops dominated in 2000.

The only significant commercial production of cotton in the region occurred at the Ord River between 1963 and 1974. Of note, the reason for the failure of the Ord River cotton industry remains unique for tropical Australia because it was due to unsustainable pest management practices (Hearn 1975). Cotton was established during the wet season (November–April) with irrigation supplementing rainfall to finish the crop early in the dry season (April–June). Yields were similar to south-eastern Australia during the same period (Hearn 1975). In hindsight, the failure of cotton was a symptom of a production system that failed to recognise the ecological limitations of the natural environment. Moreover, for many Australians the failure at the Ord River in the 1970s created a mindset against cotton and supported the ‘northern myth’ that large-scale irrigation in northern Australia was not possible.

Can cotton insect pests be managed sustainably in northern Australia?

Monsanto’s development of transgenic cotton expressing a Bt gene was the breakthrough technology that enabled cotton to be reconsidered as an option in northern Australia (Strickland *et al*. 1998). Exciting as this was, it was also accepted that the benefits of the technology could be short-lived if the lessons of the past were not heeded and the Bt proteins were used as ‘just another chemical’. Consequently, a novel new production system was proposed (Table 1). The strategy included dry-season cropping (rather than wet-season) to avoid the main pests, *Pectinophora gossypiella* Saunders (pink bollworm) and *Spodoptera litura* F. (cluster caterpillar). Integrated pest management (IPM) components evaluated included companion crops, sprays soft on non-target insects, pre-emptive resistance management and agronomic practices complementary to dry-season IPM cotton (Strickland *et al*. 1998).

Pest avoidance (dry-season cropping)

It was necessary to confirm that dry-season production would avoid key insect pests of cotton crops in north-western Australia. The two pests of most importance were *P. gossypiella* and *S. litura*. Both insects were significant in the collapse of the only cotton industry at the Ord River in the 1970s. Spraying to control overlapping generations of *S. litura* was considered the main reason for the development of resistance in *Helicoverpa*

Table 1. Key elements of a novel cotton production system for the Ord River contrasted with the previously unsuccessful system of the 1970s (from Strickland *et al.* 1998)

1970s industry	New industry
Wet-season planting window that was long—November–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–August.
Conventional cultivars	Bt transgenic cultivars
Broad-spectrum insecticides	IPM systems
No pesticide resistance management	Pre-emptive Bt-resistance management

armigera (Michael and Woods 1980). Accordingly, between 1996 and 2002, pheromone traps were used to monitor the seasonal abundance of *S. litura* and *P. gossypiella* at six sites in the ORIA, at cropping and bush sites near Katherine, and five sites between Broome and Shamrock Station (Fig. 1) (Strickland *et al*. 2003). The data confirmed for all sites that the key pests *P. gossypiella* and *S. litura* remained largely synchronised to the summer months despite host plant availability in winter. Regardless of the presence or absence of cotton, *P. gossypiella* showed high abundance during the summer and almost disappears during winter. The pest's close association with native malvaceous hosts that depend on summer rainfall to flower and fruit is a likely causal factor (Strickland *et al*. 2003).

Sucking pests are not controlled by Bt proteins and require insecticide for control. Research conducted at the Ord River (Annells *et al*. 2004) and Katherine (Ward 2005) developed local economic control thresholds for the two main sucking pests, aphids (*Aphis gossypii*) and green mirids (*Creontiades dilutes*), respectively.

Large-scale IPM trials

The scale of research into management of cotton pests at the Ord River expanded rapidly in 1997 when commercial interest from Colly Cotton Ltd, a commercial farming and ginning company from southern Australia, led to the construction of a small gin in partnership with the Ord River District Cooperative. Colly's visionary approach facilitated the involvement of local farmers in paddock-scale evaluation of best-bet IPM strategies developed earlier in small-scale research. During this phase of research, collaborating farmers grew Bt cotton alone, as well as in combination with various trap and companion-cropping options, selective insecticides, insect food sprays and other IPM tactics. In total, >2000 ha of Bt cotton was grown during the winter production window (Strickland *et al*. 1998; Annells and Strickland 2003). Whenever possible, each of these IPM systems was replicated on participating farms. Paddock size varied from 10 to 40 ha with a total annual trial area of ~400 ha from 1997 to 2002.

The results from the paddock-scale IPM trials with single-gene Bt varieties provided solid evidence for the robustness of the dry-season cropping strategy at Kununurra (Annells and Strickland 2003; Strickland *et al*. 2003). Despite the inexperience of farmers, some poor-performing IPM tactics and sprays, rudimentary agronomic knowledge, highly variable seasons, and untested varieties, the average yields were similar to those achieved in southern Australia's irrigated cotton regions over the same period. Perhaps more importantly, these IPM systems consistently gave higher yields and required fewer than four sprays per crop (Table 2). When these results are benchmarked to the 40 sprays per crop applied to conventional cotton grown in the wet season of 1973–74 (Michael and Woods 1980), the success of the novel dry-season system becomes clear.

Central to robust, pre-emptive management of Bt-resistance in *Helicoverpa* spp. was maintaining the previously observed high proportion of egg parasitism by the wasp parasitoid *Trichogramma* spp. in cotton grown in the dry or winter season (Strickland *et al*. 1998). Studies in 2001 and 2002 at the Ord River found that the introduced species *Trichogramma pretiosum* Riley dominated the parasitism of *Helicoverpa* spp. eggs in winter cotton crops (Davies and Zalucki 2008; Davies *et al*. 2009). This species was introduced to the region in the 1970s as part of IPM research (Michael and Woods 1980). High levels of parasitism (90%) of *Helicoverpa* eggs were observed early in the crop's growth, before canopy closure. However, parasitism was very sensitive to insecticide application and climatic conditions within the canopy. It was concluded the value of *Trichogramma* was greatly enhanced by avoiding broad-spectrum insecticides and implementing effective sampling techniques to measure the contribution of egg parasitism when making pest management decisions (Davies *et al*. 2011). Further surveys at other potential cotton-growing sites in northern Australia found that *T. pretiosum* was the dominant species to parasitise *Helicoverpa* eggs where cropping (a range of species) had been established (Davies and Zalucki 2008).

