A review of literature on rainfed cotton in northern Australia: A Northern Territory case study

M. Verónica Toral-Granda, Getahun Kassa & Kamaljit K. Sangha

Ecosystem Services Research Group
Research Institute for the Environment & Livelihoods
Charles Darwin University
February 10, 2024

Executive summary

Rainfed cotton has re-emerged as a significant opportunity for agricultural diversification and regional economic development in northern Australia, particularly in the Northern Territory (NT). This review examines the history of cotton production in the region, the agronomic conditions required for rainfed systems, the major production constraints, and the associated environmental and socioeconomic considerations. While northern Australia offers opportunities through wet-season rainfall, available land, and growing industry investment, the review identifies substantial challenges, including highly variable rainfall, soil limitations, pest and biosecurity pressures, extreme climatic conditions, and limited locally validated agronomic and economic data. The findings suggest that production systems developed in southeastern Australia cannot be directly transferred to northern conditions without adaptation to local environments and farming systems. In addition, significant overlap between agricultural potential and areas of biodiversity and cultural importance underscores the need for integrated land-use planning that balances agricultural development with environmental and social values. While the cotton industry is expanding in the NT, important knowledge gaps remain in areas such as crop establishment, agronomy, biosecurity, and technical capability under Top End conditions. Improving understanding of yield reliability, profitability, and whole-farm system performance will be critical for the long-term development of broadacre cropping in the Northern Territory.

1. Introduction

1.1 Background

Cotton fibre is an important agricultural product that has become the widest-traded commodity in the world market (OECD/FAO, 2024; Voora et al., 2023). Cotton is grown in 80 countries, primarily in subtropical and tropical conditions, with more than 30 million hectares planted in 2023 (OECD/FAO, 2024). China and India produce almost half of the world's cotton fibre production, followed by the United States of America, Brazil, Pakistan and Australia (OECD/FAO, 2024). Over the next ten years, global consumption of raw cotton, or lint, is projected to increase by an annual rate of 1.7% due to population growth and increasing income in middle- and low-income countries (OECD/FAO, 2024). Demand in the textiles and apparel sectors, as well as competition from substitutes, will remain key elements influencing the consumption of raw cotton. The world

cotton price is subject to many factors, including competition from synthetic fibres, yield damage due to extreme weather events, unsustainable water usage, and infestations by pests (OECD/FAO, 2024; Pines, 2024).

Cotton accounted for 20% of all global fibre production in 2023, being the second most-used fibre after polyester, and the most-used plant fibre with an expected steady production growth of 11% by 2033 (OECD/FAO, 2024). Termed 'white gold', cotton is grown for fibre, oil and animal feed (Shikha et al., 2022); therefore, comprises an integral part of the global exchange of commodities (Beckert, 2017). As a tropical and subtropical plant (Figure 1), cotton is a warm-season crop, requiring adequate sunlight, limited cloud cover, a long frost-free period and sufficient rainfall during the growing season (Shikha et al., 2022). It is grown on a wide range of soils, but medium and heavy textured, deep soils with good water holding characteristics are preferred (Australian Government, 2024; OECD/FAO, 2024; Rhebergen & Yeates, 2023). Cotton is linked to the development of intensive agriculture, fishing, craftsmanship, trade and even the emergence of civilizations through the development of material (sails, clothing), trade (Viot & Wendel, 2023) and capitalism itself (Beckert, 2017). As an agricultural produce, the cotton plant yields the lint used for textiles, its seed is processed into oil used for human consumption, soaps and cosmetics, and the meal and the hulls are used for livestock feed (Australian Government, 2024).

The cotton genus, *Gossypium* (Family Malvaceae), includes 50 species distributed in tropical and sub-tropical regions of all continents except Europe (Viot & Wendel, 2023; Wendel et al., 2010). There are three primary centres of diversity: Kimberley in Western Australia, the Horn of Africa and parts of the Arabian peninsula, and western and central Mexico and the northern Andes in South America (Wendel et al., 2010) (Figure 1). The perennial, small cotton plants in south-western Mexico (Viot & Wendel, 2023) were used for fibre for cultural material and the textile industry in pre-Columbian history (Wendel et al., 2009). Worldwide, 'cotton' refers to four domesticated species, the New World *Gossypium hirsutum* L. and *G. barbadense* L., and the Old-World *G. arboreum* L. and *G. herbaceum* L. These species are geographically limited to the tropics of Asia, Africa, and the Americas (Wendel et al., 2009) (Figure 1).

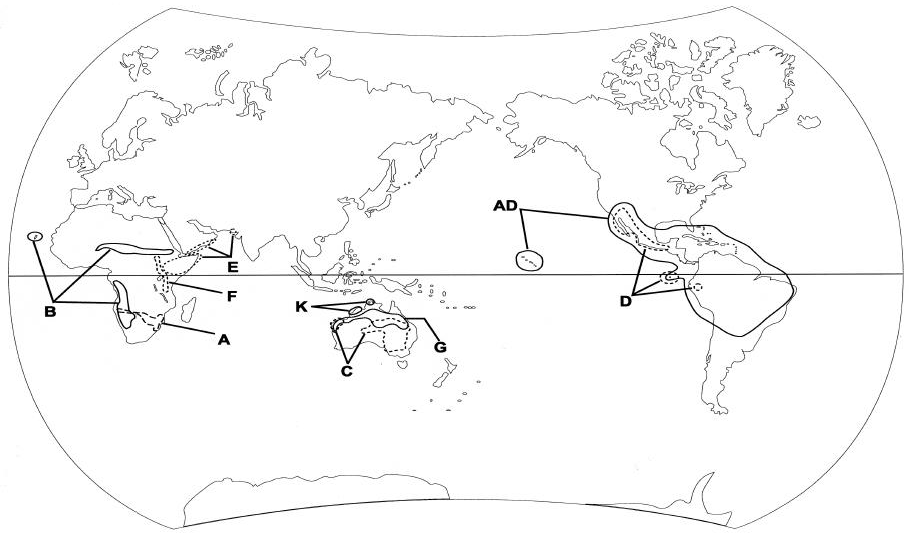


Figure 1. The three major lineages of domesticated cotton (*Gossypium* spp.) in their original distribution: Australia (C, G, K genomes), the New World *Gossypium hirsutum* L. and *G. barbadense* L. in the Americas (D genome), and Africa/Arabia *G. arboreum* L. and *G. herbaceum* L. (A, B, E, and F genomes). *Ibid in* Wendel et al. (2009).

Although many cotton varieties are grown around the world, over 90% of the cotton fibre produced worldwide comes from Upland cotton (*G. hirsutum*) and about 8% Pima cotton (*G. barbadense*) – both originating from Central and South America (Voora et al., 2023). Upland cotton yields short fibres for a variety of applications, whilst Pima cotton yields extra-long fibres primarily to produce fine fabrics (Barnhardt Purified Cotton, 2019), such as the ones found by the Spanish colonising South America, which impressed them with their 'silk-like texture' (Splitstoser et al., 2016). These two species were independently domesticated about 5,500 years ago in the Yucatan Peninsula (Mexico) and 8,000 years ago in northwest South America, now called Guayaquil, Ecuador (Viot & Wendel, 2023). India is the only country in the world that grows all four varieties of cotton and has pioneered cotton textiles since the Indus Valley civilization about 5,000 years ago; moreover, until the end of the 18th Century, only Indian cotton was known to the world (Directorate of Cotton Development - Government of India, 2017). The domestication of Upland (*G. hirsutum*) and Pima Cotton (*G. barbadensis*) transformed the wild varieties of the perennial shrubs with small capsules and seeds covered by short, tan-coloured fibre to the current white cotton plants with long fibres (Viot & Wendel, 2023) that has become the widest commodity traded in the world (OECD/FAO, 2024).

In Australia, there are 17 species of native *Gossypium* spp., all being part of a distinct group found only in Australia and distant relatives of *Gossypium barbadense* and *G. hirsutum* (Australian Government, 2024), originally found in South and Central America (Wendel et al., 2010). The highest diversity of native cotton is in northern Western Australia and the Northern Territory,

with 12 out of these 17 species found in the relatively small coastal area in northern Western Australia (Australian Government, 2024; Wendel et al., 2010). Sturt's desert rose, *Gossypium sturtianum*, is the official floral emblem of the Northern Territory, Australia (Wendel et al., 2010). Albeit, Yeates (2001) refers to Makassan traders introducing seed cotton to the Top End of Australia and as a possible 'source for some naturalised populations of Gossypium spp.' (pp. 30), this is not confirmed. An Australian National University anthropologist with expertise in material culture in Arnhem Land, Dr Louise Hamby says that "…*fabric was brought to Australia and traded for services. It may have been cotton but I cannot say that seed for growing cotton was brought and then used by Aboriginal people. The gift of seeds is plausible but growing it, harvesting, spinning etc., seems a bit too far removed from my experience*." (Hamby, L. pers. comm, 3 September 2024). However, there is no evidence that these native species supported a commercial enterprise.

Australia is the fifth largest exporter of cotton worldwide (10%), together with India (10%), Sub-Saharan Africa (12%), Brazil (26%) and the USA (31%), comprising 89% of the global output (OECD/FAO, 2024). Currently, Australia's cotton is known for its fine quality, with a value worth over AUD 3 billion per annum (Conaty et al., 2022), giving employment to ca. 12,000 people (Cotton Australia, 2024b).

Cotton is mainly grown in Queensland, New South Wales, Victoria, and recently in the Northern Territory and Western Australia (Figure 2) (CRDC & Cotton Australia, 2024). Northern Australia, the area north of the Tropic of Capricorn, has been touted as the next frontier for agricultural development since the 1860s (Hillock, 2005) however, many government-led initiatives to develop northern Australia through intensive agriculture did not yield expected results (Hillock, 1999, 2005). Regardless, diversifying the economy for a more prosperous Northern Australia has been a focus for the Federal Government since the 'Developing the North' agenda (Babacan & McHugh, 2020, Austrlaian Government 2015). Northern Australia comprises around 53% of Australia's land mass, ~3.5 million km^2 of land, with less than 5% of the national population, i.e. 1.4 million people (Ash et al., 2017).

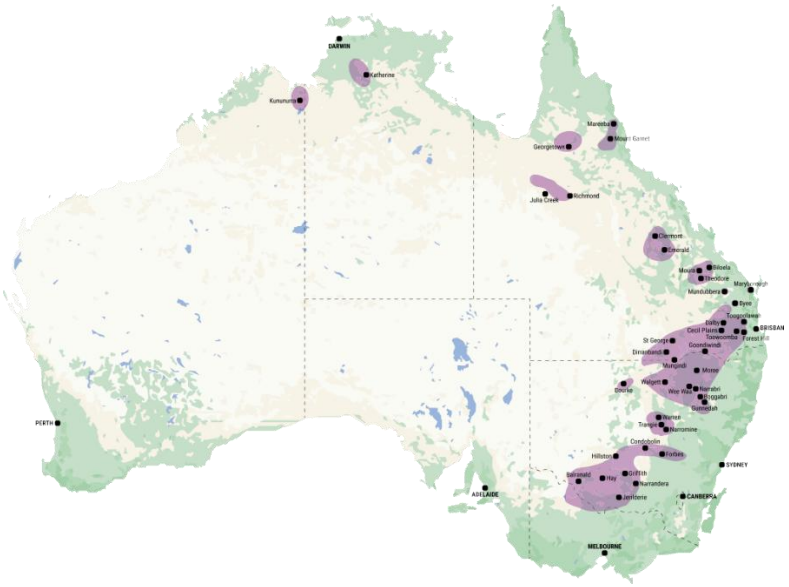


Figure 2. Indicative of where cotton may be grown in mainland Australia. No cotton region in Tasmania, hence island has been excluded from this map. Source: CRDC and Cotton Australia (2024).

The first industrial operation of cotton started in 1926 in the Emerald region of Queensland (CRDC & Cotton Australia, 2024). Agricultural development and expansion are crucial to developing northern Australia through the intensification of systems, such as cattle production, new irrigated and rainfed/dryland cropping systems, timber and forest industry development, and aquacultural and horticultural production (Babacan & McHugh, 2020). Northern Australia's agricultural sector, in particular the pastoral industry, is a significant contributor to the national economy. The annual value of north's agricultural produce was ~$7 billion in 2018 (PricewaterhouseCoopers (PWC), 2019, p. 10), constituting approximately 14% of Australia's total agricultural production (Dale et al., 2020).

The current blueprint for developing northern Australia '*Our north, our future: white paper on developing northern Australia*' (Australian Government, 2015), henceforth the 'white paper', emphasises diversification to realise the trade opportunities with South-East Asian markets to address the increasing global demand for agricultural produce and commodities, and the need to sustain vibrant regional and remote communities in Australia (Ash et al., 2017). Current water restrictions in southern states (Kimura & Antón, 2011), elevated costs for cotton production (Ash et al., 2017; Yeates & Poulton, 2019) especially land prices for established farms in southern farming regions, and the possibility of accessing available rainwater water and groundwater (Beaumont et al., 2022) have stoked the interest of developing broadacre crop production in northern Australia (Australian Government, 2015). The 'white paper' emphasised '*irrigated cropping sustaining multiple clusters of small scale, high premium horticultural and niche crop production, together with broadacre farming of crops such as*

sugar(cane), soybeans and cotton' (Australian Government, 2015), as result there has been a series of trials of broadacre agriculture in northern Australia with mixed results (see Table 1 below).

