Threatened Species Recovery Hub

National Environmental Science Programme

A national approach to the integration of koala spatial data to inform conservation planning report

Claire A Runge (UQ), Jonathan R Rhodes (UQ) & Peter Latch (DAWE)

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Contents

1. Executive summary

NESP4.4.12 A national approach to the integration of koala spatial data to inform conservation planning was a 12-month long collaboration to develop a framework and datasets to support planning and implementation of the National Recovery Plan for Koala. In this sense, the research was primarily designed to support recovery planning rather than regulatory activities.

In particular, NESP 4.4.12 has developed criteria and datasets that will contribute towards identifying Nationally Important Koala Areas (NIKA). The purpose of such areas is to delineate broad regions within which Commonwealth conservation activities and funding for koala recovery could be prioritised, and to provide guidance for states, local government authorities and non-government organisations for regions which are important for long-term koala persistence. NIKA include:

- places where there are known koala populations that are likely to survive with future climate change,
- places that may, with recovery actions, support stable and increasing koala numbers,
- places that will be important for koalas in times of drought, heatwave and bushfire
- places where koala populations are especially important to people and have cultural significance

Recovery requires increasing birth rates and/or lowering mortality rates to increase koala numbers and/or increasing carrying capacity. This research takes a **landscape-scale approach to conservation that seeks to maintain healthy habitat and stable koala numbers** across different jurisdictions, land uses and land holders. To support this NESP4.4.12 has developed a harmonised map of koala habitat across Queensland, ACT and NSW and then used this to define NIKA.

The technical criteria for NIKA proposed here prioritises large, connected areas of high-quality and relatively intact koala habitat and areas likely to remain climatically suitable for koalas (Figure 1a – Known NIKA). We expect such areas will support higher densities of breeding koalas across a diversity of environmental characteristics and threat profiles.

Large areas of koala habitat are likely to be unsuitable for koalas within the next 50 years (Figure 1b). This research did not assess what actions would be necessary, or where to recover koala numbers.

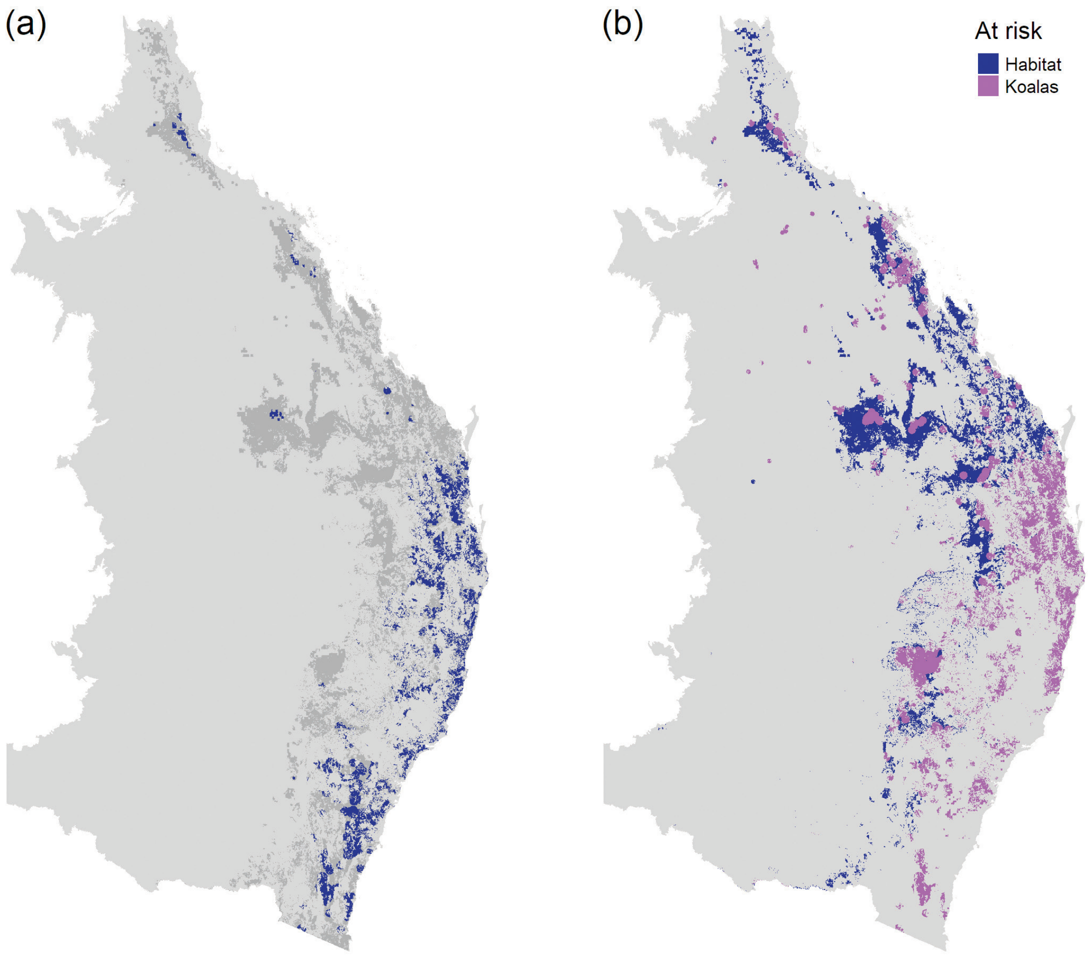

Figure 1.(a) Nationally Important Koala Areas – Known NIKA (dark blue) overlaid on current koala habitat (dark grey). (b) Koala habitat and populations at risk from climate change in the next 50 years. Some of these populations may have been lost already.

