Flowering climatic drivers of Marri (*Corymbia calophylla*) in the Wellington catchment, WA

Masters dissertation: Merryln Martha Mpofu
June 2018
Supervisor: A/Prof Bryan Boruff

CRCHBP
FOR HONEY BEE PRODUCTS

TABLE OF CONTENTS

TABLE OF FIGURES 3
TABLE OF TABLES 4
ABSTRACT 5
1 INTRODUCTION 6
1.1 Overview 6
1.2 Flowering in Australia 8
1.3 Aim, objectives and research question. 10
2 BACKGROUND 11
2.1 Honey production industry 11
2.2 Literature Review 12
2.3 Characteristics of the Marri tree 19
3 STUDY AREA 21
4 MATERIALS AND METHODS 22
4.1 Materials 22
4.2 Methods 24
4.2.1 Climate data 24
4.2.2 Flowering Data 25
4.2.3 Statistical Analysis 26
5 RESULTS 28
5.1 Climate Trends 28
5.2 Differences in climate drivers between flowering events 31
6 DISCUSSION 36
6.1 Main findings 36
6.2 Limitations and future recommendations 37
7 CONCLUSION 38
8 ACKNOWLEDGEMENTS 39
9 REFERENCES 40
10 APPENDICES 44
10.1 Appendix A: Project time line and work structure 44
10.2 Appendix B: Field trip to Harvey 46

10.3 Appendix C: Flowering proxy datasets 49
10.3.1 Hives sites 49
10.3.2 Summary of Log book information 50
10.4 Appendix D: Discarded methodologies and r scripts 51
10.4.1 Method 1 51
10.4.2 Method 2 52
10.4.3 ArcGIS processing tools 53
10.5 Appendix E: Supplementary results 56

TABLE OF FIGURES

Figure 1: Occurrence of the Marri in Southwest Western Australia. 21
Figure 2: Study site and the vegetation within the area. 22
Figure 3: Flow chart showing the processing steps for the climate data 25
Figure 4: Monthly average rainfall and maximum temperature from 2007-2017. (minimum temperature was not shown as it follows the same pattern with maximum temperatures) 29
Figure 5: Seasonal trends in i) total rainfall ii) mean monthly maximum temperatures and iii) mean monthly minimum temperatures. 31
Figure 6: Boxplot of the mean comparison for i) Average 12 months precipitation averages and ii) Mean comparisons for rainfall average total rainfall from June to January. 33
Figure 7: Boxplot of the mean comparison of minimum temperatures for i) A year before flowering and ii) 5 months before flowering. 34
Figure 8: Boxplots of mean maximum temperature comparisons for i) a 12-months period before flowering and ii) from the start of September to end of January. 35
Figure 9: Work structure, showing the different stages of progress up to the completion of the project 45
Figure 10: Marri tree in full bloom. 46
Figure 11: Initial stages of flowering some buds are not open yet 47
Figure 12: Marri flower fully open. 47
Figure 13: Another example of marri with fully open flowers. 48
Figure 14: Beehive site A 48
Figure 15: Site B with more beehives 49

Figure 16: Point locations of permit sites 50
Figure 17:Initial study area which was later amended...52
Figure 18: Model showing data processing steps 53
Figure 19: ArcGIS tools for data processing 53
Figure 20: Annual Rainfall for 2007-2017 57
Figure 21: Annual maximum and minimum temperatures...57

TABLE OF TABLES

Table 1: Data materials for the study...22
Table 2: This table highlights years identified to have had prolific or poor flowering. 26
Table 3: Summary of the means and p-values for the climatic variables over 12 months, 8 months and 5 months. 32
Table 4: Gantt chart showing the time used for this project..44

ABSTRACT

Eucalypts are iconic plant species to the landscape of Australia, they are the most important melliferous flora as they provide primary honey and nectar to apiarists. Flowering phenology is driven by multiple environmental factors however due to plant's sensitivity to climatic conditions, variables such as rainfall and temperature have been documented as the principal influential external factors. The climatic drivers of the flowering of Corymbia Calophylla (Marri) in the Wellington district of Southwestern Australia from 2007 to 2017 are described. Most studies on the effects of climate on flowering have focused on the advancement of the first and last date of flowering. This study however aims to determine differences in the climatic conditions a few months prior to flowering, which might be indicators of a prolific flowering event and/or a non-prolific event. The study employed the use of ArcGIS application to process gridded climate data and generate maps for the study site and for the extent of the Marri vegetation across Southwestern Australia. Microsoft excel was used for data management and to generate graphs for annual climate data. And lastly, R studio was used for statistical analysis to perform the comparison of the means between the years which had prolific flowering and those which had non- prolific flowering. The main results for the analysis showed that there was no significant difference in the average minimum and maximum temperatures received before a prolific flowering and those received before a non-prolific flowering. However, there was a significant difference in the rainfall and thus concluding that it is possible that high rainfall is a driver for prolific flowering.

1 INTRODUCTION

1.1 Overview

Human interests in observing the flowering behaviour of plants spans for centuries, dating back to the18th century and today it is an object of citizen science projects (Tooke and Battey, 2010, Sparks et al., 2000). Flowering phenology is a discipline which is concerned with the occurrence of the reproduction of plants or as Visser et al. (2010) would put it, it is the observation of the periodic appearance of life cycle events where the differences in these events are related to the differences in climate. The first official definition of phenology was first published in 1884 as “the observation of the first flowering and fruiting of plants, the foliation and defoliation of trees and the arrival, nesting and departure of birds, and such like” (Anon 1884, Oxford English dictionary 2008, cited from Keatley et al., 2002, p. 1). However in 1972, The International Biological Program (IBP) gave a much broader definition of phenology as “the study of the timing of recurrent biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species” (Leith 1974 cited from Richardson et al., 2013 p. 157). Timing is absolutely everything for plants because reproducing prematurely without accumulating enough nutrients or reproducing after the suitable growing season can lead to various consequences such as unsuccessful pollination of flowers and inadequate or depleted stores of nectar and pollen for pollinators (Inouye, 2008, Elzinga et al., 2007).

Moreover, flowering phenology is significant in many different aspects which include evolution, ecology and ecophysiology (Inouye et al., 2003). Evolutionary, flowering potentially provides the means for speciation over time and also regulates the probable number of mates in animals. In an ecological sense, pollinators are highly dependent on flowers for their food supply and therefore it is important that flowering occurs at a particular time to maintain the integrity of this interrelationship (Inouye et al., 2003). However there has been a noticeable shift to the reproduction of plant species, including flowering, and the distribution of individual species as a response to global climate change (Forrest et al., 2010, Amano et al., 2010, Moore and Lauenroth, 2017). The distribution of species and their abundance, adhering to certain environmental thresholds is mainly, climate driven (Grinnell, 1917; MacArthur, 1972 cited in Lambert et al., 2010). Siegmund et al. (2016) states that climate may be changing at a rate which is above the adaptive capacity of some species and will therefore lead to spatial and temporal discordances between plants and their pollinators (Hegland et al., 2009, Amano et al., 2010). This poses a great threat to environmental ecosystems as such disruptions, impede the food chain which in turn affects species health and their population size (Siegmund et al., 2016). Consequently, some species could be driven to extinction with a loss of important ecosystem services such as water supply and sustaining nutrients (Both et al., 2006, Memmot et al. 2007 cited from Amano et al., 2010, Wolkovich et al., 2012). Additionally, as of recent times most research has focused on identifying environmental factors which influence phenology because they are not very well understood (Rivera and Borchert, 2001, Inouye et al., 2003). Temperature, rainfall and photoperiod have been documented as the main environmental factors which initiate flowering (Williams and Groves, 1980, Fitter et al., 1995, Rivera and Borchert, 2001, Inouye et al., 2003, Rawal et al., 2015a, Siegmund et al., 2016).

Water is an essential component in the growth process of plants, and flowering phenology and leaf development have been illustrated be to be affected by precipitation even in places which do not lack water supply (Wielgolaski, 2001, cited in Peñuelas et al., 2004). Rainfall thus has the ability to initiate or limit flowering especially in water dependent areas such as deserts (Borchert, 1980; Inouye and Mcguire, 1991; Suay-baguio and Odtojan, 1992 cited in Inouye et al., 2003). Additionally, the amount of rainfall a given species receives during its growing season influences its flowering duration and flowering abundance (Inouye et al., 2003). Also, Pertaining to temperature, each plant has a specific minimum, maximum and optimum temperature range on which its development is dependent upon (Hatfield and Prueger, 2015). The seasonality of flowering plants is driven by photoperiod length and temperature (Tooke and Battey, 2010). Early spring and early summer is the time that most species flower as these seasons have the proper light conditions and energy for budding and fruiting (Tyler, 2001). Some plants do not flower until a threshold day-length has been exceeded, thus delaying flowering which is a coupled effect by both, the insufficient day length period and temperature (Bernier, 1988 cited from Fitter et al., 1995). Plants do not all flower the same even those found in the same forest or from the same genus, some species flower yearly although with intervals in intensity whereas others remain dormant for a couple of years before a big flowering event (Tyler, 2001). The genetic structure of a plant and the interaction with various environmental factors each play a role in determining the onset of flowering (Fitter et al., 1995).

1.2 Flowering in Australia

Eucalypt is a collective name for three closely associated genera of the Myrtaceae family which are Corymbia, Angophora and Eucalyptus (Franklin and Preece, 2014). They predominate most woodlands and forests around Australia, favouring higher rainfall areas and are sparse in the most arid regions of the continent (Slee et al., 2018, Department of Agriculture and Water Resources, 2017). Eucalypt species are extremely diverse and, their flowering time, duration and frequency is just as varied. Although the physiology aspects of this species has been widely studied, the environmental drivers of their flowering phenology are still not well understood (Wilson, 2003). And these are the drivers which are of great significance to apiarists as the Myrtaceae family is the most significant honey producing flora (Smith, 1969). Eucalypts hold cultural, economic and ecological significance nationwide. They are recognised for their importance in the conservation of Australia's rich biodiversity as they are a primary food source for a wide range of fauna including bird species which are endangered (Department of Agriculture and Water Resources, 2017). They are a significant source of nectar and pollen to the honey production industry and are renowned for their durable wood which is of significance in the timber and furniture industries. In, addition, Indigenous Australians are historically known to have sourced some of their food and medicine from the trees' oils and leaves. (Department of Agriculture and Water Resources, 2017).

The Southwest corner of Western Australia has extensive forests, of Jarrah, Karri and Tuarts with a mixture of Wandoo and Banksia woodlands. This region therefore is the hotspot for apiculture (Smith, 1969). The Wellington District is a small subdivision of the Southwest corner of Western Australia mostly encompassed by the Jarrah forests, where the Eucalyptus marginata (Jarrah) and Corymbia calophylla (Marri) are the predominant tree species. The focal species for this study is the Marri tree which is one of the many honey producing flora in the region. The Marri is a key species as it produces consistent annual honey flow and flowers more frequently than Karri or Jarrah which may bloom heavily only once every four to five years (Coleman, 1962, Smith, 1969). Currently there exists a knowledge gap in Western Australia as there is a paucity of published work focused on understanding the flowering phenology of Corymbia calophylla and its interaction with climatic variables, namely temperature and rainfall.

1.3 Aim, objectives and research question.

The aim of this study therefore was to contribute to bridging the knowledge gap on what is known about the influence climate has on the flowering phenology of Corymbia calophylla. This was achieved by examining the climatic conditions leading up to the flowering events of Marri as an indicator of heavy flowering. A decade of flowering events from 2007- 2017 were subjectively categorised as prolific flowering or poor flowering. Statistical analysis was then used to compare the two groups to identify differences in climatic characteristics (rainfall and temperature patterns) in the lead up to each year's flowering event. Examining these two important aspects of climate will help answer the following research question:

- Do the trends in climate variability prior to Marri flowering provide an indication if a season will result in prolific or poor flowering?

It is hypothesized that the results will provide apiarists with knowledge concerning the climatic conditions favourable for prolific flowering thus leading to good quality honey flows. Flowering behaviour and the production of nectar differs yearly due to its dependence on varying climatic factors. Successful beekeeping comes from a sound knowledge of nectar producing plants and when reproduce occurs (Coleman, 1962). Smith (1969) highlights that the ability of an apiarist to respond to nature and its controlling conditions such as climate, the soils, and how the bees are affected by environmental conditions is an art that ensures success in beekeeping. Thus, it is imperative that an apiarist be knowledgeable on honey plants, the climate and their responses and/or how they interact with each other.

2 BACKGROUND

2.1 Honey production industry

Across Australia melliferous flora is found predominantly in Eucalypt forests and in areas with other Myrtaceae and Protaceae flora (Sniderman et al., 2018, Bee Aware, 2018a) . Nectar and pollen production is dependent on the diverse native vegetation found within state forests, national parks and other public lands accounting for 70–80 % of the state's honey production (Gibbs, 1998, AgriFutures Australia, 2018). Additionally, honey production results from private lands in WA however, public lands are an important resource to beekeepers as they are the source of the majority of production (van Dijk et al., 2016) . Restricted access to these lands is a challenge to the industry as well as the spread of diseases and pathogens and the use of pesticides in agricultural practices. This affects the health of the colony and the quality and quantity of the honey they produce. Other factors which collectively affect honey production are droughts, floods and bushfires (van Dijk et al., 2016). Downes (2018 pers. comm., 4 April) highlighted that areas which have been excessively burnt especially affect the tree crowns and can limit the apiarists access to ideal hive sites. Recently burnt areas produce poor honey and nectar flow and as such, prescribed burning in particular has become a point of contention between apiarists, emergency service providers and politicians.

Moreover, due to climatic conditions, flowering, budding, honey flows and pollen yields can vary across time, species and location and thus apiarists tend to migrate their hives to access the best nectar flows (Ben, 2016). Migrating hives is an effective beekeeping strategy where at times apiarists travel long distances not only chasing floral resources for honey production but also to provide pollination services (Bee Aware, 2018a). Pollination services have become important to horticultural and agricultural industries as crops such as almonds, avocados, pears, cherries, apples and blueberries, to name a few, are highly dependent on bee pollination (Bee Aware, 2018b). Other services include the production of beeswax, pollen, royal jelly, selling packaged bees and queen bees (Bee Aware, 2018a).

