Final Report
Project NS021

NATIONAL INSTITUTE FOR
FOREST PRODUCTS INNOVATION

Future Proofing SA Blue Gum Plantations through improved detection of koalas in early planning and forestry operations

2024

Mount Gambier Centre
Funded by the Australian Government, South Australian Government & Industry Partners.
nifpi.org.au

Future Proofing SA Blue Gum Plantations through improved detection of koalas in early planning and forestry operations

Prepared for

National Institute for Forest Products Innovation

Mount Gambier

by

Delene Weber, Anthony Finn, Laith Al-Shimaysawee, Russell Brinkworth, Morgan Schebella and Desley Whisson

Publication: Future Proofing SA Blue Gum Plantations through improved detection of koalas in early planning and forestry operations

Project No: NIF082-1819 [NS021]

IMPORTANT NOTICE

ISBN: 978-1-922718-52-5

Researcher/s:

D. Weber, A. Finn, L. Al-Shimaysawee, M. Schebella
University of South Australia

R. Brinkworth
Flinders University

D. Whisson
Deakin University

This work is supported by funding provided to Forest and Wood Products Australia (FWPA) to administer the **National Institute for Forest Products Innovation** program by the Australian Government Department of Agriculture, Fisheries and Forestry and the Government of South Australia in partnership with the University of South Australia.

Australian Government
Department of Agriculture, Fisheries and Forestry

Government of South Australia
Department of Primary Industries and Regions

Executive Summary

Context

This project aimed to improve the early detection of koalas in blue gum plantations. The uncertainty surrounding the precise locations of koalas in blue gum plantations places significant pressure on the forest industry. Not only does the forest industry want to protect this much-valued species throughout the plantation cycle, but they also want to continue improving forest workers' safety. The current method of finding koalas by using koala spotters has inherent risks, and while these have been managed well, the industry wanted to systematically evaluate alternative methods with a view to developing an accurate method that would provide benefit to both koala welfare and forest workers.

Detection methods tested

The initial phase of the project evaluated the pros and cons of ten broad detection methods, some of which had been used extensively, and others that were considered to have potential (see Table 1). From this initial analysis, it was determined that improvements in thermal imaging had the greatest potential for accurate detection of koalas in blue gum plantations. Acknowledging that spotters would continue to have a role in detection in the immediate future, we examined different spotting techniques including technologies that could augment traditional spotting but focussed attention on thermal imaging. The second phase of the project compared eleven automated techniques including spatially based techniques, neural network techniques and bio-inspired techniques to a novel detection technique developed specifically for this project.

Methodology

The project involved the development and field testing of a novel Multi-scale Object Bio-Inspired Vision Line Scanner (MOBIVLS) to rapidly and automatically detect koalas in infrared imagery without reliance on human judgement. Over 65,000 images were analysed in the development of this technique, that specialises in detecting small and dim objects in infrared imagery.

Two field trials were conducted in blue-gum plantations in South-Western Victoria and an additional field trial was conducted over the koala enclosure at Cleland Wildlife Park in South Australia to refine the technique. All plantation trees in the compartments investigated were individually numbered and multiple spotters and confirmation processes were used to provide the necessary ground truthing to develop the automated system. The accuracy of the spotters, the time taken to complete the task was recorded. Additionally comments from the spotters regarding the spotting process they used, and challenges they experienced, were collected. In addition to the technique developed other sensors including: hyperspectral, LIDAR and visual cameras were also tested and evaluated.

Simplistically, the koala detection technique that was developed applied a post-processing technique based on insect vision, to infrared imagery. This detection technique (MOBIVLS) was compared to eleven cutting-edge detection techniques including small object detection, neural networks, and biologically inspired systems. Another system, the Automated Counting and Geolocation Algorithm (AKCoGA) was developed to work in conjunction with the MOBIVLS system. This works by matching a sparse set of pixel-wise detections across the acquired 2D image stack to determine the correlation among detections in different frames. This data is then combined with the geometry of the drone-koala relationship and the least squares method is applied to determine the 3D locations of koalas by analysing all frames where a heat signature is observed.

Key findings

The techniques developed for the project: Multi-scale Object Bio-Inspired Vision Line Scanner (MOBIVLS), and the Automated Koala Counting and Geolocation Algorithm (AKCoGA) were deemed effective in koala detection and geolocation and represent a significant improvement over existing methods. In summary:

- The new BioVis technique (MOBIVLS) developed for this project was able to detect low contrast and weak heat signatures in highly cluttered environments, such as forests, more effectively than the best current automated detection systems.
- The MOBIVLS technique facilitated a 20.5% improvement in detection over the second best method and a 27% increase in object detectability over the third best method.
- Together MOBIVLS and AKCoGA can provide an accurate three-dimensional location of the koalas and suppress the false alarms that were particularly prevalent using alternative automatic methods.
- Stems and canopy can significantly impact detection. It was found that in 40% of images, even with the enhancement generated via the technique, koalas were fully occluded (i.e. not detectable) and hence the stitching of multiple images from different angles (AKCoGA) was needed to reduce the probability of missing koalas.

- All analyses confirmed the superiority of the combined MOBIVLS and AKCoGA techniques over alternative detection methods.

These techniques met the key project selection criteria for an effective koala detection technique (safety, accuracy and reliability). However, they were only tested on pre-recorded footage, not deployed to run in the field while the data was being collected. Further research is needed to operationalise the technology and provide cost-effective real-time data.

The role of spotters therefore remains critical. Many koala spotters demonstrated outstanding skills in detecting koalas in difficult circumstances and importantly provide real-time data. The management of and support of koala spotters also improved notably over the course of the project. Spotters were more confident that they could take as much time as needed to do their job well; were often using binoculars or IR monoculars to confirm sightings when necessary; and were confident that the preference of all parties was to mark a tree as having a koala present if there was any uncertainty regarding an observation. Koala spotters will still play a necessary role in the foreseeable future for monitoring the movement of koalas in a compartment during harvesting, but the improved detection technology could reduce the number of spotters required, and hence reduce the inherent risks associated with being in the forest during a harvesting operation. A set of tips to assist spotters based on interviews with spotters and consultation with other experts is presented as Table 14.

Industry benefits

The MOBIVLS and AKCoGA techniques provide an accurate and consistent means to detect koalas. With further refinement, it will provide a real-time solution for the forest industry which is cost and time effective. Two specific issues: the maximum distance of a koala below the canopy that still allows accurate detection, and the temperature threshold of the technique, require further investigation. However, the research team is confident the techniques are a significant improvement upon all currently available alternative automatic detection methods. The report provides recommendations for future development of the MOBIVLS and AKCoGA system, including integration into harvesting machines. Potential benefits of this integration include streamlining the process, reducing risks associated with the movement of koalas between detection and harvesting, and reducing the need for people in the field during harvesting. To gain full benefit from this research, further investment is required. Specifically: more testing in hot weather conditions, commercialisation to ensure real-time data and to streamline the size and weather-proof the payload. Ideally, we envision the system to be a “plug and play” system that can be placed on a harvesting machine, a drone, or an autonomous vehicle that moves through the forest. In each case, the algorithm would require adjustments and re-testing to ensure accuracy.

Note: Changes to the intended objectives due to restrictions associated with COVID 19, Steering Group priorities; and research team advice based on initial findings included: (a) a focus on high-density sites (this was necessary to obtain sufficient data to develop the algorithm); (b) night trails were eliminated as there was no night harvesting in the koala zone during the project; and (c) a specific communication strategy was not developed, although scientific journal articles have been produced.

Table of Contents

List of Tables

List of Figures

List of Appendices

Introduction

Commercial plantation forests play an increasingly important role in the Australian forestry industry and are considered integral to the long-term sustainability and economic viability of the sector (Whittle, Lock & Hug 2019). In the 1990's much research and policy attention was paid to encouraging the expansion of Australia's commercial plantation estate (e.g. the National Forestry Policy Statement (1992), Plantations for Australia: The 2020 Vision (1997)), and more recently, a gradual decline in the size of the estate alongside the loss of 95% of Australia's forest product researchers has triggered renewed calls for forestry related research and innovation (FIAC 2016, Whittle, Lock & Hug 2019, AFPA 2021).

The establishment of three National Institute for Forest Products Innovation Centres in 2020 allowed for the targeted funding of research projects that would provide innovative solutions to region-specific forestry issues in Victoria, South Australia, and Tasmania. The focus of such work ranges from the potential to once again expand Australia's commercial plantation estate, to increasing forest profitability and sustainability, to understanding and overcoming challenges faced on the ground by existing plantation managers and owners. The study presented in this report is a direct response to the research needs identified by forestry companies operating in the Green Triangle region of South-West Victoria and South-East South Australia (NIFPI 2020).

Project background

In the Green Triangle, a key challenge exists in the form of Australia's iconic and widely loved marsupial species, the koala (*Phascolarctos cinereus*). Koalas inhabit commercial blue gum plantations across the region, creating ongoing logistical challenges to adequately protect koala welfare, meet regulatory requirements, keep forest workers safe, and navigate public relations. Plantation managers are required by law to protect koala welfare during forestry operations. Currently this is dependent upon forest workers being able to pinpoint the location of individual koalas using a tool of questionable accuracy and reliability: the human eye. To date, human spotters have been tasked with detecting koalas by traversing plantation forests on foot, where they face significant safety risks from their environment and the proximity to the harvesting operation. The forest industry has spent decades trying to minimise safety risks during a harvest operation primarily by reducing the number of people exposed in the field through mechanisation, yet the need for increased numbers of spotters to provide better data on koala locations, is the antithesis of what is desired from a safety perspective. The two larger forestry companies involved in this project reportedly spend millions per year on koala detection and reporting that is mandated by state government policies. Despite these efforts koala incidents still occur. In response to the limitations presented by traditional koala detection techniques, forestry companies have employed a variety of techniques to improve their koala detection. These have included use of UAV with infrared (IR) cameras, IR monoculars, increased numbers of spotters and intensive training, as well as improved communication and polices related to spotting. This project examined eight broad detection techniques and then conducted follow up testing and comparison on the effectiveness of 17 alternative IR methods, with the goals of: a) improving koala detection and welfare outcomes, and b) increasing worker safety by reducing the forestry industry's reliance on human spotters.

The importance of blue gum plantations

Australia's forest and wood products industry generates over $24 billion in sales and service income annually and employs more than 80,000 people across the country (AFPA 2020). Despite national forestry employment figures declining over the past decade, the industry continues to be a significant employer of people in rural and regional Australia, and in some areas such as South-West Victoria, forestry employment has increased in recent years (ABARES 2018).

The relative overall economic contribution of the forestry industry has declined in recent years, however, this is largely due to the falling value of log production from native forests, which now accounts for a far smaller proportion of Australia's wood production than in decades past. On average, the increasingly important plantation forest estate generated 84% of Australia's total log production between 2011 and 2016 (ABARES 2018). Most commercial plantation forests established in Australia over the past 20 years have been hardwood plantations, which now account for 47% of the commercial plantation estate. Tasmanian blue gum (*Eucalyptus globulus*) is an important plantation species, and is predominantly managed for pulp-log production (ABARES 2018). The Green Triangle region (Figure 1) is Australia's second highest producer of hardwood pulp-log behind Western Australia, and is expected to remain so for decades to come.

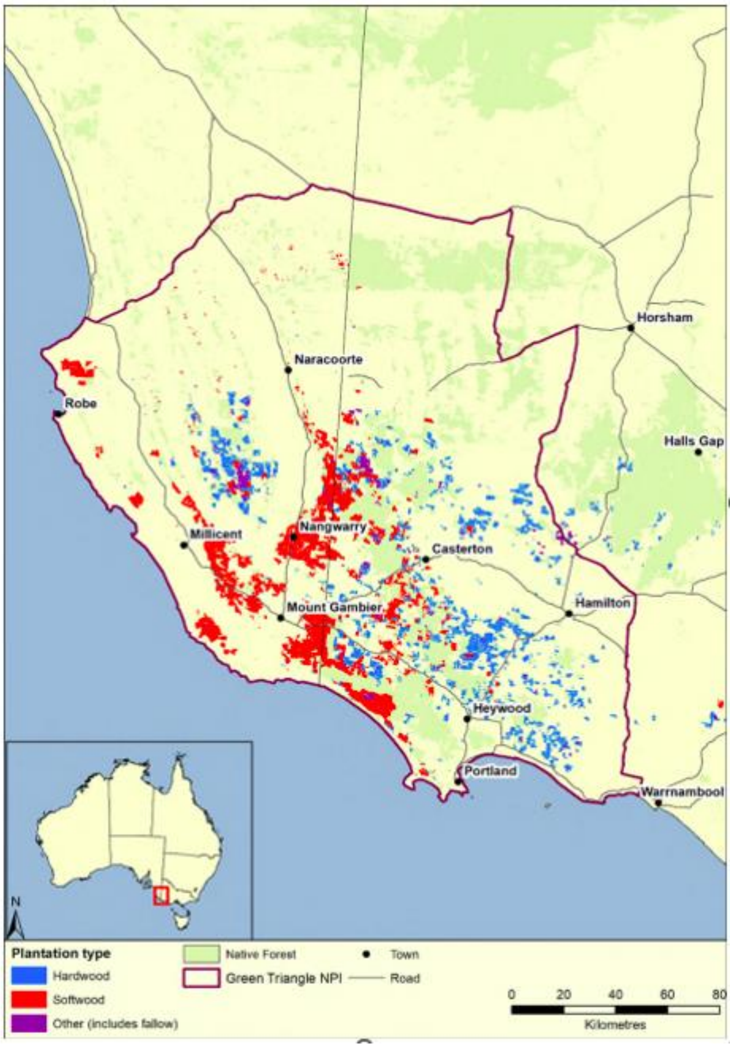


Figure 1: Map of Green Triangle Forest Plantations

(hardwoods, predominantly consisting of blue gums, shown in blue). Source: Legg, P Frakes, I & Gavran, M 2021, Australian plantation statistics and log availability report 2021, ABARES research report, Canberra, October, DOI: 10.25814/ xj7c-p829. CC BY 4.0.

In addition to their contribution to Australia's economy, commercial blue gum plantations also provide a range of important environmental benefits and ecological services such as atmospheric carbon sequestration, soil and water conservation, as well as the provision of habitat for native species like possums and koalas (e.g., Ashman et al. 2020).

Koalas in blue gum plantations

Blue gum plantations serve an important role in supplying domestic and international timber needs. In the Green Triangle region, the area of land covered by blue gum plantations increased by more than 50% between the years 2000 -2016 to more than 152,000 ha (ABARES 2016) but is predicted to decrease to about 95,000ha by 2050 (Whittle t al. 2019). ABARES (2023) reported a 3% decline in hardwood plantations across Australia from 2021-22 (0.4% decline in Victoria and 2.1% decline in South Australia. The blue gum estate in the Green Triangle now sits at 120,000 ha with the majority (60%) being owned by institutional investors (ABARES 2023). Much of this estate occurs within the range of the koala (McAlpine et al. 2015, Ashman et al. 2020). The blue gum plantations established in south-west Victoria unintentionally provide large areas of suitable habitat for koalas because they are planted in areas that overlap with the koala's spatial distribution (Menkhorst, 2016; Ashman et al. 2020) and are located on fertile soils with regular rainfall (Mercer and Underwood, 2002), which increases the nutrient levels in the leaves (Braithwaite et al, 1983). Due to the structure of the plantations, they provide abundant food, shade and shelter and as a result may support koalas at a higher density than native forest (Menkhorst, 2016). Consequently, koala numbers in the region have increased over the last 20 years (Menkhorst, 2016). (DEECA 2023 Victorian Koala Management Strategy p.29). To minimise risks to koalas, regulations now require forestry companies to actively identify koalas before putting in roads, before spraying as well as prior to and during harvesting operations. The risk to koalas is greatest during harvesting. Foresters retain a minimum of nine live trees for each koala identified in a plantation (Conservation Regulator 2023) and spotters work to maintain visual sight of koalas in those areas for the duration of the harvest operation to ensure koala safety.

Overview of current koala management

In Victoria, plantation managers and owners must comply with *The Wildlife Act 1975*, the *Prevention of Cruelty to Animals Act 1986* and the *Code of Practice for Timber Production 2014*. Any plantation of hardwood trees within the Green Triangle must have an approved 'Authorisation to Control Wildlife" (Section 28A of the Wildlife Act) in place before planation management operations can commence. This authorisation is only granted upon successful application to the Conservation Regulator, which requires submission of a Koala Management Plan (KMP) developed in consultation with an ecologist (https://www.vic.gov.au/koalas-blue-gum-plantations).

Once granted, authorisation to disturb koalas is retained only if operators are compliant with the management approach outlined in their KMP, which must identify potential risks to koalas and how forest managers will minimise risks to koalas and protect their welfare. Important components within KMPs include the identification of a clear method to determine the number of spotters and the harvesting method required; an appropriate harvesting sequence that allows for refuge paths for koalas to other suitable habitat; appropriate incident response plans; and consistency with relevant government policies (DELWP 2020).

The authorisation conditions require plantation managers to:

- Report all koala checks, observations, and incidents to the Conservation Regulator via ProofSafe;
- Engage appropriately trained koala spotters to look for and monitor koala during harvesting and other plantation management operations;
- Retain a minimum of nine live trees for each koala spotted;
- Seek immediate veterinary care for koalas involved in an incident;
- Ensure at least one person trained in koala assessment and handling is on site at all time with access to koala handling and transport equipment; and
- Assess koala welfare at the end of each day of plantation management operations, as well as on day 2/3, day 6/7, and day 10/11 following the cessation of site operations. (Conservation Regulator 2023: p9).

Furthermore, to retain their authorisation to disturb koalas, forestry companies are expected to focus on continually improving their 'Koala Index' scores. The Koala Index is a monthly measure of koala incidents versus koala observations that allows for comparisons to be made between the performance of companies across the industry (Conservation Regulator 2023; DELWP 2020). A negative Koala Index results suggest a need to explore remedial actions. The regulator will consider if any breaches were intentional, reckless or repeated, as well as the impact of the breach. Breaching the conditions outlined in a Koala Management Plan is an offence met with large fines and the risk of losing their authorisation.

Importance of maintaining koala welfare within plantations

Protecting native wildlife is important in all forest operations. The attention directed to koalas has arisen for a number of reasons including (1) a genuine desire to minimise impact on koalas (zero tolerance for incidents); (2) the localised high density of koalas in a zone within the blue gum estate in Victoria and prior to the 2020 bushfires on Kangaroo Island in South Australia; (3) an increase in already high global media attention following the Black Summer fires; (4) the listing of koalas as endangered species in Queensland, New South Wales and the Australian Capital Territory; and (5) there is not a simple technique to deal with this issue effectively.

The conservation status of koalas in Queensland, New South Wales and the Australian Capital Territory are now listed as endangered under the EPBC Act. The situation in Victoria and South Australia is different and some areas have large koala populations. In fact in some areas, such as south-west Victoria, koalas persist at such high densities that they can over-browse habitat, resulting in tree defoliation and in extreme cases, tree death (DEECA 2023 Victorian Koala Management Strategy p.3). Similar koala overabundance issues are also seen in South Australia (DEECA 2023 Victorian Koala Management Strategy p.8). Regardless of this fact, the koala is considered one of the most recognisable mammals on Earth (Cork et al. 2000), the koala is undoubtedly an Australian icon. A 2018 study ranked koalas as one of the twenty most charismatic animal species in the world, outranking the blue whale – Earth's largest animal (Albert et al. 2018). *Charisma* – a frequently used yet widely debated term describing a species' "enchanting" properties or overall appeal to humans (Lorimer 2007, Ducarmee et al. 2013) – is of great relevance to conservation and has significant implications for wildlife management. Public attention, or lack thereof, can make or break conservation efforts, which is why animals that naturally appeal to the masses are often used as flagship species to garner support for conservation endeavours. The koala, an official member of the IUCN's 10-species strong 'Climate Change Flagship Fleet' (Foden and Stuart 2009) is one such animal, having been selected in large part for its ability to attract the attention of the global public (Barua et al. 2011). The koala, and any threat to its survival, is observed on a global stage. Any action by an individual, corporation, or government that places the koala at risk carries "significant national profile" (Carver 2016, p. 197) and indeed international profile.

Consequently, industries like commercial forestry that may operate in close proximity to koalas and koala habitat, have the potential of attracting considerable public attention both domestically and overseas. Potential and actual impacts to koalas as a result of forestry operations are widely reported by mainstream media, animal activist groups, and conservation organisations. Given the iconic status of koalas in Australia and internationally, such incidents are frequently met with intense media attention and public outcry (e.g. ABC 2015, ABC 2022), adversely affecting forestry companies' public image, threatening their social licence to operate, and causing concern for their domestic and international investors

The current approach to koala welfare and management, seeks to minimise impacts on koalas in blue gum plantations by improved detection, monitoring and reporting.

Need for improved koala detection methods

Clearly, the increase in koala populations in blue gum plantations in the Green Triangle region has resulted in significant challenges for forest managers, particularly during timber harvesting operations. Both state and federal governments impose regulations on the forest industry to ensure that koalas are protected, with koala detection - through the use of trained spotters - being central to that protection (Johnson 2018). However, visually detecting small animals that are high in trees and partially obscured by vegetation is challenging, particularly during poor weather and under low light conditions. Research has shown that experienced koala spotters typically detect only 60-75% of koalas within a survey area (Corcoran et al. 2019), even in relatively low-density vegetation, whereas detection can drop to 23% for non-experienced koala spotters (Corcoran et al. 2019). These detection rates generally decrease significantly as tree density increases (Corcoran et al. 2019). Our study also showed greater tree heights were associated with lower detection rates. While many of the spotters in our study demonstrated outstanding skill, variation amongst spotters and consistency was still problematic. Despite koala spotters undergoing extensive training, the inherent weaknesses in this detection method (e.g., fatigue, ability to concentrate on repetitive tasks for long periods, distractions, visual acuity) mean that koala incidents are likely to continue if improvements to detection methods are not made.

Koala spotting also carries inherent health and safety risks to the spotters, as detection must occur directly before and during harvest operations. Spotters are exposed to multiple hazards, including falling trees and tree limbs, machine malfunction, snake bites, exposure, and tripping. In addition, the work is tedious, intensive, and fatiguing, so there is a high turnover of spotters and a continuous need to train new workers. The nature of the work is also challenging. For example, spotters need to be on site at dawn for much of the year, cope with inclement weather conditions, and the industry is prone to unscheduled shutdowns (e.g., if a ship doesn't come in when scheduled) creating unreliable employment, especially for those forest workers on a casual rate. These factors can all contribute to a high turnover rates of spotters, which reduces the 'expert capacity' and detection success rate, and also reduced situational awareness in the field which can reduce safety. The safety of spotters is a significant concern to forestry companies, with the number of serious injury claims in the forestry and logging subsector rising by 5% between 2010 and 2015 (ABARES 2018). The rate of workplace deaths and injuries is significantly higher in the forestry sector than in other Australian industries (Driscoll et al. 1995), and as such, much attention over recent decades has been directed to using mechanisation and technology to decrease the number of people in the field during harvest operations.

Rationale for Project

Given the shortcomings of traditional koala detection methods, identifying new approaches that improve upon detection rates and minimise the number of people in plantations during harvest operations is clearly warranted.

This project sought to improve the early detection of koalas in blue gum plantations by systematically testing and comparing the efficacy of a range of existing and emerging wildlife detection methods. In doing so, the project aimed to:

a) Reduce the number of koala incidents (i.e. deaths and injuries) that occur during timber harvesting operations;
b) Improve safety conditions for forest workers by examining alternatives to human spotters; and
c) Strengthen the industry's social license to operate by developing a strong evidence base for the industry's efforts and ability in this field.

Objectives

To improve on current koala detection methods, the following project objectives were met:

1. Conduct an evaluation of traditional methods and emerging technologies for the detection of koalas in blue gum plantation focusing on: safety, accuracy, reliability, cost, efficiency, and the likelihood of future improvements.

2. Develop, trial, and evaluate detection methods considered to have the greatest potential to achieve the project aims.
3. Develop and communicate recommended changes to koala management in blue gum plantations.

Methodology

This study systematically examined the efficacy of nine koala detection methods in blue gum plantations in the Green Triangle region between 2019 and 2021. In response to preliminary findings and the forest industry's interest in improving safety conditions for forest workers, there was a strong focus on technological solutions that would minimise the number of people on the ground during harvesting operations, or that would significantly improve the accuracy of human spotters when "remote" detection was not considered feasible. As such a purpose-built technique was developed and compared to 12 similar cutting-edge thermal imaging techniques. The following section of this report provides an overview of how the examined methods were selected and trialled, the criteria against which their suitability was assessed, and how the results of that assessment can ultimately be used to provide on-ground support to the plantation forestry industry.

Overview of methods

The project followed the process illustrated in Figure 2, beginning with literature reviews that allowed for the identification and selection of appropriate koala detection methods, which were trialled in subsequent stages of the study.

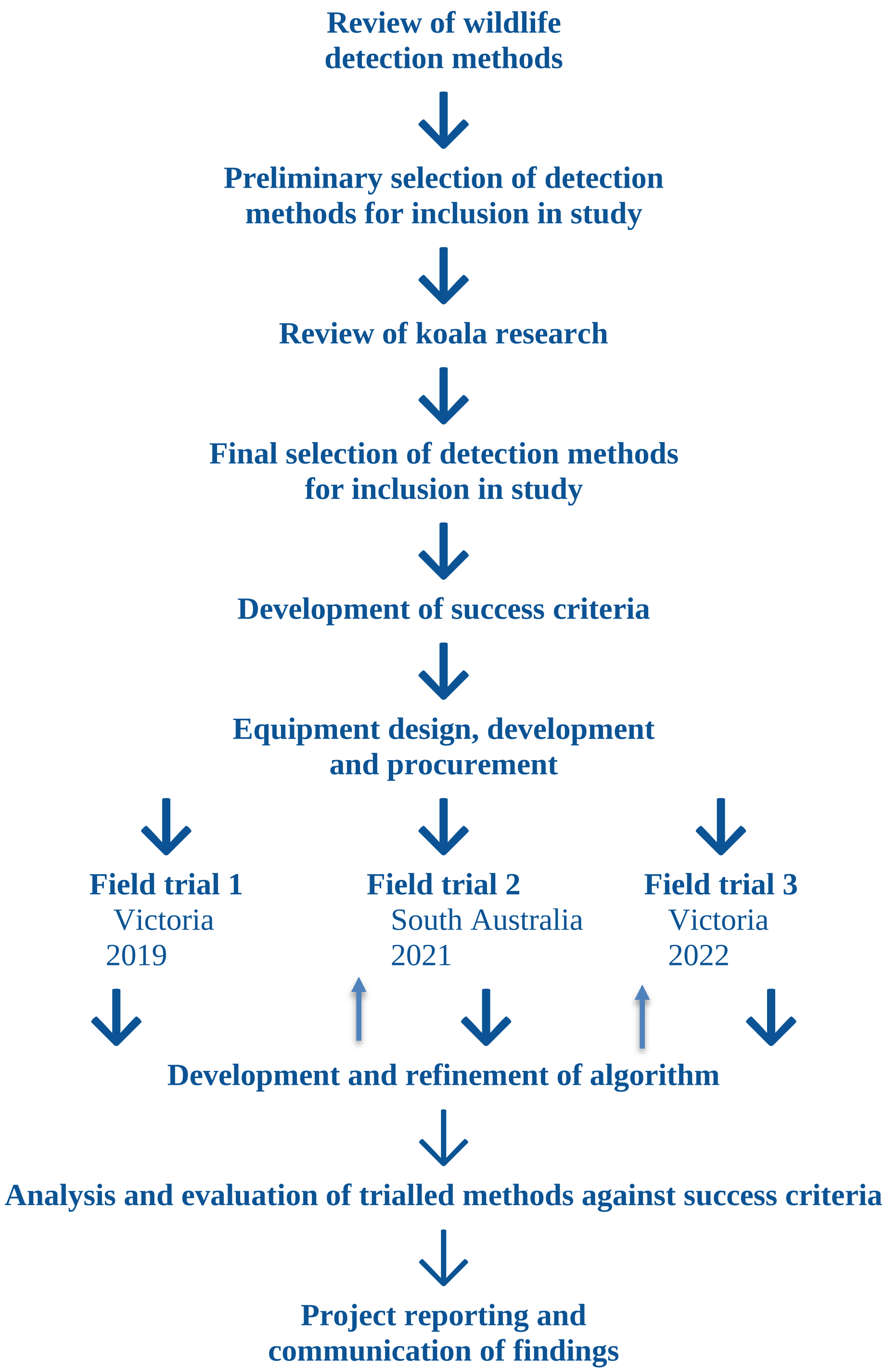


Figure 2: Project Workflow

Literature review

A review of wildlife detection methods was conducted in 2019. The strengths and weaknesses of each method – in the context of koala detection – were assessed and presented at a steering committee meeting in July 2019. A refined version of this table is included as Table 1. Nine wildlife detection methods were identified across widely ranging fields, from the monitoring of wildlife in agriculture and conservation biology, to the use of wildlife avoidance systems in aviation and highways management. Both technological and traditional approaches were examined, including: 1) human spotters, 2) human spotters with additional technology (e.g., UAV data, IR spotting scopes or binoculars) 3) scent detection dogs, 4) thermal imaging, 5) visual cameras, 6) hyperspectral sensors, 7) passive acoustic monitoring, 8) trap cameras, 9) doppler radar, and 10) LIDAR. In addition, a brief review of wildlife deterrents (e.g. exclusion, repellents) was included.

An extensive review of koala research was provided to industry partners in early 2020. This is included as Appendix 1. The review sought to provide the research team and forestry industry with a sound understanding of koala behaviour, conservation status and importance to Australia, as well as the complexities associated with the management of the species in blue gum plantations. The findings of this review, along with industry input via the steering committee meeting, contributed to the final selection of detection methods that were ultimately trialled during the study.

Selection of detection methods for inclusion in study

Nine potential methods were discussed by the research team and industry partners to determine which had the most potential for improving koala detection in blue gum plantations. As the gold standard in koala detection and the method currently used throughout the plantation forestry industry, human spotters were included and would form the benchmark against which all other methods were compared. Spotters were sub-divided into those just using their eyes and those augmenting their skills using some form of technology (e.g. binoculars, infrared spotting scopes of UAV data). Technological methods including passive acoustic monitoring, trap cameras, doppler radar and LIDAR were deemed unsuitable for koala detection for various reasons. For example, passive acoustic monitoring relies on koala vocalisations, so is only effective during the breeding season. Furthermore, while the method can be used to determine whether koalas are inhabiting a certain area, it cannot be used to pinpoint the location of individual animals.

In addition to human spotters, three methods were considered to have some potential for koala detection in a plantation forestry context and were initially selected for inclusion in the study: 1) UAV- (unmanned aerial vehicle) mounted thermal cameras, 2) UAV-mounted hyperspectral sensors, and 3) scent detection dogs.

At a subsequent steering committee meeting, scent detection dogs were removed from the study due to ongoing logistical issues associated with COVID-19; the challenge of finding dogs that had been trained on the scent of the koala rather than on the scent of koala faeces which has been found to be ineffective in high density areas; the concern that the dogs would cause stress to the koalas and the difficulty of assessing stress in koalas (based on consultation with koala veterinarian specialist Dr. Ian Hough, head of research Koala Life); and the requirement that scent detection dogs be accompanied by a handler and thus not sufficiently reducing the risk to humans during koala detection.

The industry partners' growing collective interest in technological solutions led to the study refocusing to examine the efficacy of both aerial and ground-based technologies in koala detection. As a result, a more thorough, multi-pronged investigation of thermal and hyperspectral cameras was pursued, requiring the development of a wearable gimbal-mounted camera rig to mirror the UAV-mounted setup already selected for inclusion in the study. To adequately examine the koala detecting capabilities of thermal imaging technology, lower-cost variations were also tested, including handheld infrared sensors, and a commercially operated UAV-mounted infrared camera.

Ultimately, seven detection methods were trialled during the study, including: 1) human spotters, 2) human spotters aided by infrared monoculars, 3) UAV-mounted thermal cameras, 4) UAV-mounted hyperspectral sensors, 5) wearable ground-based thermal cameras, 6) wearable ground-based hyperspectral sensors, and 7) commercial UAV-mounted thermal cameras. A detailed description of the thermal cameras and hyperspectral sensors can be found in Appendix 2.

Development of success criteria

Discussions with industry partners guided the development of criteria for evaluating the success of each method, beyond its ability to detect koalas. It was recognised early on that each detection method might perform better or worse depending on the varying characteristics of plantation environments (e.g. tree height, stand density, terrain, canopy structure) as well as seasonal and diurnal variations in climatic conditions (e.g. temperature, humidity, cloud cover, precipitation, wind speed). Furthermore, the cost of different methods, the speed at which they could carry out koala detection, and whether they were likely to significantly improve in the near future (e.g. as technologies advanced) were all attributes the forestry companies expected to influence their eventual decision to invest in a particular solution. That said, the key decision criteria emphasised by all forest companies, was safety. The broader set of criteria used to measure "success" during the trials were:

1. Safety: how many people were required to be in the forest during koala detection.

2. Accuracy**:** how well the method detected the actual number of koalas present.

3. Reliability**:** whether the method was usable during all harvesting hours/all seasons.

4. Cost**:** outright expenses and longer-term maintenance/upgrade costs associated with the method.

5. Efficiency**:** how quickly the method could survey 5ha of plantation and provide actionable data to the harvesting crew.

6. Timeliness: how quickly the information can be made available to harvest operators.

7. Likely future improvements**:** the potential for technological advancements (e.g. artificial intelligence/machine learning/algorithms) to improve the technology in the short term.

