Satellite-derived vegetation indices for flowering and non-flowering Marri (*Corymbia calophylla*)

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Abstract

Australian eucalypts are the primary source of food for Australian honey bees, and are a vital species to the bee industry. The flowering of Australian eucalypts varies each season in intensity and length; the majority of species do not having a yearly flower cycle. Understanding when and where flowering is going to occur is vital to Australian beekeepers. Limited research has been conducted into applications of remote sensing data in observing flowering in vegetation. In this study, MODIS satellite data was collected over a study area of Jarrah-Marri (*Eucalyptus marginata, Corymbia calophylla*) eucalyptus forest in south-west Western Australia, to establish whether or not satellite-derived vegetation indices can be used to observe and measure flowering in Marri. The study evaluates both non-flowering and flowering Marri, and 'good' and 'bad' Marri flowering years. Inter- and intra-seasonal differences in vegetation indices were observed between non-flowering and flowering Marri. Individual vegetation indices behaved differently, with no consistent change observed. Differences observed thus could not be confirmed to be caused either by Marri flowering or natural variation. Comparison of vegetation indices between 'good' and 'bad' Marri flowering years found there was no difference in the minimum, maximum and median values in the 12-months prior to and including the flowering period. A Welch's ANOVA with a Games-Howell post hoc test was conducted on six years of data over the Marri peak-flowering period. Statistically significant difference ($p<0.05$) was found between 'good' and 'bad' Marri flowering years for the vegetation indices. Green normalized difference vegetation index (GNDVI) was found to perform the best. These results on their own are inconclusive and require further analysis, however, this study offers a preliminary exploration of possibilities in remote sensing important to the Australian honey bee industry, and seeks to provide a foundation for further research.

1.0 Introduction

Australian eucalypts do not flower every season. Understanding the drivers of flowering and being able to measure or predict flowering events would have numerous benefits. Eucalypts are, for instance, the dominant source of food for honey bees in Australia, including in Western Australia (WA) (Manning, 1992; Benecke, 2007), and vital to the honey bee industry. The flowering of Australian eucalypts varies each season, and the majority of eucalypts are known not to have a yearly flower cycle (Gibbs and Muirhead, 1998; Benecke, 2007). Remote sensing is the acquisition of data via satellite- or aircraft-based sensor technologies through the measurement of electromagnetic radiation reflected from the surface of the earth (Jones and Vaughan, 2010). Remote sensing has the potential to provide valuable information to beekeepers and the honey bee industry as a whole, if the patterns related to eucalypt phenology, particularly flowering, are better understood. The measurement of flowering vegetation through spectral information via remote sensing may improve our capacity to assess eucalypt growth, and contribute to the development of applications of remote sensing in recognising and describing flowering for the honey bee industry. This study attempts to observe flowering *Corymbia calophylla*, also known as Marri, using satellite-derived vegetation indices in south-west WA.

Marri flowers in WA between the months of February and March (Smith, 1969; Gardner and Alpin, 1979). It is one species of many native flora targeted by WA beekeepers, growing primarily in public forests. Approximately 80-90% of WA's honey is produced from native eucalypts growing in state forests (Manning, 1992; Benecke, 2007). The spatio-temporal variation in the availability of flora and variation in flowering events each season means migratory beekeeping is practiced by necessity in Australia (Paini and Roberts, 2005; Phillips, 2014; Arundel et al, 2016). Australian beekeeping must also adjust for inconsistencies in honey flows (nectar production), meaning beekeepers maintain access to large number of sites that have varying flora species (Philips, 2014). Beekeepers move hives to sites to coincide with flowering flora. Flowering is currently predicted by beekeepers using a number of factors, including knowledge of targeted eucalypt species, rainfall, temperature, budding on trees and the history of flowering at the site (Birtchnell and Gibson, 2008; Arundel et al, 2016). Whilst beekeepers can use these factors to make an informed estimation of the timing of a flowering event at a site, the only way flowering can be validated is by physically visiting the site and observing budding and growth (Arundel et al, 2016). Beekeepers can also shift

hives four to six times a year, making the shifting of hives the most significant expense they incur (Somerville, 2005; Crooks, 2008; Phillips, 2014). Ideally, flowering would be assessed and identified through remote sensing.

Vegetation phenology is the study of specific life cycle of a plant, looking at events such as budbreak, flowering or leaf senescence (Friedl et al, 2006; Jones and Vaughan, 2010). Within the context of vegetation, land surface phenology (LSP) describes the seasonal patterning in vegetated land surfaces as observed via remote sensing (Friedl et al, 2006). The advantage of examining LSP is the broad scale applicability and repeatable monitoring methods, which can be used with both hyperspectral and multispectral sensors (Lawley et al, 2016). In applications of remote sensing focused on vegetation, the electromagnetic radiation reflected from the surface is measured and the nature of the reflection is used to understand the surface being studied (Jones and Vaughan, 2010). In forests, the reflected radiation depends on the individual characteristics of the vegetation (leaves, stems, soil and water), as well as the canopy structure being studied (Jones and Vaughan, 2010). Changes in forest characteristics also change the reflectance, absorption and transmission of solar radiation, which changes in turn the reflected radiation being measured (Jones and Vaughan, 2010).

Satellite-derived vegetation indices are dimensionless measures derived from electromagnetic radiation data, designed to measure a range of key biophysical parameters of vegetation, and are widely used in the study of vegetation in remote sensing (Pouliot et al, 2011; Blomstedt, 2014; Jarnevich et al, 2014; Delbart et al, 2015; Arundel et al, 2016; Wu et al, 2017). Whilst LSP has been widely studied, research focussing on flowering vegetation and specifically on observing flowering through satellite-derived vegetation indices has been limited. Only two studies have been conducted in Australia, one using Moderate Resolution Imaging Spectroradiometer (MODIS) multispectral data in Victoria and the other using a 3-band digital camera in WA (Arundel et al, 2016; Campbell and Fearns, 2018). Arundel et al (2016) compared a time-series analysis of the satellite-derived vegetation index, Enhanced Vegetation Index (EVI) with flowering and honey production data over an eight year period. The study focused on the flowering events of *Eucalyptus tricarpa* in central Victoria. Results comparing EVI time-series data with *E. tricarpa* flowering events and honey production were varied. Four years showed a high EVI, with strong flowering; two years showed a low EVI, with low flowering and; and two years demonstrated high EVI with low flowering (Arundel et al, 2016). Statistical comparison on the results was not performed. Campbell and Fearns

(2018) focussed on observing the flowering of the *Corymbia calophylla* (Marri) in WA using a simple 3-band (red, green, blue) digital camera. This approach was able to classify white flowers on a Marri tree at a classification accuracy of 90%, using a spatial resolution of less than 0.5cm (Campbell and Fearns, 2018). The application of this approach, however, is largely limited to studies focussed on a small geographic area.

Beyond Australia, phenological cycles have been more widely studied, in both agriculture and forestry. Observations of flowering in several studies have been established using hyperspectral data with a spatial resolution of 10 nanometres (nm) or less. Sulik and Long (2016) suggest that the influence of flowering should be consistently observable as long as the flowers targeted reflect light in the red band (e.g. white, yellow, orange, pink or red flowers) and make a significant spectral contribution to an overall canopy signal. Findings from several studies support this. In an early study, Yates and Steven (1987) found that in the flowering stage of the canola crop, floral growth reflects more and absorbs less between the 500 and 700 nm spectral region (green to red bands). More recently, Landmann et al (2015), seeking to distinguish the spectral response of flowering from non-flowering melliferous vegetation, compared hundreds of spectral bands for qualitative and quantitative analysis. Their study found spectral separability (spectral signatures) differentiating 'green' (chlorophyll active) vegetation and flowering vegetation in the 550 to 680 nm spectral region (green to red visible bands). High resolution mapping of flowering plants was demonstrated with acceptable accuracies during maximum flowering periods, where the non-woody white forbs (white flowers) provided the best results (Landmann et al, 2015). Shen et al (2009) similarly found in studying the *Halerpestes tricuspis* flower that, when present on top of the canopy, a change was observed in two satellite-derived vegetation indices, the Normalised Difference Vegetation Index (NDVI) and the EVI. The *H. tricuspis* flower is predominantly yellow, which resulted in an increase in the red band reflectance (620-670 nm) without apparent changes in the near-infrared (NIR) and blue band reflectance (Shen et al, 2009). Whilst the results show a change in spectral response of flowering vegetation, the case study being a dominant yellow flower presenting on top of the canopy and covering up to 30% of the total area could be a site-specific result.

Other studies have found that the LSP metrics, green-up and start-of-season (SOS) can be clearly related to variations in the leafing and flowering of species (Blomstedt, 2014; Delbart et al, 2015). Delbart et al (2015) found in-situ observations of flowering vegetation correlated

strongly with green-up dates derived from satellite imagery. Others, however, found flowering vegetation did not relate as well to the timing of SOS phenology (Pouliot et al, 2011). The majority of the research on green-up and SOS phenology is based on deciduous northern hemisphere vegetation. It is unclear if these findings can be related to Australian vegetation, as spring foliage and flowers in deciduous northern hemisphere vegetation develop primarily in response to increasing temperature, whereas flowering in Australian eucalypts is influenced by a variety of factors. Limited studies have likewise been conducted on the relationship between satellite data and phenology of nectar production. Those that do exist attempted to establish a correlation between satellite-derived vegetation indices, mainly NDVI and EVI, and honey bee nectar flow (HBNF) (Ward and Starks, 2000; Nightingale et al, 2008; Lynn, 2013; Blomstedt, 2014; Jarnevich et al, 2014). Nightingale et al (2008) found that NDVI was able to predict the beginning and average peak of nectar flow in a hive with a R^2 of 0.65 and 0.79 respectively. Lynn (2013) and Blomstedt (2014), however, found no correlation between EVI or NDVI with HBNF.