All Australian states have managed honeybees where some people engage in beekeeping as a pastime however those who have more than 50 hives are considered commercial beekeepers (van Dijk et al., 2016). A survey in 2015/2016 showed that there were more than 13 000 registered beekeepers nation-wide. Registration is a compulsory practice for beekeepers in all states except, Tasmania. The industry constitutes an important part of the economic sector as in 2014/15 it was estimated to have a gross product of $101 million (van Dijk et al., 2016). Australia is one of the largest honey exporters globally and has an estimated 448,000 hives, producing between 20-30 kilo tonnes of honey per annum of which 15-25% is exported to other countries (van Dijk et al., 2016, Sniderman et al., 2018). The principal area for honey production is South-eastern Australia which is responsible for almost 70% of the nation's produce (van Dijk et al., 2016). Western Australia is said to have the cleanest and greenest honey producers in the world (Downes, 2018, pers. comm., 22 January) but is a less significant honey producer contributing about 10% to the nation's total produce.

2.2 Literature Review

Temperature has been documented as the main driver of flowering (Tollenaar et al., 1979, Fitter et al., 1995, Sparks et al., 2000, García-Mozo et al., 2010, Guo et al., 2015, Li et al., 2016, Hatfield and Prueger, 2015). However, the majority of work pointing to this cause and effect relationship have focused on temperate climates where plants are not limited by rainfall but are responsive to spring temperatures changes as a catalyst for flowering (Crimmins et al., 2010, Guo et al., 2015). Analysing the relationship between plant phenology and rainfall is complicated as rainfall is closely related to soil moisture (Gordo and Sanz, 2010) but however there are few studies that have documented rainfall as an important factor to flower emergence from arid, semi-arid and Mediterranean climates (Opler et al., 1976, Tyler, 2001, Prieto et al., 2008).

In Australia, the flowering behaviour of diverse plant species, such as those belonging to the Myrtaceae family, as has been mentioned before are plagued by a lack of knowledge concerning the relationship between flowering and climatic variables. This maybe due to the lack of phenology data because although the forestry departments of Queensland, Victoria, New South Wales and Western Australia collected detailed phenological observations of eucalypts between 1920 and 1980 but only of few of these records have survived (Keatley et al., 2002). The scarcity of long term phenological records has led researchers to seek alternative measures to source data which can be used in examining flowering responses to climate as suggested by Miller-Rushing et al. 2006 and Sparks 2007 (cited in Rawal et al., 2015b). For instance, Gallagher et al. (2009) examined the changes in phenology by matching up herbarium data with annual temperature data, where they aimed identify species which could be used as a tool for monitoring schemes in the alpine and subalpine regions of Australia. They found that five out of the twenty species studied, exhibited a negative relationship to mean annual temperature and drew a conclusion that they can be used as indicator species and also that herbarium data is useful alternative data source to flowering data. Similarly, Rawal et al. (2015b) conducted a study on the flowering phenology of five eucalyptus species using linear regression modelling. They also used herbarium specimen data and mean annual temperature data to detect the effects of climate variability on flowering. This alternative data source was found to be effective as the results illustrated that

3 months prior to flowering, temperature had the greatest influence compared to humidity and rainfall for all species (Rawal et al., 2015b).

Earlier studies by Specht 1986 suggested that flowering depends on shoot development which is also impacted by temperature (cited in Keatley and Hudson, 1998) and in separate studies by Ashton 1975 and Cremer 1975 it was found that weekly mean maximum temperatures and daily mean temperatures were related to the growth response of eucalyptus species (cited in Keatley and Hudson, 1998). Similarly, a study by Porter (1978) primarily using linear regression techniques showed that flowering during the spring season was related to not only temperature but to rainfall as well. Flowering of the Eucalyptus sideroxylon was described to commence in January, reaching a maximum in July and finishing in September. An increased rate of growth for this species was favoured by high temperatures and increased rainfall. Flowering also proved to have a linear relationship with honey production where prolific flowering was directly related to abundant honey production. It was evident that climate had a major influence before the commencement of flowering and during flowering on eucalyptus sideroxylon and its honey flows (Porter, 1978).

More recently two researchers have led more robust examinations of phenology on Australia. They have conducted extensive studies on the flowering of Myrtaceous trees (eucalyptus) which have been documented on a series of papers where they have used a variety of methods to assess the drivers of flowering. Keatley and Hudson (1998) examined 51 Eucalyptus species and showed that their flowering was greatly influenced by the appearance of buds and fruiting volume. In 2007, (Keatley and Hudson, 2007) used long-term flowering records to compare mean monthly flowering patterns of five Eucalyptus species in the Havelock and Rushworth forests of Victoria. In their study they developed indices to characterise flowering patterns such as flowering probabilities, duration and the start and finish of a flowering event. They found that due to Rushworth’s warmer climate, trees at that site reached peak flowering before Havelock.

Hudson et al. (2003) explored the interrelation between temperature and flowering intensity of Eucalyptus leucoxylon using two statistical methods, Generalised additive models and Bayesian adaptation of penalized regression splines. They found that temperature significantly influenced flowering intensity and additionally that its effects were non-linear. These findings also corresponded with later research conducted by Hudson et al. (2010) where they identified flowering thresholds for higher and lower temperatures for four eucalyptus species using the Generalised additive model for Location, Scale and Shape (GAMLSS). Their results for rainfall indicated that it was not a significant driver for flowering however, temperature was very much relatable to the flowering behaviour of the four study species, thus they concluded that “the main driver for flowering in eucalyptus leucoxylon is minimum temperature” (Hudson et al., 2010, p. 2615). Eucalyptus tricarpa also had minimum temperature as a driver for its flowering whereas maximum and mean temperatures positively influenced Eucalyptus microcarpa and Eucalyptus polyanthemos (Hudson et al., 2010). Rawal et al. (2015a) conducted a study as an extension to the work already done by Hudson et al. (2010) using similar methodologies and their finding were somewhat consistent. Rawal et al. (2015a) also explored the effects of photoperiod and suggested that if other factors were required for flowering they may be usurped by a plant’s sensitivity to photoperiod although this effect is partly influence by temperature as well.

Furthermore, Law et al. (2000) concluded that rainfall was a significant driver of the flowering phenology of certain species upon observing the flowering behaviour of 20 myrtaceous trees in New South Wales over a period of 10 years. They found that there was a wide variation around when flowering occurred and its intensity across different sites and species. Nine species showed a positive response to cooler temperatures, but species were most responsive to rainfall. The most prolific flowering events for all species eventuated nine-months after the highest monthly rainfall recorded and poor flowering was observed from a number of species after an extended drought period (Law et al., 2000). A more recent study by Hudson et al. (2011) found results which were in accordance with previous research however they used more robust statistical techniques with the Wavelet analytic method. Their results illustrated that although both rainfall and temperature had a positive influence on flowering there were however contrasting, when rainfall had a negative effect on flowering, temperature had a positive effect and vice versa.

Numerous studies, most emerging from the northern hemisphere, have focused on the day of first flowering (Fitter et al., 1995, Crimmins et al., 2011, Hur and Ahn, 2015, Moore and Lauenroth, 2017) and last flowering because temperature directly affects the timing and intensity of this particular phenological phase which in turn affects species interbreeding, their interactions and synchrony (Rawal et al., 2015b). The body of evidence shows that an advancement or retardation of first flowering for a range of species is influenced by temperature and/or rainfall. To illustrate, according to a study of 243 species in central England by Fitter et al. (1995) flowering appeared at a mean of 4 days per degree earlier due to increased temperatures in the spring season, however they also found that increased temperatures in autumn resulted in a delay in flowering for species that preferred to flower in summer and spring. The temperatures 1-2 months preceding spring flowering had the most influence on 60% of the species studied whereas summer flowering species were most affected by temperatures 4 months prior indicating that flowering times were highly dependent on temperature (Fitter et al., 1995). Another example by Menzel et al. (2006) showed a 78% shift in phenology as influenced by temperatures in Europe, with significant correlations between phenology and mean monthly temperature on the month of the flowering event or a month or two earlier. Sparks et al. (2000) found a significant relationship between flowering and temperature in the 25 species they studied in the UK as well. Likewise, Moore and Lauenroth (2017) related the advancement of flowering to increasing mean temperatures for early flowering species and attributed the longer flowering of species in water limited regions to a combination of temperature and rainfall.

Moreover, Crimmins et al. (2010) conducted a 20 year study in a semi-arid environment where they estimated that about 10% of their study species showed a retardation to the onset of flowering. This delay was attributed to a decrease in precipitation and temperatures in spring and autumn. Autumn climatic conditions were found to be the main drivers of the onset of spring flowering species in low altitudes which is contrary to spring flowering species in high altitudes which were found to be driven by spring temperatures. More studies show similar results where plants flowering during the spring season are more sensitive to temperature (Gordo and Sanz, 2010, Wolkovich et al., 2012). Findings from a study in southern Spain by García-Mozo et al. (2010) were in agreement with other research (Fitter et al., 1995, Crimmins et al., 2010) as they also concluded that climate conditions a few months preceding a phenological event appeared to be the most important and also autumn temperatures rather than precipitation had more influence in the flowering and fruiting of species. Likewise, a tropical forest study by Pau et al. (2013) identified temperature as the primary cause of flower production compared to other factors such as light and clouds which were influential by seasons.

Unlike other studies which have used linear regression, Siegmund et al. (2016) looking at the effect of climate anomalies on flowering employed a new statistical tool, event coincidence analysis. They still documented results similar to other research where their evidence showed that extremely warm spring temperatures and, in some cases, cold temperatures were of relevance to the early onset of flowering in some species but there was a non-significant relationship between extreme flowering and extreme precipitation.

Additionally, Crimmins et al. (2011) conducted another study in an arid environment which showed fairly similar results to their previous research. However, without considering elevation this time, they speculated that species in that region greatly depended on soil moisture as the timing and amount of rainfall was a key factor to the onset of flowering in summer. Correspondingly, an earlier experimental study on the flowering of Globularia alypum and Erica multiflora in a Mediterranean shrubland by Prieto et al. (2008) reported that due to variation in rainfall the flowering of the species in question varied greatly each year, thus illustrating a considerable dependence on water as compared to temperature. These results were concordant with those from a study by Lesica and Kittelson (2010) in a semi-arid environment. Whereas Inouye et al. (2003) investigated different aspects of the environmental cues for flowering and found that the timing for flowering to occur in a plant species in Colorado was determined mainly by the snowmelt date and the abundance was influenced by precipitation.

Moreover, there are two studies found to illustrate results which were contradictory to other research. The first one, a 12 year study of eight species assessing how flowering abundance was impacted by humidity, temperature and rainfall done by Tyler (2001) in southeast Sweden found results which were slightly contrary to other findings as there was no significant relationship between the variation of temperature and flowering but however they did find that rainfall and/or humidity from 12 months before flowering influenced the flowering abundance of 5 of their species. And the second one a study by Michalski and Durka (2007) who upon relating flowering to temperature and humidity, did not find any significance between these climatic variables and the onset of flowering.

Lastly, a bigger portion of this comprehensive list of studies has demonstrated a significant link between flowering and the climate variables, temperature and rainfall. This implies that the changes in flowering phenology can be interpreted using climate variation and therefore it is expected that the results from this exhibit significant difference in the years with abundant flowering as compared to poor flowering.

2.3 Characteristics of the Marri tree

Corymbia calophylla is part of the Myrtaceae family and belongs to a primitive group of Eucalypts called the bloodwoods. Before 1995 it was known as the Eucalyptus calophylla, however Hill and Johnson (1995) suggested a split of the Eucalyptus genus and initiated the classification of a new genus, Corymbia. One hundred and thirteen species were drafted into this new genus and thus it being Corymbia calophylla (Slee et al., 2018). It is referred to by a number of common names including red gum and Marri, a word for blood in the Nyoongar language (Powell, 1990, Slee et al., 2018). For centuries the Nyoongar people have used the Marri tree as a food source (bush tucker) and for medicinal purposes (Botanic Gardens and Parks Authority, 2017, Wheatbelt Natural Resource Management, 2018). Marri is also an important food source for birds including the Australian ringneck and red capped parrot (Powell and Emberson, 1990).

Marri grows up to 30-40m in height an only found in Southwest Western Australia (figure 1), extends from the Darling range to the southern coast (Hall, 1970). It predominantly grows alongside the Jarrah (Eucalyptus marginata), but also occurs within the Karri forest as well and scantily in between inland regions and the south-west hills. Marri can grow in a range of soils but favours fertile lands such as alluvium and lateritic soils (Hall, 1970, Powell, 1990). It grows best in areas with higher rainfall levels, between 650-1500mm per year, and within a temperature range between 24-30 °C and 4-8 °C (Hall, 1970, Boland, 2006). Marri often produces fruit commonly known as honkey nuts. Marri flowers are large and usually white in colour but can be pink in colour. Flowering occurs between February and March but can continue until May. Heavy seeding usually follows a prolific flowering year and sometimes flowering occurs simultaneously with seeding (Downes, 2018, pers. comm., 22 January). These examples were seen during field visits to the Wellington District earlier this year (see Appendix B for pictures)

As such "Marri is one of the major honey plants of the South-west. The pollen is used for building up bee colonies and the honey is excellent" (Powell, 1990, p.99). It is a dependable honey plant as it blossoms enough to provide adequate nectar for the bees however it usually flowers less the year following a prolific flowering event, which comes around every third or fourth year (Powell and Emberson, 1990).