2. Introduction

Following the NESP 4.4.12 workshop held 9 April 2020 broad support was expressed by Commonwealth and state representatives for the mapping of a set of areas that are of national importance for the conservation and recovery of koala. The purpose of such areas (NIKA hereafter) is to delineate broad regions within which Commonwealth conservation activities and funding for koala recovery would be prioritised, and to provide guidance for states, local government authorities and non-government organisations for regions which are important for long-term koala persistence.

NESP4.4.12 has developed several spatial datasets to support the identification and implementation of NIKA. These are:

1. Proposed criteria for delineating nationally important koala areas (NIKA) and associated analysis of criteria
2. Proposed set of known NIKA[1]
3. Harmonised koala habitat map for listed Koala spanning NSW, ACT Qld and associated report outlining methods[2]
4. Map of koala habitat in Qld & associated report outlining methods[3]
5. Map of koala habitat and populations at risk from climate change[1]
6. Maps of potentially extinct koala populations and under-surveyed koala habitat[1]

NESP4.4.12 has developed criteria that will contribute towards identifying Nationally Important Koala Areas (NIKA). These criteria, outlined in this document, include:

- places where there are known koala populations that are likely to survive with climate change,
- places that may, with recovery actions, support stable and increasing koala numbers,
- places that will be important for koalas in times of drought, heatwave and bushfire
- places where koala populations are especially important to people

These criteria are intended to support the objectives of the National Recovery Plan for Koala. Their primary purpose is to delineate broad areas that will or may support nationally significant populations of koala in the long-term. They are also are important for supporting evolutionary processes and adaptation to climate change over a 50-year timescale. They are not intended to replace existing mapping for regulatory purposes at either state or Commonwealth level. They are also not intended to delineate koala habitat at a fine scale, nor replace existing maps and models of koala habitat that exist in both Queensland and NSW (e.g. Koala Habitat Suitability Model NSW4; Koala Habitat Areas Qld[5]).

This report does not attempt to define 'nationally important koala populations'. Criteria that may be included in such a definition include: size, density and birth rates of a koala population; genetic distinctiveness and adaptation potential; health and disease resistance; the extent, quality, and climate resilience of habitat; and cultural significance. Much of the information required to spatially map these qualities does not yet exist, or has been assessed for a limited set of locations only. This is not to say these criteria cannot be included in mapping important koala habitat at a national scale, only that into the near future such an analysis must rely on expert knowledge, spatial proxies or indirect indicators of these qualities.

Guidance from the Commonwealth Threatened Species Unit was that NIKA be delineated primarily on koala ecological information, with threats other than climate change assessed post-delineation. Deciding where to allocate resources on purely ecological grounds, then later assessing threats to those sites and cost of conservation remains a controversial approach in contemporary conservation theory. It can lead to inefficient allocation of scarce conservation resources[6–8]. Nonetheless, the approach is often undertaken in real-world conservation[9] and can be a useful way to focus attention and shift priorities for land use planning towards species conservation, particularly in highly valued species like koalas. Advantages of this approach include that it is readily understood by and justified to the public and politicians, and these sites can act as focal points to attract additional conservation funding and support[10]. One successful example using a similar approach is that of sage grouse conservation in the rangelands of the US. PACS (Priority Areas for the Conservation of Sage Grouse) are now are the focus of legislation regulating development, and conservation activities including species monitoring, management of predators, and habitat rehabilitation following wildfire[11]. Consequently, the species status remains favourable.

3. Context: Review of existing protocols for delineating koala areas

Both Queensland and NSW have existing protocols for delineating areas that are important to meet State conservation objectives (Table 1). In NSW these are known as Areas of Regional Koala Significance (ARKS); in Queensland, Koala Priority Areas (KPA; Figure 2). These areas are underpinned by their own assumptions, methods, and data. NIKA support rather than replace these areas.