Equipment design, development and procurement

The UAV-mounted and wearable detection payloads were designed and built by the research team at UniSA. A commercial UAV was employed to provide comparative data. Multiple spotters were used at each trial to increase confidence that all koalas were being spotted. In the first trail, UniSA provided the infrared scanner to assist spotters. The infrared spotting scopes and binoculars used by spotters in subsequent trials were purchased by individual spotters and differed in make and model.

UAV-mounted technology

A forward-looking infrared (FLIR) camera and hyperspectral sensor were mounted to a DJI Ronin gimbal for stability and carried by a DJI Matrice 600 drone (Figure 3). The model of infrared camera used was an ICI-8640 P-series, which has a spectral band of 7-14μm. The camera has a pixel-depth (dynamic range) of 14 bits encoded in a 16-bit wrapper. It was attached to a bespoke payload designed by UniSA that captures the high dynamic range (HDR) raw thermal images at a frame rate of 10 Hz. The image resolution was 640 × 512 pixels. The focal length of the lens was 12.5mm with manual focus. This translates into a field of view (FOV) of about 50° × 37.5°.

(a) (b)

Figure 3: (a) Preparing DJI Matrice 600 for flight and (b) in flight over blue gum plantations.

Wearable ground-based technology

The same payload carried by the Matrice 600 was also mounted on a bespoke chest-mounted wearable harness designed by UniSA (Figure 4). Due to equipment delays resulting from COVID-19, the ground-based version of the payload could not be tested until the final field trials in 2021. The wearable payload was believed to be a world-first attempt to replicate UAV-mounted wildlife detection technologies in a ground-based method, wherein the infrared and hyperspectral sensors looked up towards the forest canopy rather than down into the forest from above. The algorithm for detecting koalas required adjustment to the different pace and motion of a walker.

(a) (b) (c)

Figure 4: Ground-based set-up showing (a) view from back, (b) view from front and (c) easy to read wide-view screen

Infrared spotting scopes

Hand-held infrared cameras (e.g. FLIR TG267) were trialled in the first field trip. After that several spotters invested in their own IR monoculars. Some used this a primary detection method but most employed this as a preliminary rapid assessment tool or a confirmation tool to verify objects they believed were koalas. Other spotters preferred to use binoculars to assist in confirming observations.

Commercial UAV-mounted thermal camera

The use of commercial UAV-mounted thermal cameras has become mainstay during this project. The same operator that the companies regularly employ was used to provide a baseline level of a "typical" non-modified IR camera. It is important to note that this operator was not claiming to detect all koalas but was simply providing a map of potential heat signatures to spotters so as they could pay extra attention to those locations. This technology is also used in advance of the harvest operation so as the forest company has good insight into the density of koalas in an area, and hence can assign additional spotters if necessary.

Field trials

Two field trials were conducted in south-west Victoria in November 2019 and February 2022. An additional, smaller trial was conducted in the Adelaide Hills in South Australia in December 2020, amidst field work restrictions imposed by universities during the COVID-19 pandemic.

Victorian trial sites were selected in discussion with industry partners with extensive knowledge of their own plantation estates. Sites were identified using a set of characteristics that made them legally and operationally accessible for drone flights; could be safely traversed by spotters; and had high koala density to maximise data points to assist in the development of an appropriate algorithm to detect koalas. Sites were shortlisted if they exhibited:

- High koala density (from observations made by foresters during regular operations and via commercial UAV assessments)
- Absence of steep terrain
- Located at least 5.5km from the nearest airstrip
- No overhead powerlines
- Cleared land adjacent to the forest compartment to provide line of site for drone pilots

All field trials took place during the warmer months of the year, when the wildlife detection capabilities of infrared cameras is generally poor, due to high ambient temperatures that make it difficult to detect an animal's heat signature. As such, it was considered that any improvements in detection during warm weather would provide the greatest benefit to industry over existing technologies.

Site Preparation

Prior to commencing the field trials, a commercial UAV was flown over the sites to ensure the density of the sites was sufficient to warrant examination as a high number of data points was critical for developing the algorithm. To enable ground-truthing, all trees were labelled (using lumber crayons) with a unique identifier prior to the trial. Trees were labelled in a standard format, with the first row being A, second row B etc. The trees were then numbered, for example, A1, A2, A3 etc (see Figure 5). Variation in the sites and missing trees means it was not a perfect grid in terms of tree C55 being adjacent to tree B55 and D55 but there was a general pattern. Survey points were also taken at the corners of each site. Other data collected included temperature, relative humidity, wind speed and tree height.

Figure 5: Site preparation included labelling each tree in a "battleship" grid and placing signs on roads to indicate a drone was in use.

Field trial procedure

The drone flew above the study sites in a lawn mower pattern at an altitude of about 60m above the ground (35m above the forest canopy), with a constant forward speed of 8 m/s. The flight path was designed to have 50% minimum side overlap (at ground level) between images from adjacent transects (Figure 6). The geometrical relationship between the drone-camera and the koala is shown in Figure 7a & 7b.

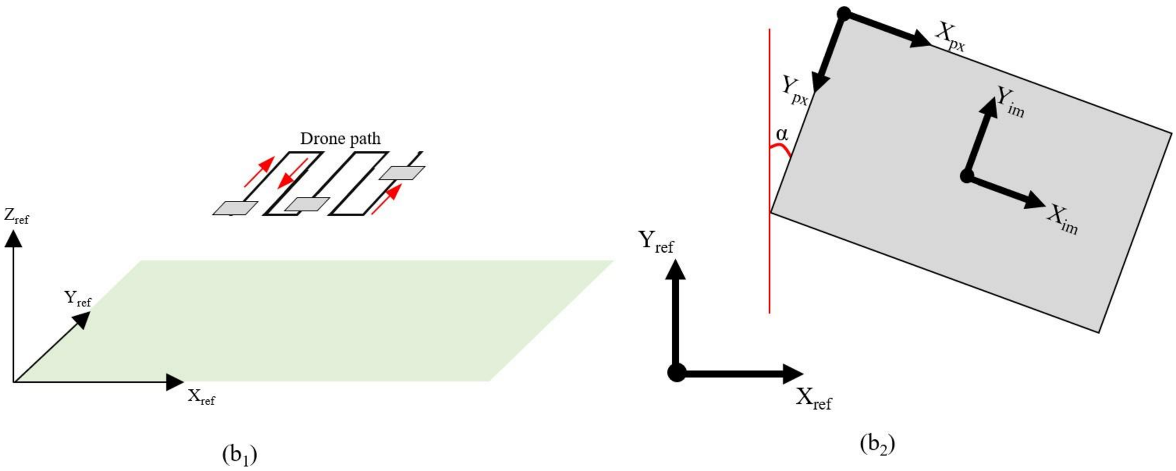


Figure 6: Relationship between pixel image and geographic coordinate systems.

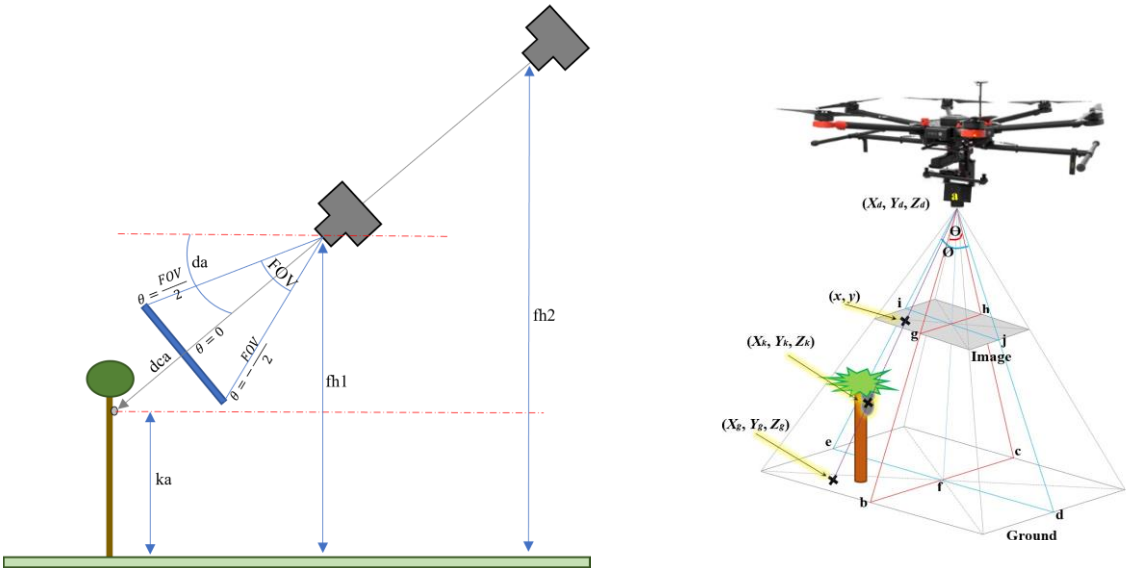


Figure 7a: Diagram demonstrating mathematical relationship between the flight height (fh), camera depress angle (dca) , koala altitude (ka), camera incident angle (da) of the field of view (FOV) and the koala size on the capture image. 7b presents a 3-dimensional view of the relationship between the koala and drone camera.

Field trial 1 - Victoria

During the first field trials in November 2019, three datasets were recorded from two sites.

The first survey site was within the Fitzgerald Plantation near Grassdale, Victoria (latitude -37.841625, longitude 141.585421). The area was known to have a high population of koalas and comprised around three hectares (300 m × 100 m). Two flights were conducted at this site, one at 10:30 am and one at 11:30 am, both on 14 November 2019.

The second survey site was within the Healy plantation in Branxholme, Victoria (latitude -37.886418, longitude 141.716864). The surveyed area was around five hectares (300 m × 168 m). One flight was conducted at this site at 11:15 am on 12 November 2019.

On the days of the trials, wind speed was around 20 km/h and the ambient temperature about 12°−17°C.

Field trial 1 ground truthing

To assess the accuracy of each detection method, a ground truthed dataset was created. Prior to conducting the trials, the trunk of every tree was marked with a unique identifier (ID) using lumber crayons or spray paint.

During the first trial, eight trained koala spotters recorded the location of any koalas by tree ID, time of day, and GPS coordinates at the base of each occupied tree. Upon completion of the spotting, a list of every koala detected by every spotter was compiled and independently verified by the research team through visual re-inspection of the sites against tree ID, to confirm the presence of identified koalas. The number of spotters exceeded the "research standard" of 3 spotters and the requirement of 2 spotters in the koala zone to be as confident as possible that all koalas in the area were located. Spotters performed their task independently, without conversing with other spotters.

The key purpose of pre-labelling all trees in a study area was to minimise potential errors associated with GPS readings which are notoriously problematic in a forested area and (b) to allow spotters to remain independent and not share information about the koalas they detected. Whilst it would be more efficient for spotters to simply mark each tree that they spotted a koala in, this would have prevented spotters from conducting their surveys blindly i.e. without prior knowledge about the number or location of koalas on site. This was essential, as human spotters were one of the detection methods being assessed in the study and we wanted to be able to evaluate this method on an individual not aggregate level. Furthermore, GPS coordinates could not be relied upon as the sole record of each koala's location, due to the varying accuracy of handheld GPS devices (particularly beneath the forest canopy) and differences between each spotter's device (despite having the same settings). Thus, the ground truthing process employed the manual recording of tree positions through IDs/labels.

The infrared and hyperspectral images of each dataset were ground truthed by first creating an orthomosaic image from the infrared imagery for each flight using Agisoft's Metashape software. Then, using the GPS coordinates and tree IDs provided by the spotters as a guide, the koalas' locations were manually marked on the orthomosaic. These locations (which were contaminated by GPS errors) were then manually adjusted to ensure all relevant aerial and ground-based observations corresponded with one another, noting that all koalas detected by ground-based spotters were clinging to a tree, i.e. no koalas were spotted on the ground. In other words, the locations of all possible koalas in the infrared imagery were extracted and the (x,y) pixel positions within each frame with a koala in it manually confirmed.

Field trial 2 - South Australia

During the second field trial in December 2020, 1 dataset was recorded from one site.

The survey site was within Cleland Wildlife Park in Cleland, South Australia (latitude 34° 56' 59.99"S, longitude 138° 40' 59.99" E). The area was selected because it had a known number of koalas in an enclosed area, providing an absolute population from which to assess the accuracy of the detection methods without a protracted period of tree marking (for the ground truthing process). The site was 0.09 hectares in size (60 m x 15 m). Eight flights were conducted at this site. Flight trails started at 7:10 am and concluded at 9:20 am on December 21st, 2020.

On the day of the trial, wind speed was around 16 km/h and the ambient temperature about 14-18◦C.

Field trial 2 ground truthing

As the number of koalas in the site was known, ground truthing was not required.

Field trial 3 - Victoria

During the third field trials in February 2022, nine datasets were recorded from two sites.

The first survey site was within the Morgan-Paylor Plantation near Orford, Victoria (latitude -38°11'27.90"S, longitude 142° 7'19.86"E). The area was known to have a high density population of koalas and comprised around 8.1 hectares 450 m × 180 m). Five flights were conducted at this site, flight trials started at 9:55am and ended at 4:57pm, on 15 February 2022. On the days of the trials, wind speed was around 11 km/h and the ambient temperature about 21°−28°C.

The second survey site was within the Dyson plantation in Bessiebelle, Victoria (latitude 38° 8'33.38"S, longitude 141°58'57.53"E). The surveyed area was around 7.4 hectares (200 m × 370 m). Four flights were conducted at this site, flight trials started at 9:41am and ended at 5:23 pm, on 16 February 2022. On the days of the trials, wind speed was around 11 km/h and the ambient temperature about 16°−21°C.

Field trial 3 ground truthing

As with the first field trials, the trunk of every tree was marked with a unique identifier (ID) prior to the trial.

During the third trial, 6 koala spotters were used to record the location of koalas using the same recording methods used in Trial 1. Upon completion of the spotting, koala positions were independently verified by the research team through visual re-inspection of the sites against tree ID.

Data analysis and evaluation of success

The initial broad evaluation of detection methods used six criteria: safety, accuracy, reliability, cost, efficiency, and likely future improvements. Given the nature of this data and the purpose being to refine the list, five simple categories (poor, low, moderate, high, excellent) were used to rate each method in terms of the criteria. This suggested the technique with the greatest potential was thermal imaging.

Interviews with spotters and observations were used to develop a list of tips to improve spotting. Special attention was paid to the advice of spotters who demonstrated outstanding ability to detect koalas. An explanation for each tip was included to provide justification and potentially to hopefully limit the perpetuation of unjustified advice. These tips were also verified by two koala experts with substantial experience in spotting and koala behaviour.

The development of koala detection and geolocation techniques can be classified into three main phases. The first phase included analyses using simulation and real data to understand issues associated with koala detection and parameters associated with flight settings. The effect of canopy cover and temperature change on koala detection was investigated using real and simulated data sets. Tree canopies have an impact on probability of koala detection for two main reasons. First, the koala's signature can be partially or fully occluded by canopy structures (tree stems, branches, foliage). This reduces the apparent size of the koala. Second, intervening canopy can (through attenuation) reduce the contrast of a koala's heat signature relative to other objects. This reduces the likelihood the koala can be discriminated from its background. Several parameters relate to the first effect. These include tree structure, tree separation distance, vegetation density, koala altitude, drone altitude above canopy, and camera depression angle. Regarding the attenuating effect, there are several more complex and interdependent parameters. These include time of the day, season, weather, temperature, humidity, moisture, atmospheric attenuation, emissivity of tree canopy (leaves, wood, etc.), koala emissivity, soil/ground emissivity, effect of wind (motion), and the sensitivity of the infrared camera. Moreover, these parameters are also dependent upon parameters related to the first effect. Simulating all these parameters with high fidelity would be a challenging task and is beyond the scope of this study. The goal here is to understand the broad impact of koala occlusion on the probability of detection; and to determine flight options that may eliminate or at least reduce such effects. Several experiments were conducted to examine this.

The second phase included developing a novel object detection technique to detect koalas. As such the MOBIVLS technique was developed and tested against 12 other existing state-of-the-art thermal imaging detection methods. The evaluation of success in terms of the most effective model was based mainly on detection rates and false alarm rates where the best technique is the one that provide highest detection rates with minimum false alarm rates.

The third phase included an automated koala counting and 3D geolocation algorithm (AKCoGA) to automatically estimate the three-dimensional coordinates of koalas by combining the information from drone images with the information from drone location for each frame. This algorithm was then tested using real and simulated results. The AKCoGA takes the detections output from

MOBIVLS, combine information from several frames and drone locations. By combining all of this information, the coordinates of detected koalas can be estimated, and false alarms can be discarded.

Project reporting and communication of findings

Results from each trial were reported at twice-yearly Project Steering Committee meetings. A thesis titled "Automated detection and geolocation of objects in low contrast and high clutter environments using biologically inspired vision techniques" was completed by Dr Laith Al-Shimaysawee at the University of South Australia. Four journal papers are currently being completed and the data will also be presented at several conferences, including the 2023 IUFRO Symposium on Forest Education. Due to sensitive nature of this project, consultation with industry partners and the Mount Gambier NIFPI Committee will be undertaken before any information dissemination occurs.

Results

The first objective involved analysing the pros and cons of detection methods that were either currently being use in koala detection, were used in detection of other wildlife species, or showed promise given the problem specifications. They represented traditional and emerging technologies for koala detection. These results are presented as Table 1. The category of "spotters" was divided into four groupings reflecting the augmented technologies being employed but it should be noted that many spotters use a combination of technologies depending on the time of day and weather conditions. In addition to the spotters, 8 other detection methods were examined (detection dogs, thermal imaging, hyperspectral sensors, visual cameras, passive acoustic monitoring, trap cameras, doppler radar, and LIDAR). These methods would likely be used together to optimise the detection ability, for example a thermal camera is often used on the same payload as a colour visual camera. It is also important to note that all koala detection techniques are costly. The upfront costs and distribution of costs vary depending on technique but as our steering committee clearly expressed safety was the number one priority, Table 1 refers primarily to labour intensiveness rather than overall financial cost.

Table 1: Overview of the Pros and Cons of Detection Methods

Method	Pros	Cons
Koala Spotters		
Spotters	• Suitable for most weather conditions (e.g. rainy, windy) • Satisfies current regulatory requirements • Has reduced koala mortality and injury (particularly since the use of multiple spotters) • Offers real-time observations to immediately assist operation • Easily justifiable and explainable	• Welfare/safety risks for spotters • Labour intensive • High turnover of spotters • Not always accurate, koalas are missed • Accuracy improves with experience, but spotters often leave within several months • Not effective/used at night • Can be slow • Detection probability may vary with weather conditions • Detection probability may vary with height of trees
Spotters with infrared spotting scopes	• Suitable in most weather conditions (including low light and overcast weather conditions) • May increase the accuracy of detection • Allows spotters to operate at night • Can increase the effectiveness of detection in low-light conditions • Offers real-time observations to immediately assist operations • Easily justifiable and explainable	• Does not improve the safety of koala spotters • Labour intensive • No existing research examining the accuracy of the method • Limited field of view and obscured sightlines due to trees means easy to miss koalas if used as primary detection method • No established techniques for using scopes effectively • Anecdotal feedback that it causes greater eye strain for spotters • May increase tripping risk for spotters • Additional expense over spotters alone • Possibly slower than without scopes • Detection probability may vary with weather conditions (e.g. bright light).

Spotters with binoculars	• Suitable in most weather conditions (e.g. rainy, windy) • May increase accuracy of detection • Generally used to confirm koala that are highly obscured, so may result in decreased false positives • Offers real time observations to immediately assist operations • Easily justifiable • An additional tool that can be deployed	• Does not improve safety of koala spotters • Labour intensive • No existing research examining accuracy of method • May increase tripping risk for spotters • Additional expense over spotters alone • Not effective at night • Likely slower than without binoculars due to increased scrutiny and decreased visibility • Detection probability may vary with weather conditions.
Spotters with infrared data	• Suitable in most weather conditions (e.g.. rainy, windy) • May increase accuracy of detection • May help in confirming obscured koalas and in detecting false positives • Offers real time observations to immediately assist operations • Easily justifiable and explainable	• Does not markedly improve safety of koala spotters • If spotters use this purely as a confirmation technique and don't systematically check all trees, any koalas the IR has missed, will also be missed by the spotter • Labour intensive • Additional expense as have to generate the infrared data and employ the spotters
Alternative Detection Methods		
Detection Dogs	• May be trained to detect individual koalas, not just scats • Can be far more accurate/effective than humans • Not sight-dependent, so effective at night, when other methods cannot be used • Potentially less labour intensive / reduce number of spotters needed (for detection not monitoring) • Suitable in most weather conditions (e.g. rainy, windy)	• Require time and expertise to train (and there are very few experienced trainers) • For purposes of trials, costly to hire a trainer/dog handler • Not likely to be effective in areas with high koala density • Doesn't eliminate the need for people on the ground (dog handler) • May cause stress to koalas

Passive acoustic monitoring	• Koala bellow carry over 40m so excellent technology to determine presence but not necessarily location • May be useful in developing koala density estimates prior to spotting (e.g. assist in planning by avoiding compartments with very high densities) • Cost-effective and easy to deploy • Suitable in most weather conditions (e.g. rainy, windy • If effective, potentially less labour intensive / reduce number of spotters needed (for detection not monitoring)	• Ineffective during the non-breeding season when koalas are less vocal (6 months of the year) • Does not eliminate the need for other detection methods as does not provide sufficiently accurate and reliable location data
Trap cameras	• May have some use when developing koala density estimates prior to spotting (e.g. assist in planning by avoiding compartments with very high densities) • Potentially less labour intensive for monitoring koalas once they have been detected.	• Would require many cameras to be placed in the whole forest/plantation area to monitor koala locations. • Cost, monitoring requirements and potential damage to cameras decreases the viability of this option in a commercial plantation setting • Would result in many false alarms, long processing times for images, and the technology is not able to accurately determine where the koala are if they have moved. • Limited scalability for large areas • On-site installation and maintenance required
Doppler radar	• Has been used successfully in the United States for detecting large animals (e.g. deer on highways) • Emerging technology in the context of wildlife detection; advances likely to be made • Potentially less labour intensive / reduce number of	• Currently low rates of success in detecting smaller animals (e.g. dogs < 30%) • Generally of greater benefit in detecting moving objects • Considered to have limited potential in the context of koalas (i.e. small and unmoving, as well as being highly insulated) • High equipment costs

	spotters needed (for detection not monitoring)	• Unlikely to be able to detect sedentary koalas amongst treetops
Alternative Types of Sensors that Could be Used in Automatic Detection		
Thermal imaging	• The most widely tested technology in this field • More consistent than spotters and generally more accurate • Cameras can be UAV-mounted or mounted on a ground-based system or hand-held • If used as the sole technique, it decreases the need for humans on the ground near harvesting machinery (would still be required to monitor koalas detected) • Effective at night (with appropriate approvals/CASA authorisation if UAV-based)	• Performance is more likely to decrease when ambient temperatures are high (generally once the sun has risen or hot weather conditions). However, initial results show that using Bio-inspired vision techniques help to detect koalas in challenging scenarios such as when koalas are highly occluded or shown in low contrast with the background • Most testing has taken place during cooler seasons; may be less effective in Summer • To overcome temperature sensitivities, data is often collected some hours before the harvest operation but koalas may have moved before operation commences
Hyperspectral sensors	• Highly effective at teasing out details in imagery of complex environments • As with thermal cameras, these sensors can be UAV-mounted Unlike thermal imagery, not reliant on a temperature difference, so may be more effective during the day/warmer weather • If effective, potentially less labour intensive / reduce number of spotters needed (for detection not monitoring)	• Dependent on solar irradiance (incidence angle of the sun) and hence not effective at all times of the day and not useful at night • Typically operates in near-infrared band (NIR), so does not detect thermal signatures • Koala signatures in NIR are unknown • Currently the technology does not provide real-time data (requires post-processing) so further development is necessary to offer a practical solution • Could be impacted from occlusion by heavy foliage and tree structure. To the best of our knowledge, no research has been conducted so far to use this sensor for koala detection

		• Typically line scan cameras, making interpretation of images more difficult than infrared or visual
Visual Cameras	• If a detection is made, relatively easy to distinguish between koala and other animals (i.e., better at classification of objects than thermal cameras) • Relatively inexpensive and easy to obtain • If effective, potentially less labour intensive / reduce number of spotters needed (for detection not monitoring)	• Difficult to detect animals using visual cameras alone • Not as amendable to automatic detection as thermal cameras
LIDAR	• Useful for developing models of the forest environment • Could enhance the performance of other automated systems • If effective, potentially less labour intensive / reduce number of spotters needed (for detection not monitoring)	• As a stand-alone technique for koala detection, LIDAR has limited potential • Using LIDAR to acquire 3D scans of the forests prior to UAV data collection may assist other methods but is time-consuming • Does not provide sufficiently accurate and reliable data on its own

The modality used to mount different types of sensors (e.g., UAV, ground-based machine, or person) also has inherent strengths and weaknesses and these are presented in Table 2. Lastly, it should be noted that an alternative to detection, is the use of deterrents to limit the number of koalas accessing a plantation. A brief description of pros and cons of commonly discussed deterrents are provided in Table 3. Because of the immediacy of the issues and the high density of koalas in existing plantations, deterrents were considered beyond the scope of this project.

Table 2: Pros and Cons Associated with Different Modalities used to Carry Sensors.

Pros and Cons of Modalities Used to Carry Sensors		
UAV	• Faster than spotters to assess a given area • Can be readily programmed to scan precise areas at specific heights • With image-processing algorithms, the method is becoming increasingly accurate and automated	• Climate dependent, as UAVs unlikely to fly during rainy/windy weather • UAVs can attract raptors which may increase the risk of getting intersected (Note: the type of drone used and the height it is flown relative to the raptors will reduce this risk) • CASA approvals can be difficult/time-consuming to obtain if forests on public land • CASA regulations prevent flying in certain conditions (e.g., nearby airports, within 30m of public road) • CASA requires pilot to maintain line-of-sight which can be difficult given height of trees if adjacent property also forested
Humans	• Has the ability to modify settings to suit environmental conditions • Has the ability to augment technology with own eye • Is likely faster than ground-machine	• Slower than UAV to collect data • People using hand-held sensors will all have different gaits so automation will be more difficult • People may be tempted to change settings which could result in differing results • Added weight of device and comfort of support materials may add challenge for user • Technology is expensive and tripping in challenging terrain is a real risk.to both person and technology
Ground-machine	• Track and walking robots that self-right themselves if they stumble on objects are available and improving rapidly • Improves safety by decreasing the need for human spotters	• Limited by type of terrain • Current technology is likely slower than spotters • Size of payload can be a limiting factor • Cost in having multiple robots to cover an area more quickly is prohibitive

	• May be easier to spot a koala using automated techniques from the ground rather than air	• High contrast on sunny days when collecting images from the ground may be image processing challenging

Table 3: Pros and Cons of Deterrent Methods

Deterrents that could reduce the need for detection		
Fencing	• Proactive rather than reactive approach designed to reduce rather than manage the issue • Reduces reliance on koala detection, as less koalas in the area prior to harvesting so long terms could be cost-effective	• Currently not practical and limited research available • Expensive • The type of fence required to effectively prevent koalas from moving between compartments would have a significant impact on the economic viability of the harvest operation (e.g. would require clear canopy breaks between adjacent forests and appropriate exclusion fence >1.8m in height), and could negatively impact on other wildlife • Does not provide direct estimate of koala presence meaning detection methods would still be required
Modifying leaf chemistry	• Proactive rather than reactive approach designed to reduce rather than manage the issue by making the foliage less palatable • Reduces reliance on koala detection, as less koalas in the area prior to harvesting so long terms could be cost-effective	• Modifying phytochemicals may take years to develop and while reducing the digestible nitrogen levels in leaves for example, may reduce their palatability to koalas, may also impact tree growth and soil properties (note – anecdotal evidence that some provenances being grown in SW are not preferred by koalas)

		• Modifying phytochemicals will not guarantee long term changes in koala browsing • Expensive • Does not provide direct estimate of koala presence meaning detection methods would still be required
Acoustic Techniques	• May be possible to use acoustic techniques (e.g. specific frequencies) at particular times to move koalas to other areas • Proactive rather than reactive approach designed to reduce rather than manage the issue • Reduces reliance on koala detection, as less koalas in the area prior to harvesting so long terms could be cost-effective	• No research to understand if sounds that deter koalas also damage hearing or cause stress in koalas • Expensive, time consuming to set up and subject to damage by rain • Does not provide direct estimate of koala presence meaning detection methods would still be required
Sensory Repellents	• The smoke from a controlled cool burn has been observed to move koalas in some situations • Proactive rather than reactive approach designed to reduce rather than manage the issue • Reduces reliance on koala detection, as less koalas in the area prior to harvesting so long terms could be cost-effective	• Does not provide direct estimate of koala presence meaning detection methods would still be required • Behaviour of koalas in smoke conditions is inconsistent

These methods were then evaluated using seven criteria: safety, accuracy, reliability, cost, efficiency, current ability to provide real-time data, and the likelihood of future improvements. This evaluation is presented as Table 4. This evaluation highlighted the potential of thermal imaging as well as human spotters. As such significant attention for the remainder of the project was directed towards developing improved thermal imaging techniques, as well as examining how spotting could be improved.

Table 4: Evaluation of detection methods in plantations with high koala populations

Method	Safety	Accuracy in detecting location of koalas	Reli-ability	Cost	Effi-ciency	Current ability to provide real-time data	Likely improve-ments
Spotters	Poor	Good	Moderate	Good	Poor	Excellent	Low
Spotters with infrared scopes	Poor	Good	Moderate	Good	Poor	Excellent	Moderate
Spotters with binoculars	Poor	Good	Moderate	Good	Poor	Excellent	Moderate
Spotters with infrared data	Poor	Good	Moderate	Good	Low	Excellent	Good
Detection Dogs	Low	Moderate	Moderate	Good	Low	Excellent	Low
Thermal imaging	Good	Good	Excellent	Good	Excellent	Excellent	Excellent
Hyperspectral sensors	Good	NA/Unknown	NA/Unknown	Good	Excellent	Low	Good
Passive acoustic monitoring	Moderate	Low	Good	Excellent	Moderate	Low	Moderate
Trap cameras	Moderate	Low	Moderate	Low	Low	Low	Moderate
Doppler radar	Good	Low	Low	Moderate	Excellent	Low	Good
LIDAR	Good	NA/Unknown	Good	Good	Excellent	Low	Low
Deterrents*	Excellent	NA/Unknown	Low	Poor	Poor	NA/Unknown	Moderate

*Reliability of fences greater.

Poor	(red)	Low	(pink)	Moderate	(orange)	Good	(light green)	Excellent	(dark green)	NA/Unknown	(white)

Field Trials

The second objective involved developing, testing and evaluating detection methods. A total of five plantations and one koala holding area were used in the testing. The second trial was used for refinement and testing of the equipment and so no formal results are reported.

First Field Trials

The first field trial was undertaken in Healy, Montrose and Fitzgerald Plantations. On average, each spotter took 3, 5 and 1.5 hours (with standard deviations of 68, 51 and 30 minutes) to survey the first, second, and third sites, respectively, while it took the drone only 15, 25 and 8 minutes to cover the same sites respectively. Upon completion of all the ground surveying, a list of every koala detected by every spotter was compiled and this was independently verified through visual re-inspection of the sites against tree ID. Although unlikely, it is possible there were koalas not detected by either the eight ground-based spotters or the drone-mounted thermal sensor. The number of koalas spotted in the first trial at the three different sites is shown as Table 5.

Table 5. Number of koalas detected using each method during First Trial

Method	Healy	Time (hr:min)	Montrose	Time (hr:min)	Fitzgerald	Time (hr:min)
Commercial UAV with IR	6	0:15	8	0:25	16	0:08
Spotter 1 with IR data from UAV	6	NR	15	1:39	22	0:54
Spotter 2 with handheld IR scanner	2	NR	23	1:09	24	1:39
Spotter 3 – spotting independently	2	NR	19	2:33	23	1:09
Spotter 4 – spotting independently	2	NR	24	1:24	24	2:33
Spotter 5 – spotting independently	3	NR	20	1:11	24	1:24
Spotter 6– spotting independently	3	NR	20	1:10	25	1:11
Spotter 7– spotting independently	4	NR	25	1:25	24	1:10
Spotters (mean)	3.14	NR	21.8	1:39	24	1:25
Confirmation	6		27		24	

NR – not recorded (At Healy – *the start time and time of each observation was recorded but unfortunately not the end time)*

Despite the small number of sites, this data suggests that commercial UAVs may underestimate the number of koalas in some situations. The variation was most notable at the Montrose site where only 30% of koalas detected by spotters were detected by the commercial UAV. Although some koalas may have moved in the three hours from the UAV flight and the commencement of the spotter surveys, this is unlikely to account for such a difference in detections. The Fitzgerald site was isolated from other koala habitat, so it seems reasonable to suggest that in that case the commercial UAV achieved a 78% accuracy rating and a 100% accuracy for the Healy site. The accuracy of koala detection is likely affected by koala density as well as tree density (greater number of koalas obscured) and tree height. For example, despite low density, the shorter trees at Healy (average 15m) resulted in very accurate results, compared to the taller trees at Montrose (average

35m). Many spotters noted that it was easier to spot in high density sites because "you get your eye in" more quickly and it is easier to maintain concentration when you are making observation regularly. Fitzgerald, for example, also had tall trees (average 35m) but the spotting results were more accurate than Healy, likely due to the high density of that site.

