Impact of climate change on flowering induction in mangoes in the Northern Territory

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Executive summary

Mangoes are a commercially important crop in the Northern Territory, which produces around half of the national mango crop.

Mango flowering leads to fruit development and determines the timing of fruit harvest. Cool temperatures are the essential climatic factor which determines the fate of growing buds in mango in the Northern Territory. Flowering is promoted by low nighttime (minimum) temperatures and can be inhibited by high day time (maximum) temperatures. Changes in maximum and minimum temperatures and the frequency of their occurrence above/below required temperature thresholds will affect flowering and fruit production in northern Australian mango production regions.

Impact assessment scope

This assessment combines projections of future climate with what we know about the response of mango flowering to particular temperature thresholds to provide an important insight into Northern Territory mango production into the future.

This assessment considers minimum and maximum temperature thresholds for six mango cultivars – Kensington Pride, Calypso®, Honey Gold and cultivars 1201, 1243 and 4069 from the National Mango Breeding Program (NMBP) – across 11 production areas in the Northern Territory as well as Kununurra in Western Australia. The production areas have been grouped into four growing regions: Darwin, comprising the Batchelor, Berry Springs, Bynoe, Tipperary, Greater Darwin, Noonamah and Marrakai production areas; Katherine, comprising the Katherine, Mataranka and Pine Creek production areas; Central Australia (Ali Curung production area) and Kununurra.

Climate projections focused on two future greenhouse gas emissions scenarios: a lower emissions scenario (RCP4.5) and a high emissions scenario (RCP8.5). Four 30-year time periods are considered. For convenience, they are referred to by their central year: 2030 (2016–2045) is relevant to the current planting; 2050 (2036–2065) is relevant for the next planting; and 2070 (2056–2085) and 2090 (2075–2104) are both relevant to breeding programs. Projections are relative to a historical climate baseline period (1981–2010).

Changing climate and mango flower induction in the Northern Territory

All regions show a decreasing trend over time in the number of days per month below 18°C and 20°C, and an increasing trend in the number of days per month above 32°C and 35°C.

This will lead to a decline in inductive conditions; however, the rate of decline is not uniform across all regions. Regions closer to the coast are more vulnerable than regions further south. As a result, the Darwin region is the most vulnerable to a changing climate.

Calypso®, NMBP 1201 and Kensington Pride are less vulnerable to a changing climate than NMBP 1243, 4069 and Honey Gold; however, by the end of the century all cultivars will be vulnerable in a high emissions scenario.

In the near term (2016–2045), all cultivars assessed in this study become vulnerable to the impacts of the declining number of inductive days between May and August, with the exception of Calypso® and Kensington Pride. The Darwin growing region will be more vulnerable than Katherine and Kununurra. The number of inductive days in Central Australia may begin to increase.

Towards the middle of the century (2036–2065), production in Katherine and Kununurra becomes more vulnerable but not to the degree of vulnerability in Darwin. All cultivars experience a substantial decline in inductive days while the indirect effects of warmer conditions on pollen viability, fruit set and fruit growth are likely.

Late in the century (2056–2085), mango production is likely to be drastically impacted, with the maximum number of inductive days reduced to ~40% in some areas under the high emissions scenario. Under the lower emissions scenario, Calypso® and Kensington Pride may experience enough inductive days to flower but only in the Kununurra region.

At the end of the century (2075–2104), the cultivars assessed are all severely limited by extreme reductions in inductive days. Only under the lower emissions scenario will conditions allow for some flowering in Calypso® and Kensington Pride in the Kununurra and Katherine regions.

Implications for climate change adaptation planning

The ongoing sustainability of the mango industry in the Northern Territory will require on-farm adaptation actions from growers, including canopy management, transition to new cultivars, orchard relocation and orchard cooling practices. Attention will also need to be given to the health and safety of farm workers as extreme heat becomes more prevalent.

Grower actions need to be supported by an industry response that may include education and extension, commercialisation of new cultivars, market development for resilient cultivars, and management of changes in fruit supply to market.

Grower and industry activity will need to be supported by policies and regulations at all levels of government that are considerate of short-term transformational change, while also accounting for the incremental change required to address longer term climate challenges.

Policy and practice will both be well served by ongoing research to better understand climate-resilient genotypes, the climatic limits of artificial chemical flower induction, protective cropping, mango genetic adaptation and development in a changing climate, harvest timing and new production sites.

Broader applications

The methodology used to conduct this impact assessment can be applied to mango industries across Australia and the rest of the world. Similarly, the process can be applied to other commodities for industries seeking to understand the potential impacts of a changing climate.

1. Introduction

Mangoes are a commercially important crop in the Northern Territory, which produces around half of the national mango crop (Hort Innovation 2020).

Mango flowering leads to fruit development and determines the timing of fruit harvest. Cool temperatures are the essential climatic factor which determines the fate of growing buds in mango in the Northern Territory. Flowering is promoted by low nighttime (minimum) temperatures and can be inhibited by high day time (maximum) temperatures. Changes in maximum and minimum temperatures and the frequency of their occurrence affects flowering and fruit production in northern Australian mango production regions.

This assessment combines projections of future climate with what we know about the response of mango flowering to particular temperature thresholds to provide an important insight into Northern Territory mango production into the future.

1.1 About this impact assessment

This assessment was carried out by the Earth Systems and Climate Change (ESCC) Hub of the Australian Government's National Environmental Science Program in partnership with the Northern Territory Department of Primary Industry and Resources (NT DPIR). This activity was supported by industry stakeholders through the Australian Mango Industry Association (AMIA) and Northern Territory Farmers Association (NTFA).

The primary aim of this assessment is to provide the Northern Territory mango industry with relevant information about the potential impact of climate change on flower induction.

Additionally, this work aims to show the potential for climate change information to help the mango industry and other primary producers better understand the impact of the changing climate on their production systems and businesses.

1.2 Scope

1.2.1 Cultivars

The assessment considers six mango cultivars: Kensington Pride, Calypso®, Honey Gold and three cultivars from the National Mango Breeding Program (NMBP), a partnership between the Northern Territory, Western Australia, Queensland and Commonwealth Scientific and Industrial Research Organisation (CSIRO) to develop hybrid mangoes by crossing the already successful cultivar, Kensington Pride, with exotic cultivars.

Kensington Pride, Calypso® and Honey Gold were selected because of their commercial significance, comprising 41%, 24% and 8% of national production in 2018/19, respectively (Hort Innovation 2020). The cultivar R2E2 is also commercially significant, comprising 18% of national production in 2018/19, but was not included as it is not widely grown in the Northern Territory.

The NMBP cultivars – NMBP 1201, NMBP 1243 and NMBP 4069 – were selected because there is significant commercial interest in the adoption of these cultivars by industry.

Temperature thresholds for these six cultivars were determined in a study carried out by Clonan et al. (2020).

1.2.2 Growing regions

Eleven production areas in the Northern Territory were considered, along with Kununurra in Western Australia. For the purposes of the assessment, they are grouped into four growing regions for analysis (Table 1.1).

Table 1.1 Production areas considered in this assessment grouped by growing region (used for analysis of impacts).

Growing region	Production areas
Darwin	Batchelor, Berry Springs, Bynoe, Tipperary, Greater Darwin, Noonamah, Marrakai
Katherine	Mataranka, Katherine, Pine Creek
Ali Curung	Ali Curung
Kununurra	Kununurra

1.2.3 Climate change information

The impact assessment looks at the projected number of days per month that are under minimum threshold temperatures (18°C, 20°C) and over maximum threshold temperatures (32°C, 35°C) for May, June, July, and August – the months when flower initiation currently occurs (Clonan et al. 2020).

Projections consider two future scenarios: a moderate emissions scenario (RCP4.5) and a high emissions scenario (RCP8.5), as used in the most recent Intergovernmental Panel on Climate Change Assessment Report (AR5) (IPCC 2013).

Four 30-year time periods are considered. For convenience, they are referred to by their central year: 2030 (2016–2045) is relevant to the current planting; 2050 (2036–2065) is relevant for the next planting; and 2070 (2056–2085) and 2090 (2075–2104) are both relevant to breeding programs. Projections are calculated relative to a historical climate baseline period (1981–2010).

1.3 Process

This assessment has been guided by a five-step climate change health check process developed by the ESCC Hub to facilitate the incorporation of climate change information into sectoral decision making. The process is summarised in Figure 1.1.

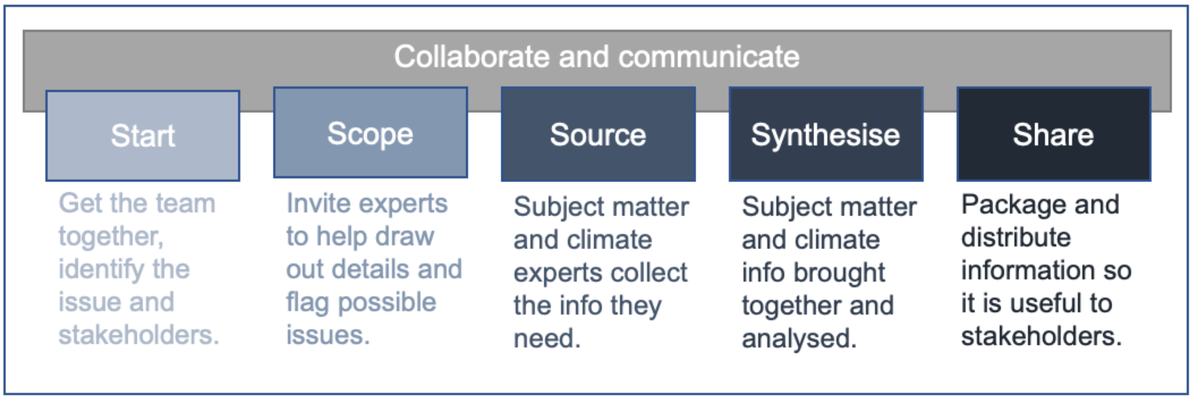


Figure 1.1 The five-step climate change health check process. Collaboration and communication occur throughout.

1.3.1 Start

An enquiry to CSIRO for climate temperature thresholds by NT DPIR identified the opportunity for an assessment of the impact of climate change on mango production in the Northern Territory by the ESCC Hub. A project team was convened comprising horticulture experts from NT DPIR, climate experts from CSIRO and the Bureau of Meteorology (through the ESCC Hub) and knowledge brokering and communication specialists from the ESCC Hub. Preliminary discussions among the project team identified the possibility of focusing on mango flowering for the assessment. The team also organised an expert meeting for the next phase of the engagement and drafted a communication and engagement plan to guide the project.

1.3.2 Scope

The expert meeting was held in Darwin in February 2019 to learn more about the Northern Territory mango industry, how the changing climate might impact it, and how climate change projections could be used to support industry resilience and sustainability into the future. In addition to the project team, the meeting was attended by NT DPIR research, policy and extension staff, representatives from the AMIA and NTFA, and a number of growers.

Following this meeting, the project team agreed that resources were available to conduct a case study examining the impact of climate change on the induction of mango flowering. The draft communication and engagement plan was updated following learnings and suggestions from this meeting.

1.3.3 Source

With the assessment clearly scoped, the mango and climate specialists each undertook the required data collection and generation. While these specialist teams worked independently, they remained in close contact to ensure that the data being collected and generated was appropriate for the assessment.

1.3.4 Synthesise

Synthesis began with a face-to-face meeting of the project team to discuss results and their implications, as well as their presentation and communication, referring back to the communication and engagement plan developed in the first phase of the project and updated in the scoping phase.

1.3.5 Share

This report is the key communication product arising from the assessment. Additional products will be developed in line with the communication and engagement plan to ensure that growers, industry representatives and policy makers are informed of the results.

2. Mango production and flowering

Mangoes are grown in southern, central and northern Western Australia, northern areas of the Northern Territory, along the coast of Queensland and northern New South Wales (Figure 2.1). However, more than 90% of the national mango crop is produced in the Northern Territory and Queensland (Hort Innovation 2020). There are key differences in the seasonality, temperature and rainfall across each production region.

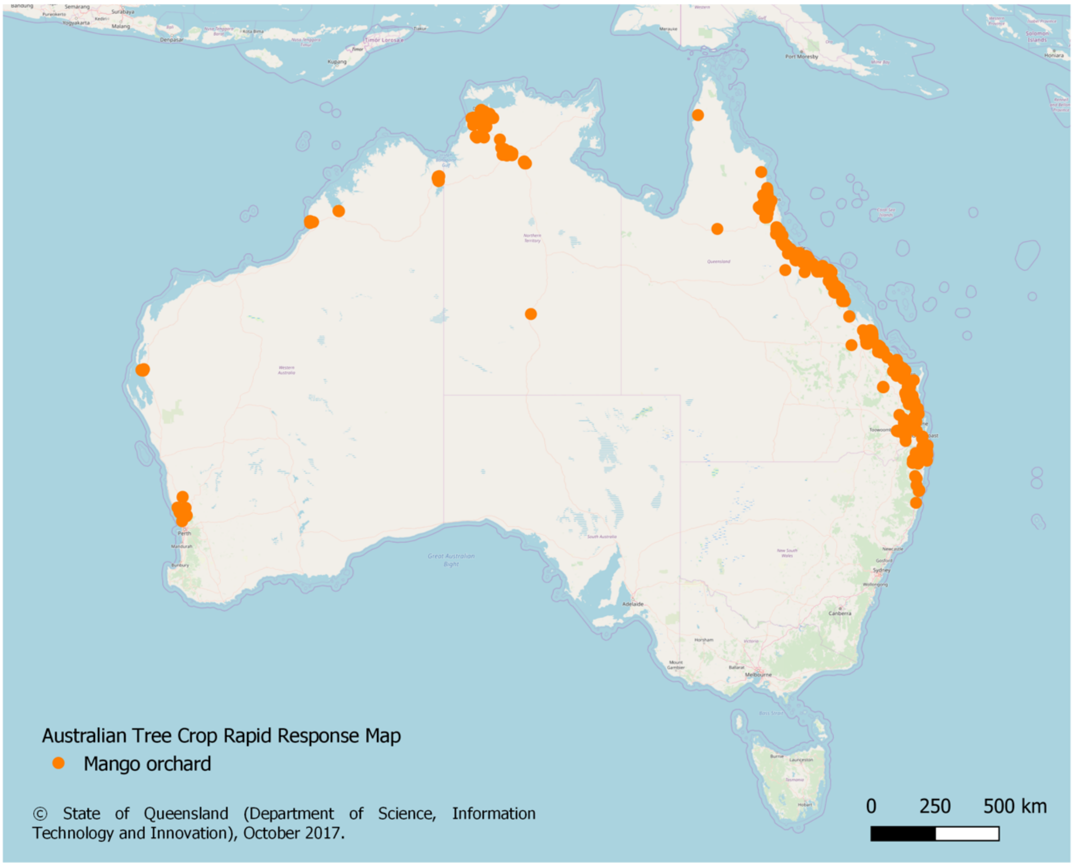


Figure 2.1 Location of mango orchards in Australia (Source: State of Queensland 2017).

2.1 Mango production in the Northern Territory

2.1.1 The industry

In 2018/19 almost half of the national mango crop, which was worth A$199 million, was produced in the Northern Territory (Hort Innovation 2020).

The industry is based around four varieties: Kensington Pride, R2E2, Calypso® and Honey Gold. Other varieties – including Keitt, Tommy Atkins, Palmer, Nam Dok Mai – are grown in much smaller quantities (NESP ESCC Hub 2019a). Around 60% of the Northern Territory's mango-growing enterprises are in the Darwin area (Table 2.1).

Table 2.1 2017/18 mango production summary statistics (ABS 2019)

	National	NT	Darwin
Number of trees	1,423,535	558,298	365,501
Number of businesses	447	92	55

1.1.2 Production cycle

The peak season for mango harvesting in the Northern Territory is from October to December; however, some fruit grown using chemical treatments is available from July.

The distinct dry and wet seasons in the Northern Territory play a strong role in dictating the mango production cycle. The arrival of cold and dry conditions at the end of a warm wet season is a strong trigger for mango flowering. Following this, mild and dry conditions are conducive of fruit development. After harvest, trees are pruned and then undergo a period of vegetative growth during the warm, wet season from December to April. As temperatures begin to drop at the end of the wet season, new vegetative growth matures (becomes hard and green) before flower induction can occur (Figure 2.2).

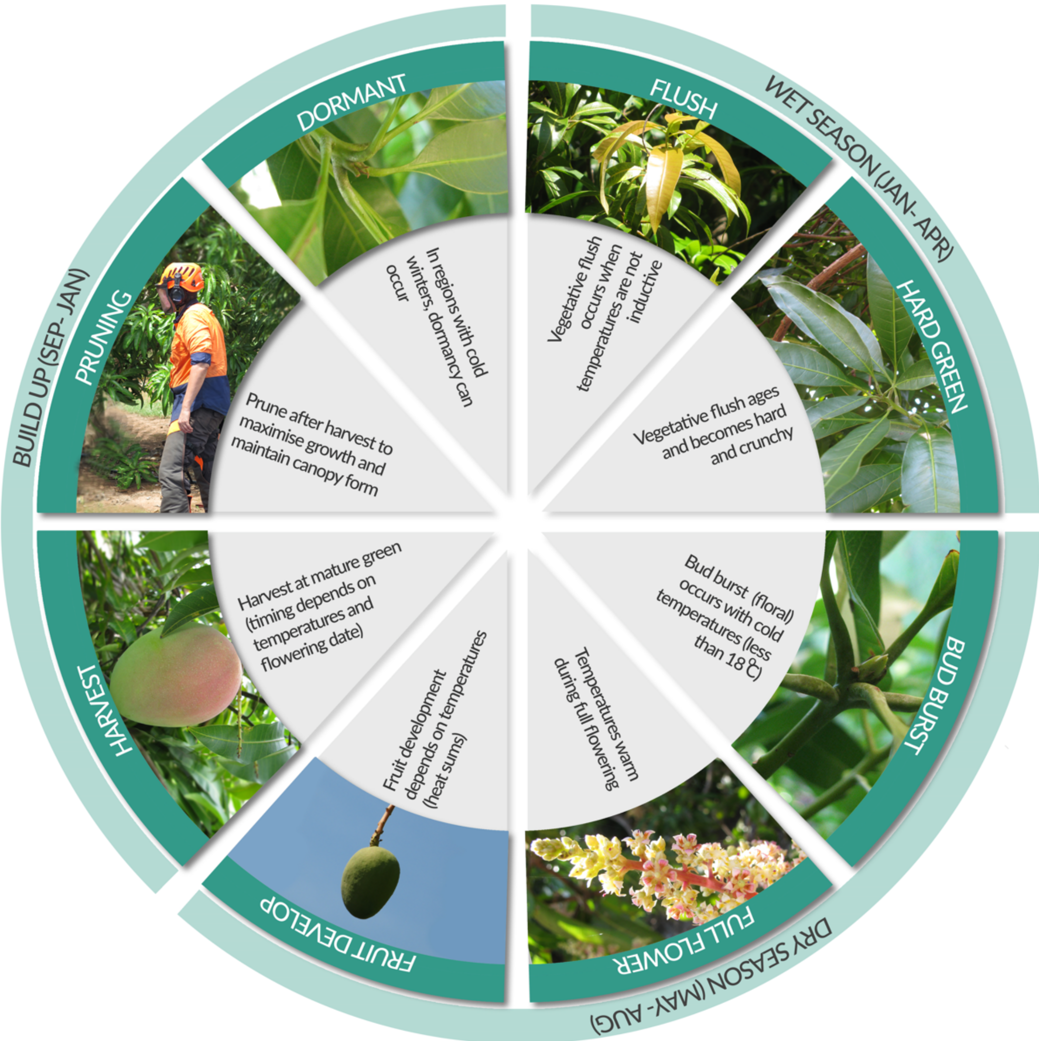


Figure 2.2 Mango production cycle in the Northern Territory (Source: NT DPIR).

Mango flowering in the Northern Territory is the earliest yearly flowering event of all mango production regions in Australia. This process leads to fruit development and determines the timing of fruit harvest. Therefore, mangoes from the Darwin region are the earliest fruit to reach the Australian market. The mechanism that triggers flowering in the Northern Territory is the onset of cooler dry season temperatures. This occurs from April onwards and flowering can occur anytime between April and August, depending upon the region, cultivar and annual weather variability. An understanding of the drivers and components that contribute to flowering in mango is critical to measuring its vulnerability to climate change.

The arrival of cold temperatures in other production regions is associated with winter and is often accompanied by winter rain. Regions south of Katherine in the Northern Territory fall into the semi-arid or desert climate zones (Beck et al. 2018). These may experience temperatures below 12°C during winter, which can be detrimental to floral induction and development. Similarly, rainfall during flower and fruit development can increase the incidence of disease. In other regions, mangoes experience a longer period of dormancy, up to five months, where no growth occurs. This delays flowering until the beginning of spring when conditions become more favourable for growth.

2.2 Flower induction

Successful flower induction in mango is essential for fruit production. It has long been known that the induction process is driven by cool temperatures that stimulate leaves to produce a signal that is transmitted to the shoot apex, resulting in flower production. (Reece et al. 1946, 1949).

Over the past two decades the molecular basis of this process has been described in controlled conditions using rapidly growing herbaceous laboratory plants (Wigge et al. 2005). Homologous molecular products have been described in mango (Geetha et al. 2016; Luo et al. 2019). The magnitude and duration of cool requirement to trigger flowering of different mango cultivars suggested by Kulkarni (1991) is not understood (Lou et al. 2019). It was anticipated that epigenetic effects, heritable changes in gene expression that do not involve changes to the DNA could control the different responses to inductive conditions in other plant species (Ahmed et al. 2010). The ability of epigenetic effects to moderate the cool temperature requirement of different herbaceous laboratory plants has been described (Zengxuan et al. 2020; Guo et al. 2020). The application of these advances to commercial mango production is some way off.

Agronomic understanding of flowering can be summarised in the schematic diagram first proposed by Davenport (1997). Davenport (2007) described the mechanism of flower induction within the mango production system (Figure 2.3). Flower induction occurs in buds that have been initiated for growth either in the presence of a floral promoter or exposed shortly after. All of the factors that occur, leading to the production of a floral promoter, are not completely understood. However, recent studies have confirmed a close relationship with temperature, as suggested throughout past research, as well as cultivar specific restriction of leaf age.

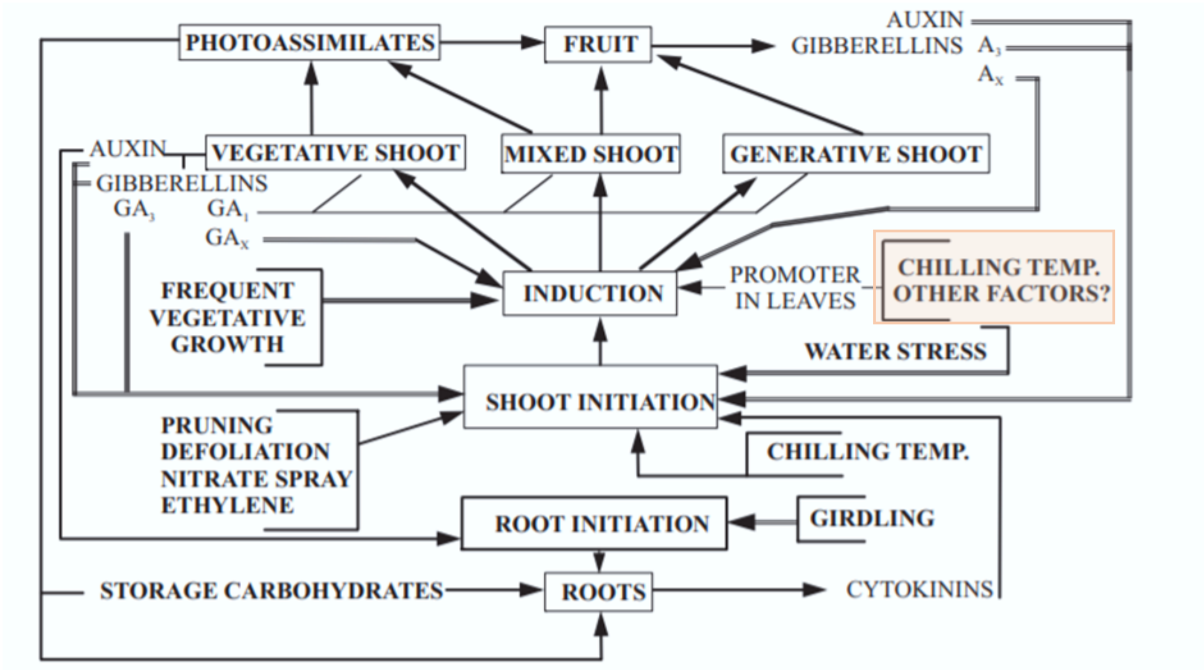


Figure 2.3 Mango flowering model adapted from Davenport (2007)

2.3 Factors affecting mango flower induction

Although there are several factors that indirectly influence the mechanism of flowering in mango, the key climatic variable linked to flower induction is temperature. The relationship between flower induction and temperature is complex and is intertwined with the physiological stage of development and epigenetic factors described in Section 2.2. For this reason, it is important to consider cultivars of mango separately. Furthermore, temperature may also affect fruit set by determining the morphology of flowers, sex ratio, pollen viability and fruit retention (Sukhvibul et al. 1999b).

2.3.1 Environmental factors

2.3.1.1 Temperature

Exposure to low daily minimum and maximum temperatures is required for initiated buds to achieve floral induction. Given that mango is adapted to tropical and sub-tropical conditions, floral induction is also limited by low temperatures. Many studies have attempted to identify the upper and lower temperature boundaries for inductive conditions, and some have found variation between cultivars (Section 2.3.3). In a recent review of the literature, Luo et al. (2019) found that most studies had shown floral induction to occur with a day/night temperature regime of between 15–19°C day and 10–15°C nighttime temperatures. However, there are mango production regions where flowering occurs outside of these temperature ranges. In these regions, it is believed that floral induction is regulated by the age of the previous flush rather than temperature. However, a recent study of mango flowering in northern Australia found that floral induction was related to relatively cool temperatures that occur after the transition from monsoonal wet summer to dry cooler winter (Clonan et al. 2020). In this study, floral induction coincided with lower daily maximum temperatures (28–32°C) that occurred when minimum night temperatures were <20°C.

These results were similar to Sukhvibul (1999b) who found that flowers induced in a day/night regime of 30/20°C produced the highest viability of pollen and best floral morphology for fertilisation. Lastly, if temperatures are too low for shoot initiation, flowering cannot occur. A day/night regime of 15/5°C was found to inhibit the development of inflorescences while other studies found that minimum temperatures up to 15°C limited flower development and fertilisation.