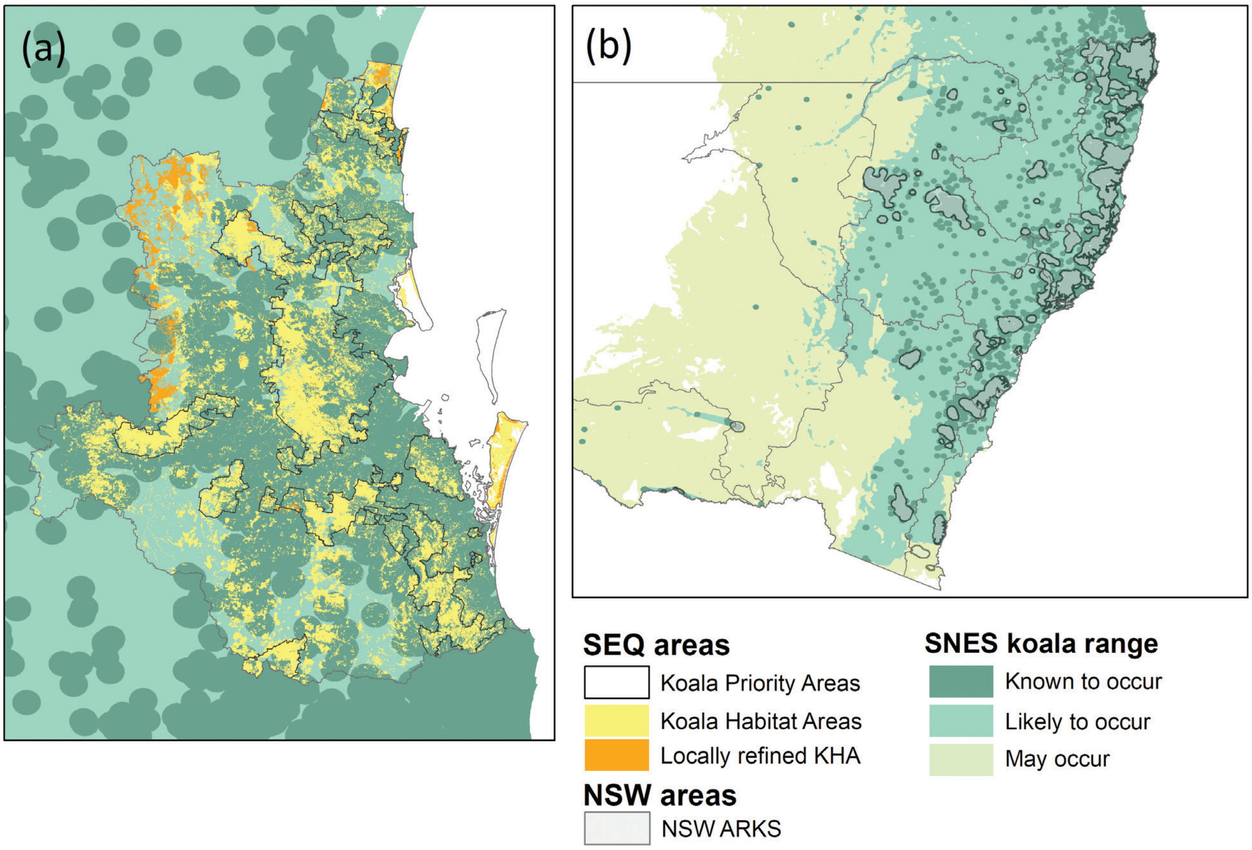

Figure 2. Areas delineated for koala in a. South-east Queensland and by the Queensland Government (Koala Priority Areas, Koala Habitat Areas and Locally Refined KHA) and b. NSW by the NSW Government (ARKS), overlaid on national koala range maps (SNES Map 2020 revision).

Identifying areas that hold populations of koalas with potential for long-term viability (ARKS, p19)[4] is the first step in the NSW spatial prioritisation of koala conservation[12]. Kernel density estimation is used to map areas that envelop koala occurrences which are clustered in space. Boundaries of koala habitat are not part of the criteria for spatial delineation of ARKS. Conceptually, this method is a shortcut for prioritisation that assumes that areas where koala are observed in high (enough) density have and will maintain the qualities that might support resilient koala populations, and, with conservation investment, turn around koala declines.

An alternative approach was used in Queensland to delineate Koala Priority Areas[13] – broad regions within South East Queensland that focus management and monitoring on areas likely to deliver conservation outcomes. Areas for koala conservation were delineated by combining information on koala habitat with data on a broad suite of threats and constraints including urban development, land clearing, dog attacks, vehicle collisions, fire management, climate change, disease, and reductions in genetic diversity; as well as opportunities and resilience measures such as existing conservation areas and climate refugia. Koala habitat was extrapolated by combining a species distribution model with known occurrence records and mapping of ecosystems containing preferred koala trees. Boundaries were drawn around the areas included most often in the resulting Marxan[14] prioritisations and snapped to cadastral boundaries. The resulting Koala Priority Areas were then finessed in consultation with local stakeholders to improve connectivity and account for existing conservation efforts.

We propose a hybrid approach that draws on the advantages and lessons learnt in both Queensland and NSW.

3.1 Risks

There are risks in defining new spatial boundaries for conservation (e.g. NIKA) within the National Recovery Plan for Koala. These include confusion amongst politicians, conservation groups and development proponents about how these new areas overlap and interact with existing state-defined important koala areas (Table 1), such as Koala Priority Areas[13] which define areas for conservation activities in South East Queensland and Koala Habitat Areas[13] which define boundaries for restrictions on development activities under Queensland planning legislation. Even with the best information currently available, data limitations mean that decisions about how to delineate these areas will require subjective decisions. This introduces risk that these decisions can be challenged or that they might not represent all of the most effective or efficient places for koala recovery. Even if their scope is well-defined initially there is a risk that NIKA can be co-opted into inappropriate uses in future.