The success of these approaches to IPM cotton at the Ord River encouraged similar, but smaller scale, research activities at other locations in northern Australia. By 2003 encouraging

Table 2. Number and purpose of insecticide sprays in the paddock-scale IPM experiments at the Ord River

Experiments compared single-gene Bt cotton with and without a companion crop and conventional cotton with a companion crop and food spray (adapted from Annells and Strickland 2003)

Treatment	Mirid sprays	Aphid sprays	*Helicoverpa* sprays	Total sprays
Bt Cotton alone	2.13	0.25	2.25	4.63
Bt Cotton + lucerne	1.25	0.13	1.75	3.13
Conventional cotton + Envirofeast® + lucerne	3.0[A]	0	7.50	10.50

[A] Includes rough bollworm as a target pest (grown 1996 only).

results had been obtained from Broome, Katherine and Richmond. However, large-scale trials tailored to local farming systems in these regions were considered necessary in the future to be able to evaluate commercial prospects (Strickland *et al*. 2003).

Beyond insect management: an integrated approach to assessing the feasibility of sustainable cotton production in northern Australia

Effective management of insect pests was an important first step in assessing the future for dry-season cotton in northern Australia. However, the region is huge and a great diversity of other important factors must be considered during a cropping systems research phase that would provide the basis for deciding to proceed to commercial development. Essential areas of research and development are: crop adaptation, production systems, environmental impact, economic issues, public awareness, legislation, and natural resources/land availability. The Cotton CRC and its partners focussed on crop adaptation and production systems and aspects of environmental impact, economic issues and public awareness.

Crop adaptation and agronomic aspects of dry-season production

Most of the research was conducted at the Ord River, with additional research sites at Katherine and near Broome. Dry-season production was a major agronomic change and included the requirement for a 5-week planting window that can commence on 1 March for Bt resistance management (Table 1). At the time there was very little literature worldwide reporting cotton grown during the tropical dry season (Yeates *et al*. 2010*a*). Hence, it was necessary to evaluate crop adaptation and agronomic aspects of the dry-season production system outlined in Table 1. This research was conducted in parallel to the IPM research described previously. Growing cotton in the dry season created new challenges for crop growth and timing of farming operations. The likely growing season for sowing in April, when trafficability is least affected by wet-season rain, then picking in October is the reverse in terms of temperature and daylength of temperate Australia where cotton is usually sown in October and picked in April.

Figure 2 compares the dry growing season in the Ord River (Kununurra, 15°S) with that for summer-grown cotton at Narrabri, NSW (30°S), a temperate production region, with respect to monthly rainfall, maximum and minimum temperature and solar radiation. Growing season rainfall is much less at Kununurra (Fig. 2*a*), although rainfall before 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. Monthly temperatures (Fig. 2*b*) are higher early and late in the season, whereas midseason minimum temperatures are cooler, averaging 14°C with extremes <10°C (Cook and Russell 1983), which could be problematic for fibre quality and boll growth (Gipson and Ray 1970; 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 ~80% of that at Narrabri during this phase (Fig. 2*c*). However, it was not known whether reduced daily radiation would translate into lower yields, as cooler temperatures may compensate via slower development rate and lower night respiration.

Hence, the following crop adaptation and management questions relevant to dry-season cotton production were identified. (*i*) What yield and quality is possible using modern genotypes and management given the potential limitations of temperature and radiation in the dry season? (*ii*) Does the photothermal regime of the tropical dry season affect crop development or limit the conversion of radiation to dry matter and its partitioning? (*iii*) What is the optimum sowing window for yield and quality given that sowing must commence after 1 March to avoid insect pests and there must be sufficient time to pick by before the start of the wet season?

Lint yield and fibre quality

In field experiments conducted over three seasons at Ord River, lint yields of upland cotton (*Gossypium hirsutum* L.) exceeded 2000 kg/ha when sowing occurred during March and April but declined rapidly when sown after mid-May (Fig. 3). Despite the photothermal limitations described above, the maximum lint yields of upland and Pima S7 (*G. barbadense* L.) cultivars were, at worst, in line with Australian commercial irrigated yields and research yields for irrigated cotton in temperate Australia and the USA at the same time (Yeates *et al*. 2010*a*). Similar potential yields were observed at Katherine and Broome (A. Dougall, NTPIF Katherine, and I. Mcleod, Western Agriculture Industries, Broome, unpubl. data). Sowing in March or April ensured that picking would occur by early October before the start of the wet season.

The lint yields at the Ord River were achieved because biomass was accumulated by sustaining modest growth rates of 6.9–12.3 g/m^2.day for a long period (78–134 days) between first square and boll opening, compared with cotton grown at temperate latitudes where growth was characterised by shorter periods (25–60 days) with greater maximum growth rates of 15–20 g/m^2.day (Yeates et al. 2010*a*, 2010*b*). There was also a positive correlation between yield and greater horizontal fruiting, i.e. more second- and ≥third-position bolls, and a lack of correlation between the number of first-position bolls and their retention and yield (Yeates *et al*. 2010*a*). This is a departure from spring-sown upland cotton in temperate climates, where first-position bolls and their retention are regularly monitored due to their positive association with yield (Constable 1991; Kerby and Hake 1996).

It was concluded that the reduced contribution to yield from first-position bolls, combined with a longer boll period due to cool temperatures, 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 (Yeates *et al*. 2010*a*, 2010*b*). Compensation for the loss of early flowers occurred due to a greater production of horizontal fruiting sites, which flowered later when temperatures were warmer