The effect flowers have on satellite-derived vegetation indices during seasonal growth in forests is not well understood (Shen et al, 2009). This is an important gap in knowledge given the relevance to bees and nectar production in Australia in particular. The majority of studies on LSP have focussed on the greening and browning of vegetated landscapes (Turner et al 1999; Huete et al, 2002; Melaas et al, 2013; Broich et al, 2015). Despite positive results with specific colours of flower and in specific situations, previous studies have been unable to conclusively find whether flowering vegetation can be observed through satellite imagery data. Vegetation indices are based on total vegetation, and may not necessarily be capable of distinguishing the blooming of species which are only a fraction of the total vegetation (Jarnevich et al, 2014). Currently, in-situ observations are still proven to be more reliable than satellite-derived vegetation indices in monitoring LSP (Delbart et al, 2015).

In this study, satellite-derived vegetation indices have been evaluated for a eucalyptus forest in south-west WA containing a mix of *Eucalyptus marginata* (Jarrah) and *Corymbia calophylla* (Marri), to identify whether or not changes in spectral response can be used to observe differences in flowering and non-flowering Marri. The objectives of this research are twofold: first, to see if there is a difference in the spectral response of flowering and non-flowering Marri trees in a near-homogenous stand; and second, to see if a difference can be observed in the spectral response across years of ‘good’ Marri flowering versus those of ‘bad’

or non-flowering seasons. For the first objective, remote sensing data was evaluated over one season to see if a change in vegetation indices occurred between non-flowering and flowering Marri trees in a eucalypt forest. For the second, vegetation indices were evaluated over multiple years between 'good' and 'bad' flowering seasons, to observe differences in yearly variations. This study is to be considered as a preliminary investigation into the possibilities of detecting flowering events using satellite-derived remotely sensed data, specifically in regards to Marri.

2.0 Methods

The information collected from human subjects for this project was done so under the approval of the University of Western Australia, Human Research Ethics Office – RA/4/1/9247.

2.1 Study area

This study focussed on a homogenous stand of Jarrah-Marri (*Eucalyptus marginata*, *Corymbia calophylla*) forest in south-west WA, located in the Department of Biodiversity, Conservation and Attractions (DBCA) Wellington District (**Figure 1**).

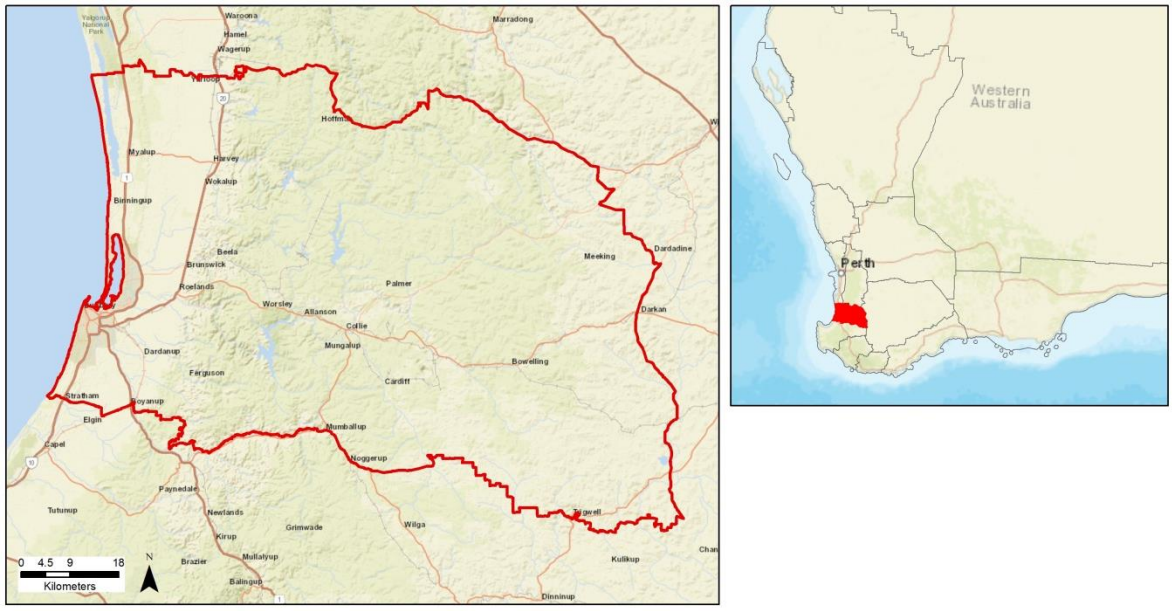

Figure 1 Left image: DBCA Wellington District. Right image: location of Wellington District in south-west WA.

Approximately 40% of the Wellington District is covered by eucalypt open forests, as defined by the National Vegetation Information System (NVIS) (**Figure 2**), with the eucalypt open forest in the Wellington District primarily subsisting of Jarrah and Marri (Beard, 1990).

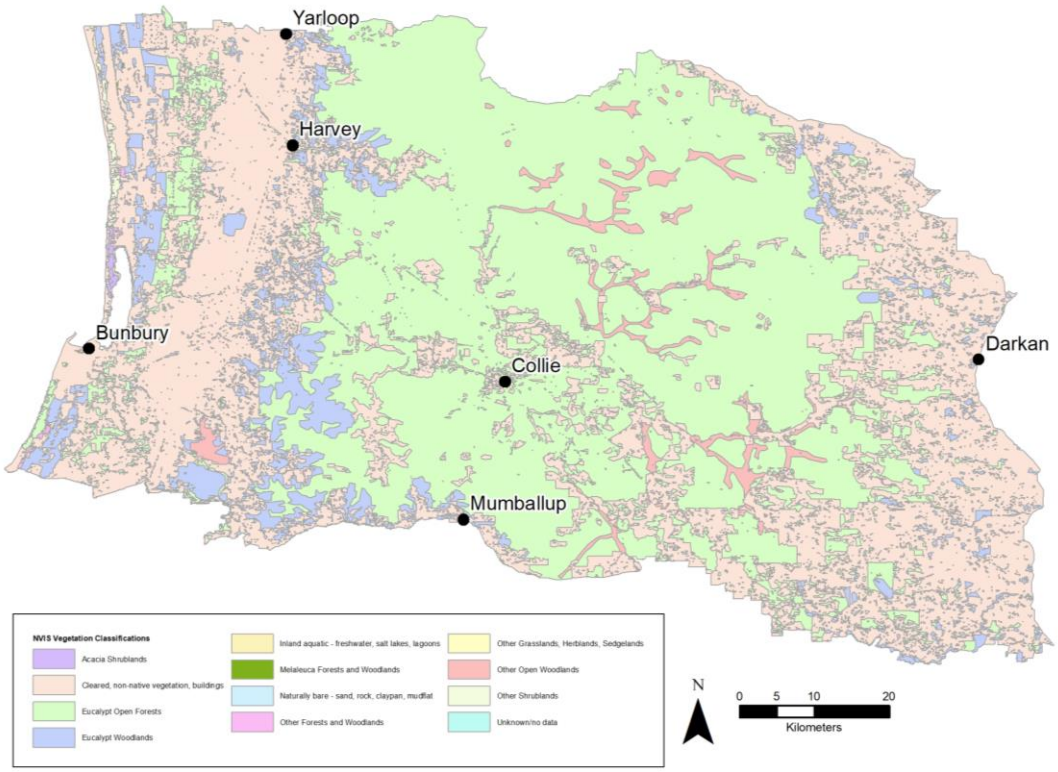

Figure 2 Wellington District land cover as defined by NVIS.

The study area, necessarily representing a homogenous stand of Jarrah-Marri forest, was identified east of Harvey in the DBCA Wellington District. The study area as found was based on the following requirements:

- Homogenous Jarrah-Marri forest over entire study area.
- Study area has not experienced land-use changes over the study period.
- Study area is used by beekeepers to target flowering Marri.
- Study area has not been impacted by bushfire over the study period.

The homogeneity of the Jarrah-Marri stand was identified using NVIS data, defined as eucalypt open forest. There are 254 current licenced hive sites used by beekeepers in the Wellington District (pers.comm. Downes, 2018). The area was refined by targeting licensed hive sites that are frequently used during Marri flowering periods as identified by the DBCA District Ranger (pers.comm. Downes, 2018). The area was additionally refined by avoiding recent bushfire occurrences in the Wellington District (13 December 2009, fire 15km north-east of Harvey (exact footprint unknown); 29 January 2015, Lower Hotham fire; 6 January 2016, Yarloop fire (**Figure 3**)). The location of the study area was further refined using the spatial location of frequented apiary sites. ‘Convex hull’ technique was then used to delineate

a polygon incorporating all frequented apiary sites and avoiding known recent bushfire footprints, resulting in a study area of 8.9 km^2, comprised primarily of Marri and located approximately 20km to the east of Harvey, WA (**Figure 3**). Defining a polygon region instead of using single points or pixels provides a less noisy time-series and is not limited to being rectangular in shape (Bradley et al, 2010; Broich et al, 2015; Arundel et al, 2016).