Table 1 Summary of areas delineated for koala

Koala area	Purpose	Scale	Regulation of development	Underlying data	Associated legislation
Commonwealth					
Species of National Environmental Significance (SNES) distribution maps applied in EPBC referral	Regulation of development	National, but applied to parcels (development areas) in first steps of decision tree for development approvals	Yes, only if meet criteria for nationally significant adverse impacts on habitat essential to survival of koala; but not required for all types of land use change	Species distribution model, combined with buffered occurrence records	Environmental Protection & Biodiversity Act 1999 (EPBC)
Recovery plans/ NIKA	Guide conservation activity	Broad scale	Yes	Detailed in this report	
Queensland					
Koala Districts	Oversight of management	Three areas – SEQ is district A, see Nature Conservation 2017 for details on B & C.	No		Nature Conservation (Koala) Conservation Plan 2017; Qld Planning Regulation 2017; South East Queensland Koala Conservation Strategy 2019–2024; Environmental
Koala Priority Areas (KPA)	Focus management and monitoring on areas likely to deliver conservation outcomes	Large connected areas within SEQ.	See KHAs below.	Spatial prioritisation of habitat, threats, costs and opportunities.	
Koala Habitat Areas (KHA) - Core Koala Habitat Areas - Locally refined koala habitat areas	Regulation of impacts on koala, including through clearing controls.	Fine-scale, based on remnant vegetation. Mapped for SEQ only.	Yes, clearing is prohibited in KHA in KPAS, with exceptions. Other development activities may be assessable under local planning schemes.	Species distribution model combined with expert opinion on habitat trees; LRKHAS, updated with local knowledge	
Koala Habitat Restoration Areas	Guide restoration and offsets	Fine-scale, based on remnant vegetation. Mapped for SEQ only.	Non-statutory.	As above.	
Koala broad-hectare areas	Allow urban development	Areas in SEQ with pre-existing, long-term, established development commitments.	Clearing allowed, some requirements for koala-friendly development.	Planning regulations and historical zoning.	

Koala area	Purpose	Scale	Regulation of development	Underlying data	Associated legislation
NSW					
Core Koala Habitat	Defines areas for regulation by NSW councils	Applied to parcels but considered within context of surrounding area. Statewide habitat and/or koala occurrence maps can be used to identify potential core habitat, which can be mapped or updated by councils.	Regulated by local councils according to their Koala Plan of Management (KPoM). Some councils have yet to develop a KPoM.	Documented presence of koala within parcel	State Environmental Planning Policy (Koala Habitat Protection) 2019 (SEPP)
Areas of Regional Koala Significance (ARKS)	Defines broad management areas to inform conservation actions appropriate to each area	Broad areas delineated around selected koala sightings, with habitat within ARKS defined by vegetation boundaries.	Non-statutory	Buffered occurrence records, koala home ranges, data on threats and geographic barriers, plus expert elicitation	
Koala Habitat Suitability Model	Predicts the probability of finding koala habitat at any location	Fine-scale based on species records and environmental predictors	Non-statutory	Predictive (MaxEnt) model relating the location of koala records to environmental factors such as vegetation, soil and topography	
Koala Likelihood Map and Koala Likelihood Confidence Map	Predicts the likelihood of finding a koala at a location	10-square-kilometre grid covering NSW	Non-statutory	Records of koalas and other arboreal species	

3.2 Summary of current NSW criteria for ARKS identification

The process for identifying ARKs is as follows (Step 1)[4,12]:

A. Map observed koala occurrences since 1990 then perform kernel density analysis in ArcGIS. Minimum occupancy density was set to 0.06 records per hectare to account for low density or poorly surveyed areas. A threshold of 10km was used (an approximation of the maximum movement of koala[15]).

B. Filter out non-habitat features a) areas smaller than 100ha were excluded b) non-habitat was excluded – places where there is no evidence of recent koala occurrence and/or are isolated by barriers (e.g. islands/river islands).

C. The remaining kernels were split into ARKS following the lines of barriers such as highways, major rivers with open water, rainforest areas, and altitudinal barriers (e.g. escarpments).

D. Refine boundaries following expert and stakeholder input on local conditions.

3.3 Summary of current Queensland criteria for KPA identification

The process for identifying KPAs is as follows[5]:

A. Generate ranked prioritisation of the landscape using spatial prioritisation software Marxan[14], accounting for koala habitat, threats and constraints (urban development, linear infrastructure, primary industries and koala stressors) and opportunities and resilience (existing reserves, conservation areas and climate refugia).