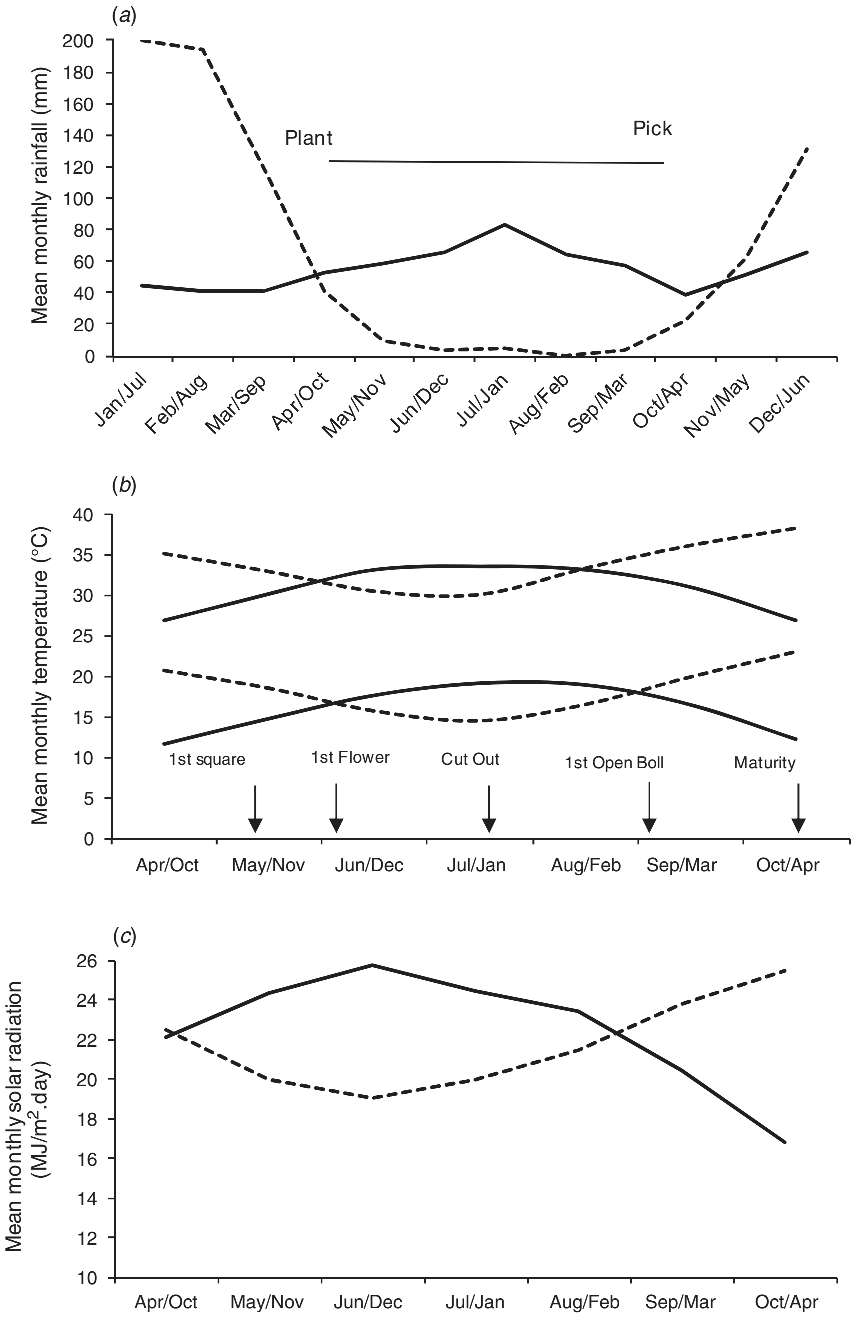

Fig. 2. Climatic comparison the proposed tropical dry or winter growing season at Kununurra in the Ord River (April–October) (- - -), and the temperate summer growing season at Narrabri 30°S (October–April) (—). (*a*) Mean monthly rainfall; (*b*) average monthly temperatures, with possible development states shown for the Ord River based on degree-day sums (Constable and Shaw 1988); (*c*) mean daily radiation for each month.

and radiation was higher. Flowers exposed to low minimum temperatures (<10°C) near anthesis were more likely to abort or produce smaller bolls (Yeates *et al*. 2013). Hence, in seasons when low night temperatures persist late into flowering, yield compensation could be prevented on later flowers and yield reduced. This risk was considered low at the Ord River but required further analysis at cooler sites such as Katherine.

Lei and Gaff (2003) found that dry-season cotton at the Ord River produced high levels of compensatory response to simulated pest damage. The rapidly rising late-season temperatures and radiation ensured full yield compensation with minimal delay in maturity following damage. The yield trends suggested overcompensation when tip damage and fruit loss occurred early in growth.

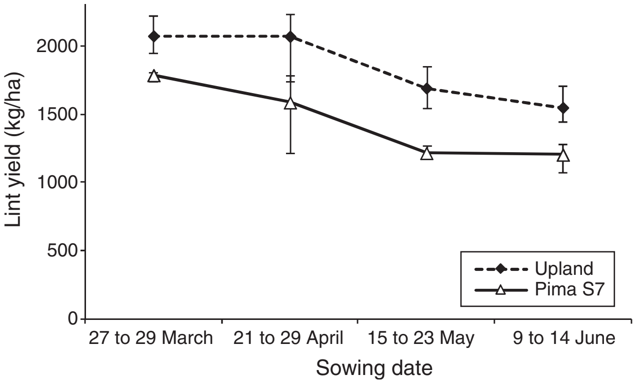

Fig. 3. Effect of sowing date on average lint yield for three seasons for upland varieties and Pima S7 at the Ord River. Capped lines show range of yields (adapted from Yeates *et al.* 2010*a*).

Fibre length and strength at the highest yielding March and April sowings were low to marginal compared with market preference values (Yeates *et al.* 2010*c*). This was due to cool temperatures during fibre development. However, there was significant variation between the *G. hirsutum* cultivars, and subsequent screening in similar temperatures has identified cultivars that exceed market preference values (P. Goldsmith, WA Department of Agriculture and Food, unpubl. data, 2011). It is likely that current *G. barbadense* cultivars will have short fibre when grown in the dry season (Yeates *et al.* 2010*c*).

Dry-season cotton husbandry and cropping systems

Crop adaptation studies at Ord River showed that the different cotton growth in the dry season had implications for crop nutrition, growth regulator use and irrigation management. Achieving a balance between yield compensation via fruiting sites towards the top and outside of the plant and appropriate vegetative growth would require careful management of these inputs. Overuse of growth regulators, insufficient irrigation or nutrient deficiency will inhibit compensatory growth and reduce yield. On the other hand, a luxury supply of water and or nutrients combined with insufficient growth regulator could lead to excessive or 'rank' vegetative growth and limit yield.

Growth regulation

Research at Ord River confirmed the need to avoid high doses of the growth regulator mepiquat chloride during fruiting-site production to permit compensation via the production of additional, later fruiting sites (Yeates *et al.* 2002*b*). However, when more rigorous, early-season growth occurred, treatment with $\leq$16 g/ha of active ingredient near squaring was recommended (Yeates *et al.* 2007). Treatment of seed with mepiquat chloride could not be recommended, because at concentrations sufficient to provide season-long suppression of vegetative growth, it also reduced crop establishment and yield (Yeates *et al.* 2005).

Crop nutrition

With the exception of some of the established cropping areas in northern Queensland, the majority of arable soils in the Australian tropics appear similar, i.e. red and yellow earths (Alfisols), and poorly drained cracking clays all having low to moderate inherent soil fertility, particularly N, phosphorus (P), sulfur (S), zinc (Zn) and potassium (K) (Jones *et al.* 1985; Chapman *et al.* 1996). This implies common issues for crop nutrition, soil surface management and irrigation distribution systems. Inherent salinity occurs within many catchments (e.g. the Flinders).