Interesting to note, the spotter with the lowest accuracy rate at Montrose was the spotter with the IR data from the UAV. In this case the UAV data was lower than expected and it is likely the spotter focussed on the confirming those koalas and quickly scanned other trees rather than did a thorough assessment of the area. Recommendations relating to this issue are included in Table 13.

Third Field Trials (February 2022)

The third trials occurred on Morgan-Paylor and Dyson Plantations. On average, each spotter took 4.3 and 3.6 hrs (with standard deviation of 73 and 49 minutes) to survey the Morgan-Paylor and Dyson. Dyson Plantation was sub-divided into two areas on either side of the road. These results are shown in Table 6. This trial was marked by an overall improvement in spotting ability (likely due to greater experience of the spotters), professionalism, and also increased use and understanding of how to best use tools such as binoculars and IR monoculars to assist spotting. What is clear from these results is variation (i.e. reliability) is still an issue but it is much less pronounced and over-estimates account for almost all of the variation. This is a very positive finding as Forestry Companies are not concerned with false alarms (i.e. their preference is to miss harvesting a tree, rather than potentially harm a koala) and this also in line with advice spotters are given, "if in doubt, assume any potential object is a koala". The most problematic results in Table 6 was Spotter 2 at Morgan-Paylor who only detected 16 of the confirmed 25 koalas. One other spotter detected 24 but all others over-estimated the number of potential koalas. The variation between spotters may be explained by koala movement during the seven hours between the UAV flight and the end of the spotter surveys. Evidence for this movement is provided by the fact that although only 25 koala observations at one point were confirmed, spotters saw koalas in 35 separate trees (generally the tree immediately adjacent). In addition to koala movement, the overestimates, may also be due false alarms (i.e. marking an object that appears to be a koala as a koala when secondary confirmation suggested that as not the case), which again, is an acceptable outcome. The outlier of 16 koalas observed by spotter 2 is concerning. The lower number detected is correlated with the shorter time taken (2:14 h) when on average the other five spotters took just over 4.5 h. The technique, or misguided use of the technique, was also an issue in this case. This spotter relied primarily on their

IR monocular, starting with a boundary assessment and then doing a very fast survey of the forest. In discussion, it seemed this individual was confident that using different angles as they walked the boundary provided a strong confidence of the number of koalas in the compartment. This is not the case. Given the density of planting and the fact that the IR can't see through trees, this technique is flawed. Spotter 2 also had the lowest results in Dyson A but was accurate in the smaller section of Dyson B, suggesting the technique used may be more effective in narrow strips of trees.

Unlike the results in Morgan-Paylor, in Dyson A the spotters may have under-estimated the number of koalas with the range being from 6 to 12 and the confirmed number being 15. In this case there were three koalas noted by 4 different spotters to be just outside the monitoring boundary so it is possible that mean difference 3 (if spotter 2 results are taken out) was a result of koala movement. The movement of koalas is also noted in Dyson B. The overall duration of spotting in this site as small because of the size of the site, yet the six koalas were still spotted in 8 different trees.

The other noteworthy result in Table 6 is the MOBIVLS result. It suggested 23 rather than 25 koalas in Morgan-Paylor, but 22 and 8 in Dyson A and B rather than the confirmed 16 and 6 respectively. The technique was further refined after this result.

Table 7 presents an overview of the five sites and the "accuracy" of the various methods. Again, it is important to note that koala movement within the site could account for some of what we are defining as inaccurate (i.e. the results are likely to be negative skewed, so in reality may be better than reported). The terrain in the area is also a potential barrier to accuracy as it is one more factor that the spotter must focus on. The improved professionalism and use of technology from the first trial to the third trial would be expected to be shown in the overall accuracy results. This is the case for Morgan-Paylor but is not the case for Dyson, which had more difficult terrain. The other notable difference is the time lapse between the commercial UAV assessment and the UniSA UAV and spotters commencing was less than hour for Morgan-Paylor but 3hrs for Dyson.

The results suggest that the greatest issue with reliability, reflected by the largest variation, was with spotters using UAV data. Although intuitively, this should help them, it is obviously being used as a confirmatory approach, and seems spotters are not carefully assessing the other trees.

Table 6: Number of koalas detected using different methods during the third trial.

Method	Morgan-Paylor	Time (hr:min)	Dyson Site A	Time (hr:min)	Dyson Site B**	Time (hr:min)
Commercial UAV with IR	27		10		9	
Spotter 1 with IR data and binoculars	27	3:19	9	1:27	5	0:33
Spotter 2 with IR monocular	16	2:14	6	1:23	6	2:23
Spotter 3 with IR monocular*	33	4:07	10	1:45	6	2:40
Spotter 4 - spotting independently	30	6:10	10	4:02	1*	1:00
Spotter 5 - spotting independently	24	4:15	12	2:31	2*	0.10
Spotter 6 - spotting independently	30	5:10	10	4:45	1*	1:00
Spotters (mean)	26.7	4:12	9.5	2:38	4.83	1:40
Different Trees where koalas spotted	35		13		8	
Manual Confirmation Result	25		16		6	
MOBIVLS Processing Result	23		24		8	

*Spotter only used IR monocular for 3 of 49 sightings. IR Monocular used for confirmation rather than primary detection.
**Due to time limitations 3 spotters did different rows in site b (i.e. 4 koalas) total. Hence average is calculated using 4 for each of these spotters.

Table 7: Overview of Data and Current Detection Methods

	Healy	Montrose	Fitzgerald	Morgan-Paylor	Dyson	Mean Variation
Approximate size of compartment assessed	(280m x 300m) = 8.4 Ha	(260m x 400m) = 10.4 Ha	(100m x 350m) = 3.5 Ha	(450m x 180m) = 8.1 Ha	(200m x 370m) = 7.4 Ha	
Mean Tree Height (metres)	15	35	35	35	35	
Ambient Temperature at time of UniSA UAV flight	15°C	12 °C	17 °C	25°C	16°C	
Time lapse between commercial UAV & spotters	3hrs	2hrs	2hrs	<1hr	3hrs	
Terrain rating from spotters	Easy	Easy	Easy	Moderate	Difficult	
Confirmed number of koalas – manual	6	27	27	25	22	
Confirmed number of koalas – automated	6	27	27	23	30	
Commercial UAV	6	8	21	27	19	
Spotters - no assistance mean (accuracy)	5 (83.3%)	21.8 (80.1%)	26.8 (99.3%)	28 (121.7%)	14.7 (70%)	-9.12%
Average time taken per hectare with no assist.(mins)	NR	28.72 mins	23.71 mins	28.9 mins	36.4 mins	29.43 mins
Spotters – bino / IR monocular assistance mean (accuracy)	2 (50%)	23 (85%)	24 (100%)	25.3 (107%)	14 (66.7%)	-18.3%
Average time taken per hectare with assistance (mins)	N/A	34.62 mins	28.29 mins	23.8 mins	27.5 mins	28.55 mins
Spotters – UAV data assistance mean (accuracy)	2 (50%)	15 (56%)	22 (92%)	(117%)	(66.7%)	-23.7%
Commercial UAV pilot	100%	30%	78%	108%	90.5%	-18.7%

Based on these results, it is recommended that spotters with UAV data be reminded to systematically search the compartment. Binocular and IR monoculars did not offer significant improvement over the human eye, but this is primarily a function of how they are being used, rather than an inherent weakness in the methodology. The spotters with no assistance did have slightly less variation in their results compared to the commercial UAV results, but this was largely a function of very poor results at one site, which did appear to have a considerable movement of koalas and was a site where there was a two-hour lapse between the UAV flight and the spotters commencing. Spotters took just under half an hour per hectare to conduct their surveys, with slightly more time when the terrain was difficult. There was not significant difference between the time taken by spotters using assistance, and those only using their eye.

Table 8 shows the marked improvement in both the Commercial UAV data and the spotter data between the first trial and the third trial.

Table 8: Comparison of 2019 and 2022 Trials showing Significant Improvement

	Trial 1 Mean	Difference from 100%	Trial 3 Mean	Difference from 100%
Commercial UAV pilot	69.33 %	-30.67%*	99.25	-0.75%
Spotters with no assistance	87.57%	-12.43%	95.85%	-4.15%
Spotters with binocular or IR monocular (without outlier)	85.96%	-14.04%	86.85% (111.36%)	-13.5% (+11.36%)
Spotters with UAV data	61.3%	-38.66%	91.85%	-8.15%

*Low figure largely due to results from one site. Other two sites suggest it is within 11%.

Given the need to improve the detection rates, various speciality sensors and a custom-designed sensor system was developed. The results of this testing are presented below.

Comparison of Automated Koala Detection Methods

Eleven existing automated detection methods were used to detect koalas. The first six comparative techniques have been widely used to detect dim and small objects in infrared images. These techniques were: average absolute gray difference (AAGD) (Deng et al. 2016), improved average absolute gray difference (IAAGD) (Aghaziyarati et al. 2019), high boost multiscale local contrast measure (HB-MLCM) (Shi et al. (2017), improved local contrast measure (ILCM) (Han et al. 2014), multi-scale local contrast measure (MLCM) (Chen et al. 2013), and multi-scale patch contrast measure (MPCM) (Wei et al. 2016). In general, each of these methods computes the contrast between an object of interest and its surrounding by sliding a window around the input image vertically and horizontally, where the window centre is intended to be the object of interest location (Chen et al., 2013). The next four comparative techniques were machine learning and neural network-based techniques that have recently been used to detect wildlife, including koalas. The first two techniques were the faster region convolutional neural network (Faster R-CNN) and you only look once (YOLOv2), which have been used widely in object detection, including wildlife. The third technique was the template matching binary mask (TMBM), which has been used to detect koalas in small areas; and the fourth is a combination of Faster R-CNN and YOLOv2. In this approach each detector processes the image sequence independently and the final output is the average of the results of both techniques on each image. This combination technique, called the Combined 2DCNN method (where 2DCNN refers to two deep convolutional neural networks) was recently used to detect koalas in natural forests (Corcoran et al. 2019; Winsen et al. 2022) and eucalyptus plantations (Hamilton et al. 2020) and used to detect Rusa deer (*Cervus timorensis*) (Sudholz et al. 2021). The final detection technique was the one we specifically designed for the task of detecting koala signatures in plantations, Multi-scale Object Bio-Inspired Vision Line Scanner (MOBIVLS).

A comparison of the 11 automated detection techniques for the three data sets from the first field trial was conducted and the results are shown as Figure 8. It shows the overall receiver operating characteristic (ROC) curves, recall vs (1 - precision) curves, and the AUROC and EER for 11 comparative detection methods (AAGD, IAAGD, HB-MLCM, ILCM, MLCM, MPCM, TMBM, Faster R-CNN, YOLOv2, combined 2DCNN, and the MOBIVLS) when tested on three datasets from the first field trial. The MOBIVLS significantly outperformed all existing methods in terms of detection and false alarm rates, irrespective of the data set.

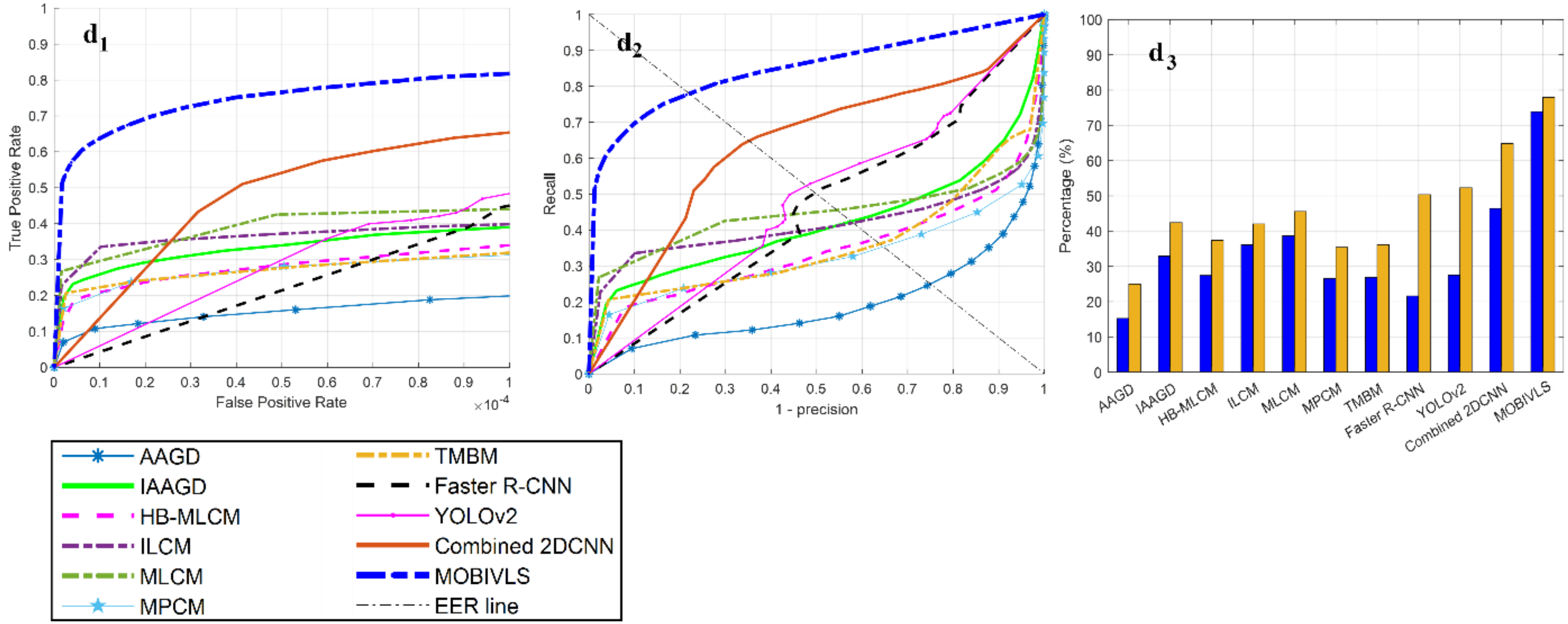


***Figure 8*: Comparison of evaluation curves for 11 automated detection techniques**

(AAGD, IAAGD, HB-MLCM, ILCM, MLCM, MPCM, TMBM, Faster R-CNN, YOLOv2, combined 2DCNN, and the MOBIVLS). Figure d1 shows the receiver operating characteristic (ROC) curves (TPR vs FPR); Figure d2 shows the recall vs (1 - precision) curves; and Figure d3 shows the AUROC and EER percentages. The FPR range over which the AUROC calculations were computed was (0 - 10^{-4}), while TPR range used was (0 - 1). For d1 and d2 curves that are up and to the left provide more accurate detection. For d3 higher bars represent more accurate detections.

The idea of combining the Faster R-CNN and YOLOv2 through averaging significantly improved the results, as the overall AUROC and EER of the combined 2DCNN is 46.4% and 64.8%, respectively. This leads to a 24.8% and 18.8% increase in AUROC over of individual Faster R-CNN and YOLOv2, respectively; and a 18.5% and 16.5% increase for the EER. However, the AUROC for the MOBIVLS was 73.9%, a 27.5% improvement over the next best method, the Combined 2DCNN. The EER result for the MOBIVLS was 77.9%, a 13.1% improvement over the Combined 2DCNN. The MOBIVLS performed better than all the other techniques in any of the metrics used and in all environmental setting tested (Table 9).

Table 9 : Comparative results of automated techniques on three datasets from the first field trial.

Several performance metrics computed for different object detection techniques at (a) FPR of 10^{-6} and (b) 10^{-5}. The total number of unique koalas was 56. The best result of each metric is highlighted by an underline and bold style. The second-best result is written in bold style only. The column 'Time' represents the processing time in seconds per frame. It should be noted that MOBIVLS is a newly developed algorithm and has not yet been optimised to run at high speed on a computer. With development significant speed improvements are easily obtainable.

No.	Methods	Recall (%)		F1 score (%)		Koala count		Avg_{kdet} (%)		Time
		a	*b*	*a*	*b*	*a*	*b*	*a*	*b*	
1	**AAGD**	3.6	11	6.6	19.1	9	24	3.6	11.1	0.06
2	**IAAGD**	9.4	25.9	15.6	40	17	35	8.7	23.7	0.18
3	**HB-MLCM**	6.7	20.9	11.8	33.5	16	28	6.5	19.7	0.06
4	**ILCM**	14.3	**33.3**	23.1	**48.6**	24	36	11.9	**28.2**	0.11
5	**MLCM**	**16.8**	29.6	**26.3**	44.9	**26**	**41**	**16**	28.1	0.37
6	**MPCM**	8	20.4	13.6	33	16	32	7.5	18.9	0.25
7	**TMBM**	8.2	22.3	13.4	35.5	14	35	7.6	20.6	0.053
8	**Faster R-CNN**	0.4	4.3	0.5	5	3	13	0.5	4.6	14
9	**YOLOv2**	0.6	6	0.8	7.6	3	17	0.7	7.2	3.5
10	**Combined 2DCNN**	1.4	13.7	1.8	17.7	3	17	1.6	15.7	17.5
11	**MOBIVLS**	**30.2**	**63.7**	**39.8**	**76.1**	**32**	**51**	**32.1**	**67.5**	0.8

At a FPR of 10^{-6}, the MOBIVLS provided a F1 score of 39.8%. This compares to a F1 score of 26.3% for the next best technique, MLCM. Allowing for a FPR of 10^{-5}, the F1 score was 76.1% (MOBIVLS) vs 48.6% (ILCM). The MOBIVLS also showed a higher likelihood of detecting more observations of the same koala as the average detectability per koala was 67.5%, as opposed to 28.2% for the next best method, ILCM (FPR 10^{-5}). Overall, the MOBIVLS was able to detect 51 of the 56 koalas present, at a false alarm rate of 10^{-5}, while the best performing alternative method (MLCM) only detected 41 and the Combined 2DCNN just 17. The fact no single detection system could spot all koalas was the impetus behind using spatially aligned, temporally distinct, images to improve koala localisation (see subsequent section on AKCoGA).

The AUROC and EER metrics indicated that the second-best technique was the Combined 2DCNN and the third best the MLCM (see Figure 8). However, the recall, F1 score, koala count, and average detectability per koala metrics indicate the second and third best techniques were the MLCM and the ILCM, while the performance of the deep learning techniques (Faster R-CNN, YOLOv2 and Combined 2DCNN) were the worst (Table 10). This is because the evaluation criteria in Table 9 were computed using a single level of FPR (10^{-6} or 10^{-5}), whereas the AUROC metric reflects the performance over range of FPR ($0 - 10^{-4}$); and EER reflects the performance when the number of false negatives equals the number of false positives. As the performance of the Combined 2DCNN, the best performing supervised learning technique, surpassed the dim object detection techniques (at a FPR of 2.5×10^{-5}, see Figure 8), the AUROC and EER metrics better reflect its overall performance.

It is important to mention that although deep learning techniques provided better results in AUROC and EER metrics than dim object detection techniques, they require large amounts of training data, high computational power, and are relatively slow. This means they are less likely to be viable running in real-time onboard a small payload out in the field.

Geometrical Model of the Koala 3D Geolocation

The camera and lens combination are assumed to be recti-linear and therefore requires no calibration matrix for distortion removal. The available information is assumed to be: the 2D koala location within the coordinates of the image plane, the drone's location in 3D geodetic coordinates (latitude, longitude, and altitude), and the orientation angles (pitch, roll, yaw) of the gimbal carrying the camera. It is further assumed that the koala does not move between image frames and that the drone's GPS location is at the centre of each image, i.e. there are no significant lever arm effects due to drone tilt. The model of koala geolocation is depicted graphically in Figure 9 for a gimbal/camera oriented at nadir. The points (x, y) and (X_k, Y_k, Z_k) represent the koala location within the image plane and world coordinates, respectively. The location of any detection fits the projected line from the camera position (X_d, Y_d, Z_d) to a ground point (X_g, Y_g, Z_g). To simplify calculations, the drone location is assumed to be that which corresponds to the centre of the image. gh and ij refer to the image dimensions. ϴ and Ø are the vertical and horizontal field of view angles of the camera lens, respectively.

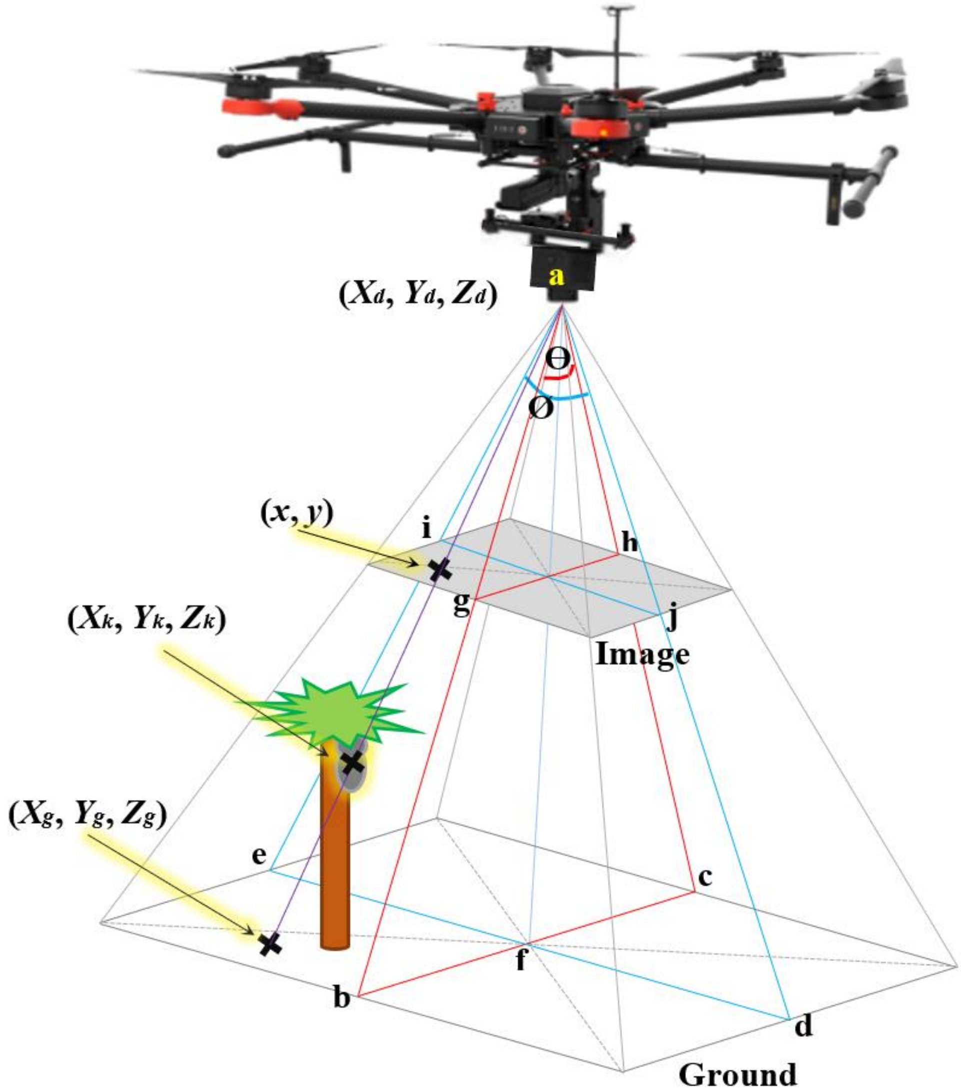


Figure 9: 3D geometrical model of the drone camera in relation to koala location.

Coordinate Systems

Five coordinate systems were used. The first is the pixel coordinate system, where the origin is the upper left corner of the image, X_{px} and Ypx, representing the columns and rows of the pixel within the image, respectively. The second is the image coordinate system, where the origin is the centre of the image, X_{im} and Y_{im}, representing the horizontal and vertical pixel coordinates, respectively. The third is the geographic coordinate system, sometimes referred to as the local or ENU (East-

North-Up) Cartesian coordinate system. It is common for East to be referred to as the x-direction, North as the y-direction, and Up as the z-direction. The fourth reference frame is the Earth Centred Earth Fixed (ECEF) coordinate system, which describes the position of points relative to the earth's centre. The last reference frame is the geodetic coordinate system, which describes the spatial position of a point in latitude, longitude, and altitude, where the reference spheroid is relative to the World Geodetic System 1984 (WGS84). Figure 10 shows the relationship between the pixel, image, and geographic coordinate systems:

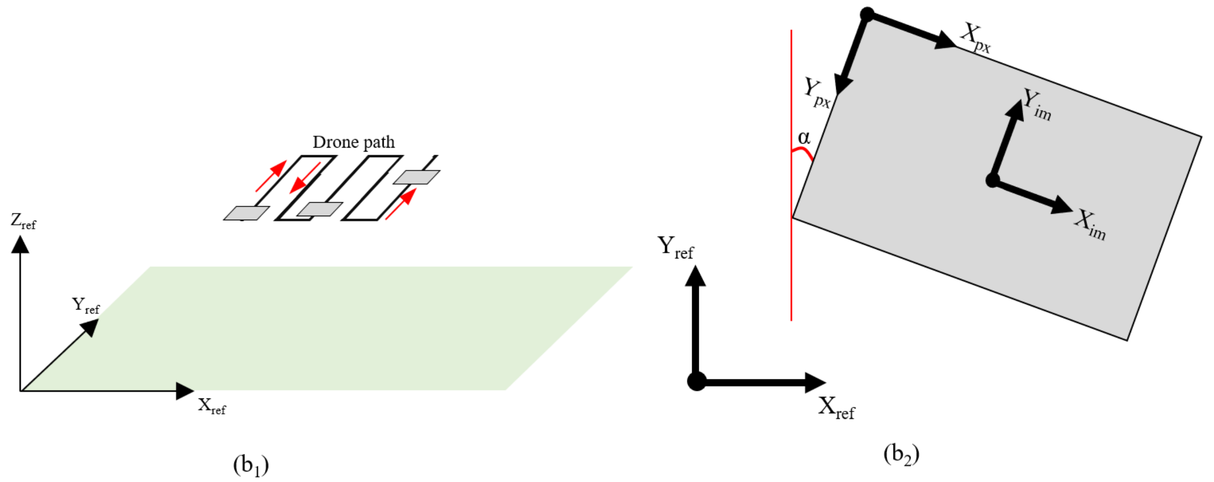


Figure 10: The relationship between pixel, image and geographic coordinate systems. A angle is the angle between the front of the drone and the north direction Y_{ref}.

Description of the Automated Koala Counting and 3D Geolocation Algorithm (AKCoGA)

To automatically populate a map with potential koala locations a system to localise the detections in 3D space was required. The proposed automated koala counting and 3D geolocation algorithm (AKCoGA) is depicted in Figure 11.

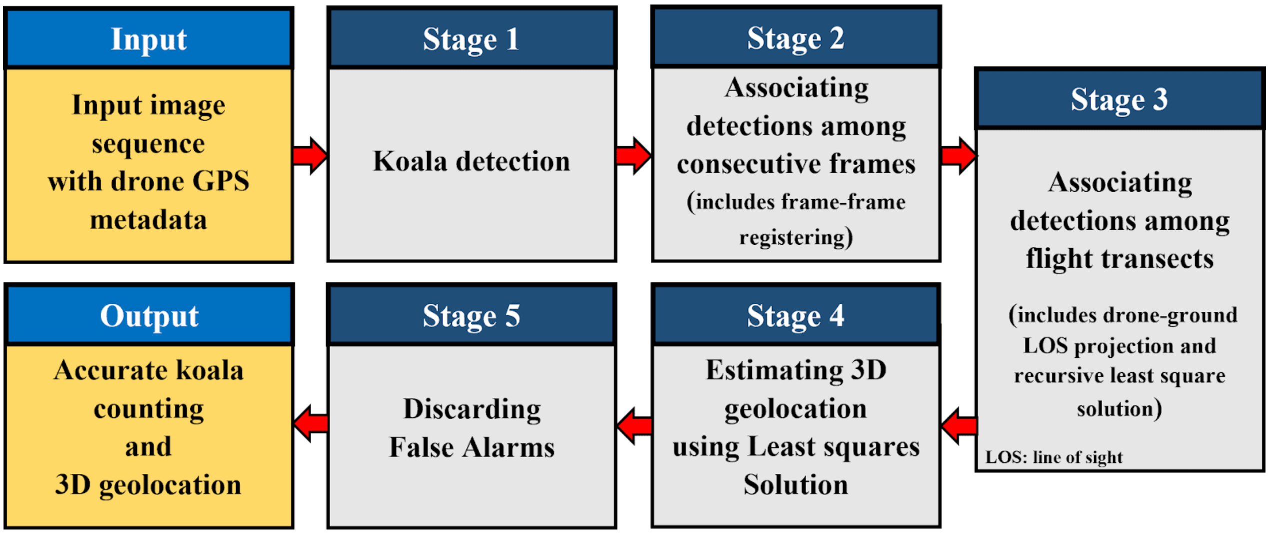


Figure 11: Block diagram of the proposed automated koala counting and 3D geolocation algorithm (AKCoGA).

The first stage in the workflow process was to use a koala detection technique to provide preliminary locations within the input sequence of IR images, where a detection technique could be any detection method that is known to perform efficiently. Based on the results of several experiments, in this analysis the best two detectors from object saliency enhancement and machine learning categories (MLCM and combined 2DCNN methods) in addition to our proposed detector (MOBIVLS) were tested with the proposed AKCoGA. Each detection technique provided a set of detections for each input image, together with a confidence level normalised in the range 0 - 1 (Note: a confidence level of 1 meant 100%). The confidence level represented the intensity of the detection after applying the threshold to the image and was normalised for each image normalising the minimum/maximum values to the range 0 - 1. The image detection maps were filtered by discarding detections with confidence levels below a threshold selected empirically.

The second stage in the workflow process involved associating detections in successive frames. To associate these detections the distance the drone moves between consecutive frames (assuming it travelled at fixed altitude and with constant forward speed) was computed from the drone's onboard navigation data and converted to a corresponding pixel distance (d) within the image. Then, each pair of detections from consecutive frames were associated if the distance between them fell within a band of ($0.5 \times d$) to ($1.5 \times d$) (in pixels).

The third stage in the process involved associating the grouped detections from the previous stage but now for each flight transect. This was achieved by first computing a projected line of sight (LOS) between the drone location and a point on the ground for each detection using the centroid point of each detection (in image coordinates) and the drone GPS tag of each frame applied. The recursive least squares method was then applied to the projected LOS of detection groups to estimate the point of intersection between these lines. The detection groups were then combined if the estimated intersection point/location of their projected LOS fits fall within the locations of the group's points and the estimated error is less than a dynamically computed threshold value. This process was applied to all groups until no further grouping could be obtained. The dynamic threshold was set to be in the range of 1 - 5 metres, where the process of combining groups was applied recursively starting by using a firm threshold. In other words, initially a 1 metre error was tolerated, then, after each iteration, this threshold was increased to allow more groups to be combined. The process of iterative/dynamically allocating a threshold allowed groups to be combined more accurately than using only a single threshold.

Least squares has been used widely to estimate object of interest location. It is a simple method (sometimes applied iteratively) for fitting points to a modelled function by minimising the sum of the squares of the residuals and it can be used to fit any characteristic function to data. Figure 12 shows projected lines from the drone to the ground that pass through a koala on a host tree. These projected lines refer to the detection of the same koala in a sequence of frames. In the ideal case these lines have one intersection point which represents the koala location. However, this is less likely to happen under real world conditions as there are many factors such as camera vibration, error in GPS coordinates, tree motion in the wind, etc. Therefore, if outliers can be removed, it is more appropriate to use a least squares estimate of the line intersections.

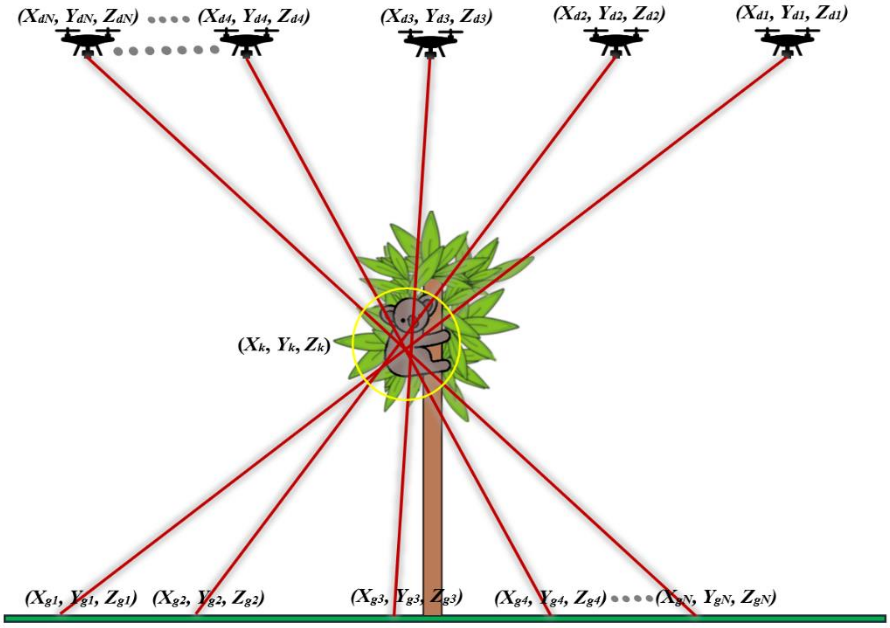


***Figure 12**: The estimated koala 3D location is the intersection point of the projected lines of sight (LOS).*

The fourth stage again used least squares, but this time to estimate the 3D location for each detection group. These detection groups represent the most probable locations of koalas at each site. In the fifth and final stage, based on the number of combined observations (associated detections), saliency of detections, and the estimated altitude of each detection group, filters were applied to eliminate false alarms. Since koalas generally live up trees (especially during the daytime when they are normally asleep) and are therefore less likely to be on the ground, the proposed algorithm can also be used to filter out groups (potential false alarms) whose estimated altitude is outside a selected band, e.g. 5 - 40 metres above the ground (note: if required, tree height can be estimated a priori using LIDAR). The number of detection points within each group, and saliency of detections provide a measure of confidence for each detection. As a result, a set of heuristic filters may be applied such that the final result is a set of detections with estimated 3D coordinates.