B. Select and aggregate the highest ranked cadastral parcels, retaining parcels selected in >40% of Marxan iterations.

C. Refine boundaries to improve connectivity and address anomalies

D. Refine boundaries following expert and stakeholder input on local conditions and ongoing conservation initiatives.

4. Issues and challenges to be addressed

After reviewing the suitability of the NSW and Queensland methodology for delineating koala areas we have identified the following issues:

- The current state methods do not specifically delineate areas important for maintaining connectivity and climate and bushfire resilience, nor unoccupied areas that might be important for maintaining koala in the future.
- Areas that sustain low-density, but potentially substantial koala populations may not meet ARKS criteria and therefore could be missed from planning.
- There is a need for representation of koalas spatially across different bioregions and genetic populations to ensure genetic variation is maintained. Using the NSW approach directly, NIKA would not be mapped within several Queensland bioregions despite substantial koala populations in these bioregions. No areas would be delineated in the ACT, as koalas have not been recorded in the ACT since 1990.
- The current NSW method uses only known koala observations to drive the delineation process. This is highly subject to sampling bias. More sophisticated methods than kernel models (e.g., spatially explicit species distribution models) can resolve some of the sampling bias to give a more accurate prediction of the location of important koala populations. The Queensland method combines koala occurrence records with species distribution modelling, regional ecosystem mapping and expert ranked lists of koala tree species. This method is less susceptible to sampling bias, though it may still miss koala populations in poorly surveyed areas.

We outline these issues and recommended solutions in detail below.

4.1 Maintain connectivity and resilience (Recommendation 1)

Genetic and landscape connections between koala populations are important for resilient koala populations. Features such as riparian corridors provide koala refuge from climate change and bushfires and are particularly important in western parts of their range[16,17]. The state's approaches do not specifically delineate areas important for maintaining genetic diversity and climate resilience into the future. The current NSW method has no mechanism for delineating corridors and refugia outside ARKS, nor candidate areas for restoration or translocation. These important areas might miss out on conservation effort and protections. Queensland has delineated non-statutory areas for guiding fine-scale restoration efforts in SEQ (Koala Habitat Restoration Areas) based on models of pre-clearing koala habitat[5].

NSW ARKS were identified using koala occurrence only, and density of koala and quality of koala habitat are not part of NSW's criteria for spatial delineation of ARKS. One advantage to this approach is that ARKS will incorporate non-remnant habitat areas such as isolated urban trees which are important to koala persistence in some areas18, so long as sufficient koala observations exist in the area. A disadvantage is that the approach may overlook areas with good quality habitat but few surveys or areas that are currently unoccupied but could contain important habitat that could sustain large koala populations in future. The QLD approach excludes koala populations falling on non-remnant habitat from the final delineation of KHA, but could be readily modified to include non-remnant habitat. QLD approach does allow unoccupied or unsurveyed habitat to be included in the delineation.

We recommend adapting the state's approaches by including four distinct categories of NIKA – Known, Recovery, Connectivity and Adaptation NIKA (Figure 4). Details on the proposed criteria can be found in Suggested conceptual criteria for spatial delineation of Nationally Important Koala Areas (NIKA).

Known NIKA.	These would delineate known koala populations of national significance.
Recovery NIKA.	These would delineate regions within each bioregion that might be expected to support significant populations of koalas with appropriate management but they are either currently absent or status uncertain.
Connectivity NIKA.	These would connect or expand known koala populations to ensure connected populations are large enough to sustain koalas long-term.
Adaptation NIKA.	These would delineate areas that are important for refuge from climate change, drought and bushfire (climate and bushfire refugia). These may overlap the other NIKA classes.

4.2 Better delineation of known koala populations (Recommendation 2)

NSW ARKS were identified using koala occurrence only using a kernel density model that does not account for spatial bias in survey effort nor include spatial predictors of koala presence. This method is sufficient for some coastal koala populations that are high density and spatially clustered and have been well surveyed, but may miss potentially important populations in less well surveyed areas or low density broadly distributed populations. Areas that sustain low-density, but substantial koala populations may not meet current NSW criteria, and thus miss out on conservation effort or protections.

The NSW approach is likely to identify NIKA predominantly within SEQ, and likely to exclude a large proportion of the estimated koala population in Queensland (Table 2). When applied by Wallis et al.[19], this approach identified 23 ARKS in SEQ, 3 in the South Brigalow, and 3 in Brigalow Belt North bioregions in Queensland. The bioregions without ARKS contain a combined 47% of the estimated Queensland koala population (Table 2). Including targets for the number or proportion of koala represented within NIKA within the delineation criteria, combined with a more sophisticated modelling approach could help alleviate this issue. We recommend the modelling approach be adjusted to account for the spatial bias in koala survey effort. We propose that known koala habitat be defined as habitat where koalas have been recorded within 10km within the past 3 generations.

Table 2. Estimated 2012 Koala population[24], records and number of areas likely to be identified in Queensland using NSW ARKS methodology19, by bioregion.

Bioregion	Percent of estimated Qld koala population[24]	Number of records total (2013-2018)[19]	Estimated number of ARKS[19]
Southeast Queensland	19.96%	41925 (1056)	23
Brigalow Belt North	19.15%	411 (140)	3
South Brigalow	13.97%	854 (168)	3
Mulga Lands	19.29%	68 (2)	0
Central Mackay Coast	11.17%	67 (20)	0
Desert Uplands	8.02%	74 (8)	0
Einasleigh Uplands and Wet Tropics	5.99%	77 (5)	0
Mitchell Grass Downs	2.45%	70 (0)	0

The kernel density algorithm is a relatively simple approach to map distributions of koalas that are clustered in space, using a circular search radius. After thresholding, this results in rounded 'kernels'. More sophisticated modelling methods such as species distribution modelling exist. These can better account for spatial bias in survey effort, and can also incorporate spatial predictors of koala presence and we recommend their use. Many models have been developed already, including by the Commonwealth.