Because a significant proportion of any future dry-season cotton production would be grown on virgin soils, P experiments focussed on the P-fertiliser requirement of cotton on a virgin Tippera clay–loam at Katherine (Dougall and Kahl 2007) and a virgin Cununurra clay at Ord River (Duggan *et al.* 2008). Both soil types required 60 kg/ha of P, applied as a band into the soil pre-sowing, to maximise lint yield in the first season of fertilisation. On the Cununurra clay, a total of 80 kg/ha of P was required when cotton was grown for two seasons. Dougall and Kahl (2007) also found that, to determine P deficiency, leaf sampling must take account of temperature as low temperatures may have reduced uptake.

The amount of available soil N following the wet season is difficult to predict due to variable rainfall and rapid rates of mineralisation, which can leach NO_3^- below the root-zone. Soil management in the previous wet season therefore had a significant impact on soil N status at cotton planting. Over 3 years on a Cununurra clay following a wet-season fallow, soil organic carbon (C, 0.6%) and plant-available soil N were low at sowing, providing 50–110 kg N/ha to the crop. Cotton crops were found to require around 200 kg/ha of fertiliser N to maximise yields at ~2250 kg lint/ha (9.9 bales/ha). Yield was reduced by 10% when 150 kg N/ha was applied, and there was no yield increase with 300 kg N/ha (Yeates *et al.* 2007). Nitrogen fertiliser was banded 15 cm below the soil surface and on the furrow side of the plant-line in these experiments, an operation that can delay sowing while the subsoil dries following the wet season. Application of all N fertiliser up to 40 days after sowing allowed earlier cotton sowing and did not affect yield. However, a slight delay in maturity (3–4 days) was measured. A similar N-fertiliser requirement was measured at Katherine on a Tippera clay–loam soil (C. Martin, NTDPIF, unpubl. data).

Tillage systems and weed management

Despite high yields, a significant climatic risk to dry-season cotton production is a late end to the wet season, which could delay sowing of commercial-scale areas until late April or May, increasing the chance of reduced yield and rain at picking. This risk is greatest in growing regions with clay soils such as the Ord River. Permanent beds were the best solution, provided they were planted using minimum tillage into either a wet-season cover crop of millet or sorghum or the stubble retained from a previous grain crop (and field drainage was maintained). This tillage system permitted sowing up to 3 weeks earlier than conventional cultivation while reducing weed competition (Duggan *et al.* 2005; Yeates *et al.* 2006).

Trafficability by machinery is less constrained by rain on sand or loam-textured soils; however, these soils are highly erodible when not protected by surface cover. Hence, no-tillage combined with a wet-season cover crop was demonstrated to be the most effective management system for these soils (Yeates and Martin 2006).

Diseases

Alternaria leaf blight (*Alternaria macrospora* Zimm. and *A. alternata* Fr.) was confirmed as the most prevalent disease of cotton in northern Australia. This contrasts with southern Australia where it is minor disease (Bhuiyan *et al*. 2007*a*, 2007*b*). The severity of the disease was greatest at Katherine, where a combination of cold night temperatures, dew during flowering, low K soils and overhead irrigation appeared to favour the disease. Surveys of crops found up to 100% of leaves were infected (Bhuiyan *et al*. 2007*a*, 2007*b*). Experiments were initiated at Katherine in 2004 and 2005. These experiments found that alternaria leaf blight was most severe on the middle leaves in the canopy, which were adjacent to early-flowering nodes that also coincided with the coolest minimum temperatures. In the presence of fungal spores, the severity of the disease was associated with leaf K concentration, so treatment with the fungicide mancozeb or KNO_3 significantly reduced the incidence and severity, and leaf shedding due to the disease. *Alternaria macrospora* was most common early in the growing season, whereas *A. alternata* was dominant late in the season. It was concluded that systemic fungicides might be more effective than mancozeb when disease incidence was greatest (Bhuiyan *et al*. 2007*a*, 2007*b*).

Water use and off-paddock movement of pesticides

This research, conducted at the Ord River and Katherine, measured the irrigation water requirement for dry-season cotton and the off-paddock movement of pesticides in irrigation water from crops grown using best-bet practices developed from the cropping systems research. The irrigation water requirement (applied to field) of cotton was measured as 7.5 ML/ha without tail-water recycling and using furrow irrigation at the Ord River, and 5.5 ML/ha using subsurface drip irrigation at Katherine. The volume of water used on cotton was similar to that used on crops having the same growing-season length such as maize and peanuts and less than half that used on perennial crops such as sugar and bananas grown at the same locations (Moulden *et al*. 2006; Yeates and Martin 2006). The concentration of cotton pesticides in the irrigation tail-water was below the Australian drinking water standards (Moulden *et al*. 2006).

Registration of Bt cotton in northern Australia—technical and political issues

The registration of genetically modified Bt cotton in southern Australia occurred in 1996, and by 2007 these varieties accounted for 92% of the area sown to cotton (Pyke 2008). However, north of latitude 22°S, further research was required to assess whether enhanced insect protection could lead to cotton becoming a weed is the broader ecosystem. It should be noted that conventional (non-Bt) cotton had never been declared a weed anywhere in Australia. These studies found that factors such as fire, competition from other plant species, cattle grazing, poor soils, and lack of seed survival in natural habitats prevented the recruitment and expansion of feral cotton populations (Eastick and Hearnden 2006). Federal Government approval to grow two-gene Bt and glyphosate-resistant genetically modified (GM) cotton north of 22°S was granted in early 2007. The Western Australian State Government moratorium on growing GM cotton was removed in late 2008. The Northern Territory Government imposed a ban on growing cotton in 2003 in response lobbying from groups opposed to GM crops and cotton. This ban was not lifted until late 2013.

Does it work? Commercial scale yields and the validation of dry-season production

Although the paddock-size IPM comparisons conducted at the Ord River between 1997 and 2001 demonstrated that insecticide use could be dramatically reduced (Table 2), yield variability between fields was very high (Table 3) independent of the IPM treatment (Annells and Strickland 2003). The highest yields were similar to the yield potential experiments conducted concurrently (Yeates *et al*. 2010*a*). While some of this variability could be attributed to grower inexperience and non-optimal pest management treatments, it was clear that a combination under-developed crop husbandry practices (being researched concurrently) and operational inefficiency (e.g. excessive cultivation delaying sowing, suboptimal irrigation application, timing and field layout), seasonal variability (e.g. cool late-season temperatures and harvest rain in 1999), and inconsistent post-flowering efficacy by single-gene Bt cotton also contributed to these variable yields.