As previously mentioned, there is not a consensus among the literature as to what the upper temperature limit is to flowering. Batten and McConchie (1995) found that a temperature regime of 27/20°C prevented inflorescence growth in potted plants of mango cultivar Irwin. However, they noted that Irwin regularly flowers in Darwin orchards in mean daily 30.4/19.2°C temperature regimes. Clonan et al. (2020) found that maximum daily temperature had a stronger positive correlation with floral response, than minimum daily temperature in five mango varieties grown in the Northern Territory. They also found that maximum temperature thresholds for flowering ranged from 28–39°C depending upon the variety. Although temperature plays a critical role in mango flower induction, the exact conditions required for induction vary significantly across cultivars, management practices and production regions.

2.3.1.2 Exposure time

The duration of exposure to inductive temperature conditions required to induce flowering in mango can vary depending upon the rate of meristematic activity (growth of undifferentiated cells). If the rate is slow, floral induction will take longer compared to when the rate of activity is rapid (Reece et al. 1949). In mango, meristematic activity is slow in cold and dry conditions. In the Northern Territory, irrigation is used during the dry season to encourage growth activity in inactive buds. Winter conditions in southern Australia or at high latitudes are too cold for mango growth, and even if temperatures are inductive, floral induction may be limited or not occur at all. In northern Australia, winter temperatures are warm enough for growth and with irrigation, floral induction can occur rapidly in the brief periods of cooler weather in the dry season (Batten and McConchie 1995). The response of the rate of meristematic activity to temperature varies with cultivar. Whiley et al. (1991) demonstrate this in a comparison of vegetative and floral growth between mango cultivars of tropical and sub-tropical origin. Cultivars of tropical origin showed greater sensitivity to low temperatures in the speed of flush development. At lower temperatures, sub-tropical cultivars could maintain flush development when tropical cultivars ceased growth. These thresholds for vegetative growth impact floral induction because shoot initiation is required for induction to occur. Tropically adapted cultivars may have the potential to be induced at lower temperatures, but without reaching a threshold for shoot initiation, cannot commence meristematic activity. Reported exposure periods range from 4 to 30 days (Whiley et al. 1991).

2.3.2 Physiological factors

2.3.2.1 Leaf age

Studies suggest that the presence of immature or young vegetative shoots can inhibit floral induction (Davenport 2009). The time taken for shoots to reach maturity varies vastly throughout studies and is likely influenced by genetic and environmental factors. There is a general consensus that in tropical mango production, four to five months is required for shoots to become receptive to induction, depending upon the cultivar. Davenport (2007) states this is due to the presence of an age-dependent vegetative promoter, which is thought to gradually decrease as stems age from the soft stage of development to hard green. Recent studies conducted in the Katherine production region of the Northern Territory found that some cultivars could commence inflorescence development between 1.5 and three months after commencing development of the previous vegetative shoot (Clonan et al. 2020). This is supported by previous investigations by Scholefield et al. (1986) in the Northern Territory that described that vegetative flush that was between two and eight months old flowered at the first occurrence of cool temperatures.

2.3.3 Genetic factors

Understanding the impact of environmental variables of the physiology of mango is vital to maximising production. Whiley and Schaffer (1997) speculated that physiological responses of mango to environmental variables (such as temperature) can be related to the evolutionary centre of origin of a specific cultivar which can be classified into one of two ecotypes. One ecotype (mono-embryonic) evolved in the dry, subtropical, monsoon regions of the Indian subcontinent where very hot summers are tempered by cool winters, and the other (poly-embryonic) in the consistently hot, humid tropics of south-east Asia. However, many commercial cultivars are a product of breeding programs that have combined cultivars of different evolutionary backgrounds. Therefore, the cultivar specific relationship with temperature must be studied for each new cultivar.

2.4 Flowering in the Northern Territory

Kensington Pride, Calypso®, Honey Gold and three cultivars from the National Mango Breeding Program were included in a recent study by the NT DPIR, which identified temperature thresholds to mango flowering (Clonan et al. 2020). In this study, Calypso® and Honey Gold were assessed on commercial orchards in the Katherine region and the remaining cultivars on a research farm. Management practices to induce flowering may have differed on each site. The results suggest some cultivars are more vulnerable to high temperatures when flowering than others. However, for the purposes of this study, the thresholds are generalised to account for the variability that may occur in other production regions. The cultivars assessed required minimum temperatures below 18°C to flower, with the exception of Calypso® and Kensington Pride which have a slightly higher minimum temperature thresholds (Table 2.2). Some cultivars could flower at higher maximum temperatures; however, ideal flowering conditions for all cultivars is a day/night regime of temperatures <32°C/<18°C.

In these trials, conducted in the Northern Territory between 2016 and 2019, the proportion of flowers produced for each cultivar was positively correlated with the proportion of days below these temperature thresholds (Figure 2.4). This positive relationship indicates that more inductive days result in a higher number of flowered terminals. Comparing the current proportion of days below these thresholds to those projected under climate change scenarios could indicate the impact on mango flowering.

Table 2.2 General minimum and maximum temperature thresholds for flower induction of cultivars grown in the Northern Territory.

	Threshold temperature			
	Minimum		Maximum	
Cultivar	**18°C**	**20°C**	**32°C**	**35°C**
Kensington Pride		x		x
Calypso®		x		x
Honey Gold	x		x	
NMBP 1201	x			x
NMBP 1243	x		x	
NMBP 4069	x		x	

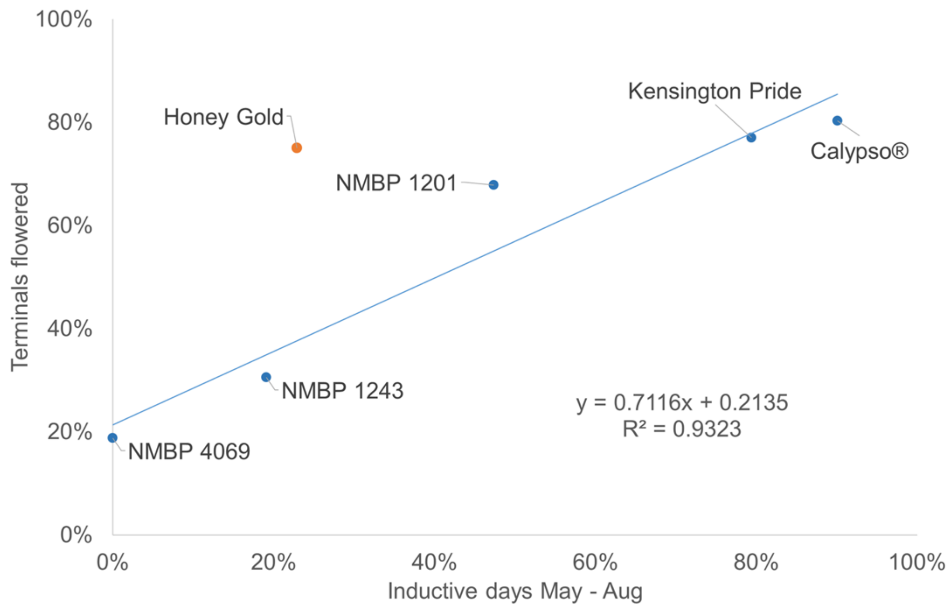


Figure 2.4 Relationship between inductive days from May to August based on temperature thresholds and percent terminals flowered, excluding Honey Gold cultivar (coloured in orange) (Clonan et al. 2020).

3 The Northern Territory's changing climate

3.1 Current climate in the Northern Territory

3.1.1 Key features of the climate in the Northern Territory

The major mango-growing regions of the Northern Territory have a tropical climate, with two distinct seasons: wet and dry. The dry season (May to October) is typically hot with average maximum temperatures above 30°C over much of the northern part of the Territory (Figure 3.1a), and very little rainfall. The wet season (November to April) is very hot and humid, with average maximum temperatures above 33°C (Figure 3.1b). Average minimum temperatures in the wet season are above 21°C for the majority of the Northern Territory, whereas in the dry season there is a stronger north-south temperature gradient, with values above 15°C for the northern part of the Territory (Figure 3.1c and d).

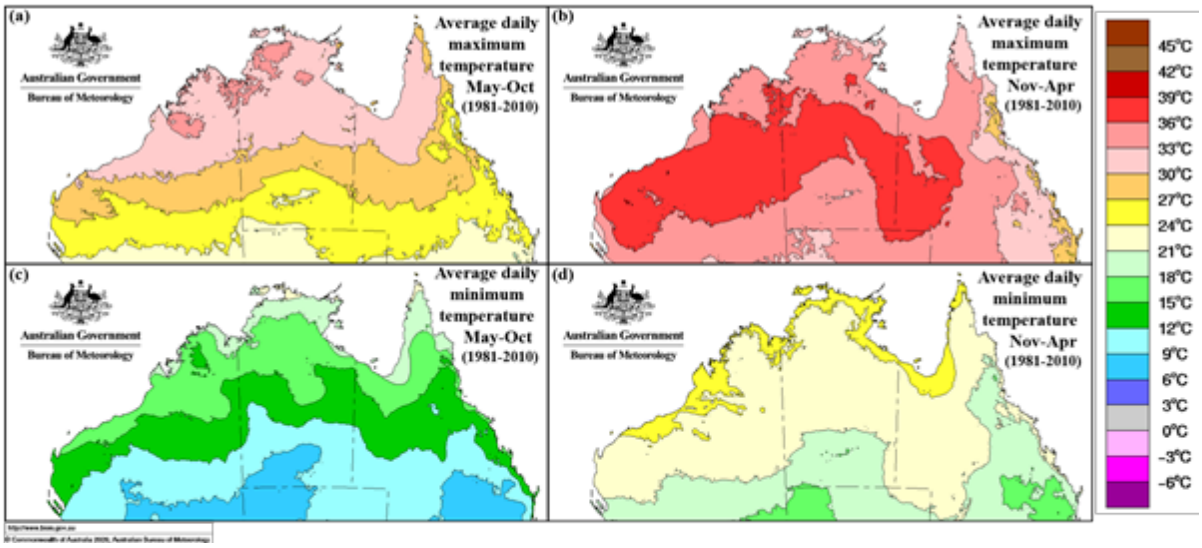


Figure 3.1 Average seasonal maximum temperature (top row) and minimum temperature (bottom row) over the 30 years 1981–2010. Dry season on left; wet season on right. (Source: Bureau of Meteorology)

Most of the annual total rainfall occurs in the wet season, which is associated with the monsoon. The monsoon is driven by the seasonal shift in wind direction, with the prevailing easterly trade winds reversing, becoming moisture-laden westerlies (NESP ESCC Hub 2019b).

The timing and amount of rainfall associated with the monsoon varies strongly from year to year, influenced by various large-scale climate drivers, including the Madden-Julian Oscillation (MJO) and the El Niño-Southern Oscillation (ENSO). Annual rainfall in northern Australia is also influenced by tropical cyclones and the Indian Ocean Dipole (IOD) (Figure 3.2).

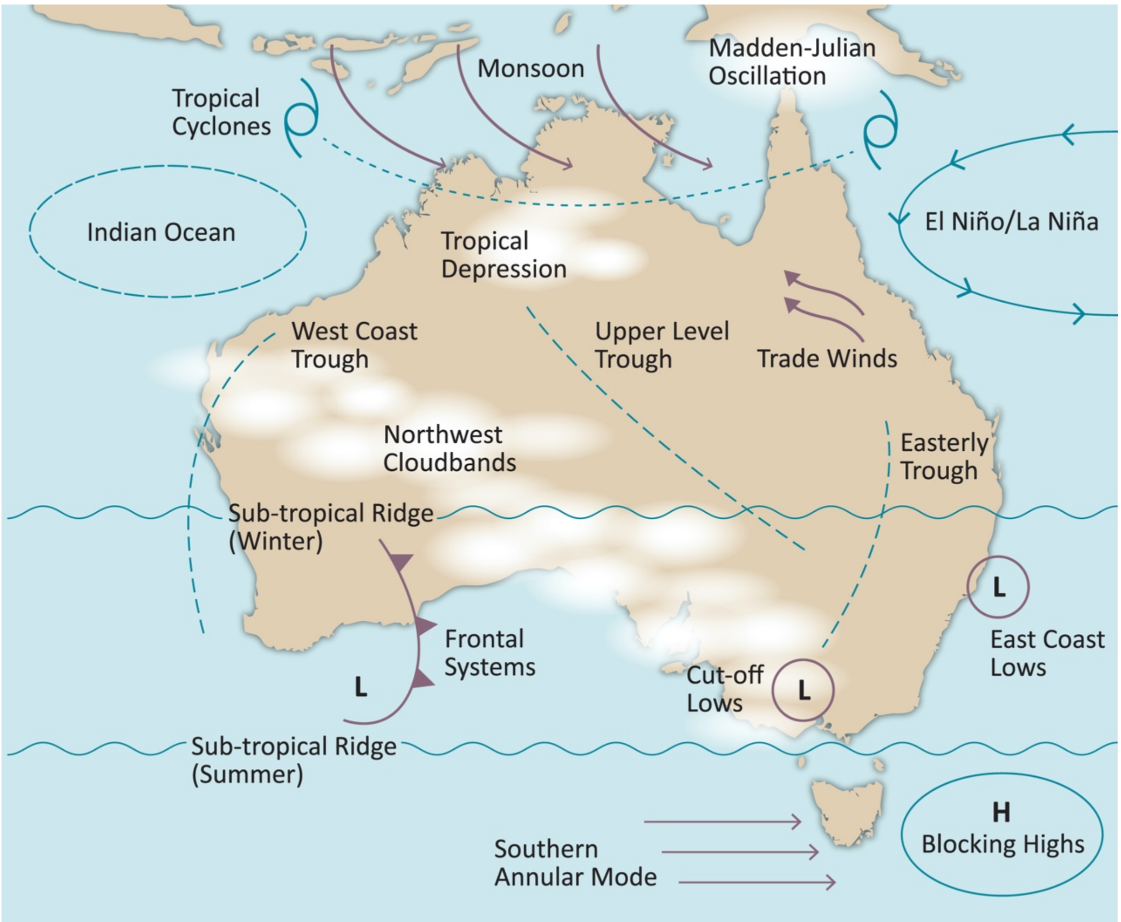


Figure 3.2 Major climate drivers affecting Australia (Source: Bureau of Meteorology)

The MJO is a ~60-day pulse of cloud and rainfall that moves eastwards around the tropics. It influences the timing, development and intensity of the monsoon. When the MJO is in the eastern Indian Ocean to the western Pacific, northern Australia can experience above-average rainfall. When it moves out of this range, northern Australia can experience below-average rainfall.

ENSO is a natural cycle that moves between El Niño and La Niña phases, driven by sea surface temperature and winds in the central and eastern tropical Pacific. ENSO influences rainfall amounts in northern Australia, with La Niña typically bringing heavier rainfall during the monsoon season, and El Niño the opposite. Temperatures are also affected: El Niño is typically associated with cooler minimum temperatures due to reduced cloud cover in the wet season, but significantly higher minimum and maximum temperatures in the following dry season. Conversely, La Niña often brings moderately cooler minimum and maximum temperatures in the following dry season.

The IOD is characterised by the difference in sea surface temperatures between the eastern and western Indian Ocean, and influences rainfall in seasons either side of the monsoon. When the IOD is positive, northern Australia experiences dry spring/build up months and central parts have a dry winter-spring. The associated absence of northwest cloud bands results in a higher maximum temperature, and lower minimum temperature, over the central Northern Territory. In contrast, in a negative IOD, there is higher rainfall over central

Northern Territory in spring and higher rainfall in the north during the early wet season. Increased sea surface temperature means warmer temperatures in the north. Increased cloud means higher minimum temperatures over central Northern Territory.

3.1.2 Observed trends in surface air temperature over the Northern Territory

There is a long-term increase in wet-season maximum and minimum temperatures since 1910 for the Northern Territory (Figure 3.3), with many more warmer-than-average nights in years after 1980 (Figure 3.3d; note average based on 30 years from 1961–1990). Over the past four decades (1980–2019), wet-season maximum temperatures (Figure 3.3b) show decadal variability but have more warmer-than-average years than cooler-than-average years (Figure 3.3).

For the dry season, there is a clear long-term increase in maximum temperatures (Figure 3.3a), but less so in the minimum temperature, which shows strong inter-decadal variability (Figure 3.3c). However, when considering the past four decades, dry-season minimum temperatures have more warmer-than-average years than cooler-than-average years (Figure 3.3c).

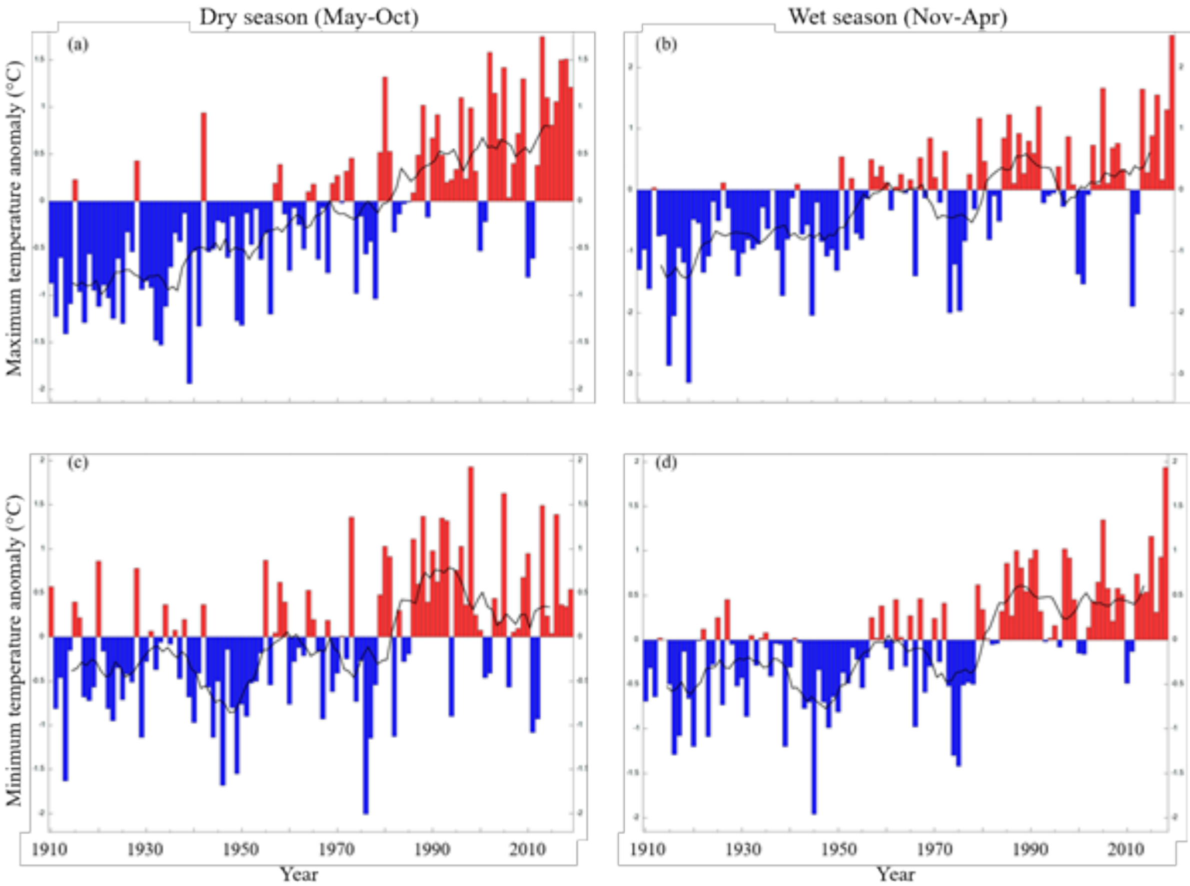


Figure 3.3 Long-term trend in maximum temperature (top row) and minimum temperature (bottom row) from 1910-2019 for the Northern Territory during the dry season (left column) and the wet season (right column). Red bars indicate above-average years, and blue bars indicate below-average years, relative to a 30-year climatology (1961–1990). Black line indicates the 10-year running average. (Source: Bureau of Meteorology; www.bom.gov.au).

These trends are also apparent in maps showing the spatial distribution of the temperature trends from the past 50 years (Figure 3.4). In the Northern Territory, maximum temperature has increased by up to 0.40°C per decade (Figure 3.4a and b). Minimum temperature has shown a warming trend in the wet season (Figure 3.4d), but in the dry season a cooling trend is apparent for some areas of the Northern Territory (Figure 3.4c). This is related to trends in rainfall and cloud cover, such as decreases in dry-season rainfall leading to more clear nights facilitating lower minimum temperatures in some regions (Figure 3.5), that will not persist in the long-term (Grose et al. 2017). There has been an observed increase in rainfall during the wet season in many regions and in annual rainfall totals, indicating an increase in seasonality (i.e., the difference between rainfall amounts in the driest and wettest periods) in northern Australia.

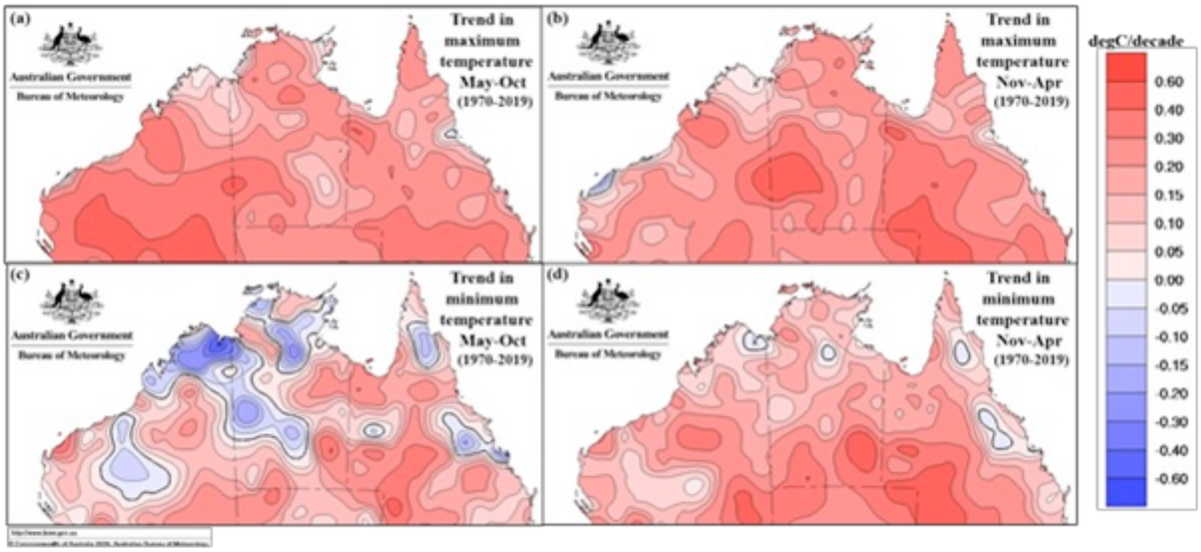


Figure 3.4 Trends (°C per decade) in maximum temperature (top row) and minimum temperature (bottom row) over the period 1970–2019. Dry season on left; wet season on right. (Source: Bureau of Meteorology)

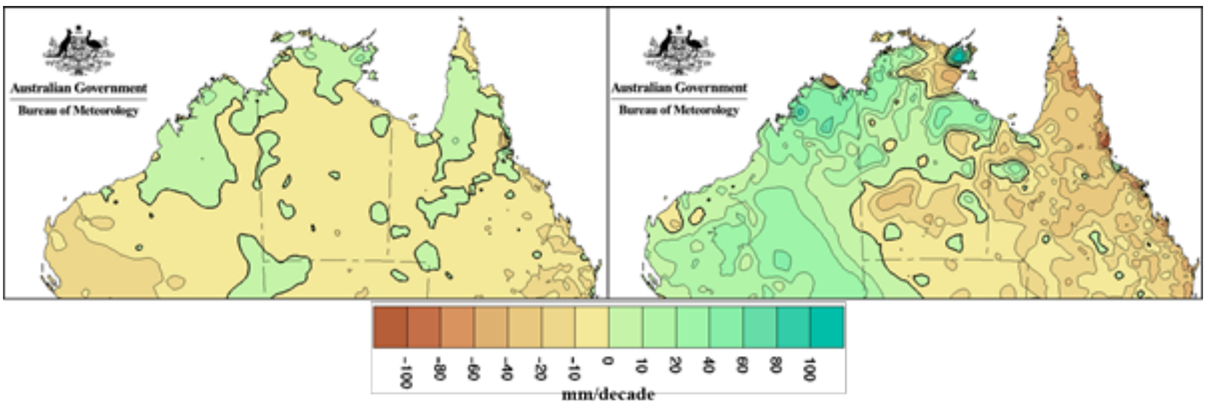


Figure 3.5 Trends (mm per decade) in total rainfall over the period 1970–2019. Dry season on left; wet season on right. (Source: Bureau of Meteorology)

3.2 Looking to the future: climate modelling and projections

Global climate models (GCMs) are mathematical representations of the climate system. They take into account interacting processes that shape the global climate, including atmospheric dynamics and physics, oceans and sea ice, land surface processes, and aerosols, and some Earth system models also represent carbon and biogeochemical cycles. The models are very complex and run on powerful supercomputers. GCMs are used to develop climate change projections, which tell us about the response of the climate system to possible future emissions scenarios.

3.2.1 Emissions scenarios

Future scenarios depend on social, economic, demographic, institutional and policy factors as well as technological developments, which together influence the trajectory of greenhouse gas emissions (Figure 3.6). Climate science uses four equally plausible scenarios, termed Representative Concentration Pathways (RCPs): RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The numbers relate to the amount of radiative forcing (a measure of the energy absorbed and retained in the lower atmosphere, measured in Watts per m^2) each emissions scenario would result in by the end of the 21st century: the higher the number, the higher the radiative forcing (Figure 3.6).

RCP2.6 is considered to be a low emissions scenario and represents aggressive mitigation. This is shown in green in Figure 3.6, where emissions peak in the 2020s and then decline quite rapidly. In contrast, under RCP8.5 (shown in blue), emissions continue to rise throughout most of the 21st century. Because of natural variability in the climate and inertia in the climate system, results from the different emissions scenarios are quite similar until 2030. After this time, the higher the emissions, the more climate change is evident.