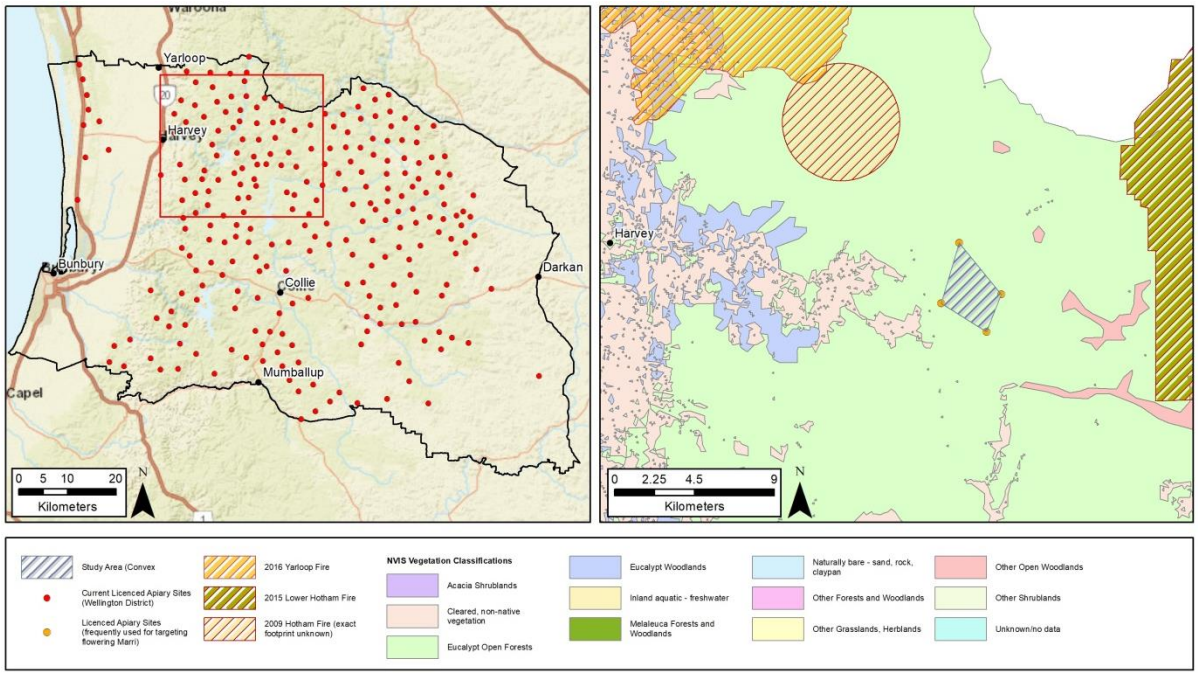

Figure 3 Left image: apiary sites in Wellington District, red-box defining extent of right-image. Right image: hive sites frequently used during Marri flowering periods, known historical bushfire extents, chosen study area defined by convex hull (blue hash).

2.2 Jarrah-Marri forest in south-west WA

The Jarrah-Marri forest in the south-west WA contains a mix of Jarrah and Marri trees with the ratio changing depending on the soil type (Beard, 1990). Jarrah is dominant on soils derived from laterite, whilst Marri is dominant on deeper sandy soil, particularly those overlying granite (Smith, 1969). Forest Blackbutt (*Eucalyptus patens*) is found on the banks of streams in the Jarrah-Marri forest (Smith, 1969). The understory of the forest contains a mix of small shrubs and trees with Banksias and Acacias most prevalent (Beard, 1990). The trees present vary between 20 to 30 m in height, with a lower layer of small tress approximately 10 m in height, including *Banksia grandis* and a smaller understorey of shrubs reaching 1 to 2 m in height (Beard, 1990). The understorey varies from swampy bottomlands to granite outcrops. The study area is a typical Jarrah-Marri forest in the south-west WA, containing approximately an even split between Jarrah and Marri eucalypts (**Figure 4**).

a)

b)

Figure 4 a) Aerial image of study area taken February 2013 (Nearmap); b) Jarrah-Marri forest canopy taken in Wellington District, February 2018.

2.3 Marri tree

The Marri tree is widely distributed in south-west WA (Gardner and Alpin, 1979). It can grow up to 30 metres in height and has large white flowers, generally seen flowering between February and March (Smith, 1969; Gardner and Alpin, 1979). The Marri displays its flowers clear of the leaves, with a typical flower size between 1.3-4.5 cm (Brooker and Kleinig, 2001). When growing as an isolated tree free from competition, Marri develops a large bulbous crown (**Figure 5**). Marri was chosen for this study because of its consistent flowering (compared to other eucalypt species), its short and vibrant flowering window (February-March), the production of flowers clear of leaves, and its importance as a species in the supply of nectar for apiarists (Smith, 1969; Gardner and Alpin, 1979).

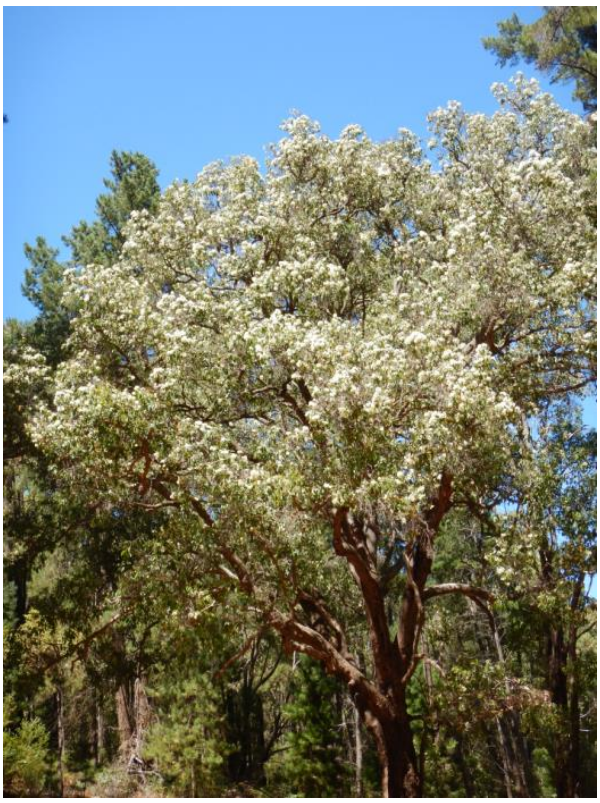

Figure 5 Image of Marri in flower in Wellington District in February 2018

2.4 Flowering data

In WA, no publically accessible data has been collected on the specific flowering periods of eucalypts at a landscape scale on an annual basis. Whilst beekeepers record data both on honey production yields from individual species and on the flowering of targeted flora, this data is not publicly shared (Arundel et al, 2016). One of the known studies conducted on honey yield from apiarist sites in WA was a beekeeper questionnaire conducted by Manning (1992). This predates the time period covered by available satellite data used in this study. Because flowering data on eucalypts is not readily available, a proxy source was identified in bee hive placement.

Data for this portion of the project was obtained through the DBCA. All beekeepers placing hives on crown land in WA must obtain a permit through the DBCA (DPaW, 2013). Under the conditions of the permit, beekeepers must contact the relevant DBCA district office prior to placing or removing any hives on a licenced site (DPaW, 2013). Other information collected by the DBCA includes (i) when the site was used, (ii) the length of time the site was occupied, (iii) when hives were removed from the site and (iv) GPS locations of all sites (DPaW, 2013). Beekeepers were found to successfully predict the onset of flowering at a site

80% of the time (Birtchnell and Gibson, 2008). This successful prediction of flowering events makes bee hive movement data a valid proxy for flowering eucalypts.

The hive site movement data of two apiarists known to target flowering Marri was used specifically as the proxy for this study (pers.comm. Patel, 2017). There are known limitations in using hive site movement data as a proxy for flowering. Beekeepers have been known to bring hives to site on speculation that flowering may occur in the future, but before flowering has actually started, generally informed by the observation of budding (pers.comm. Downes, 2018). The opposite can also be true; in that flowering can occur without or before an beekeeper having decided to bring hives onto sites. Because of this limitation, additional information was used to create multiple lines of evidence, improving confidence in the use of hive site movement data as a proxy for flowering. The additional information used includes literature on Marri flowering (Smith, 1969; Gardner and Alpin, 1979), anecdotal evidence through an interview and media releases, aerial imagery, and visual confirmation. A DBCA ranger with the Wellington District, supplied both Department hive site movement data and, in an interview, anecdotal evidence (pers.comm. Downes, 2018).

This additional information was used in categorising Marri flowering into two groups: ‘good’ or ‘bad’ flowering years. The evidence was categorised according to the following sources: hive site movement data, anecdotal evidence (DBCA ranger and media releases) and visual confirmation (aerial imagery and site visits) (**Table 1**). The information concerning yearly flowering quality was then classified based on the author’s confidence in the data’s accuracy (1 = high confidence, 2 = low confidence). Flowering years with confidence level 1 was used in the study. Four time points (2010, 2013, 2015 and 2018) were used as ‘good’ Marri flowering years and three (2014, 2016 and 2017) as ‘bad’ Marri flowering years, all with a high confidence level. (**Table 1**).