By 2003, two-gene Bt cotton varieties (Bollgard II®) were available which provided season-long protection to key caterpillar pests, and agronomic research had progressed to the point where the production package to be named 'NORpak-Ord River' could be validated in commercial-scale areas. Due to Bollgard II® not being approved for use north of latitude 22°S, combined with strict regulation by the Office of the Gene

Table 3. Lint yield (kg/ha) variability from commercial-scale integrated pest management (IPM) research at the Ord River (adapted from Annells and Strickland 2003) compared with the average Australian irrigated cotton yield (The Australian Cottongrower 1997–2001)

Year	Lowest yield	Highest yield	Australian average yield (irrigated)
1997	1112	2088	1946
1998	1544	2111	1546
1999	885	1748	1545
2000	1339	1952	1666
2001	445	1870	1785

Table 4. Lint yields (kg/ha) from paddock-scale validations of the production package 'NORpak-Ord River' (J. Moulden, WA Department of Agriculture and Food, Kununurra, unpubl. data) compared with the average Australian irrigated cotton yield for 2003–06 (The Australian Cottongrower 2003–2006)

Year	Ord yield	Australian average yield
2003	1952	2011
2004	1907	1995
2005	2247	2281
2006	1975	1901

Technology Regulator, these validations were confined to single paddocks. Nonetheless over four seasons, yields were more consistent and near the Australian average at the time (Table 4), with fibre quality at or above market preference values.

Current status of cotton-industry development in dry-season cotton production regions

The research at the Ord River has achieved its intended goal of providing a technical base for industry investment. This can be measured by two cotton industry bids (in 2000 and 2012) to the Western Australian government for the right to develop of the second stage of the irrigation area. However, both cotton bids were unsuccessful, with a sugar proposal from an international investor being selected in 2013. It should be noted that the call for development bids in 2000 was premature as native title issues were not resolved, hence the second call in 2012. In other regions of Western Australia and in most of northern Queensland, government approval for land and water development is required for the irrigated cropping of any crop species to proceed. The Northern Territory ban on growing cotton was lifted in late 2013.

Wet-season cotton

The south and eastern regions of the Australian tropics were identified as most likely to succeed with wet-season cropping (Fig. 1), due to the constraint of colder night temperatures during the dry season (Yeates 2001; Yeates and Bange 2003). Of the potential wet-season production regions identified, the lower Burdekin (tropical Australia's largest irrigation area) in North Queensland offered the best short-term possibilities since transgenic cotton was already grown in the state, it was closer to existing cotton-processing infrastructure, and cotton had the potential to be included as a crop-rotation option for sugarcane. However, growing cotton during the wet season presented other climatic risks associated with monsoonal weather and subsequently would require a different regime of crop management compared with more northern production regions and temperate Australia. Interest in cotton production in this region was driven by both local sugarcane growers looking to identify high-value rotation crops and southern cotton growers seeking to drought-proof their farming business models.

Plant protection surveys 2004–06

It was essential that the insect pest risks that might be associated with wet-season production be assessed before growing significant areas of cotton, particularly given the previous failure of growing wet-season cotton at the Ord River due to pest insect activity. Accordingly, pest insect surveys were conducted in the Flinders catchment near Richmond (Sequeira 2005) and in the Lower Burdekin (Grundy and Yeates 2006).

In the lower Burdekin, surveys were made of trial cotton paddocks leased by Queensland Cotton Ltd in 2004 (dry-season crops) and 2005 (sown in January, February, March and April) (Grundy and Yeates 2006). A leaf disease and several insect pests were identified as factors for consideration for cotton production.

As was the case in the dry-season production sites at Katherine and the Ord River, the most destructive pest was leaf blight disease caused by *A. macrospora* Zimm. and *A. alternata* Fr. This disease was prevalent during June–August for the crops sown in May during 2004 and February–April during 2005. Disease symptoms were most severe for the crops sown in May 2004 and March and April 2005 and caused partial crop defoliation. The severity of the damage to these crops confirmed the lower Burdekin was unsuited to dry-season cotton production.

A key concern had been silver leaf whitefly (*Bemisia tabaci* biotype B), an exotic pest that entered Australia around 1993 (Gunning *et al*. 1995) and has become a key pest for vegetable production in the region (De Barro and Coombs 2009). However, the impact of this pest was recently reduced due to biological control provided by the hymenopteran parasitoid *Eretmocerus hayati* (Zolnerowich and Rose), which was introduced to the region in 2005 (De Barro and Coombs 2009). The activity of this introduced parasitoid during late summer effectively suppressed whitefly population expansion within 2 months of cotton growth, negating the need for control (Fig. 4) Cooler conditions after May further suppressed whitefly populations to below detectable levels. Hence, a midsummer planting window that ensures the crop matures in June was an effective tactic for naturally suppressing whitefly populations before the susceptible boll-opening stage It was concluded that a similar set of circumstances would apply to other sucking pests such as aphids, which could be abundant in some seasons.

Cluster caterpillars (*S. litura*) were prevalent during the 2005 trial plantings and required insecticide control. The presence of this pest and its ability to tolerate exposure to Bt cotton suggests that it would need to be considered along with *H. armigera* when formulating a resistance management strategy for Bt cotton that is relevant to northern Queensland. Pests such as green mirids (*C. dilutus*) and jassids were not abundant in the region but, if they did occur, would require judicious management, as is the case for existing cotton-production regions, with key consideration being given to the use of selective insecticides that minimally disrupt parasitoid for whitefly and cluster caterpillars (Mass 2012).

An insect survey of Bt cotton grown near Richmond in the Flinders River catchment found that a pest complex was present

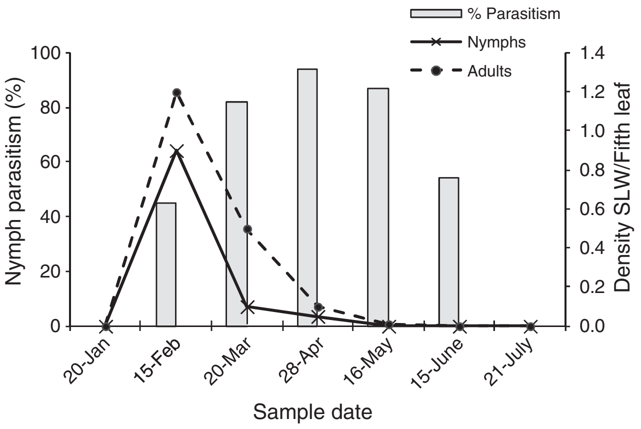

Fig. 4. Seasonal distribution of whitefly adults (SLW) and nymphs together with their parasitoids for January-sown cotton in 2005 at the Lower Burdekin.

similar to that in Emerald (Sequeira 2005). Importantly, *P. gossypiella* does not occur in north Queensland.

