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Revegetating koala habitat

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Purpose statement

The purpose of this document is to provide guidelines for revegetating koala habitat that incorporate current knowledge of koala habitat requirements and nutritional ecology from peer-reviewed literature. This document is not intended to provide instruction for growing or planting vegetation per se, although we suggest further reading and resources for this information in Appendix A and B. The aim of this document is to outline and discuss important considerations for revegetation where the goal is to restore or improve koala habitat. This information can be used by landscape managers and restoration practitioners to assess or refine the implementation of revegetation initiatives for koala management and conservation.

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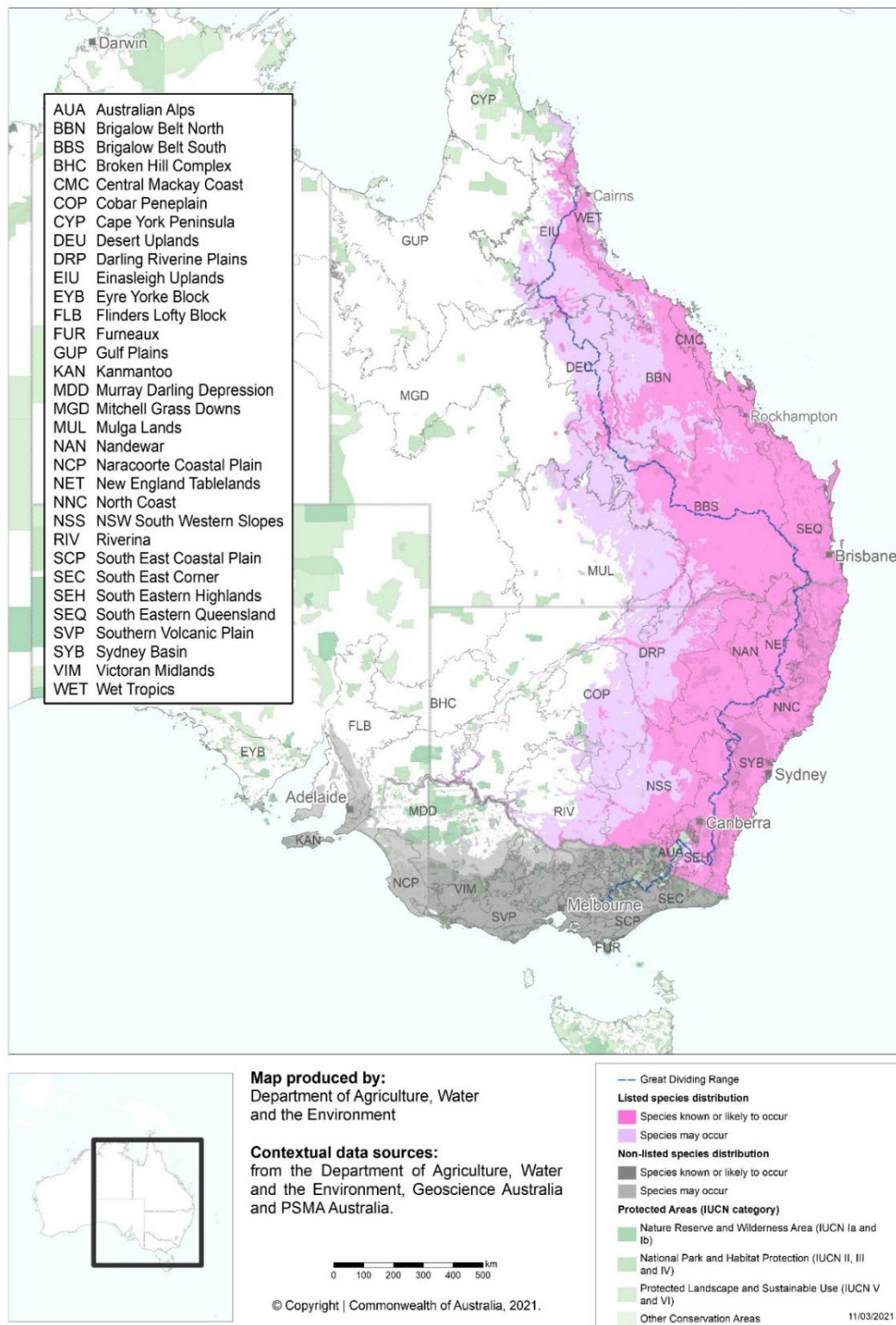
Introduction

The koala (*Phascolarctos cinereus*, Goldfuss 1817) is an iconic, marsupial folivore found in eucalypt forests and woodlands in eastern Australia, including Queensland, New South Wales, Victoria and South Australia (Map 1). Koalas are primarily nocturnal. They shelter on branches during the day and feed mostly from the leaves of eucalypts at night, usually moving between trees on the ground. The presence of koalas depends in large part on the presence and abundance of suitable koala food trees, the leaves of which make up most of their diet.

Koala numbers have declined substantially across large parts of their range and particularly in NSW and Queensland, due to key threatening processes (McAlpine et al., 2015, Ashman et al., 2019). Habitat loss and degradation have significantly reduced the quantity and quality of suitable koala habitat and may also increase the exposures to or severity of other threats including disease, predation by dogs and vehicle strike. Remaining areas of koala habitat are becoming increasingly fragmented due primarily to human activities, which can influence koala movement and landscape use, home range size, and population and metapopulation dynamics. Increasing severity and frequency of heatwaves, drought and fires as a result of climate change also have contributed substantially to declines in koala populations. A comprehensive review of threats to koalas can be found in the National Recovery Plan for the Koala, *Phascolarctos cinereus* (combined populations of Queensland, New South Wales and the Australian Capital Territory)(AWE, 2022).

Revegetating disturbed or cleared land to restore koala habitat or increase connectivity between other areas of suitable forest and woodland can help mitigate habitat loss, degradation and fragmentation. This report will provide advice on revegetating koala habitat based on peer-reviewed literature that incorporates current knowledge of koala habitat requirements and nutritional ecology. Restoring koala habitat involves identifying appropriate areas to revegetate based on the goals of the program and other landscape considerations, planting locally appropriate trees that will meet the koala's habitat requirements in terms of food, shelter, and movement, and mitigating other threatening processes that may prevent koalas or their resources from persisting in the area. The success of revegetation initiatives can be influenced by the provenance, composition and structure of plantings, the proximity and connectivity to existing koala populations, land tenure, and threat mitigation. Monitoring also plays an important role in assessing the outcomes and success of revegetation programs and responding to threats to seedling establishment, including weeds and predation by other herbivores.

Map 1: Distribution of the Koala



Source: Department of Agriculture, Water and the Environment 2021. This map shows the area where the koala is known/likely and may occur based on information from a range of groups and agencies. The Listed species distribution refers to the EPBC Act listed koala populations of Queensland, New South Wales and the Australian Capital Territory and are indicative only. While every effort has been made to ensure accuracy and completeness, no guarantee is given, nor responsibility taken by the Commonwealth for errors or omissions, and the Commonwealth does not accept responsibility in respect of any information or advice given in relation to, or as a consequence of, anything containing herein.

1 Habitat requirements

Koalas live in a wide range of different forest and woodland environments from dry, semi-arid woodlands to wet coastal forests (Fig 1). Primarily folivorous (leaf-eating), koalas are known to feed from over 100 different tree species, mostly but not entirely within the *Eucalyptus* genus (for example Phillips and Callaghan, 2000, Phillips et al., 2000, Moore et al., 2005, Smith, 2004, Youngentob et al., 2021b). However, in any given area, the number of tree species that contribute to the diet of koalas are often relatively small and typically less than the total number of tree species available. Browsing preferences depend in part on the suite of species available, their nutritional quality, and other factors that are not entirely understood but may involve individual differences in microbiomes and experience with potential foods (Blyton et al., 2019, Blyton et al., 2022). The specific habitat associations of koalas are not generalisable across their range, and should be examined at local population or metapopulation scales to understand the dietary preferences and habitat requirements of koalas in a particular area (McAlpine et al., 2008).

Drawing on the region-specific work of both NSW and Qld state governments to identify locally important tree species for koala habitat, a report on koala habitat requirements combined NSW's Koala Modelling Regions (KMRs) and Queensland's Bioregions to create Koala Management Bioregions (KMBs, Map 2; Youngentob et al., 2021b). Within KMBs, locally important koala trees (LIKT) have been identified through a combination of existing literature and expert solicitation. LIKT are trees from species that are regularly browsed by koalas, such that it could be considered a substantial portion of the koalas' diet (Youngentob et al., 2021b). The amount that a koala will feed from a tree, or its palatability, is strongly influenced by key foliar nutrients and plant secondary metabolites (PSMs), the concentrations of which vary from tree to tree, even within the same species. Koalas typically prefer foliage that is relatively high in digestible protein but are deterred from feeding by high foliar concentrations of formylated phloroglucinol compounds (FPCs), unsubstituted B-ring flavanones (UBFs), and tannins (Moore et al., 2005, Moore et al., 2010, Marsh et al., 2014, Au, 2018, Au et al., 2019, Marsh et al., 2019, Marsh et al., 2021a). The foliar concentrations of these chemicals have a strong genetic component, which contributes to within and between species variation in nutritional quality that influence what koalas choose to eat. A tree species that is highly palatable in one region may be largely ignored by koalas in another, and individual trees from typically preferred browse species occurring in the same area may be ignored for the same reason. This is why it is important for plantings to incorporate locally preferred browse species as well as genetic, and therefore chemotypic diversity. This point and strategies to accomplish this are discussed further in section 4.2.

Figure 1: Examples of landscapes that can support koala populations (a small subset of the diversity of forest and woodland environments in which koalas can live)



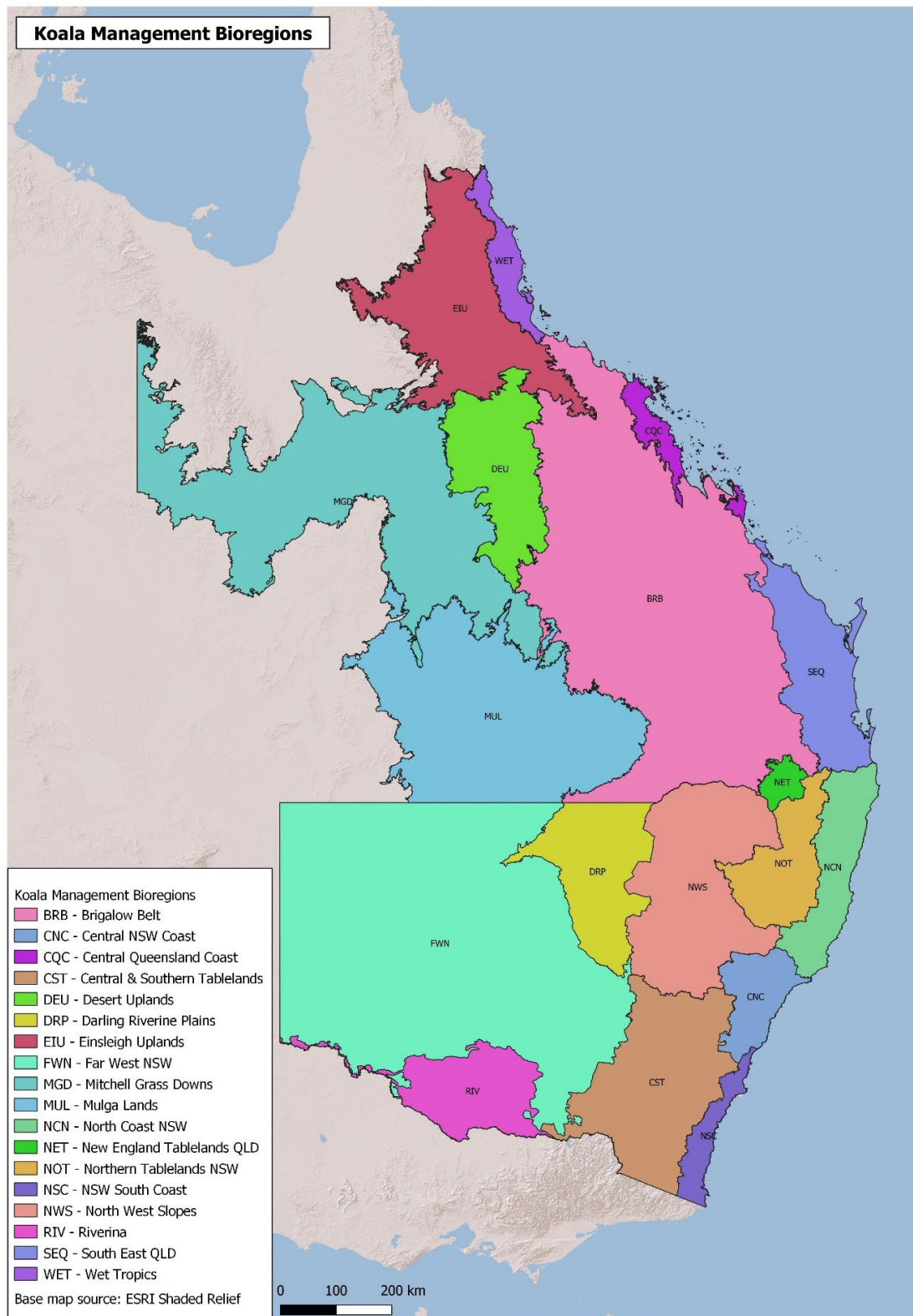
Within koala habitat, some tree species may also be important for other ancillary functions such as shelter during the day (see Youngentob et al., 2021b for KMB specific lists of ancillary trees). Koalas often choose to rest in trees that provide some thermoregulatory support, which can be achieved by selecting trees with dense canopies, particular bark types and larger thermal mass (that is, size; Ellis et al., 2010, Briscoe et al., 2014). While the trees koalas rest in are often the same trees they feed from, this is not always the case and unpalatable roosting trees may be selected for structural attributes alone. In some areas, these ancillary habitat trees can be essential for koala persistence, although koalas will not be present unless there are also LIKT for feeding, and the abundance of koalas is strongly linked to the overall nutritional quality of trees in a landscape (Au, 2018). Other habitat elements such as the proximity to water or cooler mesic areas may also become more important as the climate warms, and likely already influence the persistence of populations in the western extent of the koala's range (Gordon et al., 1988, Smith et al., 2013).

The amount of habitat required to support a population is poorly understood, and definitionally difficult (Youngentob et al., 2021b). This is due in part to disagreements over what constitutes a population and also due to variation in resource quantity and quality across the range of the koala that contributes substantially to differences in habitat area requirements. The minimum spatial extent needed to support individual animals or populations is further complicated by the fact that koalas often live in highly fragmented landscapes. Therefore, the size required for replantings to support koala populations cannot be determined on the basis of "one size fits all."

Although the definition of minimum habitat required to support a koala or koala populations is highly variable, home-range data for koalas in a similar area to the proposed planting can help guide estimates. The home range of an individual koala may be as small as 1 ha (for example Ramsay, 1999, White, 1999, Ellis et al., 2011, Goldingay and Dobner, 2014) or over 100 ha (for example Melzer and Lamb, 1994, Ellis et al., 2002, Davies et al., 2013). In western NSW and Qld, home ranges are typically larger than in the eastern part of the koala's distribution, except where they occur in relatively small patches of riparian vegetation and the scattered trees that surround those areas (Kavanagh et al., 2007, Ellis et al., 2002, Davies et al., 2013, Crowther et al., 2021). Local information on koala habitat requirements and the goals of the restoration project can help guide decisions about the extent of revegetation needed. Some states do provide guidelines for minimum area. For example, the NSW koala habitat restoration guidelines recommend a minimum revegetation area of 2 ha for an individual animal and at least 50-100 for a population, while also recognising that this amount can be highly variable across the koala's range (DPE, 2022; for example 100 Ha in the Southern Highlands).

Despite the variability and uncertainty around minimum area habitat requirements, what is clear is that improving connectivity of koala habitat is helpful at multiple scales from targeted, plantings of scattered trees (for example, across paddocks) to larger multi-hectare plantings of locally appropriate woodland or forest that increase the overall mosaic of vegetation coverage across wider areas. Connectivity in this context describes the extent to which the landscape facilitates or impedes animal movement or ecological processes. Koalas, often subadult males but also females, are known to disperse large distances across the ground (Melzer, 1995, White, 1999, Dique et al., 2003b, Matthews et al., 2016). Even within their home range, koalas traverse along the ground between isolated trees or patches of vegetation. Although koalas often persist in highly fragmented landscapes, such as urban and peri urban environments, habitat fragmentation and the need to move large distances across open ground to access food and shelter is energetically expensive and exposes animals to significant threats including motor vehicle collision and dogs. Improving connectivity where possible will help mitigate some of these threats and increase the overall quantity and quality of habitat.

Map 2: Koala Management Bioregions for the EPBC Act-listed species across NSW, ACT, and Qld. The distribution of the koala does not include the entire area of all KMBs. The probable distribution of the koala is provided in Map 1.



Source: from A review of koala habitat assessment criteria and methods by Youngentob et al. (2021b).

2 Reasons to revegetate

2.1 Mitigate habitat loss and degradation

- Natural and anthropogenic disturbance can result in the loss and degradation of koala habitat
- Degradation often follows disturbance and can be temporary or it may result in long term changes to species composition
- Revegetation can help to restore koala habitat; however, this also requires addressing other threats that are present
- Burnt landscapes can continue to provide good habitat for koalas and allowing these landscapes to recover naturally may be the best approach in many, but not all, situations

Habitat loss and degradation can occur as a result of anthropogenic or natural events, such as land clearing, wildfire, prescribed burns, catastrophic weather, timber harvesting, mineral mining, invasive exotics, die-back and drought. Habitat loss is the loss of suitable conditions required for a species to be present in a landscape (Youngentob et al., 2021b). Restoring these landscapes to habitat requires addressing any on-going threats, such as feral dogs and vehicle strike, as well as insuring that replanted vegetation composition and structure is appropriate for the climate/environment and will support local koalas. Some areas of lost habitat may never be able to support populations of koalas again due to ongoing threats that cannot be mitigated or changes in climate that make a particular area unsuitable into the foreseeable future. Restoring habitat in areas that are too isolated from other habitat may also fail if koalas are unable to immigrate or disperse. However, it is important to remember that even scattered vegetation interspersed with fragmented patches of forest and woodland can support koalas and koala populations. Therefore, there can be value in revegetation initiatives that are relatively small (for example, planting scattered trees) but that may improve the habitat value and connectivity of otherwise highly fragmented landscapes.