Table 1 Evidence of Marri flowering seasons

Flowering Season	Hive Movements[(1)]	Anecdotal Evidence (DBCA Ranger)[(1)]	Anecdotal Evidence (Media Release)	Visual Confirmation	Flowering	Confidence
2007	✔				Good	2
2008	✔				Good	2
2009				✔ [(6)]	Unknown	-
2010	✔		✔ [(2)]		**Good**	**1**
2011	✔				Bad	2
2012	✔				Good	2
2013	✔		✔ [(3)]	✔ [(6)]	**Good**	**1**
2014		✔			**Bad**	**1**
2015	✔	✔	✔ [(4)]		**Good**	**1**
2016		✔			**Bad**	**1**
2017		✔			**Bad**	**1**
2018	✔	✔	✔ [(5)]	✔ [(6, 7)]	**Good**	**1**

[(1)] (pers.comm. Downes, 2018)
[(2)] (Manning, 2010)
[(3)] (French, 2013)
[(4)] (C.P.D Tree Services, 2015)
[(5)] (Pancia, 2018)
[(6)] (Nearmap, accessed 2018)
[(7)] (Site Visit, 11 February 2018)

2.5 Vegetation indices

Remote sensing utilises different wavelengths and frequencies of electromagnetic radiation. This range of wavelengths/frequencies is referred to as the electromagnetic spectrum (Lillesand, Kiefer and Chipman, 2004; Jones and Vaughan, 2010; Jensen, 2016). The electromagnetic spectrum is grouped into different portions including visible light, x-rays, thermal, microwave and radio waves (Lillesand, Kiefer and Chipman, 2004; Jones and Vaughan, 2010; Jensen, 2016). Satellites measure the electromagnetic spectrum in specific bands, with most common spectral bands being blue, green, red, and near-infrared (NIR). Spectral bands are used in different combinations to create satellite-derived vegetation indices, which are used in turn to measure biophysical parameters such as vegetation vigour and canopy structure (Jones and Vaughan, 2010). Satellite-derived vegetation indices are dimensionless measures derived from electromagnetic radiation data and designed to measure a range of vegetation properties (Huete et al, 2002; Jones and Vaughan, 2010). The majority

of vegetation indices are based on the sharp increase in reflectance from vegetation that occurs around red and NIR region of the electromagnetic spectrum (Henebry and de Beurs, 2013). Four widely used vegetation indices are the Normalised Difference Vegetation Index (NDVI), the Enhanced Vegetation Index (EVI), the Green Normalized Difference Vegetation Index (GNDVI) and the Soil-adjusted Vegetation Index (SAVI), due to their positive relationship with canopy density or vegetation vigour and their ability to monitor spatial and temporal variations in vegetation (Jones and Vaughan, 2010). The NDVI and EVI correlate with various vegetation parameters such as chlorophyll content, leaf area index (LAI), biomass, canopy cover, and fraction of absorbed photosynthetically active radiation (fAPAR) (Rouse et al, 1974; Huete et al, 2002; Jones and Vaughan, 2010). The GNDVI aims to improve the sensitivity of results for dense vegetation with a high LAI, and SAVI attempts to minimise the noise caused by underlying soil reflectance (Huete, 1988; Gitelson et al, 1996; Jones and Vaughan, 2010). The mechanism producing variation in the four vegetation indices is that there are distinct differences between vegetation and soil reflectance (Jones and Vaughan, 2010). The ratio of soil to vegetation primarily determines the reflectance value of a single pixel. On top of this, the derived vegetation indices vary with chlorophyll concentration and other biochemical components (Jones and Vaughan, 2010). This study used NDVI, EVI, GNDVI and SAVI satellite-derived vegetation indices to evaluate if flowering vegetation produces a distinct spectral response that can be observed using remote sensing data (**Table 2**).

Table 2 Vegetation indices formula

Vegetation Index	**Formula**	**Reference**
Normalised Difference Vegetation Index (NDVI)	(NIR - R) / (NIR + R)	Rouse et al, 1974
Enhanced Vegetation Index (EVI)	2.5 x [(NIR - R) / (NIR + 6 x R- 7.5 x B + 1)]	Huete et al, 2002
Green Normalised Difference Vegetation Index (GNDVI)	(NIR-G) / (NIR+G)	Gitelson et al, 1996
Soil-Adjusted Vegetation Index (SAVI)	(1+L) x (NIR-R) / (NIR+R+L)	Huete, 1988
NIR – near-infrared; R – red; G – green; B – blue; L – constant, value of 0.5 taken for this study (Huete, 1988).		

2.6 Satellite data

Multispectral satellites are most commonly used to examine LSP due to their spatial and temporal resolutions, and historical databases allowing the study of seasonal and long-term variations of vegetation (Huete et al, 2002; Zhang et al, 2006). The spatial (ground resolution), temporal (frequency), and spectral (number of bands) resolutions influence the

vegetation indices as calculated with remote sensing data (Lawley et al, 2016). Numerous remote sensing satellites orbit the earth. For this research, MODIS satellite data was used because it provides freely available data, collects the spectral bands required to calculate the vegetation indices used in the study, and provided sufficient temporal and spatial resolution (**Table 3**). MODIS is also widely used in LSP studies (Shen et al, 2009; Pouliot et al, 2011; Blomstedt, 2014; Jarnevich et al, 2014; Delbart et al, 2015; Arundel et al, 2016). The temporal resolution of MODIS (1-2 days) proved better than alternative satellites such as Landsat TM (a coarser resolution of 8-16 days). MODIS thus offers a greater likelihood of obtaining cloud-free data, even though it has a higher spatial resolution (500 m vs 30 m respectively).

Table 3 MODIS satellite specifications

Spatial Resolution	250 m (bands 1-2) 500 m (bands 3-7) 1 km (bands 8-36)
Temporal Resolution	1-2 days
Spectral Resolution	405 nm – 14.385 µm (visible – infrared radiation)
Radiometric Resolution	12 bits
Year Launched	2000

2.7 Data analysis

2.7.1 Data acquisition and pre-processing

MODIS satellite data (MOD09A1 dataset) was downloaded and processed using the online platform Google Earth Engine (GEE). GEE provides online access to worldwide coverage of remote sensing data, and thus was useful tool for this project (Johansen et al, 2015). MOD09A1 is pre-processed Level 3 data, which has been radiometrically calibrated, atmospherically corrected and temporally composited (Vermote et al, 2011). MOD09A1 provides an 8-day composite dataset, based on collection of data every 1-2 days, and collected at a pixel resolution of 500m (Vermote et al, 2011). Composites are created by producing a mean of the corresponding pixels over a multi-day period, removing pixels that have been affected by clouds/aerosols. Band 1 (red band), band 2 (NIR band), band 3 (blue band) and band 4 (green band) were obtained from the dataset to calculate the required vegetation indices.

MOD09A1 dataset is designed to provide consistent, spatial and temporal comparisons to monitor photosynthetic activity, with the other advantages being that the product is less affected by cloud cover and atmospheric contamination (Huete et al, 2002; Arundel et al, 2016). The MOD09A1 data acquired over the study area contains 42 MODIS pixels, including individual pixel values as well as calculated means. Although MODIS data pre-processing is meant to remove pixels affected by clouds, undetected clouds have still been observed (Tang et al, 2013). In general, the surface reflectance of a land pixel varies slowly; a sharp change in reflectance could therefore be from cloud cover or an irregularity, with a sudden change of reflectance in the blue wavelength a particular sign of cloud interference (Tang et al, 2013). The MOD09A1 data was further processed to remove data that had been affected by clouds undetected in the pre-processing. This was achieved by removing data based on a sharp change in the reflectance of the blue band (50% or more), as this is the band most likely impacted by cloud interference (Tang et al, 2013).

2.7.2 Statistical treatment

Analysis of variance (ANOVA) was used to determine whether there were statistically significant differences between the means of groups. ANOVA assumes the dependent variable is normally distributed; however, normality of the data is not required when sample sizes greater than 40 are used in the analysis (Elliot and Woodward, 2007). Equality of variance is a strict requirement in the use of a one-way ANOVA. This study therefore used Welch's ANOVA, as it is suitable to use with heterogeneous data (Liu, 2015). Games-Howell post hoc test is a pairwise comparison test method which is used in the case of unequal group variance, it was used to confirm where differences occurred between groups.

The hypotheses for the comparison of means in a Welch's ANOVA are:

- Null hypothesis (H_0): $\mu_1 = \mu_2 = \ldots = \mu_k$ (the means of all groups are the same).
- Alternative hypothesis (H_a): $\mu_i \neq \mu_j$ (the means of at least two groups are different).

The evidence used to 'reject' or 'fail to reject' the null hypothesis is based on the *p*-value, with a *p*-value of less than 0.05 indicating that the null hypothesis should be rejected (Elliot and Woodward, 2007). SPSS software was used for the statistical analysis in this study.

3.0 Results

3.1 Comparing spectral response between non-flowering and flowering Marri

To compare the spectral response between non-flowering and flowering Marri, data on known flowering times was required. Reliable flowering data was available for the 2010 and 2018 seasons, based on hive site movements and anecdotal evidence. Beekeepers moving hives on- and off-site were used as a proxy for Marri flowering. Hives were moved to sites in the study area on 7 February 2010 and 10 February 2018, and off-site on the 20 March 2018 (There was no off-site data for 2010). The 7-10 February ('start') and the 20 March ('end') were used as soft indications of the Marri flowering period. From this information, three periods were examined to compare non-flowering to flowering Marri, well within the defined flowering date-points:

- Pre-flowering (9 January – 24 January)
- Peak-flowering (18 February – 5 March)
- Post-flowering (30 March – 14 April)

3.1.1 Observing direct spectral response to flowering Marri

The mean pixel values over the entire study area for the four vegetation indices (NDVI, EVI, GNDVI and SAVI) were graphed over the three periods for 2010 and 2018 (**Figure 6**). **Figure 6** represents the pre-, peak- and post-flowering periods. There is inter-seasonal and intra-seasonal variation in each vegetation index. The magnitude of results varies between years, and within years between the start of summer (December) and autumn (May). Variation in inter-seasonal results could be due to fluctuations in canopy structure and 'greenness' of the vegetation in the study area. Variation in intra-seasonal results shows all vegetation indices in 2010 and 2018 have a general increasing trend from late December to early May. **Figure 6** illustrates that NDVI and GNDVI reveal a similar pattern, whilst EVI and SAVI also exhibit similarities across the study period. The NDVI and GNDVI in both years show values decreasing at the start of the peak-flowering period and then starting to increase, whilst the EVI and SAVI in both years show values increasing at the start of the peak-flowering period and then decreasing during the peak-flowering period. **Figure 6** illustrates that index values vary between years during peak-flowering periods. Therefore, the index values themselves

should be used with caution. Trends in index values across time may, however, correspond with flowering events.