Crop adaptation issues for wet-season production

As an adjunct to the pest surveys, a desktop analysis was made of the climate and simulation of likely cotton yields using the OZCOT model (Hearn 1994). This analysis indicated that the likely optimal sowing period for yield and fibre quality was between late December and early January. This planting window would expose a crop to the wettest weather during vegetative growth and in early flowering, with the majority of boll growth occurring in March and April when conditions are likely to be drier and sunnier before cool temperatures in June (Fig. 5). Crop defoliation and picking would occur in June and July when the probability of rainfall is low. Without local validation to test these projections, it was unclear how cotton would withstand intense periods of cloudy wet weather during early-season growth or the impact of monsoonal influences that extend into March or April in some years. Specifically, the relationship between the cloudy wet weather during the monsoon, and canopy, root and fruit development was unknown. It was anticipated that the reduced photosynthesis due to low radiation from cloud would cause fruit shedding, reduced boll size, and boll rots. The overall impact on the crop and its ability to compensate was dependent on the timing and duration of the cloud cover. There was also potential for waterlogging to reduce crop growth and interact with the effects of low radiation.

Thus, a study to measure the effect of rainfall and cloud at different growth stages incorporating varieties and management practices was undertaken over five seasons. The study was conducted on a well-drained soil to minimise the confounding effect of waterlogging and used a range of sowing dates to increase the chance of cloud and rainfall occurring at different crop growth stages.

Research and test farming 2007–12

Research at the lower Burdekin was still in progress at the time of writing; therefore, findings from research to date are summarised.

Regulatory approval to grow Bollgard®II cotton in Queensland was granted in January 2007. Unlike the dry-season production areas at the Ord River, Katherine and Broome, commercial test farming of cotton in the lower Burdekin commenced at the same time as research to evaluate climatic risks and to develop a wet-season production package. Hence, there was no local research to support first-time growers in what was a little-known climate for cotton production. Growers also accepted higher production costs when test farming; for example, cotton had to be transported >600 km to Emerald for ginning.

Commercial test farming occurred on a scale across multiple farms with ~700 ha sown each year between 2007–08 and 2009–10. The sown acreage halved in 2010–11 and 2011–12 due to a succession of wetter than average summer seasons (Fig. 6), which had two impacts on cotton plantings: (*i*) the cutting of final-ratoon cane crop was prevented on some farms, so sowing of the fallow area between cane crops to cotton could not occur; and (*ii*) where cotton was sown, yields and returns were reduced by these climatic conditions due partly to a lack of knowledge for managing agronomic inputs after periods of wet weather. Monthly maximum rainfall records were set during January 2007, February 2009, March 2012, June 2008 and July 2012, which spanned most of the test-farming period. This period also coincided with a record rise in sugarcane prices.

Despite the difficulties encountered by growers test-farming cotton, these wetter than average seasons were optimal for experiments measuring crop × climate interactions as well as the development and testing of agronomic strategies for sowing, fertilising, growth regulation and varietal assessment. The climate adaption research and commercial test farming confirmed that yields comparable (>2500 kg lint/ha) with the best in temperate Australia could be produced when sunny conditions occurred during boll filling from early March to May. The climate experiments also confirmed late December to early January as the optimal sowing time for cotton (Fig. 7). However, when wet-season cloud extended into late boll filling during late March–early May, the lower radiation reduced yields by 30–50%. Importantly, it was shown that significant

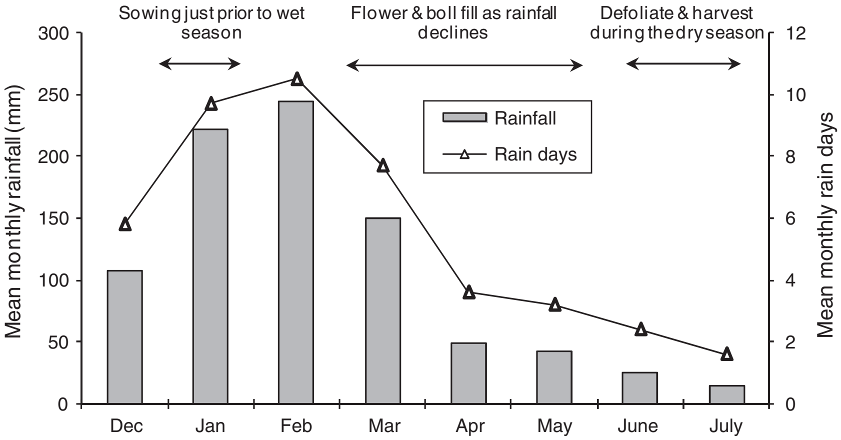

Fig. 5. Mean monthly rainfall and rain days for Ayr in the lower Burdekin between December and July from 1951 to 2011 together with the model projected cropping calendar for the region.

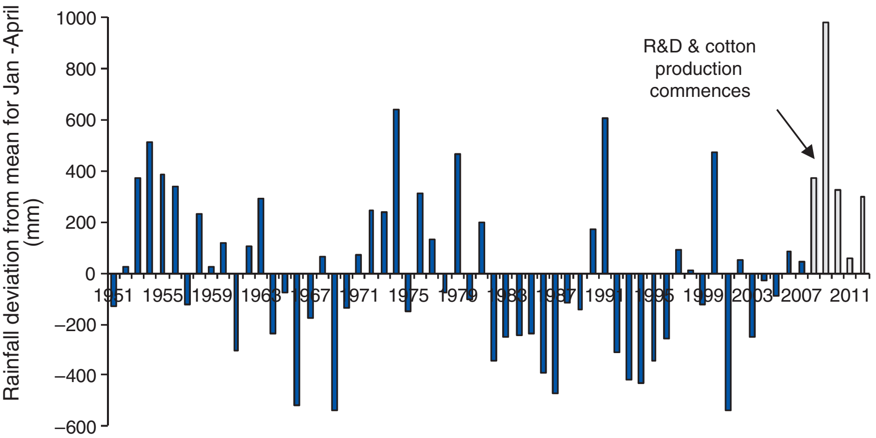

Fig. 6. Mean rainfall for January–April expressed as a deviation from the long-term mean for the lower Burdekin (Ayr) from 1951 to 2012 showing the variability between monsoon seasons (about one-third are much wetter than average). Cotton test farming coincided with a period of wetter than average conditions.