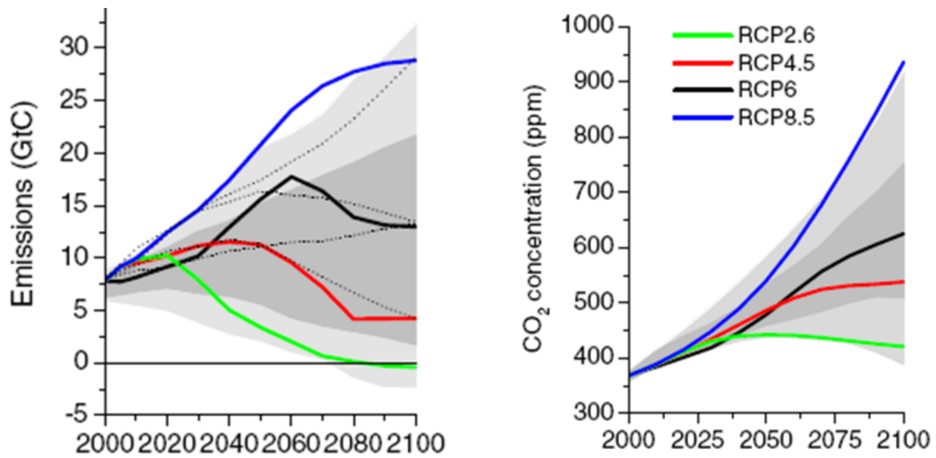


Figure 3.6 Global emissions of carbon dioxide (CO_2) over the 21st century (left) and atmospheric concentrations of CO_2 (in parts per million, right) related to each of the emissions scenarios shown on the left. Grey areas indicate the 98th and 90th percentiles (light/dark grey) of the values from the literature. Dotted lines indicate four of the previous emissions scenarios (SRES) used in older IPCC assessments (e.g., AR4; IPCC 2007). (Source: van Vuuren et al. 2011)

3.2.2 Confidence in models

Our confidence in climate projections is based on how well we understand the major climate processes that influence a particular variable (e.g. temperature, rainfall, wind) and how well the climate model can simulate these processes. Confidence is high for temperature projections because there is good understanding of the climate processes that influence temperature long-term and models can generally simulate temperature patterns very well (IPCC 2013). This includes not only the widespread global and regional patterns of warming, but also the more localised and/or shorter-term simulations of observed regional cooling (e.g. northern Australia) associated with negative or positive phases of large-scale climate drivers (Grose et al. 2017).

3.2.3 Projections required for this impact assessment

Climate models differ in certain ways, such as in their configuration, the way they parameterise certain physical processes, or how they handle certain components such as aerosols, and so the projections they produce will differ slightly among models. This is desirable because there is no single 'best' climate model that simulates everything well and in every region of the world. Some are better at simulating different processes and different regions than others, but all produce equally plausible projections. This means there is not a single projected future value for temperature thresholds in a particular growing region, but rather a range of possible futures for each emissions scenario. The large available ensemble of GCMs (n=40) produces such a range, and we sub-selected a group of seven models out of this ensemble which representatively sample the range of projected change and had been shown previously to provide plausible projections for the Australian region (CSIRO and BoM 2015).

The output from these seven GCMs was used to look at the projected number of days per month that are under minimum threshold temperatures and over maximum threshold temperatures for four months (May, June, July, and August) under two greenhouse gas emissions scenarios (RCP4.5 and RCP8.5) for four 30-year periods centred on 2030 (relevant to the current planting), 2050 (relevant for the next planting), 2070 and 2090 (both relevant to breeding programs).

The four months were selected on advice from NT DPIR on which months were most critical for mango production for the mango cultivars considered. Similarly, the four temperature thresholds were selected by NT DPIR according to their research on critical temperature thresholds for key mango cultivars.

Regions were selected from the Australian Tree Crop Rapid Response Map (State of Queensland 2017) as areas found with a high density of mango plantings. The 11 selected regions represent areas of greatest orchard density throughout the Northern Territory (Figure 3.7). One additional region was selected for inclusion from Western Australia as its climate is representative of central Northern Territory.

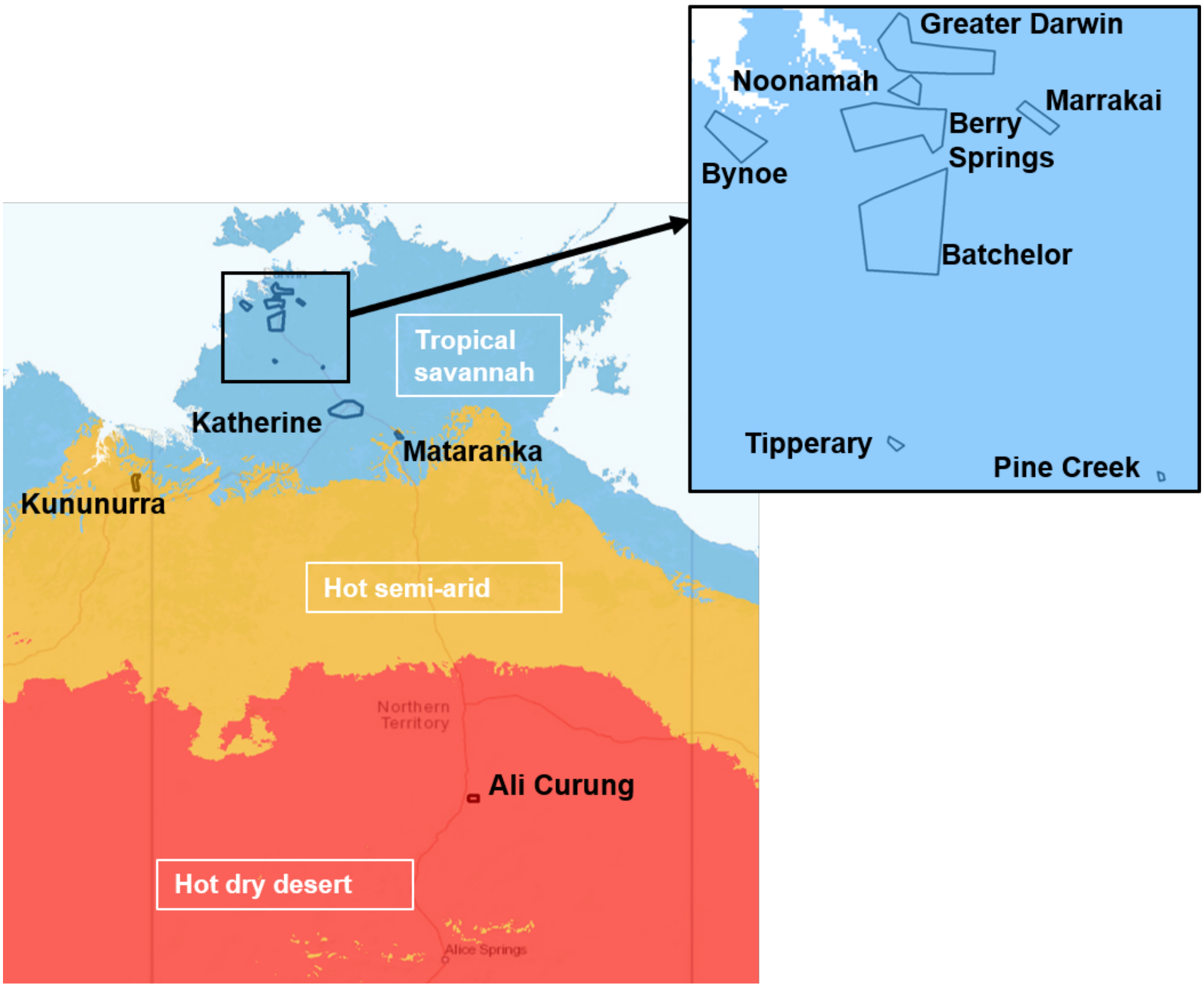


Figure 3.7 Location of the mango production regions in the Northern Territory considered in this impact assessment, with the addition of Kununurra, Western Australia. Climate categorisation follows Beck et al. (2018): hot dry desert (red); hot semi-arid (yellow); tropical savannah (blue).

3.3 Methodology for producing temperature thresholds projections

A scaling approach, where the observed climate is adjusted up or down using the change factor from GCM climate projections, was used to obtain future projections of the number of days above/below the temperature thresholds of interest. A change factor is the estimated change in the climate between a baseline period and future periods. The change factor can vary spatially due to many factors including topography, distance from the coast, relative influence of large-scale drivers, latitude, etc. To encompass natural climate variability that is evident from year to year and decade to decade, the change factor was applied to a 30-year observational dataset.

For this assessment:

1. The change factor in minimum and maximum temperatures from each of seven GCMs for each future time period was applied to each day of the corresponding month in a 30-year daily observational time-series from the Australian Water

Availability Project (AWAP)[1]. For example, the change factor from each GCM for May was applied to every May day in the 30-year observational dataset, and so on for each month of interest. This results in the future projected daily maximum (or minimum) temperature. The resultant future data are highly realistic looking because they preserve the spatial and temporal patterns present in the historic dataset[2].

2. For each of the two maximum temperature threshold values, the number of days per month when the maximum temperature is greater than the threshold value was tallied in both the historic AWAP data and projected future 30-year daily time-series. This was also done for each of the two minimum temperature thresholds, where the number of days per month below the minimum temperature threshold was tallied.
3. The average tally for each month of interest over the 30 years was calculated.
4. An area-average for each mango-growing region of interest was extracted, using area polygons provided by NT DPIR (see Section 3.2.3 and Figure 3.7).
5. The previous four steps were repeated for each temperature threshold, future period, GCM and emissions scenario (Table 3.1).

It is important to note that the AWAP gridded product is created from observations from high-quality Bureau of Meteorology station data, and the density of stations varies geographically. Gaps between the stations are filled in by interpolation (statistical methods).

Table 3.1 Parameters of data extraction and analyses

Temperature thresholds (°C)	Months	Future periods*	Emissions scenarios	Global climate models
Days with minimum temperature <20°C	May	2030	RCP4.5	ACCESS1-0
Days with minimum temperature <18°C	June	2050	RCP8.5	HadGEM2-CC
Days with maximum temperature >32°C	July	2070		NorESM1-M
Days with maximum temperature >35°C	August	2090		CNRM-CM5
				GFDL-ESM2M
				CanESM2
				CESM1-CAM5

* Years are the centre of 30-year projection period

3.4 Temperature threshold projections

In this report, for clarity and brevity, we present results that encompass the upper and lower range of plausible projections obtained from the full set of seven models under each of the emissions scenarios (but see Box 3.1). However, the results from all seven GCMs were delivered to the NT DPIR for both emissions scenarios. We provide values for the average

[1] The historic AWAP data are gridded at a spacing of 0.05 degrees longitude and latitude (approximately equal to 5 km), with 30 years (1981-2010) of daily data for each grid point.

[2] A downside is that it assumes future variability will be the same as the historic variability, which is not necessarily going to be the case.

number of days per month, noting that due to natural variability, in practice some years will have more and some less. The projected average number of days above or below each temperature threshold are shown in Figures 3.8 to 3.11 for the RCP8.5 emissions scenario, and Figures 3.13 to 3.16 for the RCP4.5 emissions scenario.

Box 3.1 Upper and lower projections ranges

When considering climate projections from multiple GCMs, it is important to maintain internal consistency, which means using datasets from the same model to ensure the data is physically plausible in terms of the climate system and is representative of what the model simulated. For example, if you were to use temperature projections for 2050 from model A, and projections for 2090 from model B, then you would end up with a trajectory of temperature increase over the 21st century that was not physically plausible and was not represented by either model.

For this reason, when showing the upper and lower range for each month and temperature threshold in this assessment, it was important to choose a representative model that consistently produced the upper (or lower) range across the four months (May–August), four temperature thresholds (<18°C; <20°C; >32°C; >35°C), and four future periods (2030; 2050; 2070; 2090). This was relatively straightforward for RCP8.5, with HadGEM2-CC consistently the upper range model and NorESM1-M the lower range model. For RCP4.5, CNRM-CM5 was consistently the lower range model, but the situation was slightly more complex for the upper range, with GFDL-ESM2M consistently the upper range model except for August when HadGEM2-CC was consistently hotter. To provide the upper and lower range, but still maintain internal consistency among months/thresholds/periods within an emissions scenario, GFDL-ESM2M was selected as the upper range model for RCP4.5, but it should be noted that for August, HadGEM2-CC was slightly hotter.

3.4.1 Key results from RCP8.5 emissions scenario

All regions show a decreasing trend over time in the average number of days per month with minimum temperatures below 18°C and 20°C, and an increasing trend over time in the number of days per month with maximum temperatures above 32°C and 35°C. That is, over the 21st century all regions have fewer days below the required minimum temperatures, and more days above the critical maximum temperatures than observed for the historical period.

While all regions show these trends, there are differences among the regions in the magnitude and rate of change. For example, Ali Curung, Katherine and Mataranka (and often Pine Creek) consistently show the least vulnerability to changing temperature thresholds in terms of the actual number of days per month that are above or below the critical temperature thresholds. In contrast, Marrakai, Berry Springs, Batchelor and Tipperary are the most vulnerable because they have a greater number of days per month above the critical maximum temperature thresholds.

There are also differences among months in the rate of change, with June and July showing a higher relative rate of change than May and August. In other words, while May and August consistently have more days than June and July above the maximum temperature threshold (because May and August are warmer months of the year than June and July), the rate of increase over the 21st century is higher in June and July. Similarly, when considering days below the minimum temperature threshold, May and August consistently have fewer days below the critical threshold than June and July, but the rate of decrease is higher in June and July. This seasonal difference in the rate of change is because May and August are already closer to the maximum (or minimum, depending on threshold) number of days per month than June and July, so there is more scope for a faster rate of change for June and July.

Regional differences are apparent in the average number of days above/below a temperature threshold and how that changes over time. For example, Kununurra currently experiences an average of 8 days per month in May where the maximum temperature is greater than 35°C, compared to Ali Curung at the other end of the scale which currently only experiences on average 0.3 days per month. By 2050, this could increase to 20 days for Kununurra and 4 days for Ali Curung. By the end of the century, nearly the whole of May (28 days) on average will be greater than 35°C for Kununurra, and Ali Curung increases to ~12 days per month (Figure 3.8). Aside from Ali Curung, other regions that consistently experience the least number of days above the threshold are Katherine and Mataranka (and often Pine Creek), although even these experience more than 10 days above the threshold by 2050 and more than 25 days by 2090 (Figure 3.8).

These patterns are also evident in the regional differences in the average number of days below the minimum temperature threshold (Figures 3.10 and 3.11). For example, Ali Curung, Katherine, Mataranka, and often Pine Creek, consistently experience the highest number of days below 18°C (Figure 3.11), whereas Bynoe, Berry Springs, Noonamah, and Batchelor consistently experience the fewest number of days below the threshold. All regions (except for Ali Curung in June and July) show a decreasing trend over the 21st century in the number of days below 18°C. Ali Curung does not fall below 25 days per month in June and July even by 2090, whereas regions such as Bynoe fall from 16 days below 18°C in July historically to half that (8 days) by 2050 and to 1 day by 2090. Similarly, Noonamah and Berry Springs experience ~22 days below 18°C in July historically, which is projected to fall to ~13 by 2050 and only 4 days by 2090.

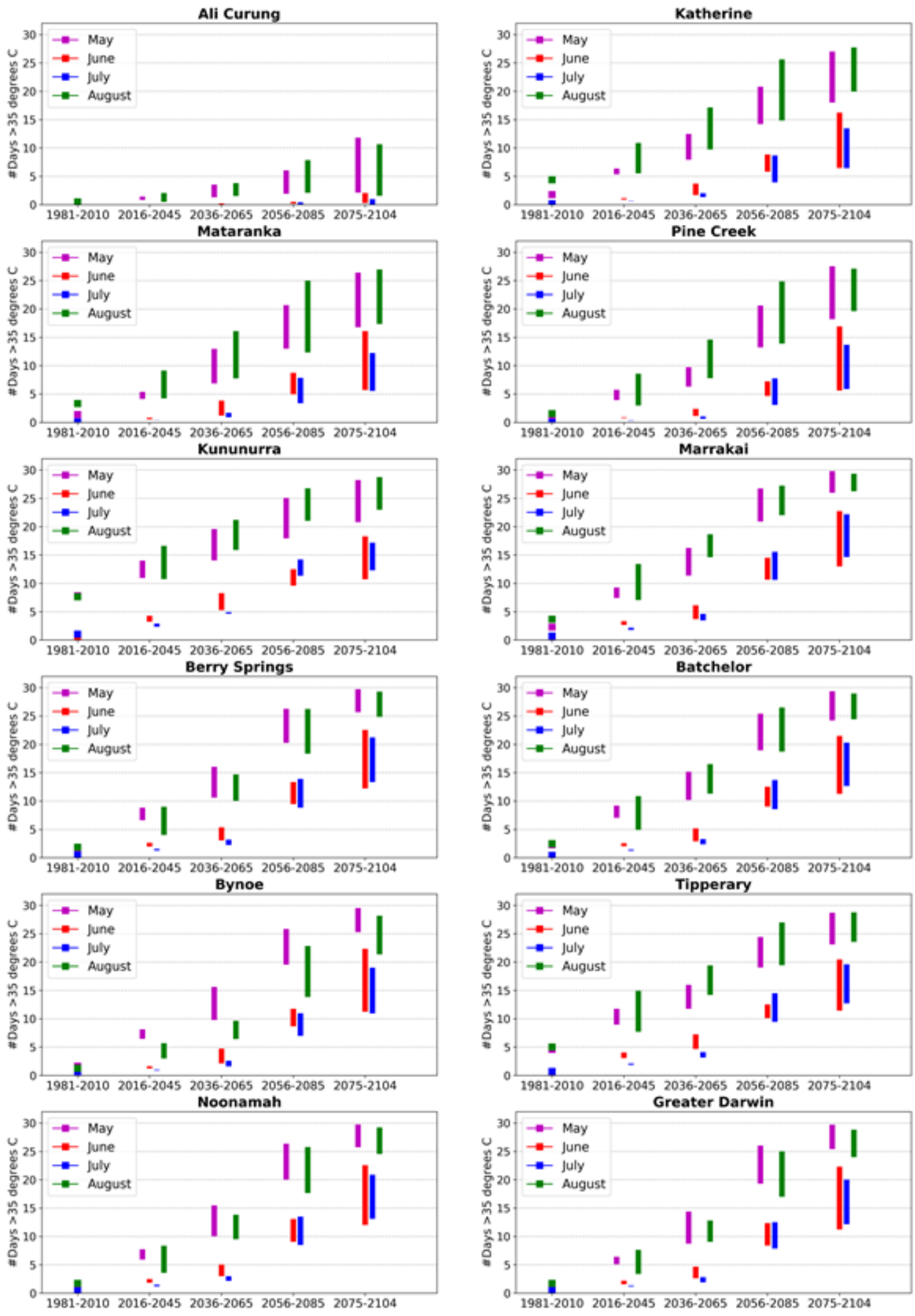


Figure 3.8 Average number of days with maximum temperature above 35°C for each month for the historical period (1981–2010) and projected over the 21st century for 12 regions under RCP8.5 emissions scenario. Coloured bars represent months and the length of the bar denotes upper and lower range projected from seven GCMs.

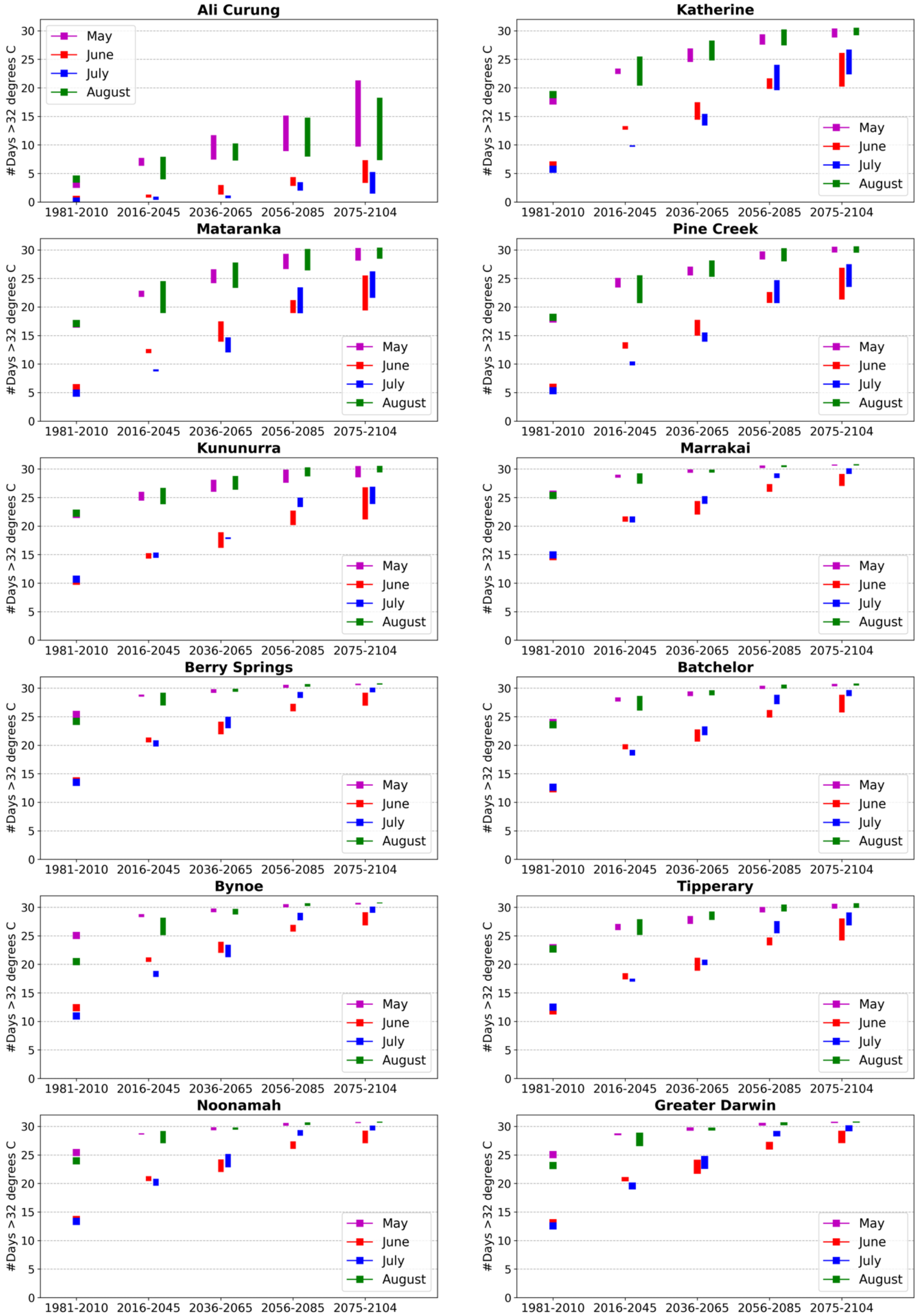


Figure 3.9 Average number of days with maximum temperature above 32°C for each month for the historical period (1981–2010) and projected over the 21st century for 12 regions under RCP8.5 emissions scenario. Coloured bars represent months and the length of the bar denotes the upper and lower range projected from seven GCMs.

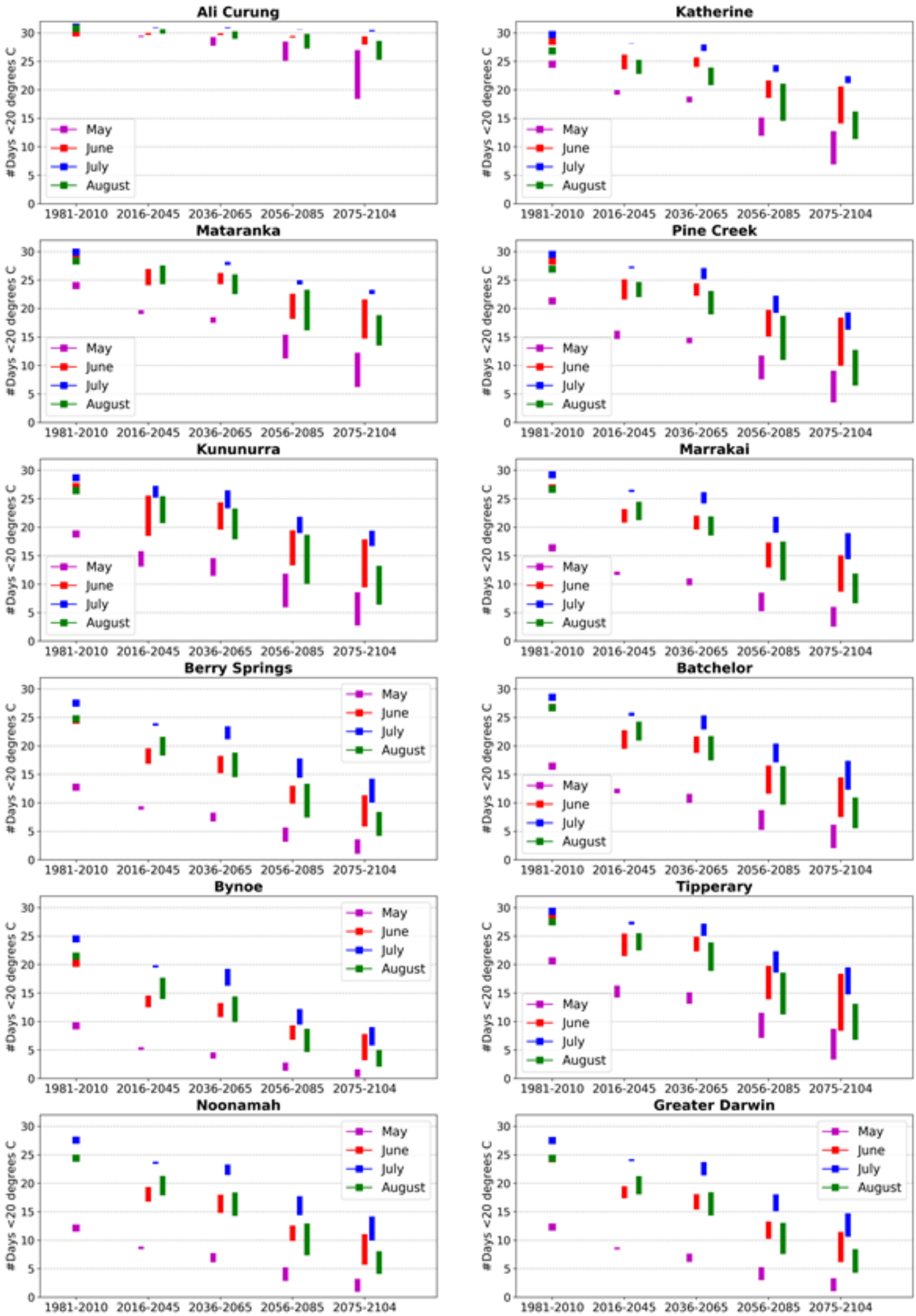


Figure 3.10 Average number of days with minimum temperature below 20°C for each month for the historical period (1981–2010) and projected over the 21st century for 12 regions under RCP8.5 emissions scenario. Coloured bars represent months and the length of the bar represents the upper and lower range projected from seven GCMs.