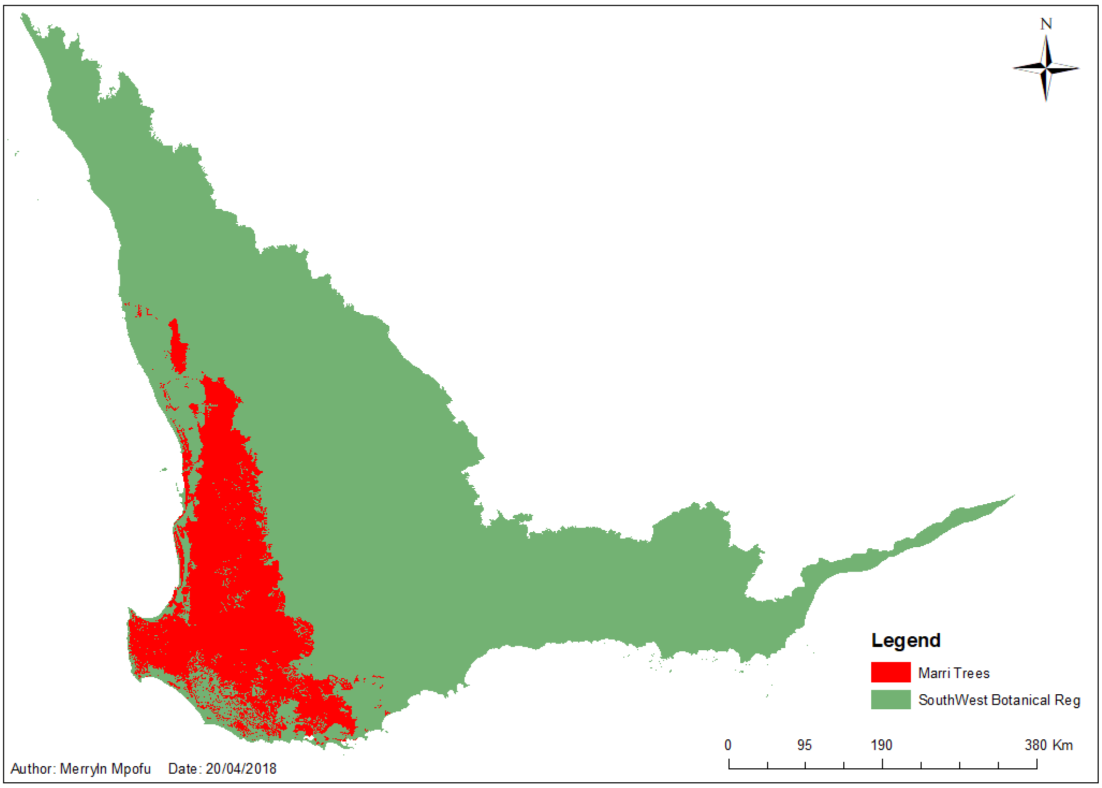


Figure 1: Occurrence of the Marri in Southwest Western Australia.

3 STUDY AREA

The study was conducted in the Wellington District in the south west corner of Western Australia. The district has a rich biodiversity and is home to unique fauna including quokkas, chuditch, brushtail possums, woylie, over 70 bird species and more than 300 different wildflower species. The District is situated between the towns of Waroona, Bunbury, Donnybrook and Darkan (Department of Parks and Wildlife, 2018). The forests in the district are dominated by Jarrah and Marri with a mixture of other tree species such as the Black gum and Wandoo (Downes, 2018, pers. comm., 22 January). The region as a whole exhibits a Mediterranean climate with hot and dry summers and highest rainfall levels in winter (Migration WA, 2018). The area of interest used for this study was focused on a portion of the Wellington district with the biggest cluster of hives sites and it is 4908 km^2 in size (figure 2).

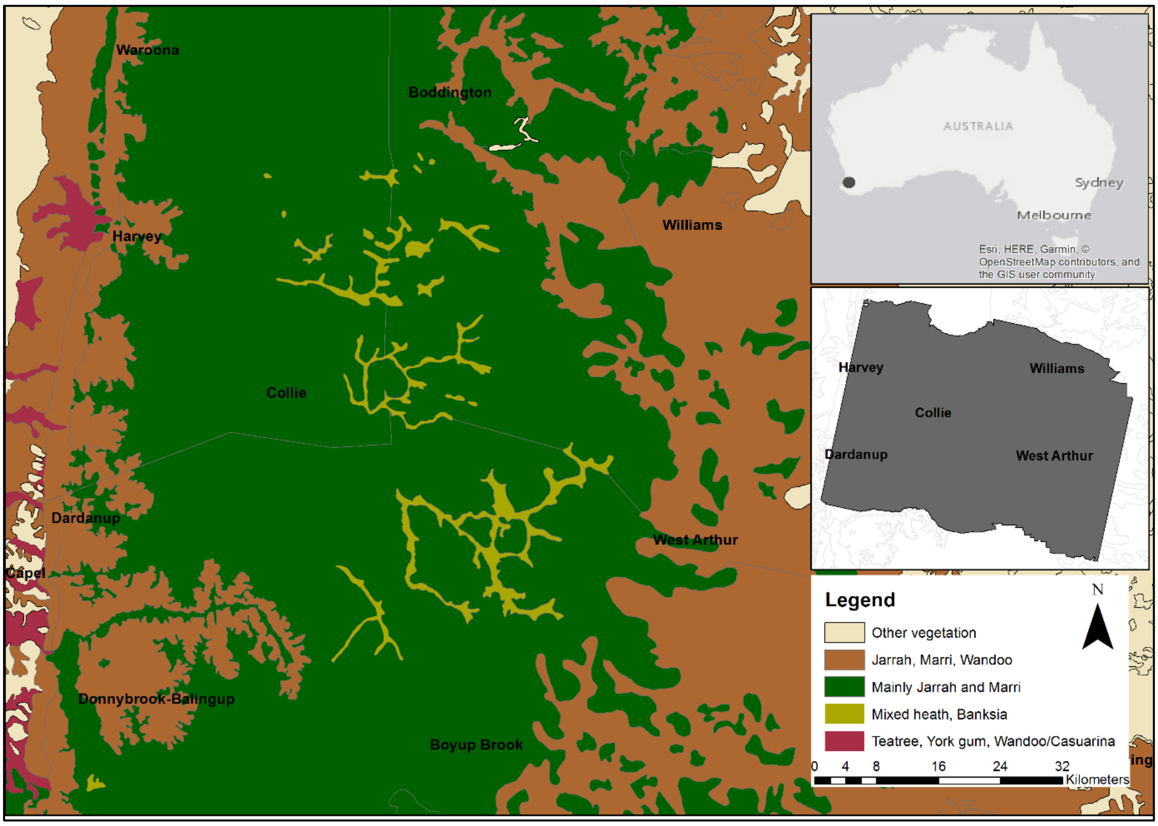


Figure 2: Study site and the vegetation within the area.

4 MATERIALS AND METHODS

4.1 Materials

The materials used for this study are organised in the table below (table 1) showing the types of data which was needed for the analysis, where it was collected from and also a summary of how it was used.

Table 1: Data materials for the study.

Data	Source	Usage
Vegetation information	National Vegetation Information System (Department of the Environment and Energy, 2018).	Shapefiles used in ArcGIS to determine where Corymbia calophylla is found within the Wellington District and Western Australia as a whole.
Wellington District boundaries	Provided by the Department of Biodiversity, Conservation and Attractions (Banks 2018, pers. comm., 12 March)	Shapefiles for ArcGIS used to refine the study area.
Flowering information i) Point locations[1]	All the flowering information was collected under the approval of The University of Western Australia, Human Research Ethics Office – RA/4/4/9247. Data source i) provided by Patel (2018, pers. comm, 27 February).	These were apiarists hive sites licenses within the Wellington district.
Flowering information ii) District rangers log book entry[1]	Data source ii) provided by Downes (2018, pers. comm, 15 February)	Identifies the hives permit numbers, the dates when hives were placed on permit locations and the date hives were removed. This was used as a proxy for when Marri was in flower over the years 2007 – 2017.
Climate data	(Bureau of Meteorology, 2018)	Daily maximum temperature data, daily minimum temperature data and daily rainfall data

[1] See Appendix C for more information on the logbook and hive site locations.

4.2 Methods

4.2.1 Climate data

Daily climate data was analysed from the years 2007 to 2017 and was procured in ASCII format with each grid cell representing an area of 5 x 5 km^2. ArcGIS was used to convert ASCII files to a native raster format to extract the climate information. An iterative process was used to convert 11 years of daily rainfall, and daily minimum and maximum temperature into raster files for further analysis. Next, each grid was projected to the Geocentric Datum of Australia 1994 (GCS_GDA_1994) coordinate system. Monthly averages for each year were then calculated from daily maximum temperature and daily minimum temperature data, the same approach was used to convert daily rainfall to monthly data (figure 3). Monthly averages were preferred over daily measures because they are easier to manage and have comprehensible statistical analysis (Fitter et al., 1995). Annual averages were not preferred either because the analysis involves examining data monthly and seasonally. All the climate data was initially procured representing the whole of Australia therefore further processing was done to resize it to the study extent (see Appendix D for the tools used to process data). The values acquired after processing in ArcGIS were entered in excel for ease of handling and statistical analysis.

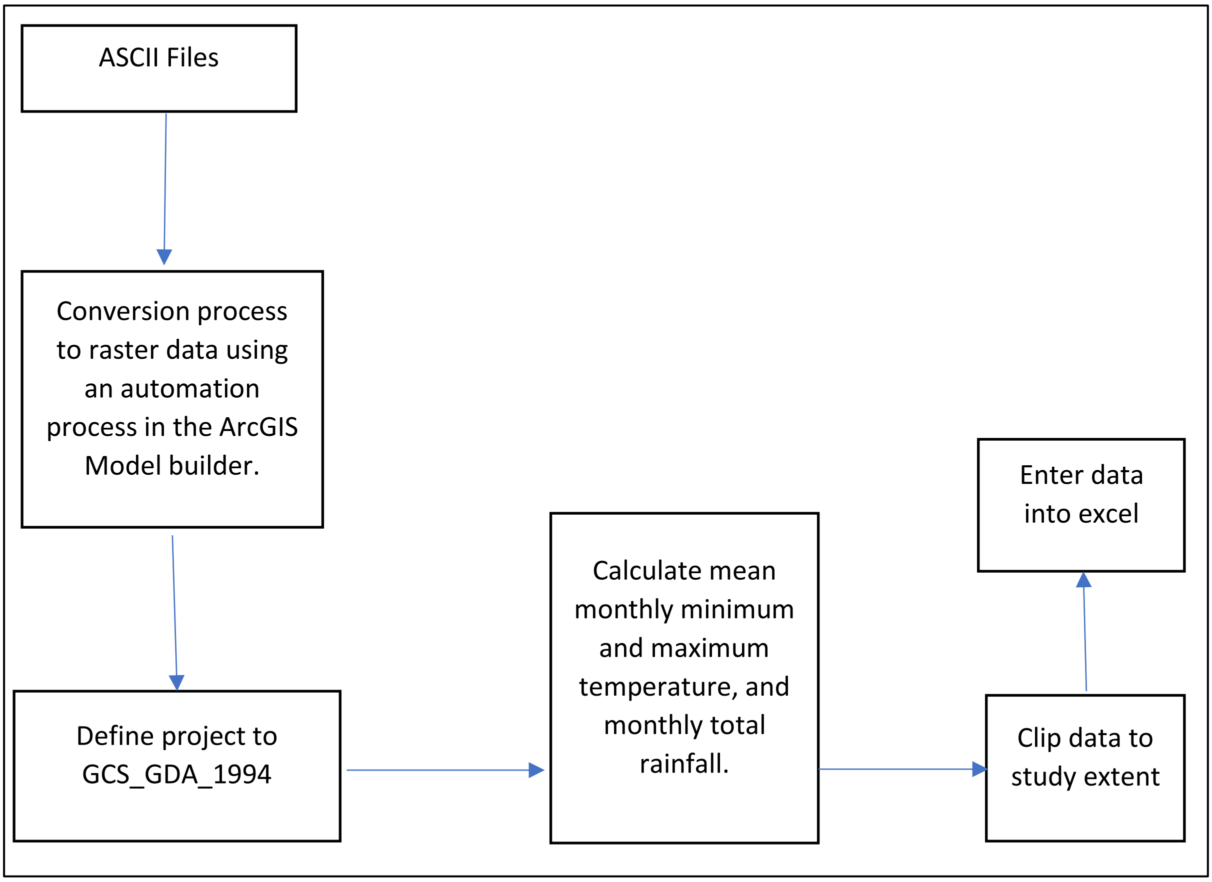


Figure 3: Flow chart showing the processing steps for the climate data

4.2.2 Flowering Data

Objective measures of yearly flowering times for Marri in the Wellington district (and most areas in WA) were not available and as such a proxy dataset was utilized. Records collected by the District Ranger (as a license requirement by the DBCA) identifies the date license holders place hives on their licensed sites and remove the hives once honey extraction is complete. This information was used as a proxy for flowering. The presence of hives at the license site was interpreted as the presence of flowering and when the apiarist removed their hives it was interpreted as the end of the flowering event. Flowering was classified as, prolific or poor (Table 2) as interpreted from a number of sources. For instance, information from Downes (2018, pers. Comm., 22 January) indicated that 2015 was a prolific year. An article by French (2013) referred to the summer of 2013 as the most prolific flowering of Corymbia calophylla like none that had been seen before. Pancia (2018) reported that some beekeepers were driving 500km or more chasing Marri flowering in 2018 and had been one of the rarest and most prolific flowering events, resulting in the label the ‘marri mega-blossom’. The climatic conditions in the lead up to each years’ flowering event were analysed to identify climatic patterns which may be used to distinguish between poor and prolific flowering from 2008-2018.

Table 2: This table highlights years identified to have had prolific or poor flowering.

PROLIFIC FLOWERING YEARS	POOR FLOWERING YEARS
2008	2009
2010	2011
2013	2012
2015	2014
2018	2016
	2017

4.2.3 Statistical Analysis

Excel and R studio were used for the statistical analysis of the climatic data and flowering data served as a guide for the presence of flowering and the sorting of the two groups. Climate variables were analysed as a time series, from 2007 to 2017 and the seasonal summary of the data was also acquired. Next, climate was analysed was based climate on two scenarios for each variable:

- Total rainfall for each month was analysed 12 months prior to the onset of flowering and 8 months before flowering, from June to January in order to capture the time of the year with the most rainfall, winter. Simply put, using the Welch t-test monthly total rainfall was used to calculate and compare the average rainfall between prolific years and poor flowering years. The r codes for this analysis can be seen in Appendix D.
- Average minimum and maximum temperatures for each month were both analysed 12 months prior to flowering and then 5 months prior to flowering that is from the beginning of spring (September) to January. 5 months was chosen for temperatures measures because a few studies have demonstrated that spring temperatures play an important role in flowering cues (Fitter et al., 1995, Crimmins et al., 2010). Just as above the average monthly minimum and maximum temperature for prolific years and poor flowering years were compared against each using the Welch t-test.

Before the data could be tested for the differences in the prolific and poor flowering it was important that a test of equal variances be used, to ensure that the t tests applied was done so with the appropriate parameters. The Levene test was used, where, the hypothesis was set as:

H_0: $\sigma_1^2 = \sigma_2^2$ all the variances are equal

H_1: $\sigma_1^2 \neq \sigma_2^2$ None of the variances are equal (Nist Sematech, 2013)

Afterwards, the Welch's t-test was applied, to analyse if the two independent samples with unequal sample size and variances had equal means, assuming a 95% confidence interval the hypothesis was set up as:

H_0: $\mu_1 = \mu_2$ the means for the two independent groups are equal,

H_a: $\mu_1 \neq \mu_2$ the means for the two independent groups are not equal

And the test statistic:

$$t = \frac{m_1 - m_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

where m is the sample mean, *s* is the standard deviation and *n* the sample size for groups 1 and 2 respectively.