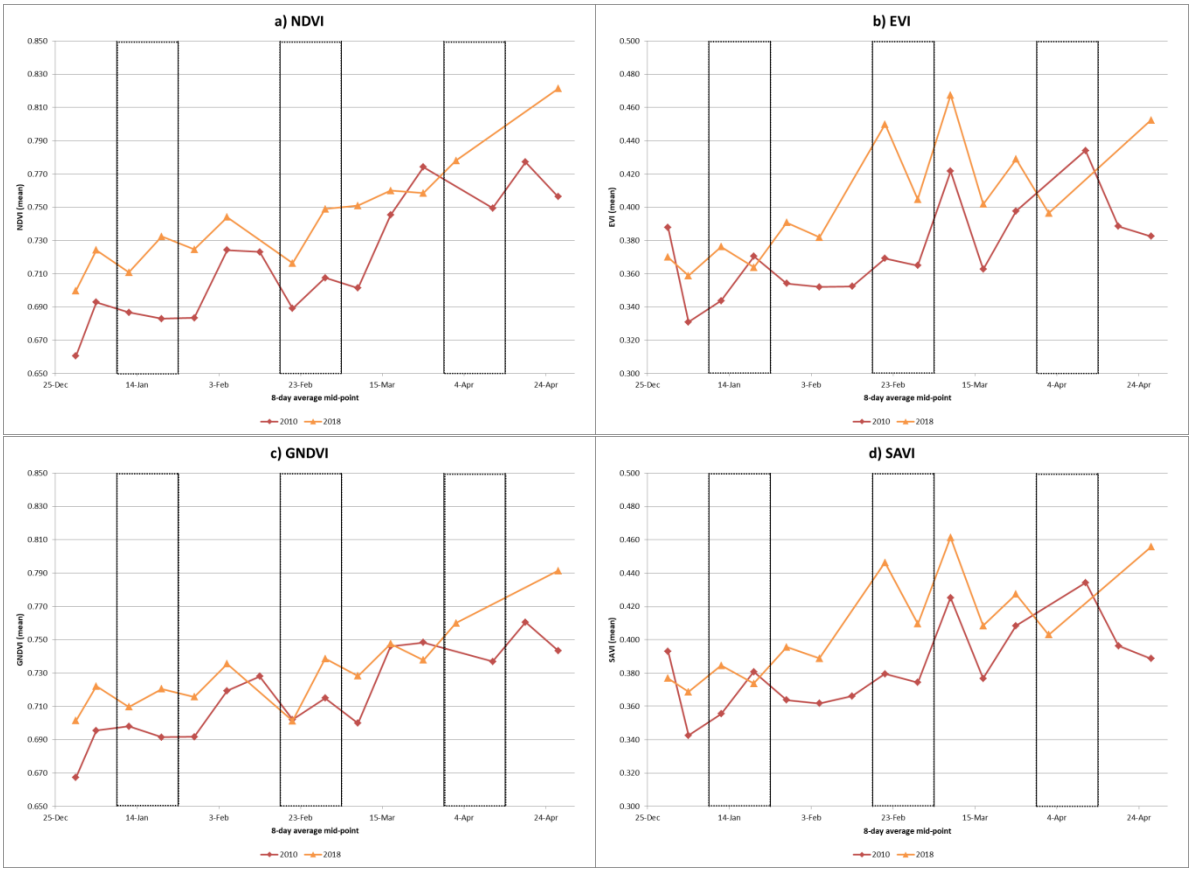

Figure 6 2010 and 2018 time-series of vegetation indices over pre-flowering, peak-flowering and post-flowering of Marri in study area. From (a) to (d): NDVI, EVI, GNDVI, SAVI. The rectangles in the charts indicate the pre-flowering, peak-flowering and post-flowering period of Marri in 2010 and 2018.

Percentage change in vegetation index values between the three periods (pre-flowering, peak-flowering and post-flowering) was calculated to look for a direct spectral response during Marri flowering (**Table 4)**. Results in **Table 4** confirm the general trends observed in **Figure 6**, with all values increasing between January and April, with the exception of the EVI and SAVI decreasing between peak-flowering and post-flowering periods in 2018. All vegetation indices show a positive percentage change in values between pre-flowering and peak-flowering periods over both years. The NDVI had similar percentage increases between years, 1.96% (2010) compared to 1.53% (2018). The GNDVI (1.98% in 2010 compared to 0.68% in 2018), EVI (2.79% in 2010 compared to 15.50% in 2018) and SAVI (2.39% in 2010 compared to 12.89% in 2018) changed significantly between years (the latter two by approximately 10%). Generally, the vegetation indices appeared to behave the same between 2010 and 2018, with all values increasing between pre-flowering and peak-flowering periods. But inquiry into the percentage change between 2010 and 2018 showed that while NDVI was

similar, the percentage change in GNDVI, SAVI and EVI differed radically, showing there is not a consistent spectral response of the vegetation indices when Marri transitions from non-flowering to flowering.

Table 4 Comparison between the pre-flowering, peak-flowering and post-flowering vegetation indices in 2010 and 2018.

	NDVI		**EVI**		**GNDVI**		**SAVI**	
	2010	**2018**	**2010**	**2018**	**2010**	**2018**	**2010**	**2018**
Pre-flowering (9-24 January) mean	0.685	0.722	0.357	0.370	0.695	0.715	0.368	0.379
Peak-flowering (18 February – 5 March) mean	0.698	0.733	0.367	0.427	0.708	0.720	0.377	0.428
Post-flowering (30 March – 14 April) mean	0.749	0.778	0.434	0.396	0.737	0.760	0.434	0.403
% Change (Pre-flowering to Peak-flowering)	**1.96**	**1.53**	**2.79**	**15.50**	**1.98**	**0.68**	**2.39**	**12.89**
% Change (Peak-flowering to Post-flowering)	7.33	6.19	18.27	-7.22	4.01	5.57	15.21	-5.84

3.1.2 Vegetation index change between non-flowering and flowering periods

Welch's ANOVA was performed to test the null hypothesis that there is no difference in the means of vegetation indices between pre-flowering, peak-flowering and post-flowering periods. Analysis was conducted on 2010 and 2018 data, with the pre-, peak- and post-flowering periods taken from the time periods listed above. The descriptive statistics for the 2010 and 2018 data are displayed in **Table 5** and **Table 6** respectively. The sample size (*N*) for each group was 84, except for the post-flowering group in 2018 which had a sample size of 42. The reduced sample size is due to cloud cover impacting on data acquisition over the time period. Whilst having an even sampling size between groups is not a requirement for Welch's ANOVA, it is recommended. Due to the limited data available, the test was still conducted. Welch's ANOVA for the three groups (pre-, peak- and post-flowering) was individually run for the two years of data (2010 and 2018) for all four vegetation indices. The results showed there was a statistically significant difference between the means ($p<0.05$) for all vegetation indices in 2010 and 2018 (**Table 7**). Since the Welch ANOVA (**Table 7**) indicates an overall significant difference amongst means, a Games-Howell post hoc test was carried out to examine all possible pairwise comparisons, to see where the differences occurred. The 2010 and 2018 Games-Howell post hoc test results indicated an overall statistically significance difference among means ($p = 0.000$) for the Peak-Post period and Pre-Post period for all vegetation indices (**Table 8**). The Games-Howell post hoc test for the 2010 Pre-Peak period comparison differed from this trend in showing mixed results for the

different vegetation indices (**Table 8**). The GNDVI results indicated a statistically significant difference among means ($p = 0.001$), but the NDVI ($p = 0.058$), EVI ($p = 0.065$) and SAVI ($p = 0.094$) all had a *p*-value greater than 0.05, indicating no statistically significant difference between means. The Games-Howell post hoc test for the 2018 Pre-Peak period comparison also had mixed results for the different vegetation indices (**Table 8**). The EVI and SAVI results indicated a statistically significant difference among means ($p = 0.000$), whilst NDVI ($p = 0.054$) and GNDVI ($p = 0.304$) both had a *p*-value greater than 0.05, indicating no statistical significant difference between means. The Games-Howell post hoc results for 2010 and 2018 suggest we fail to reject the null hypothesis that the means between pre-flowering and peak-flowering periods are equal for NDVI (2010 and 2018), EVI (2010), GNDVI (2018) and SAVI (2010). The implications of this are discussed below.