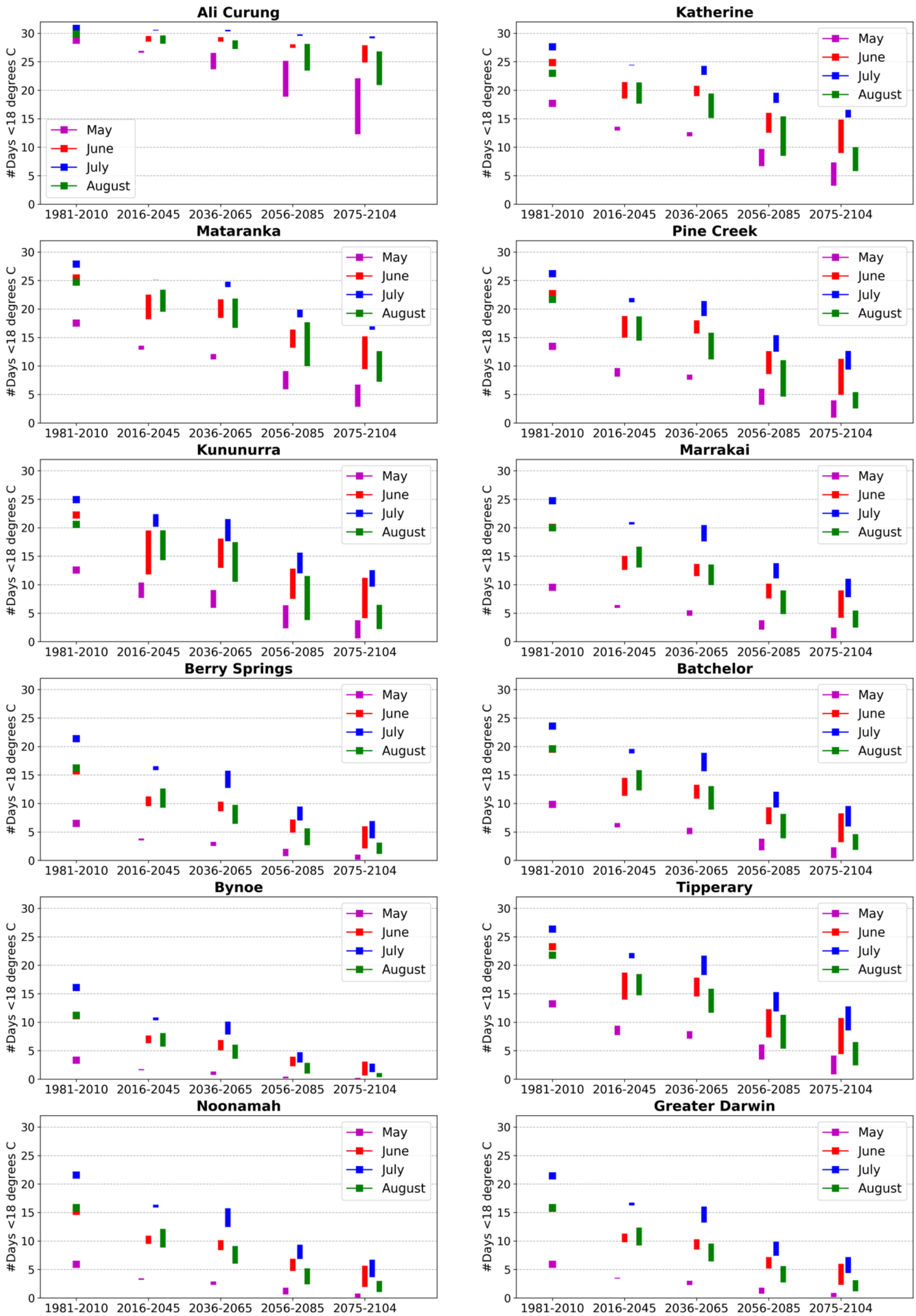


Figure 3.11 Average number of days with minimum temperature below 18°C for each month for the historical period (1981–2010) and projected over the 21st century for 12 regions under RCP8.5 emission scenario. Coloured dots represent months and the dashed lines between them represent the upper and lower range projected from seven GCMs.

The increase or decrease in days above/below the critical temperature threshold over time is not linear, which is influenced by regional variation in how many days are currently close to the threshold and the monthly upper (30/31 days) or lower (0 days) limits. Also, regions change in their ranking of which are hottest or coolest over the 21st century. For example, Kununurra has a different trajectory over time than, for example, Berry Springs. This can be explained when you examine the spatial differences in the way northern Australia warms over the 21st century. This is evident in Figure 3.12, which uses the month of July and days above 35°C to illustrate this pattern. The average number of days above the threshold is similar for Kununurra and the northernmost regions up to 2050 and 2070, but the northernmost regions show a greater increase than Kununurra by 2090 (Figure 3.12).

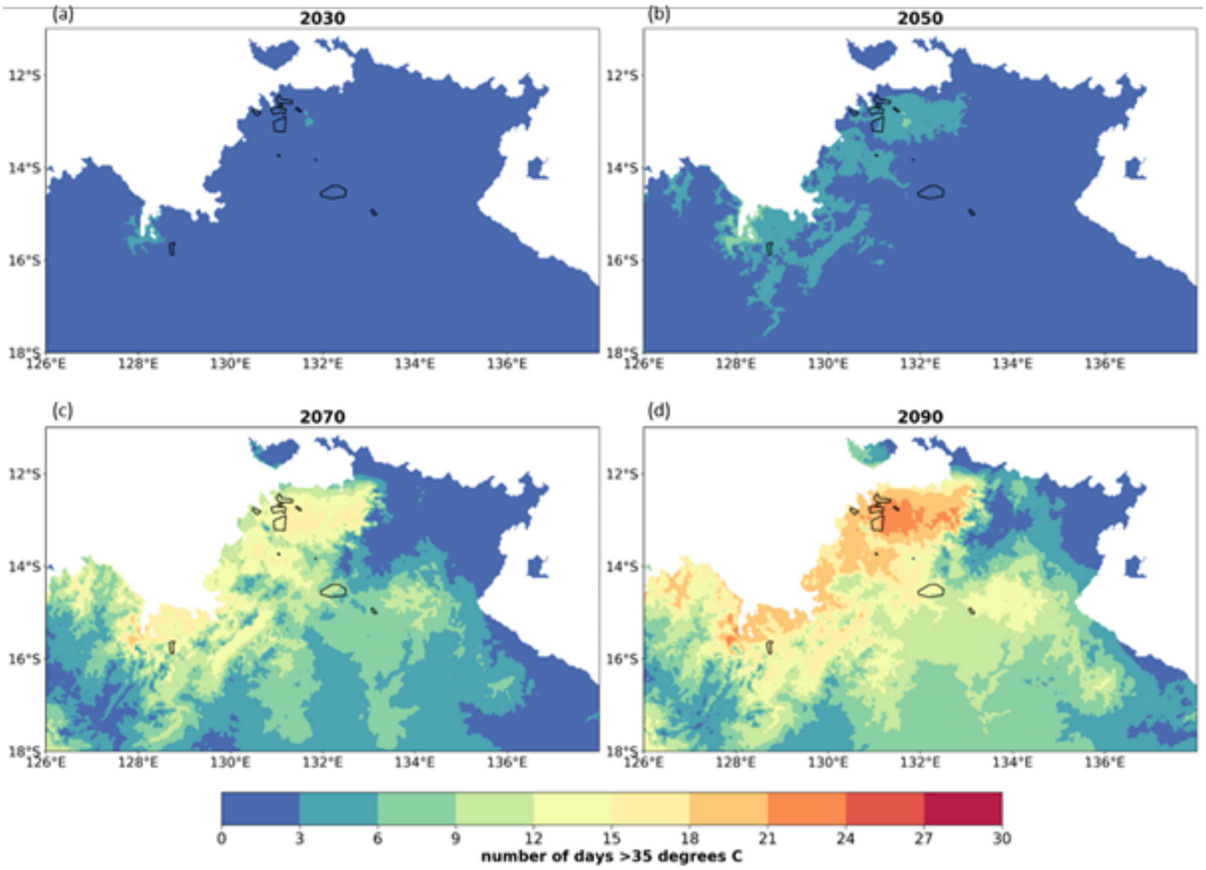


Figure 3.12 Upper range of the average number of days per month (here: July) projected to be greater than 35°C under RCP8.5 for four future periods centred on a) 2030, b) 2050, c) 2070, and d) 2090. Black outlines denote the mango-growing regions. Data were produced by scaling AWAP data by GCM change factor (see Section 3.3).

3.4.2 Key results from RCP4.5 emission scenario

Overall, the results from the RCP4.5 emissions scenario show the same **patterns** of change as RCP8.5, in terms of regional differences and increasing/decreasing trends over time, but the **magnitude** of change is less under RCP4.5 than RCP8.5 (Figures 3.13–3.16).

As with RCP8.5, results from RCP4.5 reveal the same pattern of regional differences, with (1) Ali Curung experiencing the least change in the average number of days above/below the critical temperature threshold, (2) Katherine, Mataranka, and often Pine Creek grouping together and showing intermediate levels of change, and (3) the northern regions (e.g., Tipperary, Marrakai, Batchelor) experiencing the most change.

Temperature threshold 35°C: Under RCP8.5, there was an increase in the average number of days above 35°C for every region for all months, but under RCP4.5 Ali Curung, Katherine, Mataranka, and Pine Creek experience little change over the 21st century for June and July (Figure 3.13). All regions show an increase over time in May and August but the magnitude of change under RCP4.5 is less than for RCP8.5. For example, the northern mango-growing regions (e.g., Noonamah, Bynoe, Batchelor, Berry Springs) experience over 25 days per month above 35°C by 2100 in May and August under RCP8.5, but do not go above 25 days per month under RCP4.5 (range per region of ~15–25 days per month for May). Similarly, the range for August is less under RCP4.5 (~6–15 days depending on region) than RCP8.5. Under RCP4.5, there is a large range in projected increases for May for most regions, with substantial overlap in the 2070s and 2090s.

Temperature threshold 32°C: As with RCP8.5, under RCP4.5 increases in the average number of days above 32°C are evident over the 21st century for all months and regions. By 2100, Katherine, Mataranka and Pine Creek are likely to experience ~25 days per month above the threshold in May and August, while for the far northern growing regions the full month (~30 days) will be above the threshold (Figure 3.14). For these northern regions, even June and July will have ~25 days per month above the temperature threshold. Of the 12 regions, Ali Curung experiences the fewest days above the threshold in every month across the 21st century.

Temperature threshold 20°C: As with RCP8.5, under RCP4.5 Ali Curung experiences very little change over time in the average number of days minimum temperature is below 20°C, with almost every night below 20°C up until the end of the century (Figure 3.15). For all other locations, there is a decreasing trend over time in the average number of nights below 20°C. As with RCP8.5, under RCP4.5 May has the fewest number of nights below 20°C. For June, July, and August, the far northern growing regions experience ~15–25 nights (depending on month and region) by 2100, whereas Katherine, Mataranka and Pine Creek all experience more than 23 days per month below 20°C by the end of the century.

Temperature threshold 18°C: As for RCP8.5, under RCP4.5 there is a decreasing trend in the average number of days minimum temperature is below 18°C over the 21st century for all months and regions, with May experiencing the fewest per month (Figure 3.16). The far northern growing regions experience fewer than five days per month in May by 2100, and ~5–15 days per month (depending on month and region) in June, July and August.

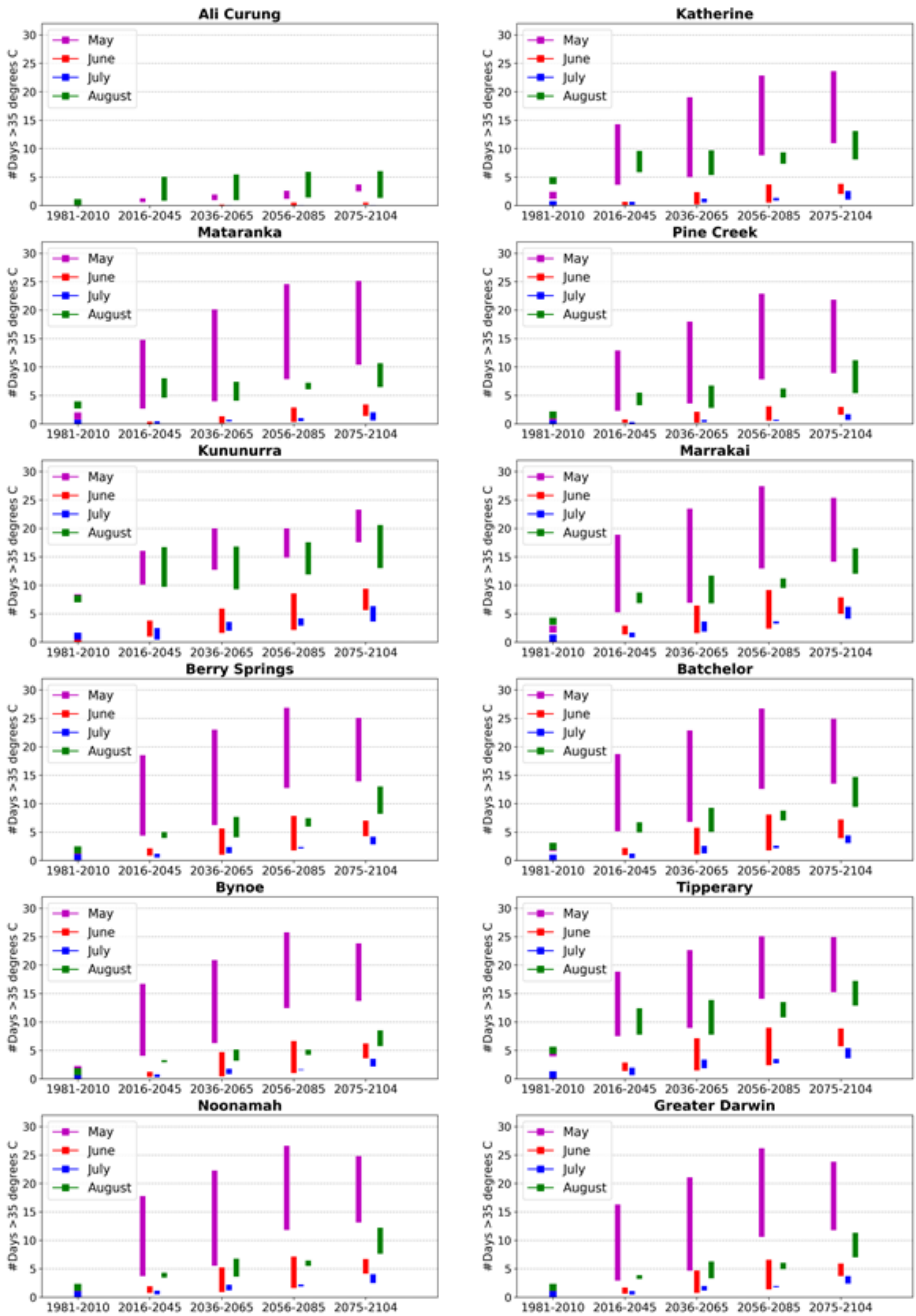


Figure 3.13 Average number of days with maximum temperature above 35°C for each month for the historical period (1981–2010) and projected over the 21st century for 12 regions under RCP4.5 emissions scenario. Coloured bars represent months and the length of the bar denotes upper and lower range projected from seven GCMs.

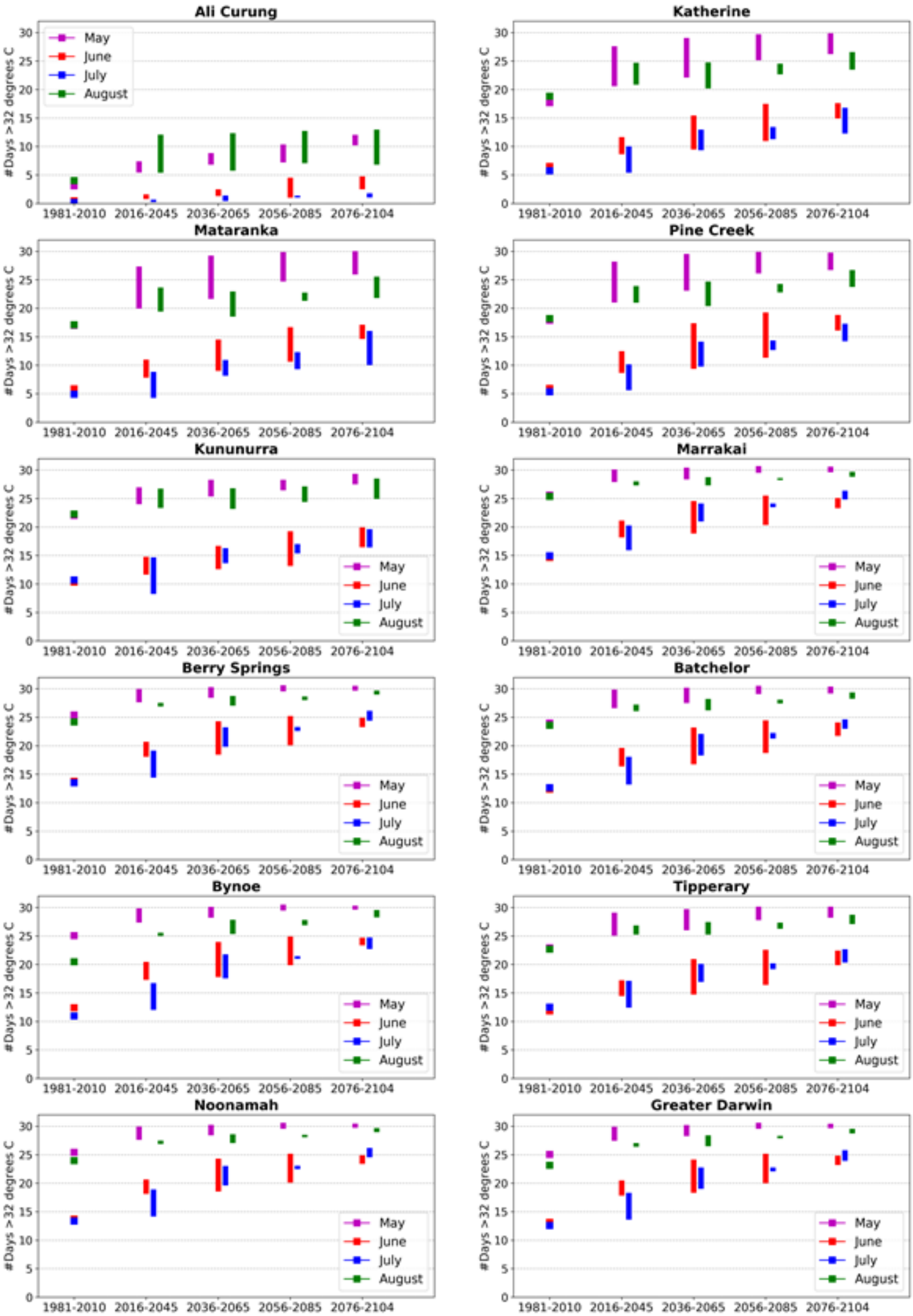


Figure 3.14 Average number of days with maximum temperature above 32°C for each month for the historical period (1981–2010) and projected over the 21st century for 12 regions under RCP4.5 emissions scenario. Coloured bars represent months and the length of the bar denotes upper and lower range projected from seven GCMs.

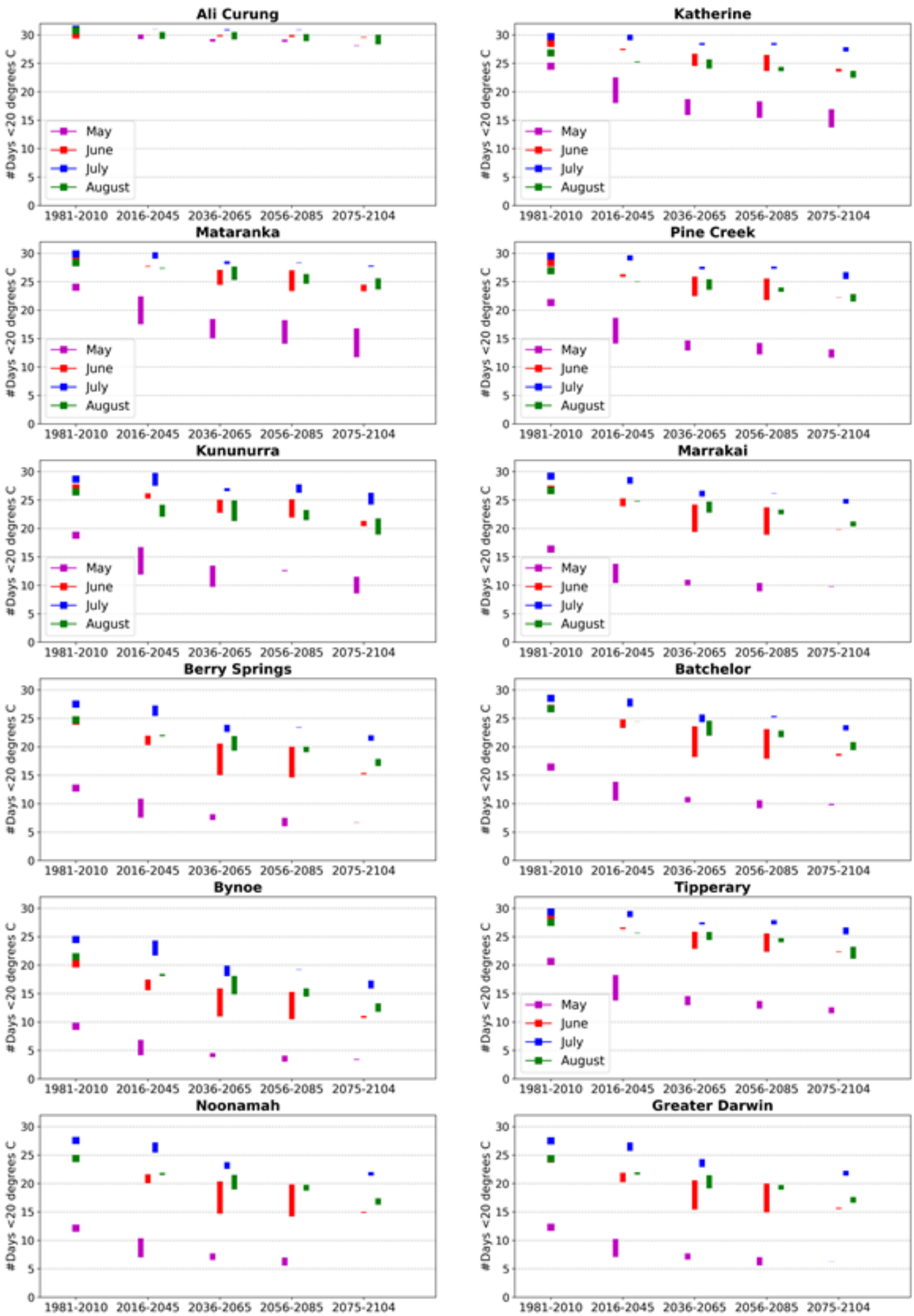


Figure 3.15 Average number of days with minimum temperature below 20°C for each month for the historical period (1981–2010) and projected over the 21st century for 12 regions under RCP4.5 emissions scenario. Coloured bars represent months and the length of the bar denotes upper and lower range projected from seven GCMs.

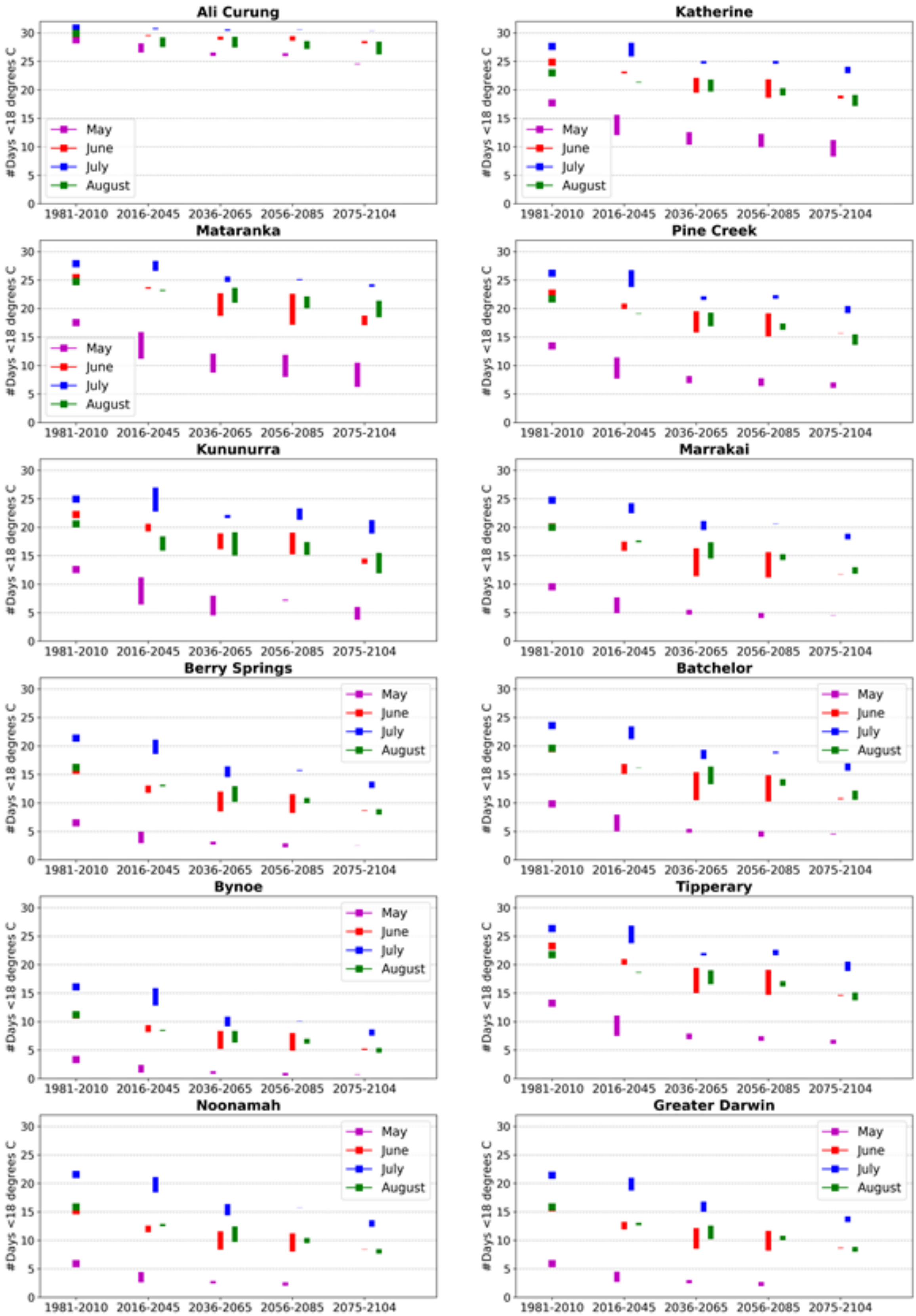


Figure 3.16 Average number of days with minimum temperature below 18°C for each month for the historical period (1981–2010) and projected over the 21st century for 12 regions under RCP4.5 emissions scenario. Coloured bars represent months and the length of the bar denotes upper and lower range projected from seven GCMs.