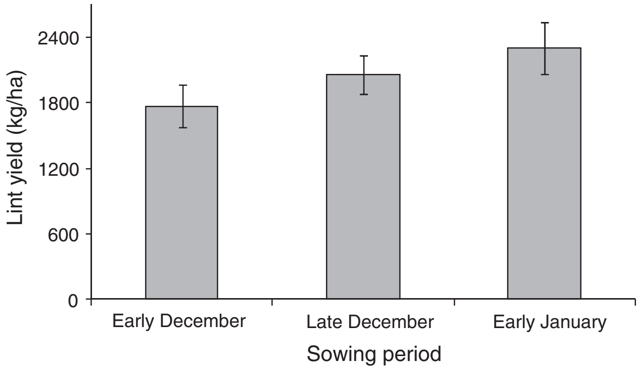

Fig. 7. Effect of sowing date on lint yield; means of seasons and cultivars from climate studies at Ayr in the lower Burdekin from 2008 to 2011. Capped lines are standard errors.

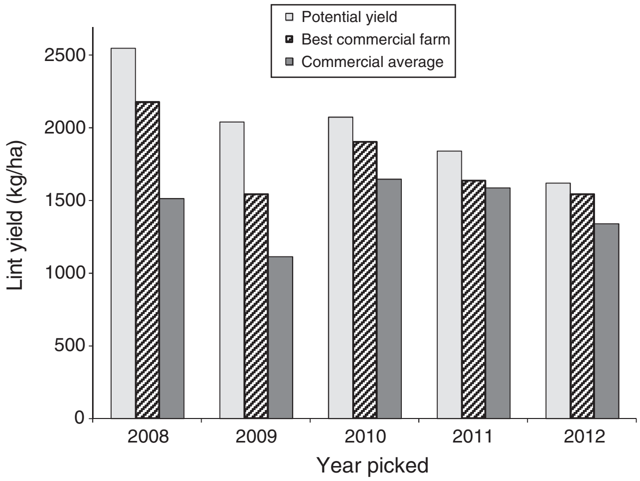

Fig. 8. Potential, best commercial farm and commercial average (all farms) lint yields grown at the lower Burdekin between 2008 and 2012. Potential lint yield was from small-plot, 'climate study' yields sown near the same date as commercial crops and grown on well-drained soil. Yield potential was higher during 2008–10 due to sunnier conditions in March and April.

yield recovery from cloud in the first 2–3 weeks of flowering was possible provided the crop was managed to ensure compensatory boll setting from later pollinated flowers. This involved tailoring crop husbandry (e.g. nutrition, growth regulators) to varieties with the greatest capacity for compensatory fruit production following cloud-induced shedding.

Many of the problems encountered during test farming helped to inform the research program, the result being the rapid formulation of basic agronomic strategies in time for the 2009–10 season, which have continued to be validated and refined. The development and extension of locally validated strategies for wet-season cotton production served to close the gap between the yield potential as defined by the small-plot climate interaction studies and the yields achieved with test farming from 2010 onwards (Fig. 8).

A key challenge for growing cotton in the lower Burdekin and a current research priority is improving crop and fertiliser uptake efficiency of N on heavy clay soils. These soils account for about one-third of the irrigation area (Donnollan 1991) and are inherently low in organic C and available N before sowing, irrespective of the crop grown previous to cotton (Grundy *et al.* 2012). It was anticipated that N-fertiliser losses would be greater in the well-drained, sandier textured soils than the clays due to leaching. Deep cotton roots (>180 cm) and in-crop application of N fertiliser has produced very efficient crop N uptake (60–80% of fertiliser N) on the course-textured soils. On the clay soils, research to date suggests that N losses were due to: (*i*) leaching of N applied at sowing into the irrigation furrow following prolonged early-season rainfall; and (*ii*) denitrification. In-crop application of N improved apparent fertiliser N uptake to >50% and increased yields by at least 30% when early-season N losses occurred. However, applying N in-crop is a high-risk option on clay soils because application needs to occur by early March when trafficability is very unreliable due to wet soil. Recent research shows fertilisers that slow the conversion of NH_4^+ to NO_3^- in the soil have significantly improved the uptake efficiency of N fertiliser applied at sowing.

Future research and development in the lower Burdekin

The publication of 'NORpak-Burdekin and NQ dry tropics' (Grundy *et al*. 2012) was an important first step in providing new growers with cotton husbandry information developed from cotton component research to date. Further cotton research is required to: (*i*) measure the impact of cotton as a rotation crop in to sugar-farming systems; (*ii*) extrapolate to a wider range of seasons to better assess climatic variability; and (*iii*) complete evaluation of options to improve the efficiency of crop uptake of soil and fertiliser N on clay soils.

To be widely adopted in the lower Burdekin, cotton must be integrated into the sugarcane farming system and be shown to contribute positively to the economic returns of the system as a whole. Research to measure the impacts of cotton and grain crops in rotation with sugarcane commenced in 2012. These are complex rotations due to several factors: (*i*) the 4-year length of the sugarcane cropping cycle; (*ii*) the duration of the break from sugarcane can be short (6–8 months, between the last ratoon and plant cane) or long (18 months, in rotation with grain crops following the last cane ratoon); and (*iii*) the date of establishment of the new plant cane crop may affect yield from the cane cycle and this date is affected by the rotation crop species and the length of the break—for example, in the short-break scenario cane would be planted at least 1 month later following cotton than if it followed soybean and up to 2 months later than if it followed mungbean.

Simulation modelling using the APSIM-OZCOT models (Hearn 1994; McCown *et al*. 1996*b*) is required to extrapolate from the seasonal range experienced to date and capture the impact of wider seasonal variation on yield and management strategies. Model enhancement is needed to adequately simulate cotton growth and yield of wet-season cotton in the Burdekin. In particular, fruiting dynamics, dry matter partitioning and leaf area development as influenced by cloud, high humidity and N uptake.