Table 5 2010 Vegetation indices descriptive statistics

Period		NDVI				EVI				GNDVI				SAVI			
	N	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
Pre	84	0.581	0.757	0.680	0.039	0.288	0.408	0.356	0.030	0.628	0.735	0.692	0.025	0.301	0.414	0.367	0.027
Peak	84	0.593	0.776	0.694	0.040	0.303	0.418	0.372	0.027	0.635	0.743	0.706	0.024	0.318	0.423	0.375	0.025
Post	84	0.632	0.805	0.757	0.036	0.341	0.466	0.414	0.027	0.633	0.768	0.740	0.027	0.346	0.459	0.420	0.023

Table 6 2018 Vegetation indices descriptive statistics

Period		NDVI				EVI				GNDVI				SAVI			
	N	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
Pre	84	0.648	0.783	0.717	0.032	0.316	0.411	0.369	0.023	0.664	0.743	0.713	0.019	0.330	0.414	0.378	0.021
Peak	84	0.561	0.813	0.732	0.050	0.357	0.515	0.425	0.040	0.561	0.777	0.721	0.043	0.362	0.498	0.426	0.034
Post	42	0.708	0.815	0.773	0.027	0.345	0.433	0.393	0.022	0.718	0.785	0.758	0.017	0.356	0.435	0.400	0.020

Table 7 2010 & 2018 Welch ANOVA results

Welch ANOVA	2010				2018			
	df1	**df2**	**F**	**Sig.**	**df1**	**df2**	**F**	**Sig.**
NDVI	2	165.714	101.025	**0.000**	2	120.979	55.122	**0.000**
EVI	2	165.729	107.232	**0.000**	2	116.556	65.804	**0.000**
GNDVI	2	165.626	72.340	**0.000**	2	117.976	89.666	**0.000**
SAVI	2	164.941	116.217	**0.000**	2	116.293	62.996	**0.000**
Note: Sig. = p-value.								

Table 8 2010 & 2018 Games-Howell post hoc test results (p-value)

Games-Howell	2010			2018		
	Pre – Peak	**Peak – Post**	**Pre – Post**	**Pre – Peak**	**Peak – Post**	**Pre – Post**
NDVI	0.058	0.000	0.000	0.054	0.000	0.000
EVI	0.065	0.000	0.000	0.000	0.000	0.000
GNDVI	0.001	0.000	0.000	0.304	0.000	0.000
SAVI	0.094	0.000	0.000	0.000	0.000	0.000
Note: grey shade – p-value >0.05.						

3.2 Comparing spectral response between 'good' and 'bad' Marri flowering years

To compare the spectral response between 'good' and 'bad' Marri flowering years, four years (2010, 2013, 2015 and 2018) representing 'good' flowering were compared with three years (2014, 2016 and 2017) representing 'bad' flowering as discussed in **Section 2.4**. The spectral responses of the four vegetation indices were analysed twofold: first, vegetation indices data from 12 months prior to and including the flowering period were compared; and second, vegetation indices data during the peak-flowering period (18 February – 5 March) were compared. For the former, the mean of the 42 pixels in the study area was used. For the latter, each individual pixel valued was used, to compensate for the smaller time period resulting in a limited sample size.

3.2.1 Comparison of full annual data (12 months prior and including flowering period) spectral response between 'good' and 'bad' flowering year

Minimum, maximum and median NDVI, EVI, GNDVI and SAVI results over the entire study area were calculated in the 12 months prior to and including the flowering in each year, 'good' and 'bad' **(Table 9).** The results suggest there is no relationship between minimum, maximum and median vegetation indices values between 'good' and 'bad' flowering years in data including the 12 months prior to and including flowering period.

Table 9 Vegetation indices values comparing 'good' vs 'bad' flowering years

	Good Flowering Years	**Bad Flowering Years**
No. of Years of Data	4	3
Min. NDVI	0.655 – 0.693	0.639 – 0.692
Max. NDVI	0.813 – 0.847	0.816 – 0.853
Median NDVI	0.724 – 0.777	0.738 – 0.745
Min. EVI	0.320 – 0.341	0.289 – 0.360
Max. EVI	0.464 – 0.507	0.417 – 0.504
Median EVI	0.372 – 0.403	0.350 – 0.407
Min. GNDVI	0.667 – 0.699	0.654 – 0.693
Max. GNDVI	0.795 – 0.828	0.814 – 0.848
Median GNDVI	0.730 – 0.774	0.742 – 0.751
Min. SAVI	0.333 – 0.354	0.302 – 0.369
Max. SAVI	0.461 – 0.498	0.420 – 0.492
Median SAVI	0.381 – 0.411	0.363 – 0.412
Note: Minimum, maximum and median values taken from 12 months prior to and including flowering season.		

Figure 7 graphically represents the 'good' flowering and 'bad' flowering year-ranges as displayed in **Table 9**. The vegetation indices charts support the conclusion that there is no clear difference in the vegetation indices values between 'good' and 'bad' flowering years in the 12 months prior to and including the flowering season.

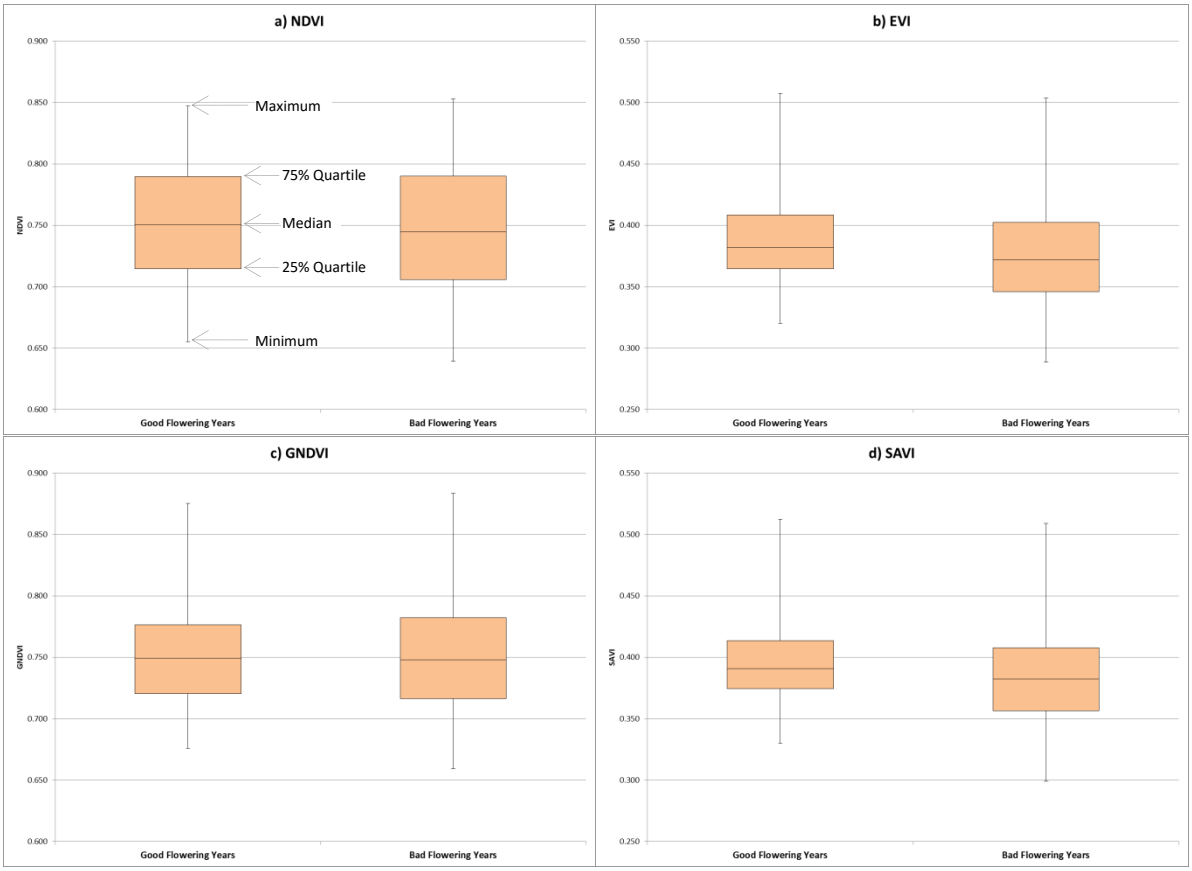

Figure 7 'Good' flowering years vs 'bad' flowering years of Marri as demonstrated by the vegetation indices for 12 months data prior to and including flowering season. From (a) to (d): NDVI, EVI, GNDVI, SAVI.

3.2.2 Comparison of spectral response during peak-flowering periods between 'good' and 'bad' Marri flowering years

Vegetation indices were also compared against the 'good' and 'bad' Marri flowering years for peak-flowering period (18 February – 5 March) in each year. While visual inspection of the mean and value ranges of all four vegetation indices suggest there is no difference between 'good' and 'bad' flowering years, the 'good' flowering data does display a larger variance in the minimum and maximum values (**Figure 8**). The inter-quartile ranges (25%-75%) for NDVI and GNDVI were slightly lower in 'good' years compared to 'bad' flowering years, while the inter-quartile ranges for EVI and SAVI showed the opposite, with 'good' years slightly higher compared to 'bad' flowering years. Further comparison through Welch ANOVA was required to see if there was a statistical difference between 'good' and 'bad' years.