Overall, the relevance of each stage of the workflow can be summarised as follows: After Stage 1 (frame-wise koala detection), it is not possible to determine how many unique koalas there are in each dataset without manually checking the output. Also, location information cannot be obtained for individual koalas as only the GPS tags of the images containing each koala detection are available. After Stage 2 (detection association between consecutive frames), many of the limitations of the previous stage still exist, except that detections can now be associated within each flight transect. After Stage 3 (detection association between flight transects), detections are associated between flight transects, and many of the limitations of the previous two stages are eliminated. In

Stage 4 (3D koala location estimation), the 3D location of all detections are estimated. However, there are often many false alarms. Therefore, in Stage 5 (false alarm filtering), as koalas are typically found above the ground, the 3D information can be used to eliminate false alarms, in addition to the saliency, and number of associated detections. Finally, detection groups with only a few detections may also be rejected as they have lower aggregate (weighted) saliency. The final output is an accurate koala count with 3D geolocation and minimal false alarms and duplicate koala counts.

Effect of Temperature on Automated Koala Detection in Thermal Imagery

In this section, we provide analysis about the effect of temperature on the results of automated koala detection methods in infrared imagery. First, an accurate ground truth dataset was created for the study site for images multiple flights. As the process of creating accurate ground truth dataset is very time consuming and require a lot of manual efforts. This section discussed the effect of temperature on one site (Fitzgerald site) and for two flights with one hour time apart. An orthomosaic infrared image for the study site was created using Agisoft's Metashape software. Then, the GPS locations of the koalas provided by the spotters were used as a guide to manually label them on the orthomosaic image. Each image associated with a koala label was checked manually to adjust the location of each label to be exactly on a koala heat signature in each image. This (very time-consuming) visual/manual process was performed for each koala and repeated several times until all the relevant aerial and ground-based observations fully corresponded with one another. Then, the ground truth information of all infrared imagery was extracted, i.e. latitude, longitude, tree label, (x,y) pixel locations of koalas within each frame. Figure 13 shows the orthomosaic infrared image of the study site and the locations of the 25 koalas found, each labelled with a flag and their host tree ID.

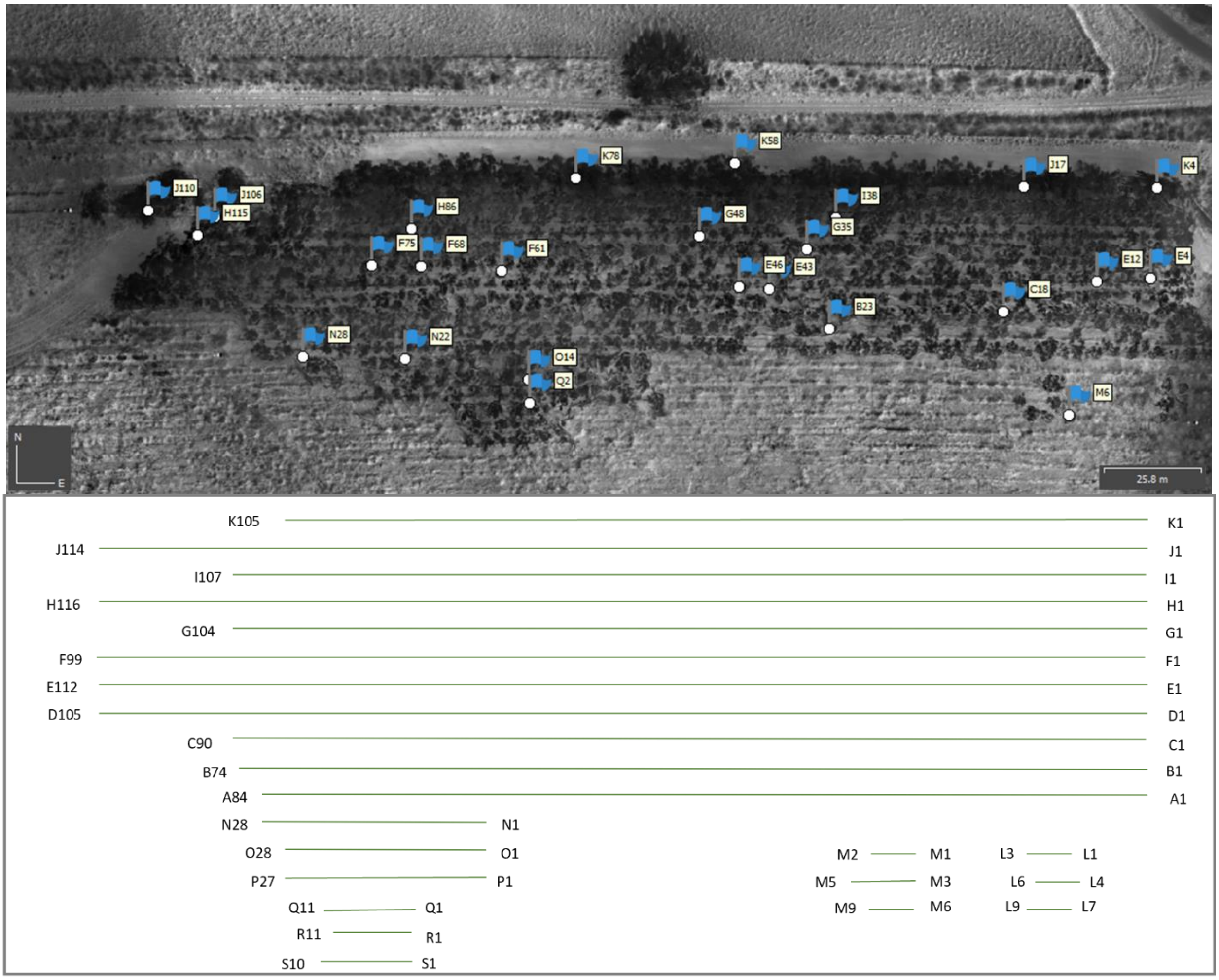


***Figure 13**: Orthomosaic infrared image of the study site at Fitzgerald, VIC.*

The site covered around 3ha (100m × 300m) and the locations of the 25 koalas (detected by spotters) are depicted on the image with flags. The code associated with each label represents the identity of koala's host tree. The bottom image shows the tree labelling system used at the study site, with each row allocated a letter and each tree a number commencing from the rightmost tree in each row.

The recall, precision and F1 score metrics (equations below) were used to evaluate the performance of the automated techniques for the two datasets of the same site (one hour time apart).

$$Recall = \frac{TP}{TP + FN}$$

$$Precision = \frac{TP}{TP + FP}$$

$$F1\ Score = 2 \times \frac{Recall \times Precision}{Recall + Precision}$$

TP, FN, and FP refer to true positives (true detections), false negatives (missed true detections) and false positives (false alarms) respectively.

Table 10 shows the results of AKCoGA for the first and second datasets of the same site when using MLCM, combined 2DCNN, and MOBIVLS individually in stage 1. AKCoGA has filtered out a significant number of false alarms and koala duplicates. The best results are obtained when using the MOBIVLS detector with AKCoGA, which delivers a (96% - 100%) recall, (100% - 92.59%) precision, and (97.96% - 96.15%) F1-score for the first dataset (10.30am) and a (76% - 80%) recall, (100% - 90.91%) precision, and (86.36% - 85.11%) F1-score for the second dataset (11.30am). The number of unique koala counts was (24 - 25) out of a total of 25 koalas with (0 - 2) false alarms and zero koala duplicates in the first dataset and (19 - 20) out of a total of 25 koalas with (0 - 2) false alarms and zero koala duplicates in the second dataset. The next best results were obtained using the combined 2DCNN detector in Stage 1 of the proposed AKCoGA algorithm. This provides a slightly lower performance, 4% for recall and 2.13% for F1-score relative to MOBIVLS + AKCoGA. However, as mentioned before, MOBIVLS does not require training and is significantly faster (and therefore does not require as much computational resource). From Table 10 it can be seen that, irrespective of the detector used in Stage1 of AKCoGA, it provides results with high precision (over 90% and up to 100%). This is because it makes use of more of the available information, combining it to not only discard false alarms but also to estimate koala locations accurately.

Table 11 provides details on koalas missed. It can be seen that the MLCM detector provides the worst results and MOBIVLS the best. It can also be seen that some koala detections were discarded during the filtering stage (Stage 5) of AKCoGA. These koalas were highly occluded and visible only in a small number of images. They also had very low contrast relative to their surroundings. It can also be seen that one koala from the second dataset could not be confirmed visually (koala ID N28), even though it was present in the first dataset and was detected by ground spotters (see Figure 14). It was also confirmed to be on the same tree at the end of the trial (3:30pm), precluding tree-to-tree movement as a likely explanation. However, whilst it is possible (but unlikely) that the koala left the tree only to return to the same spot later, it may have moved slightly within the tree and, because of occlusion, was not visible in the imagery. In the final analysis, neither explanation is considered likely.

Table 10: Koala counting results for AKCoGA using three detectors (MLCM, combined 2DCNN, and MOBIVLS) in Stage 1 of the proposed algorithm.

The total number of unique koalas was 25. These results represent the best performance when allowing up to 2 false alarms in the final output of the system (2 false alarms is equivalent to around 8% of total koalas).

Dataset	AKCoGA Stage1 Methods	Allowed FA	Unique koala count	False alarms	Recall (%)	Precision (%)	F1-score (%)
First	MLCM 2DCNN MOBIVLS	0	18 23 24	0 0 0	72 92 96	100 100 100	84 96 98
	MLCM 2DCNN MOBIVLS	≤ 2	19 25 25	1 2 2	76 100 100	95 93 93	84 96 96
Second	MLCM 2DCNN MOBIVLS	0	15 19 19	0 0 0	60 76 76	100 100 100	75 86 86
	MLCM 2DCNN MOBIVLS	≤ 2	15 20 20	0 2 2	60 80 80	100 91 91	75 85 85

Table 11: Analysis of koalas missed by AKCoGA using different detectors in its Stage 1.

The tree/koala IDs are shown in red (detected in < 10 images), and brown (detected in 10 - 20 images). It is important to highlight that the 2 false alarms are allowed in the final output of the system and not the first stage (detection stage).

Dataset	AKCoGA Stage1 Methods	Allowed false alarms	Missed koalas	Tree ID of missed koalas		
				Cannot be confirmed visually	Missed by detectors used in AKCoGA (Stage1)	Discarded by flitering in AKCoGA (Stage5)
First	MLCM	0	7	--	K4, J110, N28	E46, J106, M6, E4
	2DCNN		2	--	--	M6, N28
	MOBIVLS		1	--	--	N28
	MLCM	≤ 2	6	--	K4, J110, N28	J106, M6, E4
	2DCNN		0	--	--	--
	MOBIVLS		0	--	--	--
Second	MLCM	0	10	N28	H86, O14, E43, E4, H115, E12, J106, E46, J110	--
	2DCNN		6	N28	E46, J110	J106, E43, E12
	MOBIVLS		6	N28	E46	J106, J110, E43, E12
	MLCM	≤ 2	10	N28	H86, O14, E43, E4, H115, E12, J106, E46, J110	--
	2DCNN		5	N28	E46, J110	E43, E12
	MOBIVLS		5	N28	E46	J110, E43, E12

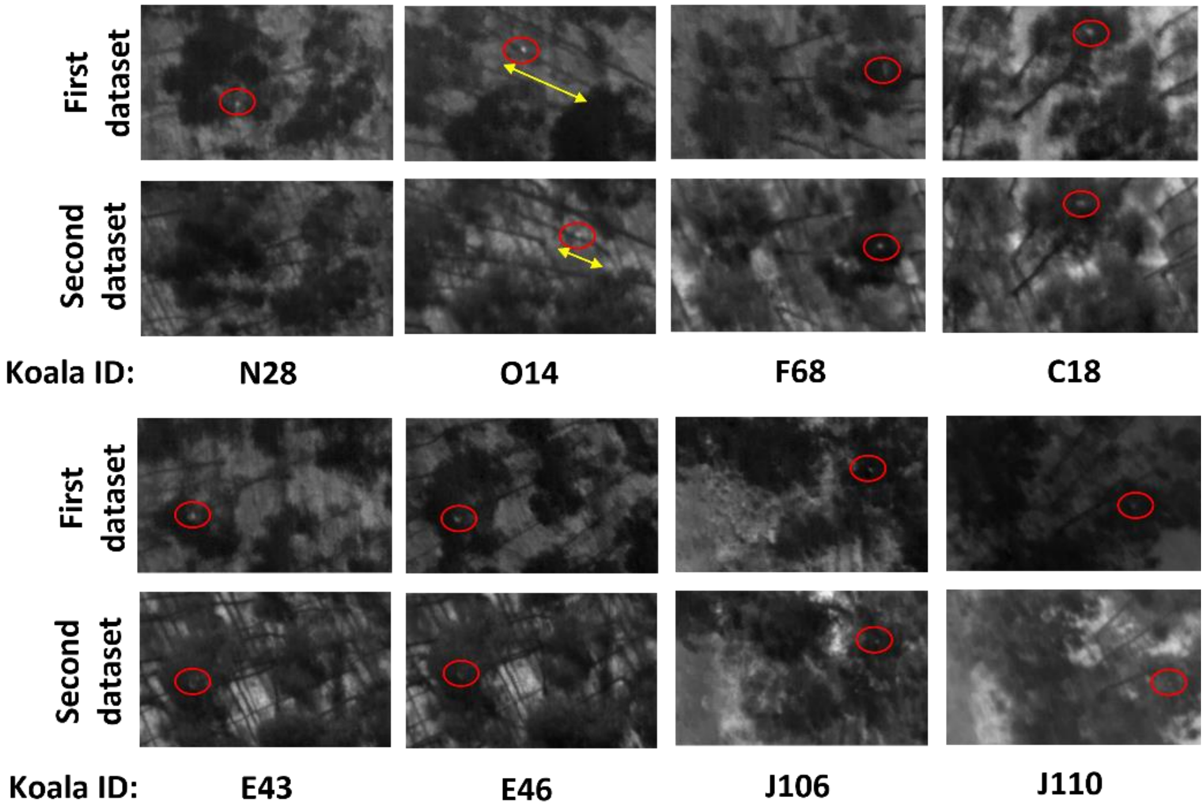


Figure 14: Image samples from the first and second datasets of the same koalas.
Most koalas have weaker heat signatures in the second dataset, e.g. koalas C18, E43, E46, J106, J110. One koala (ID F68) has a stronger heat signature in the second dataset. Koala O14 has moved down the tree. Koala N28 could not be visually confirmed in the second dataset.

Furthermore, it is noted that there were more koalas missed in the second dataset than in the first. Even though both datasets were acquired only an hour apart. That is, whilst there is a slight increase in temperature (3.2 °C ± 1.3 °C) over this period, there appears to be a significant reduction in detection performance. This is further indicated by a drop in F1-Score by roughly 10% for all methods (Table 9). This indicates that time of day has had an important role to play on the performance of the automated koala detection techniques that make use of long wave infrared (LWIR) imagery because the relative temperature between tree canopies and the animals is lower when these surveys are conducted later in the day. Figure 14 shows image samples from the first and second datasets for the same koalas. It can be seen that most koalas have weaker heat signatures in the second dataset (e.g. koalas C18, E43, E46, J106 and J110) but not ID F68. In addition, it was confirmed that one koala (ID O14) moved down the tree.

Figure 15 shows the number of images (observations) in which each of the 25 koalas appear for the first (upper figure) and second (lower figure) datasets. For each koala, the following is depicted: First: the number of images of the koala's host tree were present. This was derived from the geometry of the drone and the spotters/ground truth locations of the koala host trees and careful checking of imagery and the orthomosaic. Second: the number of images in which the koala could be visually confirmed. This was obtained from careful visual inspection of the imagery and the orthomosaic based on a knowledge of the geometry of the drone and spotter-confirmed ground truth locations of the koala, i.e. the koala was declared present even if it appeared as a single pixel with very low contrast against its surroundings. Third: the number of images in which the koala was detectable by the MLCM, combined 2DCNN, and MOBIVLS detectors when allowing a false positive rate (FPR) of 10^{-4} (considered the practical limit of operational detectors). Figure 15 shows that not all the instances of koalas were detectable as some were highly occluded. From Figure 15, it can be seen that some koalas (such as koalas F68, K4, H115, and Q2) were harder to detect in the first dataset than in the second dataset for which the temperature was higher. This is because these koalas were highly occluded as can be seen in Figure 15.

Table 9 shows that allowing up to two false alarms in the final output provides a higher detection rate (Recall) of around 4% on average for all methods. Also, it should be noted that koalas such as (E43, E12, E46, J110) were not detected by any automated method in the second dataset as these there were of very low contrast compared to their surroundings and were visible in very few images compared to other koalas. See Figure 14 for samples of these koalas in the first and second datasets and also see Figure 15 for a visual confirmation histogram. Figure 16 shows image samples of false alarms that have been allowed to enable an increase in the detection rates for each detector. It can be seen that the signature properties of the false alarms are similar to the true detections. There is therefore a trade-off between allowing detection of more koalas (even if they are highly occluded) and accepting some false alarms and forbidding false alarms while accepting some true positives are missed.

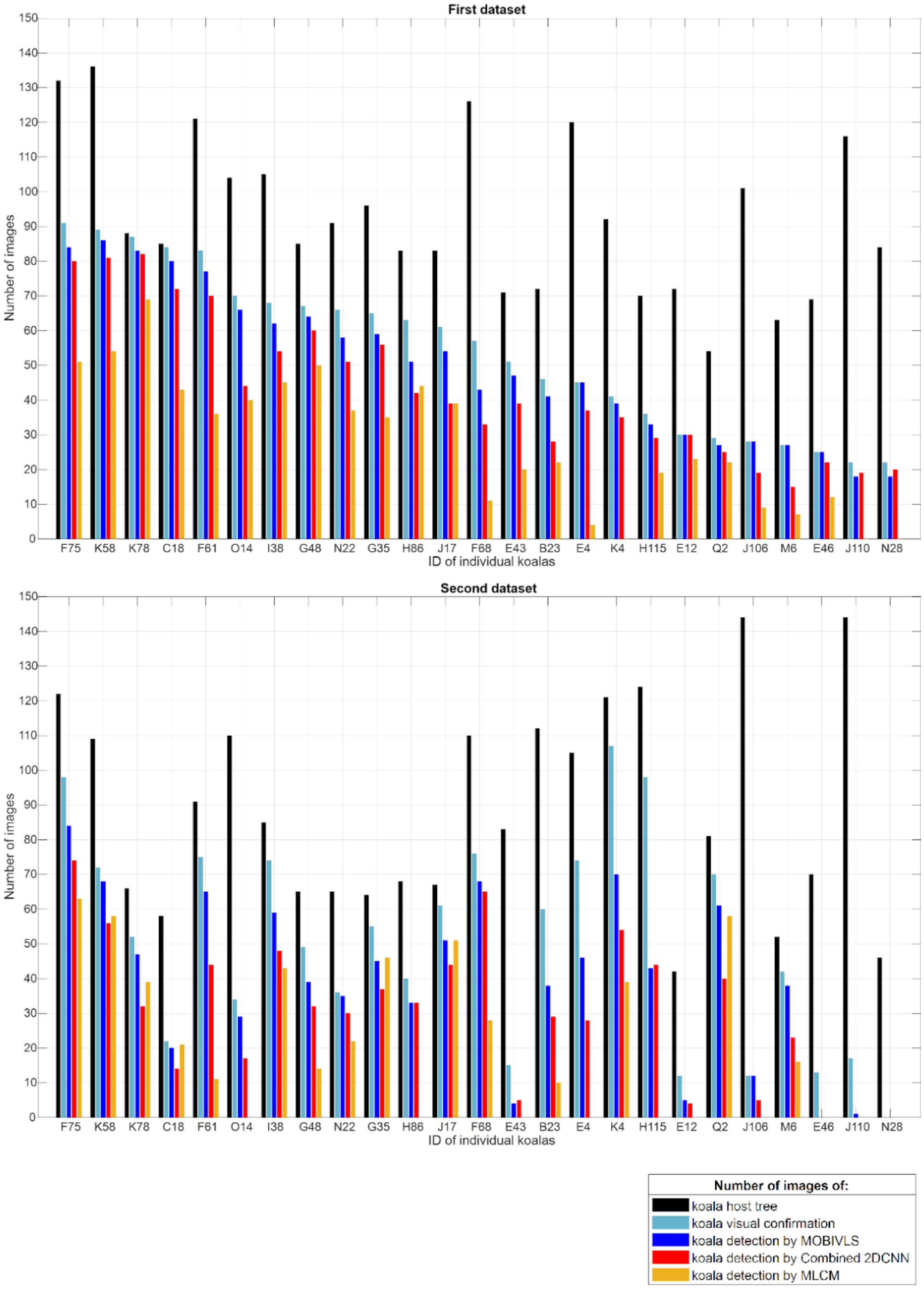


Figure 15: The number of images (observations) in which each of the 25 koalas appear for the first (upper figure) and second (lower figure) datasets.

For each koala, the following is depicted: the number of images of the koala's host tree (derived from the geometry of the drone and the spotters/ground truth locations of the koala host trees), the number of images in which the koala could be visually confirmed (derived from the geometry of the drone and spotter-confirmed ground truth locations of the koala and careful checking of imagery--the koala is declared present even if it appears as a single pixel with very low contrast to its surroundings), the number of images in which the koala is detectable by the MLCM, combined 2DCNN (YOLOv2 + Faster R-CNN), and MOBIVLS techniques when allowing a false positive rate (FPR) of 10^{-4} (considered the practical limit of operational detectors).

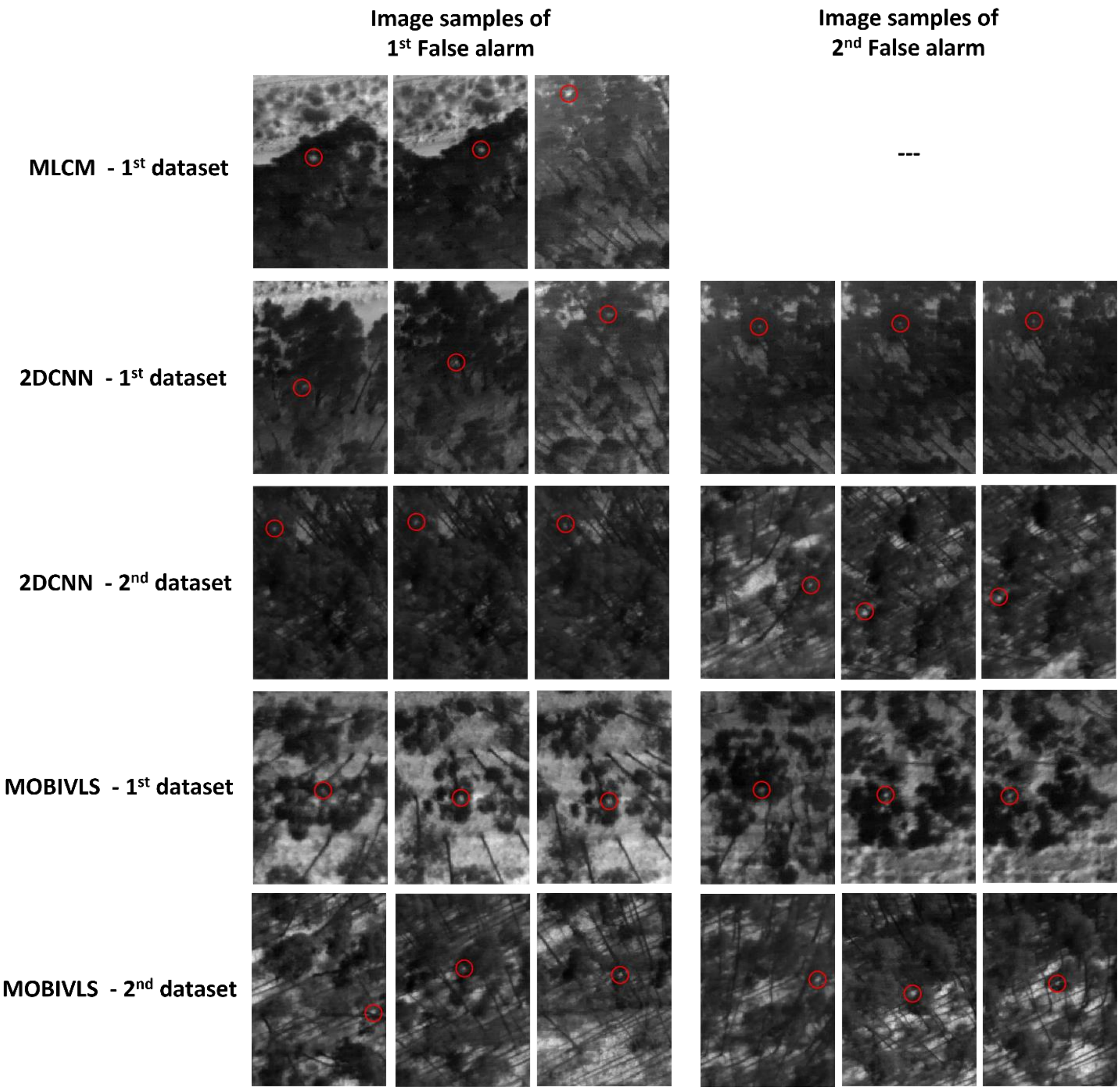


Figure 16: Image samples of false alarms that have been allowed to be able to increase the detection rates for each detector and for the two datasets.

Ground-based System

A prototype of a ground-based system was developed at UniSA for the specific purpose of koala detection. It was refined after field-testing at Cleland Wildlife Park and then evaluated as part of the third field trial. Preliminary results from this testing included:

- It could provide real-time, accurate results of koala location.
- The system needs significant refinement before it would be useful in the field.
- It was cumbersome to use; added significant weight even with the vest designed to distribute the extra weight; and testers felt the vest would be too hot on warm days.
- The screen image was too small and complex and needed to be redesigned to reduced "noise" and make it more intuitive to identify koalas. A larger screen size. use of colour, and annotations was recommended.
- The system needed to be miniaturized so it was easier to walk through the forest.
- The system needed be weather proofed and streamlined to reduce the number of cables that could easily be caught on branches.

Feedback from Spotters

The koala spotters participating in the third field trial were interviewed to provide further insights on how this technique could be improved, as well as their perceptions on safety and the pressure they felt conducting surveys. These spotters were experienced with an average of 3.6 years spotting experience with most participating in spotting 5 days a week (Table 12).

Table 12: Experience of Spotters in Third Field Trial

	Experience in spotting	**Frequency of spotting experience**
Spotter A	3.5 years	5-6 days in past – now just fills in as has another role
Spotter B	4 years	In past used to do 4-5 days spotting
Spotter C	5 years	5 days/week
Spotter D	2.5 years	5 days/week
Spotter E	3 years	3-4 days/week
Spotter F	3.5 years	2/week

These spotters were questioned on a number of issues pertaining to their attitude towards new techniques, their perceptions of safety and the pressure they felt as koala spotters. Table 13 presents a summary of these results and shows all spotters enjoyed their job and felt safe, noting that sound policies and procedures were in place. A very positive outcome of these interviews was a clear indication that spotters felt there had been significant improvements in how spotting was respected, noting that they were confident they could take as much time as they needed to do a good job and that companies would support them. There was a lack of consensus on the value of IR monoculars and binoculars but most spotters were relatively confident they were detecting all the koalas in an area most of the time. The weight and robustness of any additional gear was something spotters showed some concern about. The statement with a neutral rating and largest standard deviation was, "I think it is my mood on the day, rather than any equipment that impacts my ability to spot koalas". This result reflects one of the key limitations of spotting: consistency.

Table 13: Mean Level of Agreement by Spotters on Statements Pertaining to safety, Pressure and Techniques

	*Mean**	*SD*	*Relevant Comments from Spotters*
I am confident that most of the time I spot all the koalas at a site	*4.16*	*0.75*	*It is hard to judge, especially when you have gone from a high-density site to a low-density site but you sort of know if you are having a bad day. That's why it's good to have another spotter.*
I think using your naked eye to spot koalas is sufficient if you are well trained	*4*	*0.89*	*I just use my eye most of the time, but always looking for opportunities to improve*
I think binoculars assist me significantly in spotting koalas	*3.66*	*0.82*	*More so for confirming something is a koala*
I think an IR monocular significantly improves my ability to spot koalas	*3.33*	*0.82*	*Especially during the night and on dull days.*
I think it is my mood on the day, rather than any equipment that impacts my ability to spot koalas	*3*	*1.55*	*If your head is not in it, you can't do it.* *Concede that everyone does have bad days.* *I just leave it all behind and feel better when I am out in the forest* *I just concentrate and leave other stuff.*
I would be willing to try out any new techniques that might enhance my ability to spot koalas	*4.83*	*0.41*	*As long as not too technology based.*

I am hesitant to carry more gear to do spotting	*2.67*	*1.21*	*Depends how much and what the weight is.* *Would be an issues, especially on warm days when you need to carry a lot of water.* *We do actually carry quite a lot already - first aid, paint, water, food etc.*
I am hesitant to carry expensive gear in the forest	*2.17*	*0.75*	*Depends whose expense it is.* *As long as it's not my expensive equipment* *Owners would need to accept that things can get lost of broken* *I'd be concerned about face planting with expensive equipment. To do the job well you will fall down occasionally.*
I enjoy koala spotting	*5*	*0*	*Love every minute of it.* *Would be difficult to go back to a real job.*
I think if I had to carry extra gear it would impact my enjoyment of the role.	*2.83*	*0.98*	*People need to recognise that it can get tiring climbing over logs etc.*
I sometimes find it difficult to concentrate while spotting	*2.33*	*1.37*	*Depends on conditions, length of time and heat.* *Clear my mind - nothing else to concentrate on.*
I often find it difficult to concentrate while spotting.	*1.5*	*0.84*	*If I know I'm taking too long because I can't tell for sure if it is koala or not, I'll mark it and move on and then come back to it later.*
I sometimes feel a sense of pressure to do my job more quickly	*2*	*1.10*	*Been taught to always take as long as we need - just be slow and steady - if people are frustrated they can take it up with their boss.* *Mostly self-induced. Very few harvesters rush us. Most say take your time. They'd rather take a few more minutes not than have to wait 2 hrs for XXX[Supervisor name withheld] to turn up. It*

			used to be time is money and this equipment is too expensive to sit idle, but that attitude has really changed. *It doesn't worry me if others are faster but it's a bit of personal pride and I don't like to hold up the operation.* *Three years ago I would say yes, but not now. XXX [company name withheld] have evolved. We can take our time and we know if there is a problem we can ring them and they have our back.*
I often feel a sense of pressure to do my job more quickly	*1.25*	*0.50*	*Pretty good nowadays. XXX [company name withheld] really on top of it. Harvest operators realise if they don't have us, they can't do their job.* *Sometimes a bit borderline.*
I sometimes feel concerned about my safety while spotting	*2.4*	*0.55*	*I respect that there are safety issues but it is well managed.* *only when windy or lightning but been told to move to a different part of forest.* *If winds gusty or too hot, or working close to the machine. You are not spotting well if you haven't fallen over at some point.*
I often feel concerned about safety while spotting.	*1.4*	*0.55*	*There are good procedures in place. We do JHAs (job hazard analysis) before we start. We know safety procedures and we carry first aid kits.*

**Items were rated on a 1-5 Likert Scale, where 1=strongly disagree and 5 = strongly agree.*

What was apparent in discussions was the techniques used by individual spotters were quite distinct. While there is certainly a need for flexibility, the more successful spotters were more thorough in the approach they took, making distinct efforts to examine the tree from different angles. The most successful spotters tended to rely predominantly on the naked eye but used equipment (e.g. binoculars or IR monocular) for confirmation when they encountered particularly occluded koalas. Based on the experience of spotters and observations in the field, a series of tips that may help to improve the detection ability of spotters. These are presented as Table 14.