Habitat degradation is a reduction in the quality of habitat that affects the survival, health and/or reproductive fitness of animals in that landscape and ultimately reduces the carrying capacity, or number of animals that a landscape can sustainably support (Youngentob et al., 2021b). Degradation often, but not always, follows landscape disturbance. Disturbance can result in both short-term and long-term changes in vegetation composition and structure (Lindenmayer and Fischer, 2013). Depending on the type and severity of disturbance, some landscapes are able to recover to their previous state without intervention, given sufficient time and respite from additional disturbance. For example, eucalypt forests in the Sydney basin recovered largely to their pre-fire state within 5 years of fire (Heath et al., 2016). However, where disturbance kills a substantial proportion of the canopy trees, it is more likely that regrowth may not have the same composition or structure as the original landscape due to changes in competition dynamics and/or microclimates that can favour a different suite of species regenerating (for example Lutze and Faunt, 2006). Without intervention, the changes to these landscapes can persist much longer, and when this type of landscape change alters the environment in a way that decreases habitat quality for koalas and other species, intervention is required to return the landscape to its former composition and structure. The aim of revegetation to mitigate habitat loss and degradation is typically to restore habitat quality to a similar condition and carrying capacity to what it was previously.

Although fire can result in habitat degradation, it is not always permanent as referenced above. A comprehensive review of the effects of fire on koalas and koala habitat is provided in Beale et al. (2022) but we will touch on a few key points here as they relate to revegetation. Many eucalypt forests have evolved with regular fire and have specific adaptations that allow them to recover from this form of disturbance. In many cases, the best approach may be to allow natural regeneration. There is no evidence that the removal of mature burnt trees after fire improves habitat recovery or is beneficial for koalas. Salvage logging can remove an important source of food after fire when the tree species that are harvested would otherwise provide palatable and nutritious epicormic regrowth. Although koala densities can be reduced by high-severity fire (Phillips et al., 2021; Law et al., 2022), surviving individuals can live wholly within burnt habitat (Matthews et al., 2016; M. Lane et al. unpublished data). These individuals can traverse areas that lack intact canopy and are sometimes observed resting in dead trees during the day (M. Lane et al. unpublished data). The epicormic regrowth on some eucalypt species can be higher in nutritional quality for koalas than the mature canopy leaves, which may be important for koala population recovery (Marsh et al., 2021b). However, in some forest types, fire can alter forest species composition in ways that are detrimental to the nutritional landscape for koalas. Intervention to restore the previous tree species composition, including thinning less palatable tree species that can proliferate after fire, may be needed in these areas (Au et al. 2019).

2.2 Improve connectivity

- Koalas can move large distances across the ground, but this comes at a cost to energy reserves and increases the risk of other threats such as vehicle strike and predation
- Even small patches, strips, and isolated trees can provide valuable stepping stones to increase connectivity and overall habitat area, and they help koalas move safely
- Proximity of revegetation to existing, occupied koala habitat influences the chance that koalas will use the restored area as well.

Habitat fragmentation is a significant threatening process for koalas (Ashman et al., 2019, Hume, 1990) and increasing connectivity through targeted revegetation in otherwise open space between larger areas of forest or woodland is beneficial (Rhodes et al., 2008, Rus et al., 2021). Even narrow corridors of vegetation or tree lines are often used by koalas and can facilitate movement between larger vegetation patches (Barth et al., 2019). However, it is important to recognise that koalas can easily move 100–200 metres between trees provided there are no barriers (for example fences, buildings, water bodies, other structures) or threats (for example predators) and disperse for longer distances across open ground, which suggests that movement is not entirely reliant on corridor systems (White, 1999). On floodplains in northern NSW, female koalas can travel more than 500 metres between koala food trees, across cleared grazing paddocks (Davies et al., 2013). Some tracked koalas have walked several kilometres cross-country (Lunney et al., 2012). Although covering these distances is possible, they come at the cost of energy and risk to the koala (Rus et al., 2021).

Any reduction in distance between habitat patches provided by corridors or even scattered trees as stepping-stones can help koalas move more safely through the landscape and increase the overall carrying capacity of a landscape for koalas when more food trees are planted. In addition to providing food, trees planted in open space to improve connectivity also provide shelter from elements and offer safe refuge from most predators. Revegetation activities should aim to be connected with or close to existing koala habitat where possible, as previous research has

indicated that this has a strong influence on the likelihood that koalas will utilise newly vegetated areas (Kavanagh and Stanton, 2012).

2.3 Remediate a disturbed site

- Revegetated areas that contain appropriate vegetation structure and composition can support koalas even after largescale landscape disturbance if other threats are mitigated
- Additional research is needed to determine the relative value of onsite koala habitat enrichment compared to offsetting strategies.

Remediation is often undertaken following largescale anthropogenic landscape disturbance (for example open cut mining or quarry activities) where revegetation and other activities are implemented to rehabilitate an area in line with public expectations (Hobbs et al., 2004). Recent research has demonstrated that revegetated former mine sites can support koala populations with similar body condition and reproductive health as koalas in nearby undisturbed habitat when the revegetation strategy and methods support an appropriate vegetation composition and structure for koala habitat (Cristescu et al., 2021). Like any revegetation initiative, the success is influenced by the mitigation of other threats (Beyer et al., 2018), appropriate selection of vegetation for the location (Duguma et al., 2020), and proximity to existing koala habitat (Kavanagh and Stanton, 2012).

Although environmental offsets are the typical approach to compensate habitat loss due to development or other anthropogenic landscape change, actions to restore and improve areas of remaining habitat within the development site can also be beneficial to the local koala population if other threats can be mitigated (for example traffic, dogs, disease; Beyer et al., 2018). Additional research is needed to determine the relative value of increasing habitat quality on-site compared to, or in addition to offsetting by conserving land off-site across a variety of different land use purposes. Achieving true like-for-like offsets in close proximity to the development site would help protect habitat for local koalas into the future. However, like-for-like is not always achieved, and there is value in preserving and/or improving on-site habitat where possible for local koalas that may otherwise be displaced and/or perish. Section 2.4 discusses ways in which both on-site remediation and enrichment of existing forest and woodlands may be able to increase carrying capacity to partially compensate for habitat loss and degradation.

2.4 Increase carrying capacity

- The density of koalas is strongly influenced by site nutritional quality in terms of foliar nutrients and herbivore deterrent PSMs
- Planting more palatable chemotypes should increase the koala carrying capacity of an area; however, this has not been tested in eucalypt-folivore systems specifically
- Additional effort in tree seed and/or seedling selection is needed to increase the likelihood that highly palatable chemotypes of LIKTs are selected for enrichment planting
- Planting only highly palatable browse can lead to over browsing if a more diverse range of food quality is not already present in the landscape.

The density of koalas in areas where they occur is strongly influenced by the average site nutritional quality (Au, 2018). This finding follows on from a large body of research showing

clear relationships between the nutritional quality of trees and tree choice, total intake, and reproductive success of eucalypt folivores (Moore et al., 2005, Marsh et al., 2007, Youngentob et al., 2011, Windley et al., 2013, DeGabriel et al., 2014, Au, 2018). It is thought that animals are attracted to areas with the best quality food because it allows them to obtain the most energy for the least amount of energy expenditure (that is, optimal foraging theory; Stephens and Krebs, 2019). It is also widely accepted that landscapes with higher productivity in the form of available energy support a greater abundance of animals (that is, a higher carrying capacity) than less productive areas (Wright, 1983, Youngentob et al., 2015).

Importantly, available food for koalas is not only measured in terms of key limiting nutrients like digestible protein, but also in foliar concentrations of herbivore deterrent PSMs that limit food intake, and therefore the amount of energy an animal can obtain (Marsh et al., 2007). Given the strong genetic component to the nutritional quality of eucalypts, it is theoretically possible to increase the available energy for koalas at most sites in which eucalypt forests and woodlands can grow by planting trees from more palatable chemotypes of LIKTs (Andrew et al., 2010, Andrew et al., 2007). This in turn could increase the number of koalas at a site and potentially its overall carrying capacity. However, planting only highly palatable trees would also substantially increase the risk of overbrowsing and overabundant populations that could not be sustained by the trees in the long-term. Incorporating diversity at multiple scales can help mitigate this risk and this idea is discussed in more detail in section 4.2.

Although there is a strong theoretical basis for the assumption that planting higher nutritional quality food trees and incorporating chemical diversity in browse trees leads to more koalas per unit area, it has not been tested through statistically robust, landscape-scale experiments in eucalypt-folivore systems. However, similar principles are used in agriculture to adjust pasture and diet composition to influence livestock health, growth and stocking rates (Provenza et al., 2003, Gregorini et al., 2017). Despite some uncertainty, it is likely that targeted planting of higher nutritional quality trees in existing koala habitat as a form of habitat enrichment could result in more koalas in that area over time, but more research in this area is needed. Given that tree species alone does not dictate nutritional quality, additional effort in tree seed and/or seedling selection should be undertaken to increase the likelihood that highly palatable chemotypes of LIKTs are selected for enrichment planting aimed at increasing the carrying capacity of existing habitat ([see section 4](#)).

3 Site selection

3.1 Goals of the revegetation project

- The goals of the revegetation program should be used to guide site selection
- Understanding what factors resulted in loss or degradation of habitat on a site is important
- If the goal is to enhance connectivity, then replanting should occur in more open areas adjacent or within close proximity to larger patches of occupied koala habitat
- If the goal is to improve carrying capacity, a site should be chosen that can be improved by target planting of high-quality browse. This may also be accompanied by selective thinning of poorer quality browse where it has proliferated due to disturbance.

Considering the goals of the revegetation program is a critical first step in deciding on an appropriate site to revegetate so that the objectives can be met. Revegetation programs may aim to create new koala habitat where it has been lost, increase the quality or carrying capacity of existing habitat, or improve habitat connectivity between isolated forest or woodland areas.

If the aim is to restore koala habitat where it has been lost or degraded, an appropriate site is likely one that was koala habitat historically, but that has been cleared and/or altered through disturbance, as the landscape features and environmental conditions are likely to support the local vegetation types required for koala habitat. However, understanding the initial cause of the vegetation/habitat loss is important to avoid a similar fate befalling the landscape and resulting in habitat loss again in the future (for example dieback, climate, land tenure that allows clearing). Proximity to existing, occupied koala habitat improves the likelihood of restored habitat being utilised as well (Kavanagh and Stanton, 2012).

If the revegetation program aims to enhance connectivity between existing patches of koala habitat in forests or woodlands, then the program should identify isolated or semi-isolated habitat with areas between that could be revegetated to restore or improve koala movement across these landscapes. It is important to keep in mind that koalas can move large distances across the open ground (Davies et al., 2013, Lunney et al., 2012), and the amount of open space that would not be possible or safe for a koala to traverse would vary from place to place and interlink with the presence of other threats. Even individual trees in otherwise open areas can act as stepping stones for shelter and food when a koala is dispersing across the landscape. Practical and local environmental considerations may then determine whether the revegetation program aims to more densely revegetate a corridor or whether it is limited to planting scattered trees within a landscape to aid dispersal.

If the goal of the revegetation program is to improve the carrying capacity of a particular area, then a site should be chosen that has the potential to be improved through targeted planting of higher nutritional quality browse. The revegetation stock should be comprised of the most highly browsed locally important koala tree species. However, care should be taken to ensure that a diversity of nutritional quality browse is also present in the landscape, including less browsed and ancillary habitat trees to avoid over-browsing, which can happen when the majority of trees have very high nutritional quality and low diversity (Martin, 1985). Carrying capacity can also be improved by first thinning, or removing very low nutritional browse species that may have proliferated due to disturbance (for example silvertop ash; Au et al., 2019), and then replanting with a locally appropriate suite of higher nutritional quality, locally important koala tree species. In these landscapes, the existing ground and midstory cover can often be

preserved, reducing the amount of additional vegetation that needs to be planted along with the locally important koala tree species.

3.2 Current and future climate

- The effects of climate change on koalas are already apparent with range retraction, fire associated mortality, reduced food intake, and uncharacteristic drinking of free water
- Modelling can be used to determine the likelihood that an area will be bio-climatically suitable for koalas in the future
- Climate change will also impact the palatability, distribution and abundance of koala food trees in the future
- Koalas may select trees for resting in based on their thermal properties and these should be considered for inclusion in revegetation projects
- Edge effects, which include hotter microclimates, are less pronounced in larger habitat patches and smaller edge to area ratios of plantings

The frequency and severity of droughts, heat waves and fire are increasing across the range of the koala due to anthropogenic climate change (Bowman et al., 2021). Existing mechanistic models can be used to focus habitat restoration activities in areas that are likely to remain within the bioclimatic tolerance zone of the koala and the trees selected for planting (Briscoe et al., 2016, Adams-Hosking et al., 2012). Structurally and compositionally well-designed plantings and appropriate site selection also can positively influence microclimates to help mitigate the consequences of extreme heat and drought events that are increasing due to climate change.

The effects of climate change on koalas are already apparent. In the more arid western extent of the koala's range, intensifying periodic drought and heatwaves have resulted in lower koala numbers and a retraction in distribution (Gordon et al., 1988). Mechanistic niche models predict that many of these areas, particularly in the west, will no longer provide suitable habitat by 2070 due to heat induced water stress (Briscoe et al., 2016). Koalas obtain most of their water through their diet and ongoing heat often associated with drought can cause lower food intake at the same time as hot conditions cause increased water demand for thermoregulation (Beale et al., 2018, Youngentob et al., 2021a). This combination has resulted in observations of wild koalas uncharacteristically drinking free water. During drought, koalas may retract toward wetter refugial areas such as riparian zones along creek lines that have cooler microclimates (Gordon et al., 1988). Particularly in the western extent of the koala's range, it may be important to ensure that areas selected for revegetation where possible include these ancillary habitat elements to provide refugia in times of heat or drought.

Koalas are relatively exposed to the ambient temperature conditions because they do not use dens or hollows. Koalas have been shown to select certain trees for their thermal properties to rest in when conditions are hot (Briscoe et al., 2014). For example, hugging cooler, smooth barked trees, or sitting in trees with dense canopy shade (Briscoe et al., 2014). Consideration should be given to including tree species that meet these thermal criteria within the species selected for revegetation. If the diversity of plants selected matches good koala habitat locally, then these trees will likely be included by default. While some trees serve a purpose of both food and shelter, trees that are less important for browsing but could be important for thermoregulation are typically identified as ancillary habitat trees in Youngentob et al. (2021b).

Edge effects influence the microclimatic features of a forest such that closer to the edge of a stand of trees, the temperature is less buffered from radiant heat and winds (Craig et al., 2015, Parkins et al., 2018, Murcia, 1995). This means that revegetation programs with a smaller edge to area ratio (that is, patch rather than strip shape and larger patches where possible) would be better from a thermal perspective than strips of vegetation or smaller patches. Modelling work has also suggested that koalas are more likely to occur in landscapes with larger habitat patches (McAlpine et al., 2006). Likewise, cooler microclimates within a landscape, such as south facing slopes, gullies and creek lines, may become more important to the persistence of koalas in the future.

In addition to causing direct physiological stress to koalas, heatwaves and droughts also can cause stress and mortality to vegetation. Dieback of eucalypt and corymbia forests and woodlands as a result of drought and warming has already been observed (Nolan et al., 2021). The distributions of many important koala food trees are also likely to contract under modelled future climate scenarios (Adams-Hosking et al., 2012), and koalas can only persist where they have food. The palatability of food trees that do survive in areas with hotter and drier climates may also decline. For example, increased carbon dioxide, and heat stress may result in higher PSM and fibre concentrations, and drought may result in lower leaf moisture (McKiernan et al., 2016, Niinemets, 2015, Holopainen et al., 2018, McKiernan et al., 2012], Ellis et al., 2010, Ellis et al., 1995). However, this is an area of ongoing research and results from controlled experimental manipulations of climatic conditions may not always translate to the same effect in natural settings due to multiple interacting factors (for example Holopainen et al., 2018, McKiernan et al., 2012).

3.3 Threats

- Modelling suggests that addressing habitat loss alone is not sufficient for koala populations to recover. Revegetation programs should be integrated with other threat control programs.
- Predation by wild dogs is a significant cause of mortality in some populations, and these populations may already be below the carrying capacity of the habitat
- Revegetation projects should be away from major roads if possible, as vehicle strike can be a significant cause of death
- Chlamydial disease causes mortality, morbidity and reduced reproductive rates in koala populations which may impede population recovery.

When considering revegetating a site, the existence of other threatening processes should be closely examined as these may prevent the successful establishment of a koala population in the area, even once properly revegetated. These threats also may have contributed to the decline of koalas in the area historically. Key threats to consider are dogs attacks, nearby vehicle traffic, and disease. Given steep population declines in some areas due to these threats, many koala populations may already be at levels below the carrying capacity of the existing koala habitat.

Particularly in urban and peri-urban populations, vehicle strike can be a significant cause of mortality and contribute to decline in koala numbers (Lunney et al 2012). Both total mortality and the proportion of that mortality arising from vehicle collisions increases with reduced forest cover (Rhodes et al 2011). Death from vehicle collisions may reduce the population recovery potential of a revegetation program. Roads can impede the safe movement of koalas across the landscape, and the majority of koalas hit by cars are young healthy males who are likely dispersing (Dique et al 2003). Ideally, revegetation programs should be away from major roads,

highways, arterial, or sub-arterial roads if possible, to reduce the likelihood of vehicle strike, and/or strategies to encourage safe passage and connectivity between populations should be implemented (for example, overpasses/underpasses). While koalas can cross roads, their ability to do so safely, and hence whether a road could be considered a barrier to movement, depends on traffic volume, speed limit along the road, and a number of other interacting factors (Dique et al., 2003a).

Although koalas have survived in landscapes with wild dogs for thousands of years, dog attacks can account for a significant proportion of koala deaths. In one study examining population declines in northern Queensland, predation accounted for 49.5 – 62.5% of deaths, with 81.3% confirmed to be wild dogs and a further 4.2% from domestic dogs (Beyer et al, 2018). Through intensive management of wild dogs and disease, the population began to experience growth. This study highlighted how wild dogs can be an overlooked cause of low koala numbers and the need for intensive predator control programs to mitigate this threat. For example, a single wild dog in the study was responsible for 75 koala deaths in a four-year period, indicating that even low numbers of dogs in an area can have a substantial impact on populations. Further, given the low koala numbers due to other key threats, the population was below carrying capacity of the koala habitat in that area. Predation of koalas by wild dogs will also depend on other factors such as the presence of other prey species in the area. It is possible that predation pressure from wild dogs is greater now than what it would have been historically due to a loss in the diversity and abundance of other prey species and/or because habitat fragmentation causes koalas to spend more time on the ground to move between trees where they are vulnerable to predation.