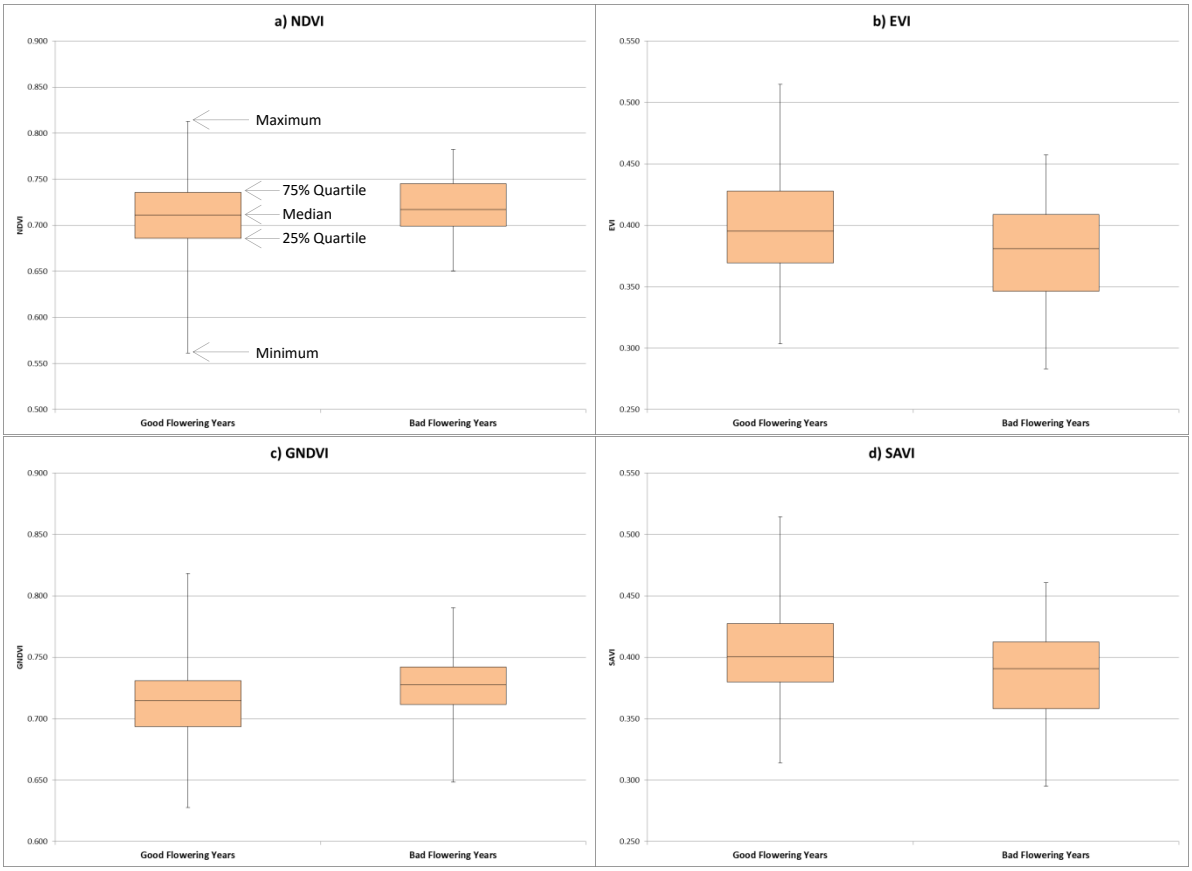

Figure 8 'Good' flowering years vs 'bad' flowering years of vegetation indices of Marri in study area for peak flowering period (18-February to 5-March). From (a) to (d): NDVI, EVI, GNDVI, SAVI.

3.2.3 Statistically comparing spectral response during peak-flowering periods between 'good' and 'bad' flowering years

Welch's ANOVA was performed to test the null hypothesis that there was no difference in the vegetation indices means between 'good' and 'bad' Marri flowering years. Multiple comparisons were also performed using Games-Howell post hoc testing. Analysis was conducted on data for the peak-flowering period (18 February – 5 March) in each year. Data for 2016 (a 'bad' Marri flowering year) was excluded from the analysis due to an absence of cloud-free data over the required time period. Data from six years (four 'good' and two 'bad' Marri flowering years) was therefore included in the analysis. The descriptive statistics for the data is displayed in **Table 10**. The sample size (N) for each group was 84. Welch's ANOVA was analysed for the six years of data over the peak-flowering period for all vegetation indices. The results showed that there was a statistical difference between the means ($p<0.05$) for all vegetation indices, between all years (**Table 11**). Since the Welch's ANOVA (**Table 11**) indicates an overall statistically significant difference among means, a Games-Howell post hoc test was carried out to examine all possible pairwise comparisons. Each year was

split into a sub-group, with all sub-groups analysed in a pairwise comparison to each other, resulting in 15 separate Games-Howell post hoc tests on each vegetation index (**Table 12** and **Table 13**). Games-Howell post hoc test results were variable between each of the vegetation indices (**Table 14**). The NDVI post hoc results had 9 pairs with a *p*-value <0.05 and 6 pairs with a *p*-value >0.05. The EVI post hoc results had 12 pairs with a *p*-value <0.05 and 3 pairs with a *p*-value >0.05. The GNDVI post hoc results had 6 pairs with a *p*-value <0.05 and 9 pairs with a *p*-value >0.05. The SAVI post hoc results had 13 pairs with a *p*-value <0.05 and 2 pairs with a *p*-value >0.05. These results could suggest that the vegetation indices with the higher number of pairwise combinations with a *p*-value <0.05 (statistically significant difference between means) are more responsive to changes in the canopy and vegetation from year to year, such as EVI and SAVI.

To evaluate the null hypothesis that there is no difference in means between 'good' and 'bad' Marri flowering years during peak-flowering period, we need to look specifically at 'good' years vs 'bad' years. There are four years (2010, 2013, 2015, and 2018) classified as 'good' flowering seasons and two years (2014, 2017) classified as 'bad' flowering seasons. Therefore 8 combinations of 'good' vs 'bad' were compared. NDVI had a *p*-value <0.05 in 5 of 8 pairs, GNDVI had a *p*-value <0.05 in 6 of 8 pairs, and EVI and SAVI had a *p*-value <0.05 in 7 of 8 pairs. This implies that EVI and SAVI exhibit differences between 'good' and 'bad' flowering years, with a statistical difference between means 7 out of the 8 years. 'Good' vs 'good' and 'bad' vs 'bad' Marri flowering years were also compared. The EVI had *p*-value <0.05 in 4 of 6 pairs and 0 out of 1 pair respectively, whilst SAVI had *p*-value <0.05 in 5 of 6 pairs and 0 out of 1 pair respectively. Indicating EVI and SAVI also have a statistical difference between means comparing 'good' vs 'good' and 'bad' vs 'bad' years. This suggests that EVI and SAVI respond strongly to vegetation changes each year and are highly variable.

Conversely, GNDVI had a *p*-value <0.05 for 6 out of the 8 pairs when comparing 'good' vs 'bad' flowering years, a *p*-value <0.05 for 0 out of 6 pairs comparing 'good' vs 'good', and 0 out of 1 comparing 'bad' vs 'bad'. This suggests that GNDVI could be capturing differences between 'good' and 'bad' Marri flowering seasons and not just responding to seasonal variation. Again, the significance of this will be discussed below.

Table 10 Vegetation indices descriptive statistics - 18-February to 5-March (Peak-Flowering period)

Period		**NDVI**				**EVI**				**GNDVI**				**SAVI**			
	N	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
'Good' flowering seasons																	
2010	84	0.593	0.776	0.694	0.040	0.303	0.418	0.366	0.027	0.635	0.743	0.706	0.024	0.318	0.423	0.375	0.025
2013	84	0.663	0.800	0.717	0.026	0.361	0.487	0.432	0.030	0.678	0.778	0.711	0.019	0.367	0.476	0.429	0.025
2015	84	0.628	0.747	0.694	0.028	0.318	0.436	0.377	0.025	0.648	0.753	0.707	0.026	0.336	0.436	0.386	0.020
2018	84	0.561	0.813	0.732	0.050	0.357	0.515	0.425	0.040	0.561	0.777	0.721	0.043	0.362	0.498	0.426	0.034
'Bad' flowering seasons																	
2014	84	0.657	0.781	0.724	0.030	0.354	0.457	0.399	0.025	0.690	0.766	0.733	0.019	0.366	0.452	0.405	0.022
2017	84	0.658	0.782	0.732	0.032	0.308	0.453	0.381	0.033	0.681	0.758	0.729	0.018	0.326	0.453	0.390	0.028

Table 11 Welch's ANOVA results (all years)

Welch ANOVA				
	df1	**df2**	**F**	**Sig.**
NDVI	5	231.070	22.344	**0.000**
EVI	5	231.671	65.362	**0.000**
GNDVI	5	230.580	24.669	**0.000**
SAVI	5	231.513	59.541	**0.000**
Note: Sig. = p-value.				

Table 12 NDVI & EVI Games-Howell post hoc test results

NDVI		2013	2014	2015	2017	2018	EVI		2013	2014	2015	2017	2018
	2010	0.000	0.000	1.000	0.000	0.000		2010	0.000	0.000	0.079	0.011	0.000
	2013		0.614	0.000	0.015	0.171		2013		0.000	0.000	0.000	0.861
	2014			0.000	0.562	0.819		2014			0.000	0.002	0.000
	2015				0.000	0.000		2015				0.902	0.000
	2017					1.000		2017					0.000

Note: green shade – 'good' flowering year; orange shade – 'bad' flowering year; grey shade – p-value>0.05.

Table 13 GNDVI & SAVI Games-Howell post hoc test results

GNDVI		2013	2014	2015	2017	2018	SAVI		2013	2014	2015	2017	2018
	2010	0.681	0.000	1.000	0.000	0.099		2010	0.000	0.000	0.026	0.007	0.000
	2013		0.000	0.761	0.000	0.483		2013		0.000	0.000	0.000	0.979
	2014			0.000	0.837	0.197		2014			0.000	0.002	0.000
	2015				0.000	0.122		2015				0.943	0.000
	2017					0.552		2017					0.000

Note: green shade – 'good' flowering year; orange shade – 'bad' flowering year; grey shade – p-value>0.05.