Table 14: Tips for Spotters

Tip	Explanation
Take your time	The number one tip from experienced spotters was to take your time, go slowly, and don't feel rushed. Finding your own pace is important. Koalas can be very hard to spot and the higher they are in the tree, the more difficult they are to spot. Systematically look around the whole tree and be patient, especially in challenging weather conditions. Sometimes the only way you will spot a koala is when the wind changes a little and you get a different perspective. Don't feel pressured by time. The companies understand the challenges of your job and the importance of it.
Be systematic in your approach and use UAV thermal imaging data as a guide only	Experienced, effective spotters used a very methodical, systematic technique to assess every tree. The techniques employed varied. The most common technique involved assessing two rows at a time by going down the middle, but others zig-zagged between 3-4 rows, frequently looking back as they did. Some started with a boundary assessment using an IR monocular and reviewed UAV data before they began so they had an idea of what to expect in the area. While some noted the advantage of applying multiple techniques (e.g. eye, IR monocular, and UAV data) our results suggest spotters need to be conscious of the potential bias associated with being given the UAV data. The data can provide a useful estimate of how many koalas to expect but It can be tempting when given the output from the UAV-based thermal imaging to just check those koalas, or quickly scan other trees as you walk directly to the tree you expect to find a koala in and then scan adjacent trees if it is not in that tree. This risks missing koalas that the UAV might have missed (e.g. they may have missed koalas halfway down the trunk) or which have moved since the assessment, which is often hours before the spotters are assessing the area.
Check every tree carefully, scanning the whole trunk, not just the canopy	Circle the whole tree and look at it from different angles and different distances Look up at every tree. Don't just check a tree once. Turn around and look at it from different angles. Get in the habit of frequently turning around and looking back. Many inexperienced spotters focus on the top of the tree and while it is more likely at any given point that they are up there, it is important to scan the whole tree as they do move. Scanning from a distance rather than directly under that tree is more effective.
Consider what is reasonable in terms of how many rows you are assessing at one time.	While some experienced spotters claimed it was possible to scan 6 rows at a time, more effective spotters only scanned 2 or 4 rows and only 4 if the trees were less tall and the undergrowth was minimal. Those scanning 4 emphasised the need to scan sideways constantly and said they stopped every 150m to speak with the harvest operator which gave them a mental break. Several spotters noted that it is easy to miss trees if you do more than 2 rows at a time. A zig-zagging technique was recommended if doing more than 2 rows as there was a direct correlation between those

	who scanned only 2 rows at a time and those who detected more koalas. It may take longer but the key is effectiveness, not the shortest time to complete the task. With that in mind, always respect the danger zones when defining your search area,
Use your ears as well as your eyes	Listen for koalas moving up and down trees and across the ground. The koalas not in the canopy are very important to detect because they are more likely to be missed by thermal imaging mounted on UAVs.
If in doubt, assume it is a koala	Using binoculars and IR monoculars to confirm if an object is or is not a koala, can be helpful but if you are unsure if something is a clump of leaves or a koala, assume it is a koala. A false positive is better than the alternative.
Be extra alert when the weather changes.	Koalas often tighten themselves into a significantly smaller space when it is cold and will be more likely to be hunkered closer to the trunk to get warmth – so what you are looking for is quite different. Give yourself time to adjust.
Use IR monoculars and binoculars as part of a systematic approach to spotting.	An infrared IR monocular can help you but it is not a substitute for sound, systematic assessment of a site. Infrared can't see through trees, so even using lots of different angles, means a perimeter assessment alone is not going to be sufficient to assess a site. Binoculars can also be useful to confirm koala sightings but the field of view makes them difficult to use as primary mechanism. A human eye has a horizontal field of view (FOV) of about 135 degrees and a vertical FOV of just over 180 degrees (peripheral vision makes up the remaining 60-70 degrees). The FOV on binoculars or IR monoculars is considerably smaller and decreases as magnification increases. For every 0.5 degree increase in FOV you will see about 8% wider view – so an 8x binocular model is likely more effective for koala spotting than a 10x model. Typical thermal IR monoculars have a field of view of 8.8 x 7.0 degrees so again are more effective than your eye in spotting close detail but can be less effective in systematically scanning an area.
Start the day rested and take regular breaks.	Breaks are vital. Take regular breaks, even if you don't feel you need one in terms of physical tiredness. If you haven't spotted a koala for a while, it may also be a sign that you need a break. Our brains are not designed for extended precise observation, so breaks will enhance your ability to stay alert. Several spotters also listed their top tip as getting plenty of sleep the night before to be more alert.
Understand the value and limitations of your tools	Most spotters reported that in daylight they just used their eyes but the IR monocular was very useful in early morning, overcast days, and at night. Some spotters did use the IR monocular in the daytime but generally just to help them confirm if something was indeed a koala. It was noted that because of the limitations of IR, IR monoculars were not particularly effective on hot days. Some spotters reported the IR monocular gave them some eyestrain. Many people found binoculars useful to confirm objects they had detected and recommended only using them from a distance, not directly under the tree.

	Most spotters noted that the commercial drone missed koalas below the canopy and suggested that koalas move more than literature suggests so the time between UAV flight and spotting commences is an issue but they felt the data was very useful to get a ballpark figure of how many koalas to expect.
Listen to suggestions but be wary of adjusting your approach	There is always a temptation to look for patterns in koala behaviour but assumptions on behaviour should not bias your search effort. For example, if you expect to find koalas on the boundaries you are probably looking more carefully (and have the advantage of being able to view from a distance) and hence more likely to spot koalas. Some common observations that were noted by multiple spotters included: • on colder days in the late afternoon koala tend to be at the top of trees to get the last sun and during the day tend to be lower down to shelter in the trees; • koalas follow the sun so in the early morning they are often on the eastern side of the tree; • when the weather is colder they often ball up so appear significantly smaller; • koalas are more likely to use large blue gums close to native forest than small blue gums further away so there may be more in the edges of forest compartments.
Consider the impact of the weather and adjust accordingly.	The weather can have a major impact on the ability of spotters to detect koalas. One spotter noted that at times the leaves can glow the same colour as the koala's bottom adding to the difficulty of detecting it (as often the lighter colour on the koala's bottom and chest are what it most noticeable to the human eye). Some spotters noted that it can be harder to focus on objects in the trees if it is too sunny, if the sun is coming from the side, or if is it too windy because the canopy closes up or swirls. Windy conditions often result in the koalas being more huddled and closer to the main stem. On the other hand, a bit of wind was considered helpful as it puffs the leaves out and makes it easier to spot koalas. Experienced spotters recommended that is you can't wait for better conditions, it is important that you take extra time when conditions are sub-optimal so you don't miss any koalas. It was also noted that extreme weather, too hot and especially too cold, takes its toll on a spotter's ability to concentrate. Appropriate clothing and frequent breaks were considered especially important in such conditions.
Take time to ensure your recording is accurate and precise	Understandably, given the nature of the work, it is easy to lose track of exactly which tree you are looking at. Added to that GPS readings within forests are notoriously problematic. However, it is important that spotters take time to accurately record their location using an appropriate tool and format. Our research suggested some spotters used different data formats and recorded numbers incorrectly (it is noted that this problem was negligible in the second trial when the importance of this was emphasised to each spotter). Although the ProofSafe app spotters use when

	doing this for non-research purposes helps minimise this problem and the use of multiple spotters means detecting the error is relatively simple, it is recommended that frequent reminders about the importance of data accuracy are provided.
Keep yourself safe	Safety has been consistently noted as the number one priority from all parties for the duration of the project. All spotters commented that they felt safe in this role and that they felt very well supported by excellent policies on safety. They felt they had good PPE and noted that the machine operators had greatly improved in the tolerance they demonstrated towards spotters, especially female spotters. Most did recognise there were inherent risks in what they were doing. They noted concern about snakes and tripping hazards but felt in terms of the process of the operation itself they were safe. Although policies seem well developed, it was noted by some spotters that certain conditions were problematic and needed extra attention. For example, where the understory is especially dense, any job that requires looking up for large periods while walking with a pack full of gear is inherently more risky.
Monitor koalas systematically	In high koala density sites it may be necessary to use additional resources to support monitoring of koalas detected. It was noted that one spotter may have to keep an eye on 10-12 koalas which is a very challenging task. Additional spotters may need to be used for this task, or a technique developed so appropriate cameras can be located at specific trees and monitored via a single device.
Commit to continual improvement	The most effective spotters were those who were looking for ways to improve their technique. They were comfortable providing feedback to the operator and were willing to ask other spotters for ways to improve.

Overall Evaluation

The new methods developed and tested as part of this project were compared to the main current methods based on the following seven criteria.

- Safety
- Accuracy
- Reliability
- Cost
- Efficiency
- Current ability to provide real time data
- Likely future improvements

This evaluation is presented as Table 15 and suggests the UAV mounted MOBIVLS technique has the greatest potential. A more detailed discussion of each method in relation to the criteria is provided.

Table 15: Comparison of Detection Methods Tested in Field Trials

Method	Safety	Accuracy	Reliability	Cost	Efficiency	Current ability to provide real-time data	Future Improve-ments
UAV-mounted MOBIVLS	High	High	Moderate	High	High	Moderate	High
Ground-based infrared	Low	Low	Moderate	Moderate	Low	Moderate	Moderate
Commercial UAV infrared	High	Moderate	Low	Moderate	High	High	Moderate
Spotters	Low	High	Moderate	Moderate	Low	High	Low
Augmented spotters	Low	Low	Moderate	Moderate	Low	High	Moderate

1. Safety

The two UAV-based methods offer considerable safety improvements over all ground-based methods, as they are not reliant on anyone being in the forest for koala detection. Any method requiring people to be in the forest during harvesting operations (spotters, augmented spotters, ground-based infrared) is considered to be inherently high risk.

2. Accuracy

UniSA's UAV-based MOBIVLS technique was significantly more accurate than all other methods (see Tables 9 and 10). Ground-based technological methods including UniSA's wearable infrared rig, and augmented spotters (i.e., those using technological aids such as infrared monoculars) were helpful as they provide a valuable confirmation tool for the spotters. It is recommended the accuracy of the wearable IR rig be re-tested following several changes: (1) the hardware and software needs to be re-designed to make it easier to carry and use in the forest environment: (2) protocols need to be developed for effective use of the technique: and (3) the users need to be trained how to use it before the testing occurs.

3. Reliability

For this study, reliability referred to whether the methods could be used (without significant loss of accuracy) under a wide range of climatic conditions, as infrared technologies have historically had limited use in warm weather. While the UniSA UAV-mounted method has successfully overcome this temperature limitation (working well in warm conditions – unfortunately we never got the hot conditions we were hoping for when in the field) use of the drone is still restricted by rain and high wind speeds.

The commercial UAV is similarly restricted by rain and wind, and by warm temperatures, ideally being used prior to sunrise. Thus, it offers reduced reliability in comparison to the UniSA drone.

The most reliable method is the non-augmented human spotter, who has no reliance on technologies that cannot be exposed to rain or high temperatures.

4. Cost

All tested methods require an initial investment, as well as ongoing costs for koala detection. The highest cost methods are those with expensive equipment that require trained personnel for ongoing use, such as the UniSA drone ($60,000) which requires an authorised drone pilot ($1200 per day). However, outsourcing detection to an external company would negate the need for this high initial investment (as per the "moderate" cost of the commercial UAV ($260/hr including pilot).

Spotters are comparatively less expensive in the short-term. Spotting has been estimated at an average rate of $58 per hour[1], per spotter, with the assumption that two spotters are generally used at each site (approximately $1160 for a typical ten-hour day, plus overtime). This equates to about $50,000 per month for koala spotting per block, with each company harvesting up to seven blocks per month. In addition, forestry companies spend additional money training each spotter prior to commencing spotting work. While we say this is less expensive, it is a significant cost. If you estimate spotting costs $\$1.5/m^3$, if stumpage was only $\$10/m^3$ spotting costs would represented 15% of costs[2].

5. Efficiency

UAV-based detection methods are more than 10 times faster than ground-based methods. A drone can survey 5ha of forest in 15 minutes, versus an average of 3 hours for human spotters.

Although all augmented spotters have been grouped in this table, certain forms of augmentation resulted in faster spotting (i.e., having maps of koala locations from the commercial drone decreased the time it took to conduct spotting) however, this also resulted in decreased accuracy.

---

[1] This reflects cost to company, not what individual spotter is paid. This cost was an agreed-on average from forestry companies and was current at the time of revision of this document but will likely have increased by time of publication.

[2] The stumpage price varies. During the project stumpage was approx. $\$35/m^3$ but was $\$10/m^3$ in 2014.

6. Ability to currently provide real-time data

While the two methods developed by UniSA were experimental for the purpose of testing showed great promise, they need to be optimised in terms of software and hardware to provide real time data. Any future phases of the project should focus on improving and refining the methods for real time tasks so they can be ready to be used by industry. Until the automated methods are further refined and commercialised, the industry will remain dependent on the existing methods,

7. Future improvements

All drone-based methods offer the greatest potential for future improvement, as technological progress will be seen in both hardware (drones, sensors) and software (image processing, algorithms) in years to come.

There is some potential for improvement in koala detection using human spotters. These are summarised in Table 14.

The final objective was to develop and communicate recommended changes to koala management in blue gum plantations. These are presented in the following section.

Discussion

The following section comprise a summary of the key findings, a discussion of those findings in relation to the project objectives and a set of recommendations for forest managers.

Summary of key findings

The techniques developed for the project: Multi-scale Object Bio-Inspired Vision Line Scanner (MOBIVLS), and the Automated Koala Counting and Geolocation Algorithm (AKCoGA) were effective in koala detection and geolocation and represent a significant improvement over existing methods. In summary:

- The new BioVis technique (MOBIVLS) developed for this project was able to detect low contrast and weak heat signatures in highly cluttered environments, such as forests, more effectively than the best current automated detection systems.
- The MOBIVLS technique facilitated a 20.5% improvement in detection over the second best method and a 27% increase in object detectability over the third best method.
- Together the newly developed automated MOBIVLS and AKCoGA techniques can provide an accurate, and reliable, three-dimensional location of the koalas and suppress the false alarms that were particularly prevalent using alternative methods.
- Stems and canopy can significantly impact detection. It was found that in 40% of images, even with the enhancement generated via the technique, koalas were fully occluded (not detectable) and hence the stitching of multiple images from different angles was needed to reduce the probability of missing koalas.
- All analyses confirmed the superiority of combining the MOBIVLS and AKCoGA techniques over alternative detection methods.

While these techniques met the key project selection criteria for an effective koala detection technique in terms of improved safety, accuracy, reliability, and likely future improvements, further research is needed to operationalise the technology and provide cost-effective real-time data, including the automatic updating of koala locations on digital maps.

Discussion of Results

The first objective sought to evaluate traditional methods and emerging technologies for the detection of koalas in blue gum plantation based on seven criteria: safety, accuracy, reliability, cost, efficiency, the current ability to provide real time data, and the likelihood of future improvements. The evaluation suggested thermal imaging had the greatest potential because of its accuracy, reliability, efficiency and likely improvements, as well as the fact that it provided a method that did not involving putting more people in the forest during harvesting, so was considered safer. At this point, the use of hyperspectral data, passive acoustic monitoring, trap cameras, doppler radar and LIDAR – as stand-alone methods, did not provide sufficient accuracy and/or efficiency.

Spotters were considered the only other accurate method, and while safety and reliability remain challenges, it was noted that distinct improvements had occurred since the beginning of the project. In terms of safety positive outcomes included:

(a) forest companies have developed stronger and clearer polices related to safety; and

(b) spotters perceived themselves to be safe and felt empowered to make decisions and seek support if at any point they did not feel safe.

Any forestry job involves inherent risks and these are exacerbated if you are in the field during a harvesting operation. No amount of PPE and policy will eliminate all risk, but it seemed the companies had made significant improvement in retaining quality spotters through acknowledging their value and demonstrating their support. Reliability was an issue with spotters in both field trials. Although in both cases, it was only one spotter (a different individual in each case) who had particularly poor results, the overall results highlight the fact that this is a challenging job. Poor technique, or a short lapse in concentration in this role can have significant implications. The professionalism demonstrated in terms of preparation, time taken, dedication to the job and willingness to help others, was notably higher at the third trial compared to the first. This was reflected in more consistent results despite a more difficult landscape to work in at both Morgan-Paylor and Dyson. The use of binoculars and IR monoculars as a tool to verify obscured koalas was also more prevalent in the third trial compared to the first. A key metric to highlight is the time taken per hectare by the spotters. The more thorough job done by the spotters in the third trial is reflected in longer times assessing the forest. This has implications for the future management of detection because the main way to improve spotting appears to be to use more spotters and to have all spotters take a slower, more methodical approach, which does necessarily mean spotters will be in the forest for longer, exacerbating the safety risk. As such attention in the project was focussed on improving thermal imaging techniques but it is important to note that spotters will remain an integral part of koala detection in the immediate future, so even small gains in improving their reliability are important.

Key tips for improving koala spotting are included in Table 14. The diverse techniques being currently used by spotters does suggest this is still an emerging field where this is not yet consensus on the best approach. Presently it does appear training is highly reliant on working with an experienced spotter and shadowing them. Extending this type of training and augmenting it with some structured support system may assist in developing more effective spotters. One possible system that could assist in improving skill development is through virtual or augmented reality programs specifically designed to develop koala detection skills. Increasingly VR/AR is being used to improve training and research has highlighted its potential to improve learning outcomes (e. g. Molan and Weber, 2021). In the context of koala spotting, VR could highlight key problematic situations such as different weather conditions and changes in seasonal behavioural that are not possible if simply shadowing an expert spotter over several consecutive days. It could also provide accuracy ratings and an automated report on areas that need more attention, for example, scanning the whole tree rather than just the canopy. Like the augmented tools used in Flaim (a fully immersive VR learning solution for training fire fighters, see flaimsystems.com), the use of binoculars and IR monoculars could be incorporated into the training tool to enhance the use of the tools and provide real time feedback on their suitability in given situations.

The second objective involved developing, testing and evaluating detection methods considered to have the greatest potential to achieve the project aims. This project showed the MOBIVLS technique was more accurate than the 11 other similar cutting-edge techniques that could be used. The use of spotters is a slower technique that has inherent safety risks. However, in the immediate future, spotters are necessary, and will likely still be necessary to monitor koala movement, even if an automated detection system is introduced. Many spotters demonstrated excellent ability in koala detection. However, results were not consistent amongst spotters and there was substantial variation in techniques.

The final objective was to discuss implications and make recommendations related to koala detection in blue gum plantations. These are listed below.

Implications for Management

Timely UAV assessments needed due to koala movement in blue gum plantations

The results suggest a number of important implications for planation management in koala areas. Firstly, the time elapsed between monitoring using a UAV and koala spotting commencing, needs to be minimised. The site with the highest accuracy, also was the site where less than an hour elapsed between the UAV monitoring and koala spotting commencing. It is policy of companies in the area to minimise this time but for a variety of reasons this did not happen at every site. The results from the delayed sites do however provide strong evidence as to the importance of timing. While we had evidence to suggest there was movement of up to 60% of koalas between a pre-survey UAV flight conducted 2 days before the survey to assess density and one done immediately preceding the survey, it seemed there was often significant movement even within hours of the UAV assessment. This has obvious and important implications for harvesting operations. If a surveying operation takes several hours to be undertaken by spotters there is a high likelihood of koala movement before spotters vacate the area and the logging operation can commence. In contrast, UAV flights are much faster, hence minimising the time between survey and harvesting. Additionally, because there are minimal safety concerns running both operations simultaneously, depending of course on the location of the drone operator relative to the harvesting machine, once the system is fully operational it would be possible to commence logging after the first section has been surveyed and spotters are in place to monitor the koalas detected.

Project staff and several spotters noted that koalas in blue gum plantations may change trees more frequently than those inhabiting native forests. Although we did not measure this, increased movement could be due to several factors including the higher levels of disturbance in plantations, the chemical composition and nutritional value of blue gum foliage that influences the duration and timing of koala feeding bouts, or koalas searching for comfortable roosting locations. Regardless of the mechanism, increased movement has significant implications for the effectiveness of detection and monitoring methods. If detection relies on UAVs, koalas may move from their initial location during the time that elapses between detection and monitoring by spotters. Additionally, the potential for koalas to change trees makes it difficult for a spotter to monitor more than one koala at a time. This finding suggests that attention needs to be directed to improving both detection and monitoring to optimise koala welfare.

Time of harvest

It is also likely that the height of the trees and the understory/terrain in the plantations impacts the detection accuracy of spotters. This poses a logistical challenge for forest companies who often delay the harvesting in high density koala sites but the resulting taller trees may make detection by spotters more difficult. Coupled with this, greater amounts of weeds or general undergrowth that accumulate in that period can also make spotting more challenging.

Limitations of UAV-based infrared koala detection

Although UAVs offer a safe and efficient method of koala detection available, the commercial option was not detecting all koalas every time, does not work well in the heat (and so is typically conducted earlier than operations and spotters commence which creates a problem of data accuracy when there is movement of koalas). In addition, the commercial UAV was not able to detect koalas below the canopy, which is concerning, especially if the movement of koalas is greater than expected. The model developed for the project is not yet usable in a commercial forestry context because it lacks the ability to provide real-time data to foresters. This means efforts to improve human spotting in the immediate future and to retain those spotters with outstanding skills is vital. It also points to the need for increased funding to operationalise the automated detection methods developed for this work.

Improving safety and retention of spotters

While UAV-based methods continue to be developed and improved, forestry companies can take immediate steps to improve safety conditions and retention rates amongst ground-based koala spotters. It was noted that attention to this issue through improved policy and training had occurred through the project. It was noted that the pay rates, security, and hours of the spotters were diverse. While some of this is to be expected given the nature of the work, attention to further professionalising the role of spotters could have long terms benefits. Adherence to policy and use of PPE was high amongst all spotters but it was noted by several spotters at Dyson that it was difficult to do their job well when the understory was so challenging. Attention to the terrain (possibly through spraying, mulching or even cool burning to reduce weeds) is one area that could result in safety benefits. More regular breaks could also benefit safety but spotters noted there was a threshold between focus and breaks, and this is likely quite dependent on individuals. It was positive to hear spotters were not feeling pressured to rush their survey as this slower pace is important for some safety outcomes (e.g. reducing tripping) as well as increased detection accuracy.

Summary of Recommendations

Recommendations related to the use of thermal imaging

- Recognise that although thermal imaging offers great potential, it is not a panacea.
- Conduct further research to improvement the ability of thermal imaging to detect. The current commercial UAV methods is not detecting these koalas which poses a problem if some other assessment, such as spotters, is not used.
- Direct research attention towards developing a IR camera that is integrated into harvesting machine that provides a clear visual output of where koalas are and signals an alarm if the koala in within range of the harvesting head.
- A visual camera could be added to the thermal payload and used to verify detections, hence further reducing false positives.

Recommendations related to use of UAVs for koala detection

- Reduce the elapsed time between UAV assessment and commencing spotting to 1h or less to decrease the probability that koalas have moved.
- Use multi-rotor UAVs rath than fixed wings as they tend to have less problem with raptors possibly because they look less like prey.
- Consider waiting or flying the UAV above raptors if they are in the area, to reduce the likelihood of interference.

- Fly over the plantation, with the camera aiming directly downwards rather than at an angle. Flying at an angle may help with a visual camera, and to reduce occlusion in some instances, but it will decrease the ability of an IR camera because it won't be maximising the overlap between images.

Recommendations for spotters

- Accurate spotting takes time and requires a methodical approach. It is critical that spotters don't rush and that they thoroughly assess each tree.
- Continue to provide sufficient spotters to accurately assess an area, and monitor the koalas found. Monitoring multiple koalas at once may fail to detect koalas moving between trees so additional resources need to be provided for this purpose. A formal check-re-check process should be applied when detection notes are not matching.
- Continue maintaining respectful communication between spotters and harvest machine operators to minimise the pressure on spotters to rush their assessment.
- Continue the use binocular or IR monoculars to assist visual identification of koalas but recognise they are likely not effective as a primary means of spotting.
- Continue to pair inexperienced spotters with experienced spotters and use experienced spotters as mentors.
- Consider the use of more structured, and scaffolded training programs, including the use of VR to expose spotters to a range of challenging situations such as glare, low light and seasonal changes.
- Continue to provide UAV data to spotters if requested, but stress that the number is likely +/-30% and the data shouldn't be used to accelerate the spotting process by targeting specific trees, but rather should be used to verify data as part of a thorough and systematic visual assessment.
- Improve security of income for spotters by reducing the number of spotters on casual contracts and providing alternative work within the industry when spotting is not needed.
- Acknowledge the actual function of the job in the title. We recognise the challenges in this recommendation as the term "spotter" is widely used in policy and strategy documents. However, semantics can be important, and we believe it is worth considering. For example, the term "Compliance officer" may be perceived quite

differently than the term “koala spotter”. This would clarify the intention of the Forest Industry in tackling this issue professionally; it would enhance respect for the people doing this role amongst people in the harvest operation and it would promote a sense of pride in the profession amongst detection specialists.

Recommendations related to safety

- Continually work to improve and communicate policies.
- Continue to foster a supportive culture where spotters are encouraged to provide feedback on safety issues and are empowered to make choices to enhance their safety.
- Invest in further research designed to minimise the number of spotters required by improving the accuracy, reliability and timely operational ability of developing technologies.

Recommendations for Future Research

The results suggest the UAV technology is promising but the time between flights and koala spotter surveys needs to be minimised. It needs to be viable in hot weather and must detect koalas that are part-way down the tree or on the ground. The MOBIVLS version works well but the need for real-time data is imperative, as is the development of an easy to module that can be readily purchased and used by commercial UAV operators.

The ground-based systems showed sufficient potential that discussions about the possibility of embedding such as system in a harvester occurred. Embedding sensors in harvesters is challenging for a range of reasons (e.g. different makes and model of harvester; instrument overload, space and rigour) but a future focus on this is important as it could streamline the detection process, increase efficiency and importantly increase detection accuracy as the assessment would be closer to the actual felling and hence there is less time for koalas to have changed location. It would also reduce the need for as many spotters on the ground. While spotters perceive the role is safe and the policies are good, it is still hazardous to have people in the field during the harvest operation. Currently the approach has been to increase the number of spotters to increase accuracy and therefore decrease risk to the koalas, but ideally an effective system that minimises risk to both humans and koalas is needed and this may be achieved through embedding sensors in harvesters. This would require major investment but is possible and the technology developed may have applications in other areas of wildlife management. We recommend that investment be made to refine and optimise the mathematical functions used by the detection products developed for this project (MOBIVLS and AKCoGA) to allow robust, automated aerial and ground-based koala detection in eucalypt plantations during the day. We further recommend the creation of prototype hardware to execute the bio-vis computations and present detections in real time; as well as examining concepts of use for the prototype hardware for integration into harvesting operations. Work on all these three recommendations would need to occur concurrently, with emphasis progressively shifting through them over the life of the project, noting outcomes from each activity are both dependent upon, and driven by, the others.

The idea of a decision-making tree or an app to assist in decision making was discussed at several steering group meetings. Preliminary thinking on this idea is shown in Appendix 3 and it may be possible to progress this idea in the future when there are more detection alternatives. At this point, the only real alternative to UAV mounted IR cameras is spotting by eye or with augmented assistance, or not harvesting the site.

Conclusions

The need for accurate detection of koalas in blue gum plantations has been a challenge for over a decade. The forest industry has responded to that challenge by employing a multi-pronged approach of human koala spotters and thermal imaging data. This project represents a coordinated approach to evaluate current methods and develop new and improved methodology for koala detection. While the project was impacted by the COVID 19 pandemic, it was encouraging to see the distinct improvements over the course of the project in terms of spotting ability, policy improvements and application of technology. However, it was clear that the problem is still a significant one. The onus on spotters to maintain concentration over long periods while navigating uneven surfaces and variable weather conditions is problematic. Our results showed that even experienced spotters have bad days. The focus on marking a tree as a potential koala if in doubt, has certainly assisted in reducing the number of incidents, but the technique is problematic for three fundamental reasons, none of which are likely to change in the immediate future:

(1) The human eye struggles to see small, often obscured objects in low contrast, high clutter environments.

(2) The executive function of the human brain doesn't deal well with a repetitive, independent task like koala spotting. While taking breaks helps people to maintain concentration, momentary lapses of concentration are likely given the nature of the task. Many spotters reported they have developed strategies to help concentration, but many also admitted how challenging the task can be if you didn't have the right "head set" on a given day.

(3) There are inherent safety risks of working in a forest environment and these are exacerbated during the harvesting operation. There have been multiple measures put in place to improve safety and empower spotters to make decisions related to their personal safety, but there is limited potential to improve on what is already being done.

Our review of potential koala detection techniques suggested, (a) spotters will remain an integral part of koala detection in the immediate improvement, and (b) use of thermal imaging technologies holds the most potential. We therefore examined ways human spotting could be improved (e.g. via augmented technologies such as IR monoculars) but focussed primarily on the development and testing of improved technologies related to IR imagery.

This project developed new technologies that suggest great potential for the future of koala detection: the Multi-scale Object Bio-Inspired Vision Line Scanner (MOBIVLS), and the

Automated Koala Counting and Geolocation Algorithm (AKCoGA). Although at this point they are not operationally useful to industry in terms of ability to provide real-time data using an existing commercial UAV contractor, they represent a significant improvement over existing methods for koala detection and geolocation. MOBIVLS was compared to 11 different automated detection system and was superior in its ability to detect low contrast and weak heat signatures in highly cluttered environments, such as forests.

While the MOBIVS and AKCoGA techniques met many of the key project selection criteria for an effective koala detection technique (safety, accuracy, reliability, likely future improvement), further research is needed to operationalise the technology and provide cost-effective real-time data. The role of spotters therefore remains critical. Many koala spotters demonstrated outstanding skills in observing koalas in difficult circumstances and importantly provide real-time data. The management of and support of koala spotters also improved notably over the course of the project. Spotters were more confident that they could take as much time as needed to do their job well; were often using binoculars or IR monoculars to confirm sightings when necessary; and were confident that the preference of all parties was to mark a tree as having a koala present if there was any uncertainty regarding an observation. Koala spotters will still play a necessary role in the foreseeable future for monitoring the movement of koalas in a compartment during harvesting, but the improved detection technology could reduce the number of spotters required, and hence reduce the inherent risks associated with being in the forest during a harvesting operation. A set of tips to assist spotters based on interviews with spotters and consultation with other experts is presented as Table 14.

Industry benefits

The MOBIVLS and AKCoGA techniques provide an accurate and consistent means to detect koalas. With further development, it will provide a real-time solution for the forest industry which is cost and time effective. While specific issues, such as the maximum distance of a koala below the canopy that still allows accurate detection; and the temperature threshold of the technique require further investigation, the research team is confident the techniques are a significant improvement upon alternative methods.

The report provides recommendations for future development of the MOBIVLS and AKCoGA system, including potential integration into harvesting machines. Potential benefits of this integration include streamlining the process, reducing risks associated with the movement of koalas between detection and harvesting, and reducing the need for people in the field during harvesting. To gain full benefit from this research, further investment is required. Specifically, more testing in hot weather conditions; commercialisation to ensure real-time data and to streamline the size and weather-proof the payload. Ideally, we envision the system to be a "plug and play" system that can be placed on a harvesting machine, a drone, or an autonomous vehicle that moves through the forest. In each case, the algorithm would require adjustments and re-testing to ensure accuracy.

Koalas detection will remain an important component of the future blue gum plantation industry. Continued commitment to research and innovation will be necessary to protect Australia's iconic koalas.

References

ABARES [Australian Bureau of Agriculture and Resource Economics and Science]. (2023). Australian Plantation Statistics 2023 Update. Canberra, Australia, Australian Government. 10pp.

ABARES [Australian Bureau of Agriculture and Resource Economics and Science] (2016). Australian plantation statistics 2016. Canberra, Australia, Australian Government**:** 1-45.

ABARES [Australian Bureau of Agriculture and Resource Economics and Science]. (2018) Australian plantation statistics 2016. Canberra, Australia, Australian Government**:** 1-21

ABC [Australian Broadcast Corporation]. (2013). Woodchip giant Australian Bluegum plantations stripped of environmental certification over koala deaths. https://www.abc.net.au/news/2013-10-28/koala-deaths-trigger-apology-from-timber-giant/5050784

ABC [Australian Broadcast Corporation]. (2022). Victorian wildlife advocates call for moratorium on blue gum harvesting to protect koalas. https://www.abc.net.au/news/2022-09-18/victoria-bluegum-plantation-koala-moratorium/101448486.

AFPA [Australian Forest Products Association]. (2020). Pre-budgets submission to Federal Government. January 29, 2020.

Aghaziyarati, S., Moradi, S., and Talebi, H. (2019). Small infrared target detection using absolute average difference weighted by cumulative directional derivatives. *Infrared Physics & Technology*, 101, 78–87.

Albert, C., Luque, G. and Courchamp, F. (2018). The twenty most charismatic species. *PLOS ONE* 13(7): e0199149.

Ashman, K., Rendall, A., Symonds, M. and Whisson, D. (2020). "Understanding the role of plantations in the abundance of an arboreal folivore." *Landscape and Urban Planning* 193: 103684.

Cai, Z. and Aguilar, F. (2013). Meta-analysis of consumer's willingness-to-pay premiums for certified wood products. *Journal of Forest Economics* 19(1): 15-31.

Carver, S. (2016). The Koala, an Iconic Animal under Threat. *Journal of Wildlife Diseases* 52(2): 197-198.

Chen, C., L., Li, H., Wei, Y., Xia, T. and Tang, Y. Y. (2013). A local contrast method for small infrared target detection. *IEEE Transactions on Geoscience and Remote Sensing* 52 (1): 574-581.

Conservation Regulator. (2023). Minimising impacts to koalas in blue gum plantations. State of Victoria: ISBN 978-1-76105-154-8.

Cork, S. J., Clark, T. and Mazur, N. (2000). Introduction: an Interdisciplinary Effort for Koala Conservation. *Conservation Biology* 14(3): 606-609.

Corcoran, E., Denman, S., Hanger, J., Wilson, B. and Hamilton, G. (2019). Automated detection of koalas using low-level aerial surveillance and machine learning. *Scientific Reports*. 9(1): 3208.

DELWP 2020, Victoria's bushfire emergency: biodiversity response and recovery, Victorian Department of Environment, Land, Water and Planning, Melbourne.

Deng, H.. Sun, X.,Liu, M., Ye, C., and Zhou, X. (2016). Infrared small-target detection using multiscale gray difference weighted image entropy. *IEEE Transactions on Aerospace and Electronic Systems*, 52, 60–72.

Driscoll, T., Ansari, G., Harrison, J., Frommer, M. and Ruck, E. (1995). Traumatic work-related fatalities in forestry and sawmill workers in Australia. *Journal of Safety Research*. 26(4): 221-233.

Ducarme, F., Luque, G. and Courchamp, F. (2013). What are "charismatic species" for conservation biologists. *BioSciences Master Reviews* 10(2013): 1-8.