Disease is a significant cause of koala mortality, and stress from habitat loss may increase susceptibility to disease (Bonier et al., 2009, Hing et al., 2016, Narayan, 2019, Narayan and Williams, 2016). Chlamydia and koala retrovirus (KoRV) are the two main diseases of concern (Ashman et al. 2019). These pathogens are found in most koalas and many live with the infections and never show outward signs of illness or suffer measurable reproductive consequences (Polkinghorne et al., 2013, Quigley and Timms, 2020). Factors that can cause chronic stress, including anthropogenic disturbance, habitat degradation, heat-stress and poor nutrition are hypothesized to play an important role in the progression from infection to disease, since the production of stress hormones like glucocorticoids have a strong negative impact on the immune system (Narayan and Williams 2016).

Integrated population modelling techniques have been used to examine the relative contributions of different causes of mortality in declining koala populations and the effectiveness of addressing individual factors at preventing population declines (Rhodes et al, 2011). While the relative importance of each threat would vary place to place, addressing habitat loss alone will not halt population declines in many areas (Rhodes et al, 2011). For example, modelling suggests that mortality from dog attacks, disease, and vehicle strike in combination would need to be reduced by 39% or more to tip the population in favour of growth in some areas of SE Queensland (Rhodes et al., 2011).

Addressing habitat loss and degradation is not meaningful in addressing koala population declines unless integrated with other threat control programs (Beyer 2018). This requires examining the relative impacts of different threats in an area and developing aggressive management programs to best address those threats in combination. Integrating threat control

with revegetation programs to restore habitat may also be the most cost-effective way to promote koala population growth (Haijowitz et al 2008).

3.4 Landscape type

- Plant the right trees in the right place and use local vegetation community types as a guide
- Plants are adapted to particular environmental conditions and planting them outside of these conditions or at inappropriate densities can reduce the success of revegetation aimed at restoring koala habitat
- Do not plant forests where they don't belong (for example, wetlands or savannahs)
- Do not plant LIKT in areas where koalas will be exposed to significant threats such as along the side of a busy road.

A broad guiding principle for selecting areas for revegetation is right tree, right place, right purpose. A surprising number of revegetation initiatives plant trees in places where they would not naturally grow in the density typical of forests or woodlands. The most widely cited example of this happening is in relation to carbon offsets (Lindenmayer et al., 2012, Cubbage et al., 2007), although it is a risk in any revegetation project that is too narrowly focused on a single environmental value and does not consider the broader ecological implications of planting large amount of woody biomass in a particular landscape type. Both forests and woodlands require a minimum rainfall gradient to persist and as that decreases, the landscape turns from woodland to savannahs and grasslands (Sala and Maestre, 2014, Bailey, 2014). Both the current and future climate should guide site selection to help determine whether the type of vegetation is appropriate and likely to persist ([see section 3.2](#)).

Grasslands and savannahs are dryer and prone to repeated fire at a higher frequency than is typical for most forest and woodland environments (Sala and Maestre, 2014). These natural processes, now exacerbated through climate change, will negatively impact the longevity of tree plantings in these landscapes and ultimately contribute to carbon emissions, fire severity and habitat loss in the long term (Lindenmayer et al., 2012). However, there are areas in savannahs and grasslands with naturally occurring pockets of forests and woodlands. These exist as a result of small-scale variations in local microclimates, such as sheltered valleys and gorges, or along persistent water courses, which provide the moisture that trees need. These scattered woodland and riparian forest areas in central and western NSW and Qld are important for koalas to persist in areas where trees are typically relatively sparse and widely spaced. The type of trees found in these regions are adapted to the conditions that allow them to survive in those landscape types, such as river red gums (*E. camaldulensis*). The value of revegetation projects for koalas in these types of landscapes should be guided by recent records of koalas within the vicinity (that is, direct observations of koalas or fresh scat or Species Profile and Threats Database records), current and future climate projections in relation to the koala's climatic niche (*sensu*, Briscoe et al., 2016), and the reliability of local water sources in riparian areas, which contribute to cooler microclimates and are essential for the survival of some trees.

Although wetlands are typically areas of high rainfall, planting forests in these environments can have a catastrophic impact on the local ecosystem and should be avoided. There are some naturally treed swampy areas in which koalas can thrive due to the presence of sufficient suitable browse species such as *Eucalyptus robusta* or *Eucalyptus ovata*. However, these treed, swampy landscapes are different than wetlands that are dominated by wet marshes and grasses

where naturally occurring trees are rare. Some tree species planted in these areas can survive, but at the cost of the persistence of the local ecosystem, which is important habitat for a wide range of other plant and animal species, and particularly amphibians and migratory birds, many of which are also vulnerable to extinction (Finlayson and Gardner, 2021). Trees have the potential to take up and store surprisingly large quantities of water (Engel et al., 2005), and increasing tree and woody vegetation cover has been used to modify local hydrology to drain wetlands in areas where they are not desired (Calder, 2002, Ram et al., 2007, Ballut-Dajud et al., 2022). Historically, wetlands have often been considered wastelands due to the difficulty in using marshy environments for human development without first removing or redirecting the surface water. Wetlands are still devalued in many contexts, but these landscapes provide a raft of essential ecosystem services from contributing to the global water cycle and water filtration, fisheries, carbon sequestration, productivity, biodiversity and influencing climate through water stores that provide a buffer against drought and cool the environment (Janse et al., 2019). Trees planted in wetlands have the potential to transform the environment by draining the surface water and changing the landscape from wetland to forest environment. This may increase koala habitat if koala browse trees are planted, but at the cost of the local ecological community and ecosystem services that wetlands provide.

It is also important to avoid planting koala browse species in areas where there is a high risk to koala mortality because the surrounding landscape type is hostile, such as road-side verges that are not separated from the road by a barrier. Consider the surrounding landscape and whether it provides suitable opportunity for koalas to move between trees safely, or whether there is a high probability that increasing koala habitat quality at that location will result in a population “sink.” A sink is an area in which mortality, or loss of animals, exceeds the number of animals that an area contributes to the overall population. If revegetation is undertaken to provide sound buffers or aesthetic landscaping along transport routes or other areas of high risk to animals, plants should be chosen on the basis that they are very unlikely to attract native wildlife, including the koala. A more detailed treatment of threats in relation to site selection is discussed in section 3.3. Where these threats can be appropriately managed, multi-purpose planting can be very successful, such as windbreaks on agricultural lands that use native eucalypts to provide koala browse instead of exotic tree species that can have less habitat value for native fauna.

3.5 Elevation and topography

- Revegetation sites should be at elevations koalas are known to exist, and LIKT should be sourced from similar elevations
- Plants sourced from high elevations may have some lower foliar nutrient and higher PSM concentrations, although this is an area of ongoing research
- Koalas can live on steep terrain and the relative value of steep verse flat ground is unknown
- There is value in including underrepresented landscape types and topographies in revegetation
- Aspect and topography influence microclimate which may be an important consideration in some areas to increase the resilience of revegetated areas to heat waves and drought.

The highest elevation at which koalas have been observed is about 1,500 m in the Nandewar ranges in northern NSW and the lowest elevation is 15 m below sea level near Lismore in NSW. Other relatively high elevation populations exist in the southern and northern tablelands in NSW

and Kosciuszko National Park (Atlas of Living Australia, 2018). Koalas in most higher elevation sites are thought to be at a lower density than many other, lower elevation sites, particularly compared to some coastal and off-coast island forests with unusually high densities. Plants growing at higher elevation may have lower foliar concentrations of some key nutrients, such as sodium (Au et al., 2017), and higher concentrations of certain herbivore deterrent plant secondary metabolites that can limit population density (Moore et al., 2004, Marsh unpublished data). Additional research is needed to confirm this hypothesis across different forest types and latitudes. Despite the common prediction from future climate models that animals will move upwards in elevation in response to increasing temperatures, there may be limits to the ability of higher elevation sites to support some folivorous species, despite the presence of the “right” tree species or their ability to grow there.

Revegetation should be focused at elevations in which koalas are currently known to exist, rather than attempt to establish or enrich habitat at higher elevation under the assumption that it will be able to support animals in a future, hotter climate. This is not to say that higher elevation sites where koalas exist at lower density have less value as koala conservation areas than lower elevation sites with more koalas, simply that the existing range limits of koalas should be recognised because koalas may not be able to utilise sites above their current range limit and there is a high degree of uncertainty around this. Similarly, trees used in planting should be sourced from a similar elevation and use local provenance where possible. Trees that are adapted for higher elevation may continue to produce higher concentrations of herbivore deterrent toxins even when planted at lower elevation because the production of these PSMs is strongly regulated by genes (Padovan et al., 2012, Andrew et al., 2007). However more research is needed to understand the influence of environmental factors in affecting gene expression.

Koalas are able to move across very steep terrain and areas should not be ruled out as potential revegetation sites on the basis that they contain steep slopes or ridgelines. However, human safety should be a priority as well in site selection and revegetation should only be attempted in areas where it can be conducted safely. It is unclear whether the relative value of a steeply sloped site for koala habitat is comparable to a forest of similar composition occurring on more even terrain. However, this is largely due to the fact that the tree species that grow on slopes and ridgelines are often different to species that are growing on flat lands, rather than that some property of topography directly influences food quality for koalas. Where species are similar and in the same area, research on the north coast of NSW found that the slope of a site did not affect nutritional quality or water content; however, trees at higher elevation did have higher concentrations of herbivore deterrent PSMs and koala abundance was lower (Marsh unpublished data, Law et al., 2017).

Site aspect and topography can influence microclimate, which can influence the ability of particular areas to support koalas through heatwaves and droughts. North facing slopes and ridgelines can expose koalas to higher temperatures and radiant heat than more sheltered, south facing slopes. The tree species and communities on contrasting aspects are likely to differ as well, which could also influence the quality of browse and the comparability of revegetation outcomes between areas with different topography and aspect. Another consideration when selecting sites for revegetation is that hilltops and ridgelines are often the last areas to be cleared of vegetation when a landscape is converted to pasture or farmland, so they are typically over represented in existing reserves and remnant koala habitat compared to vegetation down slope or on lowland sites (Lindenmayer and Fischer, 2013). For that reason alone, there is value

in making efforts to extend the vegetation line down the slopes to the flatlands and valleys, which will help provide additional food and shelter across the more commonly cleared topographies. This not only expands the nutritional landscape for koalas in a particular area but provides more options for moving across microclimate gradients as seasons and conditions change.

3.6 Soil and substrate

- Soil type, nutrients, and water can influence the species of trees that are likely to grow in a particular area, but the link between soil quality and koala habitat quality is inconsistent and not well supported by the current body of research in this area
- Both low- and high-quality soils can grow good quality koala habitat.

The type of substrate (geology) and mineral, nutrient and water content of the soil can influence what tree species naturally exist in a particular area and may influence some aspects of leaf chemistry. However, the link between soil fertility and eucalypt browse nutritional quality for koalas is equivocal. The highest nutritional quality leaves that have been recorded and the highest densities of koalas across their range (that is, Otways, Victoria, Kangaroo Island, SA, Stradbroke Island, Qld) occur in forests growing on low fertility soils derived from sand (Moore et al., 2004, Au, 2018). Other regions, such as the Monaro, NSW, were once overlooked as potentially good koala habitat due in large part to the prevalence of rocky, infertile soils but are now known to support healthy and growing koala populations. The current state of knowledge in regards to eucalypt leaf nutritional quality and soil fertility is discussed in a review of koala habitat assessment criteria and methods (Youngentob et al., 2021b). Restoration sites should not be ruled out of selection on the basis that they occur on low fertility soil, since many important koala browse species can grow well and support healthy koala populations on low fertility soil, sand and rocky substrates. However, similar to differences in representative vegetation across topographies (section 3.5), more vegetation clearing has historically occurred on higher fertility soils for agricultural purposes than lower fertility soils. For this reason, it is important to include these higher fertility landscape types in future revegetation efforts where possible to provide connectivity and heterogeneity across the range of ecological gradients in which koalas naturally occur. This will contribute positively to the resilience of koala populations and the ecosystems that support them over time.

In summary, high quality koala habitat can be planted on lower fertility soils as long as the trees are regionally appropriate and contain LIKTs. High fertility soil does not necessarily equate to better quality eucalypt food for koalas. Eucalypts are rarely nitrogen limited, meaning that soil nitrogen in various forms is typically higher than foliar nitrogen, and foliar nitrogen concentrations are resistant to change by nutrient amendment (Hawkins and Polglase, 2000). More research is needed to know whether additional inputs of other soil nutrients, such as phosphorous or potassium, may be beneficial to tree health or browse nutritional quality. Adding fertiliser to restoration sites is not generally advised due to lack of supporting evidence in relation to the specific purpose of improving koala habitat and the nutritional browse quality, but more research in this area is needed. Future research should also investigate the role of soil microorganisms and fungal mycorrhizae on revegetation health and browse quality. The outcomes of that research could help improve the selection of sites and/or success of revegetation initiatives to restore koala habitat.

3.7 Water

- Surface water is not usually an essential habitat element for koalas, although its presence may assist with population persistence during heatwaves or extended drought
- Koalas obtain most of their water by eating leaves, however reduced food intake in hot conditions coupled with increased requirements for cooling, may cause water stress in koalas.

Koalas obtain most of their water from the leaves that they eat, rather than drinking free water. Eucalypt leaves are approximately 50% water content, although concentrations from 79% to 36% have been reported (Nagy and Martin, 1985, Ellis et al., 1995). Nonetheless, changes to leaf moisture in dry conditions can be relatively small (average ~3%, Marsh unpublished data from the north coast of NSW collected during drought and non-drought periods). This is because many eucalypts have thick leaf cuticles that resist desiccation and deep tap roots that allow them to source water from underground reservoirs (Hamer et al., 2016). Forest trees require water, and a forest will not exist where there is insufficient water. However, in extreme prolonged drought, trees will desiccate and die and this is becoming more common due to climate change.

Foliar moisture is more likely to be a limiting factor in the western extent of the koala's range and the effects of heat and drought have been most pronounced on koala populations in those regions (Davies et al., 2014, Clifton, 2010, Clifton et al., 2007). In arid areas, koala populations are known to retract towards mesic zones after extended drought (Gordon et al., 1988). There are likely microclimate advantages in these wetter areas as they maintain cooler temperatures than the surrounding environment. Whether the presence of surface water in those areas is necessary to maintain adequate foliar moisture across the local browse species that koalas consume or for direct fluid consumption has not been determined.

The water requirements of koalas increase in hot conditions due to the use of body water in evaporative cooling mechanisms (Degabriele, 1980, Ellis et al., 1995). At the same time, food intake decreases in part due to changes in energy requirements but also appetite can be suppressed by warmer temperatures (Youngentob et al., 2021a). Animals may eat less when they are hot to avoid contributing additional heat as a byproduct of digesting their food (that is, diet induced thermogenesis) and because heat can reduce their capacity to metabolise the natural toxins in many plant foods (Beale et al. 2018). However, eating less comes at a cost to water balance when an animal's diet is also their usual source of water. In recent times, koalas have been observed readily drinking free water and visiting wildlife drinking stations (Mella et al., 2019). Even if foliar moisture was adequate based on typical intake rates, it is likely that these animals were unable to get the water they needed from leaves because they were too hot to eat enough of them and/or their water requirements under the conditions exceeded what was available. Additional research is needed in this area to better understand the role of foliar moisture, appetite and heat on the koala's ability to maintain its water balance.

Based on current knowledge of koala and eucalypt ecology and physiology, the availability of surface water is not an essential habitat element in most areas. However, the presence of water may affect habitat quality in some landscapes depending on how the local hydrology influences the availability of certain LIKT and microclimate conditions in particular. Surface water is not usually essential to the success of koala habitat revegetation initiatives unless dictated by the landscape or vegetation type that is being restored. However, close proximity to persistent sources of water may be an important feature of some refugial landscapes, particularly in the

western extent of the koala's range. Proximity to water is also important for some LIKTs that are adapted to those wetter environments, such as river red gums (*Eucalyptus camaldulensis*; Jensen, 2016), which are more likely to succumb to dry conditions than other tree species in the same region, which are able to persist farther away from water courses.

3.8 Land Tenure

- Revegetation activities should occur on land where this is a high probability of long-term protection, management and monitoring
- If other risks cannot be managed long term, revegetated areas can become population sinks
- Land tenure also dictates the types of permits and permissions required for revegetation.

Land tenure can have a substantial influence on the long-term success of revegetation initiatives and the processes involved in permits and permissions for activities associated with the revegetation project. Important considerations when selecting a site include the current land tenure, land-use zoning, planning regulations and potential for in-perpetuity protection (DPE, 2022). Ideally, revegetation projects should occur in areas where there is a high probability for long-term protection and/or management that supports the integrity of the size, composition and structure of the restored habitat. Koala habitat can exist within multi-use landscapes, including areas with selective timber harvesting (Law et al., 2022), suburban areas (Whisson and Ashman, 2020, Dique et al., 2004), and agricultural landscapes with remnant vegetation and scattered paddock trees (Barth et al., 2019). Revegetation projects in land outside of protected reserves and conservation areas can have value if they can be maintained and remain vegetated in the long-term. However, ongoing mitigation strategies to help protect koalas from threats that may be more common in these areas and facilitate safe movement through these landscapes is important. There are risks involved in creating habitat in areas where threats cannot be appropriately mitigated, because these can become population sinks that draw in animals from surrounding habitat but do not contribute to the larger population because mortality exceeds the contribution of the site through new births and emigration.

Land tenure also dictates the types of permits and permissions required for planting, seed collection, and on-going monitoring of vegetation and fauna. Permits to work on some land tenure types can take months to move through the approval process and be granted. The proximity of sites to human populations or outposts can also influence the feasibility and expenses involved in initial restoration work, site maintenance and ongoing monitoring. These considerations should be factored into project planning, timelines and budgets.

4 Plant selection

4.1 Local forest types and vegetation communities

- Vegetation that is suited to the local soil, climate, and topography will grow best, so the goal should be to closely replicate what would have been present before disturbance in terms of composition, structure, and spacing
- Avoid planting rainforest trees and shrubs, which can outcompete LIKTs. Rather allow them to migrate naturally into a revegetated area after koala food trees have established.
- Incorporate species, genetic and chemotypic diversity in the trees to promote dynamic-plant herbivore interactions and ecosystem resilience
- Nearby existing koala habitat can be used as a guide for the species and proportions to plant.