To further ensure large populations are included we also recommend that targets for representation of koalas be part of the delineation criteria. We acknowledge that insufficient monitoring has occurred in many populations to establish the size and rate of decline of those populations. Until monitoring programs can be undertaken, expert elicitation may be the most rapid source of information on population size and location for many koala populations. In some areas, there may already be sufficient surveys to support statistical analysis of trends. Survey effort in many western areas is sparse, and knowledge on the status of some koala populations is held by land managers but not officially recorded. We recommend that this knowledge be integrated into the delineation process.

4.3 Maintain koalas throughout their range (Recommendation 3)

Under the current NSW approach no NIKA will be delineated in the ACT and few NIKA will be in bioregions outside SEQ. This is a particular risk in poorly-surveyed regions or where survey sites or opportunistic records are located >10km apart. We recommend delineating at least one NIKA within each bioregion to maintain koala throughout their range. The viability of the return of koala to ACT and other areas where they are currently absent should be assessed. In addition to the benefit of including a large proportion of the koala population, this would help capture genetic diversity[20], and koalas from across their climate niche which may have beneficial adaptive traits that help the species persist under climate change. Koalas are culturally important to people across Australia, and supporting equitable opportunities to experience wild koalas should be a priority. With the many uncertainties around climate change, changes to rainfall and bushfires, the likely shifts in koala tree distributions and nutrition, we recommend that national conservation focus on ensuring that essential resources will be available and that mitigatable threats are addressed across and throughout landscapes.

4.4 Maintain genetic populations and flow (Recommendation 4)

Koalas are thought to exist within five genetic metapopulations, originating from Plio-Pleistocene biogeographic barriers[21]. The four metapopulations relevant to the listed koala are – Queensland, South-east Queensland, Mid-coast NSW, and South-coast NSW, with some mixing at the boundaries to these four metapopulations[21]. A fifth metapopulation occurs in Victoria and South Australia. There does not appear to be substantial genetic differentiation between coastal and inland populations[21], though it is not clear whether western populations carry genes that could be helpful against future challenges such as drought. This understanding differs from previous work considering rivers and escarpments as genetic barriers. For instance, the coastal SEQ koala population appears to be genetically similar from Brisbane to Lismore despite the presence of major rivers and this should be managed as a single population[22,23.] Genetic studies confirm that genetic diversity of koalas follows a cline from north to south, with diversity highest in the northern population.

We recommend that governance mechanisms for maintaining flow and diversity within the four metapopulations, and for maintaining landscape connectivity within each minimum viable population unit be developed and implemented. Koala management units are delineated for the purposes of managing threats, recognising that suites of threats to koalas are broadly bounded by bioregions. This delineation does not preclude individuals being moved between management units. Guidelines for the translocation of koala should be developed recognising that (i) koala metapopulations cross jurisdictional boundaries such as the Queensland-NSW border, and (ii) koala genetics transition across management unit boundaries.

The extent to which new physical barriers to koala dispersal such as roads or urban development limit genetic dispersal should be evaluated. Some finessing of barriers may be required e.g. Bruce Highway north of Gympie may not be a barrier to koala genetic dispersal. Fenced railways could also be included as barriers. There are some koala under/overpasses along the Pacific and Bruce Highway and railways, and so evaluation of the extent to which these features create a barrier to koala genetic dispersal would be advisable.

The climate is becoming hotter and rainfall patterns are increasingly uncertain across the species' range. The changing climate means koalas in the north and west of the range are declining rapidly and highly unlikely to persist beyond the coming decades. The challenge for conservation is that these populations have high genetic diversity, and may have adaptive traits that could help koala persist in the face of climate change. **Recent research indicates that natural dispersal towards refugia or milder climates cannot be relied upon as a rescue for climate-affected koalas or their genetic distinctiveness**[16,24]. We recommend that refugia be identified in each bioregion where koalas are most likely to persist in the short-term until conservation actions can ensure the long-term persistence of populations and genetic diversity can be secured. Translocation or assisted migration are potential strategies that may be used in future, but understanding of koala genetics may be insufficient to design strategies at this point in time. Knowledge should be gathered on which conservation actions are acceptable and unacceptable to different communities, including Indigenous peoples. Managed extinction and assisted migration are likely to be particularly contentious for some people.

4.5 Active participation of local and Indigenous people (Recommendation 5)

Recognition, at a societal level, that koala conservation is the responsibility of many will be essential to reverse the declines in koala populations[25]. Unsustainable values towards land and resource use have driven ecosystem loss and degradation, and ultimately underlie koala declines. Successful conservation of koalas will require concerted action in many places, across many industries and involve many people[26]. As a charismatic species, koala conservation offers an opportunity for the Australian community to participate in new ways of designing and implementing conservation[27]. The potential co-benefits of co-design and co-management of koala are many, and include increased recognition and integration of Indigenous values and protocols into Australian governance, enhanced engagement of citizens with democratic processes, and renewed ownership of environmental management.