5 RESULTS

5.1 Climate Trends

During the analysis it was noticeable that the northern part of the district has warmer temperatures compared to its south eastern parts. The climate datasets were analysed to show temperature and rainfall averages per month over the years 2007- 2017, also highlighting the seasons within the Wellington District. As previously mentioned the district experiences a Mediterranean climate, the changes in temperature and rainfall per season is shown in figure 4 where the winter months of June, July and August have the lowest temperatures and highest amount of rainfall. And as expected the summer months, December, January and February are the hottest and driest months.

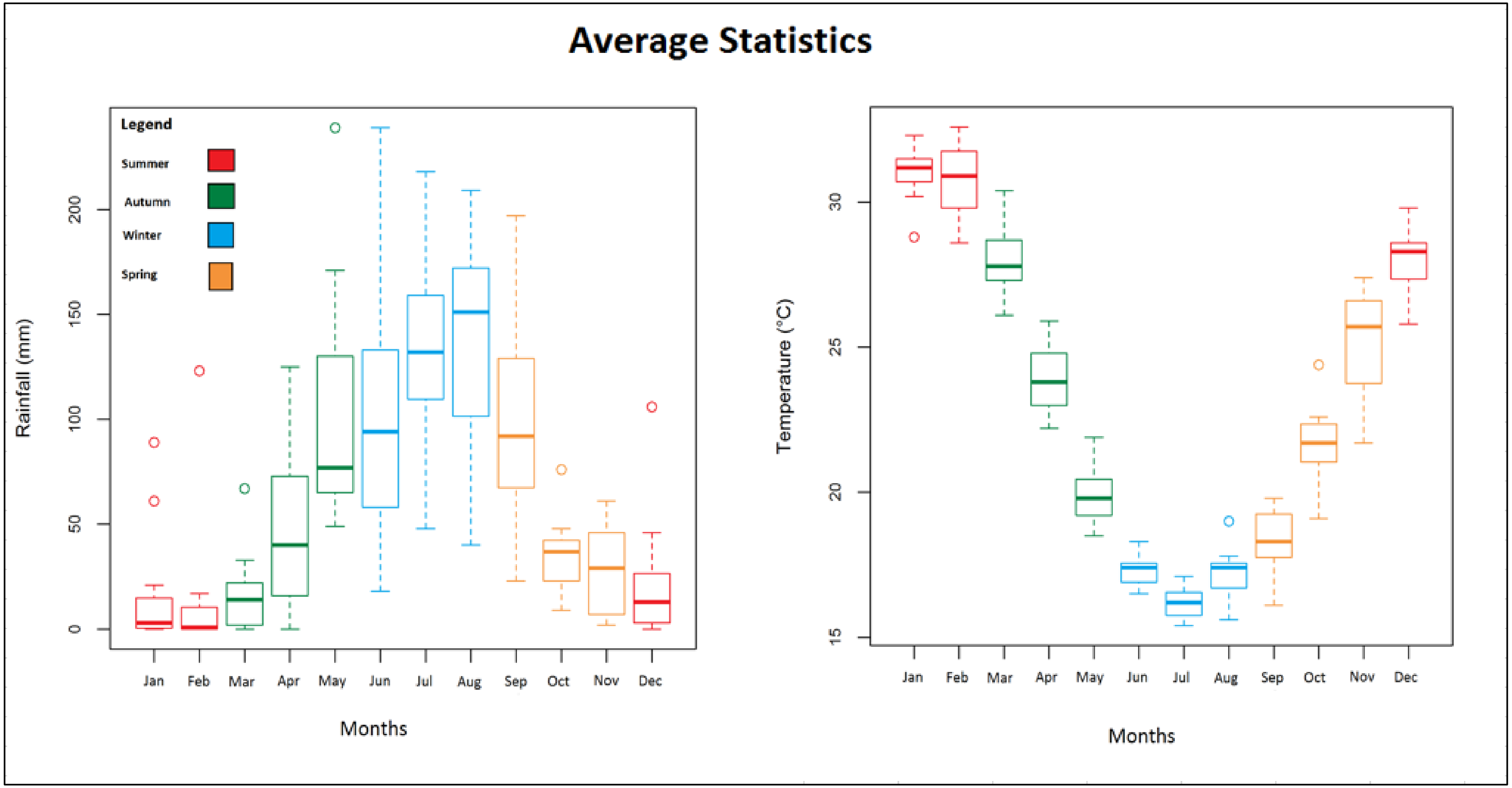


Figure 4: Monthly average rainfall and maximum temperature from 2007-2017. (minimum temperature was not shown as it follows the same pattern with maximum temperatures)

The average annual rainfall (see Appendix E) for the area over the years of study was 758mm, where 2016 had the highest total rainfall of 993mm and 2010 was the driest year with just 371mm of rain. However, looking at the seasonal rainfall trends (figure 5), during the rainiest months (winter) the greatest peaks in rainfall were seen in 2009, 2014 and 2007 in that order. Whereas, seasonal temperature patterns were a classic sinusoidal pattern (figure 5), with the highest temperatures experienced in summer and the lowest temperatures in winter. The annual average maximum and minimum temperatures between 2007-2017 were 23.1°C and 8.5°C respectively with 2010 and 2015 being the hottest years on record.

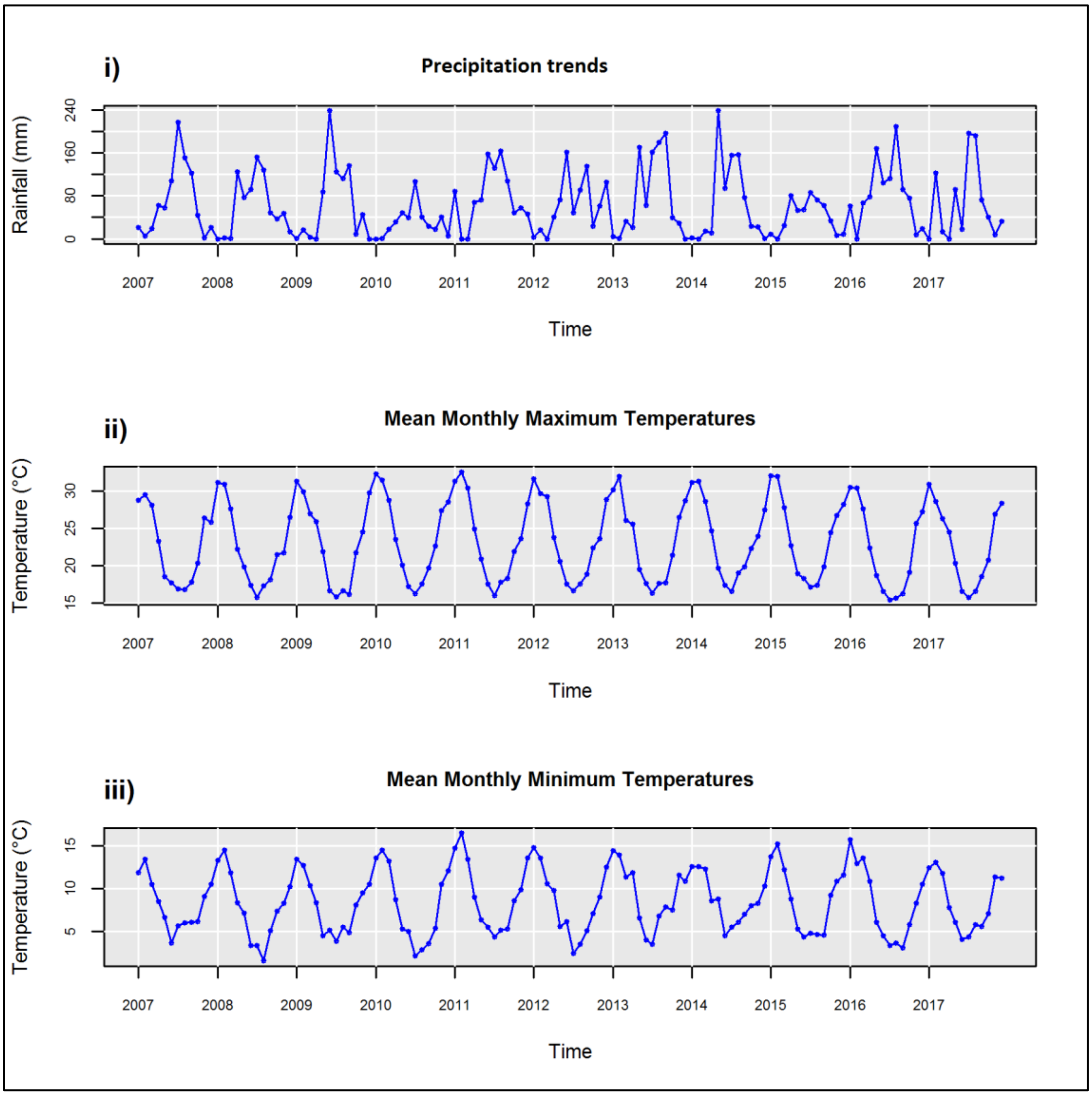


Figure 5: Seasonal trends in i) total rainfall ii) mean monthly maximum temperatures and iii) mean monthly minimum temperatures.

5.2 Differences in climate drivers between flowering events

Levene's test total monthly rainfall between 2007-2017 was statistically significant at a p-value less than 0.05 and for mean monthly minimum and maximum temperatures the results were non-significant as the p-value was greater than 0.05 and thus the t-test was applied with the correct conditions. Total rainfall mean comparisons returned a p-value was greater than 0.05 for 12 months pre-flowering thus failing to reject the null hypothesis and as can be deduced from figure 6 (i) the means of the prolific and poor flowering are similar. However, the p-value for the 8 months pre-flowering was less than 0.05 and therefore, the null hypothesis was rejected. Showing that the means for prolific and poor flowering years were different (figure 6 (ii)). The period from the start of spring to a month before the onset of flowering (February) and temperatures 12 months prior to flowering showed concordant results for both minimum temperature (figure 7) and maximum temperature (figure 8). The mean comparisons for both climatic variables had p-values which were greater than 0.05 and the null hypothesis could not be rejected. Therefore, meaning that the test could not detect any difference in mean temperatures experienced either before either flowering event. The statistical values of these results are summarised in table 3.

Table 3: Summary of the means and p-values for the climatic variables over 12 months, 8 months and 5 months.

Time	Statistics	Rainfall (mm)		Max T (°C)		Min T (°C)	
		Prolific flowering	Poor flowering	Prolific Flowering	Poor flowering	Prolific flowering	Poor flowering
12 months	Mean	56.84	53.55	22.57	22.68	9.03	9.14
	P value	0.27		0.73		0.56	
8 months	Mean	68.23	59.31				
	P value	0.02					
5 Months	Mean			21.16	21.42	8.19	8.06
	P value			0.51		0.56	

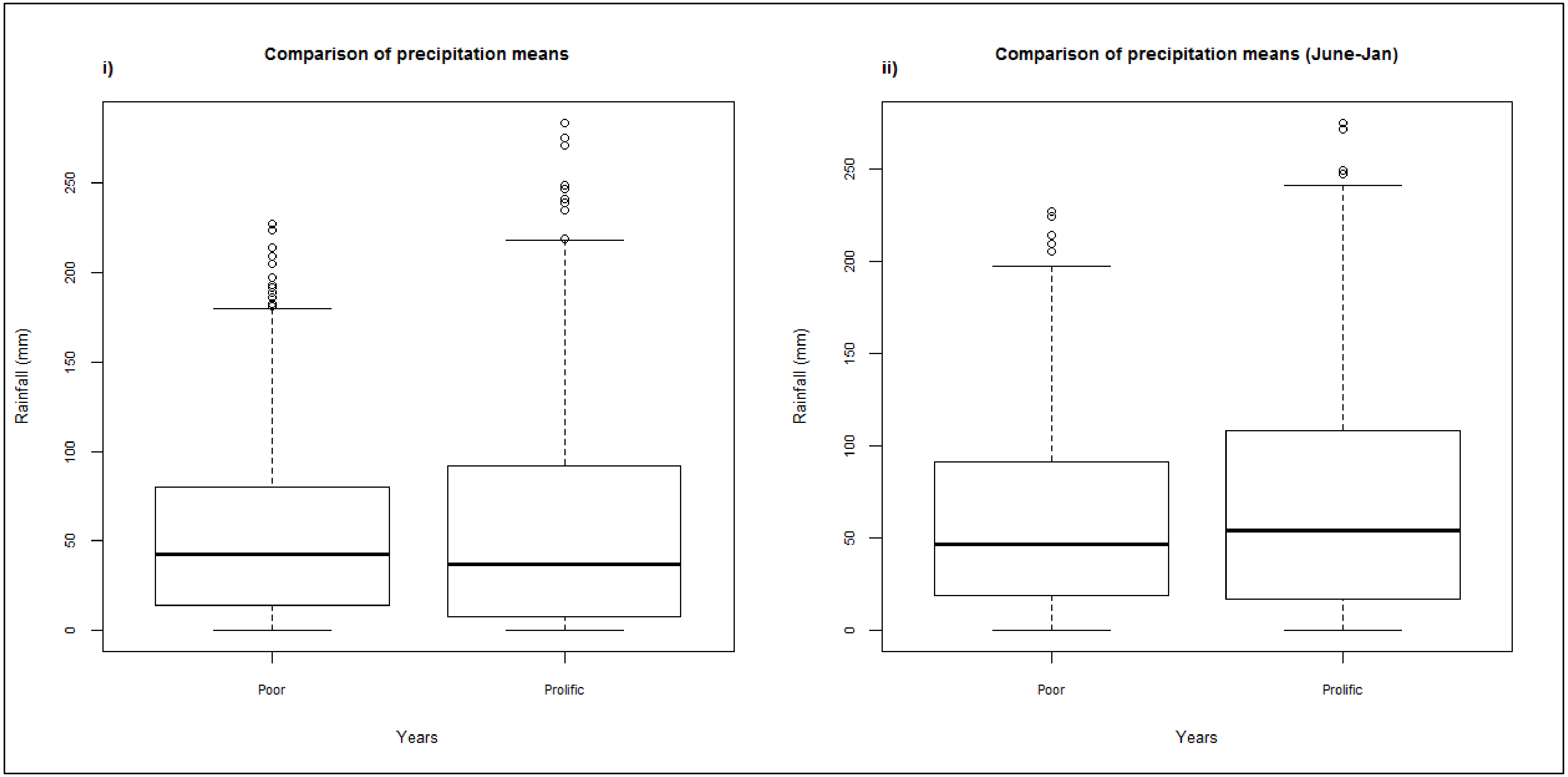


Figure 6: Boxplot of the mean comparison for i) Average 12 months precipitation averages and ii) Mean comparisons for rainfall average total rainfall from June to January.