Vegetation community types that are available through a variety of national or state databases as listed in Luxton et al. (2021) can help inform the density of vegetation plantings and the general species mix and vegetation types that are appropriate for the landscape. The attributes of forests are often determined by climatic or topographic characteristics of the region such as rainfall, geology, soil substrate, temperature, humidity, and other aspects of climate. Vegetation that is suited to the area will therefore often grow best in these conditions, so the goal should be to closely replicate what would have been present in the area before disturbance, and plant vegetation that is appropriate. Use the local forest type and vegetation communities as a guide both in terms of vegetation composition, but also structure and spacing. Plants unsuited for the site or planted at inappropriate densities may die or suffer nutrient and/or moisture stress. Under stressed conditions they can produce PSMs that can make them less palatable to koalas and other browsing herbivores (for example Niinemets, 2015, McKiernan et al., 2016).

An exception to using the local forest and vegetation types as guidelines for what to plant, is that rainforest tree species should be avoided in areas where koala habitat is desired because they will compete with koala food trees for light, moisture and nutrients (Ashton and Chinner, 1999, Harvest et al., 2008, Horton et al., 2013). While they may naturally occur in wet open forests, they can smother plantings and encourage bell miner associated dieback. Rainforest shrubs should instead be allowed to migrate naturally into revegetation areas once koala food trees have become well-established.

It is typically impossible to exactly recreate the composition of tree species that would have occurred at any given place in a landscape because detailed records at the scale of most revegetation sites do not exist (Hobbs et al., 2004). Even where they do exist, they may not account for changes that already occurred to the composition due to previous anthropogenic disturbance. However, tree species composition can have a substantial impact on the nutritional quality of landscapes, as can the chemotypes of the trees planted (Moore et al., 2005, Moore et al., 2010, Au, 2018). When revegetating landscapes for koalas, a primary consideration should be restoring appropriate local tree species diversity and also incorporating genetic and chemical diversity. This provides heterogeneity at multiple levels, and in addition to mimicking natural conditions, such heterogeneity has been shown to help improve overall ecosystem resilience in the face of disturbance and the long-term sustainability of landscapes (Broadhurst et al., 2008).

Although tree species can be identified with the naked eye, chemotypic and genetic variability cannot be easily determined without specialised equipment and training. However, areas of nearby koala habitat with healthy but not overabundant populations can be used as a template for the appropriate species mix where the landscapes share a similar climate zone, geology, slope, aspect and elevation. Where possible, and where appropriate permissions have been sought and approved, it is also ideal to source seed from multiple parent trees across the diversity of tree species for revegetation in nearby existing koala habitat. Seed and seedlings are more likely to share the nutritional qualities that allow them to contribute to good koala habitat when they are sourced from trees in good quality koala habitat.

While there are specific trees within a forest that are more important for koalas in terms of food or shelter, any revegetation program to restore koala habitat should aim to do so in its entirety by planting the diverse suite of structural and compositional forest elements that exist in the local area. This means looking at the composition of nearby similar, forest types that are populated by koalas, identifying the proportional composition and diversity of plants that exist therein and aiming to replicate that, inclusive of plants that may not be on the list of LIKT or ancillary habitat trees (Youngentob et al., 2021b), such as ground-layer and midstory flora. In addition, avoid removing coarse woody debris and fallen logs that may already exist in the restoration site, as they are important for nutrient cycling, contribute to cooler local microclimates, and provide essential habitat for a variety of species that are central to the functioning of the larger ecosystem (Manning et al., 2013, Manning et al., 2020). By considering the big picture of whole forest or woodland restoration, revegetation programs will be more likely to result in a healthy, resilient environment that can support not just koalas, but also the diversity of flora and fauna that typically coexist in these ecosystems. Reforestation programs that focus too narrowly on a single value (for example koala browse) are more likely to have unintended, perverse outcomes that negatively impact their long-term viability and ability to support the target species (Lindenmayer et al., 2008).

4.2 Pryor's rule and mixed subgenera

- Where multispecies forests are replanted, follow Pryor's rule so that the canopy contains species from more than one subgenus
- Koala habitat often contains species from the *symphyomyrtle* and *monocalypt* subgenera, so revegetation projects should aim to replicate this.
- The chemical diversity this creates promotes the co-occurrence of sympatric folivore species, provides ecosystem resilience to disturbance events such as fire, and increases the likelihood that there will be palatable epicormic growth for koalas if the revegetated area burns.

Eucalypt forests and woodlands with mixed species stands typically contain species from multiple subgenera of *Eucalyptus* (Noble 1989). This is known as Pryor's Rule (Noble 1989). By far the most common associations are between species belonging to the two major subgenera, *Symphyomyrtus* (symphyomyrtle) and *Eucalyptus* (also called *Monocalyptus* and referred to as monocalypt here to avoid confusion with the genus name). In koala habitat with multiple tree species there is almost always a mixture of species from the symphyomyrtle and monocalypt subgenera. In some areas there may be a mixture of other subgenera, such as monocalypts and *Corymbia*; however, these forests typically do not support koalas because the foliar chemical profile of trees from those species' combinations are generally less palatable to koalas.

Applying Pryor's Rule and recreating mixed symphyomyrtle and monocalypt forests is important when revegetating koala habitat for several reasons. Firstly, the subgenera contain different suites of PSMs (Marsh et al., 2019), and this chemical diversity reduces interspecific competition between folivore species and allows them to coexist as they would in a natural ecosystem. For instance, the common ringtail possum (*Pseudocheirus peregrinus*) tends to favour monocalypt species while the common brushtail possum (*Trichosurus vulpecula*) tends to favour symphyomyrtle species (Moore et al., 2004), and these two possums often coexist with koalas. Secondly, as koalas are constrained in their food intake by the detoxification of PSMs, they can potentially exploit alternative metabolic pathways by switching their feeding between subgenera (Marsh et al., 2006), allowing them to access extra nutrients. Thirdly, preliminary investigations suggest that the nutritional quality of epicormic regrowth produced by eucalypts after fire differs from mature leaves, and the response may also differ between eucalypt species and subgenera. Specifically, epicormic regrowth was of higher nutritional quality than mature leaves in most of the species examined from the symphyomyrtle subgenus, but was lower in monocalypt species (Marsh unpublished data). As a result, koalas may alter their feeding preferences in some areas after fire. By having the appropriate mixed subgenera in koala habitat, it is likely that koalas will be able to access adequate nutrition after fire should the area burn, and the forest will be more likely to regenerate by including trees with diverse regeneration strategies in response to fire.

4.3 Local koala diet and habitat

- Koala food tree preferences are best considered at a local scale as preferences can differ between regions
- Trees that are growing closer together in natural landscapes are more likely to be similar nutritionally, because chemotype is largely determined by genetics
- An appropriate chemotypic diversity is more likely to be captured by replicating the species composition and sourcing seed from nearby areas known to be browsed (but not over-browsed) by koalas

Koalas' preferences for feeding are best considered at a local scale. The trees that are preferred by koalas in one area may not be the same as those preferred by koalas in another, even if the same tree species are present. The reasons for this are multifaceted and include variability in plant chemotypes that influence palatability across their distribution, as well as individual koala preferences, possibly due to a combination of local adaptation/physiology and experience. That said, there are some tree species that are more likely to be preferred because they tend to offer more palatable, higher nutritional quality browse more consistently than other species; however, exceptions are not that unusual. Many species that are known to be preferred koala browse species also have unpalatable chemotypes. Incorporating diversity and sourcing seed from areas known to be browsed by koalas in the same region are useful strategies to avoid unintentionally planting trees that cannot be browsed (Lawler et al., 1998). However, it is possible to have too much of a good thing and seed collected from areas with *overabundant* koala populations (such as Cape Otway in Victoria) should be used sparingly if at all, as this could lead to over browsing, particularly when diversity in tree species is lacking.

Given the heritability of most determinants of nutritional quality, seeds sourced from trees in areas where koalas are living and feeding are more likely to provide adequate nutrition when grown in similar conditions elsewhere (Andrew et al., 2010). The distribution of PSMs and

nutrients within a species is not random across the landscape. There is spatial autocorrelation in the relatedness of many eucalypt trees, which also drives similarity in nutritional chemistry (Andrew et al., 2010). From a revegetation perspective, this supports the approach of sourcing seed from areas of good koala habitat that are near the restoration site, as a good strategy to produce more koala habitat for the local koalas in that area. Past research suggests that collecting seed at spaced intervals of 60-80 m between groups of trees from which seed is collected may improve the chance of increasing genetic and chemotypic diversity (Andrew et al. 2007).

In many, but not all situations, local provenance is also important to increase the probability that local koalas will recognise the trees as food (Blyton et al., 2019, Moore and Foley, 2000). Koalas will not always eat browse from other areas even if the koalas in that other area are known to eat it (Moore and Foley, 2000). Food preferences may be partially learnt through post-ingestive feedback mechanisms, such as experiencing nausea if food with a particular smell is eaten, or simply learnt associations with the food that has been available to them. It could also be there is some parental influence on preferences behaviourally, although that is yet to be shown (Blyton et al., 2022). Individual microbiomes may also be a significant determinant of koala feeding preferences given the important role of the microbiome in the digestion and metabolism of some PSMs (Kohl et al., 2014).

The determinants of feeding preferences of koalas is an area of ongoing research; however, it is quite clear that the preferences of koalas are often firmly fixed. It may be that koalas from region A can eat the leaves from trees in region B, but if the situation were reversed and koalas from region B were offered the trees from region A they would not eat them. It is impractical to test all possible combinations of leaves and koalas. This means that to maximise the probability that trees in a revegetated area will be browsed by koalas and support koala populations, sourcing an appropriate diversity of local plants from nearby koala habitat is preferred. This includes LIKT and ancillary habitat trees in similar proportions to the model ecosystem that you are trying to reproduce on the basis that it supports healthy but not overabundant koala populations and has a vegetation community and structure that is appropriate for the restoration site. The long-term sustainability of the forest or woodland ecosystem also depends on incorporating diversity and heterogeneity appropriately and at multiple scales.

4.4 Other provenances and climate-ready plants

- Trees from other provenances may not be recognised as food, provide adequate nutrition, or may contain concentrations of PSMs that inhibit intake
- More research on the use of climate-ready plants for koala habitat is needed to prevent unintended negative consequences.

Changes to the distribution of koala food tree species and other vegetation will happen as a consequence of climate change. The relatively rapid pace at which the climate is changing means that plant communities do not necessarily have time to evolve and adapt. Heat and water stress have already caused some die back of eucalypt trees (Nolan et al., 2021), and it has been suggested that revegetation programs should import plants from areas where they are adapted to hotter or drier conditions to align with predicted climate changes in the future (Prober et al., 2015, Aitken and Whitlock, 2013). This can be done in a variety of ways. For example seed can be collected from a wide variety of sources and mixed (admixture provenancing; Breed et al.,

2013) or by trying to mimic natural gene flow in the environment (composite provenancing; Broadhurst et al., 2008). From a koala nutrition perspective, sourcing non-local provenances should be approached with caution for the reasons outlined in section 4.2. Trees from another region may be more adapted to the future climate of a particular site but fail to provide koala habitat because they are not recognised as food, do not provide adequate nutrition, or contain concentrations of PSMs that inhibit intake.

The relationship between the feeding preferences of herbivores and local provenance has been demonstrated in other species as well. For example, the North American porcupine (*Erethizon dorsatum*) browsing on Fremont cottonwood (*Populus fremontii*) showed a strong preference for locally sourced cottonwood plants and plants from similar climates (Lauger et al., 2021). The experiment showed that plants adapted to similar climatic conditions were genetically more similar to each other and more likely to be browsed by porcupines. Interestingly, the distribution across North America of these plant genotypes closely matches the distribution of porcupines (Lauger et al., 2021).

What this tells us is that there has been evolutionary adaptation to climate in plants and a coevolution in the preferences of herbivores. Given that climate change is likely to outstrip the rate of evolutionary adaptation of plants, some people argue for ‘assisted migration’ in plant species (Prober et al., 2015, Aitken and Whitlock, 2013). This means selecting some plants adapted to warmer or drier areas when revegetating to increase the resilience of the plant community to these conditions. However, there may be unintended negative consequences of doing so for herbivores. Plants that are more drought resistant and/or survive in hotter temperatures also can have higher concentration of PSMs that often overlap in their function, such as protecting against climatic or environmental stressors and deterring herbivory (Liu et al. 2019, Niinemets, 2015). The likelihood of selecting overly toxic, climate resilient tree stock can be reduced by sourcing seed from trees growing successfully in hotter and dryer regions that are also readily browsed by koalas in that area. However, as discussed in section 4.3, this still does not guarantee that koalas from another area will eat the trees that grow from that seed.

To complicate this picture further, as the climate changes, trees that are not adapted to hotter/drier provenances will become more stressed. Stressed trees can respond by producing more PSMs and more fibre, making them less palatable to koalas (McKiernan et al., 2016, Niinemets, 2015). Therefore, planting local provenance only may not be the best solution in all circumstances either. More research in this area is needed. Revegetation programs should aim to maximise survival of the revegetated area, at the same time taking measures to safeguard the likelihood that the trees will offer a sustainable source of food for koalas. This means revegetation programs should ensure they include a diversity of locally sourced koala food trees and other locally appropriate vegetation. In addition, cautious inclusion of some trees sourced from other provenances, be they hotter and drier or more variable, could be considered but not to the exclusion of locally sourced stock. Tools like the Australian Network for [Plant Conservation’s Climate-ready revegetation guide](#) (Appendix A) can be used to help inform decisions about what plants may be more tolerant to future climatic conditions for the area.

5 Monitoring

In Australia, there are no national monitoring guidelines for revegetation programs at present (Atyeo and Thackway, 2009); however, a well-designed monitoring program is the only way to know whether revegetation has achieved its goals, respond to evolving threats (that is, weeds and herbivore predation), and adaptively manage to improve outcomes for current and future projects. Monitoring should be incorporated into revegetation program planning from the outset rather than added on after the fact. Importantly, vegetation and fauna should both be monitored because vegetation monitoring alone is not sufficient to determine whether an area is being used by koalas (Cristescu et al., 2013b).

In the first instance, revegetation programs should have clearly defined objectives and, as discussed in section 3.1, these objectives will help to determine characteristics of the program such as the revegetation strategy and appropriate sites for revegetation. The objectives of the monitoring program should clearly relate to the goals of the revegetation program, and this should be articulated in a series of questions that can be answered through monitoring (Atyeo and Thackway, 2009, Lindenmayer, 2020). For instance, if the goal of the revegetation program is to increase the carrying capacity of a forest for koalas, the list of questions would be different to a program which has the goal of increasing connectivity between two patches of koala habitat.

Furthermore, inputs or potential inputs that are of relevance to the predetermined “success” of the project should be monitored, and this means that the targets of a monitoring program are not always the same variables as the objective (Lindenmayer, 2020, Atyeo and Thackway, 2009). For example, if a cleared area was revegetated with the overarching goal of that area being suitable koala habitat, but the presence of wild dogs is likely to impact whether koalas can live there, then wild dogs should be monitored in the monitoring program not just the presence of koalas. This means developing a conceptual understanding of what will be influential in determining the success of the project and using this model to inform which variables are tracked over time (Lindenmayer, 2020).

Measured variables should be understood for their ecological relevance as it relates to the goals of the program, and hence how changes should guide decision making on relevant timelines (Lindenmayer, 2020). Some variables will be intermediate or indicators of change while other variables are outcomes, and these differences need to be understood. For instance, soil moisture around newly planted seedlings may help to determine whether they are getting enough water to establish, and if soil moisture is too low a management strategy of supplementary water could be applied to avoid seedling death. If the monitoring program only measured whether seedlings were alive or dead, which is an outcome, no management intervention could be instated to fix the problem. Both outcomes and indicators are therefore important to monitor.

Once the objectives are known, a framework for the system has been established, and relevant inputs and outputs have been identified, questions must be developed which can be answered through monitoring. These questions should assist with measuring success, and give opportunity for interventions where required (Lindenmayer, 2020). Adaptive management strategies should be used in instances of high uncertainty (Lindenmayer and Likens, 2009), which will include many koala revegetation programs. This means for each action, goals or targets should be set, evaluated through monitoring, and if the targets are not being met, the

actions need to be reviewed and new actions included as required (Lindenmayer and Likens, 2009). These features need to be well articulated to all project stakeholders, which may include researchers, landowners, regulators and policy makers, for the greatest chance of understanding, implementation and success (Lindenmayer, 2020).

The design of a monitoring program needs to be appropriate and powerful enough to answer the specific questions formulated (Lindenmayer, 2020). Monitoring can be undertaken outside of an experimental framework by reporting on outcomes and measuring success against milestones and objectives specified at the outset of the project. However, when testing the efficacy of particular methods or strategies, monitoring may need to be conducted within an experimental framework (Lindenmayer, 2020). This often requires consultation with a statistician to ensure the experimental design has enough replication to provide the statistical power for the effect sizes that the interventions are likely to produce. Data collection also needs to use appropriate methods and involve on the ground surveys of the actual site by trained personnel.

A benchmark should be established against which the results can be compared. Control sites are an ideal way to have a benchmark within an experimental framework (Lindenmayer, 2020). Control sites are sites that have not had any revegetation but are otherwise similar to the areas that were revegetated. Control sites are monitored in the same way as the revegetated sites. Control sites provide a comparison to show that the outcomes measured through monitoring were most likely caused by the intervention. Without a control site, extemporaneous factors cannot be ruled out. If control sites are not practical or if monitoring is conducted outside of an experimental framework, then the monitoring program should ensure baseline data are collected at the start of the project (that is, before revegetation) and then at appropriate intervals post-revegetation using the same methods.

By necessity, monitoring programs collect data on a set of variables over a given period. Importantly, collecting data is only useful when the data is organised, examined, analysed, and presented in a useful format at useful intervals (Lindenmayer, 2020). The timeline for the monitoring program needs to be relevant to the objectives of the project. This means that for some revegetation projects the monitoring program may take place over a protracted period of time and resourcing should allow for this. In addition, if through monitoring it is identified that additional management strategies are needed to maximise the chance of success, this may extend the timeline over which monitoring is required (Lindenmayer and Likens, 2009).

The management inputs and costs associated with these inputs also form important data that will help build the body of information used in planning and executing revegetation programs for koala habitat. Ideally, the costs and budgeting of monitoring programs are transparent and shared. The full breakdown of inputs, costs and outcomes will help others with planning and maximise return on investment where resources are limited. Some authors estimate the cost of monitoring should be around 10% of the total cost of the revegetation program budget (Likens and Lindenmayer, 2018).

5.1 Vegetation monitoring

- Baseline data should be collected prior to revegetation with the same methods that will be used for subsequent monitoring
- Monitoring can be used to determine whether further management interventions are required
- The number of replicates required for statistical analysis will depend on effect sizes

Vegetation monitoring is an essential part of a revegetation project as it will provide information on whether the initial sowing of seeds or planting of seedlings was successful in establishing plants, and then how the community structure changes over time, which will determine whether it is suitable koala habitat. It will also assist in determining whether any management practices such as weed control, herbivore control, thinning, or watering, needs to take place to ensure the success of the project and the desired diversity of plants is maintained to maturity.