Ernst & Young (2016). Meta-analysis of consumer's willingness-to-pay premiums for certified wood products: opportunities and challenges for sustainable growth. Canberra, Ernst & Young.

Foden, W. B. and Stuart, S. (2009). Species and climate change: more than just the polar bear. Gland, Switzerland, IUCN Species Survival Commission (SSC).

Hamilton, G., Corcoran, E., Denman, S., Ellis Hennekam, M., and Koh, L. P. (2020). When you can't see the koalas for the trees: Using drones and machine learning in complex environments. *Biological Conservation* 247 (2020): 108598.

Han, J., Ma, Y., Zhou, B., Fan, F., Liang, K. and Fang, Y. (2014). A robust infrared small target detection algorithm based on human visual system. *IEEE Geoscience and Remote Sensing Letters*, 11, 2168–2172.

Johnson, R., O'Meally, D., Chen, Z., Etherington, G., Ho, S., Nash, W., Grueber, C., Cheng, Y., Whittington, C., Dennison, S., Peel, E., Haerty, W., O'Neill, R., Colgan, D., Russell, T., Alquezar-Planas, D., Attenbrow, V., Bragg, J., Brandies, P., Chong, AY-Y., Deakin, J., Di Palma, F., Duda, Z., Eldridge, M., Ewart, K., Hogg, C., Frankham, G., Georges, A., Gillett, A., Govendir, M., Greenwood, A., Hayakawa, T., Helgen, K., Hobbs, M., Holleley, C., Heider, T., Jones, E., King, A., Madden, D., Graves, J., Morris, K., Neaves, L., Patel, H., Polkinghorne, A., Renfree, M., Robin, C., Salinas, R., Tsangaras, K., Waters, P., Waters, S., Wright, B., Wilkins, M., Timms, P. and Belov, K. (2018). Adaptation and conservation insights from the koala genome. *Nature Genetics*, 50(8), pp. 1102–1111.

Lorimer, J. (2007). Nonhuman Charisma. *Environment and Planning D: Society and Space* 25(5): 911-932.

McAlpine, C., Lunney, D., Melzer, A., Menkhorst, P., Phillips, S., Phalen, D., Ellis, W., Foley, W., Baxter, G., de Villiers, D., Kavanagh, R., Adams-Hosking, C., Todd, C., Whisson, D., Molsher, R., Walter, M., Lawler, I. and Close, R. (2015). Conserving koalas: A review of the contrasting regional trends, outlooks and policy challenges. *Biological Conservation* 192: 226-236.

Molan, S. and Weber, D. (2021) *Improving bushfire preparedness through the use of virtual reality. International Journal of Disaster Risk Reduction*. 66.

Shi, Y.,Wei, Y., Yao, H., Pan, D. and Xiao, G. (2017) High-boost-based multiscale local contrast measure for infrared small target detection. *IEEE Geoscience and Remote Sensing Letters*, 15, 33–37.

Sudholz, A., Denman, S., Pople, A., Brennan, M., Amos, M. and Hamilton, G. (2021). A comparison of manual and automated detection of rusa deer *(Rusa timorensis*) from RPAS-derived thermal imagery. *Wildlife Research* 49 (1)): 46-53.

Wei, Y., You, X., and Li, H. (2016). Multiscale patch-based contrast measure for small infrared target detection. *Pattern Recognition*, 58, 216–226.

Weston, M. and Gannon, P. (2014). Corrective Action Verification Audit (CVA) Report. Victoria, Rainforest Alliance.

Winsen, M., Denman, S., Corcoran, E. and Hamilton, G. (2022). Automated detection of koalas with deep learning ensembles. *Remote Sensing* 14 (10): 2432.

Whittle, L., Lock, P. and Hug, B. (2019) Economic potential for new plantation establishments in Australia: Outlook to 2050. ABARES research report, Australian Government, Canberra, 72pp.

Acknowledgements

Funding: This project was funded by the National Institute for Forest Products Innovation (NIFPI) with support from the Australian Bluegum Plantations, PF Olsen, Midway Limited, South West Fibre Pty Ltd, SWF and Green Triangle Plantation Forest Company of Australia Pty Ltd.

We gratefully acknowledge the following individuals for their valuable contributions to this project.

Steering committee: Martin Clark, Phillip Dohnt, Anthony Walsh, Rohan Eyre, Philip Dohnt, Braden Jenkin, Garth Turner, Joel Turner, Clint Larkins

Jim O’Hehir, UniSA

Aaron Melville-Smith, Flinders University

Ian Hough and staff at Cleland Wildlife Park and Koala Life

Steve Andriolo, Chief RPAS pilot and director of Eyesky

Chris Lafferty and Jarrod Gooden, Forest and Wood Products Australia

Dave Patience, Australian Bluegum Plantations

Allie Muneri, Victoria Stack and Tammy Doherty, PF Olsen

Tammy Auld, Timberlands

Denis Rose and the Gunditjmara traditional owners

Researcher’s Disclaimer

The Covid-19 pandemic had a major impact on the design of this project. Not as many trials as were planned occurred because of the border closures. We also were not able to plan the weather and no days ended up as hot as we had hoped in order to better gauge the ability of MOBIVLS to operate in hot conditions. However, we were able to make more progress on the development of new tools and techniques to assist in koala detection. 65,000 images later we do have a system that shows great promise in future koala detection. This report presents our best appraisal of current systems based on the data from trials.

Appendices

Appendix 1 – Review of Literature

University of South Australia

NATIONAL INSTITUTE FOR FOREST PRODUCTS INNOVATION

DEAKIN UNIVERSITY

Future Proofing SA Blue Gum Plantations Through Improved Detection of Koalas in Early Planning and Forestry Operations

A literature review

Morgan Schebella, Delene Weber, Desley Whisson, Anthony Finn, Russell Brinkworth, Stefan Peters, Laith Al-Shimaysawee

Table of Contents

Summary

This review of koala research has been written as part of a NIFPI-funded study investigating improved methods for koala detection in commercial blue gum plantations. The review is divided into five key sections and provides a broad overview of existing scientific knowledge related to koalas. This document may act as a reference point for both the research team and industry partners and will strengthen our collective understanding of the species' behaviour, history, threats, and key management challenges, as well as the societal values placed upon koalas. Developing a deeper understanding of koalas across each of these facets is integral to improving their detection and ultimately, their management.

In order to provide a comprehensive review of koala research, the studies included herein are not specific to a forestry context. However, within each section, the reader will find research of relevance to the management of koalas in commercial plantations. At times this research paints a cautionary picture, and at others, hints at the potential for further research or unexplored opportunities, as discussed in the Conclusions section. As this review shows – whether examined from a geographical, biological, historical or political standpoint – koalas and their management are inherently complex.

1. Introduction

Regarded as one of the most recognisable mammals on Earth (Cork, Clark et al. 2000), the koala (*Phascolarctos cinereus*) is undoubtedly an Australian icon. Recently, the koala was ranked by members of the Western public as being one of the twenty most charismatic animal species in the world, outranking species as remarkable as the blue whale – Earth's largest animal (Albert, Luque et al. 2018). *Charisma* – a frequently used yet widely debated term describing a species' "enchanting" properties or overall appeal to humans (Lorimer 2007, Ducarme, Luque et al. 2013) – is of great relevance to conservation and has significant implications for wildlife management. Public attention, or lack thereof, can make or break conservation efforts, which is why animals that naturally appeal to the masses are often used as flagship species to garner support for conservation endeavours. The koala, an official member of the IUCN's 10-species strong 'Climate Change Flagship Fleet' (Foden and Stuart 2009) is one such animal, having been selected in large part for its ability to attract the attention of the global public (Barua, Root-Bernstein et al. 2011). Koalas have featured in popular media since the early 1900s (Bagust 2010); for generations the animal has starred in tourism commercials, children's books, television programmes and public health campaigns; it has been made into a chocolate bar, become the official emblem of the State of Queensland, decorated countless souvenirs, and featured as a mascot for sports teams in Australia and abroad. There is no question that the koala, and any threat to its survival, is observed on a global stage. As Carver (2016, p. 197) explains, "such status and popularity of an animal inherently draws attention from the community" and it is clear that any action by an individual, corporation, or government that places the koala at risk carries "significant national profile".

Consequently, industries operating in close proximity to koalas and koala habitat, such as commercial forestry, have the potential of attracting considerable public attention both domestically and overseas. Potential and actual impacts to koalas as a result of forestry operations are widely reported by mainstream media, animal activist groups, and conservation organisations. In 2013 extensive media coverage of koala deaths and injuries arising from timber harvesting in Australia resulted in significant public outcry and culminated in the suspension of independent environmental certification for one forestry company. In the months following the pervasiveness of both media attention and public affection for koalas was evidenced by the signing of the "Koala's Cry for Help" petition – launched in Germany and signed by more than 83,000 people around the world[3]. In 2017, a second koala-related petition launched by the same organisation – "Save the Koalas' Habitat!" – was signed by more than 210,000 people[4]. Ultimately, in an industry where consumers are becoming increasingly conscious of, informed, and willing to pay for the sustainability of their purchases (Cai and Aguilar 2013, Ernst & Young 2016), and in which companies operate under the watchful eye of a concerned and vocal global public, koalas will continue to weigh heavily on the future of commercial forestry in Australia.

2. Koala behaviour

The koala, endemic to Australia, is a large arboreal marsupial that inhabits forests and woodlands from north-eastern Queensland to south-eastern South Australia (Black, Price et al. 2014). Koalas are highly specialised folivores, largely dependent upon a subset of approximately 70 of Australia's 600+ *Eucalyptus* species to meet their food and habitat requirements (IUCN 2009). However, food preferences vary between regions, and koala populations inhabiting different areas are found to have a distinct and "highly selective diet of only a handful or primary food tree species" (Black, Price et al. 2014, p. 1187). In some areas, koalas will feed on non-Eucalypt tree species, including those in the *Melaleuca* and *Allocasuarina* genera (Moore and Foley 2000), but despite regional and possibly seasonal differences in their diet, *Eucalyptus* forms at least part of the diet of all koalas (Moore and Foley 2000). Given their highly specialised habitat requirements, koalas are thought to be particularly vulnerable to environmental changes such as vegetation clearing and fragmentation, bushfires, and climate change (IUCN 2009, Black, Price et al. 2014, McAlpine, Lunney et al. 2015). Furthermore, the koala's dietary preferences come at a cost: as the foliage of eucalypt trees contains toxic compounds (a chemical defence against herbivory) (Moore and Foley 2005) and is relatively nutrient-poor, koalas expend considerable energy detoxifying ingested leaves and extracting vital nutrients (Ellis, Melzer et al. 2009). As a result, koalas remain inactive for long periods of time; they are stationary for 75% (Ryan, Whisson et al. 2013) to 80% (Martin and Handasyde 1999) of a 24-hour day, primarily moving between trees at night to forage (Marsh, Moore et al. 2014); to seek mates during the breeding season (generally from September to

---

[3] Rainforest Rescue petition: "Australia: the koala's cry for help" [https://www.rainforest-rescue.org/petitions/925/australia-the-koalas-cry-for-help]

[4] Rainforest Rescue petition: "Australia: save the koalas' forest!" [https://www.rainforest-rescue.org/petitions/1119/australia-save-the-koalas-forest]

February) (Ryan, Whisson et al. 2013); and to drink water during periods of high night-time temperatures (Ellis, Melzer et al. 2009).

Despite living largely solitary lives, koalas live in complex social communities and have evolved a range of strategies that minimise resource competition between individuals. For example, not only do koalas rarely share trees with other koalas, they will rarely visit the same tree twice or even visit trees that have been visited by another koala whose home range overlaps their own[5] (Ellis, Melzer et al. 2002, Matthews, Lunney et al. 2007, Ellis, Melzer et al. 2009). It is believed that the energy costs required to actively monitor and defend territory or prevent other koalas from accessing it, far outweigh the benefits of staying in one place, and to this end, koalas are non-territorial animals that "sustain fewer costs by continually shifting locations" (Ellis, Melzer et al. 2009, p. 1186).

As their habitat becomes more and more fragmented due to expanding urban development and agriculture (Shumway, Seabrook et al. 2014), koalas are increasingly required to traverse across the ground, exposing them with greater frequency to some of their most significant threats: vehicle collisions and wild and domestic dog attacks (Griffith, Dhand et al. 2013). Furthermore, greater exposure to such threats is likely to cause elevated levels of physiological stress in koalas – and just as in humans – this may suppress immune function and increase susceptibility to disease (Brearley, Rhodes et al. 2013, Tisdell, Preece et al. 2017), another leading cause of koala morbidity and mortality (Griffith, Dhand et al. 2013).

3. Koala history

The state of Australia's koala population is geographically, biologically, historically, and politically complex (McAlpine, Lunney et al. 2015). The species, which "has one of the longest fossil records of any of Australia's modern marsupial families" (Black, Price et al. 2014, p. 1187), is thought to have once existed throughout most of Australia, with the exception of Tasmania and the Northern Territory (Price 2008). The koala's range contracted severely during the late Pleistocene – when the continent underwent substantial changes in climate and

[5] This natural ranging behaviour of koalas is less prevalent in over-populated habitats (e.g. Mitchell (1990) observed multiple koalas in trees at the same time).

vegetation – and following this, koala population numbers are believed to have been maintained at relatively low levels as a result of Aboriginal hunting and/or fire regimes until the decades following European settlement in 1788 (Black, Price et al. 2014). This subsequent period saw rapid koala population growth, or irruptions, likely as a consequence of European impacts on Aboriginal people and their customs (Jurskis 2017). Whilst "koalas were rare under Aboriginal management" and there was no written record of a single koala sighting during the first 10 years of European settlement (Jurskis 2017, p. 471) and few references prior to 1850 (Black, Price et al. 2014), population irruptions began occuring in New South Wales in the 1830s, in Victoria in the 1860s, and in Queensland at the end of the 19th century (Jurskis 2017). Up until the late 1920's the animals supplied a substantial export fur trade, and in 1924 alone, two million koala pelts were exported from Victoria, Queensland and New South Wales (Black, Price et al. 2014). Although there is no historical record of koala distribution throughout South Australia during this period, they "were by no means uncommon" and were similarly hunted on a commercial scale in the south-east of the state (Jurskis 2017, p. 473). Towards the late 1800's, commercial hunting compounded the effects of habitat loss from urban and agricultural expansion, and the koala's range contracted to the eastern and south-eastern parts of the continent (Black, Price et al. 2014).

In the face of population declines resulting from the combined pressures of habitat clearing, wildfire, and hunting, it was feared mainland koalas would suffer extinction. Between the 1870s and 1890s koalas were introduced or 'marooned' to refuges on Quail, French, and Phillip islands off the coast of Victoria (Menkhorst 2008). Koalas rapidly proliferated on the islands, causing widespread defoliation as their populations reached unsustainable levels (Menkhorst 2008, Black, Price et al. 2014). Between 1923 and 1925, 18 adult koalas and an unknown number of their young were translocated from the seemingly overabundant population on French Island, to an enclosed area in Flinders Chase National Park on Kangaroo Island, off the coast of South Australia (Wilks 2008). Although koalas were believed to be extinct on the South Australian mainland by the 1930s (Jurskis 2017), the koalas on Kangaroo Island – having escaped their enclosure and dispered throughout Flinders Chase National Park – had undoubtedly flourished, and by 1965 there were reports of over-browsing (Duka and Masters 2005). Along with the apparent koala extinction on mainland South Australia, koala populations were thought to have reached very low levels in Victoria and New South Wales during this period. Beginning in the 1940s, thousands of koalas were translocated back to mainland

Australia from Quail, French, and Phillip islands (Black, Price et al. 2014) to both re-establish mainland populations and to prevent "disastrous" population crashes on the islands as a result of over-browsing (Menkhorst 2008). In the 1990s, strategies to reduce the overabundant koala population on Kangaroo Island included the translocation of more than 1100 surgically sterilised koalas to the south-eastern corner of South Australia (Duka and Masters 2005). Today, despite a turbulent history of population irruptions and declines, local extinctions, translocations, and occurrences of overabundance, koalas continue to inhabit a large part of the continent, from Queensland to South Australia.

4. Current status and key threats

The koala has an uneven distribution throughout its range: it is thought to be declining across much of Queensland and New South Wales, with some stable populations, but Victorian and South Australian populations are generally stable, increasing, or overabundant and "actively managed for decline" through sterilisation and translocation (McAlpine, Lunney et al. 2015, p. 230). Given the vastness of the area the species occupies, and the low density of koala populations in many areas, "population estimates at regional, state, and national scales are few and inconsistent" (Jurskis 2017, p. 471). Conducting a comprehensive assessment of koala numbers across the species' range would be an immense undertaking. In general, it is widely believed that the population has declined by more than 50% since European settlement (Melzer, Carrick et al. 2000). However, it has been suggested that estimates of population declines – including those used to secure increased legislative protection for koalas – are based on the false assumption that koalas were abundant at the time of European settlement, when "historical evidence indicates that natural populations were invisible" because they existed in such low numbers, and furthermore, that estimates indicating declines in recent decades from formerly high koala densities have failed to recognise that those populations were irrupting (Jurskis 2017, p. 471). Because of the uncertainty surrounding koala population data, and in recognition of the species' uneven distribution and expected vulnerability to climate change, the koala was listed as 'vulnerable' on the IUCN Red List in 2016 (Woinarski and Burbidge 2016).

Koalas are protected by legislation in all Australian States and Territories, and their management is primarily the responsibility of State governments (Wilks 2008). In 2012, koalas were listed as 'vulnerable' under the *Environment Protection and Biodiversity Conservation*

Act 1999 (EPBC Act) in Queensland, New South Wales (NSW) and the Australian Capital Territory (ACT) – regions where koala populations are believed to have declined substantially in recent years (Shumway, Seabrook et al. 2014). However, prior to its listing in 2012, the koala's status had been assessed on two separate occasions by the Threatened Species Scientific Committee (TSSC), in 2004 and 2007, with both assessments deeming the koala ineligible for listing as a threatened species (McAlpine, Lunney et al. 2015). Upon completion of the second assessment, a national Senate Inquiry into koalas was conducted, and the TSSC subsequently amended its recommendation to enable koalas to be listed as vulnerable under the EPBC Act in only those areas it was considered to be at significant risk of decline, that is, in the northern part of its range and not in Victoria or South Australia (McAlpine, Lunney et al. 2015). According to the listing, habitat loss and fragmentation have increased the susceptibility of koala populations to "drought, climate change and disease… vehicle strike, and the threat of predation by dogs" (DSEWPC 2013, p. 3).

4.1 Habitat loss and fragmentation

The koala's highly selective diet, as discussed previously, limits its ability to find new food sources when habitat loss occurs as a result of urban expansion, agriculture, or wildfire. In order to appreciate the koala's vulnerability to environmental change, an understanding of the animal's specialised habitat needs is required. Koalas are not only selective about the tree species they will feed upon in different regions; they are equally as selective about the individual plants they visit within a given species, and furthermore, the leaves on selected plants that they find palatable enough to consume. Much research has been conducted to identify the characteristics of palatable foliage for koalas, as such knowledge has important implications for habitat conservation and landscape management. The importance of "high quality" forage for koalas is highlighted by the stark differences observed in the size of individuals' home ranges, with koalas in semi-arid (poorer-quality) woodland habitat having home ranges of up to 300 ha in size, whilst home ranges in temperate coastal (higher-quality) forests may be less than 2 ha in size (Ellis, Melzer et al. 2002). Unfortunately, "as yet, no study has identified a single factor that will consistently predict koala leaf preference either across eucalypt species or between individual trees" (Jackson 2007, p. 83), however, a range of attributes have been found to influence leaf palatability. These include nitrogen, phosphorous, and potassium levels in leaves; leaf moisture; fibre and insoluble sugar content; plant secondary metabolites including terpenoids, tannins, and formylated phloroglucinol compounds (FPCs) (Moore, Lawler et al. 2010); leaf age (Ullrey, Robinson et al. 1981); tree girth (Ellis, Melzer et al. 2009); soil fertility (Cork, Clark et al. 2000), and foliar fibre content (Moore, Wallis et al. 2012). All of these factors play a role (to varying degrees, and not consistently between tree species[6]), in palatability, however, FPCs are thought to be "the single most powerful deterrent of koala feeding" (Moore, Lawler et al. 2010, p. 3166).

Given the koala's nutrient-poor, high-toxicity diet – and the behavioural repercussions of it – it is clear that all koala diet choices represent a "tradeoff between toxins and nutrients" (Stalenberg, Wallis et al. 2014, p. 11). A koala may avoid high levels of FPCs by consuming leaves with lower levels of essential nutrients such as nitrogen, however, the disadvantages associated with having to consume "large quantities of gut-filling indigestible tissues" in order to absorb enough essential nutrients for sustenance, mean food decisions must carefully balance the costs and benefits of different foliage sources (Stalenberg, Wallis et al. 2014, p. 12). Koala habitat that is partially cleared (e.g. during the selective harvesting of commercial timber) may deliberately retain specific trees for koala forage, however, given the complexities surrounding koala browse selection, there is no guarantee that retained trees will be viable food sources (e.g. in Stalenberg, Wallis et al. (2014), koalas were found to actively avoid neighbouring trees of the same species as those they fed upon, based on differences in the chemical composition of their foliage, which are not visible to the naked eye). Furthermore, although koalas are not considered to have specialised shelter requirements (Moore, Wallis et al. 2012), their need for non-browse shelter trees becomes more pronounced during times of extreme heat (Crowther, Lunney et al. 2014). Healthy koalas can endure cold conditions, but are not able to cope well in hot weather, during which will they seek out large trees with denser canopies (Marsh, Moore et al. 2014) – an important but often overlooked koala habitat requirement (Crowther, Lunney et al. 2014). When examined holistically, the combined effects of koalas' highly selective diet, the need to minimise energy loss from movement, and the social complexities described in Section 2, demonstrate how habitat loss and fragmentation present significant challenges for koala populations.

---

[6] For example, koalas do not appear to discriminate amongst *Eucalyptus globulus* (blue gum) trees according to leaf nitrogen concentrations, providing they exceed a threshold of approximately 12 m/g (Moore, Lawler et al. 2010).

In recent years, population declines as a result of habitat loss have been most pronounced in Queensland, NSW and the ACT (McAlpine, Lunney et al. 2015). In far south-east Queensland, extensive habitat clearing prior to 1996 caused koala populations to decline long after the period of major habitat loss (populations were estimated to have fallen by 75% by 2012) in what is considered to be a case of extinction debt (McAlpine, Lunney et al. 2015), however, these declines have been debated, as discussed previously (Jurskis 2017). In Queensland and NSW, habitat clearing (and an associated ongoing decline in koala numbers) is expected to result from the continued urbanisation of coastal regions, as well as from extensive agricultural expansion and resource extraction such as open-cut coal mining and coal-seam gas developments (McAlpine, Lunney et al. 2015).

4.2 Vehicle strikes and predation

Although koalas, as a general rule, minimise movement to conserve energy, prevent water loss, and seek shelter from the heat to maintain physiological homeostasis, in most cases they will move trees every day (Ellis, Melzer et al. 2009). This movement frequently occurs via the ground, rather than through the canopy of trees (Ellis, Melzer et al. 2009, Marsh, Moore et al. 2014), and as such, places the animals at risk of being struck by vehicles or preyed upon by wild and domestic dogs. As habitat quality declines, and the distribution of palatable browse trees becomes increasingly patchy as a result of climate change, drought, or bushfire, koala home ranges expand (Ellis, Melzer et al. 2002), likely increasing the amount of time koalas spend on the ground. Analysis of 30 years of data from a koala hospital in New South Wales (Griffith, Dhand et al. 2013), found that trauma – from vehicle strikes and dog attacks – was the most common reason for admission to the facility (41% of all koala admissions) between 1975 and 2004. Furthermore, the researchers found that vehicle strikes increased substantially from 1985, coinciding with a period of time in which the human population of the surrounding area almost tripled. The fatality rate of koalas being struck by vehicles has previously been estimated at 83% (Dique, Thompson et al. 2003), and as such, it is a significant and growing cause of koala deaths. Over the same time period, the prevalence of dog attacks did not increase despite population growth, and the authors posit this may indicate laws surrounding responsible pet ownership have been relatively successful (Griffith, Dhand et al. 2013). However, a recent Queensland study found that while domestic dogs caused only 2.5% of koala deaths, dingoes (and dingo-hybrids) were responsible for 52% of all deaths (Beyer, de Villiers et al. 2018), suggesting dogs will continue to be a key source of koala mortality even if responsible pet ownership legislation is strengthened. A study seeking to ascertain the level of community support for a range of different koala conservation actions – many of which related to pet ownership and driving behaviours – found that while respondents were likely to report participating in beneficial behaviours such as keeping their dogs inside at night and electing to drive slower between dusk and dawn, they were unlikely to accept road control measures to slow driving, such as speed bumps or lower speed limits (Shumway, Seabrook et al. 2014). Furthermore, whilst men and women held similarly positive views about koalas, "men were considerably less likely than women to drive slowly at night or support decreased speed limits in koala habitat areas" (Shumway, Seabrook et al. 2014, p. 50), highlighting the importance of understanding the precursory conditions that facilitate compliant behaviour (e.g. koala-related attitudes and beliefs and the perceived and actual barriers to behaviour change). Little research examining these conditions in the context of koalas has been conducted.

4.3 Climate change, drought and fire

Over the past 100 years, annual average temperatures in Australia have risen, and most parts of the eastern seaboard (where koalas are found) have seen a reduction in annual rainfall (Garnaut 2008). Future climate change predictions for Australia indicate a shift to a hotter and drier climate, increased frequency of drought and bushfires, and elevated atmospheric CO_2 concentrations that will affect plant growth, all of which have direct consequences for koalas (Reckless, Murray et al. 2017). In some areas, such as the Pilliga forests of NSW, stress caused by high summer temperatures is already a major threat for koalas (Kavanagh, Stanton et al. 2007). As temperatures rise, and the frequency of heatwaves increases, koalas will have a growing need for habitats containing suitable, large shelter trees – which are often not covered by the same protective legislation as food trees (Matthews, Lunney et al. 2007) – and greater water requirements that they will find harder to meet through the ingestion of eucalypt foliage. A rise in CO_2 levels is predicted to cause declines in foliage quality, with plants found to produce higher concentrations of toxic compounds and decreased levels of nitrogen when grown under elevated CO_2 conditions (Black, Price et al. 2014). Yet, koalas are "shackled by severe metabolic restraints" (Ellis, Melzer et al. 2009, p. 1186) that will limit their ability to compensate for such changes. In order to survive higher temperatures, they will need to place a premium on limiting water loss caused by movement, for example by resting for longer periods of time in the shade. Furthermore, they will either need to descend trees to drink water more frequently, or modify their foraging activities to seek trees with higher leaf moisture content (Ellis, Melzer et al. 2009), both of which come at an energy cost and place the animals at risk of predation and vehicle collisions. A decline in the nutritional quality of eucalypt foliage will require koalas to consume more leaves by spending additional time eating, or be more selective about the trees they feed on (IUCN 2009), which will also likely result in increased time spent travelling, particularly in fragmented landscapes. As koalas are restricted by the size of their stomachs (IUCN 2009) and the length of resting time required to detoxify ingested leaves, a warming climate will lead to increased koala mortality, either through heat stress, greater exposure to ground-based risks from increased travel time, or through malnutrition.

A drier, warmer climate will lead to increased frequency and severity of bushfires (Garnaut 2019), particularly in areas already prone to frequent fires such as south-eastern Australia (Matthews, Lunney et al. 2016) where koalas are most populous. Although koala populations have been found to recover quite quickly from bushfires (e.g. Curtin, Lunney et al. 2001, Matthews, Lunney et al. 2007), their recovery is largely dependent upon the retention of patches of unburnt habitat, which act as refuges from which the population can be re-established (Matthews, Lunney et al. 2016). Smaller, more isolated, or highly fragmented habitats have much less likelihood of retaining unburnt areas, and as such, the impacts of bushfires on these vulnerable populations can be catastrophic and cause local extinctions (Lunney, O'Neill et al. 2002). As discussed previously, koala habitats are becoming increasingly fragmented, placing koala populations at substantial risk as bushfires become more prevalent. Prior to widespread urbanisation and agricultural development, forest cover in many areas of key koala habitat would have been less fragmented, allowing surviving koalas to repopulate burnt habitats quite easily (Matthews, Lunney et al. 2016). Matthews, Lunney et al. (2016) highlight that the main risk associated with bushfires today is not the number of koalas who are killed in the fires themselves, but the number of neighbouring koalas that are retained in unburnt habitat with the potential to re-establish fire-affected populations. If these neighbouring populations are not in close proximity to burnt habitat, the natural re-establishing populations is difficult.

Hot crown fires can cause a high number of koala deaths. In the 2019-2020 Black Summer Fires, it was estimated that more than 60,900 koalas were impacted[7], and furthermore, a significant proportion of injured koalas that are rescued during bushfires do not survive[8]. However, post-bushfire survival and reproduction rates of koalas that are released after being successfully rehabilitated for burn injuries is found to be similar to that of uninjured animals living in nearby unburnt forest (Lunney, Gresser et al. 2004). Furthermore, as there is an initial period of significantly reduced carrying capacity in burnt forests due to the widespread loss of foliage for food and shelter, the mass, off-site rehabilitation of injured koalas may help to reduce subsequent resource competition amongst koalas surviving *in situ*[9] (Lunney, Gresser et al. 2004) but later relocation may be problematic (see Section 5.2). Many species of Australian plants, including eucalypts, have evolved great resistance to, and even reliance upon bushfires, which can stimulate their growth for decades after being burnt (Mount 1969). Most eucalypts will survive a complete canopy burn and recover well after fire, quickly exhibiting a flush of new growth from lignotuberous and epicormic buds (Matthews, Lunney et al. 2007). In Matthews, Lunney et al. (2007), koalas were observed feeding extensively on the regenerating foliage of burnt trees within three months of a severe bushfire, generally utilising these trees more frequently than unburnt trees. It has been suggested that the epicormic growth of eucalypts offers high-quality feed for koalas, largely due to elevated concentrations of nitrogen and moisture in these leaves, as well as reduced fibre (Moore, Wallis et al. 2012). Thus, although bushfires substantially modify landscapes, resource depletion for koalas is thought to be quite brief, and the animals can rapidly recolonise burnt habitats if there are nearby populations unaffected by fire, or if rehabilitated animals are returned to the site (Matthews, Lunney et al. 2016).

4.4 Disease

For the most part, even where koala populations are stable or increasing, their genetic diversity is low (Sequeira, Roetman et al. 2014) as a result of the many population crashes, bottlenecks, local extinctions, and translocations the species has experienced since European colonisation[10].

---

[7] World Wildlife Fund (2020) 60,000 koalas impacted by bushfire crisis. Accessed online <https://wwf.org.au/news/2020/wwf-60000-koalas-impacted-by-bushfire-crisis/ >

[8] Pers. Comm. Ian Hough (koala vet at Cleland Wildlife Park]and Chris Daniels (CEO Koal Life].

[9] Such endeavours also serve to garner public support and engage local communities, which have broader, long-term benefits for species conservation (Lunney, Gresser et al. 2004).

[10] Research also suggests koala genetic diversity may have been low prior to European settlement, possibly as a result of ancient climatic changes or Aboriginal hunting pressures (Tsangaras, Avila-Arcos et al. 2012).

Low genetic diversity may hinder the ability of the species to adapt to changes in its environment – such as those caused by climate change – and may also be responsible for the limited inability of the koala to resist diseases[11] such as *Chlamydia* and koala retrovirus (KoRV) (Tsangaras, Avila-Arcos et al. 2012). Koala populations may host a range of pathogens, including koala retrovirus (comprising nine subtypes, the four major ones being KoRV-A, -B, -D and -F), trypanosomes, and two strains of *Chlamydia*: *C. pecorum* and *C. pneumonia* (Beyer, de Villiers et al. 2018).

Retroviruses – which may be endogenous or exogenous – have been found in all studied vertebrate species, including humans[12]. Endogenous retroviruses (ERV) are the remnants of ancient retroviruses or "fossil viruses" that have evolved with their host species and become integrated into their genome over a long period of time (Feschotte and Gilbert 2012, Dodou and Whitely 2014). In all known mammalian species, ERVs endogenised millions of years ago, however, KoRV is unique in that it exists as both an ERV and an exogenous virus, suggesting that it has only begun integrating into the koala genome within the past 50,000 years (Quigley, Phillips et al. 2019). Of the nine KoRV subtypes, KoRV-A is the most prevalent and is the only subtype to have become endogenous thus far. The prevalence of KoRV-A ranges from 100% in QLD and northern NSW populations, to an estimated 15-35% on Kangaroo Island (Denner and Young 2013). The less-prevalent KoRV-B is prevalent in 25% of QLD and NSW koalas, while SA and Victorian populations are believed to be KoRV-B free (Quigley, Phillips et al. 2019). Koala retrovirus has been linked to higher incidence of chlamydial disease, neoplasia, leukemia and lymphoma, with "mounting evidence that KoRV appears to be exacerbating and/or promoting these serious health challenges" across the country (Quigley, Phillips et al. 2019, p. 5).

Of the diseases known to affect koalas, *C. pecorum* has received the most research attention by far (Polkinghorne, Hanger et al. 2013). It is thought to have crossed over from introduced cattle and sheep to koalas within the last 300 years, and is the more pathogenic of the two *Chlamydia*

[11] Low genetic diversity is thought to have similarly reduced the ability of the Tasmanian Devil's immune system to recognise and destroy tumour cells, causing population declines of up to 90% as a result of the highly contagious devil facial tumour disease (Wedrowicz, Wright et al. 2017).