4. Understanding climate change impacts on mango flowering

Using temperature thresholds for mango flowering, the impact of projected changes in climate can be measured by the proportion of inductive conditions in the months where flowering occurs. As temperature thresholds are determined as the point where 50% flowering occurs, inductive days are those where greater than 50% of flowering can occur. Therefore, it is important to note that flowering could occur outside of inductive days; however, it would be limited. The number of inductive days for each cultivar represents the minimum number of days where induction can occur. This is found by identifying the most limiting threshold (35°C, 32°C, 20°C or 18°C) for flower induction of each cultivar. The percentage of inductive days is found from the total number of days between May and August. Impacts on flower induction are not inclusive of other variables that may also impact induction, such as water stress, leaf age, tree age and health.

4.1 Regional impacts

Four key production regions were selected for further investigation. The Darwin and Katherine regions amalgamate several smaller regions whereas the Kununurra and Central Australian regions represent a single production area. These four greater regions represent the diversity of current mango production sites across the Northern Territory and into northern Western Australia. To simplify the following discussion only projections for RCP8.5 are used for maps; however, both RCP4.5 and RCP8.5 are presented in the assessment of cultivar vulnerability. Only the results of the models (HadGEM2-CC and GFDL-ESM2M) that represented the upper range of change (i.e. most increase in hot days/most decrease in cool nights) is presented in mapping and to identify vulnerability in cultivars. This combination of high emissions and upper range of projected change would result in the maximum projected impact. Results for all models and emissions scenarios included in this assessment are available in the appendix to this report.

4.1.1 Darwin

The Darwin region includes the Batchelor, Berry Springs, Bynoe, Tipperary, Greater Darwin, Noonamah and Marrakai production regions. Given the proximity to the coast, this region typically experiences milder extremes in maximum and minimum temperatures when compared to the rest of the Northern Territory. Due to this, the Darwin region is highly vulnerable to a decline in inductive conditions under rising temperatures.

4.1.1.1 Number of inductive days

The limiting temperature variables for mango flowering in this region are the number of days with minimum temperatures below 18°C and maximum temperatures above 32°C. A greater number of days above 32°C than days with minimum temperatures below 18°C suggests that maximum temperatures are slightly more limiting than minimum. Recorded conditions (1981–2010) suggest that current temperatures during the flowering period are already limiting mango flower induction of cultivars with low temperature thresholds. Under both emissions scenarios, the number of inductive days for mango flowering in May and August declines rapidly to fewer than five days by the end of the century. Orchards positioned closer to the coast are more vulnerable than those further inland. In the 2075–2104 time period, centred on the year 2090, floral induction will be restricted to the month of July where in some areas more than 20 inductive days could occur (Figure 4.1).

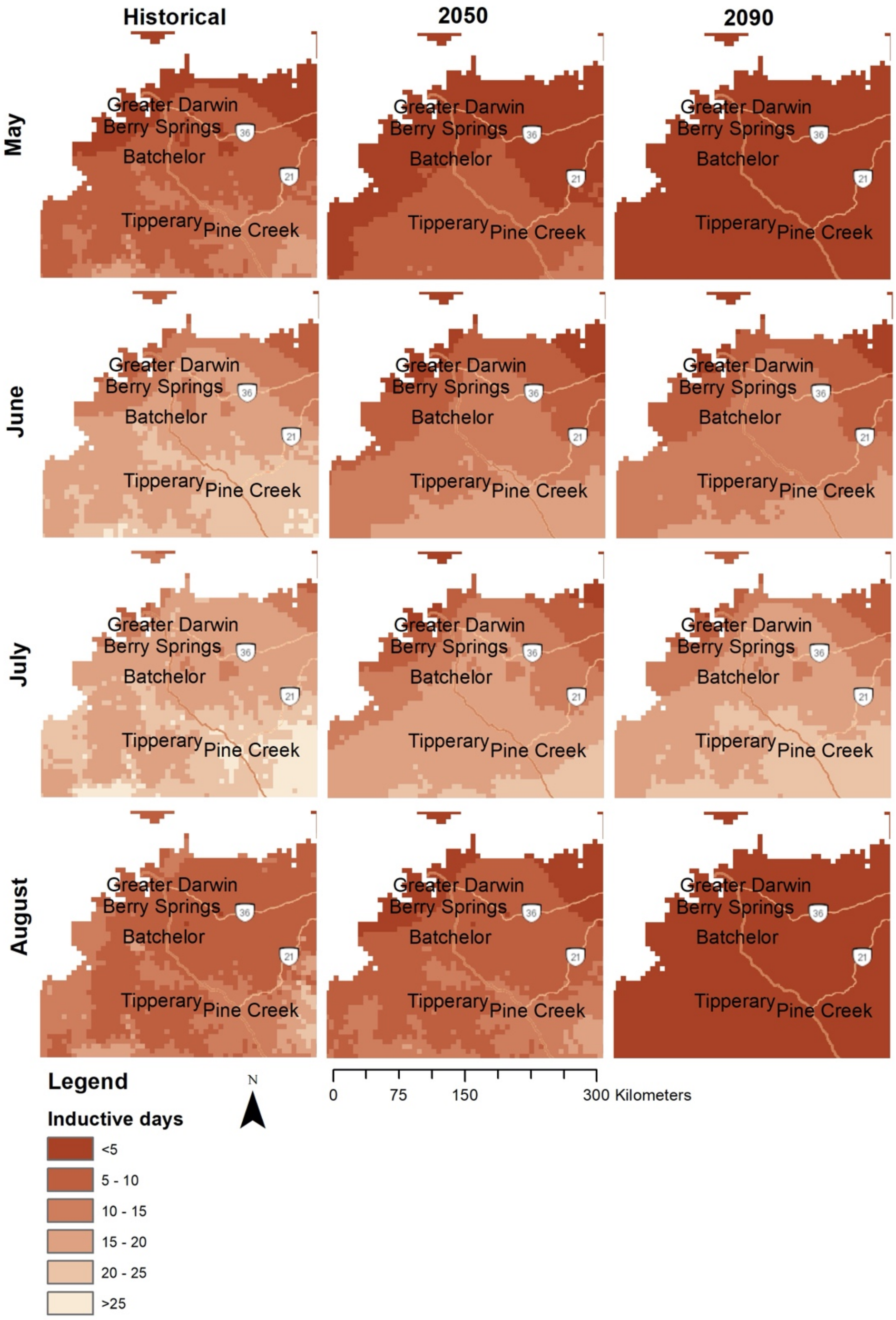


Figure 4.1 Number of inductive days in May, June, July and August in the Darwin region for 2050 (middle column) and 2090 (right column) as projected by HadGEM2-CC under RCP8.5 compared with historical values (1981–2010; left column).

4.1.1.2 Vulnerability of cultivars

Cultivar-specific analysis identified vulnerability in all cultivars assessed under both future scenarios. Calypso® and Kensington Pride are the least vulnerable as they have high thresholds for both minimum and maximum temperatures. However, a decline to 40% of inductive days between May and August is projected by the end of the century for both cultivars and more so for the other cultivars. Under RCP8.5, the worst-case model (of the seven evaluated) suggests fewer than 10% inductive conditions for all cultivars assessed within this study. Within this scenario, none of the assessed cultivars would be suitable for production systems in the Darwin region (Figure 4.2).

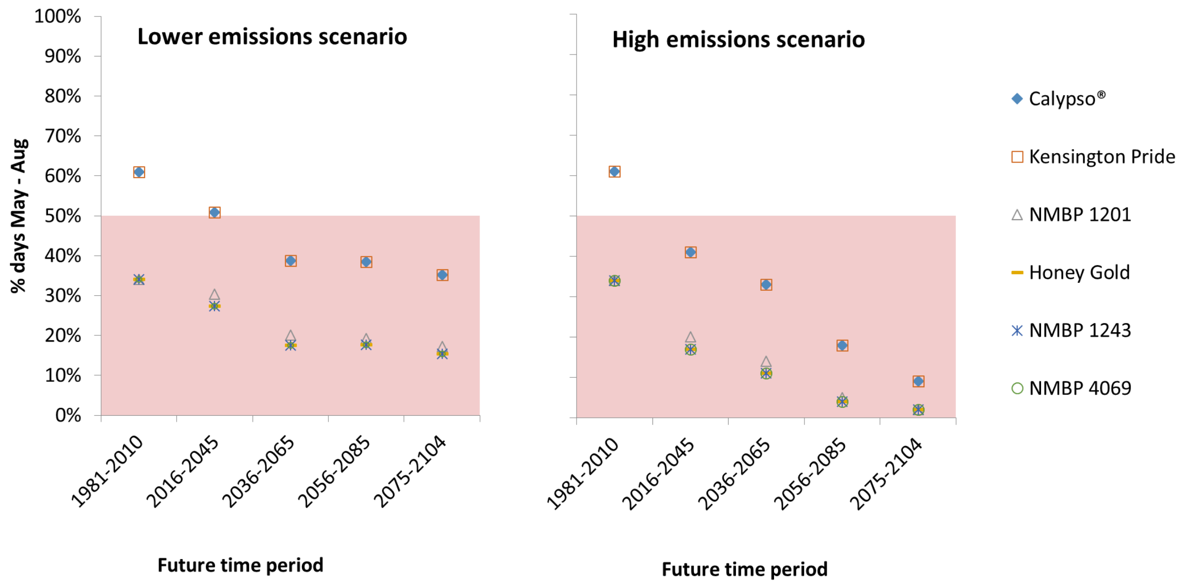


Figure 4.2 Percentage of inductive days in May to August for each mango cultivar in Darwin, as projected by the upper range model for each emissions scenario compared with historical values (1981–2010). Cultivars with fewer than 50% inductive days in May to August are deemed vulnerable (indicated by red shading).

4.1.2 Katherine

The Katherine region is inclusive of Mataranka and Pine Creek. This region experiences typically cooler minimum temperatures and higher maximum temperatures than the Darwin region.

4.1.2.1 Number of inductive days

In the Katherine region, both minimum and maximum temperatures are projected to limit mango flower induction; however, higher maximum temperatures are the most limiting. In current conditions, the number of days between May and August that have maximum temperatures below 32°C is 74. By the end of the century, this could decline to 32 under RCP4.5 and 7 under RCP8.5. The months of May and August are the most vulnerable, projected to have fewer than five inductive days by 2090. Flower induction will be restricted to June and July, with more opportunities for induction in July. As in Darwin, orchards positioned further south will be less vulnerable (Figure 4.3).

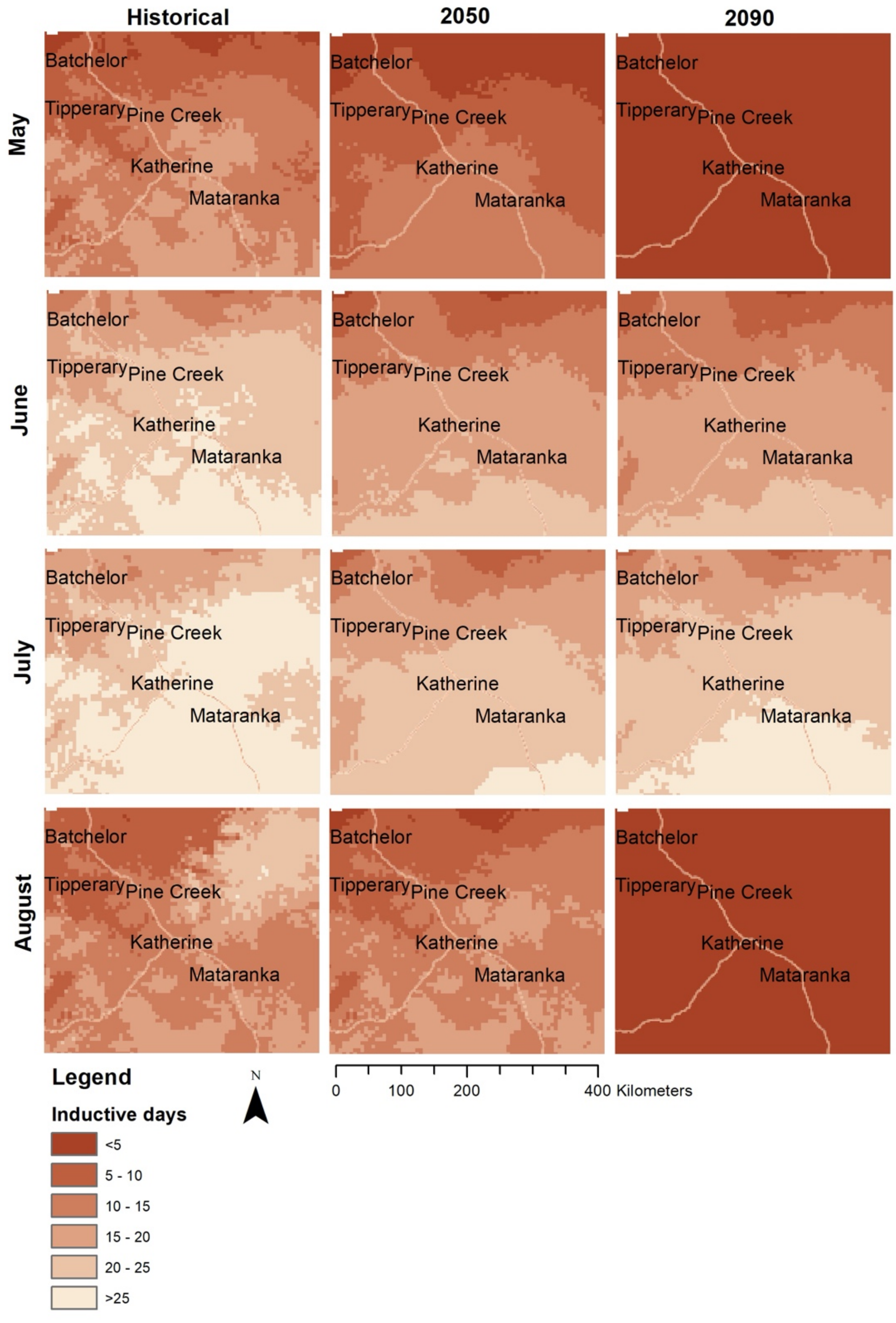


Figure 4.3 Number of inductive days in May, June, July and August in the Katherine region for 2050 (middle column) and 2090 (right column) as projected by HadGEM2-CC under RCP8.5 as compared with historical values (1981–2010; left column).

4.1.2.2 Vulnerability of cultivars

Under RCP4.5, Calypso®, Kensington Pride and NMBP 1201 will experience greater than 50% inductive days between May and August up until the end of the century. The remaining, more vulnerable cultivars are projected to experience change from 60% inductive days from historical averages, to <50% in the 2030 period. This suggests that some cultivars may become vulnerable within the next decade in the Katherine region. Under RCP8.5, all cultivars are expected to become vulnerable within the next decade, with the exception of Calypso® and Kensington Pride. By the end of the century, all cultivars will experience fewer than 29% inductive days between May and August (Figure 4.4).

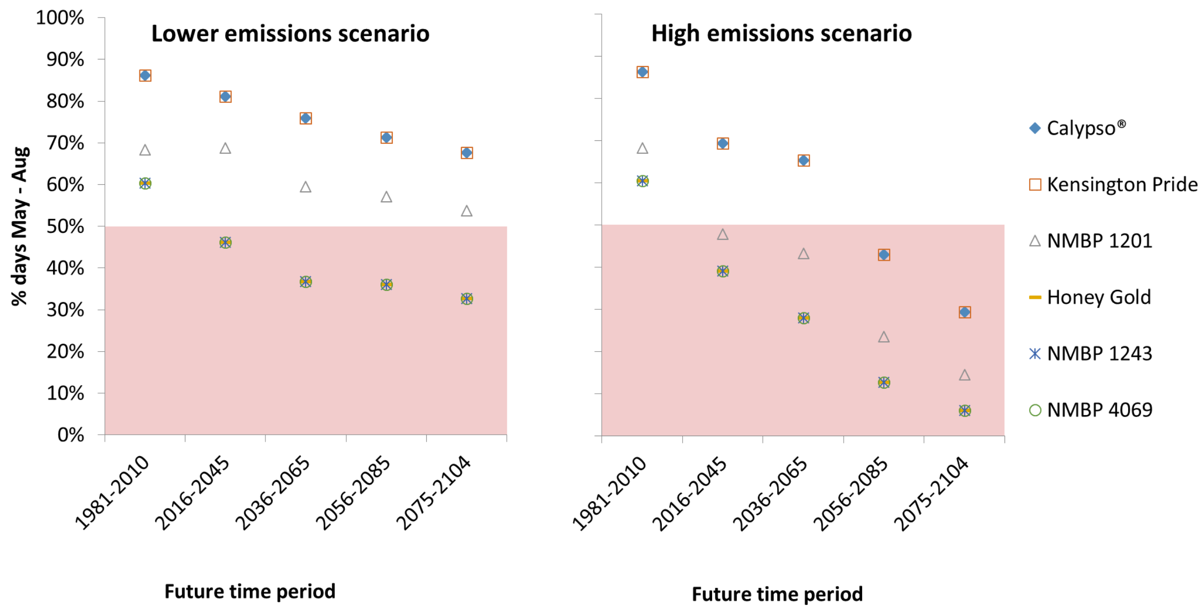


Figure 4.4 Percentage of inductive days in May to August for each mango cultivar in Katherine as projected by the upper range model for each emissions scenario compared with historical values (1981–2010). Cultivars with fewer than 50% inductive days in May to August are deemed vulnerable (indicated by red shading).

4.1.3 Central Australia

The southern regions of the Northern Territory experience a significantly different climate to that of northern mango production regions. Based on the temperature thresholds for mango flowering in northern production regions, this assessment finds that Central Australia has ample inductive days through May to August. However, this region experiences much colder winter conditions, with minimum temperatures regularly dropping below 12°C, which can negatively impact flower and fruit development. Rising temperatures in Central Australia may create more opportunities for mango flower induction during the colder months of May to August, if the number of days with minimum temperatures below 12°C declines.

The number of days below 18°C in the period from May to August is projected to decrease, suggesting rising minimum temperatures. This could increase the number of actual inductive days in Central Australia. Under this projected change, cultivars which respond well to colder temperatures during flowering (are able to support bud growth in colder conditions) may be preferred. Maximum temperatures are also projected to rise; however, the impact of this on inductive conditions is restricted to the months of May and August. Representing the upper range of projected change In June and July, there remain ample opportunities for induction with minimal change from current conditions (Figure 4.5).

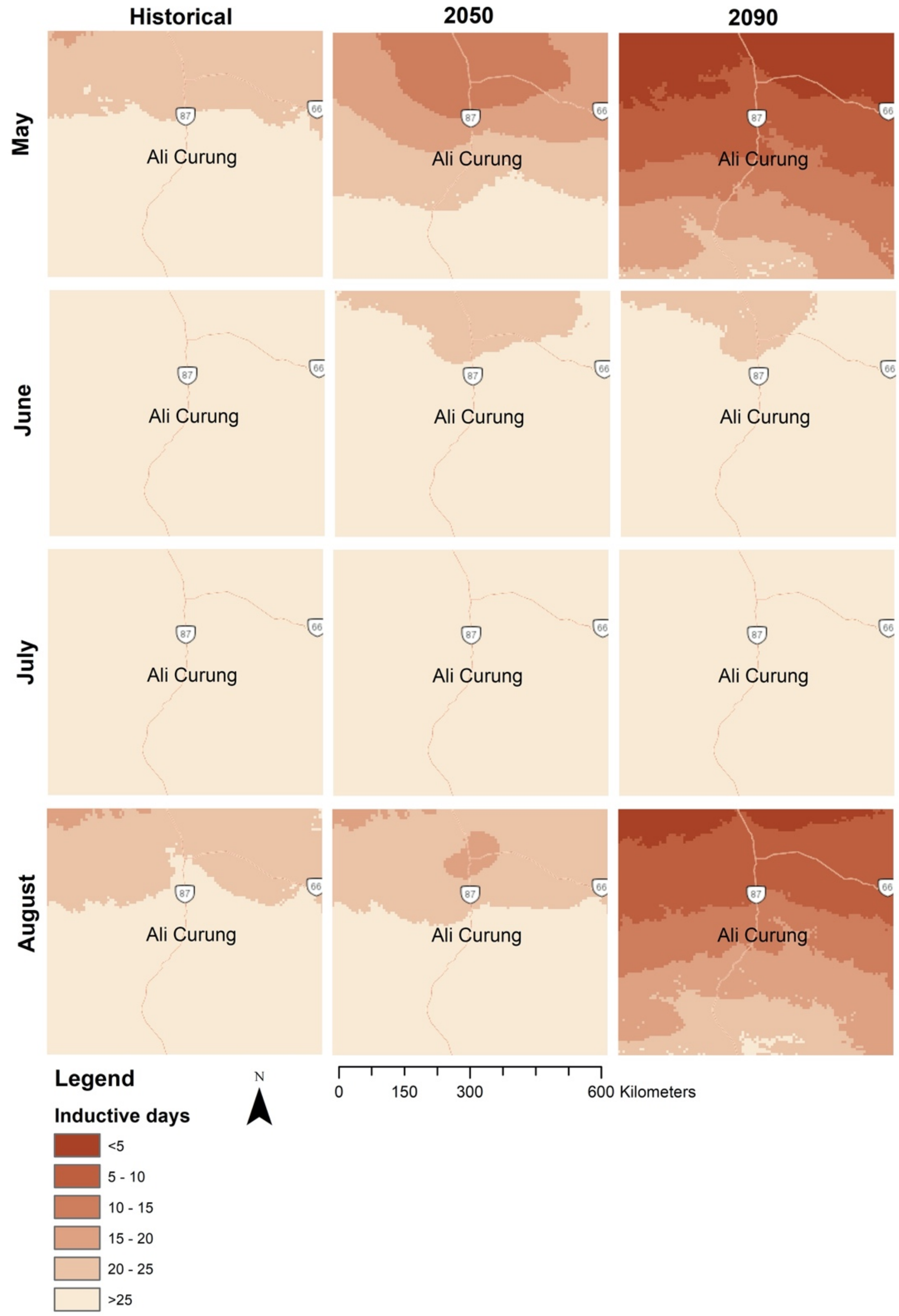


Figure 4.5 Number of inductive days in May, June, July and August in the region surrounding Ali Curung, as projected by HadGEM2-CC under RCP8.5 for 2050 (middle column) and 2090 (right column) compared with historical values (1981–2010; left column).

Many mango production regions outside of the Northern Territory experience temperatures that are too cold for successful flower induction and growth at certain times of the year (Figure 4.6). During these cold periods, mango trees will often enter a state of dormancy. Without any active growth, flower induction cannot occur. When temperatures rise above a threshold for growth, often at the transition of winter to spring, flower induction can occur. This explains the delayed flowering response to cool winter conditions around Australia.

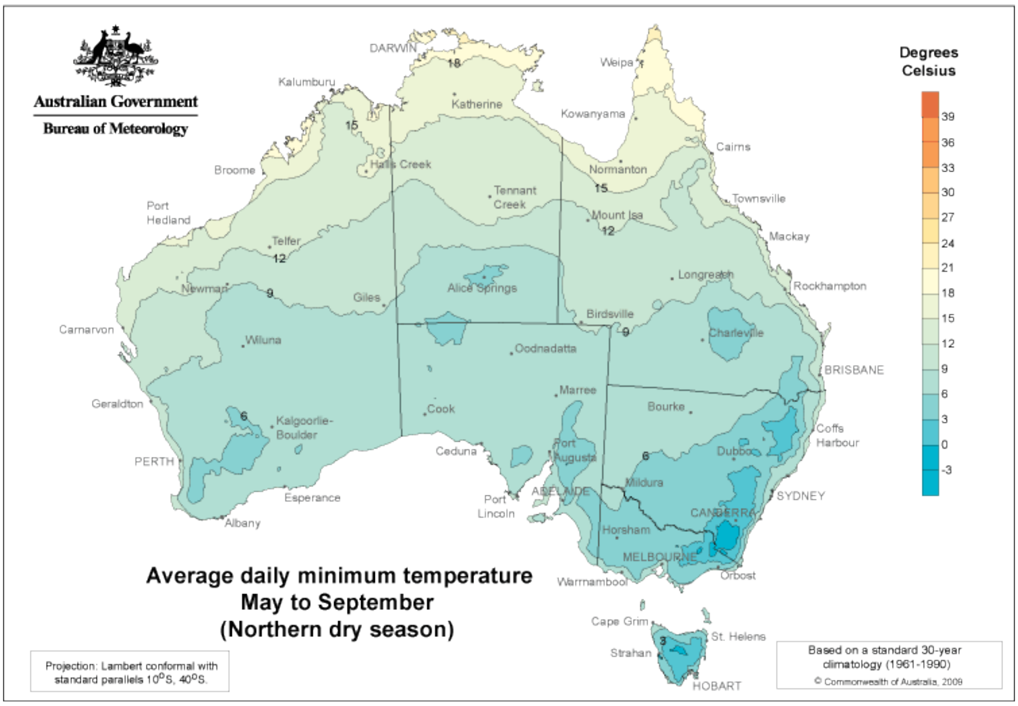


Figure 4.6 Map showing areas of Australia susceptible to temperatures below 12°C (Source: Bureau of Meteorology)

Extending this assessment beyond the impact the northern mango production regions would require the incorporation of a minimum temperature threshold for growth. In these regions, a rise in temperature could contribute to an increase in the number of inductive days or shift of the inductive period to earlier in the year, if there is a decline in the number of days with minimum temperatures below 12°C. This means that the current spread of the national mango season from August to March may contract, causing greater cross over in supply from the different regions.