Before starting a revegetation project, baseline data should be collected at both the revegetation site(s) and the control site(s) and then the same method used for subsequent monitoring of the site (Lindenmayer, 2020). Once seeds have been sown, the number of seeds in kilogram per hectare should be recorded and systematic, unbiased monitoring should be used to collect data on germination of seeds. Where seedlings are used, the original planting density should be recorded, and systematic unbiased monitoring should be used to collect data on seedling survival by species. This data is used to see whether the treatment has worked and then to identify whether further management interventions are required. The NSW koala habitat restoration guidelines suggest monitoring every 6 months over the first 2-3 years and then each year or on an as needs basis after that (DPIE, 2021).

The number of replicates required for statistical analyses will depend on the effect size being measured and how variable it is. The plots or transects should be well marked and the coordinates recorded so that the monitoring can occur at the same locations over time. When evaluating plant survival, indexes of plant health or height could also be useful in addition to descriptions of vegetation spacing, height and girth and structural qualities specific to ground, mid and canopy strata. Photographs from particular locations, transects, plots, or from above, can also be a useful way to track changes over time (DPIE, 2021).

The origin of individual plants when tracking their survival are useful details to record and monitor if possible. Details of where the seedlings or seeds came from, their provenance, and if the habitat was occupied by koalas should be recorded. Ideally the exact GPS location of where the plants were collected and how many individuals of the same species were planted should also be recorded. The chemotype of these individuals may or may not be palatable to koalas and the success of the area as koala habitat depends on the chemotypic diversity represented.

5.2 Koala monitoring

- Revegetation does not always guarantee recolonisation by koalas, and it may be necessary to monitor them separately
- A variety of different methods exist for monitoring koalas and the most appropriate one/s should be selected for the situation and question

Research has shown that monitoring vegetation is not a good indicator of colonisation by koalas. Biologically relevant attributes of vegetation such as canopy cover or food tree species richness may predict likely value for koalas, but ideally the animals themselves need to be monitored (Cristescu et al., 2013b). There are a variety of methods for monitoring koala presence, absence, and density and they all have different benefits, limitations, costs, and skill levels required. Some methods are best for presence or absence while others are useful to determine density, and the best approach is often to use a combination of different methods. Since koalas are cryptic and easily missed in visual searches, many methods used are indirect and involve searching for scats or using audio recordings. Both indirect and direct methods are discussed in detail in Youngentob et al. (2021b) but are also briefly outlined in the next paragraph. As with vegetation monitoring, an initial survey should be conducted at the start of the project and the same method used throughout the monitoring program for continuity and comparison of results.

The SAT, rapid-SAT, and RGB-SAT are established, easy to follow methods that are often used to determine koala presence or activity in medium to high density populations. These methods involve searching on the ground within 1 m of the trunk of a specified number (and sometimes species) of trees (Phillips and Callaghan, 2011). While they are relatively easy and cheap, false negatives are common, particularly in medium to low density populations (Youngentob et al., 2021b). KRAM and BKSS are both methods that build on SAT but use randomly selected trees and different search times and efforts. Like SAT, they are suitable for determining presence rather than density and false negatives are still possible in low density populations (Phillips and Callaghan, 2011, Jiang et al., 2019, Ellis et al., 2013, Cristescu et al., 2015, Woosnam-Merchez et al., 2013). Scat detection dogs can also be used to rapidly expand the search area in scat surveys, and well-trained dogs can substantially reduce the rate of false negatives, particularly in difficult substrate (Cristescu et al., 2015). However, their use in protected areas or areas that have been baited may be limited (Youngentob et al., 2021b). Koala abundance can be estimated from scat using the faecal standing crop method. However, this method requires the collection of all faecal pellets in a specified area and an understanding of the number of pellets produced per koala per day, the probability of detection, and the rate of scat decomposition or approximate pellet age, specific to the site and the season (Sullivan et al., 2004, Seabrook et al., 2011, McGregor et al., 2013). Alternatively, if fresh scats are collected and resourcing allows, genetic sampling could potentially be used to determine abundance as has been done in other animal species (Wedrowicz et al., 2013, Schultz et al., 2018, Arandjelovic and Vigilant, 2018).

Playing a koala bellow and listening for a response is a simple method to survey for the presence of males during the breeding season, however no response does not mean there are no koalas, and it is possible that the method is disruptive to individuals (Jurskis et al., 2001). More recently, acoustic methods have shifted to the use of passive acoustic recording devices, which can be deployed during the breeding season and then evaluated for the bellows of male koalas (Hagens et al., 2018, Law et al., 2020, Law et al., 2018). When recorders are appropriately positioned at

the correct time of year, the method is useful for establishing koala presence. Arrays of acoustic recording devices can also be used to determine abundance and to obtain some spatial information on distribution (Hagens et al., 2018, Law et al., 2020, Law et al., 2018).

Direct and indirect methods are often used in conjunction to improve the likelihood of detecting koalas (Youngentob et al., 2021b). Direct searches can occur at points or along transects using a variety of approaches (for example strip transects, distance sampling, or double observer transects) for presence detection in medium to high density populations or for abundance if appropriate corrections for detection probability are made (Dique et al., 2004, Crowther et al., 2021). In low density populations, the power of transects can be improved by conducting them at night as eye shine while spotlighting may increase detectability (Wilmott et al., 2019). Thermal detection drones are good for detecting koala presence and abundance even in low density populations and can cover larger areas, although their use may be limited by access to specialised knowledge, equipment, and image processing software. Furthermore, since they require a difference between animal temperature and environmental temperature they may not be as useful in hot conditions (Witt et al., 2020, Wilmott et al., 2019).

Some more invasive and labour-intensive methods for monitoring koalas include mark-recapture (or mark-resight), radio tracking, or GPS tracking. In the case of GPS or radio tracking, information about home range sizes and landscape use can also be obtained and this can be related to population density (Crowther et al., 2021). These methods are useful for both presence and density with the added benefit of providing an opportunity to gather health and demographic data on the population which may feed into further management of the revegetation program (Crowther et al., 2021). They will also provide information about whether an animal resides in the area or is transiting through, which may be of particular interest in projects that are trying to enhance koala habitat connectivity (Crowther et al., 2021). These methods can also assist with determining the feeding preferences of koalas which may help in understanding how plant selection relates to palatability (Crowther et al., 2021, Youngentob et al., 2021b).

Detecting the presence of mothers with joeys, juvenile koalas, or demonstrating bellowing activity in breeding season are all useful indicators that a koala population is reproducing in a revegetated area, indicating that the replanting is providing adequate nutrition for the koalas. Direct observation methods including transects, spotlighting or thermal imaging are the best for detecting joeys, and passive acoustics are used to detect bellowing. Using methods appropriate for density and abundance over time will also show whether there is population growth, however it may be difficult to account for migration into the area.

5.3 Adaptive management

- Adaptive management incorporates learning and allows intervention if monitoring reveals that target outcomes are not being met
- Some revegetation efforts may require a multi-stage process to create the necessary environment for some species

Adaptive management describes the incorporation of learning and management into revegetation projects (Lindenmayer and Likens, 2009). It is best practice where there is a high level of uncertainty as there is in koala habitat revegetation. Monitoring is required to determine

whether the project is going according to plan, if not, why not, and what management strategies can address and resolve insufficiencies.

Adaptive management strategies may be particularly important for ensuring the species composition of the planting is not compromised over time. This is because some species may rapidly grow tall, outcompeting other seedlings and causing a change in the intended species composition of the mature forest. In particular, disturbance adapted species may be faster to grow and suppress the growth of other plants (Au et al., 2019). These may require thinning to reduce competition and allow other species to grow.

Since different species of plants require different conditions to grow, forest regeneration may need to be a multistage process. Pioneer species can be used to create the environment necessary for other species to grow. Known as facilitation effects, these pioneer species may be trees, shrubs, or undergrowth depending on the situation. Where pioneer species do not naturally thin over time, management strategies should include thinning these pioneers to promote the next successional stage of forest growth.

If there is a high rate of mortality amongst seedlings, monitoring can help detect the cause of mortality and hence what management interventions may be needed. For instance, seed guards or pesticide sprays can be applied to deter predation from herbivores and have variable success depending on the type of herbivore and plant communities. These interventions may need to be re-applied over time and this should be included in the monitoring and management plan.

5.4 How often and how long to monitor?

- Monitoring intervals and timeframes will depend on the goal and questions
- Monitoring should be more frequent in situations of high uncertainty

Once an initial baseline has been established, the NSW koala habitat restoration guidelines suggest monitoring vegetation every 6 months over the first 2-3 years and then each year or on an as needs basis after that (DPE, 2022). In the initial period, or in situations of high uncertainty, monitoring may need to be more frequent. Monitoring for koalas could be conducted annually and, depending on the methods, monitoring at specific times of year may be preferable (for example acoustic monitoring in breeding season).

Ideally, monitoring should happen into perpetuity because of the long timescales—hundreds of years or more—that forest and woodlands can take to mature. However, this is unrealistic in most circumstances. Perhaps the best endpoint for a revegetation project is once the project has been shown to be successful (or failure has been accepted). Success will depend on the initial objectives of the project, for instance if the goal is to revegetate an area as koala habitat it may be that monitoring can be stopped once the site has been demonstrated to support a healthy, reproducing koala population. If the goal is to enhance connectivity between koala habitat fragments, then success may be that koalas are demonstrated to safely disperse through the area. If the goal is to improve the carrying capacity of an area, then success may be when the population has increased in density and then remained stable for several years beyond that peak. Monitoring should be continued for a period of time after the specified target goals have been reached to ensure the measurements were not spurious and the outcome(s) will likely be maintained over time.

The minimum time before a revegetated area with some existing mature trees has been shown to be used by koalas is two years. In the Liverpool Plains, koalas have been shown to use revegetated areas as young as two to four years old, but they would retreat to nearby remnant vegetation to shelter during the day. Once the trees were four to seven years old koalas were also observed using them for shelter during the day but more mature remnant vegetation still formed a part of their home ranges (Kavanagh and Stanton, 2012). In a rehabilitated mine site on North Stradbroke Island, koalas used revegetated areas as young as six years old, had similar tree reuse indicating likely adequate shelter in these areas, and had similar diet species composition in remnant versus revegetated habitat (Cristescu et al., 2013a). Another study on North Stradbroke Island demonstrated that koalas used revegetated landscapes that were 30 years old, although were detected in fewer revegetated sites than undisturbed areas (Woodward et al., 2008). Relatively young, revegetated areas can be used by koalas, however, there is little information available on the use of revegetated areas over time making it difficult to determine minimum monitoring periods or understand how their use may change as the site matures. This is a knowledge gap that could be filled by better monitoring programs for koala revegetation projects.

Ideally, monitoring should extend to the length of time required for a forest or woodland to reach a late successional stage. Monitoring only to an early successional stage has limited value for a koala revegetation project, because the site may not yet be mature enough to be utilised by koalas and the vegetation is subject to ongoing shifts in composition and structure due to changing competition dynamics among species and variable susceptibility to weeds, insects and other herbivores. A suggested monitoring timeline is provided in Table 1, with example targets for monitoring at each stage in the monitoring timeline. This is not an exhaustive list. The appropriate schedule, items and methods for monitoring should be tailored to the project.

Table 1: Suggested timeline and targets for monitoring of a koala habitat revegetation project.

When	What	Why
Before revegetating	Baseline data on the site including soil type, climatic conditions, presence of water, presence of weeds, presence of herbivores.	This provides a starting point to compare other measures, helps inform what type of vegetation may be appropriate and what site preparation activities or management practices may be required once the project starts. For example the presence of wallabies may mean the seedlings will need to be guarded when planted.
Initial monitoring and then first 2-3 years after planting. The timing of the first monitoring event after planting will vary site to site and depends on local climate, season, rainfall and the anticipated rate of growth.	If revegetation has been done by seed sowing, monitoring should look for evidence of germination. Seedling survival, the presence of weeds, evidence of herbivory, water or nutrient stress in the seedlings should be examined. Monitoring for koala use could begin, using techniques particularly suited to low density populations such as acoustic arrays	Seed germination, and seedling survival demonstrate whether the site has been adequately prepared. Indications of stress need to be addressed with adaptive management strategies such as watering, fertilising, pesticides, guards. Although some mortality is inevitable, if there are higher rates of mortality than expected also consider whether appropriate vegetation has been sourced for the site.

Revegetating koala habitat

Medium term After initial monitoring to around 7 years after planting.	The same parameters as the initial monitoring period (survival, weeds, herbivory, stress) plus composition, forest structure, and plant attributes should be monitored. Monitoring for koala use could begin, using techniques particularly suited to low density populations such as acoustic arrays Threats to koalas in the area should be monitored for example camera traps for dogs and records from local wildlife care groups to vehicle strikes and disease.	As the trees grow some species will have competitive advantage over others, for instance the degree of shade tolerance in different species will impact their growth rates as the canopy closes. If the species composition doesn't match the target, management such as selective thinning or supplementary plantings may be required. The forest structure should be appropriate for successional stage. For example if the forest has an open canopy ground cover plants should be present but as the canopy closes these are reduced. Integrated threat reduction programs should be enacted. For instance, wild dog control programs if wild dogs are detected, or measures to prevent mortality on roads if there is a high vehicle strike rate. Without management of threats the revegetated area may become a sink for koalas.
Long term 7 years after planting to perpetuity.	Vegetation attributes as for medium and initial monitoring. Koala occupancy should be monitored for example scat, wildlife detection dogs, acoustic arrays. Threats to koalas in the area should be monitored for example camera traps for dogs and records from local wildlife care groups to vehicle strikes and disease.	The vegetation will continue to change in composition as the replating ages. Adaptive management such as coppicing or selective thinning should be considered particularly if LIKT are being lost. Integrated threat reduction programs should be enacted. For instance, wild dog control programs if wild dogs are detected, or measures to prevent mortality on roads if there is a high vehicle strike rate. Without management of threats the revegetated area may become a sink for koalas.

Appendix A:

External resources that may provide useful guidance on practical aspects of revegetation outside of the scope of this document. This non-exhaustive list should be updated as new information arises and be used in conjunction with the current scientific literature.

South East Queensland Ecological Restoration Framework:

Ten local councils in South-East Queensland developed regional standards in 2011 for undertaking restoration work in that region. This was in partnership with the community to maintain, enhance, and protect biodiversity in the area in the face of ongoing development (not specific to koalas). The goals of the framework are to improve the condition and extent of native, ensure economic and environmental sustainability, and ongoing improvement and maintenance of ecosystem services. The framework includes a code of practice which reflect the policy environment, a decision-making tool to guide people in restoration projects, and a technical manual reflecting minimum best practice ecological restoration.

HLW. 2011. SEQ Ecological Restoration Framework [Online]. Available: <https://hlw.org.au/resources/seqecologicalrestorationframework/>

National standards for the practice of ecological restoration in Australia:

Prepared by the Society for Ecological Restoration Australasia (an independent, non-profit ecological restoration organisation). The Standards “identifies the principles underpinning restoration philosophies and methods, and outlines the steps required to plan, implement, monitor and evaluate a restoration project to increase the likelihood of its success. The Standards are relevant to—and can be interpreted for—a wide spectrum of projects ranging from minimally resourced community projects to largescale, well-funded industry or government projects.”

Standards Reference Group SERA (2021) National Standards for the Practice of Ecological Restoration in Australia. Edition 2.2. Society for Ecological Restoration Australasia. Available from URL: Available from: <http://www.seraustralasia.com/standards/home.html>

NSW DPIE Koala habitat restoration guidelines

The NSW department of planning industry and environment developed [koala habitat restoration guidelines](#) to provide evidence-based recommendations to help land managers, community groups and private landholders identify, connect and restore koala habitat using best-practice methods (DPE, 2022).

DPIE 2021. Koala habitat restoration guidelines: A practical guide to identify, connect and restore koala habitat in New South Wales. [online]. Available: <https://www.environment.nsw.gov.au/research-and-publications/publications-search/koala-habitat-restoration-guidelines>

Climate ready revegetation: a guide for natural resource managers

A guide to and compilation of online tools available to assist natural resource managers incorporate the uncertainties associated with climate change when planning revegetation activities. The guide provides instructions on where to find and how to use climate projections and how to consider the suitability of species and provenances for revegetation. It is based on the premise that survival and resilience will be enhanced for species and local populations with large, genetically diverse populations and is not specific to koalas.

Hancock, N., Harris, R., Broadhurst, L. and Hughes, L. 2018. Climate-ready revegetation. A guide for natural resource managers. Version 2. Macquarie University, Sydney. Accessible from: http://anpc.asn.au/resources/climate_ready_revegetation

Appendix B:

Sources of information for LIKTs in each KMB. Some western and central KMBs in QLD and NSW have no data, or limited data on koala tree use. Species names of LIKT and ancillary habitat trees for each KMB are also listed in *A review of koala habitat assessment criteria and methods* (Youngentob et al 2021, <https://www.dcceew.gov.au/environment/epbc/publications/review-koala-habitat-assessment-criteria-and-methods>). It is important to note that sometimes koala food trees have been identified indirectly, such as through sightings of koalas in trees or scat at the base of a tree, and these are not always reliable indicators that koalas eat that tree so care should be taken to ensure known food trees are included where possible.

[A national list of trees koalas are thought to use arranged by local government area](#) has also been prepared by the Australian Koala Foundation (AKF, 2020).

A review of koala tree use across NSW has been prepared by DPIE which lists trees by Koala Management Area (DPIE, 2018). DPIE has also prepared [local government fact sheets](#) which list koala tree species for each koala management area.

The [NSW State Environmental Planning Policy \(Koala Habitat Protection\) 2019](#) under the *Environmental Planning and Assessment Act 1979* also provides a list of koala tree species arranged by management area in NSW.

Brigalow Belt

Runge, C.A, Rhodes, JR and Lopez-Cubillos, DS 2021b, [Queensland Koala Habitat Mapping. RE sp. tree suitability appendix table1](#). Dataset. Threatened Species Recovery Hub. The University of Queensland, Brisbane, QLD.

Wu, H, McAlpine, CA and Seabrook, LM 2012, [The dietary preferences of koalas, *Phascolarctos cinereus*, in southwest Queensland](#). Australian Zoologist 36(1), pp. 93–102.

Runge, CA, Rhodes, JR and Lopez-Cubillos, DS 2021a, [Mapping koala habitat for greater Queensland: Koala tree list - TableA2](#). Dataset. Threatened Species Recovery Hub. The University of Queensland, Brisbane, QLD.