[12] The koala retrovirus (KoRV) is an immunosuppressive retrovirus, akin to human immunodeficiency virus (HIV), which causes AIDS (Denner and Young 2013).

species that infect koalas[13] (Wilson, Craig et al. 2015). *Chlamydia pecorum* is predominantly sexually transmitted, but transmission of the infection from mother to offspring also occurs (Fabijan, Caraguel et al. 2019). It is considered by many to be the disease of greatest concern to the long-term survival of the species, due to its impacts on fertility and reproduction (Fabijan, Caraguel et al. 2019). The disease can be debilitating, causing conjunctivitis and blindness, pneumonia, urinary incontinence, urinary tract infections, as well as reproductive tract infections that lead to infertility in both male and female koalas (Fabijan, Caraguel et al. 2019). However, in many cases, koalas may be infected with *C. pecorum* and have no clinical disease (e.g. 28% of *Chlamydia* infected koalas in the Mount Lofty Ranges showed no signs of disease in Speight, Polkinghorne et al. (2016)). In NSW, 20.4% of koalas treated at a wildlife hospital over a 30-year period were admitted with clinical signs of chlamydial disease, including 'wet bottom' or 'dirty tail' and eye disease (Griffith, Dhand et al. 2013). The researchers saw no increase in disease prevalence over that time span, however, they note that subclinical chlamydiosis is common in koalas, and as such, hospital admissions based on clinical signs of disease may underestimate the true prevalence of the infection amongst wild koala populations (Griffith, Dhand et al. 2013). In QLD, it is estimated that 90% of koalas are infected, and severe chlamydial disease is common in these populations (Fabijan, Caraguel et al. 2019). As with KoRV, *Chlamydia* is found to be more prevalent in northern koalas than in South Australian and Victorian koalas, however, *Chlamydia* has been shown to spread quickly, with 93% of *Chlamydia*-free koalas becoming infected within 19 months of translocation to a site containing *Chlamydia*-positive animals (Wedrowicz, Wright et al. 2017). Whilst the population did not display clinical signs of the disease, breeding success fell from 35% to just 6% by the second breeding season[14] (Wedrowicz, Wright et al. 2017).

Infected koalas that are taken into care may be treated with antibiotics (Beyer, de Villiers et al. 2018), however, the use of these drugs can be a great detriment to the koala's gut microflora, inhibiting digestion of eucalyptus foliage and leading to malnutrition or starvation (Nyari, Khan et al. 2018). Treatment with antibiotics may be ineffective in severe cases, and does not protect koalas from subsequent reinfection (Nyari, Khan et al. 2018), and furthermore, the use of antibiotics on a broad scale is impractical, as individuals require daily injections for 14-28 days

[13] *C. pneumonia* infection can cause pneumonia and respiratory tract infections in koalas. It is more commonly found in captive animals, with much lower prevalence in wild koala populations (Fabijan, Caraguel et al. 2019).
[14] Modelling by Wilson, Craig *et al.* (2015) suggests that systematically euthanizing diseased and infertile koalas would result in a larger population after seven years than if these koalas remained in the population.

(Wilson, Craig et al. 2015). For these reasons, a *Chlamydia* vaccine is likely to be a much more effective option for the long-term management of koala populations, and several vaccines are in the process of being developed and tested (Beyer, de Villiers et al. 2018).

Some researchers believe that *Chlamydia* may be a natural population regulator for koalas (Brearley, Rhodes et al. 2013). In high-density koala populations, where habitat is threatened with overbrowsing, *Chlamydia* may simply limit population density; however in highly modified environments where koala mortality is elevated due to multiple risk factors such as predation and vehicle strikes, *Chlamydia* can contribute to population crashes (Brearley, Rhodes et al. 2013). In contrast, Jurskis (2017), dismisses the idea that *Chlamydia* is a natural control mechanism, suggesting that the disease is yet another sign of irrupting koala populations; a consequence of the stress caused by malnutrition in habitats supporting unsustainably high numbers of koalas. Jurskis' argument is two-fold: firstly, in low-density populations, koalas are often infected with *Chlamydia* but free of clinical disease; secondly, in disease-free koalas, a population may double in size within a span of three years, and although this speed is reduced in diseased koalas, populations can still double within 12 years (Menkhorst 2008). Irrupting populations are an indication of ecological imbalance, and according to Jurskis (2017, p. 479) their "decline is inevitable". There are thought to be only two *Chlamydia*-free populations of wild koalas left in Australia, those on Kangaroo Island in South Australia and on French Island in Victoria. The Kangaroo Island population was significantly reduced by the 2019-2020 bushfires that burnt a large proportion of the island.

4.5 Over-population

In South Australia and Victoria, most koala populations are stable, and in some areas, such as Kangaroo Island (SA), The Budjm Bim World Heritage area (Vic) and Cape Otway (Vic) populations have reached unsustainable numbers that are actively managed for decline (McAlpine, Lunney et al. 2015). In those regions, the establishment of commercial eucalypt plantations has played an integral role in population growth, particularly where those plantations replaced previously cleared agricultural land (Ashman, Rendall et al. 2020). Such plantations are thought to make semi-cleared landscapes more permeable for koalas (Lee, Ellis et al. 2013, Law, Chidel et al. 2017), and as such "provide valuable resources to wildlife by increasing the area of habitat and connectivity, thus facilitating an increase in abundance" (Ashman, Rendall et al. 2020, p. 2).

Where koalas are present in very high densities, they can cause extensive tree damage, often grazing heavily on selected trees while leaving neighbouring trees untouched (Wilks 2008) (as discussed in Section 4.1 this may be due to differences in the nutritional quality of foliage that is not visible to the human eye). Koalas "have a tendency to preferentially eat out the upper central canopy of a tree, leaving only the inaccessible extremities [and also] they are 'messy' feeders, damaging more foliage than they actually consume" (Wilks 2008, p. 2). As a consequence of the pressures they exert, unsustainably high koala numbers will cause extensive tree death from repeated defoliation, at times resulting in widespread starvation and catastrophic population crashes for the animal (Whisson, Dixon et al. 2016). Mass starvation as a result of overabundant koalas decimating their food source is not a recent occurrence, and such events have been observed since the early 1900s (Kershaw 1934). Unfortunately for koalas and their habitat, the widespread loss of food resources does not necessarily elicit an "effective survival response" in the animals, and many individuals are unable or unwilling to disperse to other sites when their habitat declines (Whisson, Dixon et al. 2016, p. 9). An overabundant koala population being monitored at Cape Otway, Victoria, almost doubled in density within a two-year period, and severely defoliated more than 71% of their preferred browse species, the manna gum (*E. viminalis*). As a result, 71% of koalas being monitored as part of the study either starved to death or were humanely euthanized (Whisson, Dixon et al. 2016).

Some researchers suggest koala populations are more likely to irrupt in (and subsequently over-browse) patchy or isolated habitats (Menkhorst 2008) that are dominated by *E. viminalis* and contain only one or two species of preferred food trees (Herbert 2007). Population growth may occur in response to an abundance of nitrogen-rich foliage that is produced by eucalypts experiencing ecological stress as a result of habitat fragmentation and disrupted fire regimes and nutrient cycles (Herbert 2007). This nitrogenous foliage may stimulate population growth because it is thought to be more palatable and nutritious for koalas (Jurskis and Turner 2002), however, the widespread production of such foliage indicates eucalypts are in the early stages of dieback (Herbert 2007, Jurskis 2017). As such, koala numbers may spike rapidly in collapsing ecosystems that are only able support such high population densities temporarily before they inevitably decline (Jurskis 2017).

Although koalas are thought to be declining in many parts of Australia, Jurskis (2017, p. 480) argues that there is a pervasive lack of recognition amongst policy-makers, environmentalists and the general public that "healthy eucalypt forests provide little food for herbivores, so that they [naturally] live in low densities as do their predators" and as such, many koala populations in Australia may actually be irrupting – even in Queensland and NSW. According to Jackson (2007, p. 10), "koala populations are larger now than at any point in their distant history," which is consistent with Jurskis' claim that there is no koala population in Australia that has experienced a documented long-term decline in density compared with the numbers existing at the advent of European settlement[15]. Jurkis suggests that the loss of frequent mild burning that was historically carried out by Aboriginal peoples is a major contributor to eucalypt dieback and the subsequent koala irruptions that are triggered by such vegetation changes. Whilst sick and starving koalas attract significant media coverage and research focus, their overabundance must have considerable consequences for many other species that receive far less attention, but generally speaking, the broader impacts of high koala densities on ecosystems are currently "poorly understood" (Whisson, Dixon et al. 2016, p. 9).

5. Challenges in koala management

Regardless of the distribution of, or causes for, unsustainably dense koala populations, it is clear that they present a considerable challenge for natural resource managers and consume "a significant proportion of the wildlife management budgets of the Victorian and South Australian Governments" (Menkhorst 2008, p. 73). Because of the widespread public attention that koalas attract, the management of their overabundance has been a contentious topic for decades. Where koalas exist in such high numbers that they cause widespread defoliation, the pressure the animal exerts on its habitat must be alleviated. Whilst there are some highly polarising means for achieving this (e.g. culling or introducing diseases), Duka and Masters (2005) state that the modern management of overabundant wildlife species has shifted away from methods that seek to increase a population's death rate, toward methods that seek to decrease birth rates, such as fertility control.

---

[15] Recognition of very low koala densities prior to European settlement is not widespread in the literature, but this view is held by some researchers (e.g. Jurskis 2017, Black, Price et al. 2014, Jackson 2007, Flannery 1994) including those examining koala genetics (Tsangaras, Avila-Arcos et al. 2012).

5.1 Fertility control

In 1996, an independent 'Koala Management Task Force' was formed to advise the South Australian government on the management of the State's koalas, particularly the overabundant population on Kangaroo Island (Duka and Masters 2005). Prior to delivering their recommendations, the Task Force evaluated six different management options for Kangaroo Island, including: doing nothing; restoring degraded habitat; introducing *Chlamydia* to suppress koala fertility; sterilising koalas; translocating koalas to other sites; and culling koalas. Similar solutions were considered by the Department of Sustainability and Environment for Victorian koala populations (Herbert 2007). The Task Force subsequently recommended the use of four different approaches, having rejected the options of doing nothing or introducing disease to the island. However, there was vehement public opposition to culling, both in Australia and internationally, and consequently the government opted for the use of sterilisation and translocation (Duka and Masters 2005) and to date, "large sterilisation programs have been the cornerstone of many koala management programs in southern Australia" (Herbert 2007, p. 129).

Sterilisation is often carried out in conjunction with the translocation of sterilised individuals to other sites, in order to immediately reduce population density at the source site and alleviate browsing pressure, however, sterilised koalas may also be re-released into their original habitat (Duka and Masters 2005). Three different fertility control methods have been used in koalas, including the surgical sterilisation of males and females, steroidal contraceptives (e.g. levonorgestrel), and non-steroidal gonadotropin-releasing hormone (GnRH) agonist contraceptives (e.g. deslorelin) (Herbert 2007). Sterilisation is a permanent form of fertility control that essentially removes an individual's genetics from the population, and as such, is considered to be analogous to culling in terms of its impact on the genetic diversity of koala populations. In contrast, contraceptives, which are implanted subcutaneously (generally between the shoulder blades), are effective for periods of 1-6 years (levonorgestrel-based implants providing the longer-term control) and are reversible (Menkhorst 2008). In comparison to contraceptives, sterilisation is more invasive, more expensive, and must be performed under general anaesthetic by a veterinarian. Furthermore, animals that are translocated shortly after surgical sterilisation have been found to experience elevated rates of mortality (Whisson, Holland et al. 2012), and although these effects may have been exacerbated by unseasonably cold weather at the release site, the practice is no longer recommended (Menkhorst 2017). There is no decline in survivorship from surgical sterilisation in the absence of translocation (Duka and Masters 2005). Since 2004, the management of overabundant koala populations in Victoria has utilised levonorgestrel contraceptive implants rather than sterilisation (Menkhorst 2017), and the same strategy has been adopted in South Australia since 2018 (KINRC 2019). As a female koala has a breeding life of about 8-10 years (Menkhorst 2008), this long-lasting contraceptive ensures she will not produce young for most of her life; perhaps not at all if she is recaptured and contracepted again at a later date. No adverse effects on koala health have been observed from levonorgestrel implants (Hynes, Handasyde et al. 2011). Female koalas that received a levonorgestrel implant were found to range further than control koalas in Hynes, Handasyde et al. (2011), however, this was believed to be due to the absence of offspring, rather than a direct effect of the contraceptive. In some species, "treatment with contraceptives has been associated with extended longevity due to individuals being released from the costs of reproduction" however, this has not yet been demonstrated in koalas (Hynes, Shaw et al. 2019, p. 323).

In all currently available methods of fertility control, a major financial cost is associated with the capture of koalas in order to perform sterilisation or implant contraceptives. Recently, strategies have been trialled to reduce the costs of fertility control, such as simultaneously treating dependent young and their mothers with contraceptive implants, rather than only adult females. Such a strategy reduced the cost of the procedure by more than 28% when compared with the costs of only treating adult koalas ($413 per two adult koalas versus $296 for mother and offspring) (Hynes, Shaw et al. 2019). However, the costs remain a significant obstacle when the scale of fertility control programs is examined. Where fertility control is used in the absence of translocation, more than 30% of koalas within a population must be treated every year to achieve a reduction in population size (Hynes, Shaw et al. 2019). In some regions, such as Kangaroo Island – with an estimated 48,506 koalas prior to the 2019-2020 bushfires (Molsher 2017) – the magnitude of the costs associated with the management of overabundant populations becomes clear. Carrying out the 15-minute contraceptive implant procedure (Hynes, Shaw et al. 2019) on 30% of the Kangaroo Island koala population would take an estimated 70 hours per week, every week of the year, excluding the time required to actually locate and capture each individual. According to Herbert (2007), if an insufficient proportion of the population is sterilised or contracepted, the density of the population will continue to increase, and although “absolute numbers of treated animals may sound impressive to the individuals footing the bill for management… they will not govern the success or failure of the operation” (p. 133). In high-density populations, fertility control will be ineffective unless adequate funding can be guaranteed long-term, the animals are accessible, and accurate estimates of total population size and density have been calculated (Duka and Masters 2005). On Kangaroo Island, the surgical sterilisation of more than 4500 koalas between 1997 and 2001 failed to achieve targeted population densities due to a gross underestimation of koala numbers on the island, which was later revised to be five times greater than originally thought (Duka and Masters 2005). Since the Kangaroo Island fertility control program commenced in 1997, more than 13,500 koalas have been sterilised or contracepted at a cost of $9.2 million, yet the most recent koala census shows that koala densities have increased significantly since 2010 and remain unsustainably high[16] (Molsher 2017). As such, fertility control of very large, dense populations has been criticised by some as being a short-sighted and expensive solution that channels funding away from other environmental projects (Duka and Masters 2005).

5.2 Translocation

For more than 100 years translocation has played an important role in the distribution and management of koala populations throughout the southern States of Victoria and South Australia. Whilst the earliest translocations were used to establish offshore island populations to safeguard the species, in recent decades translocation has almost always been used as a means of alleviating the pressures caused by overabundant koalas and to prevent widespread tree death and koala suffering (Whisson, Holland et al. 2012). Since the translocation of koalas first occurred in the late 1800s, koala populations on the mainland have been successfully re-established from the overabundant populations that emerged on French and Phillip islands. Today, almost all koala populations in Victoria and South Australia are descended from a small number of founding individuals that were ‘marooned’ on those offshore islands for conservation reasons (Wedrowicz, Wright et al. 2017). So successfully has the species recolonised the mainland, that koalas now occupy almost all suitable habitat in Victoria, and it

[16] Catastrophic bushfires across much of Kangaroo Island during the 2019-2020 summer period have undoubtedly had a significant effect on the island’s koala population, with substantial loss of life. However, as discussed in Section 4.3, koala populations can recover quite quickly from bushfires, if refuges are retained. The five-yearly koala census is due to occur later this year, which will provide a much clearer picture of the fires’ impact on the local koala population.

has been suggested that translocation cannot continue to be a viable management option due to the lack of suitable remaining habitat (Menkhorst 2008). Since the 1920s more than 40,000 koalas have been translocated in Victoria alone (Menkhorst 2017). More than 3800 koalas have been translocated from Kangaroo Island to the south-eastern corner of South Australia since 1996 (KINRC 2019).

As with sterilisation, the efficacy of translocation as a control measure has been questioned by those who view it as simply being a redistribution of the problem, rather than a solution to it. At times translocated koalas overbrowse their new sites and exert significant habitat pressure, however, to minimise these chances, since 2004 all adult female koalas translocated in Victoria have had to be sterilised or contracepted (Menkhorst 2017). Nevertheless, minimising the impacts of translocation has likely taken a backseat to lessening the impacts of over-browsing, as traditionally, the success of translocation programs has been measured at the 'source' (i.e. determining whether removing koalas results in improved outcomes for the remaining population and their habitat). However, Whisson, Holland et al. (2012) argue that the fate of translocated koalas and the sites they are moved to must also be assessed.

A recent review of all research examining the success of koala translocations in southern Australia has highlighted that survival rates for translocated koalas is high when they are released into large (at least 100 ha) high quality habitat patches (Menkhorst 2017), and when individuals are in good health prior to translocation (Santamaria 2002). In studies finding elevated rates of mortality amongst translocated koalas (Whisson, Holland et al. 2012), koala deaths were likely related to the recent surgical sterilisation of those individuals (Menkhorst 2017), and as fertility control is now largely achieved through contraceptive implants, this is no longer considered to be a significant issue. There are no apparent health consequences of translocating animals soon after they have been contracepted (Menkhorst 2017). Although the concept has been raised, translocating overabundant southern koalas to Queensland and NSW, where they are declining, is believed to be unfeasible. It is thought that translocated individuals would not survive such a translocation due to differences in the diet and climate adaptations between koalas from southern and northern Australia (KINRC 2019). Additionally, there are concerns about the spread of disease associated with translocation between these regions, with very few koala populations now considered to be *Chlamydia*-free (possibly only the Kangaroo Island and French Island populations). In the past, these concerns related to preventing the introduction of disease to non-infected populations, however, today there are also ethical concerns about the inhumaneness of introducing *Chlamydia*-free individuals to infected populations, where they are much more likely to develop severe symptoms and be rendered infertile within 12 months of translocation (Menkhorst 2017). In general, koalas appear to be "relatively robust to the rigours of translocation" (within the southern States) with research showing that translocated koalas "readily utilise unfamiliar forage tree species… [and] readily adapt to trees with far different structure" to those present in their source habitat (Menkhorst 2017, p. 23). As such, translocation of contracepted koalas may be an effective means of achieving an immediate reduction in browsing pressure, but its future viability is likely limited by a lack of suitable sites to which overabundant koalas can be moved.

5.3 Culling

Although many environmentalists and scientists recommend the culling of koalas in overabundant populations (Wilks 2008, Drijfhout and Kendal 2019), lethal control is highly polarising and receives vocal public opposition in Australia and overseas (Duka and Masters 2005). According to Wilks (2008, p. 8), despite the widespread environmental damage caused by overabundant koalas and the immense costs associated with fertility control and translocation programs, a minority group of "activists have effectively promulgated and reinforced the soft, fluffy, harmless image of the koala permanently in the media" and as a result they have "frozen the scene" so that no government would be willing to support the lethal control of koalas. This is reflected in the National Koala Conservation Strategy, which excludes the use of lethal control measures for the species (ANZECC 1998). In fact, lethal control of koalas has not been sanctioned since the 1920s, despite such measures being used for other species, including marsupials[17] (Menkhorst 2008).

In some cases, public resistance to the lethal control of wildlife can be overcome on the grounds of protecting human health and safety (e.g. bird control at airports is generally acceptable to most people) (Duka and Masters 2005), or on ethical grounds (e.g. the euthanasia of critically

[17] Culling is widely used as a population reduction measure for other marsupial species throughout Australia, including red kangaroos, eastern grey kangaroos, western grey kangaroos, wallaroos, whiptail wallabies, swamp wallabies, Tasmanian bettongs, Bennett's wallabies, tammar wallabies (Jackson 2007), brushtail possums and wombats (Menkhorst 2008).

ill or injured animals – as in Whisson, Dixon et al. (2016) – is likely to be considered humane). It is thought that public resistance to culling is much stronger for native species, as lethal control measures are frequently used in the management of introduced species such as feral pigs and goats without widespread opposition. In addition, it has been suggested that the public "think differently about koalas" (Drijfhout and Kendal 2019, p. 31); highlighted by the fact that kangaroo harvesting operations have existed in Australia for some time without attracting the same degree of opposition that koalas evoke, despite also being a native Australian animal (Duka and Masters 2005).

A recent survey about attitudes towards culling wildlife found that 68% of experts considered it acceptable to cull koalas, whereas only 36% of the public shared the same view (Drijfhout and Kendal 2019). In comparison, 57% of the general public supported the culling of kangaroos – which was even higher than the 53% who supported the culling of brumbies (an introduced species). Similar patterns were observed in regard to the commercial use of the species, with 31% of the public considering it acceptable to use koalas for commercial purposes (e.g. for fur), but 58% supporting the same measures for kangaroos. It has been argued that the money spent funding sterilisation and translocation programs would be better spent educating the public about lethal control options for overabundant koala populations (Duka and Masters 2005). Accordingly, the study conducted by Drijfhout and Kendal (2019) examined whether providing the public with information about the negative consequences of koala overabundance made the concept of culling more acceptable. To some extent it did, (43% of informed respondents found culling acceptable), however, in contrast to tangible control measures, "diverting funds to educate the public… provides no guarantee of success in overcoming resistance to culling" (Duka and Masters 2005). It is not clear what information the public was provided with in the survey, nor how it was conveyed, but it is possible that the use of interpretive communication techniques could help garner more support for particular control methods, if a strong understanding of the public's views is established. Heberlein (2012) does caution that a "cognitive" fix alone is rarely the best solution, advocating for attention to multiple methods including structural and technological solutions.

5.4 Forestry

In the Green Triangle region of south-east South Australia and south-west Victoria, the amount of land covered by blue gum plantations has increased by more than 50% since the year 2000; now occupying an area of more than 152,000 ha (ABARES 2016), much of which occurs within the range of the koala (McAlpine, Lunney et al. 2015, Ashman, Rendall et al. 2020). As commercial trees are destined for harvesting, habitat loss eventually becomes an issue for koalas inhabiting plantations. Koalas present a "challenging animal welfare issue" during harvesting operations (McAlpine, Lunney et al. 2015, p. 230) with significant repercussions for both koalas and forest managers. Furthermore, as these plantations (now very successfully colonised by koalas) are cleared, the animals must disperse to other sites: if plantation forest, the issues associated with tree harvesting are compounded; and if native forest, the overabundance of koalas may lead to overbrowsing of valuable remnant vegetation, negatively impact other native species (Jurskis 2017) and ultimately result in the "mass starvation" of koalas (Whisson, Dixon et al. 2016, p. 8). In order to minimise impact on koalas during harvesting, regulations now require forestry companies to actively identify koalas prior to and during harvesting, and retain nine trees for each koala identified in a plantation (ABP 2018). Knowing the highly selective diet of koalas and research suggesting "a threshold in habitat quality for the koala may exist corresponding to the presence of at least 20 eucalypt trees ha^{-1}" (Kavanagh, Stanton et al. 2007, p. 100), this provides a vital short term refuge for koalas. As discussed in Section 4.5, there is some evidence that koalas are more likely to become overabundant in habitats that contain only one or two species of preferred browse species, suggesting research investigating the establishment of mixed-species plantations may offer some potential for limiting koala numbers in a forestry context.

6. The value of koalas

The stance taken by past and present governments regarding koala management is a clear indication of the perceived value of koalas to the Australian people. The refusal to consider culling as a management strategy during development of the nation's koala strategy; the vast sums of public money spent on sterilisation and translocation programs in lieu of lethal control; and the existence of laws that make it illegal to kill or injure koalas anywhere in the country, are all reflections of some of the "deepest values" of the Australian community (Takacs 2018, p. 165), or at the very least, the government's perceptions of them.

A 2014 report examining the value of koalas from an economic standpoint, estimated that the species contributes approximately $3.2 billion to the Australian economy through tourism each year, and generates employment for 30,000 people (Conrad 2014). Although recent data are not available, a 1997 study found that 72% of international travellers to Australia hoped to see a koala during their visit, and 11% of inbound tourists stated that they would not have visited Australia were it not for the country's wildlife (Hundloe and Hamilton 1997). In general, Australian wildlife is an important tourist attraction, and of all animal species in the country, the koala is the most sough-after. Upon departure, 70% of international tourists reported having had a koala experience during their visit (Hundloe and Hamilton 1997), demonstrating quite clearly why, "despite the difficulty and expense involved in keeping them, nearly every zoo and fauna park in Australia holds koalas" (Jackson 2007, p. 138). In Queensland, Western Australia, and South Australia, tourists are allowed to hold koalas at some zoos and wildlife parks, however, the practice has been banned in NSW, Victoria, the ACT and Tasmania. According to the Director of Cleland Wildlife Park in South Australia, the koala hold experience is invariably booked to capacity every day, and is the major drawcard for visitors (Daniels 2020, personal communication, 6 March).

Clearly, Australians and the global public love koalas[18], however, this has not always been the case. Many early European settlers considered the koala to have a "fierce and menacing look", were critical of the animal for being "sloth-like", and named a fossil (at the time mistakenly thought to be a koala specimen) *Koalemus ingens*, which is derived from the Greek term for "stupid or foolish fellow" (Jackson 2007, p. 143). However, in the late 19th century and early 20th century, the koala began featuring in popular books, including 'The Exciting Adventures of Dot and the Kangaroo' (1899), 'The Magic Pudding' (1918), and 'Blinky Bill' (1933) (Jackson 2007), which likely played an important role in changing how people saw the animal. Public attitudes toward the koala were already beginning to shift when concerns were raised about the magnitude of the number of animals being lost to the fur trade in the early 20th century (Jackson 2007) and the practice was outlawed. Thus, a new era for the koala emerged; one in which the species had a "hold on the public" and the animal began featuring as the star of books, magazines, soft toys, jigsaw puzzles, chocolate bars, cookies, poems, computer games, and a

[18] The world's love for koalas is also reflected in the magnitude of international donations being raised for koalas affected by Australia's recent bushfires. An online fundraising campaign for the Port Macquarie Koala Hospital in NSW, is the most successful Australian GoFundMe campaign to have ever been launched, raising more than $1.8 million and receiving donations from people in 90 different countries: https://10daily.com.au/news/australia/a191119bdupl/koala-bushfire-gofundme-second-most-successful-aussie-fundraiser-of-all-time-20191129

Paul McCartney song; an era where, due to its broad appeal, the koala could be used to advertise everything from sliced peaches to credit cards and everything in between (Jackson 2007, p. 149). When international tourism became more commonplace at the end of World War II, the koala was launched onto the global stage, and it began capturing people all over the world.

In modern Australia, urban inhabitants are often disconnected from the natural environment (Ives, Abson et al. 2018), and because they have "no personal connections to or responsibilities for wildlife in place or in country" their interests in wildlife are generally "abstract and distanced" (Aslin and Bennett 2000, p. 15). As opposed to Aboriginal concepts of 'belonging' to Country (a belief system steeped in personal responsibility for the land), most urban Australians will only develop a relationship with the natural environment by choice, and as such, their "connections to wildlife (if they have any at all) may stem from personal preferences rather than from any necessary social obligations" (Aslin and Bennett 2000, p. 20). This may be one reason why Australians have seemingly disparate views regarding the acceptable treatment of different native species. Rather than these views being derived from knowledge about the ecological importance of the species, its nativeness, its vulnerability, or the impacts it has on the environment, people appear to simply *like* koalas more than other wildlife.

But why do people have this apparent 'preference' for koalas? A key reason for the species' widespread and universal appeal is thought to be its physical appearance, which resembles that of a human baby or toddler, with a "relatively large head and eyes, a medium-sized body, short legs and tiny feet… and forward-facing eyes" (Jackson 2007, p. 143). The head-to-body proportions of a human baby elicit a strong maternal or protective response in people, and it is thought that the koala also triggers this same response (Martin and Handasyde 1999). Just as the public appear to favour koalas over other marsupials, it has been suggested that the "extraordinarily high degree of protection granted to the koala by state and federal legislation is based on an emotional attitude rather than a rational assessment of the species' status" (Jackson 2007, p. 144). It could be argued that the government's motivations are largely economic-driven rather than emotional in nature – or they may simply be a pragmatic reflection of the voting public's adoration of koalas – given the importance of koalas to the tourism industry. In a recent article published by *The Conversation*, Kevin Markwell, Professor of Tourism at Southern Cross University[19], argues that because the vast majority of tourists' koala

[19] Markwell, K. (2020) Koalas are the face of Australian tourism. What now after the fires? *The Conversation*. Professor in Tourism, Southern Cross University. [https://theconversation.com/koalas-are-the-face-of-australian-tourism-what-now-after-the-fires-129347]

experiences involve captive rather than wild koalas, the tourism appeal of the species is not necessarily dependent upon its survival in the wild (Markwell gives the example of Tasmania's thylacine, which is used to promote tourism despite the last known individual having died in 1936 (Turner 2009)). However, given the magnitude of the publicity that koalas receive (see Section 1), the public's response to the two species is certain to differ, and it is a reasonable assumption that decreasing koala numbers would indeed have a substantial and negative impact on international tourism. While Tasmania has successfully used the thylacine as a tourism drawcard, it is unlikely, and certainly undesirable, that our national tourism marketing strategy would focus on extinct wildlife.

It is interesting that, in spite of the great value placed on koalas and the legal protections it is bestowed, the species increasingly struggles with population issues (decline and overabundance) in many areas. If the species is one of the most highly valued on the planet, why does its situation continue to deteriorate? Clearly, public adoration is no guarantee that a species will endure, with almost all of the world's most charismatic species now facing imminent extinction in the wild (Courchamp, Jaric et al. 2018). For some charismatic species, their immense popularity can cause people to take their protection for granted, and such species may become "beloved but ignored" (Courchamp, Jaric et al. 2018, p. 2). Although there is some evidence of this (e.g. Tisdell and Nantha (2007) found that the public's willingness to fund conservation endeavours to protect the critically endangered northern hairy-nosed wombat was higher than that for the koala), it is unlikely that koalas will suffer from the "beloved but ignored" phenomenon, as the public continues to express its clear and vocal opposition to any operation that threatens the species. It is possible, though, that this vocal support for koalas interferes with conservation priorities, whereby the survival of individuals is prioritised over the stability of the species as a whole, and as such, the koala may still be a victim of its own charisma.

As shown in the preceding sections of this review, not everyone shares the same attitudes towards koalas (e.g. there are people who believe overabundant koalas or those with *Chlamydia* should be culled, and there are people who are vehemently opposed to such measures being used on koalas). According to Shumway, Seabrook et al. (2014, p. 43), "wildlife managers are increasingly confronted with the task of successfully representing a diverse number of public interests and, often, conservation of species hinges on the effectiveness of this task." In a study examining public attitudes toward koalas on Kangaroo Island, Wilks (2008) identified four different types of people, or four different ways of viewing koalas, namely:

- Conservation-minded people who viewed koalas as having intrinsic value but acknowledge that conservation efforts must consider the broader ecosystem, not just koalas;
- Farmers who viewed koalas in the same manner as any other animal, believing they should be controlled if their numbers are causing problems;
- Activists who viewed koalas as cute, harmless, loveable, vulnerable, in need of protection, and compared the culling of koalas to the killing of children; and
- Scientists who viewed koalas as overabundant on the island and advocated significant reductions in numbers.

According to Wilks, activists control the playing field in any debate about koalas. Their views about the vulnerability of koalas – as well as their damaging views about other "actors" in the koala arena such as farmers and scientists – are those that are publicised most widely by the media, both nationally and overseas. Any dissent (e.g. recommendations of culling) "are dealt with swiftly and effectively in ways that permit no meaningful discussion of alternative management solutions" by activists' online (social-media) activities, efficiently "reaching voters, letter writers, emailers, and potential overseas and domestic visitors" (Wilks 2008, p. 8). As such, Wilks (2008, p. 8) suggests that the koala's iconic status and charisma has empowered a minority group of vocal activists to "enrol political and management processes towards… preventing any harm to any individual animal" and that significant ecological damage will occur if this continues.

The role of the media, particularly online platforms, in propagating the view that koalas are universally harmless and at risk cannot be overlooked. It is of no surprise that the government is wary of media attention regarding koalas, and has been for many decades. In 1944, a film was shown in a Melbourne cinema that depicted emaciated koalas from an overabundant population on Quail Island in Victoria. So fearful of the international backlash that would be felt if the film was viewed overseas, the federal government employed wartime censorship powers to prevent the film from being shown outside of Australia (Bagust 2010). In more recent years, "the entrance into the fray of sound-bite friendly, web-accessible lobby groups… like the Australian Koala Foundation" (Bagust 2010, p. 493) have ensured that the views of the "activists" identified by Wilks (2008) continue to be heard globally. Furthermore, during incidents in which koala lives are lost or threatened, whether naturally occurring (e.g. bushfires) or human-caused (e.g. logging), "the 'viral stickiness' of iconic animal narratives" becomes undeniable (Bagust 2010, p. 495). For example, a YouTube video of 'Sam' the koala accepting water from a volunteer fire-fighter during the 2009 Victorian bushfires received more than two million views around the world (Hess and Waller 2009); more international media exposure than any other incident from the devastating fires that killed 173 people (Due, Thompson et al. 2014), and was arguably the defining media image of the Black Saturday fires (Hess and Waller 2009). According to Hess and Waller (2009, p. 82), although the media could have used Sam's popularity to educate the public about koala issues (such as *Chlamydia*, which Sam died from six months after the fire) they did little more than use the koala to "create maximum exchange value out of material which lacks hard news qualities but has clear public appeal."