Table 14 Analysis of 'good' vs 'bad' Games-Howell post hoc results (correct observations)

	'Good' vs 'Good'	'Bad' vs 'Bad'	'Good' vs 'Bad'
NDVI	2/6	1/1	**5/8**
EVI	2/6	0/1	**7/8**
GNDVI	6/6	1/1	**6/8**
SAVI	1/6	0/1	**7/8**

Note: 'Good' vs 'Good' correctly observed with p-value >0.05.
'Bad' vs 'Bad' correctly observed with p-value >0.05.
'Good' vs 'Bad' correctly observed with p-value <0.05.

4.0 Discussion

The first objective of this research was to see if a difference in satellite-derived vegetation indices can be observed or measured between flowering and non-flowering Marri. Whilst changes were observed in all vegetation indices between non-flowering and flowering periods, the results are inconclusive in determining whether the spectral change observed is due to flowering or to natural variation in canopy structure and vegetation greenness. The spectral change observed was not consistent across the four vegetation indices, or between the two years analysed. These results are supported by the statistical analysis comparing the pre-flowering and peak-flowering period data. The NDVI, EVI and SAVI in 2010, and NDVI and GNDVI in 2018 all had results with a *p*-value greater than 0.05, failing to reject the null hypothesis. These results imply there is no statistically significant difference in the means between the pre-flowering and peak-flowering periods for these vegetation indices. This suggests that there is limited change in the reflectance of the canopy occurring between pre- and peak-flowering of Marri. Other studies have suggested that white flowers on a canopy can cause an increase in the red band canopy reflectance, prompting a decrease in NDVI, EVI and SAVI vegetation indices (Shen et al, 2009; Landman et al, 2015; Sulik and Long, 2016; Campbell and Fearns, 2018). To observe the changes in red, blue, green and NIR bands, these bands were graphed over the pre-, peak- and post-flowering periods in 2018 (**Figure 9**). Shen et al (2009) found that flowering caused the red band reflectance to increase, whilst the NIR and blue band remained constant. In the 2018 data, we see the red band reflectance increased at the start of the peak-flowering period, but the NIR, blue and green band reflectance also increased, suggesting that the change in values observed are possibly not a result of white Marri flowers.

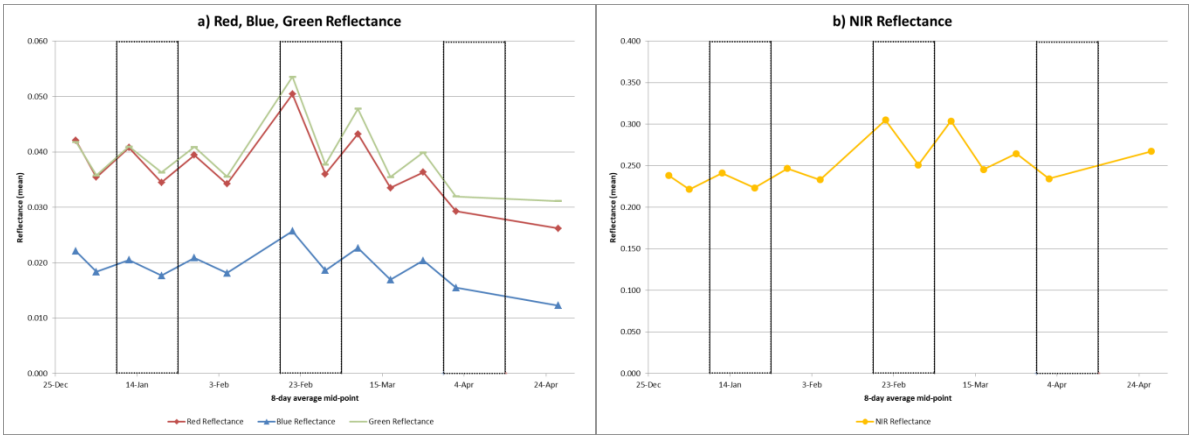

Figure 9 a) 2018 red-band, green-band and blue-band reflectance, b) 2018 near-infrared reflectance.

There are a number of reasons the MODIS data is not able to observe the white flowers on the Marri canopy. The typical flower size of the Marri is 1.3-4.5 cm, and while Campbell and Fearns (2018) were able to classify flowers on a Marri tree, a digital camera with a resolution of less than 0.5 cm was required to produce an accuracy of 90%, compared to the MODIS resolution of 500 m. Landman et al (2015) suggests that to find a spectral response during flowering, the canopy-level flowering as a phenological effect has to be larger than the leaf-level response. For this study, this means the eucalypt canopy-flowering response would have to exceed the leaf response of the canopy as a whole. Given the near-even mix of Marri and Jarrah in the study area, it may not be possible for the flowering response to exceed the leaf response in the canopy, as only approximately 50% of the trees in the Jarrah-Marri forest will ever be flowering at the same time (**Figure 10**).

Figure 10 Image of flowering Marri canopy in Wellington District in February 2018.

The second objective of the study was to see if a difference can be observed in the spectral response across years of ‘good’ Marri flowering versus ‘bad’ or non-flowering years. The first comparison encompassed data from the vegetation indices over the 12 months prior to and including the flowering season(s) in question. Arundel et al (2016) infers that vegetation indices need to exceed a certain threshold to reflect the occurrence of a flowering event in a eucalyptus forest. Results from this study suggest that there is no evidence to support this conclusion, with no difference between the minimum, maximum or median NDVI, EVI, GNDVI or SAVI values between ‘good’ and ‘bad’ Marri flowering years.

The second comparison was between ‘good’ and ‘bad’ Marri flowering years during peak-flowering period. Results from the statistical analysis were mixed, mirroring those found by Arundel et al (2016) when comparing EVI to eucalyptus flowering. The GNDVI performed the best, finding a statistical difference between ‘good’ and ‘bad’ Marri flowering years 6 out of 8 times, but at the same time found no statistical difference between means 0 out of 6 times for ‘good’ vs ‘good’ and 0 out 1 for ‘bad’ vs ‘bad’. The GNDVI is known to perform better with dense vegetation and a high leaf area index, and it can be up to five times more sensitive to changes in chlorophyll concentration (Gitelson et al, 1996; Jones and Vaughan, 2010). It is not clear if the intensity of flowering in Marri impacts chlorophyll concentrations reflected in the GNDVI. But the performance of the index in this study in observing statistical difference in pairs of years combining ‘good’ and ‘bad’ flowering, but no statistical difference across years identified as similarly ‘good’ or ‘bad’, suggests that it is potentially capable of observing difference in the spectral response caused by flowering.

The results suggest that EVI and SAVI may not be the best vegetation indices to compare ‘good’ and ‘bad’ flowering years, as they appear to be more responsive to changes in the canopy and vegetation from year to year. This also implies that in trying view a subtle change in the canopy, such as Marri transitioning from non-flowering to flowering, EVI and SAVI may be better suited. Whilst there were statistically significant differences observed using Welch’s ANOVA and Games-Howell post hoc test, there was no clear differences in the results of all the vegetation indices (NDVI, EVI, GNDVI and SAVI) between ‘good’ and ‘bad’ Marri flowering years during peak-flowering period. These results on their own are therefore inconclusive and require further analysis.

This study contains a number of limitations which have to be acknowledged. The use of a proxy for Marri flowering may result in false positives when comparing ‘good’ and ‘bad’ flowering years. It also limited the analysis that was able to be performed for the study as a whole, with no data available on flowering intensity or canopy coverage percentage. This would make the comparison of non-flowering to flowering periods significantly more robust (Shen et al, 2009).

5.0 Conclusion

Whilst understanding the vegetation phenology of Australian eucalypts is extremely important to beekeepers to be able to predict spatial and temporal flowering of targeted species, limited research has been conducted in examining the LSP of flowering Australian eucalypts. The evaluation of MODIS satellite-derived vegetation indices focused on a homogenous Jarrah-Marri stand in south-west WA found no conclusive results. Inter- and intra-seasonal differences in vegetation indices were observed between non-flowering and flowering Marri; however, these changes could not be confirmed to be caused by Marri flowering and may have been a product of natural variation in canopy structure and vigour. Limited research conducted suggests that hyperspectral satellite data with a spatial resolution of 10 nm or less is required to directly observe a spectral response to flowering vegetation. A difference in the spectral response between 'good' and 'bad' Marri flowering was measured in vegetation indices, looking at values leading up to and during the flowering period. There was no evidence that vegetation indices leading up to a flowering period offer a spectral response which can distinguish between a 'good' and 'bad' Marri flowering years. Likewise, comparing vegetation indices during the Marri flowering period found mixed results. Results from the GNDVI cautiously suggest that this vegetation index can observe different spectral signatures between 'good' and 'bad' Marri flowering years, but further analysis is required to confirm this finding.

Whilst no conclusive results were found in this study, it is useful when considered as a preliminary exploration of an important issue to the Australian bee industry and has provided a useful foundation for further research. A number of possibilities exist for taking this research further. These include: the collection of more robust flowering data to compare vegetation indices; a comparison between vegetation indices and nectar flow data, as has been conducted in the northern hemisphere (Ward and Starks, 2000; Nightingale et al, 2008; Lynn, 2013; Blomstedt, 2014; Jarnevich et al, 2014); the exploration of different satellite data and vegetation indices; and combining data with known environmental factors that have a relationship to flowering (rainfall, temperature, solar exposure). Research into a predictive model would have a wide application and use in the Australian bee industry, as beekeepers need to know ahead of time when and where flowering is going to occur in order to plan hive migration (Arundel, 2015).

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