Koalas are beloved and their persistence is important to many people, both Indigenous and non-Indigenous, in Australia and abroad. Koalas provide cultural ecosystem services including spiritual, cultural and identity services. People prefer to experience koalas in natural habitats, but close to home[28]. Managing equitable access to the ecosystem services provided by koalas is particularly challenging in urban and peri-urban areas where ecosystem services provided by koalas are high, but threats to koala persistence are also high. Managing expectations for which populations will be prioritised and the scale at which national conservation efforts operate, will be important to maintain trust in government management of the species.

We recommend developing and funding processes for participation of local and Indigenous people in the design and management of koala conservation. Specifically:

A. Engage indigenous groups to co-design a program for appropriate participation in actions that contribution to koala conservation, understanding that there are many peoples and many cultures across the range of koalas.

B. Fully fund a process for participation of Indigenous groups across Queensland, NSW and ACT to co-create culturally appropriate regional management that supports healthy country and koala recovery, recognising that not all groups or people will be willing or able to share their knowledge, and that koalas may not be important to all Indigenous peoples, and some people may prefer to engage with actions to maintain healthy country such as traditional fire management and climate change actions. Indigenous perspectives and intellectual property and the principle of free, prior and informed consent must be respected in the design and implementation of koala recovery plans. We suggest this process follows the protocols laid out in https://www.nespthreatenedspecies.edu.au/media/kwfpxdwk/tsr-hub-indig-protocols-report_v6.pdf and could complement and draw on lessons from work currently underway to incorporate Indigenous values into koala conservation in NSW.

C. As part of the above process, we suggest Indigenous perspectives and cultural processes around conservation actions be sought and respected. It may be that in some regions Indigenous perspectives on appropriate and necessary conservation actions will differ from that of other stakeholders or from conservation managers. We suggest culturally and gender appropriate processes for reconciliation of differing views on koala conservation be developed, funded and undertaken. Conservation actions likely to be controversial to many people, both Indigenous and non-Indigenous, include assisted migration (moving koalas from a place that is affected by drought and heatwaves to a place where they are more likely to survive) and managed extinction (recognising that not all koala populations can be saved from climate change). Funding to allow cultural processes should be undertaken as part of the implementation of such conservation actions.

5. Recommendations

After reviewing the NSW and Queensland methodology, and the data currently available, we make the following recommendations:

Recommendation 1: Adopt delineation criteria that recognise four distinct categories of NIKA – *Known NIKA* (known populations of koalas), *Recovery NIKA* (areas requiring urgent triage or monitoring that may support koalas), *Connectivity NIKA* (areas that would be important for maintaining connectivity between NIKA), and *Adaptation NIKA* (areas that are important climate, drought, heatwave or bushfire refugia for koalas). Adopt a hybrid approach that integrates across different types of data and models to better identify both known koala habitat and regions that have a good chance of maintaining koala numbers in that habitat.

Recommendation 2: Adopt delineation criteria that are based on modelling and mapping of known and likely koala habitat rather than occurrence records alone to account for the spatial bias in koala records, and to ensure large but sparsely surveyed populations are included in the recovery program.

Recommendation 3: Delineate at least one known NIKA within each bioregion known to contain koalas to maintain koala diversity and resilience to maintain koalas throughout their range.

Recommendation 4: Develop guidelines for the translocation of koala and for maintaining flow and diversity recognising that (i) koala populations cross jurisdictional boundaries such as the Queensland-NSW border, and (ii) koala genetics transition across management boundaries.

Recommendation 5: Develop and fund processes to for active participation of local and Indigenous people in the design and management of koala conservation.

6. Conceptual foundation: Supporting koalas long-term

Koala are found at low densities across a very large area of eastern Australia. Many of the pressing threats to their persistence, including climate change and drought, operate at broad-scales. Rather than seeking to protect particular islands of habitat, we recommend that NIKA operate within a **landscape-scale to regional-scale approach to conservation that seeks to maintain healthy habitat and stable koala numbers** across different jurisdictions, land uses and land holders. Under this approach, maintaining large areas of connected habitat throughout the koala's range will be key to their long-term persistence.

Such an approach uses concepts of clustered, connected habitat that targets sufficient habitat in a landscape rather than focussing on population targets in relation to minimum viable population sizes. Targets of 30-50% habitat coverage are likely to support stable koala populations, and are supported by empirical evidence[29]. Koalas in many areas are declining and thus trending towards local extinction. In these cases, concepts of MVP are not particularly useful since they are based on stochastic extinction risk of stable populations, not extinction risk of deterministically declining populations. Many bioregions currently hold fewer than 5000 koalas[30], though this may be sufficient for long-term persistence provided threats are addressed.

In reality, it is difficult to define discrete koala populations. The habitat mapping presented in this report highlights that koala habitat is near continuous across eastern Australia and 'koala populations' as distinct entities exist only in a few rare cases. Thus, the ecological basis for delineating populations is slim. Rather, populations are a construct of management and policy, and may be defined at different scales. *Populations* as used in this document can be regarded as a synonym for koala management units.

Two key questions underpin our delineation of nationally important koala areas:

How much habitat is required for koala to persist long-term?

Which areas will support stable or increasing koala numbers?