This document aims to set the baseline for the rain-fed cotton industry in the Northern Territory. Every action has risks, and the final document arising from this project hopes to provide a one-stop shop for information on (i) environmental risks (water, land, biosecurity), (ii) sociocultural risks (sacred sites, impacts on Country) and (iii) economic factors (gross margins, externalities).

1.2 History of growing cotton in northern Australia

Commercial cotton variety was introduced to Australia shortly after the arrival of the First Fleet' in 1788. The earliest attempts to grow cotton date back to 1862 in Queensland and had limited success (Australian Government, 2024; Cotton Australia, undated-a). In 1921, the unrealised potential of Queensland as one of the world's top cotton producers led to the establishment of the Australian Cotton Growing Association Limited (Queensland Cotton, 2024). In 1926, this association became the Queensland Cotton Marketing Board, which strengthened the industry, leading to government subsidies to promote cotton production in central Queensland (Cotton Australia, undated-a; Queensland Cotton, 2024). Nonetheless, cotton production declined by 50% over two seasons after a series of drought events in the late 1920s, and by the 1930s the industry was in decline due to The Great Depression and its impact on world markets (Queensland Cotton, 2024). In 1958, the first irrigated cotton project was started at Namoi River in north-western New South Wales. Southeastern Queensland followed suit in 1963 (Queensland Cotton, 2024), leading to the current irrigated cotton production (Conaty et al., 2022) of which, now approximately 66% of Australia's cotton is grown in New South Wales and 33% in Queensland (Figure 2).

In the Northern Territory cotton growing was attempted for the first time in 1882 (Hillock, 1999, 2005) and in the 1960s in the Kimberley (WA) under the Ord River Irrigation Area (ORIA) scheme. The only significant period of cotton production in the ORIA was from 1963 to 1974 with the highest yield (4.8 bales/ha) achieved in 1971 (Annells & Strickland, 2001). The cotton grown in ORIA came to a stop in 1974 due to problems that reduced yields, including the spread of insect pests, development of insecticide resistance, and challenging weather conditions (Annells & Strickland, 2001). Yeates et al. (2006) states that its failure "*were symptoms of a production system that in hindsight failed to recognise the ecological limitations of the environment*" (Yeates et al. 2006, pp1). Overall, irrigated agriculture, such as cotton, fruit and vegetables, accounts for the use of 75% of water in Australia and the Murray-Darling Basin alone accounts for ca. 66% of the irrigated land in Australia (Kimura & Antón, 2011).

Expanding the agriculture frontier in Australia's tropical north (north of the Tropic of Capricorn – 22°S) has been in demand since first settlers (Davidson, 1965; Greiner & Johnson, 2000; Hillock, 1999; Irving, 2014; Rhebergen & Yeates, 2023; Woinarski & Dawson, 2017; Yeates et al., 2013). A combination of environmental and economic drivers, technological advances, and the increasing limitations such as water and social licence in traditional growing regions, particularly in southern cotton-growing regions like the Murray-Darling Basin, has driven the cotton industry to seek new areas with more consistent rainfall (Rhebergen & Yeates, 2023; Yeates, 2001; Yeates et al., 2013).

In northern Australia, broadacre crops have been trialled since the 1860s (Hillock, 1999, 2005; Woinarski & Dawson, 2017) (Table 1). In 1858, the South Australian (SA) government requested the British Crown to allow expansion to the northern coast of Australia for development (Hillock, 1999) and it immediately assumed that tropical agriculture would be a success in the Territory (Hillock, 1999). By 1864, a small population had settled at the mouth of the Adelaide River although people did not stay. Shortly after the founding of Port Darwin in 1869, the general mentality was that to develop the Territory all "*what was needed were capitalists who would create vast plantations of rice, cotton, coffee and […] sugar cane*" (Hillock, 1999; pp. 39) and by 1883 it was a reality that a "large self-supporting population" (Hillock, 2005, pp. 240) was needed in order for cultivation by available cheap local labour (Hillock, 1999). The telegraph line connecting Adelaide to Darwin (Williams, 2024), which eventually helped connect Australia to London, was finished in 1872, adding to the needed infrastructure for development, investment and market opportunities for the Northern Territory (Hillock, 1999). The first major tragic failure of agriculture in the Top End was a sugar cane plantation between 1879 and 1889 around the Daly and Adelaide rivers (Hillock, 1999). Total sugar yields were a mere 180 kg that were exported from the Northern Territory through this venture (Hillock, 2005) (see Table 1 – historic overview of cotton growing in the Northern Territory). Many ventures to develop broadacre agriculture in the Northern Territory suffered from similar challenges irrespective of the crop; for example, limited yield due to the extreme weather variability, lack of workforce, and limited markets that were vast distances away (Table 1). This meant that the trialling of a vast array of crop and pasture species in the north was usually fruitless (Cook, 2009).

As with historical information, the available published information on these initiatives to develop northern Australia has retained little specifics (i.e. quantity of rain, mean low/high values, specific sites), yet these provide the best available information to date (references in Table 1). The explorers' reports, with findings of green and lush vegetation, plentiful of water and land, are among the reasons why northern Australia keeps being pushed as Australia's next agricultural area.

It has been noted that transplanting cotton farming practices from southern states to northern Australia were not successful due to little research to understand local conditions (Yeates et al., 2013). It is not that the crops do not grow, it is that the farming practice used does not achieve the yield potential for the climate, so the business does not generate the returns required to stay viable. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) cotton breeding program (Conaty et al., 2022) has been conducting research to address the cotton industry needs, but mainly in southern Queensland, New South Wales and Victoria (Conaty et al., 2022).

Table 1: Summary of agricultural development projects in the Northern Territory from 1860 onwards.

Year	Agricultural attempt with location	Crop	Environmental challenges (T°C, cloud cover, rain)	Conducted by	Political and social challenge	Pest challenges	Reference
1869	Optimism for agriculture potential; general NT region	Not specified	High temperatures, low rainfall	SA Government	Lack of climate adaptation planning	None specified	Hillock 2005
1882	Early plantation trials in Darwin	**Cotton**, sugarcane, coffee, rice	Heat and rain inconsistency	Private initiatives	Labor shortage, high input costs?	Cotton bollworm, coffee borer	Hillock 2005
1912	Demonstration farm crop trials in Batchelor	Potatoes, maize, sorghum	Poor germination due to dry season Variable rainfall and seasonal flooding	Federal Government	Infrastructure limitations	None specified	Hillock 2005
1946	Post-WWII agricultural trials across NT	Maize, rice	Extreme temperature variations	Commonwealth (CSIRO)	Limited infrastructure, funding challenges	None specified	Hillock 2005
1947	Trials for drought-resistant crops, NT region	Sorghum, peanuts	High temperatures, inconsistent rain	CSIRO	Limited infrastructure	Mealybug	Yeates et al. 2013
1950	Tropical fruit trials in NT	Mango, banana	Rain variability, heat stress	NT Government	Transport limitations	Fruit flies in mango	Hillock 2005
1955	Dryland farming trials in Katherine	Millet, legumes	Low rainfall	CSIRO	Soil degradation, infrastructure challenges	Aphids, white grubs	Yeates 2001
	Irrigated area near the Adelaide River at Humpty Doo	Rice	Invasion of magpie geese and soil salinity levels	Territory Rice Limited	None specified	None specified	Ling 2011
1956	Large scale field trials with irrigated rice at Beatrice Hill Research Station	Rice	Proliferation of weeds, inability to sow rice into the soil	NT Government	Bad management, advice from local agronomist ignored	None specified	McGuffog 2005
1959	Beatrice Hill (60 km east of Darwin, near the Adelaide River)	Coffee, cotton	Pest control and climate conditions had led to poor performance and the trials were abandoned	NT Government and CSIRO	None specified	None specified	Ling 2011
1960	Pasture crop trials for cattle in NT	Pasture grasses, legumes	Extreme heat, drought	Federal Government	Transport costs for livestock	Cattle ticks	Yeates, et al. 2013

Year	Agricultural attempt with location	Crop	Environmental challenges (T°C, cloud cover, rain)	Conducted by	Political and social challenge	Pest challenges	Reference
1970	Tropical fruit production trials in Darwin	Mango, citrus	Temperature fluctuations, seasonal rain	NT government	Limited market access	Citrus leaf miner	Hillock 2005
1980	High-value exotic fruit trials in NT	Durian, rambutan	Cloud cover reducing light, heat stress	NT government	High infrastructure costs	Fruit flies	Grundy et al. 2020
1990	Irrigated cotton trials in Katherine, tropical dry season	**Cotton**	Low overnight temperatures, cloud cover	Commonwealth (CSIRO)	Infrastructure cost,	Pink bollworm, bollworm	Yeates et al. 2010
1995	Expanded sustainable cotton trials, Katherine	**Cotton**	High temperatures, low sun radiation	CSIRO	None specified	Cluster caterpillar, pink bollworm	Yeates et al. 2013
2005	Sustainable cotton and pest management in NT	**Cotton**	Monsoonal rain, cloud cover	CSIRO	Planning for resistance management	Cluster caterpillar, *Helicoverpa* spp.	Yeates et al. 2013

The most common reasons for the failure of broadacre cropping in the Northern Territory were the environmental extremes i.e. too much rain or too little rain, poor soils and disease outbreaks (Table 1). Yeates et al. (2013) in their review of the research by the Australian Cotton Cooperative Research Centre (CRC) mentioned that '*Bauer (1985) gave three reasons for failure of large-scale commercial agriculture in northern Australia at the time: (i) distance to markets, (ii) ignorance of the physical environment, and (iii) 'a reprehensible aversion to learning by experience'* (Yeates et al. 2013, pp. 1).

When cotton was grown in the ORIA in the Kimberley region of Western Australia in 1947, the industry failed due to its inability to manage insect pests and by 1974 it had ceased production (Conaty et al., 2022). Post WWII, the Australian Commonwealth Government established the experimental and research stations in Katherine in 1952, Berrimah (on the outskirts of Darwin) in 1956, and Beatrice Hill (east of Darwin on the road to Kakadu) in 1959 (Ling, 2011) recognising the value of research and development for enabling the Territory's agricultural industry.

In 1954, the Australian Institute of Political Science in Canberra convened a summer school where the scholars present debated on how to develop Northern Australia beyond its military, mining and pastoral activities into extensive agriculture (Australian Institute of Political Science, 1956). The overall conclusion was "*that there is no vast potential, but neither is the picture as barren of opportunity as has been painted in the past*" (Australian Institute of Political Science, 1954 pp. 245) which albeit highlighting the many existing challenges – namely the physical and environmental conditions of

northern Australia, possibilities lay with innovation and technology and the increased understanding of cotton's agronomy (Yeates et al., 2013).

A few years after, the noted agricultural economist, Bruce R. Davidson (1924-1994) in his book 'The Northern Myth' (1965) argued that any large-scale agricultural development in northern Australia would not succeed due to the small population base (233,000 people; ABS 2022), distance to markets and the tyranny of long-distance transportation, and highly variable environmental systems (Davidson, 1965; Woinarski & Dawson, 2017).

Davidson (1965) concluded that intensive agriculture would better suit Australia's southern latitudes than its tropics, and that northern Australia was best suited to large scale cattle farms (Davidson, 1965). Parts of the myth of developing the north that Davidson (1965) proposed regarding cotton viability has been partially addressed with intensive research and development that has led to specific varieties of cotton suitable for the Australian growing regions (Conaty et al., 2022). Since the first commercial release of CSIRO's cotton varieties in 1984, CSIRO has released 113 cotton varieties, including varieties with high yield and broad adaptation (CSIRO, 2024), yet no specific variety for the extreme biophysical conditions (i.e. extreme rainfall or lack of rain; extreme heat, boll drop after long periods of cloud coverage) of the Northern Territory has been produced.

In 1984, CSIRO released Australia's first transgenic cotton variety, 'Bt' cotton, which was grown commercially in the southeastern states of Australia since 1996 (Australian Government, 2024). Genetic modification provided the opportunity to overcome biotic and abiotic stresses by including suitable genes in crops, such as cotton (Carberry et al., 2011). This Bt cotton contains one or more foreign genes derived from the soil-dwelling bacterium, *Bacillus thuringiensis*; thus, they are genetically modified (GM). The insertion of the genes from *B. thuringiensis* causes cotton plant cells to produce insecticidal proteins that are toxic specific to the pest caterpillar *Helicoverpa* (Insecta: Lepidoptera) when they eat the plant (Australian Government, 2024).

Bollgard 3® is the most widespread Bt cotton grown in Australia (Cotton Australia, 2024b). It contains three different insecticidal proteins (cry1Ac, cry2Ab and vip3A – or 'stack') that contribute to pest resistance management as it is more difficult for the pest to overcome all three toxins simultaneously (Australian Government, 2024). Additionally, Roundup Ready®, an herbicide-tolerant cotton, was commercially released in Australia in 2001. The Roundup Ready® cotton is resistant to the herbicide glyphosate, allowing greater flexibility in weed control options. Genetically modified cotton plants are either tolerant to herbicide (allowing the use of glyphosate

to control weeds) and/or resistant to the major caterpillar pest *Helicoverpa* spp. (Australian Government, 2024).