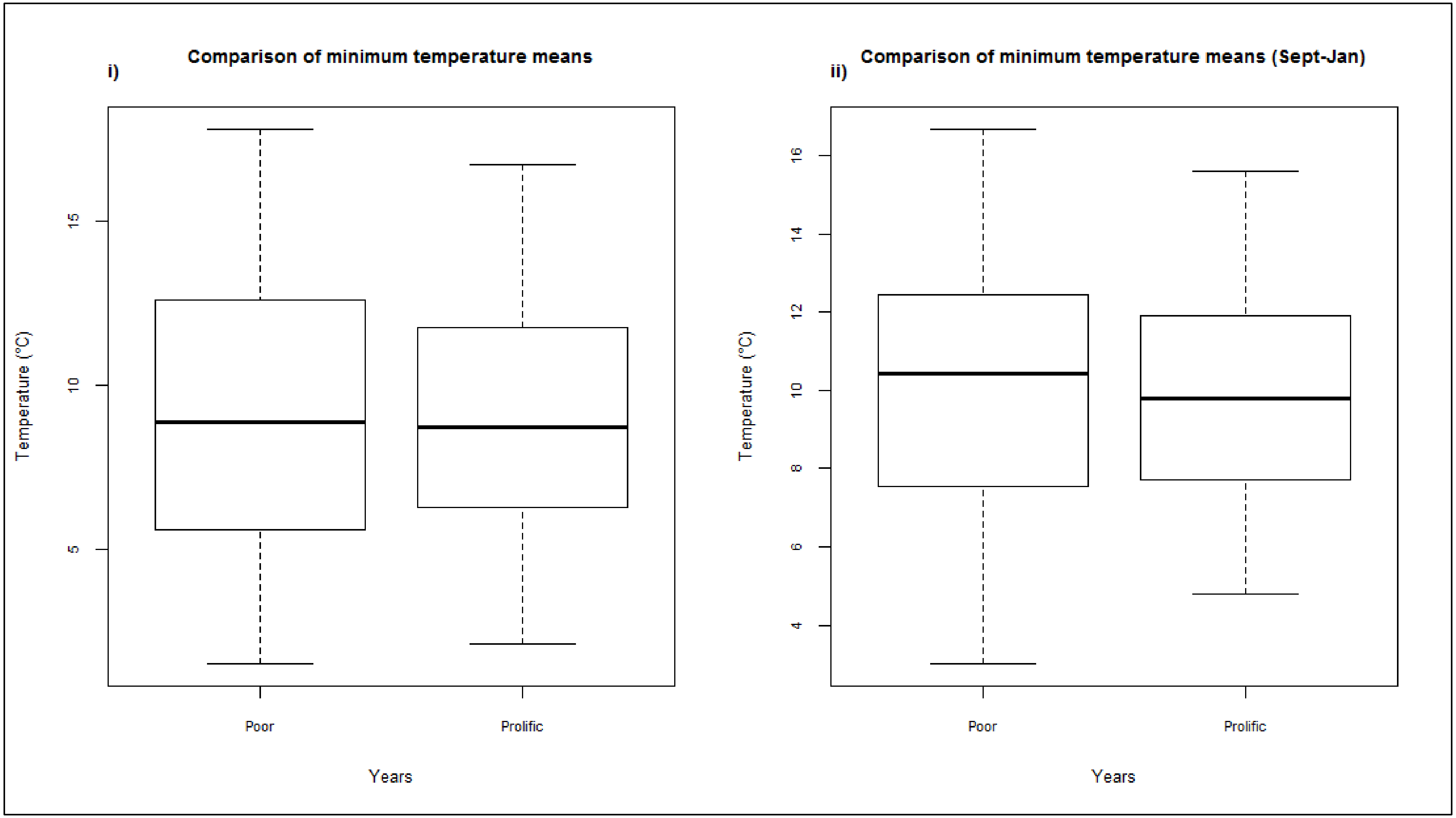


Figure 7: Boxplot of the mean comparison of minimum temperatures for i) A year before flowering and ii) 5 months before flowering.

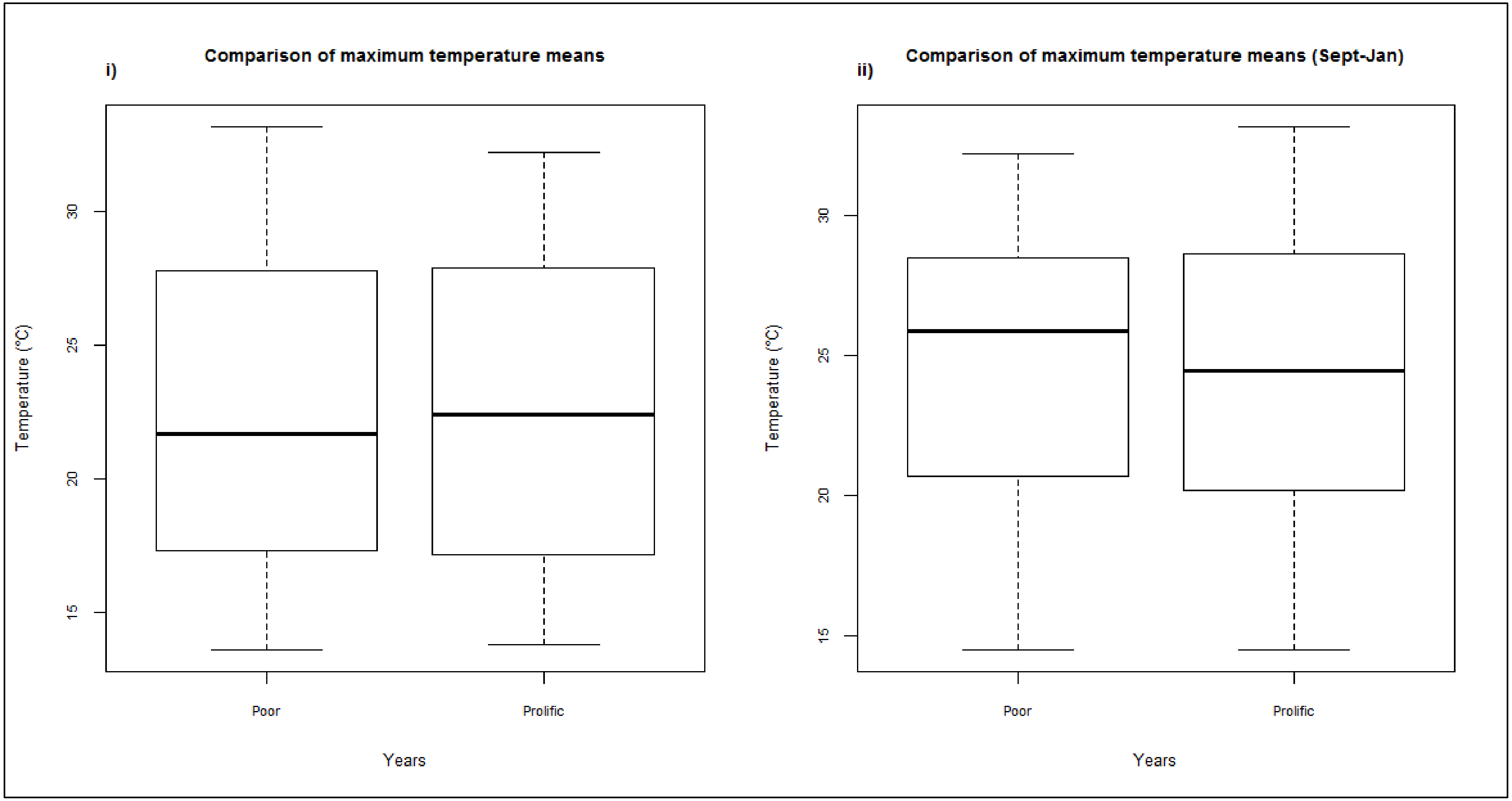


Figure 8: Boxplots of mean maximum temperature comparisons for i) a 12-months period before flowering and ii) from the start of September to end of January.

6 DISCUSSION

6.1 Main findings

Studies conducted in different locations around the world and on different species have mostly come to a common conclusion that temperature is a primary driving factor for flowering phenology (Fitter et al., 1995, Hudson et al., 2010, Hatfield and Prueger, 2015). Pancia (2018) presumed that the right combination of temperatures and rainfall during summer resulted in the prolific flowering of Marri. However, the observed temperature results in this study are not consistent with this statement nor with previous research. Average monthly maximum temperatures the year prior to a prolific flowering event and those prior a poor flowering event showed no significant difference. This was also true for analysis carried out 5 months before the onset of flowering as there was no significant differences in the average monthly maximum temperatures. Mean minimum temperature for the year prior and 5 months prior to flowering also returned similar results. There was no significant difference in the average monthly temperatures before the onset of a prolific or poor flowering event, and therefore this can be interpreted as temperature cannot be viewed as an indicator of a prolific or poor flowering event in the years 2007-2017. These results can, to some degree, be viewed to carry similarities to a different research by Michalski and Durka (2007) who related flowering to daily climate and failed to find any significant relationship between flowering and temperature.

Moreover, the average monthly rainfall received the year before a prolific flowering event and that received before a poor flowering event also did not exhibit any significant differences. However, looking at the average rainfall at a much finer scale, there was a statistically significant difference between the two groups. There were significantly higher monthly rainfall averages 8 months prior to a prolific flowering event as compared to the rain received before a poor flowering event. We can infer that increased rainfall during the winter season and the proceeding months leading up to the flowering time can be used as an indicator for a prolific flowering season and low rainfall can be an indicator of a poor flowering season. These results are in agreement with Law et al. (2000) who identified prolific flowering 9 months after a period of heavy rains. Likewise, Crimmins et al. (2011) demonstrated that monsoon rains were the main drivers of the commencement of flowering and Prieto et al. (2008) determined that the availability of water was more crucial than temperature for the flowering of their species. Additionally, Tyler (2001) failed to find a relationship between flowering and temperatures but noticed that rainfall was an important factor in the flowering of their study species. Therefore, to formally answer the research question mentioned in the introduction, there are no identifiable signals in the temperature records which can be attributed to a prolific or poor flowering season however high rainfall in the period prior to flowering is a potential indicator of prolific flowering

6.2 Limitations and future recommendations

Availability of flowering has a limitation and there is a lack of published material exclusively relating to the flowering phenology of Corymbia calophylla. There are general descriptions in scholarly and grey literature, but limited information was available on the flowering behaviour of the Marri or its relationship with climatic conditions. With that said, the use of hive license data was a viable proxy for flowering however the Wellington District is one of the few regions within WA which collects and maintains such a database. In many locations rangers do not record the hive site access information and/or apiarists do not inform local rangers when they are using these licensed sites.

In the future, longer time series of analysis using flowering observations and quantitative measurements of flowering quality would enhance the robustness of this analysis. This approach would also allow for further statistical analysis (prediction) to establish the relationship between climate factors and flowering phenology. Another alternative would be to use herbarium datasets if available as seen in Gallagher et al. (2009) and Rawal et al. (2015b).

7 CONCLUSION

This study intended to find indicators for flowering phenology in the climatic record using mean comparisons to analyse inherent differences in monthly precipitation, mean monthly maximum and minimum temperatures a few months before a prolific flowering event or a poor flowering event. It was illustrated that although both temperature variables could not be used as indicators for flowering, increased rainfall however could be used as a probable indicator of prolific flowering and low rainfall average can be associated with poor flowering. This study, therefore has achieved its objective of adding onto the knowledge apiarists have on the interrelationship between the Marri and climate. Additionally, it also takes us one step closer to understanding the complex relationship between the flowering phenology of Corymbia calophylla and climate. In that regard, there are inexhaustible opportunities for future research as different aspects of the climate are yet to be assessed and more robust methodologies explored.

8 ACKNOWLEDGEMENTS

This research was conducted under the auspice of the Cooperative Research Centre for Honey Bee Products. The author would like to acknowledge the support of the Australian Government's Cooperative Research Centres Program. Also extending acknowledgement to the University of Western Australia for providing the proper infrastructure to conduct this study.

I am eternally grateful to my supervisor Dr Bryan Boruff for his unending patience, guidance and continued support. Completing this project would not have been possible without his insightful ideas, comments and broad knowledge in GIS and beyond. I would also like to thank my peers Vidushi Patel and Lucas Dowell with whom I could share information and bounce off ideas. And finally, I extend my gratitude to my family and friends for their tremendous support and much needed words of encouragement.

9 REFERENCES

AGRIFUTURES AUSTRALIA. 2018. *Beekeeping (honey bees) | AgriFutures Australia* [Online]. @AgriFuturesAU. Available: http://www.agrifutures.com.au/farm-diversity/beekeeping-honey-bees/ [Accessed 29 March 2018].

AMANO, T., SMITHERS, R. J., SPARKS, T. H. & SUTHERLAND, W. J. 2010. A 250-year index of first flowering dates and its response to temperature changes. *Proceedings: Biological Sciences,* 277**,** 2451-2457.

BEE AWARE. 2018a. *Industry Bee Aware* [Online]. Available: http://beeaware.org.au/industry/ [Accessed 29 March 2018].

BEE AWARE. 2018b. *Pollinator reliant crops* [Online]. Available: http://beeaware.org.au/pollination/pollinator-reliant-crops/ [Accessed 29 March 2018].

BEN. 2016. *The Beekeeping Industry in Australia. - Ben Bees* [Online]. Available: https://www.bensbees.com.au/2016/08/14/beekeeping-industry-australia/ [Accessed 7 April 2018].

BOLAND, D. J. 2006. *Forest Trees of Australia,* Collingwood, CSIRO Publishing.

BOTANIC GARDENS AND PARKS AUTHORITY. 2017. *March 2017-Corymbia calophylla* [Online]. Available: https://www.bgpa.wa.gov.au/about-us/conservation/plant-of-the-month/2341-march-2017 [Accessed 16 February 2018].