4.1.4 Kununurra

The Kununurra production region experiences similar inductive conditions to Katherine. The cool nights and warm days are ideal for mango flower induction; however, daily maximum temperatures tend to be higher than in Katherine.

4.1.4.1 Number of inductive days

Historical averages indicate that current conditions for induction in Kununurra are suitable for cultivars with high maximum temperature thresholds. This is due to a high percentage of days between May and August falling below 20°C at night, but fewer days have maximum temperatures below 32°C. Therefore, the most limiting factor is the number of days below 32°C or daily maximum temperature. Under the projected conditions for RCP4.5 the number of days from May to August with maximum temperatures below 32°C declines from 57 to 30 by the end of the century. Under RCP8.5, the number of days declines to eight by the end of the century, while it is projected that 17 days will fall below 20°C at night. Under RCP4.5, by the end of the century, there are projected to be just 30 days from May to August with maximum temperatures below 35°C. Similar to the other regions analysed, flower induction becomes restricted to July by the end of the century and orchards further south are less vulnerable (Figure 4.7).

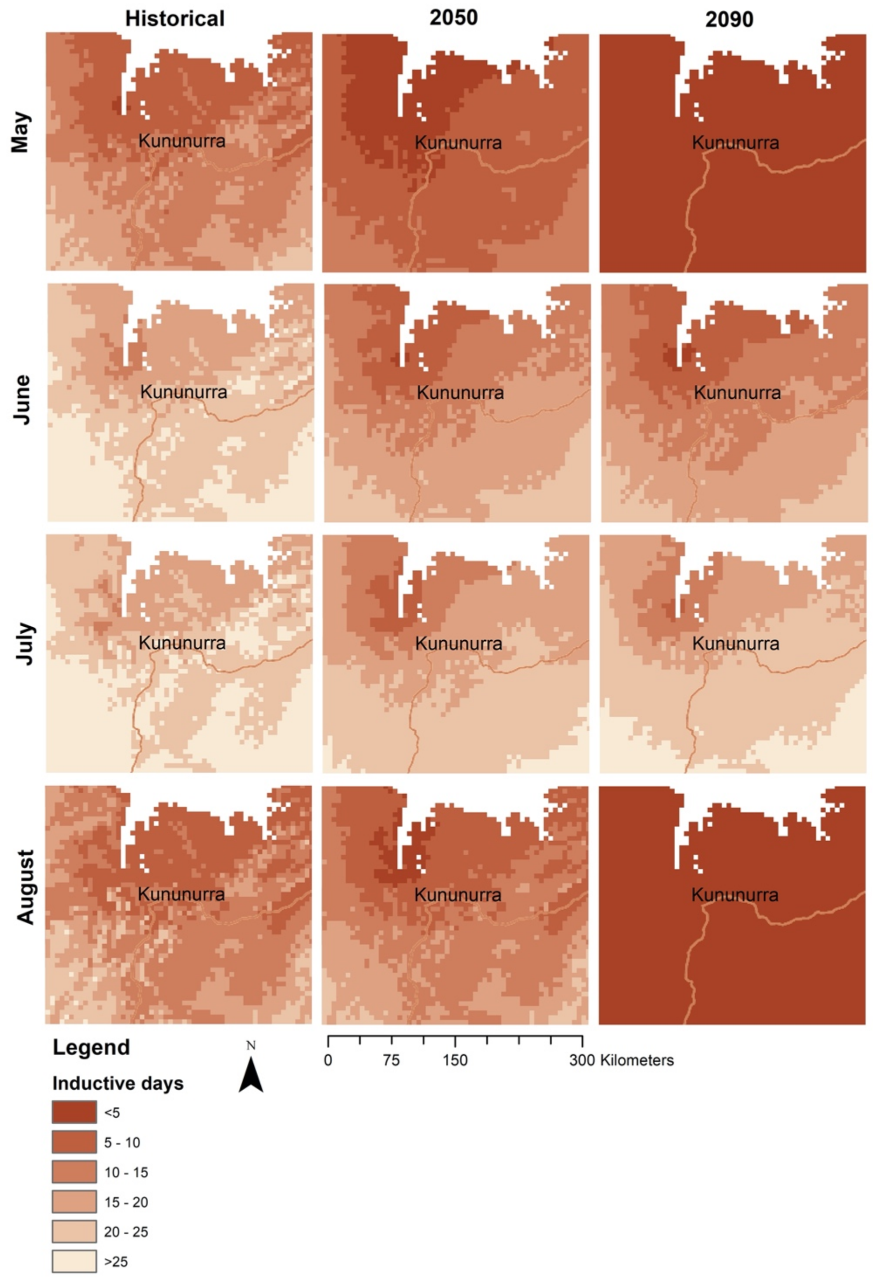


Figure 4.7 Number of inductive days in May, June, July and August in the region surrounding Kununurra, as projected by HadGEM2-CC under RCP8.5 for 2050 (middle column) and 2090 (right column) compared with historical values (1981–2010; left column).

4.1.4.2 Vulnerability of cultivars

Under current conditions as described by historical averages, NMBP 1243, NMBP 4069 and Honey Gold are already experiencing fewer than 50% inductive days between May and August. Under RCP8.5, all cultivars become vulnerable after the 2050 time period, with the cultivars mentioned previously being the most vulnerable. Under RCP4.5, Calypso® and Kensington Pride are the only cultivars that are projected to experience more than 50% inductive days by the end of the century (Figure 4.8).

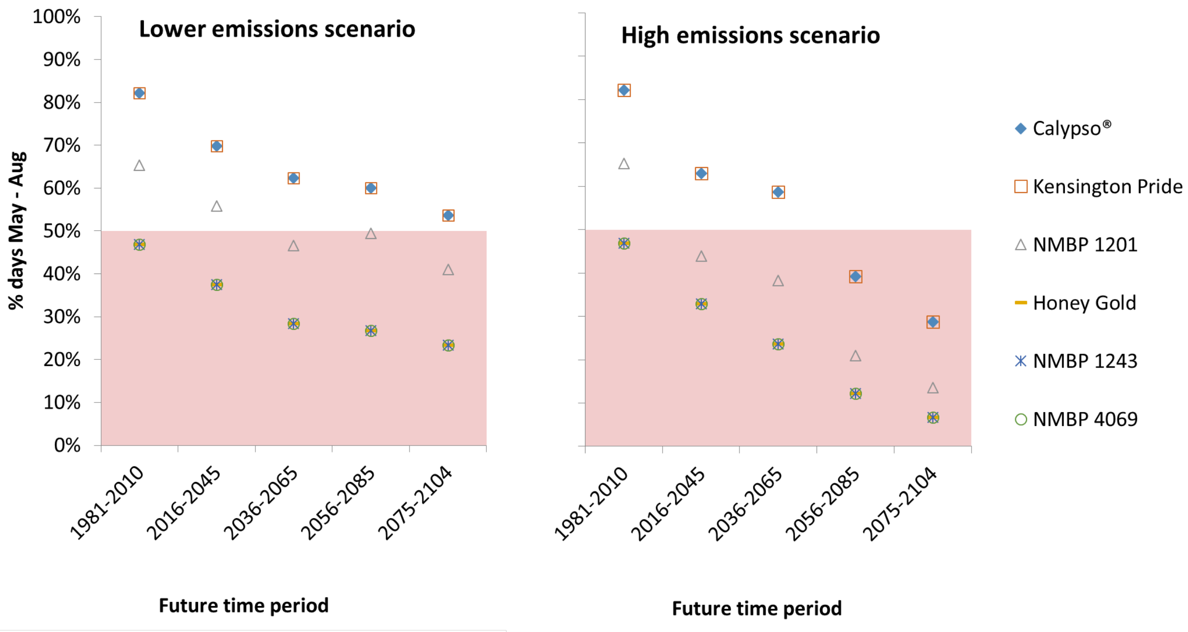


Figure 4.8 Percentage of inductive days in May to August for each mango cultivar in Kununurra, as projected by the upper range model for each emissions scenario compared with historical values (1981–2010). Cultivars with fewer than 50% inductive days in May to August are deemed vulnerable (indicated by red shading).

4.2 Potential impact on yield and other mechanisms for flowering

A decline in the number of days below 20°C and 18°C and an increase in the number of days above 32°C and 35°C may also impact other important mango flower and fruit development mechanisms that are key to production. Further investigation of these will be critical to the adaptation of production systems in the Northern Territory.

4.2.1 Timing of flowering

Fewer days with inductive conditions may change the timing of mango flowering in the Northern Territory. Flowering will become restricted to June and July in some areas, flowering will occur earlier or later than present, depending upon the cultivar. While earlier flowering events may not impact fruit growth or yield, later flowering events may promote a decline in fruit quality if harvesting is moved closer to the commencement of the wet season. Flowering over a longer period may lead to fruit being of varying maturities, while shorter flowering periods may limit opportunities for flowering and reduce productivity.

4.2.2 Fruit growth

Warmer conditions after flowering can increase the rate of fruit growth. Extreme heat during this period, as projected by some models, may negatively impact fruit set and development if trees undergo heat and moisture stress. Fruit developing on the western side of the tree canopy is vulnerable to sun burn damage in existing conditions. This may be exasperated in all cultivars which could warrant different management practices on each side of the tree canopy.

4.2.3 Timing of harvest

With an increased rate of fruit development, it is likely that fruit will mature earlier. However, in areas with cultivars that usually flower in April and May, a shift of inductive conditions to June and July may push harvest dates later towards the end of the year.

4.2.4 Pollen viability

There is published evidence that suggest the temperature limits for survival of pollen in mango is more restricted than flower induction (Issarakraisila and Considine 1994; Sukhvibul et al. 1999a). As pollen viability is key to fruit set in mango flowers, the projected impacts should be assessed. There may also be differences between the range of suitable temperatures for maintaining pollen viability across cultivars.

4.3 Impact timeline for Northern Territory mango flowering

4.3.1 2016–2045

It is likely that mango production regions are experiencing conditions projected for the 2016–2045 time period currently. During this period, under RCP8.5, all cultivars assessed in this study become vulnerable to the impacts of the declining number of inductive days between May and August, with the exception of Calypso® and Kensington Pride. The Darwin production region will be more vulnerable than Katherine and Kununurra. The number of inductive days in Central Australia may begin to increase.

4.3.2 2036–2065

In the period 2036–2065, production in Katherine and Kununurra becomes more vulnerable but not to the degree of vulnerability in Darwin. All cultivars have now experienced a substantial decline in inductive days in all areas, with the most vulnerable cultivars experiencing fewer than 20%. During this period, the indirect effects of warmer conditions on pollen viability, fruit set and fruit growth are likely to be experienced.

4.3.3 2056–2085

Under RCP8.5 in the period 2056–2085, there are likely to be severe effects on flowering of the mango cultivars assessed in this study. Mango production is likely to be drastically impacted, with the maximum number of inductive days reduced to ~40% in some areas.

Under RCP4.5, Calypso® and Kensington Pride may experience enough inductive days to flower but only in the Kununurra region.

4.3.4 2075–2104

During the period 2075–2104, the cultivars assessed are all severely limited by extreme reductions in inductive days. Only conditions under RCP4.5 will allow for some flowering in cultivars Calypso® and Kensington Pride in Kununurra and Katherine regions. Flowering is restricted to July, with some opportunity for flowering in June.

5 Implications for climate change adaptation planning

Although vulnerable to projected changes in climate, improving the adaptive capacity of the Northern Territory mango industry could reduce the potential impacts. While there is some interest in industry, there have been few efforts to identify impacts and develop options for adaptation. Some of the options discussed in this chapter are based on our existing understanding and technology, while others will require further investigation. When making plans for adaptation it is important to keep in mind the spatial and temporal variability of impacts, current adaptive capacity and flow on impacts for all stakeholders.

5.1 Grower actions

Farm level adaption will require integration of regionally specific climate change information into current and future farm planning. Key areas for grower consideration that directly address the climate change impacts on floral induction are changes in canopy management, transition to adapted cultivars, orchard relocation and orchard cooling. Farm workers' health and safety must also be considered at the farm level.

5.1.1 Canopy management

There are several practices currently employed in mango production systems that may reduce the impact of climate change on mango flower induction (Figure 5.1).

Phenological stage	Vegetative growth	Stress induced dormancy	Flowering	Fruit growth
Environmental conditions	Non inductive conditions		Inductive conditions	
Canopy management	Nutrient and water stress		Reversal of stresses	
	Time			

Figure 5.1 Environmental conditions linked to phenological stages and the key management practices that enhance mango flowering.

Canopy management practices are based on an understanding of the natural canopy functions of mango trees. These practices can be manipulated to enhance mango flower induction in poor environmental conditions, but do not induce flowering in the absence of environmental triggers.

Nutrient and water availability, and phenological stage can be manipulated to enhance mango flower induction. Key to these practices is timing around the arrival of inductive conditions. Using the mechanism for predicting the arrival of cool conditions in the Northern Territory described in Chapter 2 will be critical to the success of canopy management practices. Nutrient stress prior to inductive conditions can minimise vegetative growth, synchronising the stage of shoot development and preparing shoots for floral induction. Nitrogen is the key nutrient that has demonstrated this mechanism. However, nitrogen is fundamental in flower and fruit development, so it must be supplied in moderation to trees upon the arrival of induction temperatures. Sufficient availability of calcium, boron, iron, zinc, potassium and phosphorus has been linked to increases in floral induction (Nehete et al. 2011; Singh and Banik 2011).

Water stress, similar to nutrient stress, acts by minimising vegetative growth prior to the arrival of inductive conditions. Reversing water stress initiates shoot development and, if timed closely with inductive conditions, can result in synchronous floral induction. Shoot initiation in non-inductive conditions will result in vegetative flushing. Sufficient water availability is critical to flower development and fruit set, therefore inducing water stress beyond shoot initiation could be detrimental to the tree/process.

Shoots can also be manipulated to prepare for floral induction with chemical or physical pruning. The removal or maturation of the youngest vegetative flush will prepare new buds for shoot initiation. Mechanical pruning of the youngest shoots will achieve this, as well as applications of growth regulating chemicals such as paclobutrazol and ethephon.

5.1.2 Transition to resilient cultivars and orchard relocation

New research to compare the temperature thresholds for floral induction of mango cultivars will allow for resilient cultivars to be selected for future production systems. Of the cultivars assessed in this study, Calypso® and Kensington Pride are the least vulnerable to high temperatures during floral induction. Cultivars that are yet to be studied can be observed for their performance in various climatic conditions in production regions around the world. For example, Nam Dok Mai grown in the Darwin region has been observed to flower in non-inductive conditions, suggesting it may have a different temperature threshold to those cultivars which do not flower (Ping and Chacko 2000). Similarly, the influence of rootstock selection on flowering is not well understood and widespread use of Kensington Pride rootstock in the Northern Territory does not allow for this to be observed.

The best practice for orchard transition is not well documented. Mango orchards in the Northern Territory remain productive for 30+ years and most orchards are yet to undergo a transition. However, there has been some demonstrated success in the transition of relatively a young orchard to new cultivars with the grafting of new scions onto established trees. Alternatively, and more commonly, new orchards are established on newly developed land or old orchards are removed. Older mango trees become more difficult to manage as trees increase in size. Orchard spacing used in the past is now outdated, providing further reasoning for the removal of old orchards. Barriers to transitioning an orchard can be the delay in production of two to three years, followed by another two to four years to reach full productivity, reestablishment of irrigation infrastructure, expenses for new plant material and labour and, if necessary, purchase of land.

Growers may consider new regions for production in their forward planning. Suitability of regions for mango production, based upon the impact assessment presented in this report, will assist the selection of new regions that are currently suitable, or may become suitable in the future. Extensive considerations should be made all of regionally specific conditions that support the sustainable production of mangoes.

5.1.3 Orchard cooling

Practices to lower the temperatures of tree crop orchards have been investigated extensively in apple, pear, avocado and conifer seed crops. Mechanisms for cooling explored in the literature include shading and evaporative cooling (EC) with irrigation. In one study, EC reduced leaf and fruit temperature by 4% in apples (Van den Dool 2006) and 3–4°C in avocado orchards (Miller et al.1963). However, there is no current evidence to suggest that these practices would reduce temperatures in Northern Territory mango orchards sufficiently to induce flowering or mitigate high temperature effects. In addition, the increased humidity in the orchard at the time of flowering can contribute to the development of fungal and bacterial outbreaks that may negatively impact flower and fruit development.

5.1.4 Farm workers' health and safety

An increase in the number of days above 32°C and 35°C during the period of floral induction in mango, and also throughout the remainder of the year, will impact the health and safety of outside workers on mango farms. Outside work activities and recovery from work in high temperatures overnight will both be impacted by the projected change in temperatures. There are a range of factors that will influence the extent of impact on the health and safety of workers and these differ across regions and operational specifics of different orchards. The acute and chronic health effects of exposure to extreme heat range of heat stroke to chronic kidney disease and can include mental health problems. Levy and Roelofs (2019) identified several studies that could associated chronic diseases with heat stress in agricultural workers.

Indirect effects of extreme heat on agricultural workers could include an increase in exposure to hazardous chemicals and environmental pollutants, decline in productivity, restriction of work hours and increase in the incidence of work-related injuries. A heat index that incorporates absolute temperature and humidity is used to determine limitations for outside work throughout regions where extreme heat is already common. Employers should develop and implement workplace strategies for managing the risk of heat related health issues. They can prepare by devoting resources to identifying risks, performing an analysis of the vulnerability of workers, and implementing control strategies that eliminate or minimise impacts (Levy and Roelofs 2019).

5.2 Industry responses

Successful adaptation will require industry responses and support to help and consolidate grower activities, and to provide a broader strategic planning approach with a focus on industry-wide resilience. Key areas for industry actions are knowledge, plant material and markets.

5.2.1 Education and extension

Industry-wide extension of the knowledge required for growers to identify and manage impacts of climate change is critical. Industry bodies, consultants and extension officers can play a role in building skills and awareness for adaptation throughout industry. This can be facilitated through extension and education activities, support of industry wide networks and appropriate framing of published information.

5.2.2 New cultivar commercialisation

The commercialisation of new, less vulnerable cultivars could provide industry adaptive capacity in the medium to long-term. As transitioning to a new cultivar could take some time, new cultivars need to be adapted to the conditions that are expected to be experienced over the next five to 30 years and beyond. The conditions projected to occur within the 2050 time period could be used to identify existing and new cultivars with thresholds that allow for sufficient floral induction during this time period. After selection of these cultivars, industry, development and extension bodies could lead the commercialisation and availability of these for growers. As conditions beyond 2050 may continue to change, new cultivars may need to be identified for production systems that exist to the end of the century.

5.2.3 Market development for resilient cultivars

In conjunction with a shift to more climate resilient cultivars, markets will need to be developed or managed to transition from existing cultivars. This includes the establishment of specific supply chains, wholesalers and consumer interest in new cultivars.

5.2.4 Projecting and managing changes to fruit supply to market

There are existing challenges in the supply of fruit to market that occur when extreme or unusual conditions impact flower induction. These events impact on the volume and timing of fruit supplied to the market. Storage and transport of mangoes is highly restricted due to the short shelf life and sensitivity to storage conditions. Similarly, transport of mangoes overseas to export markets is difficult due to biosecurity and quality issues. Mangoes are therefore more susceptible to changes in harvest timing than many other commodities. These confounding effects make managing supply of mangoes at the market stage challenging.

Currently, national industry crop forecasts are used to convey any changes to volume or supply to the whole industry. The national industry body also facilitates information supply between growers, marketers, wholesalers and retailers. Research to aid this has been supported by industry through the multi-scale monitoring assessment to determine crop yield accurately through remote sensing. A further consideration for improving market adaptability would be to introduce flexibility into the supply chain system. For example, cataloguing for major retail chains requires six weeks' notice of supply. Similarly, bookings for transport must be made well in advance. Integrating adaptation to change in supply and timing of fruit into the entire supply chain, rather than simply at production, will support management at the market end.

5.3 Policy considerations

Policy certainty and adaptability is integral to the adaptation of production systems to climate change, including monitoring and evaluation feedback loops to assess policy outcomes. There is a real risk that the effects of the impacts of climate change will outpace policy changes, leaving industry to manage inappropriate or non-existent policies. Adaptation to climate change will require flexible policies that are considerate of short-term transformational change, while also accounting for the incremental change required to address longer term climate challenges.

All levels of government can support agriculture through policies and regulations that target sectors from environmental conservation through to supply and markets. For example, water markets have been a significant driver of change in irrigation-dependent areas. Areas where new policies or changes to policies may be required to enable industry adaption to climate change include (NCCARF 2013):

- Protection of or access to prime agricultural land to secure food production, specifically in regions projected to become suitable for mango flowering
- Orchard relocation, transition to new cultivars and cooling technology.

There are several other considerations for policy development that may support the adaptation of mango production systems to climate change. Public services and support could aid in crop diversification and substitution, including the development of new varieties, water resource management, income loss and disaster risk management. Examples of other target areas for policies could be:

- Support of seed banks and production of plant material
- Development of communication and extension schemes
- Incentives for adaptation practices
- Encouragement of improved water use efficiency
- Promotion of crop varieties that are less reliant on water
- Strengthening of community groups
- Development of support schemes for managing financial risk
- Support for dissemination and development of climate information
- Encouragement of drought management programs
- Cross-boundary decision making and resourcing for biosecurity risk
- Ensuring management of vital infrastructure and services including energy supply and cost, transport and telecommunications.

5.4 Research

There is significant potential for adaptation options to be developed through research. A review of current literature to assess the potential impact of climate change on mango production globally identified several partial models for simulating processes of the mango tree but not whole crop model (Normand et al. 2015). Research to further the development of a crop model would aid in the understanding of impacts and potential avenues for adaptation. Further to this, there is significant variation in production systems globally so regionally specific research is required to accurately develop adaptation practices. Key areas of research that would aid adaption in the Northern Territory include assessment of genotypes, chemical manipulation, protective cropping and breeding. Adapting to the other potential impacts of climate change will require research in the areas of fruit set (reproductive biology or floral function) and development, harvest timing and identification of new production areas.

5.4.1 Identify genotypes better adapted to climate extremes

Research to identify mango genotypes that are resilient to climate extremes both locally and internationally could ensure production continuation in existing production regions. There are indications that some mango genotypes currently in production through Asia may be less susceptible to extreme temperatures during floral induction. Conducting these assessments would require establishing new or using existing interstate and international partnerships to facilitate a transfer of knowledge and genetic material. To date, key research outcomes from mango programs funded by the Australian Centre for International Agricultural Research are progressing this area of research (Hickey et al. 2019).

5.4.2 Define limits for chemical based flower induction

In the last 20 years, significant advances have been made globally in understanding the phenological mechanism of mango flowering. This is critical to enabling the design of chemical and molecular solutions that manipulate specific components of the flowering process. There is significant research potential in this area. Chemical based management of mango flowering is a highly preferable adaptation practice as it requires little to no adjustments in existing production systems. However, other climate change impacts on existing production systems may warrant chemical and molecular solutions to mango flowering useless, if they target only mango flower induction. The opportunities and limits of chemical and molecular solutions need to be defined.

5.4.3 Investigate capacity of protective cropping (shade structures) to support flowering

Studies comparing netted and open field mango orchards have found that nets can be effective in reducing maximum temperatures, depending upon the cloud cover and humidity. However, this also causes minimum temperatures to increase (Medany et al. 2009). In another study, 90% and complete shading of leaves during cool, inductive conditions reduced or prevented floral induction. This is likely due to the inhibited development or translocation of the floral promoter that is producer in leaves of mango trees (Kulkarni 1991). Plastic shading reduced leaf temperature compared to sunlit natural conditions. In conditions with excessive solar radiation in hot climates, shading resulted in increased stomatal conductance and photosynthetic rates, especially from morning to midday. In these environments, shading increased the total number of fruits produced (Jutamanee et al. 2016). Investigation into the specific use of shade structures in mangoes for reducing temperatures during induction should be furthered.

5.4.4 Breeding

Previous mango breeding programs have not accounted for the temperature threshold for floral induction in selection of new cultivars. The thresholds developed in Clonan et al. (2020) enable the screening process required to select for resilience to high temperatures. As in this assessment, climate information should be integrated into new breeding programs.

Similarly, varieties of mango in other production areas across the world could be assessed for tolerance to climate change and incorporated into existing production systems. Traditional breeding programs can take several years, sometimes decades to develop and release new genetic material. Advances in gene editing, particularly CRISPR technology (see Wang et al. 2019), have the potential to drastically increase the speed of development of new cultivars. However, this would require investigating the genes associated with temperature thresholds for floral induction. However, impacts of the projected changes to days below and above threshold temperatures may extend beyond mango flower induction with potential impacts to areas such as tree growth, fruit development, biosecurity, health and market supply. Successful breeding will need to consider these implications.

5.4.5 Pollen viability, fruit set, retention, development and quality

Some research has been done to establish an understanding of the temperature relationships with other key mechanisms in the mango production cycle (Perez et al. 2019; Fitchett et al. 2016; Geetha et al. 2016; Gadallah et al. 2019). These studies suggest strong links between temperature and pollen germination and viability, fruit set, fruit retention, the rate of fruit development and the quality of fruit. The processes are vital in the production of quality mangoes. By expanding these studies to encompass commercial cultivars throughout the Northern Territory and then incorporating climate information, the impacts of climate change could be identified on the whole production system. This comprehensive assessment would provide a detailed timeline for impacts and inform the adequate development of adaptation.

5.4.6 Harvest timing

The timing of fruit harvest has significant flow-on effects for the entire supply chain, including influencing market prices. As changes in flower induction and conditions during fruit development directly influence harvest timing, further investigations could identify mechanisms for accurately forecasting this impact. The impacts of extreme events and other changes in climate need to be well understood and then integrated into crop forecast models. This should include evaluations of other production regions around Australia to establish the possible shifts in national supply of fruit to market as this may alter prices as supply and demand fluctuates.