Lessons for the development of a new crop industry in northern Australia in the 21st Century

Cotton is only one crop under investigation in tropical Australia. This phase of research and development by the Cotton CRC and its partners has both built on past experiences with cotton and other crops in the region and developed original methodologies. Much of the experience gained from the cotton research and development activities described here could be applied to the assessment of any new crop in the Australian tropics. While the research conducted by the Cotton CRC focussed on biotic, climatic and environmental impacts relevant to cotton production, other key factors essential for development of a new crop industry in northern Australia were also identified. These are described below:

Importance of government in the development of new agriculture industries in northern Australia

The role of government is critical for new crop industry development in northern Australia. Governments control natural resource availability and influence infrastructure development, environment protection, vegetation management, chemical registration, changes to land title and public works. It is clear from the discussion above that governments in some jurisdictions have had a major role in influencing the development of a cotton industry to date. However, cotton is an extreme case, being one of Australia's first GM crops and having inherited a negative perception as a 'thirsty pesticide-using crop' from southern Australia.

Need for a local skills base and mechanisms to gain 'cheap experience'

Just as farming practices cannot be adequately transferred from southern Australia, nor can human skills and experience. Maintenance of a local skills base has always been a challenge in northern Australia. Except for the east coast, there is a significantly smaller local research and development (R&D) capacity than 20 years ago, and the farmer base and commercial support services remain small and scatted geographically. The recent cotton evaluations at the Ord River and the Burdekin have had success in overcoming this constraint by partnering local agronomists and farmers, often without cotton knowledge, with cotton specialists (farming and research) from southern Australia who did not know the northern environment or its farming practices.

Mistakes due to inexperience can be costly in the early years of new crop evaluation. Research that can deliver 'cheap experience' is the only way to improve early yields. That is, research focussed on the development of robust cultural practices that account for climate and soil variability combined with an

Table 5. Basic research required to evaluate a new irrigation area (adapted from Yeates 2001)

1. Geohydrological surveys/studies. These will determine potential salinity problems, watertable effects and identify appropriate irrigation and agronomic practices
2. Detailed soils surveys. Irrigation development would require at least 1 : 100 000 with reference areas at 1 : 25 000 in locations having potential for irrigated cropping
3. Production system research. Integrated crop research is required with the objective of identifying which crop species to grow and developing a management system that is sustainable economically and has minimal environmental impacts
4. Ecological studies into pest and disease dynamics and effects on native flora and fauna
5. Water licensing processes and associated studies, e.g. quantifying water availability and sustainable extractions
6. Infrastructure studies. Location of processing infrastructure, transport links, container needs, etc.
7. Whole-scheme economic and social analysis to put in state/national context. This should include an assessment of community values including indigenous values

effective delivery mechanism is essential. Production practices from southern Australia are seldom transferable.

Major outputs of the Cotton CRC were two production guides, 'NORpak-Ord River' (Yeates *et al.* 2007) and 'NORpak-Burdekin and NQ coastal dry tropics' (Grundy *et al.* 2012), which synthesised the research involving the Cotton CRC and its partners into a rational blueprint for sustainable cotton production in each region. NORpak-Ord River confronted the GM debate by demonstrating the merits of GM varieties as part of a production system that had a reduced environmental footprint compared with the old, non-GM system. Recent commercial-scale validations proved that growers, with little cotton experience, could produce high-yielding cotton using NORpak.

An R&D model tailored for northern agriculture development is needed

For the 13 years the Cotton CRC functioned in northern Australia, it developed an effective process for new crop R&D before commercial-scale development. This has been achieved by supporting permanently based researchers, facilitating collaboration between organisations, providing specialist expertise from outside and prioritising research support to regions where commercial investment was committed. However, the current trend in northern Australia is for 'fly-in-fly-out' short-term projects, which has produced a plethora of uncoordinated initiatives from a range of funding sources. Unfortunately, the current funding model for most agricultural research, development and extension in Australia is industry-based and places small groups in northern Australia at a disadvantage when the new industry is too small to produce R&D levies. The current funding model is also focussed on individual crops, not the farming system.

Where agricultural R&D in northern Australia is funded by commercial proponents, a long-term commitment is required from proponents if they are to be successful. Demonstration that a proponent can produce high-yielding crops is not sufficient to argue for large-scale agricultural development. Environmental, social and cultural issues all need to be adequately addressed before governments and the community will support large-scale agricultural development. Hence, there is also a question of balance between what proportion of the total R&D cost of starting a new industry should be considered as public good, and what proportion is of direct benefit to the proponent.

An integrated approach requiring seven areas for data collection and research was identified as essential to evaluate the irrigated crop potential of new cropping areas in northern Australia (Yeates 2001) (Table 5). An R&D process that only addresses some of these seven areas can be a poor investment. For example, good knowledge of available land and water resources is of no value if what crop to grow is unknown (the reverse is also true).

Land tenure is critical

In northern Australia, the establishment of new agriculture industries will require a change in land use, which can also change the class of land title. Traditional owners are major landholders and successful agricultural enterprises are increasingly being developed by traditional owners alone or in partnership (e.g. horticulture, agroforestry and beef).

New markets and technologies can create new opportunities

Many crop species have been evaluated in the past in northern Australia, with only a few successes to date. New crops continue to be introduced; for example, in recent years new market opportunities have seen Indian sandalwood (*Santalum album*) and chia (*salvia hispanica*) produced in northern Australia for the first time. Genetically modified Bt cotton is a very good example of a new technology providing a key ingredient in an integrated approach that has overcome a biotic constraint (Tables 1 and 2), and has permitted cotton to be reconsidered in northern Australia. Similarly, the development of insecticide fipronil has greatly enhanced the prospects of re-establishing plantation timber and other tree crops due to its high efficacy on termites and low toxicity to mammals and other non-pest species.

Conclusions

The question 'Can sustainable cotton production systems be developed for tropical Australia?' has in part been answered by developing novel dry- or wet-season cotton production systems that minimise the biotic risk due to insect pests (e.g. *H. armigera* and *B. tabaci*) and climatic limitations (radiation, intense rainfall, temperature extremes) while producing yields equivalent to southern Australia. The approach taken by the Cotton CRC to conduct rigorous integrated research that developed a deep understanding of these biotic and environmental constraints, then tailoring production practices, was central to this achievement. However, this research identified key additional factors that were essential to sustain cotton production. These included: identifying sustainable water withdrawals combined with an arable soil area sufficient to sustain ginning facilities and grow viable rotation crops; the inclusion of traditional owners; the development and maintenance of a skilled local work force; and availability of cost-effective transport and port infrastructure.

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