BUREAU OF METEOROLOGY. 2018. *Climatological gridded data information - Australian Maps* [Online]. Available: http://www.bom.gov.au/climate/averages/climatology/gridded-data-info/gridded-climate-data.shtml [Accessed 16 January 2018].

COLEMAN, R. 1962. Bee farming: honey flora of Western Australia. *Journal of the Department of Agriculture, Western Australia, Series 4,* 3**,** 649-664.

CRIMMINS, T. M., CRIMMINS, M. A. & BERTELSEN, C. D. 2011. Onset of summer flowering in a ‘Sky Island’ is driven by monsoon moisture. *New Phytologist,* 191**,** 468-479.

CRIMMINS, T. M., CRIMMINS, M. A. & DAVID BERTELSEN, C. 2010. Complex responses to climate drivers in onset of spring flowering across a semi-arid elevation gradient. *Journal of Ecology,* 98**,** 1042-1051.

DEPARTMENT OF AGRICULTURE AND WATER RESOURCES. 2017. *Forests Australia Eucalypt forest - ABARES* [Online]. Available: http://www.agriculture.gov.au/abares/forestsaustralia/profiles/eucalypt-forest [Accessed 5 April 2018].

DEPARTMENT OF PARKS AND WILDLIFE. 2018. *Wellington Distric recreation sites* [Online]. Available: https://parks.dpaw.wa.gov.au/sites/default/files/downloads/parks/20140733-WellingtonDistrict.pdf [Accessed 26 February 2018].

DEPARTMENT OF THE ENVIRONMENT AND ENERGY. 2018. *National Vegetation Information System (NVIS) Version 5.0 Vector Data - AUSTRALIA (WA only) - Extant Vegetation* [Online]. Available: http://www.environment.gov.au/fed/catalog/search/resource/details.page?uuid=%7BC01CF8B6-8BB8-4B59-83CB-8011FEF002E0%7D [Accessed 2 February 2018].

ELZINGA, J. A., ATLAN, A., BIERE, A., GIGORD, L., WEIS, A. E. & BERNASCONI, G. 2007. Time after time: flowering phenology and biotic interactions. *Trends in Ecology & Evolution,* 22**,** 432-439.

FITTER, A., FITTER, R., HARRIS, I. & WILLIAMSON, M. 1995. Relationships between first flowering date and temperature in the flora of a locality in central England. *Functional Ecology***,** 55-60.

FORREST, J., INOUYE, D. W. & THOMSON, J. D. 2010. Flowering phenology in subalpine meadows: Does climate variation influence community co-flowering patterns? *Ecology,* 91**,** 431-440.

FRANKLIN, D. C. & PREECE, N. D. 2014. The Eucalypts of Northern Australia: An Assessment of the Conservation Status of Taxa and Communities. *A report to Kimberley to Cape and the Environment Centre NT.*

FRENCH, M. 2013. *Mass flowering of Marri* [Online]. Available: http://www.eucalyptsofwa.com.au/EucMedia/EucMedia_1stEd_Dec2013.pdf [Accessed 22 February 2018].
GALLAGHER, R., HUGHES, L. & LEISHMAN, M. 2009. Phenological trends among Australian alpine species: using herbarium records to identify climate-change indicators. *Australian Journal of Botany,* 57**,** 1-9.
GARCÍA-MOZO, H., MESTRE, A. & GALÁN, C. 2010. Phenological trends in southern Spain: a response to climate change. *Agricultural and Forest Meteorology,* 150**,** 575-580.
GIBBS, D. M. I. 1998. *The economic value and environmental impact of the Australian beekeeping industry* [Online]. Available: http://www.honeybee.com.au/Library/gibsmuir.html [Accessed 07 September 2017].
GORDO, O. & SANZ, J. J. 2010. Impact of climate change on plant phenology in Mediterranean ecosystems. *Global Change Biology,* 16**,** 1082-1106.
GUO, L., DAI, J., WANG, M., XU, J. & LUEDELING, E. 2015. Responses of spring phenology in temperate zone trees to climate warming: A case study of apricot flowering in China. *Agricultural and Forest Meteorology,* 201**,** 1-7.
HALL, N. 1970. *Forest trees of Australia,* Canberra, Australian Government Publishing Service.
HATFIELD, J. L. & PRUEGER, J. H. 2015. Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes,* 10**,** 4-10.
HEGLAND, S. J., NIELSEN, A., LÁZARO, A., BJERKNES, A. L. & TOTLAND, Ø. 2009. How does climate warming affect plant-pollinator interactions? *Ecology Letters,* 12**,** 184-195.
HUDSON, I. L., BARNETT, A., KEATLEY, M. R. & ADES, P. K. Investigation into drivers for flowering in eucalypts: effects of climate on flowering. 18th International Workshop on Statistical Modelling, 2003. 195.
HUDSON, I. L., KEATLEY, M. & KANG, I. 2011. Wavelet characterization of eucalypt flowering and the influence of climate. *Environmental and Ecological Statistics,* 18**,** 513-533.
HUDSON, I. L., KIM, S. W. & KEATLEY, M. R. 2010. *Climatic influences on the flowering phenology of four eucalypts: A GAMLSS approach*, Springer Netherlands.
HUR, J. & AHN, J. B. 2015. Seasonal prediction of regional surface air temperature and first-flowering date over South Korea. *International Journal of Climatology,* 35**,** 4791-4801.
INOUYE, D. W. 2008. Effects of climate change on phenology, frost damage, and floral abundance of montane wildflowers. *Ecology,* 89**,** 353-362.
INOUYE, D. W., SAAVEDRA, F. & LEE-YANG, W. 2003. Environmental influences on the phenology and abundance of flowering by Androsace septentrionalis (Primulaceae). *American Journal of Botany,* 90**,** 905-910.
KEATLEY, M. & HUDSON, I. 1998. The Influence of Fruit and Bud Volumes on Eucalypt Flowering--An Exploratory Analysis. *Australian Journal of Botany,* 46**,** 281-304.
KEATLEY, M. & HUDSON, I. 2007. A comparison of long-term flowering patterns of Box-Ironbark species in Havelock and Rushworth forests. *Environmental Modeling & Assessment,* 12**,** 279-292.
KEATLEY, M. R., FLETCHER, T. D., HUDSON, I. L. & ADES, P. K. 2002. Phenological studies in Australia: potential application in historical and future climate analysis. *International Journal of Climatology,* 22**,** 1769-1780.
LAMBERT, A. M., MILLER-RUSHING, A. J. & INOUYE, D. W. 2010. Changes in snowmelt date and summer precipitation affect the flowering phenology of Erythronium grandiflorum (glacier lily; Liliaceae). *American Journal of Botany,* 97**,** 1431-1437.
LAW, B., MACKOWSKI, C., SCHOER, L. & TWEEDIE, T. 2000. Flowering phenology of myrtaceous trees and their relation to climatic, environmental and disturbance variables in northern New South Wales. *Austral Ecology,* 25**,** 160-178.
LESICA, P. & KITTELSON, P. M. 2010. Precipitation and temperature are associated with advanced flowering phenology in a semi-arid grassland. *Journal of Arid Environments,* 74**,** 1013-1017.

LI, L., LI, X., LIU, Y. & LIU, H. 2016. Flowering responses to light and temperature. Beijing: Springer Science & Business Media.

MENZEL, A., SPARKS, T. H., ESTRELLA, N., KOCH, E., AASA, A., AHAS, R., ALM-KÜBLER, K., BISSOLLI, P., BRASLAVSKÁ, O. G., BRIEDE, A., CHMIELEWSKI, F. M., CREPINSEK, Z., CURNEL, Y., DAHL, Å., DEFILA, C., DONNELLY, A., FILELLA, Y., JATCZAK, K., MÅGE, F., MESTRE, A., NORDLI, Ø., PEÑUELAS, J., PIRINEN, P., REMIŠOVÁ, V., SCHEIFINGER, H., STRIZ, M., SUSNIK, A., VLIET, A. J. H. V., WIELGOLASKI, F. E., ZACH, S. & ZUST, A. N. A. 2006. European phenological response to climate change matches the warming pattern. *Global Change Biology,* 12**,** 1969-1976.

MICHALSKI, S. G. & DURKA, W. 2007. Synchronous Pulsed Flowering: Analysis of the Flowering Phenology in Juncus (Juncaceae). *Annals of Botany,* 100**,** 1271-1285.

MIGRATION WA. 2018. *Living in Western Australia - Climate* [Online]. Available: http://www.migration.wa.gov.au/living-in-western-australia/climate [Accessed 7 April 2018].

MOORE, L. M. & LAUENROTH, W. K. 2017. Differential effects of temperature and precipitation on early- vs. late-flowering species. *Ecosphere,* 8**,** e01819.

NIST SEMATECH. 2013. *1.3.5.10. Levene Test for Equality of Variances* [Online]. Available: https://www.itl.nist.gov/div898/handbook/eda/section3/eda35a.htm [Accessed 15 April 2018].

OPLER, P. A., FRANKIE, G. W. & BAKER, H. G. 1976. Rainfall as a Factor in the Release, Timing, and Synchronization of Anthesis by Tropical Trees and Shrubs. *Journal of Biogeography,* 3**,** 231-236.

PANCIA, A. 2018. *Beekeepers rush to cash in on rare megablossom* [Online]. Australian Broadcasting Corporation. Available: http://www.abc.net.au/news/2018-03-15/wa-bees-and-keepers-alike-abuzz-with-marri-megabloom/9550312 [Accessed 29 March 2018].

PAU, S., WOLKOVICH, E. M., COOK, B. I., NYTCH, C. J., REGETZ, J., ZIMMERMAN, J. K. & JOSEPH WRIGHT, S. 2013. Clouds and temperature drive dynamic changes in tropical flower production. *Nature Climate Change,* 3**,** 838-842.

PEÑUELAS, J., FILELLA, I., ZHANG, X., LLORENS, L., OGAYA, R., LLORET, F., COMAS, P., ESTIARTE, M. & TERRADAS, J. 2004. Complex spatiotemporal phenological shifts as a response to rainfall changes. *New Phytologist,* 161**,** 837-846.

PORTER, J. W. 1978. Relationships between flowering and honey production of red ironbark, Eucalyptus sideroxylon (A. Cunn.) Benth., and climate in the Bendigo district of Victoria. *Australian Journal of Agricultural Research,* 29**,** 815-829.

POWELL, R. 1990. *Leaf and branch : trees and tall shrubs of Perth,* Perth, W.A.], Dept. of Conservation and Land Management.

POWELL, R. & EMBERSON, J. 1990. *Leaf and branch: trees and tall shrubs of Perth*.

PRIETO, P., PEÑUELAS, J., OGAYA, R. & ESTIARTE, M. 2008. Precipitation-dependent Flowering of Globularia alypum and Erica multiflora in Mediterranean Shrubland Under Experimental Drought and Warming, and its Inter-annual Variability. *Annals of Botany,* 102**,** 275-285.

RAWAL, D. S., KASEL, S., KEATLEY, M. R. & NITSCHKE, C. R. 2015a. Climatic and photoperiodic effects on flowering phenology of select eucalypts from south-eastern Australia. *Agricultural and forest meteorology,* 214**,** 231-242.

RAWAL, D. S., KASEL, S., KEATLEY, M. R. & NITSCHKE, C. R. 2015b. Herbarium records identify sensitivity of flowering phenology of eucalypts to climate: Implications for species response to climate change. *Austral Ecology,* 40**,** 117-125.

RICHARDSON, A. D., KEENAN, T. F., MIGLIAVACCA, M., RYU, Y., SONNENTAG, O. & TOOMEY, M. 2013. Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. *Agricultural and Forest Meteorology,* 169**,** 156-173.

RIVERA, G. & BORCHERT, R. 2001. Induction of flowering in tropical trees by a 30-min reduction in photoperiod: evidence from field observations and herbarium specimens. *Tree Physiology,* 21**,** 201-212.

SIEGMUND, J. F., WIEDERMANN, M., DONGES, J. F. & DONNER, R. V. 2016. Impact of temperature and precipitation extremes on the flowering dates of four German wildlife shrub species. *Biogeosciences,* 13**,** 5541.

SLEE, A. V., BROOKER, M. I. H., DUFFY, S. M. & WEST, J. G. 2018. *Learn about eucalypts* [Online]. CSIRO Publishing. Available: https://www.anbg.gov.au/cpbr/cd-keys/euclid3/euclidsample/html/learn.htm [Accessed 7 April 2018].

SMITH, F. G. 1969. Honey plants in western Australia.

SNIDERMAN, J. K., MATLEY, K. A., HABERLE, S. G. & CANTRILL, D. J. 2018. Pollen analysis of Australian honey. *PloS one,* 13**,** e0197545.

SPARKS, T. H., JEFFREE, E. P. & JEFFREE, C. E. 2000. An examination of the relationship between flowering times and temperature at the national scale using long-term phenological records from the UK. *International Journal of Biometeorology,* 44**,** 82-87.

TOLLENAAR, M., DAYNARD, T. B. & HUNTER, R. B. 1979. Effect of Temperature on Rate of Leaf Appearance and Flowering Date in Maize1. *Crop Science,* 19**,** 363-366.

TOOKE, F. & BATTEY, N. H. 2010. Temperate flowering phenology. *Journal of Experimental Botany,* 61**,** 2853-2862.

TYLER, G. 2001. Relationships Between Climate and Flowering of Eight Herbs in a Swedish Deciduous Forest. *Annals of Botany,* 87**,** 623.

VAN DIJK, J., GOMBOSO, J. & LEVANTIS, C. 2016. Australian Honey bee industry: 2014-15 survey results. *In:* REPORT, A. R. (ed.). Canberra.

VISSER, M. E., CARO, S. P., VAN OERS, K., SCHAPER, S. V. & HELM, B. 2010. Phenology, seasonal timing and circannual rhythms: towards a unified framework. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 365**,** 3113-3127.

WHEATBELT NATURAL RESOURCE MANAGEMENT. 2018. *Bush Tucker plant - Kardan / Marri* [Online]. Available: https://www.wheatbeltnrm.org.au/whats-happening/news/aboriginal-nrm/bush-tucker-plant-kardan-marri [Accessed 04 May 2018].

WILLIAMS, J. D. & GROVES, R. H. 1980. The influence of temperature and photoperiod on growth and development of Parthenium hysterophorus L. *Weed Research,* 20**,** 47-52.