5.4.7 New production sites

The methodology used in this assessment could be expanded to new regions with a focus on assessing suitability for mango production. However, a comprehensive assessment of suitability is required to minimise risk, and this would require incorporating several other growth factors into the assessment. Some relocation at the farm level is already happening in regions across Australia and much discussion on the topic is centred on opportunities for relocation to high rainfall regions of northern Australia. The Agriculture Land Suitability Evaluator (ALSE) has been used successfully to assess the suitability of land for mango production (Elsheikh et al. 2013). However, temperature requirements for mango flower induction are not considered within the ALSE. These could be included, as shown in the following assessment of suitability for mango production in Carnarvon, Western Australia.

Case study: Framework for assessment of suitability of Carnarvon for mango production

This is an example of the use of temperature thresholds and climate change data in the assessment of suitability of a region for mango production to demonstrate the utility and practical application of the results of this study – not to provide an accurate assessment of Carnarvon's suitability.

Current situation

There are 20 commercial mango growers in the Carnarvon region with a total area of approx. 130 ha. In 2015, around 1000 tonnes of mangoes were produced in Carnarvon with a value of ~$3.4 million.

Methodology

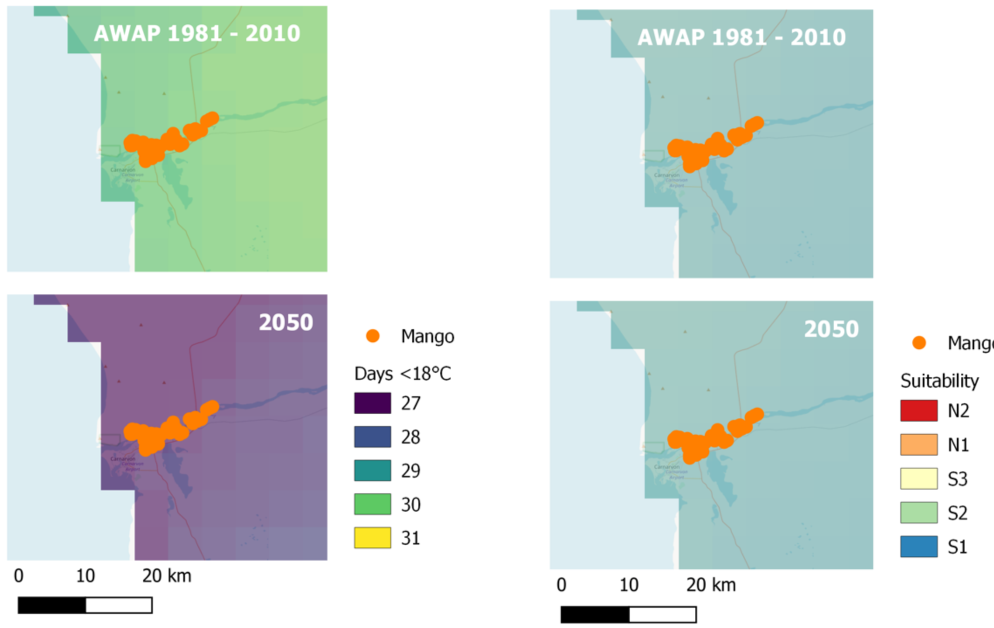
1. Select a time period (current, future period).
2. Collect data for each variable.
3. Grade suitability for each variable using the FAO's framework, with divisions of suitability classes that indicate the degree of suitability. These classes are: 'S1' = suitable, 'S2' = moderately suitable, 'S3' = marginally suitable, 'N1' = unsuitable for economic reasons but otherwise marginally suitable, 'N2' = unsuitable for physical reasons (FAO 1976, 1983, 2007).
4. Develop a weighting scheme specific for mango for each variable.
5. Amalgamate variables into an integrated suitability model.
6. Ground validation of final suitability assessment.

Potential variables for assessment

	Current conditions	Future conditions (2050, RCP8.5)
Climate	• Annual precipitation • Length of dry season • Days below 20°C (May–Aug): 120 • Days above 32°C (May–Aug): 2	• Annual precipitation • Length of dry season • Days below 20°C (May–Aug): 109 – 114 • Days above 32°C (May–Aug): 6 – 9
Soil	• pH • Depth to sulphate • Organic matter • Apparent CEC Clay • Base saturation • Coarse fragment • Soil depth • Texture/Structure • Porosity	• pH • Depth to sulphate • Organic matter • Apparent CEC Clay • Base saturation • Coarse fragment • Soil depth • Texture/Structure • Porosity
Topography	• Slope	• Slope
Infrastructure	• Distance to market • Availability of suitable transport	• Distance to market • Availability of suitable transport
Market viability	• Harvest timing/seasonality • Potential yield • Fruit quality	• Harvest timing/seasonality • Potential yield • Fruit quality
Water	• Quantity • Quality • Licensing/security	• Quantity • Quality • Licensing/security
Evaluation form	• Current suitability • Future suitability	• Current suitability • Future suitability

Results: example of variable specific assessment for mango flower induction

Days below 18ºC in Carnarvon **Suitability for mango production**



Map showing number of days in Carnarvon with minimum temperature below 18°C for current conditions (AWAP 1981–2010; top left) and projected conditions for 2050 (HadGEM2-CC, RCP8.5; bottom left) and the corresponding degree of suitability for mango production currently (top right) and in 2050 (bottom right).

Conclusion

Based solely on the number of days below 18°C in August, the Carnarvon region of Western Australia will remain suitable for mango production until the 2050 assessment period.

5.5 Broader applications of impact assessment

The impact assessment methodology used here can be applied to mango industries across Australia and the rest of the world. It can also be applied to other commodities.

Globally, mangoes are an important horticultural crop in tropical and subtropical communities. Further assessment of the key mango varieties globally would allow for a comprehensive assessment of the impact on mango production. This would require the consistent use of methodology for establishing temperature thresholds and identifying impacts of projected conditions. Similarly, the methodology could be applied to other commodities. Particularly, tropical and subtropical tree crops which exhibit similar limit to flowering as mango, such as lychee, macadamia and rambutan.

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Appendix: Data tables

Table A.1 Projected and historic number of days above/below temperature threshold for May. Range represents upper and lower values from seven global climate models.

Region	Temperature threshold (°C)	Historic 1981–2010	RCP 4.5				RCP 8.5			
			2016–2045	2036–2065	2056–2085	2076–2104	2016–2045	2036–2065	2056–2085	2076–2104
Ali Curung	< 18	28.8	26.6 - 28.2	26.0 – 26.6	25.9 – 26.4	24.5 – 24.6	26.6 – 26.9	23.7 – 26.6	18.9 – 25.2	12.3 – 22.1
	< 20	30.4	29.3 – 30.1	28.8 – 29.3	28.8 – 29.2	28.1 – 28.2	29.3 – 29.5	27.7 – 29.3	25.1 – 28.5	18.4 – 27.0
	> 32	3.1	5.4 – 7.4	6.8 – 8.9	7.2 – 10.4	10.2 – 12.0	6.4 – 7.7	7.5 – 11.7	8.9 – 15.2	9.7 – 21.3
	> 35	0.3	0.6 – 1.3	1.0 – 1.9	1.2 – 2.6	2.5 – 3.7	0.9 – 1.4	1.3 – 3.5	1.9 – 6.0	2.1 – 11.8
Batchelor	< 18	9.8	5.0 – 8.0	4.8 – 5.5	4.1 – 5.1	4.5 – 4.6	5.8 – 6.6	5.8 – 4.6	1.8 – 3.8	0.4 – 2.3
	< 20	16.4	10.6 – 13.8	10.2 – 11.2	9.2 – 10.6	9.7 – 10.0	11.7 – 12.5	10.0 – 11.6	5.3 – 8.8	2.1 – 6.2
	> 32	24.0	26.6 – 29.9	27.5 – 30.2	29.1 – 30.6	29.2 – 30.4	27.7 – 28.4	28.6 – 29.5	29.9 – 30.4	30.3 – 30.8
	> 35	2.3	5.2 – 18.7	6.8 – 22.9	12.6 – 26.7	13.5 – 24.9	7.1 – 9.2	10.2 – 15.2	19.0 – 25.4	24.3 – 29.4
Berry Springs	< 18	6.5	2.9 – 4.9	2.7 – 3.2	2.2 – 2.9	2.5 – 2.5	3.5 – 3.9	2.6 – 3.3	0.8 – 2.0	0.1 – 1.0
	< 20	12.7	7.6 – 10.9	7.1 – 8.1	6.0 – 7.5	6.7 – 6.7	8.8 – 9.4	6.7 – 8.3	3.2 – 5.7	1.1 – 3.6
	> 32	25.4	27.6 – 30.0	28.4 – 30.3	29.6 – 30.6	29.7 – 30.5	28.5 – 28.9	29.2 – 29.8	30.1 – 30.6	30.6 – 30.8
	> 35	1.6	4.4 – 18.5	6.3 – 23.0	12.8 – 26.9	13.9 – 25.1	6.6 – 8.8	10.6 – 16.1	20.3 – 26.3	25.7 – 29.7
Bynoe	< 18	3.3	1.1 – 2.4	0.9 – 1.3	0.6 – 1.0	0.7 – 0.8	1.6 – 1.8	0.8 – 1.3	0.2 – 0.5	0.1 – 0.2
	< 20	9.2	4.2 – 6.9	3.8 – 4.6	3.1 – 4.1	3.3 – 3.5	5.0 – 5.5	3.5 – 4.6	1.3 – 2.8	0.3 – 1.6
	> 32	25.1	27.4 – 29.9	28.2 – 30.1	29.5 – 30.5	29.6 – 30.3	28.3 – 28.8	29.1 – 29.8	30.0 – 30.6	30.5 – 30.8
	> 35	1.6	4.1 – 16.7	6.3 – 20.9	12.5 – 25.8	13.7 – 23.9	6.5 – 8.2	9.8 – 15.6	19.6 – 25.8	25.3 – 29.5
Carnarvon	< 18	25.2	20.8 – 20.9	19.5 – 22.2	19.0 – 20.7	18.6 – 19.8	21.6 – 21.6	16.6 – 20.6	14.8 – 17.3	9.5 – 14.6
	< 20	29.5	26.7 – 26.7	25.9 – 27.8	25.4 – 26.7	24.7 – 26.2	27.1 – 27.2	22.9 – 26.6	21.6 – 23.6	15.9 – 21.4
	> 32	2.1	4.1 – 4.9	3.8 – 4.4	5.1 – 5.4	5.0 – 5.5	4.2 – 4.2	5.3 – 6.5	7.4 – 7.7	8.8 – 11.6
	> 35	0.3	0.8 – 1.1	0.6 – 0.9	1.3 – 1.4	1.2 – 1.4	0.8 – 0.9	1.4 – 1.8	2.1 – 2.2	2.9 – 3.9
Greater Darwin	< 18	5.9	2.7 – 4.5	2.5 – 3.0	2.0 – 2.7	2.3 – 2.3	3.4 – 3.6	2.3 – 3.0	0.8 – 1.8	0.2 – 0.9
	< 20	12.3	7.1 – 10.3	6.6 – 7.7	5.6 – 7.1	6.2 – 6.3	8.4 – 8.7	6.2 – 7.7	3.0 – 5.3	1.1 – 3.3
	> 32	25.1	27.5 – 29.9	28.3 – 30.2	29.6 – 30.6	29.7 – 30.5	28.4 – 28.8	29.2 – 29.9	30.1 – 30.6	30.6 – 30.8
	> 35	0.9	3.0 – 16.3	4.7 – 21.1	10.6 – 26.2	11.8 – 23.8	5.1 – 6.4	8.7 – 14.4	19.3 – 26.0	25.4 – 29.7

Region	Temperature threshold (°C)	Historic 1981–2010	RCP 4.5				RCP 8.5			
			2016–2045	2036–2065	2056–2085	2076–2104	2016–2045	2036–2065	2056–2085	2076–2104
Katherine	< 18	17.7	12.1 – 15.6	10.4 – 12.6	10.0 – 12.3	8.3 – 11.2	12.9 – 13.6	11.9 – 12.7	6.7 – 9.7	3.3 – 7.3
	< 20	24.5	18.0 – 22.5	15.9 – 18.7	15.4 – 18.3	13.7 – 16.9	19.1 – 20.0	17.8 – 18.8	11.9 – 15.2	6.9 – 12.7
	> 32	17.7	20.6 – 27.6	22.1 – 29.1	25.1 – 29.7	26.2 – 29.9	22.4 – 23.4	24.5 – 26.9	27.6 – 29.4	28.9 – 30.4
	> 35	1.8	3.7 – 14.3	5.0 – 19.1	8.8 – 22.9	11.0 – 23.6	5.4 – 6.4	7.9 – 12.5	14.2 – 20.8	18 .0– 27.0
Kununurra	< 18	12.6	6.4 – 11.2	4.5 – 8.0	7.1 – 7.3	3.8 – 6.0	7.7 – 10.4	6.0 – 9.1	2.4 – 6.4	0.6 – 3.8
	< 20	18.8	11.9 – 16.7	9.7 – 13.5	12.5 – 12.7	8.6 – 11.5	13.1 – 15.8	11.5 – 14.6	6.0 – 11.9	2.8 – 8.6
	> 32	22.0	24.0 – 27.0	25.4 – 28.3	26.5 – 28.3	27.5 – 29.4	24.5 – 26.0	26.0 – 28.1	27.6 – 29.9	28.6 – 30.5
	> 35	7.8	10.1 – 16.1	12.7 – 20.0	14.9 – 20.0	17.6 – 23.3	11.0 – 14.0	14.1 – 19.6	17.9 – 25.1	20.8 – 28.2
Marrakai	< 18	9.5	4.9 – 7.7	4.7 – 5.5	4.1 – 5.0	4.5 – 4.6	5.9 – 6.4	4.6 – 5.5	2.1 – 3.8	0.6 – 2.5
	< 20	16.4	10.4 – 13.8	10.0 – 11.0	9.0 – 10.4	9.8 – 9.8	11.6 – 12.2	9.8 – 11.0	5.3 – 8.5	2.5 – 6.0
	> 32	25.6	27.9 – 30.1	28.4 – 30.4	29.5 – 30.7	29.6 – 30.6	28.5 – 29.0	29.4 – 29.9	30.2 – 30.7	30.6 – 30.8
	> 35	2.3	5.2 – 18.9	6.9 – 23.5	13.0 – 27.4	14.2 – 25.4	7.4 – 9.3	11.4 – 16.3	20.9 – 26.8	26.0 – 29.8
Mataranka	< 18	17.5	11.2 – 15.9	8.8 – 12.1	8.0 – 11.9	6.2 – 10.5	12.9 – 13.6	11.2 – 12.1	5.9 – 9.1	2.8 – 6.7
	< 20	24.0	17.5 – 22.4	15.1 – 18.5	14.1 – 18.3	11.7 – 16.8	19.1 – 19.7	17.5 – 18.5	11.2 – 15.4	6.2 – 12.3
	> 32	17.0	20.0 – 27.4	21.7 – 29.3	24.7 – 29.9	25.9 – 30.0	21.8 – 22.9	24.2 – 26.6	26.7 – 29.3	28.2 – 30.4
	> 35	1.4	2.7 – 14.8	4.0 – 20.1	7.9 – 24.6	10.4 – 25.1	4.2 – 5.4	6.9 – 13.0	13.0 – 20.7	16.8 – 26.4
Noonamah	< 18	5.9	2.7 – 4.4	2.4 – 2.9	2.0 – 2.6	2.3 – 2.3	3.2 – 3.5	2.3 – 2.9	0.6 – 1.8	0.1 – 0.8
	< 20	12.1	7.0 – 10.4	6.6 – 7.7	5.6 – 7.0	6.1 – 6.1	8.4 – 8.9	6.1 – 7.7	2.9 – 5.2	1.0 – 3.2
	> 32	25.4	27.6 – 30.0	28.4 – 30.3	29.6 – 30.6	29.7 – 30.5	28.6 – 28.8	29.3 – 29.9	30.1 – 30.6	30.6 – 30.8
	> 35	1.1	3.7 – 17.8	5.5 – 22.3	11.8 – 26.6	13.2 – 24.8	6.0 – 7.8	10.1 – 15.5	20.1 – 26.4	25.8 – 29.8
Pine Creek	< 18	13.4	7.7 – 11.4	6.9 – 8.2	6.4 – 7.8	6.1 – 7.0	8.1 – 9.6	7.6 – 8.5	3.2 – 6.0	0.9 – 4.0
	< 20	21.3	14.1 – 18.6	12.9 – 14.7	12.2 – 14.2	11.7 – 13.1	14.7 – 16.1	13.9 – 14.9	7.6 – 11.8	3.5 – 9.1
	> 32	17.9	21.0 – 28.2	23.1 – 29.6	26.1 – 29.9	26.7 – 29.8	23.4 – 25.1	25.5 – 27.1	28.3 – 29.8	29.6 – 30.6
	> 35	0.9	2.3 – 12.9	3.6 – 18.0	7.8 – 22.9	8.9 – 21.8	3.9 – 5.8	6.3 – 9.7	13.2 – 20.6	18.2 – 27.5
Tipperary	< 18	13.2	7.5 – 11.1	6.9 – 7.9	6.6 – 7.5	6.1 – 6.8	7.8 – 9.4	7.1 – 8.4	3.5 – 6.1	0.9 – 4.2
	< 20	20.6	13.8 – 18.3	13.0 – 14.6	12.4 – 13.7	11.6 – 12.6	14.2 – 16.3	13.1 – 15.1	7.1 – 11.5	3.3 – 8.8
	> 32	22.9	25.1 – 29.1	26.0 – 29.7	27.8 – 30.2	28.2 – 30.2	26.0 – 27.1	27.1 – 28.5	29.1 – 30.1	29.8 – 30.6
	> 35	4.6	7.5 – 18.9	9.0 – 22.7	14.1 – 25.1	15.3 – 25.0	9.0 – 11.8	11.8 – 16.0	19.1 – 24.4	23.1 – 28.7

Table A.2 Projected and historic number of days above/below temperature threshold for June. Range represents upper and lower values from seven global climate models.

Region	Temperature threshold (°C)	Historic 1981–2010	RCP 4.5				RCP 8.5			
			2016–2045	2036–2065	2056–2085	2076–2104	2016–2045	2036–2065	2056–2085	2076–2104
Ali Curung	< 18	29.8	29.6 – 29.5	28.8 – 29.4	28.6 – 29.4	28.2 – 28.6	28.6 – 29.5	28.5 – 29.3	27.5 – 28.1	24.9 – 27.9
	< 20	30.0	30.0 – 30.0	29.7 – 29.9	29.7 – 30.0	29.5 – 29.7	29.7 – 30.0	29.6 – 29.9	29.2 – 29.5	28.0 – 29.4
	> 32	0.4	0.8 – 1.6	1.3 – 2.5	1.0 – 4.5	2.5 – 4.8	0.8 – 1.3	1.3 – 3.0	2.8 – 4.4	3.3 – 7.3
	> 35	0.0	0 – 0	0 – 0.1	0 – 0.5	0.1 – 0.5	0 – 0	0 – 0.2	0.2 – 0.5	0.3 – 2.1
Batchelor	< 18	19.5	15.1 – 16.9	10.5 – 15.4	10.3 – 14.9	10.7 – 10.9	11.4 – 14.5	10.9 – 13.3	6.4 – 9.3	3.2 – 8.3
	< 20	26.7	23.3 – 24.8	18.2 – 23.6	17.9 – 23.1	18.5 – 18.8	19.5 – 22.8	18.8 – 21.7	11.6 – 16.6	7.5 – 14.5
	> 32	12.4	16.4 – 19.6	16.7 – 23.2	18.8 – 24.5	21.7 – 24.1	19.3 – 20.2	20.6 – 22.8	24.9 – 26.2	25.7 – 28.8
	> 35	0.2	1.0 – 2.2	1.1 – 5.8	1.8 – 8.1	3.9 – 7.2	2.1 – 2.6	2.9 – 5.2	9.0 – 12.5	11.3 – 21.5
Berry Springs	< 18	15.7	11.8 – 13.1	8.5 – 12.0	8.2 – 11.6	8.6 – 8.7	9.6 – 11.2	8.6 – 10.3	4.9 – 7.2	2.1 – 6.0
	< 20	24.5	20.3 – 22.0	15.1 – 20.6	14.6 – 20.0	15.2 – 15.4	16.9 – 19.6	15.2 – 18.3	9.9 – 13.0	5.9 – 11.3
	> 32	13.7	18.1 – 20.7	18.5 – 24.3	20.1 – 25.2	23.3 – 24.9	20.5 – 21.4	21.9 – 24.1	26.0 – 27.3	27.0 – 29.2
	> 35	0.1	0.9 – 2.1	1.0 – 5.7	1.8 – 7.9	4.3 – 7.0	2.0 – 2.6	3.1 – 5.4	9.5 – 13.4	12.2 – 22.6
Bynoe	< 18	11.1	8.2 – 9.4	5.2 – 8.4	4.9 – 8.0	5.1 – 5.3	6.4 – 7.7	5.1 – 6.9	2.3 – 4.0	0.7 – 3.1
	< 20	20.2	15.6 – 17.5	11.0 – 15.9	10.5 – 15.3	10.8 – 11.1	12.5 – 14.6	10.8 – 13.3	6.8 – 9.3	3.2 – 7.8
	> 32	12.4	17.3 – 20.5	17.8 – 24.0	19.9 – 24.9	23.4 – 24.7	20.4 – 21.2	22.0 – 24.0	25.8 – 27.0	26.8 – 29.2
	> 35	0.0	0.3 – 1.3	1.4 – 4.7	1.0 – 6.7	3.6 – 6.2	1.3 – 1.6	2.2 – 4.8	8.7 – 11.8	11.3 – 22.4
Carnarvon	< 18	28.1	26.7 – 27.0	26.2 – 26.9	26.1 – 26.4	25.6 – 26.2	26.7 – 27.1	26.0 – 26.2	23.0 – 24.7	21.4 – 22.9
	< 20	29.8	29.2 – 29.4	28.8 – 29.4	28.5 – 29.0	28.2 – 28.8	29.2 – 29.5	28.5 – 28.8	27.0 – 27.8	26.1 – 26.9
	> 32	0.0	0 – 0.1	0 – 0.1	0.1 – 0.2	0.1 – 0.1	0.– 0.0	0.2 – 0.2	0.6 – 1.1	1.3 – 2.6
	> 35	0.0	0 – 0	0 – 0	0 – 0	0 – 0	0 – 0	0 – 0	0 – 0	0 – 0.1
Greater Darwin	< 18	15.7	11.9 – 13.3	8.5 – 12.2	8.2 – 11.7	8.6 – 8.7	9.8 – 11.3	8.5 – 10.3	5.2 – 7.2	2.3 – 6.0
	< 20	24.3	20.2 – 21.9	15.4 – 20.6	15.0 – 20.0	15.5 – 15.7	17.4 – 19.5	15.4 – 18.1	10.3 – 13.3	6.2 – 11.5
	> 32	13.1	17.8 – 20.5	18.3 – 24.2	20.0 – 25.2	23.2 – 24.9	20.4 – 21.1	21.7 – 24.2	25.9 – 27.3	27.1 – 29.2
	> 35	0.1	0.6 – 1.7	0.8 – 4.7	1.4 – 6.6	3.7 – 6.0	1.6 – 2.2	2.7 – 4.7	8.4 – 12.4	11.2 – 22.3

Region	Temperature threshold (°C)	Historic 1981–2010	RCP 4.5				RCP 8.5			
			2016–2045	2036–2065	2056–2085	2076–2104	2016–2045	2036–2065	2056–2085	2076–2104
Katherine	< 18	24.8	22.9 – 23.2	19.5 – 22.1	18.6 – 21.8	18.5 – 19.0	18.5 – 21.5	19.0 – 20.8	12.5 – 16.0	9.0 – 14.9
	< 20	28.5	27.3 – 27.6	24.5 – 26.7	23.7 – 26.5	23.6 – 24.1	23.6 – 26.2	24.0 – 25.7	18.6 – 21.7	14.1 – 20.6
	> 32	6.5	8.7 – 11.7	9.5 – 15.5	11.0 – 17.5	14.9 – 17.6	12.7 – 13.3	14.4 – 17.5	19.8 – 21.7	20.2 – 26.1
	> 35	0.0	0.1 – 0.7	0.2 – 2.4	0.5 – 3.7	2.0 – 3.8	0.9 – 1.2	1.7 – 3.7	5.8 – 8.9	6.5 – 16.2
Kununurra	< 18	22.2	19.3 – 20.6	16.2 – 19.0	15.2 – 19.1	13.6 – 14.5	11.8 – 19.5	13.0 – 18.1	7.5 –12.8	4.1 – 11.2
	< 20	27.2	25.3 – 26.2	22.8 – 25.1	21.9 – 25.1	20.4 – 21.3	18.5 – 25.6	19.6 – 24.4	13.3 – 19.5	9.4 – 17.9
	> 32	10.3	11.7 – 14.8	12.6 – 16.7	13.2 – 19.3	16.5 – 20.0	14.3 – 15.3	16.2 – 18.9	20.2 – 22.7	21.2 – 26.8
	> 35	0.5	1.0 – 3.8	1.6 – 5.9	2.2 – 8.6	5.6 – 9.4	3.3 – 4.3	5.3 – 8.3	9.6 – 12.5	10.7 – 18.3
Marrakai	< 18	20.1	15.9 – 17.5	11.4 – 16.3	11.2 – 15.6	11.7 – 11.8	12.6 – 15.1	11.5 – 13.7	7.6 – 10.2	4.2 – 9.0
	< 20	26.9	23.9 – 25.3	19.4 – 24.2	18.9 – 23.7	19.8 – 19.9	20.8 – 23.2	19.6 – 22.0	12.9 – 17.3	8.7 – 15.1
	> 32	14.6	18.2 – 21.1	18.9 – 24.6	20.4 – 25.5	23.3 – 25.1	20.8 – 21.7	22.0 – 24.4	26.0 – 27.4	27.0 – 29.2
	> 35	0.6	1.4 – 2.9	1.6 – 6.4	2.4 – 9.2	5.0 – 7.9	2.7 – 3.3	3.7 – 6.1	10.7 – 14.5	13.0 – 22.8
Mataranka	< 18	25.4	23.5 – 23.8	18.7 – 22.7	17.2 – 22.6	17.1 – 18.8	18.2 – 22.5	18.4 – 21.7	13.2 – 16.4	9.4 – 15.2
	< 20	28.8	27.6 – 27.8	24.5 – 27.1	23.4 – 27.0	23.3 – 24.5	24.1 – 27.0	24.3 – 26.3	18.2 – 22.6	14.7 – 21.6
	> 32	5.9	7.8 – 11.0	9.0 – 14.5	10.7 – 16.7	14.6 – 17.1	11.9 – 12.7	13.9 – 17.5	18.9 – 21.2	19.4 – 25.5
	> 35	0.0	0.0 – 0.4	0.1 – 1.3	0.3 – 2.9	1.4 – 3.4	0.6 – 0.8	1.2 – 3.8	5.0 – 8.8	5.7 – 16.1
Noonamah	< 18	15.2	11.4 – 12.6	8.4 – 11.6	8.0 – 11.2	8.4 – 8.5	9.5 – 11.0	8.4 – 10.2	4.8 – 6.9	2.0 – 5.7
	< 20	24.4	20.1 – 21.6	14.7 – 20.4	14.2 – 19.9	14.8 – 15.0	16.8 – 19.4	14.8 – 18.0	9.9 – 12.6	5.7 – 11.1
	> 32	13.7	18.1 – 20.7	18.6 – 24.3	20.1 – 25.2	23.4 – 24.9	20.5 – 21.3	22.0 – 24.2	26.1 – 27.4	27.1 – 29.3
	> 35	0.1	0.8 – 2.0	0.9 – 5.2	1.6 – 7.2	4.2 – 6.7	1.9 – 2.5	3.0 – 5.1	9.1 – 13.1	12.0 – 22.6
Pine Creek	< 18	22.7	19.9 – 20.9	15.8 – 19.5	15.1 – 19.2	15.6 – 15.7	15.0 – 18.8	15.7 – 18.0	8.6 – 12.6	4.9 – 11.3
	< 20	28.3	25.9 – 26.3	22.5 – 25.9	21.8 – 25.6	22.2 – 22.3	21.6 – 25.1	22.2 – 24.4	15.1 – 19.8	9.9 – 18.4
	> 32	5.9	8.7 – 12.5	9.4 – 17.4	11.3 – 19.3	16.1 – 18.8	12.7 – 13.8	15.0 – 17.8	20.7 – 22.6	21.3 – 26.9
	> 35	0.0	0.2 – 0.8	0.2 – 2.1	0.6 – 3.1	1.6 – 3.0	0.8 – 0.9	1.1 – 2.4	4.7 – 7.2	5.6 – 16.9
Tipperary	< 18	23.2	20.0 – 21.0	15.0 – 19.5	14.7 – 19.1	14.6 – 14.7	14.0 – 18.7	14.6 – 17.8	7.4 – 12.3	4.4 – 10.8
	< 20	28.3	26.3 – 26.7	22.9 – 25.9	22.4 – 25.6	22.3 – 22.4	21.5 – 25.4	22.3 – 24.9	13.9 – 19.8	8.4 – 18.4
	> 32	11.8	14.5 – 17.3	14.7 – 21.0	16.4 – 22.6	19.9 – 22.5	17.4 – 18.5	18.9 – 21.2	23.4 – 24.7	24.2 – 28.1
	> 35	0.5	1.4 – 2.9	1.5 – 7.2	2.4 – 9.0	5.7 – 8.9	3.1 – 4.1	4.7 – 7.3	10.1 – 12.5	11.5 – 20.5

Table A.3 Projected and historic number of days above/below temperature threshold for July. Range represents upper and lower values from seven global climate models.