Melzer, A, Cristescu, R, Ellis, W, et al. 2014, [The habitat and diet of koalas \(*Phascolarctos cinereus*\) in Queensland](#). Australian Mammalogy 36(2), pp. 189–199.

Ellis, WAH, Melzer, A, Carrick, FN, et al. 2002, [Tree use, diet and home range of the koala \(*Phascolarctos cinereus*\) at Blair Athol, central Queensland](#). Wildlife Research 29(3), pp. 303–311.

Central NSW Coast

SEPP 2021, [State Environmental Planning Policy \(koala habitat protection\) 2021](#). NSW Department of Planning Industry and Environment, NSW Government. Sydney, NSW.

DPIE 2019, [Koala habitat information base technical guide](#). Sydney: Department of Planning, Industry and Environment, NSW Government. Sydney, NSW.

OEH 2018, [A review of koala tree use across New South Wales](#). Office of Environment and Heritage, State of NSW Government. Sydney, NSW.

Central Queensland Coast

Runge, C.A, Rhodes, JR and Lopez-Cubillos, DS 2021b, [Queensland Koala Habitat Mapping. RE sp. tree suitability appendix table1](#). Dataset. Threatened Species Recovery Hub. The University of Queensland, Brisbane, QLD.

Runge, CA, Rhodes, JR and Lopez-Cubillos, DS 2021a, [Mapping koala habitat for greater Queensland: Koala tree list - TableA2](#). Dataset. Threatened Species Recovery Hub. The University of Queensland, Brisbane, QLD.

Melzer, A, Cristescu, R, Ellis, W, et al. 2014, [The habitat and diet of koalas \(*Phascolarctos cinereus*\) in Queensland](#). Australian Mammalogy 36(2), pp. 189–199.

Central and Southern Tablelands

SEPP 2021, [State Environmental Planning Policy \(koala habitat protection\) 2021](#). NSW Department of Planning Industry and Environment, NSW Government. Sydney, NSW.

DPIE 2019, [Koala habitat information base technical guide](#). Sydney: Department of Planning, Industry and Environment, NSW Government. Sydney, NSW.

OEH 2018, [A review of koala tree use across New South Wales](#). Office of Environment and Heritage, State of NSW Government. Sydney, NSW.

Darling Riverine Plains

SEPP 2021, [State Environmental Planning Policy \(koala habitat protection\) 2021](#). NSW Department of Planning Industry and Environment, NSW Government. Sydney, NSW.

DPIE 2019, [Koala habitat information base technical guide](#). Sydney: Department of Planning, Industry and Environment, NSW Government. Sydney, NSW.

Desert Uplands Locally

Runge, C.A, Rhodes, JR and Lopez-Cubillos, DS 2021b, [Queensland Koala Habitat Mapping. RE sp. tree suitability appendix table1](#). Dataset. Threatened Species Recovery Hub. The University of Queensland, Brisbane, QLD.

Runge, CA, Rhodes, JR and Lopez-Cubillos, DS 2021a, [Mapping koala habitat for greater Queensland: Koala tree list - TableA2](#). Dataset. Threatened Species Recovery Hub. The University of Queensland, Brisbane, QLD.

Melzer, A, Cristescu, R, Ellis, W, et al. 2014, [The habitat and diet of koalas \(*Phascolarctos cinereus*\) in Queensland](#). Australian Mammalogy 36(2), pp. 189–199.

Einasleigh Uplands

Runge, C.A, Rhodes, JR and Lopez-Cubillos, DS 2021b, [Queensland Koala Habitat Mapping. RE sp. tree suitability appendix table1](#). Dataset. Threatened Species Recovery Hub. The University of Queensland, Brisbane, QLD.

Far West NSW

SEPP 2021, [State Environmental Planning Policy \(koala habitat protection\) 2021](#). NSW Department of Planning Industry and Environment, NSW Government. Sydney, NSW.

DPIE 2019, [Koala habitat information base technical guide](#). Sydney: Department of Planning, Industry and Environment, NSW Government. Sydney, NSW.

OEH 2018, [A review of koala tree use across New South Wales](#). Office of Environment and Heritage, State of NSW Government. Sydney, NSW.

Mitchell Grass Downs

Runge, CA, Rhodes, JR and Lopez-Cubillos, DS 2021a, [Mapping koala habitat for greater Queensland: Koala tree list - TableA2](#). Dataset. Threatened Species Recovery Hub. The University of Queensland, Brisbane, QLD.

DES 2020, [Spatial modelling for koalas in South East Queensland: Report version 1.1. Koala Habitat Areas \(KHA\) v1.0, Locally Refined Koala Habitat Areas \(LRKHA\) v1.1, Koala Priority Areas \(KPA\) v1.0, Koala Habitat Restoration Areas \(KHRA\) v1.0](#). Department of Environment and Science, Queensland Government. Brisbane, QLD.

Runge, C.A, Rhodes, JR and Lopez-Cubillos, DS 2021b, [Queensland Koala Habitat Mapping. RE sp. tree suitability appendix table1](#). Dataset. Threatened Species Recovery Hub. The University of Queensland, Brisbane, QLD.

Wu, H, McAlpine, CA and Seabrook, LM 2012, [The dietary preferences of koalas, *Phascolarctos cinereus*, in southwest Queensland](#). Australian Zoologist 36(1), pp. 93–102.

Mulga Lands

Runge, CA, Rhodes, JR and Lopez-Cubillos, DS 2021a, [Mapping koala habitat for greater Queensland: Koala tree list - TableA2](#). Dataset. Threatened Species Recovery Hub. The University of Queensland, Brisbane, QLD.

Runge, C.A, Rhodes, JR and Lopez-Cubillos, DS 2021b, [Queensland Koala Habitat Mapping. RE sp. tree suitability appendix table1](#). Dataset. Threatened Species Recovery Hub. The University of Queensland, Brisbane, QLD.

Wu, H, McAlpine, CA and Seabrook, LM 2012, [The dietary preferences of koalas, *Phascolarctos cinereus*, in southwest Queensland](#). Australian Zoologist 36(1), pp. 93–102.

Smith, AG, McAlpine, C, Rhodes, JR, et al. 2013, [At what spatial scales does resource selection vary? A case study of koalas in a semiarid region](#). Austral Ecology 38(2), pp. 230–240.

Sullivan, BJ, Norris, WM and Baxter, GS 2003, [Low-density koala \(*Phascolarctos cinereus*\) populations in the mulgalands of south-west Queensland](#). II. Distribution and diet. Wildlife Research 30(4), pp. 331–338.

Sullivan, BJ, Baxter, GS and Lisle, AT 2002, [Low-density koala \(*Phascolarctos cinereus*\) populations in the mulgalands of south-west Queensland](#). I. Faecal pellet sampling protocol. Wildlife Research 29(5), pp. 455–462.

North Coast NSW

SEPP 2021, [State Environmental Planning Policy \(koala habitat protection\) 2021](#). NSW Department of Planning Industry and Environment, NSW Government. Sydney, NSW.

DPIE 2019, [Koala habitat information base technical guide](#). Sydney: Department of Planning, Industry and Environment, NSW Government. Sydney, NSW.

OEH 2018, [A review of koala tree use across New South Wales](#). Office of Environment and Heritage, State of NSW Government. Sydney, NSW.

New England Tablelands QLD

Runge, C.A, Rhodes, JR and Lopez-Cubillos, DS 2021b, [Queensland Koala Habitat Mapping. RE sp. tree suitability appendix table1](#). Dataset. Threatened Species Recovery Hub. The University of Queensland, Brisbane, QLD.

SEPP 2021, [State Environmental Planning Policy \(koala habitat protection\) 2021](#). NSW Department of Planning Industry and Environment, NSW Government. Sydney, NSW.

DPIE 2019, [Koala habitat information base technical guide](#). Sydney: Department of Planning, Industry and Environment, NSW Government. Sydney, NSW.

OEH 2018, [A review of koala tree use across New South Wales](#). Office of Environment and Heritage, State of NSW Government. Sydney, NSW.

Northern Tablelands NSW

SEPP 2021, [State Environmental Planning Policy \(koala habitat protection\) 2021](#). NSW Department of Planning Industry and Environment, NSW Government. Sydney, NSW.

DPIE 2019, [Koala habitat information base technical guide](#). Sydney: Department of Planning, Industry and Environment, NSW Government. Sydney, NSW.

OEH 2018, [A review of koala tree use across New South Wales](#). Office of Environment and Heritage, State of NSW Government. Sydney, NSW

NSW South Coast

SEPP 2021, [State Environmental Planning Policy \(koala habitat protection\) 2021](#). NSW Department of Planning Industry and Environment, NSW Government. Sydney, NSW.

DPIE 2019, [Koala habitat information base technical guide](#). Sydney: Department of Planning, Industry and Environment, NSW Government. Sydney, NSW.

OEH 2018, [A review of koala tree use across New South Wales](#). Office of Environment and Heritage, State of NSW Government. Sydney, NSW

North West Slopes

SEPP 2021, [State Environmental Planning Policy \(koala habitat protection\) 2021](#). NSW Department of Planning Industry and Environment, NSW Government. Sydney, NSW.

DPIE 2019, [Koala habitat information base technical guide](#). Sydney: Department of Planning, Industry and Environment, NSW Government. Sydney, NSW.

OEH 2018, [A review of koala tree use across New South Wales](#). Office of Environment and Heritage, State of NSW Government. Sydney, NSW

Riverina

SEPP 2021, [State Environmental Planning Policy \(koala habitat protection\) 2021](#). NSW Department of Planning Industry and Environment, NSW Government. Sydney, NSW.

DPIE 2019, [Koala habitat information base technical guide](#). Sydney: Department of Planning, Industry and Environment, NSW Government. Sydney, NSW.

South East QLD

Runge, CA, Rhodes, JR and Lopez-Cubillos, DS 2021a, [Mapping koala habitat for greater Queensland: Koala tree list - TableA2](#). Dataset. Threatened Species Recovery Hub. The University of Queensland, Brisbane, QLD.

DES 2020, [Spatial modelling for koalas in South East Queensland: Report version 1.1. Koala Habitat Areas \(KHA\) v1.0, Locally Refined Koala Habitat Areas \(LRKHA\) v1.1, Koala Priority Areas \(KPA\) v1.0, Koala Habitat Restoration Areas \(KHRA\) v1.0](#). Department of Environment and Science, Queensland Government. Brisbane, QLD.

Callaghan, J, McAlpine, C, Thompson, J, et al. 2011, [Ranking and mapping koala habitat quality for conservation planning on the basis of indirect evidence of tree-species use: A case study of Noosa Shire, south-eastern Queensland](#). Wildlife Research 38(2), pp. 89–102.

de Villiers, D 2021, Moreton bay rail project data on tree use 2013-2017.

Barth, BJ, FitzGibbon, SI, Gillett, A, et al. 2020, [Scattered paddock trees and roadside vegetation can provide important habitat for koalas \(*Phascolarctos cinereus*\) in an agricultural landscape](#). Australian Mammalogy 42, pp. 194–203.

Lollback, GW, Castley, JG, Mossaz, AC, et al. 2018, [Fine-scale changes in spatial habitat use by a low-density koala population in an isolated periurban forest remnant](#). Australian Mammalogy 40(1), pp. 84–92.

Runge, C.A, Rhodes, JR and Lopez-Cubillos, DS 2021b, [Queensland Koala Habitat Mapping. RE sp. tree suitability appendix table1](#). Dataset. Threatened Species Recovery Hub. The University of Queensland, Brisbane, QLD.

de Oliveira, SM, Murray, PJ, de Villiers, DL, et al. 2013, [Ecology and movement of urban koalas adjacent to linear infrastructure in coastal south-east Queensland](#). Australian Mammalogy 36, pp. 45–54.

Woodward, W, Ellis, WA, Carrick, FN, et al. 2008, [Koalas on North Stradbroke Island: Diet, tree use and reconstructed landscapes](#). Wildlife Research 35(7), pp. 606–611.

Wet Tropics

Runge, C.A, Rhodes, JR and Lopez-Cubillos, DS 2021b, [Queensland Koala Habitat Mapping. RE sp. tree suitability appendix table1](#). Dataset. Threatened Species Recovery Hub. The University of Queensland, Brisbane, QLD.

Glossary

Term	Definition
Ancillary habitat element	Landscape elements such as commonly used shelter vegetation species and the ground that contribute to koala habitat when they co-occur with locally important koala trees (see definition of LIKT).
Barrier	A natural or artificial landscape feature that prevents genetic dispersal of koalas such that fewer than one individual capable of breeding can naturally move between populations over 3 generations. Barriers include geographic features such as escarpments or inhospitable landscapes but do not include structures such as roads where movement is possible even if irregular or results in an increased rate of mortality.
Browse	Leaves or foliage for consumption by an animal
Chemotype	A type of plant that has similar morphological characteristics to another plant (for example same species or subspecies) but differs in quantities and/or types of chemical components.
Connectivity	How physically linked habitat patches are so that koalas can move unimpeded between them
Corridor	A strip of habitat that connects 2 or more habitat patches. Corridors differ from the landscape that borders them on both sides, which is not habitat.
Diet	The mixture of different foods eaten across multiple meals.
Disturbance	An event or force that results in a change in the structure of an ecosystem, a loss or organisms, or altered distributions of organisms. For example fire, flood, logging
Foliage	The leaves on a tree or shrub
FPCs	Formylated Phloroglucinol Compounds
Formylated Phloroglucinol Compounds (FPCs)	A specific group of plant secondary metabolites found in some <i>Eucalyptus</i> species from the <i>Symphyomyrtus</i> subgenus known to influence the nutritional quality of browse and feeding by the koala.
Genotype	For the purpose of this document, a genotype refers to the genetic material (that is alleles) that determine a trait or a number of traits in an organism.
Habitat Fragmentation	The subdivision of a large area of habitat into multiple smaller areas of habitat.
Habitat Loss	Loss of suitable conditions required for a species to be present in a landscape.
KMB	Koala management bioregion
Koala Management Bioregion (KMB)	A management unit designated for the purpose of this document, consisting of delineated land areas within New South Wales and Queensland derived from Koala Modelling Regions and Queensland Bioregions in New South Wales (NSW) and Queensland (QLD), respectively.
LIKT	Locally Important Koala Trees
Locally Important Koala Trees (LIKT)	Trees from species that are regularly browsed by koalas in a particular KMB, such that it could be considered a substantial portion of the koalas' diet. Where data from feeding observations or nutritional quality is lacking, then the tree species must be associated with medium or high use by koalas from observations of animals in a tree or scat associations with trees in published literature or from direct feedback from local koala researchers and/or koala carers in the region. See section 3.2 for a more detailed definition.
Metapopulation	The set of biological populations within a larger area, where movement or gene flow from one biological population to at least some other patches is possible, even if irregular.
Microbiome	The combination of microorganisms in a particular environment such as the gut
Nocturnal	Active at night and asleep during the day.

Term	Definition
Nutrients	A substance from food which provides nourishment essential for the maintenance of life, growth and reproduction.
Nutritional Quality	Used in reference to eucalypt browse in this document, nutritional quality refers to foliar concentrations of digestible nitrogen, which is a proxy for protein and a key limiting nutrient for the koala, and plant secondary metabolites that are known to influence palatability, feeding tree choice and population densities of the koala.
Palatability	How much leaf an animal will eat (that is total intake of browse).
Plant Secondary Metabolites (PSMs)	Chemical compounds produced by a plant through metabolic pathways, which are not used for primary processes (that is growth and reproduction).
Population	A set of individuals that live in the same habitat patch and interact with one another, commonly forming a breeding unit within which the exchange of genetic material is more or less unrestricted.
PSM	Plant secondary metabolites. Chemicals in plants which act as feeding deterrents to koalas as well as having other functions in plants.
Refugia	A habitat that provides spatial and/or temporal protection from one or more threats.
Remnant	Native vegetation that has never been cleared
Revegetation	Planting vegetation
Species	Following the EPBC Act (s528), a species is a group of biological entities that (a) interbreed to produce fertile offspring; or (b) possess common characteristics derived from a common gene pool; and includes (c) a sub-species.
Stepping Stone	A relatively isolated, locally important koala tree or collection of trees in the matrix that contribute to functional connectivity between habitat patches and/or expand the area of useable habitat around a habitat patch. If a barrier separates a tree from a habitat patch, it cannot be a Stepping Stone, but a Stepping Stone can prevent distance between patches from becoming a barrier.
Tannins	A common class of plant secondary metabolites found in many plants that can bind to foliar protein and make it unavailable for digestion.
Thermoregulation	An animal's regulation of body temperature.
Threat	A natural or anthropogenic process, activity or event that can negatively affect the survival, abundance or evolutionary potential of a species or ecological community.
Topography	Arrangement of the physical features in a landscape
UBFs	Unsubstituted B-Ring Flavanones
Unsubstituted B-ring Flavanones (UBFs)	A specific group of plant secondary metabolites found in some <i>Eucalyptus</i> species from the <i>Eucalyptus</i> (formerly <i>Monocalyptus</i>) subgenus and known to influence the nutritional quality of browse and feeding by the koala.