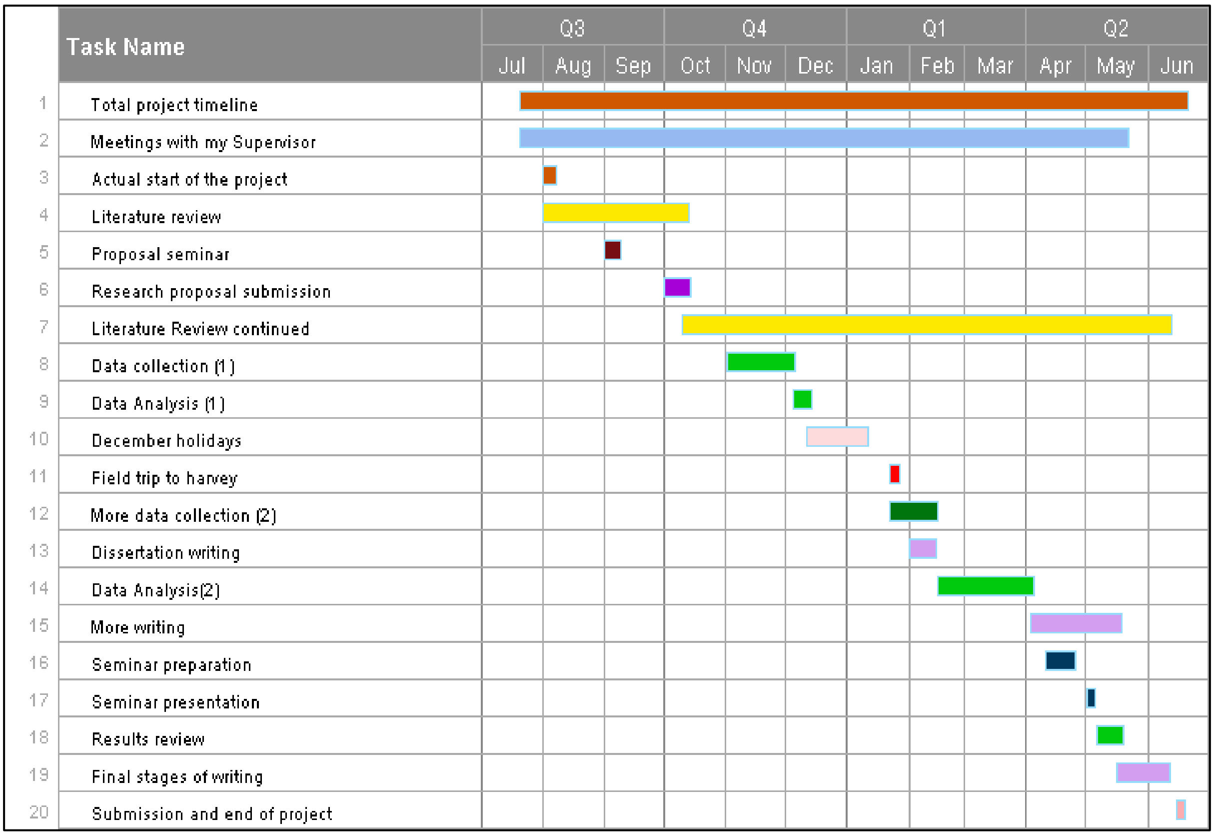
WILSON, J. 2003. Flowering ecology of a box-ironbark eucalyptus community. Deakin University.

WOLKOVICH, E. M., COOK, B. I., ALLEN, J. M., CRIMMINS, T. M., BETANCOURT, J. L., TRAVERS, S. E., PAU, S., REGETZ, J., DAVIES, T. J. & KRAFT, N. J. 2012. Warming experiments underpredict plant phenological responses to climate change. *Nature,* 485**,** 494.

10 APPENDICES

10.1 Appendix A: Project time line and work structure

Table 4: Gantt chart showing the time used for this project.



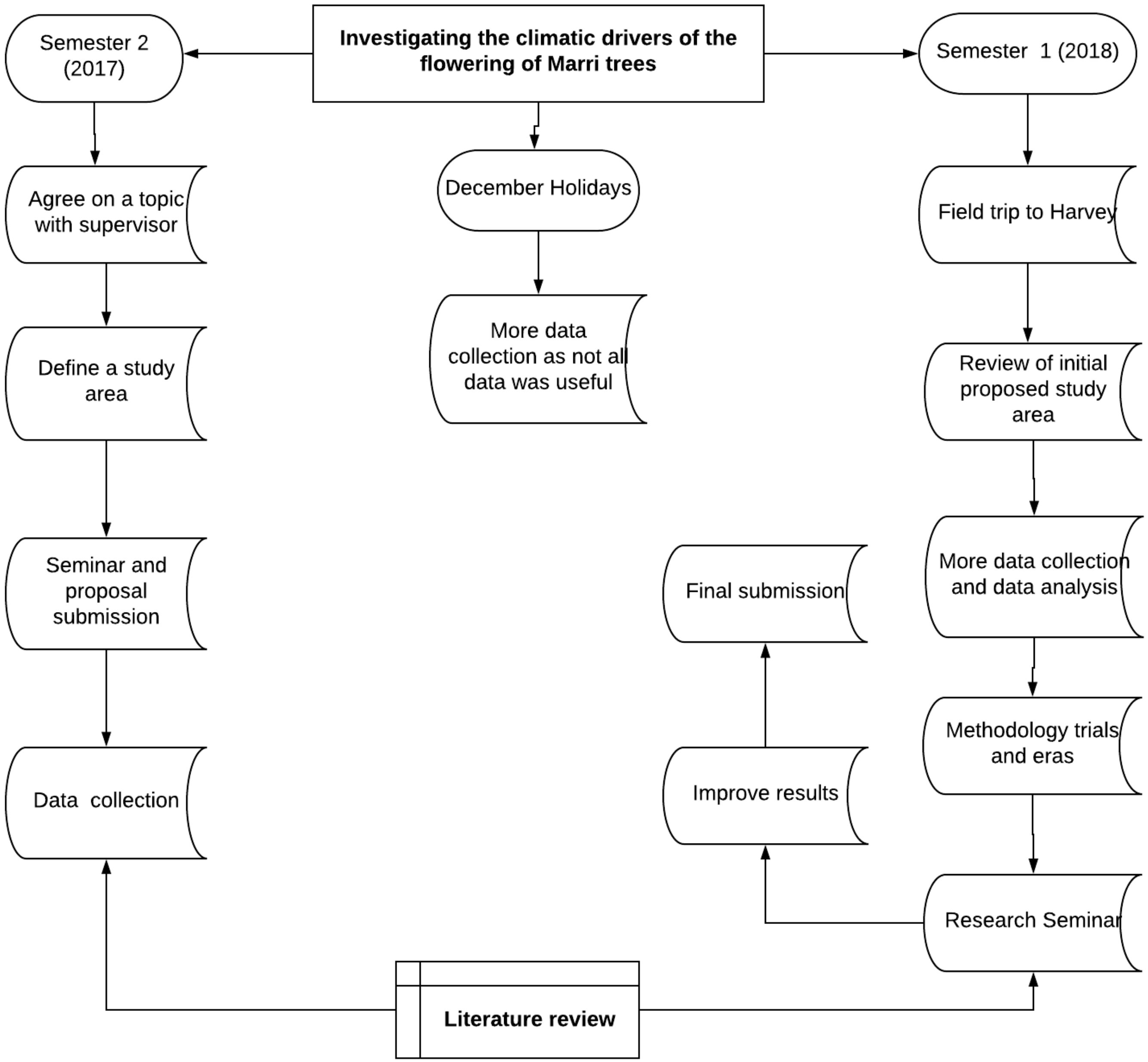


Figure 9: Work structure, showing the different stages of progress up to the completion of the project

10.2 Appendix B: Field trip to Harvey

On 22 January 2018 we embarked on a field trip to Harvey where we met one of the rangers of the area Charles Downes who had very valuable information on the area and thus was a very useful resource for this project. On this trip we were able to learn about the vegetation in the district in general not just the Marri which ended up being the main study species. The following pictures were taken on site, as on that period the Marri trees were starting to flower and also some trees were seen flowering and fruiting at the same time. Some texts suggest that fruiting only occurs after the flowering has finished.

Figure 10: Marri tree in full bloom.

Figure 11: Initial stages of flowering some buds are not open yet

Figure 12: Marri flower fully open.

Figure 13: Another example of marri with fully open flowers.

Figure 14: Beehive site A

Figure 15: Site B with more beehives

10.3 Appendix C: Flowering proxy datasets

10.3.1 Hives sites

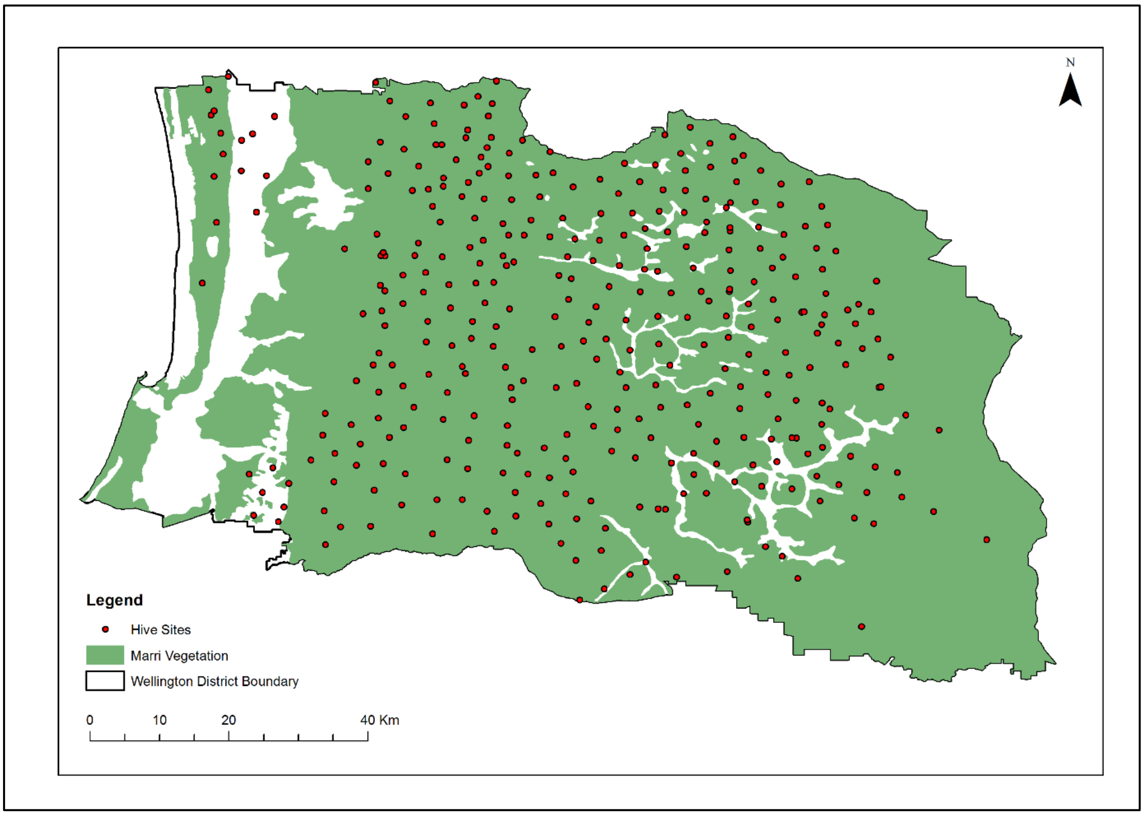


Figure 16: Point locations of permit sites

10.3.2 Summary of Log book information

A summary of the log book information is provided below of apiarists placing their hives from mid-summer to the time Marri started to flower, table 3 also summarises and highlights the good and bad flowering years.

2007 hives were onsite from 08/01/2007 - 18/04/2007

2008 hives onsite from 09/01/2008 - 18/03/2008

2009 hives onsite from 05/01/2009 - 14/02/2009

2010 hives onsite from 03/02/2010 - 30/04/2010

2011 No records

2012 hives onsite from 04/01/2012- 31/03/2012

2013 hives onsite from the previous year 30/10/2012 to 31/03/2013

2014 No records.

2015 hives onsite from 30/11/2014 to 30/03/2015

2016 NO records

2017 hives onsite from October 2016 therefore we can extrapolate that they were removed

2018 hives onsite from 08/02/2018- 30/03/2018 there was a lot however burn areas constricted the apiarists in terms of accessing the sites they normally use

Table 3: Showing the presence of the bee hives at DBCA managed sites in the Wellington district.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Oct	Nov	Dec
2007											
2008											
2009											
2010											
2011	MR										
2012											
2013											
2014	MR										
2015											
2016	MR										
2017											
2018											

*****MR = Missing record,
*pink= bad flowering year,
*green = good flowering year.

Some flowering data was sourced from ClimateWatch (N. Roslan, 2018, pers communication, 21 March) on the flowering of Marri trees but however this information could not be used as it did not have enough data on my study area and the time when some observations where made was not in agreement with my study timeline. Their observations for Marri were from 2011 to 2015. This dataset can be downloaded on (www.ala.org.au).

10.4 Appendix D: Discarded methodologies and r scripts

10.4.1 Method 1

Initially my study was focused on the entire Wellington district this did not work due to that some areas which were included were not predominantly Marri thus the decision to exclude these areas came later. Where a lot of time processing climate data using batch processing to convert ASCII files to raster, used the clip tool to clip files to study extent and then transferred pixel values to excel.