Region	Temperature threshold (°C)	Historic 1981–2010	RCP 4.5				RCP 8.5			
			2016–2045	2036–2065	2056–2085	2076–2104	2016–2045	2036–2065	2056–2085	2076–2104
Ali Curung	< 18	30.8	30.6 – 30.8	30.4 – 30.6	30.5 – 30.6	30.3 – 30.4	30.5 – 30.6	30.4 – 30.6	29.6 – 29.8	29.1 – 29.5
	< 20	31.0	31.0 – 31.0	30.8 – 31.0	30.9 – 31.0	30.8 – 30.8	30.8 – 31.0	30.8 – 31.0	30.6 – 30.6	30.2 – 30.5
	> 32	0.2	0.3 – 0.7	0.4 – 1.4	1.0 – 1.4	1.0 – 1.8	0.4 – 0.9	0.7 – 1.1	2.0 – 3.5	1.5 – 5.3
	> 35	0.0	0 – 0	0 – 0.1	0 – 0.1	0 – 0.1	0 – 0	0 – 0.1	0.1 – 0.4	0.1 – 1
Batchelor	< 18	23.6	21.2 – 23.4	17.7 – 19.3	18.7 – 19.0	15.7 – 17.0	18.8 – 19.6	15.7 – 18.9	9.3 – 12.1	6.0 – 9.6
	< 20	28.5	27.1 – 28.5	24.3 – 25.7	25.2 – 25.4	22.9 – 23.8	25.3 – 25.9	22.9 – 25.4	17.1 – 20.4	12.3 – 17.4
	> 32	12.6	13.2 – 18.1	18.3 – 22.1	21.3 – 22.3	23.0 – 24.6	18.2 – 19.2	21.8 – 23.3	27.2 – 28.9	28.6 – 29.7
	> 35	0.4	0.5 – 1.2	1.3 – 2.6	2.2 – 2.6	3.1 – 4.1	1.3 – 1.5	2.4 – 3.3	8.6 – 13.7	12.7 – 20.3
Berry Springs	< 18	21.4	18.6 – 21.1	14.6 – 16.4	15.7 – 15.8	12.7 – 13.8	15.9 – 16.6	12.7 – 15.8	7.0 – 9.5	3.9 – 6.9
	< 20	27.5	25.4 – 27.3	22.6 – 23.9	23.4 – 23.5	21.1 – 22.0	23.5 – 24.0	21.2 – 23.5	14.4 – 17.8	10.1 – 14.3
	> 32	13.5	14.4 – 19.2	19.8 – 23.3	22.6 – 23.3	24.4 – 26.1	19.8 – 20.9	23.0 – 25.0	28.3 – 29.3	29.3 – 30.1
	> 35	0.5	0.5 – 1.2	1.3 – 2.4	2.1 – 2.4	2.8 – 4.2	1.3 – 1.6	2.3 – 3.2	8.9 – 13.9	13.4 – 21.2
Bynoe	< 18	16.1	12.8 – 15.9	9.2 – 10.9	10.1 – 10.1	7.6 – 8.6	10.3 – 10.8	7.8 – 10.1	3.0 – 4.8	1.3 – 2.7
	< 20	24.5	21.7 – 24.4	18.1 – 19.9	19.2 – 19.2	15.9 – 17.3	19.5 – 19.9	16.3 – 19.3	9.5 – 12.2	5.8 – 9.1
	> 32	11.0	16.8 – 12.0	17.6 – 21.8	21.0 – 21.5	22.7 – 24.8	17.8 – 18.9	21.3 – 23.4	27.7 – 29.0	29.0 – 30.1
	> 35	0.2	0.3 – 0.8	0.9 – 1.8	1.6 – 1.7	2.2 – 3.5	0.9 – 1.0	1.6 – 2.6	7.0 – 11.0	11.0 – 19.0
Carnarvon	< 18	30.4	30.0 – 30.0	29.8 – 30.0	29.5 – 29.7	29.1 – 29.7	29.5 – 29.9	29.0 – 29.1	27.3 – 28.1	26.0 – 27.8
	< 20	31.0	30.8 – 30.9	30.8 – 30.9	30.7 – 30.8	30.6 – 30.7	30.6 – 30.8	30.5 – 30.6	29.8 – 30.1	29.3 – 30.0
	> 32	0.0	0 – 0	0 – 0	0 – 0	0 – 0	0 – 0	0 – 0.1	0.2 – 0.3	0.4 – 1.2
	> 35	0.0	0 – 0	0 – 0	0 – 0	0 – 0	0 – 0	0 – 0	0 – 0	0 – 0
Greater Darwin	< 18	21.4	18.8 – 21.0	15.0 – 16.8	16.1 – 16.1	13.2 – 14.2	16.2 – 16.8	13.2 – 16.1	7.4 – 9.9	4.4 – 7.2
	< 20	27.5	25.8 – 27.2	22.9 – 24.3	23.7 – 23.7	21.4 – 22.3	23.9 – 24.2	21.4 – 23.7	15.1 – 18.1	10.6 – 14.8
	> 32	12.6	13.6 – 18.3	19.0– 22.8	22.1 – 22.8	23.9 – 25.8	19.0 – 20.2	22.6 – 24.8	28.3 – 29.2	29.2 – 30.2
	> 35	0.4	0.5 – 1.1	1.2 – 2.0	1.8 – 2.0	2.4 – 3.7	1.2 – 1.4	1.9 – 2.8	7.9 – 12.5	12.2 – 20.1

Region	Temperature threshold (°C)	Historic 1981–2010	RCP 4.5				RCP 8.5			
			2016–2045	2036–2065	2056–2085	2076–2104	2016–2045	2036–2065	2056–2085	2076–2104
Katherine	< 18	27.6	25.9 – 28.3	24.6 – 25.1	24.6 – 25.1	22.9 – 24.1	24.4 – 24.5	22.7 – 24.3	17.8 – 19.6	15.2 – 16.6
	< 20	29.7	29.1 – 30.1	28.3 – 28.6	28.2 – 28.6	27.1 – 27.9	28.1 – 28.2	26.8 – 28.0	23.2 – 24.4	21.2 – 22.4
	> 32	5.7	5.4 – 10.1	9.3 – 13.0	11.3 – 13.5	12.3 – 16.8	9.7 – 10.0	13.4 – 15.4	19.6 – 24.0	22.4 – 26.7
	> 35	0.1	0.1 – 0.7	0.6 – 1.2	0.9 – 1.3	1.1 – 2.6	0.6 – 0.7	1.3 – 2.0	4.0 – 8.7	6.5 – 13.5
Kununurra	< 18	24.9	22.8 – 27.0	21.6 – 22.2	21.3 – 23.3	18.9 – 21.3	20.2 – 22.4	17.6 – 21.5	12.0 – 15.6	9.7 – 12.6
	< 20	28.7	27.5 – 29.8	26.6 – 27.1	26.3 – 27.8	24.2 – 26.3	25.2 – 27.3	23.3 – 26.5	19.0 – 21.8	16.7 – 19.4
	> 32	10.7	8.3 – 14.7	13.7 – 16.3	15.4 – 17.0	16.4 – 19.6	14.5 – 15.4	17.8 – 18.1	23.3 – 25.0	23.9 – 26.9
	> 35	1.0	0.5 – 2.5	2.0 – 3.6	2.9 – 4.2	3.7 – 6.3	2.4 – 2.9	4.7 – 4.9	11.4 – 14.2	12.3 – 17.2
Marrakai	< 18	24.7	22.5 – 24.2	19.5 – 21.1	20.6 – 20.6	17.9 – 18.9	20.6 – 21.0	17.6 – 20.5	11.1 – 13.8	7.8 – 11.1
	< 20	29.2	27.9 – 29.1	25.6 – 26.7	26.2 – 26.2	24.4 – 25.2	26.2 – 26.6	24.2 – 26.2	19.0 – 21.9	14.4 – 19.0
	> 32	15.0	15.9 – 20.3	21.0 – 24.1	23.5 – 24.2	24.8 – 26.4	20.7 – 21.7	23.9 – 25.3	28.4 – 29.3	29.2 – 30.1
	> 35	0.7	0.9 – 1.7	1.9 – 3.7	3.3 – 3.7	4.1 – 6.2	1.8 – 2.2	3.5 – 4.6	10.6 – 15.6	14.7 – 22.2
Mataranka	< 18	27.9	26.6 – 28.4	24.7 – 25.6	25.0 – 25.2	23.8 – 24.2	25.1 – 25.2	23.9 – 24.8	18.5 – 19.9	16.4 – 17.0
	< 20	29.9	29.1 – 30.2	28.1 – 28.6	28.3 – 28.4	27.7 – 27.9	28.4 – 28.4	27.7 – 28.2	24.2 – 25.0	22.5 – 23.3
	> 32	4.9	4.3 – 8.9	8.2 – 10.9	9.3 – 12.3	10.0 – 16.0	8.7 – 9.1	12.1 – 14.7	18.9 – 23.5	21.6 – 26.3
	> 35	0.1	0.1 – 0.5	0.4 – 0.7	0.5 – 1.0	0.6 – 2.0	0.5 – 0.5	0.9 – 1.7	3.4 – 7.9	5.6 – 12.3
Noonamah	< 18	21.6	18.4 – 21.1	14.4 – 16.4	15.7 – 15.8	12.4 – 13.6	15.9 – 16.4	12.5 – 15.8	6.9 – 9.4	3.7 – 6.7
	< 20	27.6	25.5 – 27.2	22.6 – 23.8	23.3 – 23.3	21.4 – 22.0	23.4 – 23.8	21.5 – 23.3	14.4 – 17.7	10.0 – 14.2
	> 32	13.4	14.2 – 18.9	19.6 – 23.1	22.5 – 23.1	24.6 – 26.2	19.6 – 20.8	22.8 – 25.2	28.4 – 29.4	29.3 – 30.2
	> 35	0.4	0.5 – 1.2	1.2 – 2.2	1.9 – 2.2	2.5 – 4.1	1.2 – 1.5	2.2 – 3.0	8.5 – 13.5	13.1 – 20.9
Pine Creek	< 18	26.2	23.8 – 26.8	21.5 – 22.2	21.7 – 22.4	19.2 – 20.5	21.2 – 21.9	18.8 – 21.4	12.5 – 15.4	9.4 – 12.6
	< 20	29.5	28.7 – 29.7	27.2 – 27.6	27.3 – 27.7	25.5 – 26.7	27.1 – 27.4	25.2 – 27.1	19.2 – 22.3	16.3 – 19.3
	> 32	5.3	5.6 – 10.2	9.8 – 14.2	12.7 – 14.4	14.2 – 17.3	9.8 – 10.5	13.9 – 15.5	20.7 – 24.7	23.5 – 27.5
	> 35	0.0	0 – 0.3	0.3 – 0.7	0.5 – 0.7	0.7 – 1.7	0.3 – 0.4	0.6 – 1.0	3.1 – 7.8	5.9 – 13.7
Tipperary	< 18	26.3	23.8 – 26.9	21.6 – 22.1	21.7 – 22.6	18.9 – 20.5	21.2 – 22.2	18.3 – 21.7	11.9 – 15.3	8.6 – 12.8
	< 20	29.3	28.5 – 29.5	27.2 – 27.5	27.2 – 27.9	25.4 – 26.6	27.0 – 27.6	25.1 – 27.2	18.6 – 22.4	14.8 – 19.5
	> 32	12.5	12.4 – 17.2	16.9 – 20.1	19.2 – 20.2	20.4 – 22.7	17.0 – 17.5	19.9 – 20.8	25.5 – 27.6	26.8 – 29.1
	> 35	0.7	0.7 – 2.0	1.9 – 3.4	2.7 – 3.5	3.6 – 5.4	1.9 – 2.1	3.2 – 4.1	9.5 – 14.5	12.7 – 19.6

Table A.4 Projected and historic number of days above/below temperature threshold for August. Range represents upper and lower values from seven global climate models.

Region	Temperature threshold (°C)	Historic 1981–2010	RCP 4.5				RCP 8.5			
			2016–2045	2036–2065	2056–2085	2076–2104	2016–2045	2036–2065	2056–2085	2076–2104
Ali Curung	< 18	29.9	27.5 – 29.2	27.4 – 29.3	27.2 – 28.6	26.2 – 28.5	28.2 – 29.6	27.3 – 28.8	23.5 – 28.1	20.9 – 26.8
	< 20	30.8	29.3 – 30.5	29.2 – 30.5	28.9 – 30.2	28.3 – 30.1	29.9 – 30.7	29.0 – 30.3	27.3 – 29.8	25.3 – 28.6
	> 32	4.0	5.4 – 12.1	5.8 – 12.3	7.1 – 12.8	6.8 – 13.0	4.0 – 8.0	7.3 – 10.3	8.0 – 14.8	7.3 – 18.3
	> 35	0.5	0.9 – 5.1	1.0 – 5.5	1.4 – 5.9	1.3 – 6.1	0.5 – 2.1	1.5 – 3.8	2.1 – 7.9	1.6 – 10.7
Batchelor	< 18	19.6	16.1 – 16.2	13.3 – 16.4	13.0 – 14.2	10.6 – 12.2	12.3 – 15.9	8.9 – 13.1	3.9 – 8.2	1.8 – 4.6
	< 20	26.7	24.4 – 24.5	22.0 – 24.6	21.7 – 22.8	19.4 – 20.9	21.0 – 24.3	17.5 – 21.7	9.7 – 16.5	5.5 – 11.0
	> 32	23.6	26.1 – 27.2	26.2 – 28.2	27.4 – 28.1	28.3 – 29.4	26.1 – 28.7	28.8 – 29.7	29.9 – 30.6	30.5 – 30.8
	> 35	2.5	4.9 – 6.7	5.1 – 9.3	7.1 – 8.8	9.4 – 14.7	4.9 – 10.9	11.3 – 16.5	18.7 – 26.5	24.5 – 29.0
Berry Springs	< 18	16.2	12.9 – 13.2	10.2 – 13.0	10.0 – 10.9	8.0 – 8.9	9.3 – 12.6	6.5 – 9.8	2.7 – 5.7	1.2 – 3.2
	< 20	24.7	21.9 – 22.1	19.3 – 21.9	19.1 – 20.0	16.6 – 17.9	18.3 – 21.6	14.5 – 18.8	7.4 – 13.4	4.2 – 8.4
	> 32	24.2	26.9 – 27.6	27.0 – 28.8	28.0 – 28.6	29.0 – 29.7	27.0 – 29.2	29.4 – 29.9	30.3 – 30.7	30.6 – 30.9
	> 35	1.9	4.0 – 5.0	4.1 – 7.7	6.0 – 7.5	8.2 – 13.0	4.0 – 9.0	10.1 – 14.7	18.4 – 26.2	24.9 – 29.3
Bynoe	< 18	11.2	8.4 – 8.6	6.3 – 8.4	6.1 – 7.0	4.6 – 5.4	5.8 – 8.1	3.6 – 6.1	1.0 – 2.9	0.4 – 1.1
	< 20	21.4	18.1 – 18.5	14.9 – 18.1	14.5 – 15.9	11.8 – 13.3	14.0 – 17.7	9.9 – 14.4	4.7 – 8.7	2.1 – 5.0
	> 32	20.5	25.0 – 25.6	25.4 – 27.9	26.9 – 27.8	28.3 – 29.6	25.1 – 28.2	28.8 – 29.7	30.2 – 30.7	30.7 – 30.9
	> 35	1.3	2.9 – 3.3	3.2 – 5.2	4.2 – 5.2	5.8 – 8.6	3.0 – 5.7	6.4 – 9.7	13.9 – 22.9	21.4 – 28.2
Carnarvon	< 18	29.9	28.7 – 28.8	28.0 – 28.3	27.7 – 27.9	27.4 – 27.5	28.3 – 29.0	27.1 – 28.1	26.0 – 26.9	23.2 – 26.2
	< 20	31.0	30.5 – 30.7	30.2 – 30.3	30.1 – 30.2	30.1 – 30.1	30.2 – 30.7	29.9 – 30.2	29.0 – 29.9	27.5 – 29.2
	> 32	0.0	0.1 – 0.2	0.4 – 0.5	0.5 – 0.9	0.5 – 0.9	0.1 – 0.3	0.5 – 0.5	0.8 – 0.9	1.0 – 2.0
	> 35	0.0	0 – 0	0 – 0	0 – 0	0 – 0	0 – 0	0 – 0	0 – 0	0 – 0.1
Greater Darwin	< 18	15.9	12.7 – 13.1	10.2 – 12.6	10.1 – 10.8	8.0 – 8.9	9.2 – 12.4	6.4 – 9.6	2.7 – 5.6	1.2 – 3.1
	< 20	24.3	21.6 – 22.0	19.2 – 21.5	18.9 – 19.7	16.6 – 17.7	18.1 – 21.3	14.4 – 18.4	7.6 – 13.1	4.3 – 8.5
	> 32	23.1	26.4 – 27.1	26.5 – 28.4	27.9 – 28.3	28.7 – 29.6	26.6 – 28.9	29.3 – 29.8	30.2 – 30.7	30.7 – 30.9
	> 35	1.7	3.2 – 3.9	3.3 – 6.3	4.9 – 6.1	7.0 – 11.3	3.4 – 7.7	9.1 – 12.8	17.0 – 25.0	24.0 – 28.8

Region	Temperature threshold (°C)	Historic 1981–2010	RCP 4.5				RCP 8.5			
			2016–2045	2036–2065	2056–2085	2076–2104	2016–2045	2036–2065	2056–2085	2076–2104
Katherine	< 18	23.0	21.3 – 21.4	19.7 – 21.8	19.0 – 20.3	17.2 – 19.1	17.7 – 21.4	15.1 – 19.4	8.5 – 15.4	5.8 – 10.0
	< 20	26.8	25.2 – 25.4	24.1 – 25.7	23.6 – 24.4	22.5 – 23.7	22.8 – 25.3	20.8 – 23.9	14.6 – 21.1	11.4 – 16.2
	> 32	18.8	20.9 – 24.7	20.2 – 24.8	22.7 – 24.5	23.5 – 26.6	20.4 – 25.5	24.8 – 28.3	27.4 – 30.3	29.2 – 30.5
	> 35	4.4	5.9 – 9.6	5.4 – 9.7	7.3 – 9.4	8.1 – 13.1	5.5 – 10.9	9.7 – 17.2	14.9 – 25.6	20.0 – 27.8
Kununurra	< 18	20.6	15.9 – 18.4	15.0 – 19.1	15.2 – 17.4	11.9 – 15.5	14.3 – 19.6	10.5 – 17.5	3.8 – 11.5	2.2 – 6.5
	< 20	26.4	22.1 – 24.2	21.3 – 24.9	21.5 – 23.3	18.9 – 21.8	20.7 – 25.5	17.9 – 23.3	10.1 – 18.7	6.4 – 13.2
	> 32	22.3	23.4 – 26.8	23.2 – 26.8	24.4 – 27.2	25.0 – 28.5	23.9 – 26.7	26.4 – 28.8	28.7 – 30.3	29.4 – 30.6
	> 35	7.6	9.7 – 16.7	9.3 – 16.8	11.9 – 17.6	13.0 – 20.6	10.8 – 16.6	15.9 – 21.2	21.0 – 26.8	23.0 – 28.8
Marrakai	< 18	20.0	17.4 – 17.7	14.5 – 17.4	14.3 – 15.3	11.8 – 13.0	13.0 – 16.7	10.0 – 13.6	4.9 – 9.0	2.5 – 5.5
	< 20	26.6	24.8 – 24.9	22.8 – 24.7	22.5 – 23.3	20.4 – 21.2	21.3 – 24.5	18.6 – 21.9	10.7 – 17.5	6.7 – 11.9
	> 32	25.4	27.3 – 28.0	27.3 – 28.8	28.3 – 28.6	28.8 – 29.7	27.4 – 29.3	29.4 – 29.9	30.3 – 30.7	30.6 – 30.9
	> 35	3.7	6.9 – 8.7	6.9 – 11.7	9.6 – 11.2	12.0 – 16.5	7.1 – 13.4	14.6 – 18.7	22.0 – 27.3	26.3 – 29.3
Mataranka	< 18	24.7	23.1 – 23.3	21.0 – 23.7	20.1 – 22.1	18.5 – 21.4	19.5 – 23.4	16.7 – 21.9	10.0 – 17.7	7.2 – 12.6
	< 20	28.3	27.3 – 27.5	25.3 – 27.7	24.6 – 26.4	23.7 – 25.6	24.3 – 27.6	22.5 – 26.0	16.2 – 23.3	13.5 – 18.8
	> 32	17.1	19.4 – 23.6	18.6 – 23.0	21.3 – 22.8	21.8 – 25.6	18.9 – 24.6	23.4 – 27.8	26.4 – 30.2	28.5 – 30.4
	> 35	3.3	4.6 – 8.0	4.1 – 7.4	6.1 – 7.3	6.5 – 10.7	4.3 – 9.2	7.8 – 16.1	12.3 – 25.0	17.4 – 27.0
Noonamah	< 18	15.8	12.5 – 12.9	9.7 – 12.5	9.5 – 10.4	7.7 – 8.5	8.9 – 12.1	6.0 – 9.1	2.4 – 5.2	1.0 – 3.0
	< 20	24.4	21.5 – 21.9	19.0 – 21.5	18.8 – 19.8	16.3 – 17.4	17.9 – 21.3	14.3 –	7.4 – 13.0	4.1 – 8.1
	> 32	24.0	26.9 – 27.5	27.1 – 28.6	28.1 – 28.5	29.0 – 29.7	27.1 – 29.2	29.4 – 29.8	30.3 – 30.7	30.7 – 30.9
	> 35	1.7	3.5 – 4.3	3.6 – 6.8	5.5 – 6.5	7.6 – 12.2	3.6 – 8.4	9.5 – 13.9	17.7 – 25.8	24.6 – 29.2
Pine Creek	< 18	21.7	19.1 – 19.2	16.9 – 19.3	16.3 – 17.4	13.6 – 15.5	14.5 – 18.7	11.2 – 15.8	4.6 – 11.0	2.6 – 5.4
	< 20	26.9	25.0 – 25.1	23.6 – 25.4	23.2 – 24.0	21.5 – 22.8	22.0 – 24.7	19.0 – 23.1	11.0 – 18.7	6.5 – 12.7
	> 32	18.2	21.0 – 23.9	20.4 – 24.7	22.8 – 24.3	23.8 – 26.7	20.7 – 25.6	25.3 – 28.2	28.0 – 30.3	29.5 – 30.6
	> 35	1.5	3.3 – 5.5	2.8 – 6.7	4.6 – 6.2	5.4 – 11.2	3.0 – 8.6	7.8 – 14.6	13.9 – 24.9	19.6 – 27.1
Tipperary	< 18	21.8	18.6 – 18.7	16.6 – 19.0	16.2 – 17.1	13.8 – 15.1	14.7 – 18.5	11.7 – 15.9	5.4 – 11.3	2.5 – 6.5
	< 20	27.5	25.6 – 25.7	24.4 – 25.9	24.1 – 24.8	21.1 – 23.2	22.5 – 25.5	18.9 – 23.9	11.2 – 18.6	6.8 – 13.1
	> 32	22.7	25.3 – 26.9	25.3 – 27.5	26.3 – 27.4	27.1 – 28.7	25.2 – 27.9	27.8 – 29.3	29.3 – 30.5	29.9 – 30.7
	> 35	5.0	7.8 – 12.4	7.8 – 13.9	10.8 – 13.5	12.9 – 17.3	7.7 – 14.9	14.2 – 19.4	19.4 – 27.0	23.6 – 28.8

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