Australia's regulatory guidelines did not allow commercial production of Bt cotton north of the 22°S (Williams et al., 1996), which omitted all of northern Australia. After the 'white paper' (Australian Government, 2015) identified broadacre agriculture with cotton as one of the diversification options, 'Bt' cotton was allowed in 2018 (Cotton Australia, 2024e). All cultivars now grown in the Northern Territory are transgenic, expressing the *Bacillus thurengiensis*-derived toxins in Bollgard 3® Monsanto for ongoing control of lepidopteron caterpillar pests as well as glyphosate-resistant Roundup Ready Flex® Monsanto.

The ongoing steady growth of cotton trade globally provides the perfect market opportunity for Australia to meet this demand and increase financial outcomes; this has led to the current resurgence in cotton farming in the Northern Territory. This was also influenced by drought and water limitations in the traditional southeastern growing regions (i.e. Murray–Darling Basin) (Kimura & Antón, 2011) and the commitment from the Australian and Northern Territory governments to find diversification options for continuous agricultural growth in the north. Cotton is at the forefront of this initiative as a proven, established and profitable commodity that has innovative research and development available (see Conaty et al. (2022)), although these are not available for northern Australia conditions in general, or for those in the Northern Territory specifically.

Southeast Asia, specifically Vietnam, is where spun yarn industry has been established successfully (OECD/FAO, 2024) requiring cotton lint. Australia's cotton is well known for its quality, hence having a cotton production area in northern Australia would allow tapping that market in Asia (Conaty et al., 2022; Yeates et al., 2013). Moreover, its seed is a valued fodder for cattle, hence benefiting the local pastoral/livestock industries, especially during drought conditions (PricewaterhouseCoopers, 2019) yet, in most southern cropping systems, cotton seed is considered a waste stream and exported. The Northern Territory has the advantage of receiving 'consistent and sufficient rainfall' (PricewaterhouseCoopers, 2019), hence able to produce both cotton lint and cotton seed as a summer crop, with the latter working as a by-product that can be used for cattle feed (Auty, 1964).

Spatial and temporal variations in rainfall in tropical Australia significantly influence ecological and agricultural systems (Garnett & Williamson, 2010). This spatial and temporal variability affects the timing of biological (i.e. seed germination, growth, flowering), physical (i.e. soil saturation, erosion)

processes (Garnett & Williamson, 2010) and, henceforth, the overall returns from cotton in the Northern Territory.

The Northern Territory potentially offers vast areas for broadacre cropping such as cotton with current innovations in crop technology presenting both, rainfed and irrigated cotton, as a valid option (Australian Government, 2015).

2. Rainfed cotton in northern Australia

Worldwide, irrigated cotton is the prevalent cotton production system, with rainfed cotton contributing a small amount (OECD/FAO, 2024). Rainfed cotton refers to Upland cotton (*Gossypium hirsutum*) grown without irrigation, relying only on natural rainfall during the crop cycle. Rainfed cotton is where farming takes advantage of wet-season rainfalls, with the crop highly dependent on the general availability of rain (Godfrey et al., 2019; Godfrey et al., 2023). Cotton can be grown as either rainfed, fully irrigated or supplementary irrigated cotton (requiring supplemented water supply) (DITT, undated). Rainfed cotton has a greater intrinsic risk as it relies on natural rainfall (Godfrey et al., 2019; Kimura et al., 2010; Welsh et al., 2022). Australia has one of the most variable climates in the world, which makes the agricultural sectors, particularly rainfed cotton sensitive and at high risk (Welsh et al., 2022). Even though there have been substantial technological and agronomical developments in cotton (see Conaty et al. 2022), most of these have focused on increasing overall yield by improving cotton's response to modern management (Liu et al., 2013).

CottonInfo, the Australian cotton industry's joint extension program, refers to rainfed or rain-grown cotton as dryland cotton (CottonInfo, 2024). Rainfed cotton is largely grown in the 400–800mm summer-rainfall zone in Australia (Cotton Australia 2018; ABARES 2020) comprising latitudes from 21°S to 37°S (but may extend to 42°S) in the semi-arid to dry sub-humid regions that receive 300–600mm of annual rainfall (Squires & Tow, 1991). Average yield is 1.34 bales/ha (Godfrey et al., 2023). Overall, in Australia, the area under rainfed cotton production system depends on commodity prices, soil moisture levels and projected rainfall (Bange et al., 2010).

In Australia, majority of the cotton crop is irrigated, returning a reliable higher yield of roughly 9 bales/ha in 2020/21 season (Godfrey et al., 2023). Yield can be up to 12 bales/ha depending on irrigation method (i.e. furrow irrigated cotton with Bollgard3® and Roundup Ready Flex® (AgEcon & CottonInfo, 2024c) (Table 2). An analysis of the 2023–24 cotton planting season in Australia showed that up to 23% of cotton production areas in Australia are dryland/rainfed (Table 2), with the remaining 77% in (various) irrigated systems (Cotton Australia, 2024a). Consistently, yield is consistently higher in New South Wales and Queensland, with rainfed cotton yield for

Katherine similar to those in rainfed systems in eastern Australia (Table 2). The data available to date did not allow the identification of the number of bales from irrigated vs rainfed cotton in the different regions (Table 2). Irrigated cotton production in the ORIA in Western Australia is expected to expand to 10,000 ha, with the opening of the cotton gin in Kununurra in June 2025 (Noel Wilson, Western Australia Department of Primary Industries and Regional Development, pers. comm.).

Table 2. Irrigated and rainfed cotton areas and yield (bales/ha) for different cotton growing areas in Australia for the 2023-24 season. Source: Cotton Australia (2024a). The data did not allow identification of the number of bales produced from irrigated vs dryland/rainfed cotton.

State	Region	Irrigated (ha)	Rainfed (ha)	Total (ha)	yield (bales)	Region average yield (bales/ha)
NSW	Macquarie Valley	37,549	791	38,340	544,460	14
	Gwydir Valley	54,000	34,000	88,000	857,000	10
	Namoi Valley	53,000	31,000	84,000	822,000	10
	Walgett & Bourke	15,000	11,000	26,000	231,000	9
QLD	St George	10,000		10,000	120,000	12
	Dirranbandi	12,300		12,300	148,000	12
	Mungindi	18,000		18,000	211,000	12
	MacIntyre Valley	28,500	7,000	35,500	363,000	10
	Darling Downs and South Burnett	28,500	4,500	33,000	310,000	9
	Dawson and Callide Valleys	7,300		7,300	73,730	10
	Central Highlands	19,400	1,150	20,550	240,000	12
	Far North Qld	1,500	500	2,000	15,000	8
NT	Northern Territory (**Rainfed**)	575	12,500	13,075	50,000	4
WA	Kununurra*****	2,000		2,000		11
Total		**299,349** (77%)	**90,516** (23%)	**389,865**	**400,5190**	

*****No data for Kununurra for 2023-24 season. Data presented is for 2022. Source: Noel Wilson, DPIRD, pers. comm.

The search for a continued growth of the cotton industry and the need to meet societal licences on the use of water (Beaumont et al., 2022), together with the possibility of rainfed cotton providing a profitable summer option in Australia has expanded cotton production to non-traditional growing regions (Anwar & Darbyshire, 2017). There are also improved varietal choices and the potential for increased profitability, in which cotton cropping is compared with alternative summer crops such as sorghum (Godfrey et al., 2023).

Rainfed cotton has a higher risk profile as extreme heat events across its growing cotton regions could reduce yield (Godfrey et al., 2019; Shikha et al., 2022). High temperature can also increase cotton boll shedding, reduce pollen viability at flowering and collectively reduce boll size and yield (Anwar & Darbyshire, 2017). Rainfed cotton requires adequate soil moisture to plant with incremental use of water at the different growth stages (December and January in the Northern Territory) and frequent rainfall during the remainder of the wet season. Red Kandosols (or Alfisols/Ultisols (USDA) are the predominant soils suitable for rainfed cotton in the Northern Territory albeit lacking strong texture contrast, not being calcareous throughout, acidic to neutral (pH 5.5–8.0), and have low fertility and poor water-holding capacity (Rhebergen & Yeates, 2023).

Hartley et al. (2021) mentioned the Daly River catchment, Larrimah, Wildman River, Keep River, Victoria River District plains and Roper River catchment as regions in the Northern Territory that could support rain-fed and some irrigated cotton production (Figure 3). In general, rainfall decreases towards the south – the average long-term median is > 1,000 mm in Tipperary and < 600 mm for Larrimah (Hartley et al., 2021; Rhebergen & Yeates, 2023). Additionally, the frequency of low and high temperatures that are detrimental to cotton growth increases with greater variability in rainfall and temperature (Hartley et al., 2021; Rhebergen & Yeates, 2023).

With the introduction of Bt cotton in the Northern Territory in 2018 , cotton growers started trials in the Big Rivers region (Figure 3) with limited support. Over 95% of cotton in the NT is grown using natural rainfall, and more than 80% is expected to be grown this way in the future (NT Farmers, 2022).

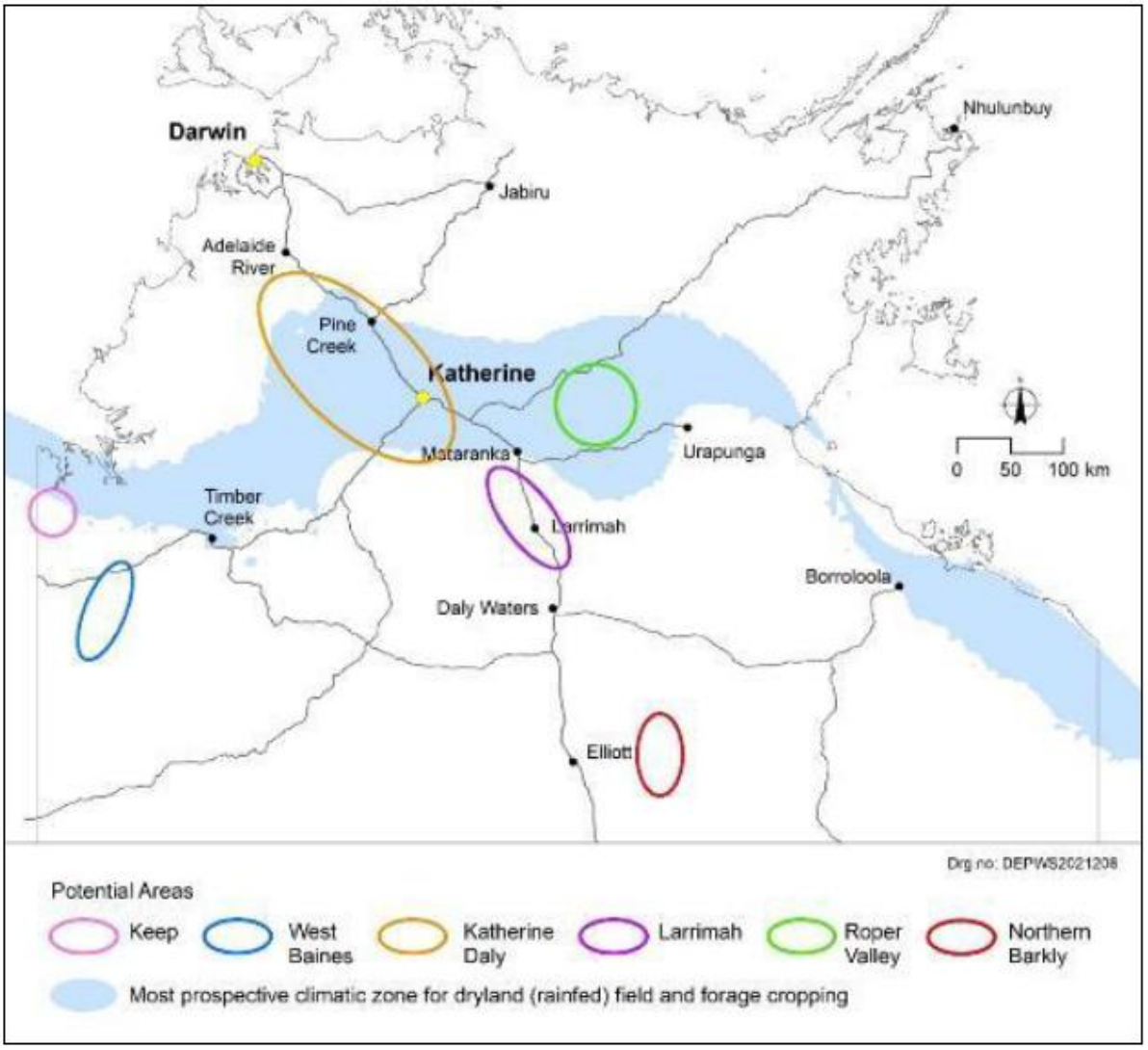


Figure 3. Prospective rain-fed areas for different crops in the Northern Territory. Source: *ibid in* Hartley et al. (2021) based on Pascoe-Bell et al. (2014).

There has been a steady increase in the number of cotton growers as well as the area under cotton cultivation in the Northern Territory (Table 3). To date, there are 12,407 ha of rainfed cotton with an additional 575 ha of irrigated cotton in the Northern Territory (Cotton Australia, 2024d) (Table 3). The information available does not allow for a more precise analysis at this stage.

Table 3: Development of the rainfed cotton industry in the Northern Territory, showing the total number of cotton growers and the number of hectares under rainfed and irrigated cotton production within the Big River region, Northern Territory since the start of the rainfed cotton trials in 2018/19.