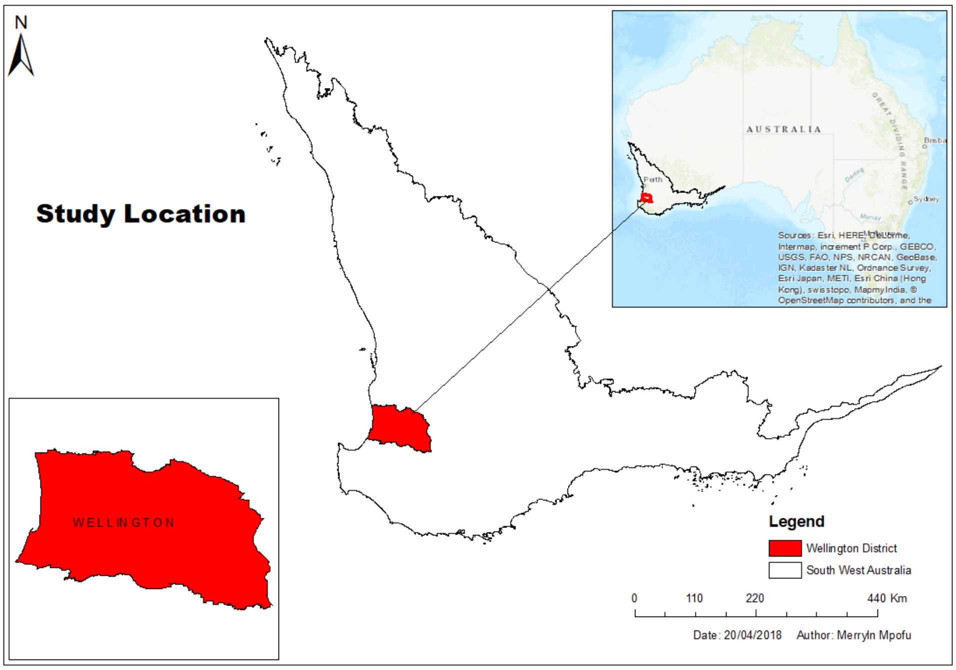


Figure 17:Initial study area which was later amended.

10.4.2 Method 2

After amending the research area, a new processing method was followed seen in figure 14. Where the zonal statistics tool was used to get an overall pixel value for the study area. However, this method was discarded due to that, one pixel value was not enough for the sample size in order to get an accurate statistical result, hence the final decision to pick 10 pixel values per month for each year.

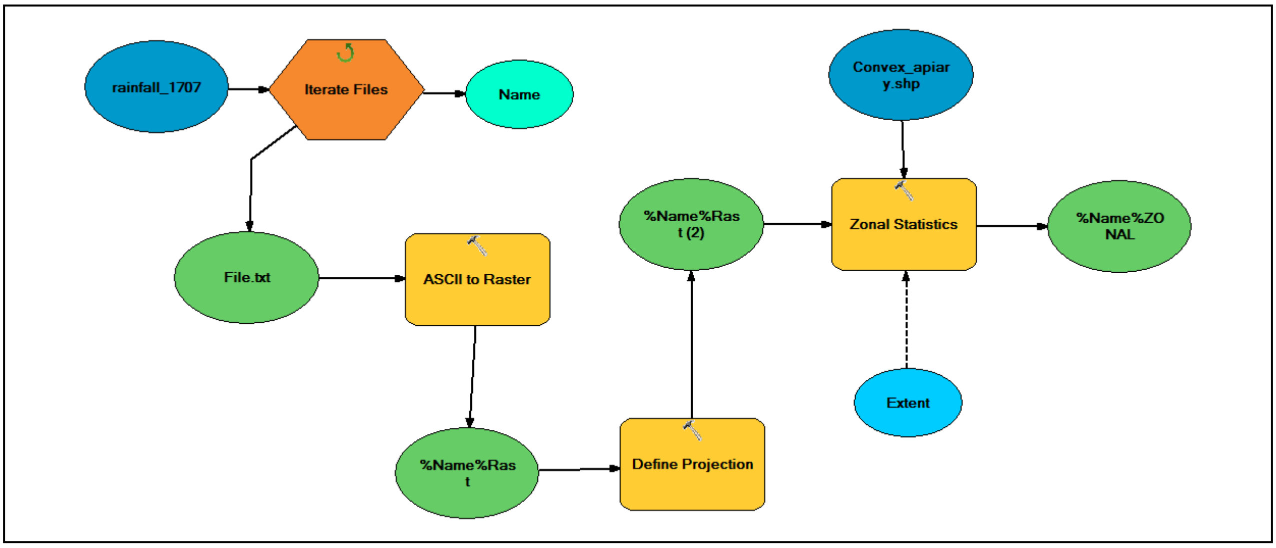


Figure 18: Model showing data processing steps

10.4.3 ArcGIS processing tools

The tools used for analysing the data are as listed,

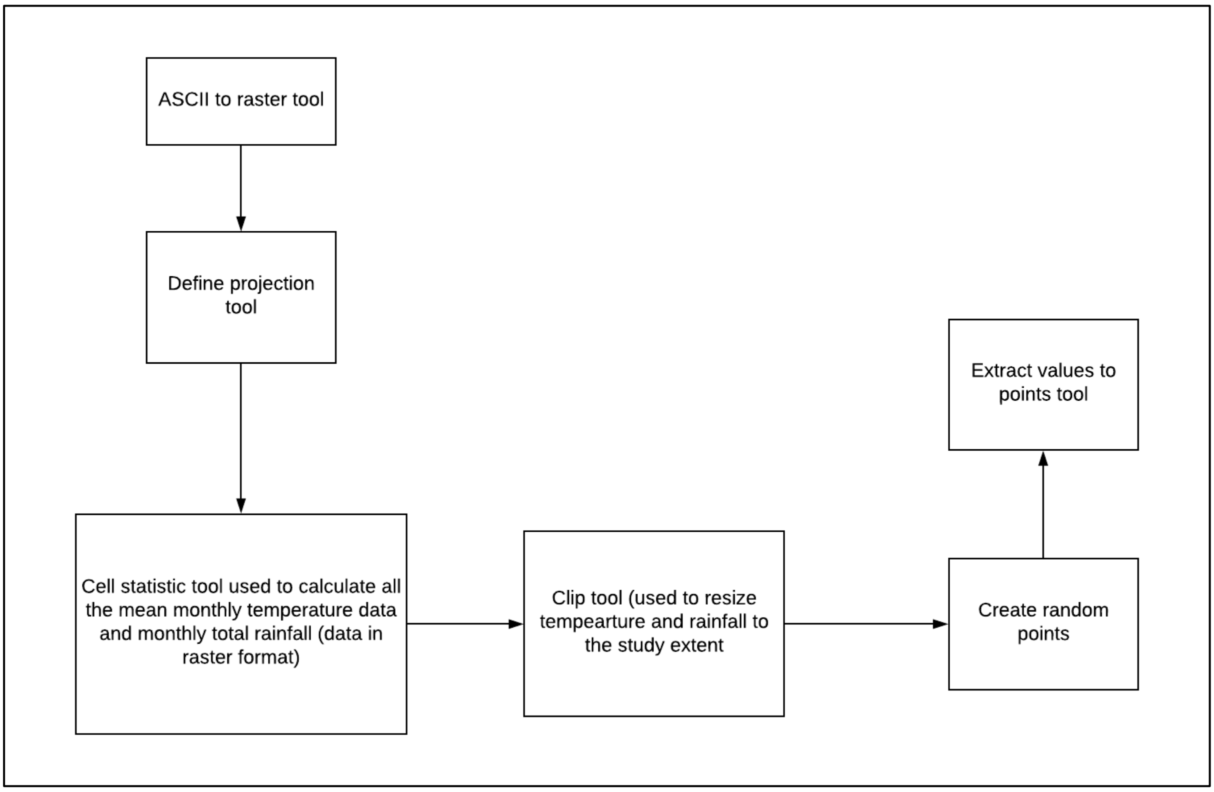


Figure 19: ArcGIS tools for data processing

10.4.3.1 R-scripts

The codes below were used for the statistical analysis for rainfall data and these very same steps were used in the processing of minimum and maximum temperature.

Time series plots

```
rain2 <- scan("Rain_TimeS.csv")

prec2 <- ts(rain2, frequency = 12, start = c(2007))

cycle(prec2)

#boxplot summarising the weather over the 11 years per month (seasonal boxplot).

png(file="sum_box_Rain2.png", width = 15, height = 15, units = "cm", res = 300)

boxplot(prec2~cycle(prec2), xlab = "Time", ylab = "Rainfall (mm)",font.lab=2, cex.lab=0.9,

        main = "Monthly Precipitation Summary", cex.axis= 0.75, cex.main=1)


dev.off()

png(file="LastRa.png", width = 15, height = 15, units = "cm", res = 300)

#timeseries trend plot

plot.ts(prec2, xlab = "Time", ylab = "Rainfall (mm)",font.lab=2, cex.lab=0.9,

        main = "Monthly Precipitation", xaxt = "n", yaxt= "n", cex.main=1)

axis (1,seq (2007,2017,1),cex.axis = 0.7)

axis(2, seq(0,280,40), cex.axis= 0.7)

#forming a background for my plot

rect(par("usr")[1],par("usr")[3],par("usr")[2],par("usr")[4],col=gray(.9,.9))

#forming a grid

abline(h=c(seq(0,240,40)),v=c(seq(2007,2017,1)), col="white")

#making the lines visible

lines(prec2, type='o', col="blue", cex=0.5)
```

Mean comparisons (a)

#rainfall for 12 months

```
#read the file into r
Rain2<- read.csv("Flows.csv")
summary(Rain2)
names(Rain2)


#levene test that population variances homogeneity
install.packages("car")
library(car)
#Ho = variances are equal
#if p value is low we reject the null hypothesis therefore variances are not equal
leveneTest(rains~Flwr,data = Rain2 )


par(mfrow= c(1,2))
#boxplot for the two groups for visualisation before applying t-test
plot(rains~Flwr, data = Rain2, ylab= "Rainfall (mm)",
    main = "Comparison of precipitation means", cex.main= 0.9,
    xlab= "Years", cex.axis= 0.7, cex.lab= 0.8)
mtext ("i)", side = 3, line = 1, adj=0, font=2, cex=0.9)


#Welch t-test
t.test(rains~Flwr,mu=0, alt= "two.sided", conf = 0.95, var.eq= F,
      paired= F, data = Rain2)
```

Mean Comparison (b)

#rainfall for 8 months

```
#read data

reyn<- read.csv("Fall_8mon.csv")


#Levene test

leveneTest(mm~Ratt,data = reyn )

summary(reyn)

names(reyn)

plot(mm~Ratt, data = reyn ,font.lab=3, ylab= "Rainfall (mm)",

   main = "Comparison of precipitation means (June-Jan)",

   cex.main= 0.9, xlab= "Years", cex.axis= 0.7, cex.lab= 0.8)

mtext ("ii)", side = 3, line = 1, adj=0, font=2, cex=0.9)


#Perform the Welch t.test

t.test(mm~Ratt,mu=0, alt= "two.sided", conf = 0.95, var.eq= F,

    paired= F, data = reyn)
```

10.5 Appendix E: Supplementary results

These results are annual temperature and rainfall data which were generated on excel.

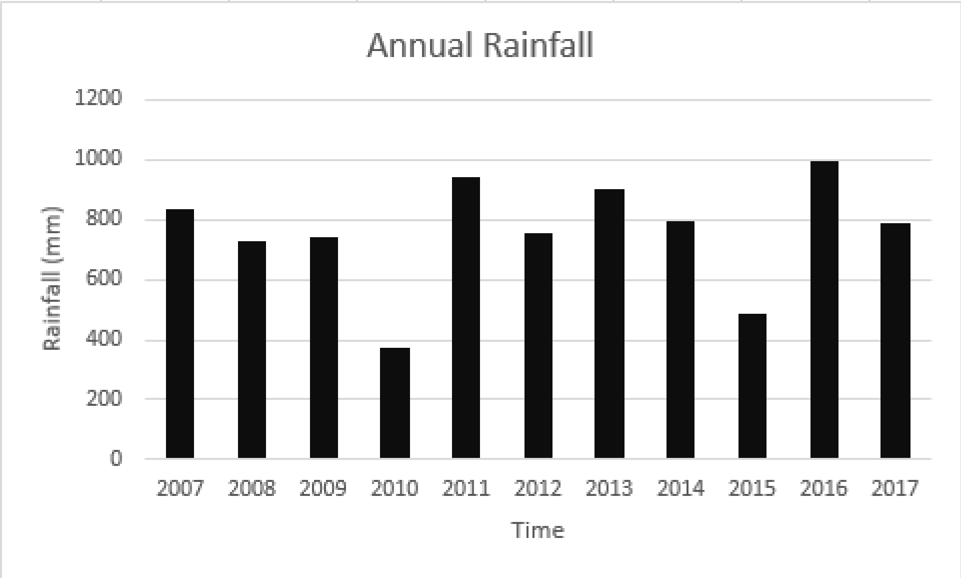


Figure 20: Annual Rainfall for 2007-2017

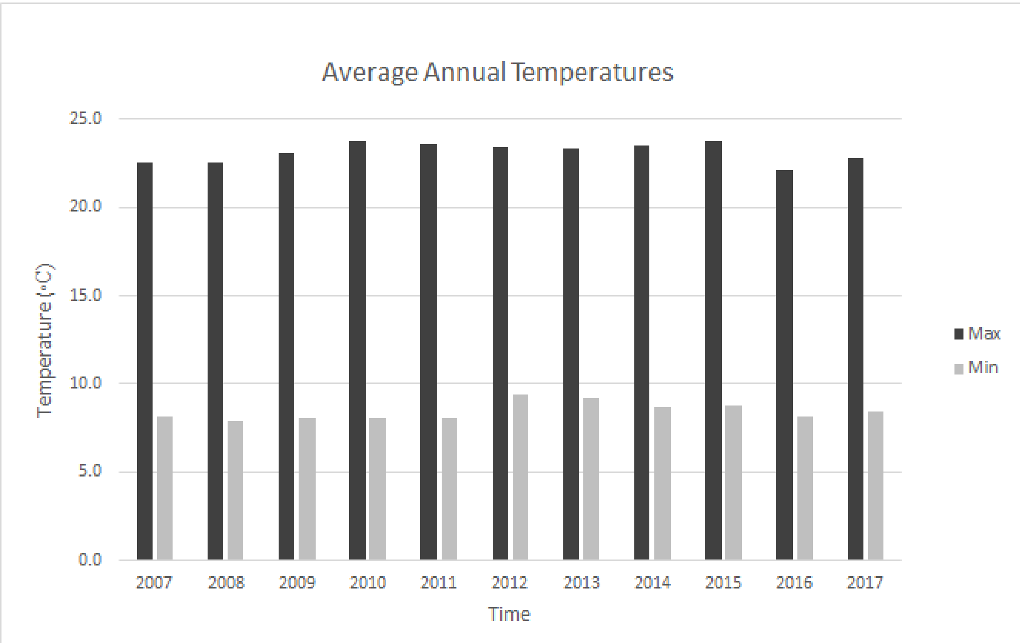


Figure 21: Annual maximum and minimum temperatures

Australian Government
Department of Industry, Science, Energy and Resources

AusIndustry
Cooperative Research Centres Program