References

- ADAMS-HOSKING, C., MCALPINE, C., RHODES, J. R., GRANTHAM, H. S. & MOSS, P. T. 2012. Modelling changes in the distribution of the critical food resources of a specialist folivore in response to climate change. *Diversity and Distributions*, 18, 847-860.
- AITKEN, S. N. & WHITLOCK, M. C. 2013. Assisted gene flow to facilitate local adaptation to climate change. *Annual review of ecology, evolution, and systematics*, 44, 367-388.
- AKF. 2020. *Trees for koalas* [Online]. Available: <https://www.savethekoala.com/how-to-help/trees-koalas/#:~:text=The%20Koala%20Phascolarctos%20cinereus%20is,wide%20variety%20of%20eucalypt%20species>. [Accessed June 2022].
- ANDREW, R. L., WALLIS, I. R., HARWOOD, C. E. & FOLEY, W. J. 2010. Genetic and environmental contributions to variation and population divergence in a broad-spectrum foliar defence of *Eucalyptus tricarpa*. *Annals of Botany*, 105, 707-717.
- ANDREW, R. L., WALLIS, I. R., HARWOOD, C. E., HENSON, M. & FOLEY, W. J. 2007. Heritable variation in the foliar secondary metabolite sideroxylonal in *Eucalyptus* confers cross-resistance to herbivores. *Oecologia*, 153, 891-901.
- ARANDJELOVIC, M. & VIGILANT, L. 2018. Non-invasive genetic censusing and monitoring of primate populations. *American Journal of Primatology*, 80, e22743.
- ASHMAN, K. R., WATCHORN, D. J. & WHISSON, D. A. 2019. Prioritising research efforts for effective species conservation: a review of 145 years of koala research. *Mammal Review*, 49, 189-200.
- ASHTON, D. H. & CHINNER, J. H. 1999. Problems of regeneration of the mature *Eucalyptus regnans* F. Muell, (The Big Ash) forest, in the absence of fire at Wallaby Creek, Victoria, Australia. *Australian Forestry*, 62, 265-280.
- ATLAS OF LIVING AUSTRALIA. 2018. *Phascolarctos cinereus* (Goldfuss, 1817) [Online]. Available: www.ala.org.au [Accessed May 2022].
- ATYEO, C. & THACKWAY, R. 2009. Mapping and monitoring revegetation activities in Australia – towards national core attributes. *Australasian Journal of Environmental Management*, 16, 140-148.
- AU, J. 2018. *Multi-scale effects of nutrition on an arboreal folivore*. PhD Thesis, Australian National University.
- AU, J., CLARK, R. G., ALLEN, C., MARSH, K. J., FOLEY, W. J. & YOUNGENTOB, K. N. 2019. A nutritional mechanism underpinning folivore occurrence in disturbed forests. *Forest Ecology and Management*, 453, 117585.
- AU, J., YOUNGENTOB, K. N., CLARK, R. G., PHILLIPS, R. & FOLEY, W. J. 2017. Bark chewing reveals a nutrient limitation of leaves for a specialist folivore. *Journal of Mammalogy*, 98, 1185-1192.
- AWE 2022. National Recovery Plan for the Koala *Phascolarctos cinereus* (combined populations of Queensland, New South Wales and the Australian Capital Territory).
- BAILEY, R. G. 2014. Ecoregions. *New York*.
- BALLUT-DAJUD, G. A., SANDOVAL HERAZO, L. C., FERNÁNDEZ-LAMBERT, G., MARÍN-MUÑIZ, J. L., LÓPEZ MÉNDEZ, M. C. & BETANZO-TORRES, E. A. 2022. Factors Affecting Wetland Loss: A Review. *Land*, 11, 434.
- BARTH, B. J., FITZGIBBON, S. I., GILLETT, A., WILSON, R. S., MOFFITT, B., PYE, G. W., ADAM, D., PREECE, H. & ELLIS, W. A. 2019. Scattered paddock trees and roadside vegetation can provide important habitat for koalas (*Phascolarctos cinereus*) in an agricultural landscape. *Australian Mammalogy*, 42, 194-203.
- BEALE, P. K., MARSH, K. J., FOLEY, W. J. & MOORE, B. D. 2018. A hot lunch for herbivores: physiological effects of elevated temperatures on mammalian feeding ecology. *Biol Rev Camb Philos Soc*, 93, 674-692.

- BEALE, P. K., YOUNGENTOB, K. N. & MARSH, K. J. 2022. Effects of Fire on Koalas and Their Habitat: Report prepared for DAWE. ANU.
- BEYER, H. L., DE VILLIERS, D., LOADER, J., ROBBINS, A., STIGNER, M., FORBES, N. & HANGER, J. 2018. Management of multiple threats achieves meaningful koala conservation outcomes. *Journal of Applied Ecology*, 55, 1966-1975.
- BLYTON, M. D. J., SOO, R. M., HUGENHOLTZ, P. & MOORE, B. D. 2022. Maternal inheritance of the koala gut microbiome and its compositional and functional maturation during juvenile development. *Environmental Microbiology*, 24, 475-493.
- BLYTON, M. D. J., SOO, R. M., WHISSON, D., MARSH, K. J., PASCOE, J., LE PLA, M., FOLEY, W., HUGENHOLTZ, P. & MOORE, B. D. 2019. Faecal inoculations alter the gastrointestinal microbiome and allow dietary expansion in a wild specialist herbivore, the koala. *Animal Microbiome*, 1, 6.
- BONIER, F., MARTIN, P. R., MOORE, I. T. & WINGFIELD, J. C. 2009. Do baseline glucocorticoids predict fitness? *Trends in Ecology & Evolution*, 24, 634-642.
- BOWMAN, D. M. J. S., WILLIAMSON, G. J., GIBSON, R. K., BRADSTOCK, R. A. & KEENAN, R. J. 2021. The severity and extent of the Australia 2019–20 Eucalyptus forest fires are not the legacy of forest management. *Nature Ecology & Evolution*, 5, 1003-1010.
- BREED, M. F., STEAD, M. G., OTTEWELL, K. M., GARDNER, M. G. & LOWE, A. J. 2013. Which provenance and where? Seed sourcing strategies for revegetation in a changing environment. *Conservation Genetics*, 14, 1-10.
- BRISCOE, N. J., HANDASYDE, K. A., GRIFFITHS, S. R., PORTER, W. P., KROCKENBERGER, A. & KEARNEY, M. R. 2014. Tree-hugging koalas demonstrate a novel thermoregulatory mechanism for arboreal mammals. *Biology Letters*, 10.
- BRISCOE, N. J., KEARNEY, M. R., TAYLOR, C. A. & WINTLE, B. A. 2016. Unpacking the mechanisms captured by a correlative species distribution model to improve predictions of climate refugia. *Global Change Biology*, 22, 2425-2439.
- BROADHURST, L. M., LOWE, A., COATES, D. J., CUNNINGHAM, S. A., MCDONALD, M., VESK, P. A. & YATES, C. 2008. Seed supply for broadscale restoration: maximizing evolutionary potential. *Evolutionary Applications*, 1, 587-597.
- CALDER, I. R. 2002. Eucalyptus, water and the environment. *Eucalyptus. The genus Eucalyptus*, 36-51.
- CLIFTON, I. D. 2010. High koala mortality associated with low browse moisture in tropical environments. *Australian Mammalogy*, 32, 157-159.
- CLIFTON, I. D., ELLIS, W. A. H., MELZER, A. & TUCKER, G. 2007. Water turnover and the northern range of the koala (*Phascolarctos cinereus*). *Australian Mammalogy*, 29, 85-88.
- CRAIG, M. D., STOKES, V. L., HARDY, G. E. S. & HOBBS, R. J. 2015. Edge effects across boundaries between natural and restored jarrah (*Eucalyptus marginata*) forests in south-western Australia. *Austral Ecology*, 40, 186-197.
- CRISTESCU, R. H., BANKS, P. B., CARRICK, F. N. & FRÈRE, C. 2013a. Potential ‘Ecological Traps’ of Restored Landscapes: Koalas *Phascolarctos cinereus* Re-Occupy a Rehabilitated Mine Site. *PLOS ONE*, 8, e80469.
- CRISTESCU, R. H., FOLEY, E., MARKULA, A., JACKSON, G., JONES, D. & FRÈRE, C. 2015. Accuracy and efficiency of detection dogs: a powerful new tool for koala conservation and management. *Scientific Reports*, 5, 8349.
- CRISTESCU, R. H., GARDINER, R., TERRAUBE, J., MCDONALD, K., POWELL, D., LEVENGOOD, A. L. & FRÈRE, C. H. 2021. Difficulties of assessing the impacts of the 2019–2020 bushfires on koalas. *Austral ecology*.
- CRISTESCU, R. H., RHODES, J., FRÈRE, C. & BANKS, P. B. 2013b. Is restoring flora the same as restoring fauna? Lessons learned from koalas and mining rehabilitation. *Journal of Applied Ecology*, 50, 423-431.
- CROWTHER, M. S., DARGAN, J. R., MADANI, G., RUS, A. I., KROCKENBERGER, M. B., MCARTHUR, C., MOORE, B. D., LUNNEY, D. & MELLA, V. S. A. 2021. Comparison of three methods of estimating the population size of an arboreal mammal in a fragmented rural landscape. *Wildlife Research*, 48, 105-114.

- CUBBAGE, F., MAC DONAGH, P., SAWINSKI JÚNIOR, J., RUBILAR, R., DONOSO, P., FERREIRA, A., HOEFLICH, V., OLMOS, V. M., FERREIRA, G., BALMELLI, G., SIRY, J., BÁEZ, M. N. & ALVAREZ, J. 2007. Timber investment returns for selected plantations and native forests in South America and the Southern United States. *New Forests*, 33, 237-255.
- DAVIES, N., GRAMOTNEV, G., SEABROOK, L., BRADLEY, A., BAXTER, G., RHODES, J., LUNNEY, D. & MCALPINE, C. 2013. Movement patterns of an arboreal marsupial at the edge of its range: a case study of the koala. *Movement Ecology*, 1, 8.
- DAVIES, N., GRAMOTNEV, G., SEABROOK, L., MCALPINE, C., BAXTER, G., LUNNEY, D. & BRADLEY, A. 2014. Climate-driven changes in diet composition and physiological stress in an arboreal folivore at the semi-arid edge of its distribution. *Biological Conservation*, 172, 80-88.
- DEGABRIEL, J. L., MOORE, B. D., FELTON, A. M., GANZHORN, J. U., STOLTER, C., WALLIS, I. R., JOHNSON, C. N. & FOLEY, W. J. 2014. Translating nutritional ecology from the laboratory to the field: milestones in linking plant chemistry to population regulation in mammalian browsers. *Oikos*, 123, 298-308.
- DEGABRIELE, R. 1980. The physiology of the koala. *Sci Am*, 243, 94-9.
- DIQUE, D. S., PREECE, H. J., THOMPSON, J. & VILLIERS, D. L. D. 2004. Determining the distribution and abundance of a regional koala population in south-east Queensland for conservation management. *Wildlife Research*, 31, 109-117.
- DIQUE, D. S., THOMPSON, J., PREECE, H. J., PENFOLD, G. C., VILLIERS, D. L. D. & LESLIE, R. S. 2003a. Koala mortality on roads in south-east Queensland: the koala speed-zone trial. *Wildlife Research*, 30, 419-426.
- DIQUE, D. S., THOMPSON, J., PREECE, H. J., VILLIERS, D. L. D. & CARRICK, F. N. 2003b. Dispersal patterns in a regional koala population in south-east Queensland. *Wildlife Research*, 30, 281-290.
- DPE, N. D. O. P. A. E. 2022. Koala habitat restoration guidelines: A practical guide to identify, connect and restore koala habitat in New South Wales. In: NSW DEPARTMENT OF PLANNING AND ENVIRONMENT – ENVIRONMENT & SCIENCE, E. A. (eds.). Sydney, NSW.
- DPIE 2018. A review of koala tree use across New South Wales.
- DPIE 2021. Koala habitat restoration guidelines: A practical guide to identify, connect and restore koala habitat in New South Wales.
- DUGUMA, L., MINANG, P., AYNEKULU, B., CARSAN, S., NZYOKA, J., BAH, A. & JAMNADASS, R. H. 2020. From Tree Planting to Tree Growing: Rethinking Ecosystem Restoration Through Tree. *World Agroforestry Working Paper*.
- ELLIS, W., BERCOVITCH, F., FITZGIBBON, S., ROE, P., WIMMER, J., MELZER, A. & WILSON, R. 2011. Koala bellows and their association with the spatial dynamics of free-ranging koalas. *Behavioral Ecology*, 22, 372-377.
- ELLIS, W., FITZGIBBON, S., MELZER, A., WILSON, R., JOHNSTON, S., BERCOVITCH, F., DIQUE, D. & CARRICK, F. 2013. Koala habitat use and population density: using field data to test the assumptions of ecological models. *Australian Mammalogy*, 35, 160-165.
- ELLIS, W., MELZER, A., CLIFTON, I. & CARRICK, F. 2010. Climate change and the koala *Phascolarctos cinereus*: water and energy. *Australian Zoologist*, 35, 369-377.
- ELLIS, W., MELZER, A., GREEN, B., NEWGRAIN, K., HINDELL, M. & CARRICK, F. 1995. Seasonal-Variation in Water Flux, Field Metabolic-Rate and Food-Consumption of Free-Ranging Koalas (*Phascolarctos-Cinereus*). *Australian Journal of Zoology*, 43, 59-68.
- ELLIS, W. A. H., MELZER, A., CARRICK, F. N. & HASEGAWA, M. 2002. Tree use, diet and home range of the koala (*Phascolarctos cinereus*) at Blair Athol, central Queensland. *Wildlife Research*, 29, 303-311.
- ENGEL, V., JOBBÁGY, E. G., STIEGLITZ, M., WILLIAMS, M. & JACKSON, R. B. 2005. Hydrological consequences of Eucalyptus afforestation in the Argentine Pampas. *Water Resources Research*, 41.
- FINLAYSON, C. M. & GARDNER, R. C. 2021. Ten key issues from the Global Wetland Outlook for decision makers. *Marine and Freshwater Research*, 72, 301-310.

- GOLDINGAY, R. L. & DOBNER, B. 2014. Home range areas of koalas in an urban area of north-east New South Wales. *Australian Mammalogy*, 36, 74-80.
- GORDON, G., BROWN, A. S. & PULSFORD, T. 1988. A koala (*Phascolarctos cinereus* Goldfuss) population crash during drought and heatwave conditions in south-western Queensland. *Australian Journal of Ecology*, 13, 451-461.
- GREGORINI, P., VILLALBA, J. J., CHILIBROSTE, P. & PROVENZA, F. D. 2017. Grazing management: setting the table, designing the menu and influencing the diner. *Animal Production Science*, 57, 1248-1268.
- HAGENS, S. V., RENDALL, A. R. & WHISSON, D. A. 2018. Passive acoustic surveys for predicting species' distributions: Optimising detection probability. *PLOS ONE*, 13, e0199396.
- HAMER, J. J., VENEKLAAS, E. J., RENTON, M. & POOT, P. 2016. Links between soil texture and root architecture of Eucalyptus species may limit distribution ranges under future climates. *Plant and soil*, 403, 217-229.
- HARVEST, T., DAVIDSON, N. J. & CLOSE, D. C. 2008. Is decline in high altitude eucalypt forests related to rainforest understorey development and altered soil bacteria following the long absence of fire? *Austral Ecology*, 33, 880-890.
- HAWKINS, B. & POLGLASE, P. J. 2000. Foliar concentrations and resorption of nitrogen and phosphorus in 15 species of eucalypts grown under non-limited water and nutrient availability. *Australian Journal of Botany*, 48, 597-602.
- HEATH, J. T., CHAFER, C. J., BISHOP, T. F. A. & VAN OGTROP, F. F. 2016. Post-Fire Recovery of Eucalypt-Dominated Vegetation Communities in the Sydney Basin, Australia. *Fire Ecology*, 12, 53-79.
- HING, S., NARAYAN, E. J., THOMPSON, R. C. A. & GODFREY, S. S. 2016. The relationship between physiological stress and wildlife disease: consequences for health and conservation. *Wildlife Research*, 43, 51-60.
- HOLOPAINEN, J. K., VIRJAMO, V., GHIMIRE, R. P., BLANDE, J. D., JULKUNEN-TIITTO, R. & KIVIMÄENPÄÄ, M. 2018. Climate Change Effects on Secondary Compounds of Forest Trees in the Northern Hemisphere. *Frontiers in plant science*, 9, 1445-1445.
- HORTON, B. M., GLEN, M., DAVIDSON, N. J., RATKOWSKY, D., CLOSE, D. C., WARDLAW, T. J. & MOHAMMED, C. 2013. Temperate eucalypt forest decline is linked to altered ectomycorrhizal communities mediated by soil chemistry. *Forest Ecology and Management*, 302, 329-337.
- HUME, I. 1990. Biological basis for the vulnerability of koalas to habitat fragmentation. *Lunney D, Urquhart CA, Reed P, editors*, 32-38.
- JANSE, J. H., VAN DAM, A. A., HES, E. M. A., DE KLEIN, J. J. M., FINLAYSON, C. M., JANSSEN, A. B. G., VAN WIJK, D., MOOIJ, W. M. & VERHOEVEN, J. T. A. 2019. Towards a global model for wetlands ecosystem services. *Current Opinion in Environmental Sustainability*, 36, 11-19.
- JENSEN, A. 2016. Monitoring of Die Back in River Red Gum (*Eucalyptus camaldulensis*) Communities in the Northern & Yorke Region 2008-2016. Natural Resources Northern & Yorke SA.
- JIANG, A., TRIBE, A. & MURRAY, P. 2019. The development of an improved scat survey method for koalas (*Phascolarctos cinereus*). *Australian Journal of Zoology*, 67, 125-133.
- JURSKIS, V., DOUCH, A., MCCRAY, K. & SHIELDS, J. 2001. A playback survey of the koala, *Phascolarctos cinereus*, and a review of its distribution in the Eden Region of south-eastern New South Wales. *Australian Forestry*, 64, 226-231.
- KAVANAGH, R. P. & STANTON, M. A. 2012. Koalas use young Eucalyptus plantations in an agricultural landscape on the Liverpool Plains, New South Wales. *Ecological Management & Restoration*, 13, 297-305.
- KAVANAGH, R. P., STANTON, M. A. & BRASSIL, T. E. 2007. Koalas continue to occupy their previous home-ranges after selective logging in *CallitrisEucalyptus* forest. *Wildlife Research*, 34, 94-107.
- KOHL, K. D., WEISS, R. B., COX, J., DALE, C. & DEARING, M. D. 2014. Gut microbes of mammalian herbivores facilitate intake of plant toxins. *Ecology Letters*, 17, 1238-1246.