Year/Season	Number of growers	Hectares under rainfed (irrigated in parentheses)	References
2018–19	1	200	DITT (2023)
2019–20	6	800 (160)	DITT (2023)
2020–21		4,029 (185)	DITT (2023)
2021–22	12	7,930 (155)	DITT (2023)
2023	9	10,000	NTG (2024)
2024	13	12,410 (575)	Cotton Australia (2024b)

2.1 Agronomic conditions for growing cotton

The growth and development of cotton is complex compared to other broad-acre crops. In cotton, vegetative and reproductive growth happens at the same time, making it difficult to interpret responses to climate and management (Bange et al., 2010). The agronomic conditions required for commercial cotton production (either rainfed or irrigated) are sunny, warm days with maximum temperatures between 27°C and 32°C and overnight minimums of 16°C to 20°C (Australian Government, 2024).

Temperature is the primary factor affecting the rate of plant development (Hatfield & Prueger, 2015). Warmer temperatures accelerate the rate of crop development and could potentially shorten the time to maturity, which may then impact crop management decisions. Higher temperatures can also cause significant loss of cotton bolls, reduce the plant's water-use efficiency, lower the yield, and change the quality of the fibre (Anwar et al., 2020; Bange et al., 2016). Moreover, extended exposure of cotton seeds to temperatures above 30°C to 40°C negatively impacts seed germination and establishment (Hatfield & Prueger, 2015). Generally, temperatures below 11°C or above 36°C will shock the plant and temporarily prevent development (CRDC & Cotton Australia, 2024).

Sunlight availability is crucial for carbohydrate production and reproductive development in cotton, directly impacting yield (Echer & Rosolem, 2015). Solar radiation, which is often erratic in tropical areas of Australia, is influenced by the monsoon as the cloud cover would limit the amount of sun (Grundy et al., 2020). During flowering time, deficiency of sunlight impacts cotton boll survival and yield in northern Queensland (Grundy et al., 2020). ***Shading***, caused by cloud cover or dense planting, reduces photosynthesis and boll weight, especially during flowering, leading to

lower yields (Echer & Rosolem, 2015). Clouded and hot nights (>24°C) can cause fruit shedding (Grundy et al., 2020).

Soils with high fertility, well-drained with adequate moisture retention are the best for cotton. Ideal soils include sandy loams, loams, and clay loams, which balance drainage and water-holding capacity (Pascoe-Bell et al., 2014; Rhebergen & Yeates, 2023). The Northern Territory is characterised for poor soils, which leave Red Kandosols as the most suitable soils for cotton (Rhebergen & Yeates, 2023). While Rhebergen & Yeates (2023) study considered only rainfed cotton on light-textured soils (Kandosols) in the NT, these soils are usually well drained and have low moisture-holding capacity (Table 4). While these soils can support cotton growth, they require management to improve fertility (i.e. addition of fertilizers) and moisture retention (i.e. mulch) (Hartley et al., 2021).

Table 4. Maximum and minimum cotton yield (bales/ha), soil types and optimal planting date in **rainfed cotton** producing areas.

Region	**Site**	**Soil type**	**Maximum Yield**		**Minimum Yield**		
			Bale/ha	**Planting time**	**Bale/ha**	**Planting time**	**Reference**
NT	DDLF	Blain	3.8	Jan 15	2.0	Feb 1	Yeates and Poulton (2019)
	KRS	Blain	3.5	Jan 15	1.75	Feb 1	
	Tipperary	Blain	3.8	Jan 1	2.6	Feb 1	
	Larrimah	Blain	3.5	Dec 15	2.4	Feb 1	
NSW	Wee Waa	Vertosol	4.3	Nov 15	4.0	Sep 30	Anwar et al. (2020)
	Gunnedah	Vertosol	4.7	Oct 30	2.7	Sep 30	
	Moree	Vertosol	4.2	Oct 30	2.6	Sep 30	
QLD	Emerald	Vertosol	5.0	Oct 30	4.5	Sep 30	Anwar et al. (2020)
	Dalby	Vertosol	6.0	Oct 30	4.2	Sep 30	
	Bungunya	Sodosol	3.2	Oct 30	2.7	Sep 30	

Cotton has a strong tap root system (Wrona et al., 1999) which enables the plant to access soil water and nutrients deeper in the soil profile than can be accessed by other crops. Cotton requires a good and reliable source of water during the critical developmental stages as any deviation from that would impact final yield and gross margins (Yeates & Poulton, 2019). The impact of limited water at different plant stages is hotly discussed (see Loka et al. 2011). If cotton does not receive the appropriate amount of water, the quality of the lint is affected negatively, affecting its marketability (Shikha et al., 2022). Too much rain can cause waterlogging and plant death, with well-documented effects on the cotton plant (Grundy et al., 2020) and lint quality (Echer & Rosolem, 2015; Grundy et al., 2020).

Using historical climatic records from the late 1990s, the sowing season was established from December to mid-January (Constable, 1976; Hearn, 1994). Yeates (2001) supports this, but adds

that for the drier Katherine region, planting should be later due to a lack of mulch (Hartley et al., 2021). This proposed planting window (Table 4) takes advantage of likely periods of dry weather for sowing in a moisture rich soil, as expected with the onset of monsoon season, while avoiding sub-optimal overnight temperatures from June onwards (Garnett & Williamson, 2010). Cotton is a summer crop; rain in the seasonal tropics stops almost completely for 4-6 months, which makes the region the perfect example for extreme rainfall seasonality.

Table 4. Overall average physical and environmental conditions for **rainfed cotton** in Australia. Data for the Northern Territory (NT) from Rhebergen and Yeates (2023), and for Queensland & New South Wales (NSW) from Anwar et al. (2020).

State	Region	Temp (cropping season) (^{0}C)		Rainfall (cropping season) (mm)	Planting Window
		Max	Min		
Northern Territory	Douglas Daly Research Farm	34.2	19.6	896	Dec - Jan
	Katherine Research Station	38.0	21.0	367	
	Tipperary	38.0	17.1	724	
QLD	Dalby	30.6	16.6	488	Oct-Nov
	Emerald	33.5	20.0	489	
	Bungunya	32.4	18.1	295	
NSW	Moree	31.5	17.2	396	Oct - Dec
	Wee Waa	31.8	16.8	391	
	Gunnedah	30.3	16.0	407	

2.2 Associated factors affecting cotton production in Northern Australia

Addition of nutrients (nitrogen, phosphorus, potassium) is an extra, variable cost for growers in the Northern Territory, as the soils are poor and nutrient-deficient (Rhebergen & Yeates, 2023; Australian Government, 2024; Rathnayake et al., 2023). **Nitrogen (N)** is crucial for cotton production, as the plant requires substantial nitrogen for growth, particularly during flowering and boll development (Ghaderi et al., 2012; Macdonald et al., 2018; Rhebergen & Yeates, 2023). However, at the same time, nitrous oxide (N_2O), a potent greenhouse gas from using nitrogen fertiliser in agriculture, contributes about one-third of national emissions (Garnett & Williamson, 2010). As with any commercial crop, rainfall and temperature variability (Godfrey et al., 2023) and solar radiation (Grundy et al., 2020) during the growing season are critical factors affecting cotton yield (CRDC & Cotton Australia, 2024; Yeates, 2001; Yeates et al., 2013).

Carberry et al. (2011) highlight the risks faced by rainfed agriculture in Australia, which include high variability in rainfall (Figure 4), low soil moisture retention, and increased susceptibility to the impacts of climate change (Welsh et al., 2022). The Top End of northern Australia receives ca. 13-16% less solar radiation per day than a cotton growing area in Queensland; however, potential

yield for dryland/rainfed cotton is less affected by the solar radiation than by water availability (Yeates & Poulton, 2019).

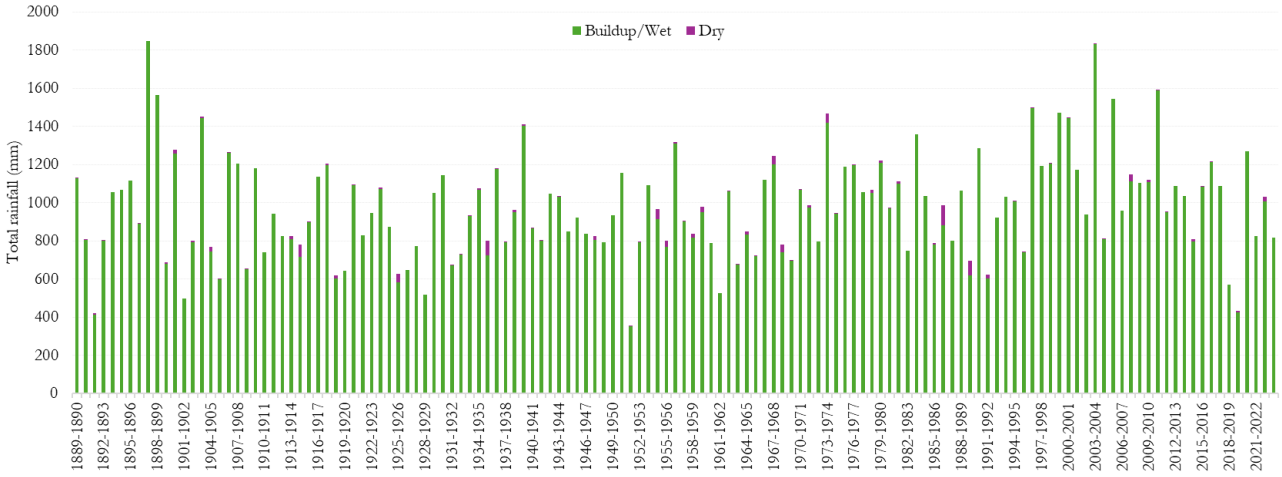


Figure 4. Total rainfall for the wet (green bars) and dry (purple bars) at the Northern Territory Government's Katherine Research Station. The wet season is from September to April, and the dry season is from May to August. Rainfall corresponds to the financial years, allowing for wet season rainfall to be included in yearly totals. Data is from 1889 to 2023 from the Australian Bureau of Meteorology (BOM).

As with any other commercial crop, rainfall and temperature variability (Godfrey et al., 2023) and solar radiation (Grundy et al., 2020) during the growing season are critical factors affecting cotton yield (CRDC & Cotton Australia, 2024; Yeates, 2001; Yeates et al., 2013).

Managing optimizing crop rotations and nutrient use is also challenging in rainfed farming due to vulnerability to erosion and unpredictable rainfall. For example, in Brazil, the lack of rainfall during critical stages affects the photosynthetic complex by inducing a reduction in leaf area, limiting plant transpiration and gas exchange and thus reducing yield capacity and fibre quality. Such risks make agricultural yields unpredictable and heavily dependent on seasonal rainfall. These factors collectively contribute to financial risks for farmers.

Cotton, as a naturally drought-resistant crop, is highly plastic, allowing it to tolerate high temperatures and moderate water stress (Carvalho et al., 2019). However, the extreme environmental conditions in the north pose a significant challenge to the cotton plant, particularly during flowering and boll development (Figure 5).

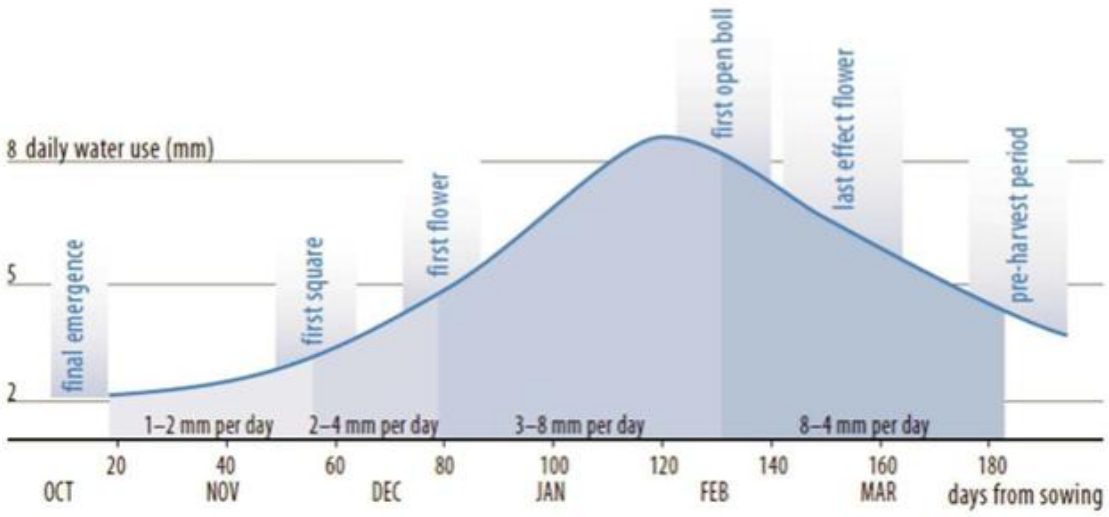


Figure 5. Daily water use (mm/day) for cotton production. *Ibid in* CottoInfo (2015).