It is unlikely that the views and apparent "power" of activists – particularly on media platforms – will subside, and in fact, it is probable that such views will become increasingly widespread. According to Steg and de Groot (2013), the wildlife value orientations of modern societies are undergoing a shift from that of 'domination' (the belief that wildlife should be used and managed for human benefit) to that of 'mutualism' (the belief that wildlife has intrinsic value and is deserving of rights and care). In the United States, the percentage of the population with a mutualism orientation was greater in states with higher state-level income, education, and degree of urbanisation (Teel and Manfredo 2010), and as such, this inter-generational transition toward mutualism is expected to continue as the socio-demographic structure of modern societies evolves. Because wildlife value orientations predict human attitudes and social norms regarding wildlife-related behaviours and management issues, public support for traditional forms of management such as culling – widely considered acceptable to those with a domination value orientation – will almost certainly decline (Steg and de Groot 2013).

7. Conclusions

This review of koala research demonstrates the complexity of koala issues across seemingly disparate domains, from dietary requirements to the public acceptability of lethal control. As in any field of study, there are some aspects of koala research on which the academic community has reached consensus, and others that continue to be debated and require further research. Key findings within each of the five main sections of the review are summarised below, with some interpretation of their potential importance to the forestry industry.

Koala behaviour

- Although largely solitary, koalas live in complex social communities. They have evolved strategies to avoid resource competition with other individuals (e.g. not sharing trees). Where multiple koalas are frequently observed in a single tree, such as in some blue gum plantations, this is a sign of ecological imbalance and overabundance.

- Certain aspects of koala behaviour (resulting from biological constraints) – such as their need to remain stationary for long periods of time and their dietary "fussiness" – make the animals particularly susceptible to changes in their environment, e.g. habitat fragmentation, which has implications for how trees are retained during harvesting operations. Further investigation into the retention of corridors to connect forest fragments may offer improved outcomes for koalas.

Koala history

- There is debate surrounding koala population densities prior to European settlement, with evidence suggesting koala numbers were much lower than widely believed (and much lower than the figures used to obtain increased legislative protection for koalas). Further research is required to understand why the overwhelming perception is that the species is universally threatened, a perception that colours society's responses to koala incidents and management approaches.

Current status and key threats

- Koalas have a complex population status, ranging from vulnerable to overabundant. Population estimates are few and inconsistent across Australia, due in part to the vastness of the country and the very low densities at which the species occurs in many areas. The immense costs and labour involved in conducting population estimates in these areas is prohibitive. Furthermore, as demonstrated by our report on the detection accuracy of trained spotters, there is also some question as to how reliable such estimates would be using traditional methods.

- Although koala management in commercial forestry is challenging and subject to negative media attention, forestry is not a key threat to koala populations. Ultimately the largest threat to koalas is habitat loss and fragmentation arising from urbanisation, which increases the species' susceptibility to:

    - Vehicle strikes and dog predation: the resulting trauma is responsible for 41% of koala morbidity in many areas; the mortality rate of vehicle strikes is estimated at 83%.
    - Climate change, drought and bushfires: a warming climate and higher CO_2 levels will reduce the nutritional quality of foliage and compound the existing behavioural limitations of koalas; bushfires will become more frequent and severe, resulting in very high koala mortality.
    - Diseases: *Chlamydia* is considered to be the disease of most concern to the species' long-term survival due to its effects on reproduction. However, it has been suggested that *Chlamydia* is yet another sign of overabundant and malnourished populations that will inevitably decline.

    That said, no koala deaths are acceptable and it is a step forward that the forestry industry is working together with researchers in an attempt to minimise the industry's impact on koalas.

- The principal reason for the species' vulnerability to habitat loss is its highly specialised diet. Although much research has been conducted, no study has identified a single factor that will consistently predict koala leaf preferences amongst trees species or between individual trees. However, FPCs (formylated phloroglucinol compounds) are thought to be the single most powerful deterrent of koala browsing, and further research into these compounds may offer some potential for decreasing the appeal of plantation trees through selective breeding. Importantly, at the time of planting it was thought *E. globulus* was less appealing to koalas than other *Eucalypt* species – and yet koalas readily moved into *E. globulus* plantations – suggesting strategies seeking to reduce the browsing appeal of commercial forests must be approached with caution and thorough research. However, unlike a reliance on tree *species* to deter browsing, it is very unlikely that koalas could adapt to ingesting very high concentrations of FPCs because they are toxic.

- Although the harvesting of commercial plantations results in habitat loss for koalas, it should not be ignored that blue gum plantations often provide temporary habitat in what was formerly cleared agricultural land. When harvesting operations are managed carefully it is possible to sustain a larger population of koalas than would be possible without the existence of the plantation. There is value in exploring this perspective and evaluating the benefits of communicating it to the wider community.

Challenges in koala management

- Although many scientists and conservationists support the culling of species – including koalas – where they are present in such high densities that they cause deforestation, community support for lethal control is very low, and the practice is not sanctioned.

- To date, large fertility control programs (whether through surgical sterilisation or the use of contraceptive implants) have been the cornerstone of many koala management programs in southern Australia. These programs are costly and time consuming, largely due to the time it takes to locate and capture koalas to perform the procedures.

- Fertility control is often used in conjunction with translocation. Although survival rates for translocated koalas have been a point of contention in the past, survival rates are now considered to be high when healthy koalas are released into large, high quality habitat patches, under appropriate conditions (e.g. weather). However, areas suitable for receiving translocated koalas are becoming increasingly rare, particularly in Victoria, because of the successful colonisation of koalas across much of the state. As such, translocation may soon cease to be a viable option for the control of overabundant koalas.

- There is some evidence that koalas are more likely to become overabundant in habitats containing only one or two species of preferred browse species, as is the case in commercial plantations. This suggests there may be potential for establishing mixed-species plantations to limit koala population densities, however, this would require further research.

The value of koalas

- From an economic perspective, koalas are of great importance to Australia: koalas are estimated to contribute $3.2 billion to the national economy each year through tourism and generate employment for 30,000 people. Approximately 70% of international visitors to Australia seek out koala experiences.

- Domestically and overseas, people have a very strong attachment to koalas. The forestry industry is keenly aware of this, given the role international investment plays in the sector.

- The physiological characteristics of koalas are thought to trigger a protective or maternal response in people (i.e. perhaps because the animal is reminiscent of a human toddler, given the small size of its body, its forward-facing eyes, large head and short legs).

- It is thought that the public's strong and vocal support for koalas interferes with conservation priorities. This is reflected by the public's staunch opposition to the culling of koalas, even when many other native mammals are regularly controlled via lethal means. The forestry industry is clearly also a target of the public's strong and vocal views about koala management, however, in many cases it is not clear *why* the community holds the views it does about koalas. Some research suggests these widespread views are the result of activists controlling the "playing field" when it comes to any discussion of koalas. Given the widespread appeal of the animal, activists are able to rapidly and frequently promulgate particular storylines and viewpoints amongst a large, global audience using social media. Further research is required to develop a deeper understanding of this relationship and the roles different groups play in communicating koala information to the public via domestic and international media.

- Wildlife value orientations in modern societies are evolving, and increasingly, people are coming to share the belief that wildlife has intrinsic value and should be cared for. This suggests that strong and vocal support for koalas is only likely to become more prevalent in the future. It is clear that failing to engage in strategic, informed, and well-designed communication with the public about koala management, could compound koala-related issues for the forestry industry. However, by that same token, adapting the industry's communication to keep pace with a changing society will also be key to strengthening the industry's social license to continue operating in Australia well into the future.

7. References

ABARES (2016). Australian plantation statistics 2016. A. B. o. A. a. R. E. a. Sciences. Canberra, Australia, Australian Government**:** 1-45.

ABP (2018). Koala Management Plan. Victoria, Australian Bluegum Plantations.

Albert, C., G. M. Luque and F. Courchamp (2018). "The twenty most charismatic species." PLOS ONE **13**(7): e0199149.

ANZECC (1998). National Koala Conservation Strategy. A. a. N. Z. E. a. C. Council.

Ashman, K. R., A. R. Rendall, M. R. E. Symonds and D. Whisson (2020). "Understanding the role of plantations in the abundance of an arboreal folivore." Landscape and Urban Planning **193**: 103684.

Aslin, H. J. and D. H. Bennett (2000). "Wildlife and world views: Australian attitudes toward wildlife." Human Dimensions of Wildlife **5**(2): 15-35.

Bagust, P. (2010). "The South Australian ‘koala wars’: Australian fauna and mediagenic fitness selection." Continuum **24**(4): 489-502.

Barua, M., M. Root-Bernstein, R. J. Ladle and P. Jepson (2011). "Defining flagship uses is critical for flagship selection: a critique of the IUCN climate change flagship fleet." Ambio **40**(4): 431-435.

Beyer, H. L., D. de Villiers, J. Loader, A. Robbins, M. Stigner, N. Forbes and J. Hanger (2018). "Management of multiple threats achieves meaningful koala conservation outcomes." Journal of Applied Ecology **55**(4): 1966-1975.

Black, K. H., G. J. Price, M. Archer and S. J. Hand (2014). "Bearing up well? Understanding the past, present and future of Australia's koalas." Gondwana Research **25**(3): 1186-1201.

Brearley, G., J. Rhodes, A. Bradley, G. Baxter, L. Seabrook, D. Lunney, Y. Liu and C. McAlpine (2013). "Wildlife disease prevalence in human-modified landscapes." Biol Rev Camb Philos Soc **88**(2): 427-442.

Cai, Z. and F. X. Aguilar (2013). "Meta-analysis of consumer's willingness-to-pay premiums for certified wood products." Journal of Forest Economics **19**(1): 15-31.

Carver, S. (2016). "The Koala, an Iconic Animal under Threat." Journal of Wildlife Diseases **52**(2): 197-198.

Conrad, E. (2014). The Economic Value of the Koala, The Australian Koala Foundation

Cork, S. J., T. W. Clark and N. Mazur (2000). "Introduction: an Interdisciplinary Effort for Koala Conservation." Conservation Biology **14**(3): 606-609.

Courchamp, F., I. Jaric, C. Albert, Y. Meinard, W. J. Ripple and G. Chapron (2018). "The paradoxical extinction of the most charismatic animals." PLOS Biology **16**(4): e2003997.

Crowther, M. S., D. Lunney, J. Lemon, E. Stalenberg, R. Wheeler, G. Madani, K. A. Ross and M. Ellis (2014). "Climate-mediated habitat selection in an arboreal folivore." Ecography **37**(4): 336-343.

Curtin, A., D. Lunney and A. Matthews (2001). "A survey of a low-density koala population in a major reserve system, near Sydney, New South Wales." Australian Mammalogy **23**(2): 135-144.

Daniels, C. B. (2020). Cleland Wildlife Park, South Australia.

Denner, J. and P. R. Young (2013). "Koala retroviruses: characterization and impact on the life of koalas." Retrovirology **10**(1): 108.

Dique, D. S., J. Thompson, H. J. Preece, G. C. Penfold, D. L. d. Villiers and R. S. Leslie (2003). "Koala mortality on roads in south-east Queensland: the koala speed-zone trial." Wildlife Research **30**(4): 419-426.

Dodou, K. and P. Whitely (2014). "We are all part virus — the role of human endogenous retroviruses." The Pharmaceutical Journal.

Drijfhout, M. and D. Kendal (2019). The Koala Conundrum. Australasian Science.

DSEWPC (2013). Koala populations in Queensland, New South Wales and the Australian Capital Territory and national environmental law. E. Department of Sustainability, Water, Population and Communities, Australian Government.

Ducarme, F., G. M. Luque and F. Courchamp (2013). "What are “charismatic species” for conservation biologists." BioSciences Master Reviews **10**(2013): 1-8.

Due, C., K. Thompson and D. Every (2014). "‘An Image of Hope in a Week of Despair’: Representations of Sam the Koala in the Australian Mainstream News Media." Media International Australia **151**(1): 47-55.

Duka, T. and P. Masters (2005). "Confronting a tough issue: Fertility control and translocation for over-abundant Koalas on Kangaroo Island, South Australia." Ecological Management & Restoration **6**(3): 172-181.

Ellis, W. A. H., A. Melzer and F. B. Bercovitch (2009). "Spatiotemporal dynamics of habitat use by koalas: the checkerboard model." Behavioral Ecology and Sociobiology **63**(8): 1181-1188.

Ellis, W. A. H., A. Melzer, F. N. Carrick and M. Hasegawa (2002). "Tree use, diet and home range of the koala (<emph type="2">Phascolarctos</emph> <emph type="2">cinereus</emph>) at Blair Athol, central Queensland." Wildlife Research **29**(3): 303-311.

Ernst & Young (2016). Meta-analysis of consumer's willingness-to-pay premiums for certified wood products: opportunities and challenges for sustainable growth. Canberra, Ernst & Young.

Fabijan, J., C. Caraguel, M. Jelocnik, A. Polkinghorne, W. S. J. Boardman, E. Nishimoto, G. Johnsson, R. Molsher, L. Woolford, P. Timms, G. Simmons, F. Hemmatzadeh, D. J. Trott and N. Speight (2019). "Chlamydia pecorum prevalence in South Australian koala (Phascolarctos cinereus) populations: Identification and modelling of a population free from infection." Scientific Reports **9**(1): 6261.

Feschotte, C. and C. Gilbert (2012). "Endogenous viruses: insights into viral evolution and impact on host biology." Nature Reviews Genetics **13**(4): 283-296.

Flannery, T. (1994) *The future eaters: an ecological history of the Australasian lands and people*. Reed Books, Chatswood, New South Wales.

Foden, W. B. and S. N. Stuart (2009). Species and climate change: more than just the polar bear. Gland, Switzerland, IUCN Species Survival Commission (SSC).

Garnaut, R. (2008). The Garnaut climate change review : final report / Ross Garnaut. Port Melbourne, Vic, Cambridge University Press.

Garnaut, R. (2019) *Superpower: Australia’s low-carbon opportunity*. Latrobe University Press, Melbourne.

Griffith, J. E., N. K. Dhand, M. B. Krockenberger and D. P. Higgins (2013). "A retrospective study of admission trends of koalas to a rehabilitation facility over 30 years " Journal of Wildlife Diseases **49**(1): 18-28.

Heberlein, T. (2012) *Navigating Environmental Attitudes*. Oxford University Press, New York.

Herbert, C. A. (2007). From the urban fringe to the Abrolhos Islands: management challenges of burgeoning marsupial populations. Pest or Guest**:** 129-141.

Hess, K. and L. Waller (2009). Play It Again, Sam: How Journalists Cashed in on Youtube's Favourite Koala.

Hundloe, T. and C. Hamilton (1997). Koalas and tourism: an economic evaluation, The Australia Institute.

Hynes, E. F., K. A. Handasyde, G. Shaw and M. B. Renfree (2011). "The effects of gestagen implants on the behaviour of free-ranging female koalas." Applied Animal Behaviour Science **134**(3): 209-216.

Hynes, E. F., G. Shaw, M. B. Renfree and K. A. Handasyde (2019). "Contraception of prepubertal young can increase cost effectiveness of management of overabundant koala populations." Wildlife Research **46**(4): 317-325, 319.

IUCN (2009). Koalas and climate change, The International Union for Conservation of Nature.

Ives, C. D., D. J. Abson, H. von Wehrden, C. Dorninger, K. Klaniecki and J. Fischer (2018). "Reconnecting with nature for sustainability." Sustainability Science **13**(5): 1389-1397.

Jackson, S. (2007). Koala: origins of an icon. Crows Nest, NSW, Allen & Unwin.

Jurskis, V. (2017). "Ecological history of the koala and implications for management." Wildlife Research **44**(6–7): 471-483, 413.

Jurskis, V. and J. Turner (2002). "Eucalypt dieback in eastern Australia: a simple model." Australian forestry **65**(2): 87-98.

Kavanagh, R. P., M. A. Stanton and T. E. Brassil (2007). "Koalas continue to occupy their previous home-ranges after selective logging in CallitrisEucalyptus forest." Wildlife Research **34**(2): 94-107.

Kershaw, J. A. (1934). "The koala on Wilson's Promontory." The Victorian Naturalist **1**: 76-77.

KINRC (2019). Kangaroo Island Koala Management Project. N. R. K. Island. South Australia.

Law, B. S., M. Chidel, T. Brassil, G. Turner and L. Gonsalves (2017). "Winners and losers among mammals and nocturnal birds over 17years in response to large-scale eucalypt plantation establishment on farmland." Forest Ecology and Management **399**: 108-119.

Lee, K. E., W. A. H. Ellis, F. N. Carrick, S. W. Corley, S. D. Johnston, P. R. Baverstock, C. J. Nock, K. C. Rowe and J. M. Seddon (2013). "Anthropogenic changes to the landscape resulted in colonization of koalas in north-east New South Wales, Australia." Austral Ecology **38**(3): 355-363.

Lorimer, J. (2007). "Nonhuman Charisma." Environment and Planning D: Society and Space **25**(5): 911-932.

Lunney, D., S. M. Gresser, P. S. Mahon and A. Matthews (2004). "Post-fire survival and reproduction of rehabilitated and unburnt koalas." Biological Conservation **120**(4): 567-575.

Lunney, D., L. O'Neill, A. Matthews and W. B. Sherwin (2002). "Modelling mammalian extinction and forecasting recovery: koalas at Iluka (NSW, Australia)." Biological Conservation **106**(1): 101-113.

Marsh, K. J., B. D. Moore, I. R. Wallis and W. J. Foley (2014). "Continuous monitoring of feeding by koalas highlights diurnal differences in tree preferences." Wildlife Research **40**(8): 639-646, 638.

Martin, R. W. and K. A. Handasyde (1999). The koala: natural history, conservation and management (2nd ed). Malabar, Florida, Krieger Publishing Company.

Matthews, A., D. Lunney, S. Gresser and W. Maitz (2007). "Tree use by koalas (Phascolarctos cinereus) after fire in remnant coastal forest." Wildlife Research **34**(2): 84-93.

Matthews, A., D. Lunney, S. Gresser and W. Maitz (2016). "Movement patterns of koalas in remnant forest after fire." Australian Mammalogy **38**(1): 91-104.

McAlpine, C., D. Lunney, A. Melzer, P. Menkhorst, S. Phillips, D. Phalen, W. Ellis, W. Foley, G. Baxter, D. de Villiers, R. Kavanagh, C. Adams-Hosking, C. Todd, D. Whisson, R. Molsher, M. Walter, I. Lawler and R. Close (2015). "Conserving koalas: A review of the contrasting regional trends, outlooks and policy challenges." Biological Conservation **192**: 226-236.

Melzer, A., F. Carrick, P. Menkhorst, D. Lunney and B. St. John (2000). "Overview, Critical Assessment, and Conservation Implications of Koala Distribution and Abundance." Conservation Biology **14**(3): 619-628.

Menkhorst, P. (2008). Hunted, marooned, re-introduced, contracepted: a history of koala management in Victoria. Too Close for Comfort: Contentious Issues in Human-Wildlife Encounters. D. Lunney, A. Munn and W. Meikle. Mosman, NSW, Royal Zoological Society of New South Wales**:** 73-92.

Menkhorst, P. (2017). Literature review: responses of koalas to translocation. Victoria, Arthur Rylah Institute for Environmental Research.

Mitchell, P. (1990). Social behaviour and communication of koalas. Biology of the Koala. A. K. Lee, K. A. Handasyde and G. D. Sanson. Sydney, Surrey Beatty

Molsher, R. (2017). Kangaroo Island koala population survey 2015. South Australia.

Moore, B. D. and W. J. Foley (2000). "A review of feeding and diet selection in koalas (<emph type="2">Phascolarctos cinereus</emph>)." Australian Journal of Zoology **48**(3): 317-333.

Moore, B. D. and W. J. Foley (2005). "Tree use by koalas in a chemically complex landscape." Nature **435**(7041): 488-490.

Moore, B. D., I. R. Lawler, I. R. Wallis, C. M. Beale and W. J. Foley (2010). "Palatability mapping: a koala's eye view of spatial variation in habitat quality." Ecology **91**(11): 3165-3176.

Moore, B. D., I. R. Wallis, K. J. Marsh and W. J. Foley (2012). The role of nutrition in the conservation of the marsupial folivores of eucalypt forests. Conservation of Australia's Forest Fauna**:** 549-575.

Mount, A. B. (1969). Eucalypt ecology as related to fire. 9th Tall Timbers Fire Ecology Conference, Tall Timbers Research Station, Tallahassee, FL.

Nyari, S., S. A. Khan, G. Rawlinson, C. A. Waugh, A. Potter, V. Gerdts and P. Timms (2018). "Vaccination of koalas (Phascolarctos cinereus) against Chlamydia pecorum using synthetic peptides derived from the major outer membrane protein." PLOS ONE **13**(6): e0200112.

Polkinghorne, A., J. Hanger and P. Timms (2013). "Recent advances in understanding the biology, epidemiology and control of chlamydial infections in koalas." Veterinary Microbiology **165**(3): 214-223.

Price, G. J. (2008). "Is the modern koala (Phascolarctos cinereus) a derived dwarf of a Pleistocene giant? Implications for testing megafauna extinction hypotheses." Quaternary Science Reviews **27**(27): 2516-2521.

Quigley, B. L., S. Phillips, O. Olagoke, A. Robbins, J. Hanger and P. Timms (2019). "Changes in Endogenous and Exogenous Koala Retrovirus Subtype Expression over Time Reflect Koala Health Outcomes." J Virol **93**(18).

Reckless, H. J., M. Murray and M. S. Crowther (2017). "A review of climatic change as a determinant of the viability of koala populations." Wildlife Research **44**(7): 458-470.

Ryan, M. A., D. A. Whisson, G. J. Holland and J. P. Y. Arnould (2013). "Activity Patterns of Free-Ranging Koalas (Phascolarctos cinereus) Revealed by Accelerometry." PLOS ONE **8**(11): e80366.

Santamaria, F. (2002). Outcomes and implications of a koala translocation in the Ballarat region. PhD, University of Ballarat.

Sequeira, A. M. M., P. E. J. Roetman, C. B. Daniels, A. K. Baker and C. J. A. Bradshaw (2014). "Distribution models for koalas in South Australia using citizen science-collected data." Ecology and Evolution **4**(11): 2103-2114.

Shumway, N., L. Seabrook, C. McAlpine and P. Ward (2014). "A mismatch of community attitudes and actions: A study of koalas." Landscape and Urban Planning **126**: 42-52.

Speight, K. N., A. Polkinghorne, R. Penn, W. Boardman, P. Timms, T. Fraser, K. Johnson, R. Faull, S. Bate and L. Woolford (2016). "PREVALENCE AND PATHOLOGIC FEATURES OF CHLAMYDIA PECORUM INFECTIONS IN SOUTH AUSTRALIAN KOALAS (PHASCOLARCTOS CINEREUS)." Journal of Wildlife Diseases **52**(2): 301-306.

Stalenberg, E., I. R. Wallis, R. B. Cunningham, C. Allen and W. J. Foley (2014). "Nutritional Correlates of Koala Persistence in a Low-Density Population." PLOS ONE **9**(12): e113930.

Steg, L. and J. I. M. de Groot (2013). Environmental Psychology: An Introduction, Wiley.

Takacs, D. (2018). "Are koalas fungible: biodiversity offsetting and the law." New York University Environmental Law Journal **26**(2): 161-226.

Teel, T. L. and M. J. Manfredo (2010). "Understanding the Diversity of Public Interests in Wildlife Conservation." Conservation Biology **24**(1): 128-139.

Tisdell, C. and H. S. Nantha (2007). Comparison of funding and demand for the conservation of the charismatic koala with those for the critically endangered wombat Lasiorhinus krefftii. Vertebrate Conservation and Biodiversity. D. L. Hawksworth and A. T. Bull. Dordrecht, Springer Netherlands**:** 435-455.

Tisdell, C. A., H. J. Preece, S. Abdullah and H. L. Beyer (2017). "Strategies to conserve the koala: cost-effectiveness considerations." Australasian Journal of Environmental Management **24**(3): 302-318.

Tsangaras, K., M. C. Avila-Arcos, Y. Ishida, K. M. Helgen, A. L. Roca and A. D. Greenwood (2012). "Historically low mitochondrial DNA diversity in koalas (Phascolarctos cinereus)." BMC Genet **13**: 92.

Turner, S. (2009). "Negotiating Nostalgia: The Rhetoricity of Thylacine Representation in Tasmanian Tourism." **17**(2): 97.

Ullrey, D., P. Robinson and P. Whetter (1981). "Composition of Preferred and Rejected Eucalyptus Browse Offered to Captive Koalas, Phascolarctos Cinereus (Marsupialia)." Australian Journal of Zoology **29**(6): 839-846.

Wedrowicz, F., W. Wright, R. Schlagloth, F. Santamaria and F. Cahir (2017). "Landscape, koalas and people: A historical account of koala populations and their environment in South Gippsland." Australian Zoologist **38**(4): 518-536.

Weston, M. and P. Gannon (2014). Corrective Action Verification Audit (CVA) Report. Victoria, Rainforest Alliance.

Whisson, D. A., V. Dixon, M. L. Taylor and A. Melzer (2016). "Failure to Respond to Food Resource Decline Has Catastrophic Consequences for Koalas in a High-Density Population in Southern Australia." PLOS ONE **11**(1): e0144348.

Whisson, D. A., G. J. Holland and K. Carlyon (2012). "Translocation of overabundant species: Implications for translocated individuals." The Journal of Wildlife Management **76**(8): 1661-1669.

Wilks, S. L. (2008). "Different Portrayals of Koalas on Kangaroo Island: What Gets Whose Attention (and What Doesn't)." Australian Zoologist: 22-32.

Wilson, D. P., A. P. Craig, J. Hanger and P. Timms (2015). "The paradox of euthanizing koalas (Phascolarctos cinereus) to save populations from elimination " J Wildl Dis **51**(4): 833-842.

Woinarski, J. and A. A. Burbidge (2016). Phascolarctos cinereus. The IUCN Red List of Threatened Species 2016.

Appendix 2: Description of the thermal cameras and hyperspectral sensors used in this study.

Visible Light Sensors

Red-green-blue or RGB cameras create images using the visible components of the electromagnetic spectrum. Visible light reflected by objects excites the camera's Bayer filter, allowing photons of certain frequencies to excite the sensor's mosaic arrangement of RGB-tuned photo receptors (pixels). Each charge coupled device (CCD) array represents a red, green or blue channel that converts the amount of reflected light at the relevant wavelength into an amount of charge, which can be stored. The colour image is then generated by combining the charge for the three channels. The wavelength range for visible light is 400-700 nm, with 400-500 nm, 500-600 nm, and 600-700 nm for blue, green and red channels, respectively.

Hyperspectral Near Infrared (NIR) Sensors

While RGB cameras have three channels, hyperspectral cameras measure the illumination within hundreds of channels and they typically cover a larger spectral band within the near infrared (NIR) component of the spectrum, 400-2,400 nm. The large number of channels provides much more information about the spectral response of the object, which is akin to knowing about the surface chemistry of the object. Hyperspectral object identification is thus typically made by analysing the spectral and spatial information of the observed object. There are four main approaches to acquiring hyperspectral data: spatial scanning, spectral scanning, non-scanning and spatio-spectral scanning.

Spatial scanning technique refers to a line (push broom) or point (whisk broom) scanners where each scan acquires information from the whole spectral range. In spectral scanning technique, each scan acquires information from a single spectral band for the whole spatial area, and to acquire information for the whole spectral band, the sensor is required to be stationary. In a non-scanning (snapshot) technique, all the spatial and spectral information are acquired at the same time. In spatio-spectral scanning technique, each scan acquires information from a specified spectral band and to obtain all the spatial and spectral information, the sensor is required to be moved.

Infrared Sensors

Infrared (IR) cameras capture images using radiation and can be divided into three types based on the range of radiation wavelength: Short wave infrared (SWIR), mid wave infrared (MWIR), and long wave infrared (LWIR) are (1,000-2,500 nm), (2,500-5,000 nm), and (7,000-14,000 nm) respectively. IR cameras can differentiate between objects based on heat differences. The infrared radiation received by a thermal camera is composed of the accumulation of the thermal radiation emitted by the object directly, the radiation reflected by other objects, and the radiation emitted by the atmosphere (noting that the atmosphere also absorbs the thermal radiation emitted by the object).

The visible light, hyperspectral and SWIR, MWIR and LWIR cameras are of great importance to be used in object detection since they acquire detailed information from different spectral bands in the electromagnetic spectrum which can be used to detect objects in several environments. There are a wide range of other sensors. However, these are not of significance to this research.

Appendix 3: Example of a Proposed App.

One line of investigation to assist in decision-making was a smartphone application that helps foresters select the optimal koala detection method for a given plantation site on a given day. It is based on the premise that UAV detection is always the *preferred* solution, due to its superior detection capabilities over human spotters and the inherent risks to spotters when working on the forest floor during harvesting. However, there are certain site attributes and climatic conditions that prevent UAV detection from taking place. In such cases, the app will suggest the next best detection method, based on the measures of "success" assessed during this project (accuracy, safety, efficiency, etc).

Similarly, if the "next best" method is also limited by site conditions, foresters must then weigh the risk of false negatives (failure to detect a koala prior to tree harvest) against the need to harvest the site in question. In areas of very high koala density, the risk may be too high.

Accessing (or building) datasets related to site attributes such as koala density, weather, and topographical and geographical features, will permit the integration of GIS overlays into the app. This would allow the decision-making process to become increasingly automated over time, however, in its infancy the application would rely on such data being input by the foresters.

We have included a basic outline of how this may work but at this point we believe there is no effective alternative to spotters in high density koala sites if UAVs cannot be used, therefore we did not complete development of this proposed tool.

<u>Background assumptions guiding decision</u>

Site attributes that prevent UAV detection entirely:

Airstrip within 5km of the site
Overhead powerlines within site/on site boundary
No line of site for drone pilot (lack of cleared space adjacent to forest)

→ If any condition is met, suggest the next best detection method.

Climatic conditions that prevent UAV detection entirely:

Wind speeds >60kmph(?)
Rain?

→ If any condition is met, suggest the next best detection method.

→ If site attributes and climatic conditions <u>allow</u> for UAV detection:

Site attributes that make UAV detection challenging:

Presence of wedge-tailed eagles in the area

→ If condition is met, application provides warning and weighs risk against koala density (high koala density, still use UAV? Lower density, use next best detection method).

Climatic conditions that make UAV detection challenging:

Temperature >35 degrees celsius

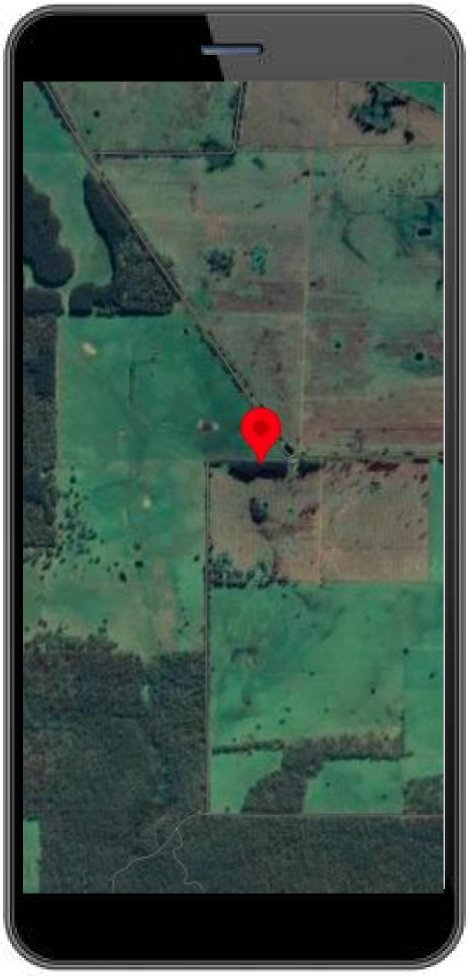
→ If condition is met, application provides warning and weighs risk against koala density (high koala density, still use UAV? Use multiple methods?).

All attributes impacting decision:

- Airstrips (within 5km, drone can’t fly)
- Powerlines (on site, drone can’t fly)
- Line of site (if poor, drone can’t fly)
- Wind speed (high - spotters preferred, drone can’t fly)
- Rain (heavy - spotters preferred, drone can’t fly?)
- Wedge tailed eagles (if present, drone risky)
- Temperature (if high, infrared may struggle)
- Tree height (high - drone preferred, spotters less reliable) 25m too high for spotters
- Terrain (steep - drone preferred, difficult for spotters to traverse)

Procedure

Step 1: user manually enters site coordinates or drops location pin on Google map.



Using GIS layer [airstrips] application confirms:

No airstrip within 5km
Proceed to Step 2a

Airstrip within 5km
Proceed to Step 2b

Step 2a: application prompts user to zoom in on the site, so that the target area is wholly within the yellow box on the screen.

Using GIS layer [powerlines] application confirms:

No powerlines on site/boundary
Proceed to Step 3a

Powerlines on site/boundary
Proceed to Step 2b

Step 3a: application prompts user to conduct visual inspection of aerial imagery and/or on-site assessment, and asks whether there is cleared land adjacent to the site to allow for line-of-sight.

Cleared space present
Proceed to Step 4a

No cleared space
Proceed to Step 2b

Step 4a: user enters the proposed date for the harvest, within the next seven days.

Using Bureau of Meteorology data, application confirms:

Favourable weather conditions
Proceed to CASA approval

Unfavourable weather conditions
Proceed to Step 2b

Step 2b: UAV-based detection not possible.
Default to spotters (further options could be incorporated once technologies are developed).