- LAUGER, K. K., MAHONEY, S. M., ROTHWELL, E. M., CORBIN, J. P. M. & WHITHAM, T. G. 2021. A mammalian herbivore prefers locally adapted populations in a common garden: implications for climate change mitigation. *bioRxiv*, 2021.12.01.470780.
- LAW, B., GONSALVES, L., BILNEY, R., PETERIE, J., PIETSCH, R., ROE, P. & TRUSKINGER, A. 2020. Using Passive Acoustic Recording and Automated Call Identification to Survey Koalas in the Southern Forests of New South Wales. *Australian Zoologist*, 40, 477-486.
- LAW, B. S., BRASSIL, T., GONSALVES, L., ROE, P., TRUSKINGER, A. & MCCONVILLE, A. 2018. Passive acoustics and sound recognition provide new insights on status and resilience of an iconic endangered marsupial (koala *Phascolarctos cinereus*) to timber harvesting. *PLOS ONE*, 13, e0205075.
- LAW, B. S., GONSALVES, L., BURGAR, J., BRASSIL, T., KERR, I. & O'LOUGHLIN, C. 2022. Fire severity and its local extent are key to assessing impacts of Australian mega-fires on koala (*Phascolarctos cinereus*) density. *Global Ecology and Biogeography*, 31, 714-726.
- LAWLER, I. R., FOLEY, W. J., ESCHLER, B. M., PASS, D. M. & HANDASYDE, K. 1998. Intraspecific variation in *Eucalyptus* secondary metabolites determines food intake by folivorous marsupials. *Oecologia*, 116, 160-169.
- LIKENS, G. & LINDENMAYER, D. 2018. *Effective ecological monitoring*, CSIRO publishing.
- LINDENMAYER, D. 2020. Improving Restoration Programs Through Greater Connection With Ecological Theory and Better Monitoring. *Frontiers in Ecology and Evolution*, 8.
- LINDENMAYER, D., HOBBS, R. J., MONTAGUE-DRAKE, R., ALEXANDRA, J., BENNETT, A., BURGMAN, M., CALE, P., CALHOUN, A., CRAMER, V., CULLEN, P., DRISCOLL, D., FAHRIG, L., FISCHER, J., FRANKLIN, J., HAILA, Y., HUNTER, M., GIBBONS, P., LAKE, S., LUCK, G., MACGREGOR, C., MCINTYRE, S., NALLY, R. M., MANNING, A., MILLER, J., MOONEY, H., NOSS, R., POSSINGHAM, H., SAUNDERS, D., SCHMIEGELOW, F., SCOTT, M., SIMBERLOFF, D., SISK, T., TABOR, G., WALKER, B., WIENS, J., WOINARSKI, J. & ZAVALA, E. 2008. A checklist for ecological management of landscapes for conservation. *Ecology Letters*, 11, 78-91.
- LINDENMAYER, D. B. & FISCHER, J. 2013. *Habitat Fragmentation and Landscape Change: An Ecological and Conservation Synthesis*, Island Press.
- LINDENMAYER, D. B., HULVEY, K. B., HOBBS, R. J., COLYVAN, M., FELTON, A., POSSINGHAM, H., STEFFEN, W., WILSON, K., YOUNGENTOB, K. & GIBBONS, P. 2012. Avoiding bio-perversity from carbon sequestration solutions. *Conservation Letters*, 5, 28-36.
- LINDENMAYER, D. B. & LIKENS, G. E. 2009. Adaptive monitoring: a new paradigm for long-term research and monitoring. *Trends in Ecology & Evolution*, 24, 482-486.
- LUNNEY, D., CROWTHER, M. S., WALLIS, I. R., FOLEY, W. J., LEMON, J., WHEELER, R., MADANI, G., ORSCHEG, C., GRIFFITH, J. E., KROCKENBERGER, M. & RETAMALES, M. 2012. Koalas and climate change: a case study on the Liverpool Plains, north-west New South Wales. In: LUNNEY, D. & HUTCHINGS, P. (eds.) *Wildlife and Climate Change: Towards Robust Conservation Strategies for Australian Fauna*. Mosman, NSW, Australia: Royal Zoological Society of NSW.
- LUTZE, M. & FAUNT, K. 2006. The East Gippsland Silvicultural Systems Project. III: Site occupancy, species composition and growth to 12 years. *Australian Forestry*, 69, 198-212.
- LUXTON, S., LEWIS, D., CHALWELL, S., ADDICOTT, E. & HUNTER, J. 2021. Australian advances in vegetation classification and the need for a national, science-based approach. *Australian Journal of Botany*, 69, 329-338.
- MANNING, A. D., CUNNINGHAM, R. B. & LINDENMAYER, D. B. 2013. Bringing forward the benefits of coarse woody debris in ecosystem recovery under different levels of grazing and vegetation density. *Biological Conservation*, 157, 204-214.
- MANNING, A. D., CUNNINGHAM, R. B., TONGWAY, D. & LINDENMAYER, D. B. 2020. Woodlands and woody debris: Understanding structure and composition to inform restoration. *PLOS ONE*, 15, e0224258.

- MARSH, K. J., BLYTON, M. D. J., FOLEY, W. J. & MOORE, B. D. 2021a. Fundamental dietary specialisation explains differential use of resources within a koala population. *Oecologia*, 196, 795-803.
- MARSH, K. J., MOORE, B. D., WALLIS, I. R. & FOLEY, W. J. 2014. Feeding rates of a mammalian browser confirm the predictions of a 'foodscape' model of its habitat. *Oecologia*, 174, 873-82.
- MARSH, K. J., SARAF, I., HOCART, C. H., YOUNGENTOB, K., SINGH, I.-P. & FOLEY, W. J. 2019. Occurrence and distribution of unsubstituted B-ring flavanones in Eucalyptus foliage. *Phytochemistry*, 160, 31-39.
- MARSH, K. J., WALLIS, I. R. & FOLEY, W. J. 2007. Behavioural contributions to the regulated intake of plant secondary metabolites in koalas. *Oecologia*, 154, 283-90.
- MARSH, K. J., YOUNGENTOB, K. N. & CLARK, R. G. 2021b. Determining the effects of forest harvesting on habitat nutritional quality for koalas: Report prepared for NSW NRC.
- MARTIN, R. 1985. Overbrowsing, and decline of a population of the koala, *Phascolarctos cinereus*, in Victoria. I. Food preference and food tree defoliation. *Wildlife Research*, 12, 355-365.
- MATTHEWS, A., LUNNEY, D., GRESSER, S. & MAITZ, W. 2016. Movement patterns of koalas in remnant forest after fire. *Australian Mammalogy*, 38, 91-104.
- 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. & CLOSE, R. 2015. Conserving koalas: A review of the contrasting regional trends, outlooks and policy challenges. *Biological Conservation*, 192, 226-236.
- MCALPINE, C. A., RHODES, J. R., BOWEN, M. E., LUNNEY, D., CALLAGHAN, J. G., MITCHELL, D. L. & POSSINGHAM, H. P. 2008. Can multiscale models of species' distribution be generalized from region to region? A case study of the koala. *Journal of Applied Ecology*, 45, 558-567.
- MCALPINE, C. A., RHODES, J. R., CALLAGHAN, J. G., BOWEN, M. E., LUNNEY, D., MITCHELL, D. L., PULLAR, D. V. & POSSINGHAM, H. P. 2006. The importance of forest area and configuration relative to local habitat factors for conserving forest mammals: A case study of koalas in Queensland, Australia. *Biological Conservation*, 132, 153-165.
- MCGREGOR, D. C., KERR, S. E. & KROCKENBERGER, A. K. 2013. The Distribution and Abundance of an Island Population of Koalas (*Phascolarctos cinereus*) in the Far North of Their Geographic Range. *PLOS ONE*, 8, e59713.
- MCKIERNAN, A. B., O'REILLY-WAPSTRA, J. M., PRICE, C., DAVIES, N. W., POTTS, B. M. & HOVENDEN, M. J. 2012. Stability of plant defensive traits among populations in two Eucalyptus species under elevated carbon dioxide. *J Chem Ecol*, 38, 204-12.
- MCKIERNAN, A. B., POTTS, B. M., BRODRIBB, T. J., HOVENDEN, M. J., DAVIES, N. W., MCADAM, S. A., ROSS, J. J., RODEMANN, T. & O'REILLY-WAPSTRA, J. M. 2016. Responses to mild water deficit and rewatering differ among secondary metabolites but are similar among provenances within Eucalyptus species. *Tree Physiol*, 36, 133-47.
- MELLA, V. S. A., MCARTHUR, C., KROCKENBERGER, M. B., FREND, R. & CROWTHER, M. S. 2019. Needing a drink: Rainfall and temperature drive the use of free water by a threatened arboreal folivore. *PLOS ONE*, 14, e0216964.
- MELZER, A. 1995. *Aspects of the ecology of the koala, Phascolarctos cinereus (Goldfuss, 1817), in the sub-humid woodlands of central Queensland*. Ph.D, The University of Queensland.
- MELZER, A. & LAMB, D. 1994. Low density populations of the koala (*Phascolarctos cinereus*) in central Queensland. . *Proceedings of the Royal Society of Queensland* 104, 89-93.
- MOORE, B. D. & FOLEY, W. J. 2000. A review of feeding and diet selection in koalas (*Phascolarctos cinereus*). *Australian Journal of Zoology*, 48, 317-333.
- MOORE, B. D., FOLEY, W. J., WALLIS, I. R., COWLING, A. & HANDASYDE, K. A. 2005. Eucalyptus foliar chemistry explains selective feeding by koalas. *Biology Letters*, 1, 64-67.
- MOORE, B. D., LAWLER, I. R., WALLIS, I. R., BEALE, C. M. & FOLEY, W. J. 2010. Palatability mapping: a koala's eye view of spatial variation in habitat quality. *Ecology*, 91, 3165-3176.

- MOORE, B. D., WALLIS, I. R., WOOD, J. T. & FOLEY, W. J. 2004. Foliar nutrition, site quality, and temperature influence foliar chemistry of tallowwood (*Eucalyptus microcorys*). *Ecological Monographs*, 74, 553-568.
- MURCIA, C. 1995. Edge effects in fragmented forests: implications for conservation. *Trends in ecology & evolution*, 10, 58-62.
- NAGY, K. & MARTIN, R. 1985. Field Metabolic Rate, Water Flux, Food Consumption and Time Budget of Koalas, *Phascolarctos cinereus* (Marsupialia: Phascolarctidae) in Victoria. *Australian Journal of Zoology*, 33, 655-665.
- NARAYAN, E. 2019. Physiological stress levels in wild koala sub-populations facing anthropogenic induced environmental trauma and disease. *Scientific Reports*, 9, 6031.
- NARAYAN, E. J. & WILLIAMS, M. 2016. Understanding the dynamics of physiological impacts of environmental stressors on Australian marsupials, focus on the koala (*Phascolarctos cinereus*). *BMC Zoology*, 1, 2.
- NIINEMETS, Ü. 2015. Uncovering the hidden facets of drought stress: secondary metabolites make the difference. *Tree Physiology*, 36, 129-132.
- NOLAN, R. H., GAUTHEY, A., LOSSO, A., MEDLYN, B. E., SMITH, R., CHHAJED, S. S., FULLER, K., SONG, M., LI, X., BEAUMONT, L. J., BOER, M. M., WRIGHT, I. J. & CHOAT, B. 2021. Hydraulic failure and tree size linked with canopy die-back in eucalypt forest during extreme drought. *New Phytologist*, 230, 1354-1365.
- PADOVAN, A., KESZEI, A., WALLIS, I. R. & FOLEY, W. J. 2012. Mosaic Eucalypt Trees Suggest Genetic Control at a Point That Influences Several Metabolic Pathways. *Journal of Chemical Ecology*, 38, 914-923.
- PARKINS, K., YORK, A. & DI STEFANO, J. 2018. Edge effects in fire-prone landscapes: Ecological importance and implications for fauna. *Ecology and Evolution*, 8, 5937-5948.
- PHILLIPS, S. & CALLAGHAN, J. 2000. Tree species preferences of koalas (*Phascolarctos cinereus*) in the Campbelltown area south-west of Sydney, New South Wales. *Wildlife Research*, 27, 509-516.
- PHILLIPS, S. & CALLAGHAN, J. 2011. The Spot Assessment Technique: a tool for determining localised levels of habitat use by Koalas *Phascolarctos cinereus*. *Australian Zoologist*, 35, 774-780.
- PHILLIPS, S., CALLAGHAN, J. & THOMPSON, V. 2000. The tree species preferences of koalas (*Phascolarctos cinereus*) inhabiting forest and woodland communities on Quaternary deposits in the Port Stephens area, New South Wales. *Wildlife Research*, 27, 1-10.
- POLKINGHORNE, A., HANGER, J. & TIMMS, P. 2013. Recent advances in understanding the biology, epidemiology and control of chlamydial infections in koalas. *Veterinary Microbiology*, 165, 214-223.
- PROBER, S., BYRNE, M., MCLEAN, E., STEANE, D., POTTS, B., VAILLANCOURT, R. & STOCK, W. 2015. Climate-adjusted provenancing: a strategy for climate-resilient ecological restoration. *Frontiers in Ecology and Evolution*, 3.
- PROVENZA, F. D., VILLALBA, J. J., DZIBA, L. E., ATWOOD, S. B. & BANNER, R. E. 2003. Linking herbivore experience, varied diets, and plant biochemical diversity. *Small Ruminant Research*, 49, 257-274.
- QUIGLEY, B. L. & TIMMS, P. 2020. Helping koalas battle disease – Recent advances in Chlamydia and koala retrovirus (KoRV) disease understanding and treatment in koalas. *FEMS Microbiology Reviews*, 44, 583-605.
- RAM, J., GARG, V. K., TOKY, O. P., MINHAS, P. S., TOMAR, O. S., DAGAR, J. C. & KAMRA, S. K. 2007. Biodrainage potential of *Eucalyptus tereticornis* for reclamation of shallow water table areas in north-west India. *Agroforestry Systems*, 69, 147-165.
- RAMSAY, S. 1999. *The ecology and dispersal patterns of juvenile koalas, phascolarctos cinereus, in fragmented habitat*. University of Sydney.
- RHODES, J. R., CALLAGHAN, J. G., MCALPINE, C. A., DE JONG, C., BOWEN, M. E., MITCHELL, D. L., LUNNEY, D. & POSSINGHAM, H. P. 2008. Regional variation in habitat-occupancy thresholds: a warning for conservation planning. *Journal of Applied Ecology*, 45, 549-557.

- RHODES, J. R., NG, C. F., DE VILLIERS, D. L., PREECE, H. J., MCALPINE, C. A. & POSSINGHAM, H. P. 2011. Using integrated population modelling to quantify the implications of multiple threatening processes for a rapidly declining population. *Biological Conservation*, 144, 1081-1088.
- RUS, A. I., MCARTHUR, C., MELLA, V. S. & CROWTHER, M. S. 2021. Habitat fragmentation affects movement and space use of a specialist folivore, the koala. *Animal Conservation*, 24, 26-37.
- SALA, O. E. & MAESTRE, F. T. 2014. Grass-woodland transitions: determinants and consequences for ecosystem functioning and provisioning of services. *Journal of Ecology*, 102, 1357-1362.
- SCHULTZ, A. J., CRISTESCU, R. H., LITTLEFORD-COLQUHOUN, B. L., JACCOUD, D. & FRÈRE, C. H. 2018. Fresh is best: Accurate SNP genotyping from koala scats. *Ecology and Evolution*, 8, 3139-3151.
- SEABROOK, L., MCALPINE, C., BAXTER, G., RHODES, J., BRADLEY, A. & LUNNEY, D. 2011. Drought-driven change in wildlife distribution and numbers: a case study of koalas in south west Queensland. *Wildlife Research*, 38, 509-524.
- SMITH, A. G., MCALPINE, C. A., RHODES, J. R., LUNNEY, D., SEABROOK, L. & BAXTER, G. 2013. Out on a limb: habitat use of a specialist folivore, the koala, at the edge of its range in a modified semi-arid landscape. *Landscape Ecology*, 28, 415-426.
- SMITH, A. P. 2004. Koala conservation and habitat requirements in a timber production forest in north-east New South Wales. *Conservation of Australia's Forest Fauna*, 2, 591-611.
- STEPHENS, D. W. & KREBS, J. R. 2019. Foraging theory. *Foraging theory*. Princeton university press.
- SULLIVAN, B. J., BAXTER, G. S., LISLE, A. T., PAHL, L. & NORRIS, W. M. 2004. Low-density koala (*Phascolarctos cinereus*) populations in the mulgalands of south-west Queensland. IV. Abundance and conservation status. *Wildlife Research*, 31, 19-29.
- WEDROWICZ, F., KARSA, M., MOSSE, J. & HOGAN, F. E. 2013. Reliable genotyping of the koala (*Phascolarctos cinereus*) using DNA isolated from a single faecal pellet. *Molecular Ecology Resources*, 13, 634-641.
- WHISSON, D. A. & ASHMAN, K. R. 2020. When an iconic native animal is overabundant: The koala in southern Australia. *Conservation Science and Practice*, 2, e188.
- WHITE, N. A. 1999. Ecology of the koala (*Phascolarctos cinereus*) in rural south-east Queensland, Australia. *Wildlife Research*, 26, 731-744.
- WILMOTT, L., CULLEN, D., MADANI, G., KROGH, M. & MADDEN, K. 2019. Are koalas detected more effectively by systematic spotlighting or diurnal searches? *Australian Mammalogy*, 41, 157-160.
- WINDLEY, H. R., WALLIS, I. R., DEGABRIEL, J. L., MOORE, B. D., JOHNSON, C. N. & FOLEY, W. J. 2013. A faecal index of diet quality that predicts reproductive success in a marsupial folivore. *Oecologia*, 173, 203-212.
- WITT, R. R., BERANEK, C. T., HOWELL, L. G., RYAN, S. A., CLULOW, J., JORDAN, N. R., DENHOLM, B. & ROFF, A. 2020. Real-time drone derived thermal imagery outperforms traditional survey methods for an arboreal forest mammal. *PLOS ONE*, 15, e0242204.
- WOODWARD, W., ELLIS, W. A., CARRICK, F. N., TANIZAKI, M., BOWEN, D. & SMITH, P. 2008. Koalas on North Stradbroke Island: diet, tree use and reconstructed landscapes. *Wildlife Research*, 35, 606-611.
- WOOSNAM-MERCHEZ, O., CRISTESCU, R., DIQUE, D., ELLIS, B., BEETON, R., SIMMONDS, J. & CARRICK, F. 2013. What faecal pellet surveys can and can't reveal about the ecology of koalas *Phascolarctos cinereus*. *Australian Zoologist*, 36, 192-200.
- WRIGHT, D. H. 1983. Species-Energy Theory: An Extension of Species-Area Theory. *Oikos*, 41, 496-506.
- YOUNGENTOB, K. N., LINDENMAYER, D. B., MARSH, K. J., KROCKENBERGER, A. K. & FOLEY, W. J. 2021a. Food intake: an overlooked driver of climate change casualties? *Trends in Ecology & Evolution*, 36, 676-678.

- YOUNGENTOB, K. N., MARSH, K. J. & SKEWES, J. 2021b. *A review of koala habitat assessment criteria and methods*, report prepared for the Department of Agriculture, Water and the Environment, Canberra, November. CC BY 4.0.
- YOUNGENTOB, K. N., WALLIS, I. R., LINDENMAYER, D. B., WOOD, J. T., POPE, M. L. & FOLEY, W. J. 2011. Foliage chemistry influences tree choice and landscape use of a gliding marsupial folivore. *Journal of Chemical Ecology*, 37, 71-84.
- YOUNGENTOB, K. N., YOON, H.-J., STEIN, J., LINDENMAYER, D. B. & HELD, A. A. 2015. Where the wild things are: using remotely sensed forest productivity to assess arboreal marsupial species richness and abundance. *Diversity and Distributions*, 21, 977-990.