In Australia, projected climate change will have both positive and negative impacts on cotton as increased atmospheric carbon dioxide (CO_2) may enhance photosynthesis and radiation-use efficiency, leading to higher yields in well-watered environments. However, higher temperatures can lead to fruit loss, reduce yields, and lower water use efficiency, particularly in water-limited conditions (Bange et al., 2010). Rising temperatures may extend the growing season in short-season regions, but excessive heat (>35°C) can impair photosynthesis and increase boll shedding. Additionally, elevated temperatures may affect fibre quality by altering the thickness of cotton fibre cells and their air permeability and reducing fibre length. Reduced water availability due to lower rainfall and higher evaporative demand will increase competition for irrigation resources, necessitating improvements in water use efficiency (Bange et al., 2016; Bange et al., 2010). Optimal management of planting time, row spacing, and cultivar selection can mitigate shading effects and maintain fibre quality (Echer & Rosolem, 2015). No specific information was found for either rainfed or irrigated systems in the Northern Territory, hindering our ability to understand how these factors affect cotton cropping locally.

Climate change may also influence pest dynamics and diversity, which could lead to new pests and types of damage to cotton crops, potentially requiring further research and development for new Bt cotton alternative. Moreover, weed competition could intensify under elevated CO_2, and certain weeds may develop increased tolerance to glyphosate. Adaptation strategies include breeding for tolerance to heat and drought, optimising irrigation practices, adjusting planting dates, and integrating pest and weed management approaches to maintain productivity and fibre quality.

Extreme weather events, including droughts, heatwaves, and tropical cyclones, may also disrupt production and supply chains (Hennessy et al., 2010).

Rhebergen and Yeates (2023), using APSIM-OZCOT modelling, recommended that rainfed cotton production in the Northern Territory, particularly in regions like Tipperary, Douglas Daly, Katherine, Mataranka, and Larrimah (Big Rivers region), should prioritise soils with high plant-available water capacity (PAWC) such as deep Kandosols, as they support root penetration beyond two meters and optimize yields. Additionally, early planting in December is advised for higher rainfall areas (i.e. Daly) to maximise yield potential, although the risks of pre-picking fibre discoloration due to rainfall must be managed. In lower rainfall regions (i.e. Larrimah), timely crop establishment is critical to address challenges like high soil temperatures and rapid drying, which can be mitigated by utilising wet-season cover crops such as sorghum and robust mulch systems (Abrecht & Bristow, 1996; Rhebergen & Yeates, 2023). Implementing zero-tillage practices, optimising planting timings, and assessing economic viability compared to existing land uses are essential for sustainable industry growth while minimising land-use change (Abrecht & Bristow, 1996; Rhebergen & Yeates, 2023). Further research is needed to adapt agronomic practices to mitigate climatic constraints such as waterlogging from monsoonal bursts, and improve sowing opportunities (Rhebergen & Yeates, 2023).

To date, CSIRO's research in cotton has led to improvements in genetically modified approaches to better yield, fibre quality, disease resistance, resistance to arthropods and to the herbicide glyphosate, and abiotic stress resistance (Conaty et al., 2022). More research is needed on improving the hardiness of the plant to the extreme weather conditions prevalent in northern Australia.

2.3 Challenges to growing rainfed cotton in northern Australia

Monsoonal climate characteristics present a main challenge for most production systems in the north with long wet and dry periods (Garnett & Williamson, 2010). As expected, northern rainfed cotton faces different challenges from temperate growing regions in southeastern Australia (Carberry et al., 1996; Carberry et al., 2011; Squires & Tow, 1991). These include higher temperatures, highly variable rainfall, poor soils with lower water-holding capacity that are prone to crusting, reduced solar radiation due to cloud cover and extreme events that all affect cotton crop growth and yield (Godfrey et al., 2019; Godfrey et al., 2023; Shikha et al., 2022). Farming practices are still adapting to northern Australia's climate and include the use of fallows in rainfed cropping regions or seasonal adjustment of fertilizer inputs (Carberry et al., 2011).

Australian semi-arid conditions result in poor seedling emergence and crop establishment, directly related to the soil conditions (i.e. type) that allow rapid soil drying and high soil temperature in the Daly basin of the Northern Territory (Table 3) (Abrecht & Bristow, 1996). There are key issues that can limit cotton production, for example:

- The cotton plant is well known to abort its fruiting points during periods of extreme cloud cover (Goodman, 1955; Grundy et al., 2020). This shedding is due to decreased photosynthetic activity (no sun, cloud cover) and decreased amount of carbohydrates (from photosynthesis) (Goodman, 1955).
- Yield potential for rainfed cotton production systems depends on rainfall, leading to variable and unpredictable outcomes, affecting financial returns (Constable & Bange, 2015; Godfrey et al., 2023).
- The spatial and temporal variation of the rainy season in tropical Australia has important implications for broadacre cropping, such as: (i) unpredictability in planting, with delays or early starts affecting the growth cycle and yield; (ii) risk of crop damage as heavy early rains can cause erosion on tilled soils, damage crops and deteriorate the soil, whilst the opposite can stress crops, especially young plants; (iii) irregular distribution of rainfall affects soil moisture, which is critical for seed germination and growth; and, (iv) high risk due to challenges in predicting rainfall patterns for optimal timing for planting, pesticide application, and other agronomic practices (Garnett & Williamson, 2010).
- Australian field experiments and simulation analyses found important year-to-year variability in rainfed cotton yields (Garnett & Williamson, 2010). Early heavy rains can damage crops (i.e. waterlogging), while lack of rain at critical times in the cotton life cycle causes stress and reduces lint quality (Shikha et al., 2022). Growers are planting cotton with sufficient soil moisture at the start of the rainy season to maximise potential yield in rainfed cotton whilst also reducing the risks of crop failure (Godfrey et al., 2023).

3. Socio-economic concerns of growing cotton in the north: intangible values

First Nations peoples are intrinsically connected to Country and have shaped the Australian landscape over thousands of years of continuous Indigenous occupation, land use and management (Bowman, 1998; Woinarski & Dawson, 2017). First Nation's practices, such as right-way-fire, maintained biodiversity and landscapes and created habitat mosaics essential for native fauna (Russell-Smith et al., 2018). Peoples' cosmovision sees them as a part of the landscape. The term '*intangible*' here refers to non-material cultural connections (or values) such as cultural traditions, spiritual associations, and symbolic meanings, exemplified by First Nations cultural

heritage, family lineage, and shared community identity, which influence how individuals and groups define and relate to their heritage (Smith & Campbell, 2017). Such values are integral to cultural heritage, representing community identity and traditions (Harcourt, 2021; Smith & Campbell, 2017). Some of these are tied to physical assets such as sacred places which are vital to the identity and continuity of First Nations (Daley, 2001).

Overall, the impact of establishing a cotton industry in the Northern Territory encompasses both economic opportunities and substantial environmental, social and cultural risks (Beaumont et al., 2022). Economically, cotton has the potential to diversify the agricultural sector, generate jobs, and increase regional export revenues (see Section 2.7: Tangible gains and losses: an economic overview). Modification of the northern landscape with cropping could interfere with traditional land management practices, disrupt cultural knowledge transmission, and reduce access to culturally significant sites (Pocock et al., 2015). As cotton farming often requires extensive land clearing, this change may alter landscapes of cultural and historical importance, affecting the cultural heritage and identity of First Nations.

The proposed expansion of the cotton industry in the Northern Territory poses substantial risks to peoples' heritage values that shape the region (Beaumont et al., 2022). These values are subjective and difficult to quantify but play a crucial role in shaping behaviours, beliefs, and identities (Smith & Campbell, 2017). Development of cultural maps, identified through a co-creation process with First Nations peoples, could be a good tool for guiding development proposals on Indigenous lands (Togni, 2023).

To date, 95% of cotton produced in the Northern Territory uses only rainwater; however, development projections consider irrigated cotton (DITT, 2023, undated). There is vast information on the impact of irrigated cotton on environmental and societal values worldwide, such as in the Aral Sea in Uzbekistan/Kazakhstan (Ahn et al., 2024), the Indus delta in Pakistan (Raza et al., 2023), and the Baaka and northern Murray-Darling Basin (Bates et al., 2024).

Broadacre expansion in general, and cotton in particular, may also pose a challenge to local economies that are dependent on fishing, cultural tourism, and recreation, potentially leading to reduced employment and economic resilience, especially if the surrounding landscape undergoes extensive land-change use. These societal shifts may result in tensions as communities navigate the trade-offs between cotton's economic promises and the sustainability of traditional livelihoods (Beaumont et al., 2022).

3.1 Environmental values

Change in land use is one of the major drivers for habitat degradation and species extinction worldwide (IPBES, 2019; WWF, 2024). Nearly 50% of Australian natural vegetation has been cleared or severely modified since 1788, leading to the extinction of numerous species and threatening many others (Lindenmayer & Possingham, 2013; Lindenmayer et al., 2010). Land clearing is spatially uneven across Australia, with only one-third of natural vegetation remaining in southeastern Australia. Northern Australia offers a relatively intact swathe of savannas, covering an area of 1.9M km^2, globally with significant ecological and environmental values (Legge et al., 2023; Stokeld et al., 2018; Woinarski et al., 2020). Based on soil properties, only ~20% of that is considered highly suitable for agricultural intensification (Wilson et al., 2009). The Northern Territory supports a unique blend of biodiversity within ecosystems such as rainforests, mangroves, tropical heathlands, and a vast network of natural rivers and wetlands (Beaumont et al., 2022; Morán-Ordóñez et al., 2017; Woinarski et al., 2020).

The environmental impact of cotton farming in the Northern Territory is considerable as it needs vast areas of land to be cleared. This land clearing for cotton could lead to habitat loss, soil degradation, and increased carbon emissions, collectively called externalities, that threaten the region's environmental sustainability (Abrecht & Bristow, 1996; Bristow et al., 2016; Morán-Ordóñez et al., 2017).

Externalities are the unintended consequences of farming practices that affect society and the environment. These are not accounted for in market transactions (Rohr et al., 2020). Negative externalities include soil erosion, water pollution, greenhouse gas emissions, and biodiversity loss (Griffith et al., 2014; Macháč et al., 2021).

The over-application of fertilisers contributes to greenhouse gases (GHG) emissions as well as pollution of surface and ground waters due to run-off and leaching of dissolved organic nitrogen, urea, and nitrate (Macdonald et al., 2018) becoming a contamination risk to both surface and groundwater water quality (Pearson & Gorman, 2010)– reflecting extenralities, and the costs of such risks are largely borne by society. Addressing such externalities requires integrating their monetary value into decision-making processes through approaches such as cost–benefit analysis and ecosystem service valuation (Macháč et al., 2021).

First introduced by English economist Arthur C. Pigou in the early 1900s, the concept of externalities gained prominence as economists began to recognise the significant environmental problems created by industrialisation. Today, externalities and their effects on environmental outcomes remain central to agriculture-related businesses due to global concerns about climate

change and hence require them to meet environmental standards in the form of Corporate Social Responsibility or Environmental Social Governance (Costanza et al., 1997; Helbling, 2024).

The market failure[1] of not including externalities in the cost of doing business generates impacts on every level of society and the environment. With harm to the environment, there is an expected increased expense (private or public) to remediate the issues arising from such industry. For example, in the Martuwarra (Fitzroy River) region of Western Australia, attempts to extract water for agriculture, including proposals for large-scale irrigation, threatening the ecological balance and cultural connections of the Nyikina people to their living waters, which are spiritually embodied by the Rainbow Serpent, Yoongoorrookoo, a symbol of life and law (Bates et al., 2024). In the Baaka (also known as the Darling River) region, externalities of cotton development are being accounted for through the 'Better Baaka' program, which focuses on infrastructure projects such as fish passages, weir modifications, and restoration of rock bars to improve environmental and cultural outcomes for First Nations communities (Bates et al., 2024). Inclusion of externalities right from the start can help align the private and social costs of businesses to promote sustainable agriculture practices (Costanza et al., 1997; Turner et al., 2007). For example, in cotton farming, pollution by fertilisers such as nitrous oxide (N_2O) as a greenhouse gas and cost to the society can be estimated using an established market price (Rathnayake et al., 2023) which should be considered when analysing business gross margins.

At this stage, accounting for externalities represent a significant challenge for the Australian cotton industry, where the private costs of emitting activities fail to account for broader societal impacts such as global warming (Cotton Australia, 2023) and its associated risks, including lower agricultural productivity and economic losses from climate change (Helbling, 2024).

The GHG emissions market, often referred to as a 'carbon market', operates through mechanisms designed to limit and reduce greenhouse gas emissions by assigning an economic value to the abatement of emissions. Currently, there is no account of the greenhouse gas emissions from land clearing for rainfed cotton in the Northern Territory. As the Douglas–Daly River catchment has been identified as an area for potential intensification of horticulture, plantation forestry and cattle grazing (Australian Government, 2015; DITT, 2023; NTG, 2020) we used a study on savanna clearing, including burning of debris in the Northern Territory, as a proxy.

Bristow et al. (2016) conducted field measurements of greenhouse gas emissions from September 2011 to July 2013 in the Douglas–Daly River catchment with Blain and Oolloo sub-orders of the

[1] Neoclassical economists recognized that the inefficiencies associated with technical externalities constitute a form of "market failure" (Helbling 2024)

red kandosol soils. The key phases included pre-clearing observations starting in September 2011, deforestation in March 2012, debris burning in August 2012, and subsequent land preparation extending into July 2013. It calculated that each hectare cleared emits 148.3 t of CO_2-equivalent per hectare (Bristow et al., 2016). Burning of the debris alone was responsible for 121.9 tonnes of CO_2-equivalent per hectare or 82% of the total emissions (Bristow et al., 2016), costing about $2539/ha as described below. To date, due to a lack of monetary transactions, most of the environmental-related costs are borne by the public (Costanza, 2024; Costanza et al., 1997; Sangha et al., 2024).

In Australia, the price of greenhouse gas emissions is not directly regulated through a fixed carbon price. The government offers a carbon price of $33.47 per *tonne* of greenhouse gas emissions abatement (average in Q2, 2024; Clean Energy Regulator, 2025) under the Australian Carbon Credit Unit (ACCU) Scheme, used here to estimate the monetary value. If the Northern Territory Government's agribusiness strategy of having 100,000 ha of broadacre cropping (DITT, 2023) materialises, this will add about 3% to Australia's emissions account, assuming this occurs over a 15-year period (Bristow et al., 2016).

Morán-Ordóñez et al. (2017) analysed the trade-offs and synergies between biodiversity conservation, carbon farming, and agricultural development in the tropical savanna of northern Australia. There was a significant overlap between high-priority biodiversity areas and suitable agricultural soils, leading to potential conflicts. Through a scenario-planning framework, the authors identified applying strategic planning for agricultural development, the north prioritising biodiversity and carbon storage, and the south on agriculture. Further results suggest that strategic, adequate prior planning can enable agricultural development while minimising biodiversity loss and maintaining carbon-farming potential (Morán-Ordóñez et al., 2017). While the study provides a useful foundation for considering environmental trade-offs in northern development, future scenario-planning exercises should also consider industry direction, production potential, infrastructure, and the practical realities influencing agricultural expansion in the Northern Territory.

3.2 Tangible gains and losses: Economic overview

Cotton represents significant economic potential for the Northern Territory for supporting agricultural diversification, creating local jobs, and enhancing exports (Australian Government, 2015; DITT, 2023). With the reliance on cotton for textile production worldwide and Australia's commitments to cotton production, the possibility of improving agribusiness in the Big Rivers region in the Northern Territory (see Table 3) is an attractive one. The industry has already

attracted local and international investment (PricewaterhouseCoopers, 2019). With the increase in the number of cotton growers and total hectares under cultivation (Table 1), the first cotton gin opened in Katherine in October 2024. Before that, cotton growers had to send their harvest to Queensland for processing with added expenses. With a capacity to process between 150,000 and 200,000 bales per year (Cotton Australia, undated-b), the cotton gin addressed the challenge of transport to market (Cotton Australia, 2024c). The local gin will further reduce production costs, boost profitability, and create valuable byproducts for the Northern Territory's cattle industry (PricewaterhouseCoopers, 2019). In September 2024, the first containers of Northern Territory cotton were exported to Asia (Cotton Australia, 2024c). The Tipperary Station in the Northern Territory, a shareholder in the gin was the first farm to export cotton while being at the forefront of rainfed cotton. Cotton is an emerging industry in the Northern Territory (NT), growing from about 800 hectares planted across six properties in 2019–20 to around 10,000 hectares planted by nine growers in the Big Rivers region in 2023–24, and the area is expected to keep expanding (NTG, 2026).

Cotton yield is a complex result of agronomic, genetic and environmental factors. A gross margin represents the difference between gross income and the variable costs of producing cotton (Table 6). It provides an indication of the profits and costs needed to grow cotton. A gross margin analysis for cotton is performed biannually by AgEcon and CottonInfo (Table 6).

For this report, we used the gross margins information sheets for the Northern Territory (or Northern Australia rainfed, AgEcon and CottonInfo (2024d)), Queensland (Dryland cotton – single skip, Darling Downs region, AgEcon and CottonInfo (2024b)) and irrigated cotton in the Ord River, in Western Australia (Northern Australia furrow Irrigated, AgEcon and CottonInfo (2024a)). The main author confirmed with AgEcon, Principal Economist Ms Janine Powell who corroborated that "*The northern rainfed GM* [gross margins] *is largely based on Northern Territory, the irrigated GM reflects the Ord where water comes from Lake Argyle. Unfortunately, [AgEcon] don't have any additional data (given the many nuisances of growing a crop, the numbers can vary from paddock to paddock, let alone between neighbours and regions*)" (J. Powell, pers. comm - 9 October 2024 7:31 AM).

Table 6. Examples of activities and products that make the variable costs for calculating the gross margins (GM) for cotton in northern Australia.

Type of operation	**Activity**
Ground preparation	Herbicides, farming
Nutrition	Diammonium phosphate (DAP) Sulfate of potash (SOP) Urea (nitrogen)
Planting & in-crop farming	Machinery & Seed: Roundup Ready Flex® Bollgard3®
Crop insurance	Insurance premium depends on various factors
Crop protection, application & licence fee	Insecticides, Fungicides, Growth regulant, Herbicides, Licence ®, consultants, refuge crop, farming Bollgard 3® stacked RRF Licence Fee
Defoliation	Thidiazuron, Ethepon, spraying oil
Picking, cartage and ginning	Contractors, fuel, wrap, fright, fibre processing, research levy, CottonAU levy
Post-crop	Mulcher, herbicide, farming

The GM analysis shows that rainfed cotton in the Northern Territory presents higher gross income than rainfed cotton in Darling Downs in Queensland. However, the GM is lower in the Queensland region (Table 7). The variable costs in the Northern Territory are much higher than in Queensland, including high costs for fertilizers to improve poor soils and labour for picking, cartage, and ginning (Table 7). Cotton production in the Ord River Scheme is irrigated and presents the best GM in comparison to the other two rainfed production areas.

Table 7. Gross margin analysis for the 2023-24 for **rainfed** cotton in the Northern Territory (or Northern Australia Rainfed, AgEcon and CottonInfo (2024d)), Queensland (dryland cotton – single skip, Darling Downs region, AgEcon and CottonInfo (2024b)) and **irrigated** cotton in the Ord River, in Western Australia (Northern Australia furrow irrigated, AgEcon and CottonInfo (2024a)) at the farm gate. Overhead costs and labour are not included. The average weight of an Australian cotton bale is 227 kg. The data freely available from AgEcon.com presents rounded up figures.

		Unit	Rainfed		Irrigated
			NT	QLD	WA
Yield	Lint	bale/ha	4	3.6	10
	Seed price	$/bale	93	93	93
	Lint price	$/bale	594	594	594
	Discount	$/bale	-50	-25	-5
(A) Income (bales/ha x price lint)#		$/ha	2,696	2,381	6,815
Variable Costs	Ground preparation (i.e. clearing and tilling)	$/ha	n/a	n/a	67
	Fallow management	$/ha	53	59	
	Nutrition (NPK)	$/ha	358	55	975
	Planting and in-crop farming	$/ha	73	93	117
	Crop insurance	$/ha	65	99	143
	Irrigation (8.1 ml applied)	$/ha	n/a	n/a	75
	Crop protection (insecticide, herbicide), application, and license	$/ha	624	395	870
	Defoliation	$/ha	125	71	125
	Picking, cartage, and ginning	$/ha	1,036	487	2,144
	Farming post crop	$/ha	89	78	152
(B) Total variable costs		$/ha	2,423	1,337	4,668
Gross margin ($/ha) (A – B)		$/ha	**273**	**1,044**	**2,147**

Cotton Australia (2024a) reported that 8% of the cotton production was rainfed, yielding 1.34 bales/ha on average, although, the modelled values from Queensland and the Northern Territory showed an average of 4–5 bales/ha (Rhebergen & Yeates, 2023). The overall area of rainfed cotton in Australia varies from 5,000 ha to 120,000 ha, depending on the year's commodity prices, soil moisture levels and rainfall (Godfrey et al., 2023). The gross margin indicates that irrigated cotton is more rewarding in terms of profit and yield than rainfed/dryland cotton (Table 7).

The cost of greenhouse gas emissions of land clearing in savannas in the NT (following Bristow et al. 2016), is estimated at $**2,539/ha** for carbon abatement (see Section 2.3 Environmental values above), which needs to be considered as part of the GM. It is clear that once the environmental costs are accounted for ($2,539/ha), the profit ceases to exist, meaning that the Northern Territory dryland/rainfed cotton growers will have a loss of -$2,265. Considering this environmental

externality is crucial for understanding the impact of development practices, as the profit margin ($) is taken by the investor, whilst the environmental costs are fronted by society.

4. Conclusion

Dryland/rainfed cotton holds potential for agricultural diversification and economic growth in the Northern Territory; however, there are significant challenges that must be addressed before any further development. Some of these challenges are being addressed through on-going agronomic research (i.e. Northern Territory Government, CSIRO), but many are yet to be addressed at local scale. Among the key challenges are highly variable rainfall, soil limitations (such as low fertility and poor water retention), and the constant risk of extreme weather events. Effective production systems require strategic planting during the wet season, supported by sound knowledge of appropriate planting windows, row configuration, and soils with high plant-available water capacity, alongside adaptive agronomic practices such as zero-tillage, cover crops, and mulching. However, realizing these conditions at scale requires mapping of suitable soils to guide regional planning. Such targeting can help ensure that cotton production is confined to viable areas, thereby minimizing unnecessary land clearing and reducing potential biodiversity and cultural impacts.

Additional points are:

- Cotton production in Australia is exposed to climatic variability and pest pressures, which can affect yield outcomes and economic returns.
- The general assumption that cotton production practices from southeastern Australia can be applied to the Northern Territory (and northern Australia) with limited modifications needs to be thoroughly analysed to identify which lessons are applicable in the Northern Territory, which could work with alterations, and which are definitely not appropriate.
- The availability of data to analyse current cotton rainfed cotton production in the Northern Territory in relation to different variables (i.e. geographical location, variable costs, soils, rainfall, row spacing, biosecurity issues) was scant during the writing of this report. The availability of local data could offer a starting point to support the cotton industry in the Northern Territory.
- The substantial overlap between agricultural potential and biodiversity value suggests that agricultural development, based solely on production considerations, may lead to significant impacts on ecologically and socially important sites. This highlights the need for integrated land-use planning approaches that explicitly account for biodiversity conservation and for emerging mechanisms, such as carbon markets, as alternative diversification options.

- While the cotton industry is expanding in the NT, important knowledge gaps remain in areas such as crop establishment, agronomy, biosecurity, and technical capability under Top End conditions. Improving understanding of yield reliability, profitability, and whole-farm system performance will be critical for the long-term development of broadacre cropping in the Northern Territory.
- Climatic data from 1961 to 2020 across nine regions in north-eastern Australia show fewer early-season cold shocks, higher minimum overnight temperatures, increased extreme heat events (> 40°C), greater heat accumulation, and elevated evapotranspiration at some locations. The time to first flower has decreased, but trends in the length of the effective flowering period, harvestable boll period and reproductive periods were reported inconsistent. These findings partially support the hypothesis of increasing climatic impacts on crop phenology.
- As cropping systems in the Northern Territory develop, it is likely that irrigation infrastructure will be needed to support cropping activities during the dry season. Currently, rainfed cotton is sown in December and harvested in July. Under the current rainfed conditions, only one crop can be grown per year without irrigation infrastructure which is economically not sustainable. Only exception is areas where good soil and water resources could enable year-round cropping, which would require a water extraction licence for irrigation.
- Significant investments are being made to expand cotton production in the Northern Territory over the next decade, with Australian Federal funding supporting this along with increased investment for roads, ports, agricultural precincts, etc.
- There is also the increased societal expectations, to account for an industry that co-exists with the societal values of the Northern Territory and more broadly globally for marketing purposes.
- Additional validation datasets are needed to improve model accuracy to project yield in different regions. Investigations into the effects of erratic monsoonal rainfall on planting and seedling establishment, as well as strategies to mitigate waterlogging and optimize planting windows are essential. These efforts will inform industry development, guide investments, and maximize the productivity and economic viability of rainfed cotton systems in northern Australia.

5. Acknowledgements

The authors acknowledge the financial support of the Cooperative Research Centre for Developing Northern Australia (CRCNA), which is part of the Australian Government's

Cooperative Research Centre Program to support this work. The CRCNA also acknowledges the financial and in-kind support of the project participants.

6. References

Abrecht, D. G., & Bristow, K. L. (1996). Coping with soil and climatic hazards during crop establishment in the semi-arid tropics. Australian Journal of Experimental Agriculture,

ABS. (2022, 28/06/2022). *Snapshot of Northern Territory. High level summary data for Northern Territory in 2021*. Australian Bureau of Statistics (ABS). https://www.abs.gov.au/articles/snapshot-nt-2021

AgEcon, & CottonInfo. (2024a). *GM Budget: Northern Australia Furrow Irrigated Cotton* (Cotton Industry Gross Margins, Issue. https://www.cottoninfo.com.au/publications/australian-cotton-industry-gross-margin-budgets

AgEcon, & CottonInfo. (2024b). *Gross Margin Budget: Dryland Cotton*. Gross Margin Budget: Dryland Cotton

AgEcon, & CottonInfo. (2024c). *Gross Margin Budget: Furrow Irrigated Cotton*. Retrieved 26/11/2024 from chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.cottoninfo.com.au/sites/default/files/inline-files/Furrow%20Irrigated%2023-24.pdf

AgEcon, & CottonInfo. (2024d). *Gross Margin Budget: Northern Australia Raingrown Cotton* **https://www.cottoninfo.com.au/publications/australian-cotton-industry-gross-margin-budgets**

Ahn, Y.-J., Kamalov, B., & Juraev, Z. (2024). Revisiting the Aral Sea crisis: a geographical perspective. *International Journal of Environmental Studies*, 1-18. https://doi.org/10.1080/00207233.2024.2422695

Annells, A. J., & Strickland, G. R. (2001). Review of the current cotton research in the Ord. Sixth Workshop on Tropical Agricultural Entomology, Darwin 11 – 15 May 1998.

Anwar, M. R., & Darbyshire, R. (2017, 24 – 28 September 2017). Effect of climate variability on Australian dryland cotton yield. 18th Australian Society of Agronomy Conference, Ballarat, Australia.

Anwar, M. R., Wang, B., Liu, D. L., & Waters, C. (2020). Late planting has great potential to mitigate the effects of future climate change on Australian rain-fed cotton. *Science of The Total Environment*, *714*, 136806. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.136806

Ash, A., Gleeson, T., Hall, M., Higgins, A., Hopwood, G., MacLeod, N., Paini, D., Poulton, P., Prestwidge, D., Webster, T., & Wilson, P. (2017). Irrigated agricultural development in northern Australia: Value-chain challenges and opportunities. *Agricultural Systems*, *155*, 116-125. https://doi.org/https://doi.org/10.1016/j.agsy.2017.04.010

Australian Government. (2015). *Our north, our future: White paper on developing Northern Australia*. Australian Government Canberra.

Australian Government. (2024). *The biology of Gossypium hirsutum L. and Gossypium barbadense L. (cotton). Version 3.1*. D. o. H. a. A. Care.

Australian Institute of Political Science. (1956). *Northern Australia - Task for a nation*. Angus And Robertson.

Auty, J. H. (1964). Range feeding of cotton by-products in the Kimberleys. Journal of the Department of Agriculture, Western Australia, Series 4: Vol. 5: No. 8, Article 10. Available at: https://library.dpird.wa.gov.au/journal_agriculture4/vol5/iss8/10

Babacan, H., & McHugh, J. (2020). Re-thinking agricultural supply chains in Northern Australia [Journal Article]. *The Australasian Journal of Regional Studies*, *26*(3), 239-268. https://search.informit.org/doi/10.3316/informit.017453426505251

Bange, M. P., Baker, J. T., Bauer, P. J., Broughton, K. J., Constable, G. A., Luo, Q., Oosterhuis, D. M., Osanai, Y., Payton, P., & Tissue, D. T. (2016). *Climate change and cotton production in modern farming systems* (Vol. 6). CABI.

Bange, M. P., Constable, G. A., McRae, D., & Roth, G. (2010). Cotton. In C. Stokes & M. Howden (Eds.), (pp. 49-66). CSIRO Publishing.

Barnhardt Purified Cotton. (2019). *Types of cotton* https://barnhardtcotton.net/blog/types-of-cotton/

Bates, W. B., Chu, L., Claire, H., Colloff, M. J., Cotton, R., Davies, R., Larsen, L., Loughrey, G., Manero, A., Marshall, V., Martin, S., Nguyen, N.-M., Nikolakis, W., Poelina, A., Schulz, D., Taylor, K. S., Williams, J., Wyrwoll, P., & Grafton, R. Q. (2024). A tale of two rivers – Baaka and Martuwarra, Australia: Shared voices and art towards water justice. *The Anthropocene Review*, *11*(1), 228-261. https://doi.org/10.1177/20530196231186962

Beaumont, T., Pursey, A., & Booth, C. (2022). *A fork in the river: The consequences of a major new cotton industry in the Northern Territory*. https://territoryrivers.org.au/report/a-fork-in-the-river/

Beckert, S. (2017). Cotton and the global origins of capitalism. *Journal of World History*, 107-120.

Bowman, D. M. J. S. (1998). The impact of Aboriginal landscape burning on the Australian biota. *New Phytologist*, *140*(3), 385-410. https://doi.org/10.1046/j.1469-8137.1998.00289.x

Bristow, M., Hutley, L. B., Beringer, J., Livesley, S. J., Edwards, A. C., & Arndt, S. K. (2016). Quantifying the relative importance of greenhouse gas emissions from current and future savanna land use change across northern Australia. *Biogeosciences*, *13*(22), 6285-6303. https://doi.org/10.5194/bg-13-6285-2016

Carberry, P., Chapman, A., Anderson, C., & Muir, L. (1996). Conservation tillage and ley farming systems in the Australian semi-arid tropics. *Australian Journal of Experimental Agriculture*, *36*, 915-1089.

Carberry, P. S., Bruce, S. E., Walcott, J. J., & Keating, B. A. (2011). Innovation and productivity in dryland agriculture: a return-risk analysis for Australia. *The Journal of Agricultural Science*, *149*(S1), 77-89. https://doi.org/10.1017/S0021859610000973

Carvalho, J. F. d., Cavalcanti, J. J. V., Farias, F. J. C., Ramos, J. P. C., Queiroz, D. R., & Santos, R. C. d. (2019). Selection of upland cotton for the Brazilian semi-arid region under supplementary irrigation. *Crop Breeding and Applied Biotechnology*, *19*, 185-192.

Clean Energy Regulator. (2025). *Quarterly Carbon Market Report June Quarter 2024*. Clean Energy Regulator. Retrieved 27/04/2025 from https://cer.gov.au/markets/reports-and-data/quarterly-carbon-market-reports/quarterly-carbon-market-report-june-quarter-2024

Conaty, W. C., Broughton, K. J., Egan, L. M., Li, X., Li, Z., Liu, S., Llewellyn, D. J., MacMillan, C. P., Moncuquet, P., Rolland, V., Ross, B., Sargent, D., Zhu, Q.-H., Pettolino, F. A., & Stiller, W. N. (2022). Cotton Breeding in Australia: Meeting the Challenges of the 21st Century [Review]. *Frontiers in Plant Science*, *13*. https://doi.org/10.3389/fpls.2022.904131

Constable, G. (1976). Temperature effects on the early field development of cotton. *Australian Journal of Experimental Agriculture*, *16*(83), 905-910. https://doi.org/https://doi.org/10.1071/EA9760905

Constable, G. A., & Bange, M. P. (2015). The yield potential of cotton (Gossypium hirsutum L.). *Field Crops Research*, *182*, 98-106. https://doi.org/https://doi.org/10.1016/j.fcr.2015.07.017

Cook, G. (2009). Historical perspectives on land use development in northern Australia: with emphasis on the Northern Territory. *Northern Australian land and water science review*.

Costanza, R. (2024). Misconceptions about the valuation of ecosystem services. *Ecosystem Services*, *70*, 101667. https://doi.org/https://doi.org/10.1016/j.ecoser.2024.101667

Costanza, R., Cumberland, J. H., Daly, H., Goodland, R., & Norgaard, R. B. (1997). *An introduction to ecological economics*. Crc Press.

CottoInfo. (2015). *Preparing a water budget*. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.cottoninfo.com.au/sites/default/files/documents/Water%20budgeting%20fact%20sheet%20v2.pdf

Cotton Australia. (2024a). *Annual Report 2023-24* (Advancing Australian Cotton Issue. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://cottonaustralia.com.au/assets/general/Documents/CA-annual-Report-2024.pdf

Cotton Australia. (2024b). *Biotechnology and Cotton*. https://cottonaustralia.com.au/biotechnology-and-cotton

Cotton Australia. (2024c, 21 September 2024). *A major step for NT cotton as Darwin Port exports first containers* https://cottonaustralia.com.au/media-release/a-major-step-for-nt-cotton-as-darwin-port-exports-first-containers

Cotton Australia. (2024d, 19 August 2024). *Public Statement regarding ABC Four Corners report 'Water Grab'19 August 2024* https://cottonaustralia.com.au/news/public-statement-regarding-abc-four-corners-report-water-grab-19-august-2024

Cotton Australia. (2024e). *Timeline - 1972 to 2022*. Cotton Australia. Retrieved 25/11/2024 from https://cottonaustralia.com.au/timeline

Cotton Australia. (undated-a). *Chapter 3 - The History of Cotton*. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://cottonaustralia.com.au/assets/general/Education-resources/CA-resources/CEK_Chap_3_The_History_of_Cotton.pdf

Cotton Australia. (undated-b). *Katherine Cotton Gin opening marks a milestone for Northern Territory agriculture*. Cotton Australia. https://cottonaustralia.com.au/news/katherine-cotton-gin-opening-marks-a-milestone-for-northern-territory-agriculture

CRDC, & Cotton Australia. (2024). *Australian cotton sustainability update 2023*. A. C. S. F. P. P. Paddock. https://crdc.com.au/publications/australian-cotton-sustainability-update-2023

CSIRO. (2024). *Over 100 cotton varieties and counting*. CSIRO. https://www.csiro.au/en/research/plants/crops/cotton/100-varieties

Dale, A., Keith, C., Matz, J., & MacLean, B. (2020). *Securing outcomes and measuring progress: A preliminary report into agricultural development and tropical health servicing in Northern Australia*. https://crcna.com.au/resources/publications/securing-outcomesand-measuring-progress-preliminary-report-agriculturaldevelopment-and-tropical-health-servicing-northern-australia.

Daley, J. (2001). The intangible economy and Australia. *Australian journal of Management*, *26*(1_suppl), 3-19.

Davidson, B. R. (1965). *The Northern Myth: Limits to Agricultural and Pastoral Development in Tropical Australia* (2nd Edition ed.). Melbourne University Press.

Directorate of Cotton Development - Government of India. (2017). *Status Paper of Indian Cotton* C. a. F. W. Department of Agriculture. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.nfsm.gov.in/StatusPaper/Cotton2016.pdf

DITT. (2023). *Agribusiness 2030*.

DITT. (undated). *Cotton in the Northern Territory. Facts and Stats*. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://industry.nt.gov.au/__data/assets/pdf_file/0005/1062518/cotton-facts-and-stats.pdf

Echer, F. R., & Rosolem, C. A. (2015). Cotton yield and fiber quality affected by row spacing and shading at different growth stages. *European Journal of Agronomy*, *65*, 18-26. https://doi.org/https://doi.org/10.1016/j.eja.2015.01.001

Garnett, S. T., & Williamson, G. (2010). Spatial and temporal variation in precipitation at the start of the rainy season in tropical Australia. *The Rangeland Journal*, *32*(2), 215-226.

Godfrey, S., Anwar, M. R., & Nordblom, T. (2019). Financial risk profiles for dryland cotton by APSIM-Ozcot and@ Risk®. 19th Australian Agronomy Conference 2019,

Godfrey, S. S., Nordblom, T. L., Anwar, M. R., Ip, R. H. L., Luckett, D. J., Bange, M. P., & Rengel, Z. (2023). Untangling the complex mix of agronomic and economic uncertainties inherent in decisions on rainfed cotton. *Crop & Pasture Science*, *74*(12), 1223-1237. https://doi.org/10.1071/cp22145

Goodman, A. (1955). Correlation between Cloud Shade and Shedding in Cotton. *Nature*, *176*(4470), 39-39. https://doi.org/10.1038/176039a0

Greiner, R., & Johnson, A. (2000). The Northern Myth revisited. *Australian Agribusiness Perspective*, *8*.

Griffith, G., Fleming, E., Mounter, S., & Malcolm, B. (2014). Accounting for Externalities in Agriculture and Food Sector Value Chains and Systems: Chain Failure, Chain Goods and Chain Bads. In: Final Report to Meat and Livestock Australia on Project B. COM.

Grundy, P. R., Yeates, S. J., & Bell, K. L. (2020). Cotton production during the tropical monsoon season. I – The influence of variable radiation on boll loss, compensation and yield. *Field Crops Research*, *254*, 107790. https://doi.org/https://doi.org/10.1016/j.fcr.2020.107790

Harcourt, W. (2021). Rethinking life-in-common in the Australian landscape. *Environment and Planning E: Nature and Space*, *4*(4), 1330-1345. https://doi.org/10.1177/2514848621989602

Hartley, N., Shotton, P., Yeates, S., Rhebergen, T., Chauhan, Y., Huth, N., Stanford, J., Lamprecht, M., Eastick, R. J., Frahm, S., Pembleton, K., Radanielson, A., Anderson, R., Crawford, C., & Cameron, S. (2021). *Potential for broadacre cropping in the NT*. CRCNA. https://crcna.com.au/resources/publications/potential-broadacre-cropping-nt/

Hatfield, J. L., & Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, *10*, 4-10. https://doi.org/https://doi.org/10.1016/j.wace.2015.08.001

Hearn, A. B. (1994). OZCOT: A simulation model for cotton crop management [Article]. *Agricultural Systems*, *44*(3), 257-299. https://doi.org/10.1016/0308-521X(94)90223-3

Hedayati, M., Brock, P. M., Nachimuthu, G., & Schwenke, G. (2019). Farm-level strategies to reduce the life cycle greenhouse gas emissions of cotton production: An Australian perspective. *Journal of Cleaner Production*, *212*, 974-985. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.11.190

Helbling, T. (2024). *Externalities: Prices Do Not Capture All Costs*. International Monetary Fund. Retrieved 4 Decemer 2024 from https://www.imf.org/external/pubs/ft/fandd/basics/38-externalities.htm

Hennessy, K. J., Whetton, P. H., & Preston, B. (2010). Climate Projections. In C. Stokes & M. Howden (Eds.), *Adapting agriculture to climate change: Preparing Australian agriculture, foresty and fisheries for the future* (pp. 13-20). CSIRO Publishing.

Hillock, I. M. (1999). *Plantation agriculture in the Northern Territory (1878-1889)* NT University]. Darwin.

Hillock, I. M. (2005). *Rethinking colonial endeavour in relation to agricultural settlement in the Northern Territory, 1863 to 1945: a critical perspective* Charles Darwin University]. Darwin.

IPBES. (2019). *Summary for policy makers of the Global Assessment Report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* https://ipbes.net/sites/default/files/ipbes_7_10_add.1_en_1.pdf

Irving, S. (2014). Governing Nature: The Problem of Northern Australia. *Australian Historical Studies*, *45*(3), 388-406. https://doi.org/10.1080/1031461X.2014.946521

Kimura, S., & Antón, J. (2011). Risk Management in Agriculture in Australia. https://doi.org/doi:https://doi.org/10.1787/5kgj0d8bj3d1-en

Kimura, S., Antón, J., & LeThi, C. (2010). Farm level analysis of risk and risk management strategies and policies: cross country analysis. https://www.oecd-ilibrary.org/agriculture-and-food/farm-level-analysis-of-risk-and-risk-management-strategies-and-policies_5kmd6b5rl5kd-en

Legge, S., Rumpff, L., Garnett, S. T., & Woinarski, J. C. Z. (2023). Loss of terrestrial biodiversity in Australia: Magnitude, causation, and response. *Science*, *381*(6658), 622-631. https://doi.org/doi:10.1126/science.adg7870

Lindenmayer, D. B., & Possingham, H. P. (2013). No Excuse for Habitat Destruction. *Science*, *340*(6133), 680-680. https://doi.org/doi:10.1126/science.340.6133.680-a

Lindenmayer, D. B., Steffen, W., Burbidge, A. A., Hughes, L., Kitching, R. L., Musgrave, W., Stafford Smith, M., & Werner, P. A. (2010). Conservation strategies in response to rapid climate change: Australia as a case study. *Biological Conservation*, *143*(7), 1587-1593. https://doi.org/http://dx.doi.org/10.1016/j.biocon.2010.04.014

Ling, T. (2011). *Commonwealth government records about the Northern Territory. Research guide (National Archives of Australia)*. N. A. o. Australia.

Liu, S. M., Constable, G. A., Reid, P. E., Stiller, W. N., & Cullis, B. R. (2013). The interaction between breeding and crop management in improved cotton yield. *Field Crops Research*, *148*, 49-60. https://doi.org/https://doi.org/10.1016/j.fcr.2013.04.006

Loka, D. A., Oosterhuis, D. M., & Ritchie, G. L. (2011). Water-deficit stress in cotton. *Stress physiology in cotton*, *7*, 37-72.

Macdonald, B. C. T., Latimer, J. O., Schwenke, G. D., Nachimuthu, G., & Baird, J. C. (2018). The current status of nitrogen fertiliser use efficiency and future research directions for the Australian cotton industry. *Journal of Cotton Research*, *1*(1), 15. https://doi.org/10.1186/s42397-018-0015-9

Macháč, J., Trantinová, M., & Zaňková, L. (2021). Externalities in agriculture: How to include their monetary value in decision-making? *International Journal of Environmental Science and Technology*, *18*(1), 3-20. https://doi.org/10.1007/s13762-020-02752-7

Morán-Ordóñez, A., Whitehead, A. L., Luck, G. W., Cook, G. D., Maggini, R., Fitzsimons, J. A., & Wintle, B. A. (2017). Analysis of Trade-Offs Between Biodiversity, Carbon Farming and Agricultural Development in Northern Australia Reveals the Benefits of Strategic Planning. *Conservation Letters*, *10*(1), 94-104. https://doi.org/https://doi.org/10.1111/conl.12255

NT Farmers. (2022). Cotton in the NT – Factsheet. https://ntfarmers.org.au/cotton-in-the-nt-factsheet/

NTG. (2026). Cotton production in the NT. https://nt.gov.au/industry/agriculture/food-crops-plants-and-quarantine/cotton

NTG. (2020). *Modern Cotton. A cornerstone to the Northern Territory's agricultural sector*. Department of Primary Industry and Resources. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://industry.nt.gov.au/__data/assets/pdf_file/0012/899175/modern-cotton-dtbi.pdf

OECD/FAO. (2024). OECD-FAO Agricultural Outlook 2024-2033. In *Agricultural Outlook 2024-2033* (pp. 212-222). Food and Agriculture Organization (FAO),.

Pascoe-Bell, A., Green, C., Lynch, B., Hill, J., Tickell, S. J. D., Cameron, A., & SMith, S. D. (2014). *Potential Land for Long-term Sustainable Food Production* (Soil and Water Suitability Assessment, Issue. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://frackinginquiry.nt.gov.au/__data/assets/pdf_file/0008/456164/Attachment-P4-Potential-Land-Longterm-food-production.pdf

Pearson, D. M., & Gorman, J. T. (2010). Managing the landscapes of the Australian Northern Territory for sustainability: Visions, issues and strategies for successful planning. *Futures*, *42*(7), 711-722. https://doi.org/https://doi.org/10.1016/j.futures.2010.04.008

Pines, L. (2024). *Cotton: Essential guide to this staple commodity. How is cotton grown, Why is it valuable, and what drives the price of cotton?* Commodity.com. https://commodity.com/soft-agricultural/cotton/

Pocock, C., Collett, D., & Baulch, L. (2015). Assessing stories before sites: Identifying the tangible from the intangible. *International Journal of Heritage Studies*, *21*(10), 962-982.

PricewaterhouseCoopers. (2019). *NT Farmers Association. Business case for the construction of a cotton gin in the Northern Territory*.

Queensland Cotton. (2024). *100 Years*. Queensland Cotton. Retrieved 25/11/2024 from https://qcotton.com.au/100-years/

Rathnayake, C., Malcolm, B., Griffith, G., Sinnett, A., & Deane, P. (2023). Using nitrogen fertilizer to grow irrigated cotton in Australia: Marginal benefits and costs of nitrogen and nitrous oxide emissions [Journal Article]. *Australian Farm Business Management Journal*, *20*, 55-79. https://search.informit.org/doi/10.3316/informit.459608148272203

Raza, S. M., Aslam, M., & Vazhayil, A. M. (2023). A Tail-End Tale: the story of the Indus Delta. In K. M. Wantzen (Ed.), *River Culture: Life as a dance to the rhythm of the waters* (pp. 213-240). UNESCO. https://doi.org/https://doi.org/10.54677/HHMI3947

Rhebergen, T., & Yeates, S. J. (2023). Climate and soil-based constraints to rainfed cotton yield in the Northern Territory, Australia – A modelling approach using APSIM-OZCOT. *European Journal of Agronomy*, *151*, 126998. https://doi.org/https://doi.org/10.1016/j.eja.2023.126998

Rohr, S., Mounter, S., Fleming, E., & Griffith, G. (2020). A Diagrammatic Framework for Accounting for Externalities in Agriculture and Food Sector Value Chains. *Australasian Agribusiness Review*, *28*(5), 106-121.

Russell-Smith, J., Sangha, K. K., Costanza, R., Kubiszewski, I., & Edwards, A. (2018). Towards a sustainable, diversified land sector economy for North Australia. In *Sustainable land sector development in Northern Australia* (pp. 85-132). CRC Press.

Sangha, K. K., Ahammad, R., Russell-Smith, J., & Costanza, R. (2024). Payments for Ecosystem Services opportunities for emerging Nature-based Solutions: Integrating Indigenous perspectives from Australia. *Ecosystem Services*, *66*, 101600. https://doi.org/https://doi.org/10.1016/j.ecoser.2024.101600

Shikha, A., Dimri, A. P., Singh, K. K., Maharana, P., & Mina, U. (2022). Risk assessment and adaptation strategies for irrigated and rainfed cotton crop production under climate change. *Journal of Earth System Science*, *131*(4), 267. https://doi.org/10.1007/s12040-022-01995-x

Smith, L., & Campbell, G. (2017). The Tautology of "Intangible Values" and the Misrecognition of Intangible Cultural Heritage. *Heritage & Society*, *10*(1), 26-44. https://doi.org/10.1080/2159032X.2017.1423225

Splitstoser, J. C., Dillehay, T. D., Wouters, J., & Claro, A. (2016). Early pre-Hispanic use of indigo blue in Peru. *Science Advances*, *2*(9), e1501623.

Squires, V., & Tow, P. G. (1991). *Dryland Farming: a Systems Approach (An Analysis of Dryland Agriculture in Australia)*. Sydney University Press.

Stokeld, D., Fisher, A., Gentles, T., Hill, B. M., Woinarski, J. C. Z., Young, S., & Gillespie, G. R. (2018). Rapid increase of Australian tropical savanna reptile abundance following exclusion of feral cats. *Biological Conservation*, *225*, 213-221. https://doi.org/https://doi.org/10.1016/j.biocon.2018.06.025

Togni, S. (2023). *Centrefarm Co-mapping Country and Two-way Governance with Traditional Owners 2023. Developmental Evaluation Final Report*. https://northernhub.au/centrefarm-co-mapping-two-way-knowledge-exchange/

Turner, W. R., Brandon, K., Brooks, T. M., Costanza, R., da Fonseca, G. A. B., & Portela, R. (2007). Global Conservation of Biodiversity and Ecosystem Services. *BioScience*, *57*(10), 868-873. https://doi.org/10.1641/b571009

Viot, C. R., & Wendel, J. F. (2023). Evolution of the Cotton Genus, Gossypium, and Its Domestication in the Americas. *Critical Reviews in Plant Sciences*, *42*(1), 1-33. https://doi.org/10.1080/07352689.2022.2156061

Voora, V., Bermudez, S., Joy Farrell, J., Larrea, C., & Luna, E. (2023). *Global Market Report. Cotton prices and sustainability* (Sustainable commodities marketplace series, Issue.

Welsh, J. M., Taschetto, A. S., & Quinn, J. P. (2022). Climate and agricultural risk: Assessing the impacts of major climate drivers on Australian cotton production. *European Journal of Agronomy*, *140*, 126604. https://doi.org/https://doi.org/10.1016/j.eja.2022.126604

Wendel, J. F., Brubaker, C., Alvarez, I., Cronn, R., & Stewart, J. M. (2009). Evolution and Natural History of the Cotton Genus. In A. H. Paterson (Ed.), *Genetics and genomics of cotton* (pp. 3-22). Springer US. https://doi.org/10.1007/978-0-387-70810-2_1

Wendel, J. F., Brubaker, C. L., & Seelanan, T. (2010). The origin and evolution of Gossypium. In *Physiology of cotton* (pp. 1-18). Springer.

Williams, R. (2024, 21 December 2024). *Science Show Summer - A wire around the world*. https://www.abc.net.au/listen/programs/scienceshow/a-wire-around-the-world/104462844

Williams, R. J., Duff, G. A., Bowman, D. M. J. S., & Cook, G. D. (1996). Variation in the Composition and Structure of Tropical Savannas as a Function of Rainfall and Soil Texture Along a Large-Scale Climatic Gradient in the Northern Territory, Australia. *Journal of Biogeography*, *23*(6), 747-756. http://www.jstor.org/stable/2846001

Wilson, P., Ringrose-Voase, A., Jacquier, D., Gregory, L., Webb, M., Wong, M., Powell, B., Brough, D., Hill, J., & Lynch, B. (2009). Land and soil resources in northern Australia. *Northern Australia Land and Water Science Review. Report coordinated by CSIRO to The Northern Australia Land and Water Taskforce, Canberra, ACT*.

Woinarski, J., & Dawson, F. (2017). Limitless lands and limited knowledge: Coping with uncertainty and ignorance in northern Australia. In *Ecology, Uncertainty and Policy: Managing Ecosystems for Sustainability* (pp. 83-115). https://doi.org/10.4324/9781315847832-5

Woinarski, J. C. Z., Andersen, A. N., & Murphy, B. P. (2020). The Tropical Savannas of Northern Australia. In M. I. Goldstein & D. A. DellaSala (Eds.), *Encyclopedia of the World's Biomes* (pp. 827-834). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-409548-9.12023-8

Wrona, A. F., Oosterhuis, D. M., & McMichael, B. (1999). Getting to the root of your crop's health. . *Cotton Physiology*. https://www.cotton.org/tech/physiology/cpt/plantphysiology/upload/CPT-v10No1-99-REPOP.pdf

WWF. (2024). *Living Planet Report 2024 - A system in peril*. WWF. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://assets.wwf.org.au/image/upload/f_pdf/LPR.9.30.24_Full_Report_Embargo10Oct_REDUCED?_a=ATO2Bcc0

Yeates, S., Moulden, J., Plunkett, G., & Strickland, G. (2006). Assessing the feasibility of GM cotton in the Ord River Irrigation Area: tillage systems for late wet season sowing.

Yeates, S. J. (2001). *Cotton research and development issues in northern Australia. A review and scoping study*. CSIRO.

Yeates, S. J., & Poulton, P. L. (2019). Preliminary Determination of Dryland Cotton Yield Potential in the NT.

Yeates, S. J., Strickland, G. R., & Grundy, P. R. (2013). Can sustainable cotton production systems be developed for tropical northern Australia? *Crop and Pasture Science*, *64*(12), 1127-1140. https://doi.org/https://doi.org/10.1071/CP13220