6.1 How much habitat is required for koala to persist long-term?

The area of land required to support koalas long-term required depends on many factors: habitat quality and configuration; the frequency of climate events like bushfire and drought; and adaptation of the koala population to that environment. It has been estimated that koalas will decline when habitat cover drops to between 10 and 60% of a landscape, depending on the landscape[29a].

The technical criteria for NIKA proposed here prioritises large, connected areas with high landscape coverage of koala habitat (>50% coverage, Figure 3), under the assumption that such areas are likely to support stable koala numbers across a diversity of environmental characteristics and threat profiles.

One limitation to this approach is that it prioritises relatively intact remnant landscapes, which tend to be located in lower productivity areas[31]. Good quality non-remnant regrowth, and some riparian areas may not be prioritised under these criteria. Some of these areas may be prioritised under the yet to be developed criteria for climate and bushfire refugia. We recommend NIKA delineation be evaluated by regional experts.

6.2 Which areas will support stable or increasing koala numbers?

Recovery means increasing birth rates and/or lowering mortality rates to increase koala numbers and/or increasing carrying capacity of habitat. Much of the high-quality habitat that supports high birth rates in breeding koalas is urbanised, fragmented or has been lost to other land uses[32]. The question for recovery planning is, **will the habitat that remains and is climatically suitable support the recovery of koalas**? A second, associated question is what actions would be necessary, and where, to recover koala numbers? This project did not assess the cost-effectiveness[33] or likelihood of reversing koala declines across different landscapes and threat profiles[32]. Such an assessment would support the implementation of effective and efficient conservation interventions[8,32,34] and may be informed by NESP Project 7.7[35].

In the absence of estimates of koala trajectories and birth and mortality rates across the koala's range, we propose delineating NIKA using modelled habitat suitability as proxy for habitat quality. This approach makes the assumption that habitat modelled as higher suitability for koalas will support higher numbers of breeding koalas. We combine modelled habitat with current and historical koala records to predict the locations of patches of occupied and potentially occupied habitat.

One of the main challenges to designing strategies for the recovery of koalas is the lack of range-wide koala monitoring. While areas such as south-east Queensland are well-surveyed, koala trajectories and densities remain uncertain in many areas, particularly in western or northern parts of the range. The most recent estimates are almost a decade out of date, and drought, heatwaves and bushfires have negatively impacted many populations since then. In section 8.2 we identify areas where monitoring could help to determine the presence of koalas and trajectory of koalas.

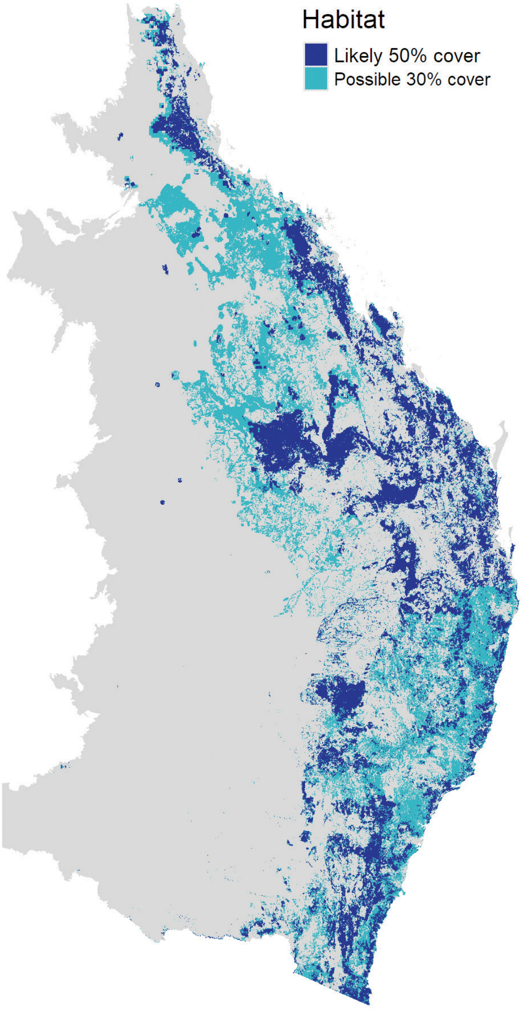

Figure 3. Current koala habitat. Planning units with > 50% coverage of likely habitat is shown in dark blue, overlaid on 100ha planning units with >30% coverage of likely or possible habitat shown in teal. Data is drawn from Runge et al. 2021[2].

7. Suggested conceptual criteria for spatial delineation of Nationally Important Koala Areas (NIKA)

This section outlines the conceptual criteria proposed for NIKA, summarised in Figure 4. An area may be classified as more than one type of NIKA (e.g. bushfire refugia may overlap Known NIKA).

Factors that were not considered in NIKA criteria and are suggested for consideration post-delineation and in prioritising conservation actions for NIKA include threats such as urban pressure, likelihood of mortality from dogs, traffic and disease, fragmentation and degradation; cost; and likelihood of conservation success. Potential approaches and datasets can be found in NESP 3.3 report[36] and in documentation associated with Queensland KPAs and NSW ARKs[4,5].

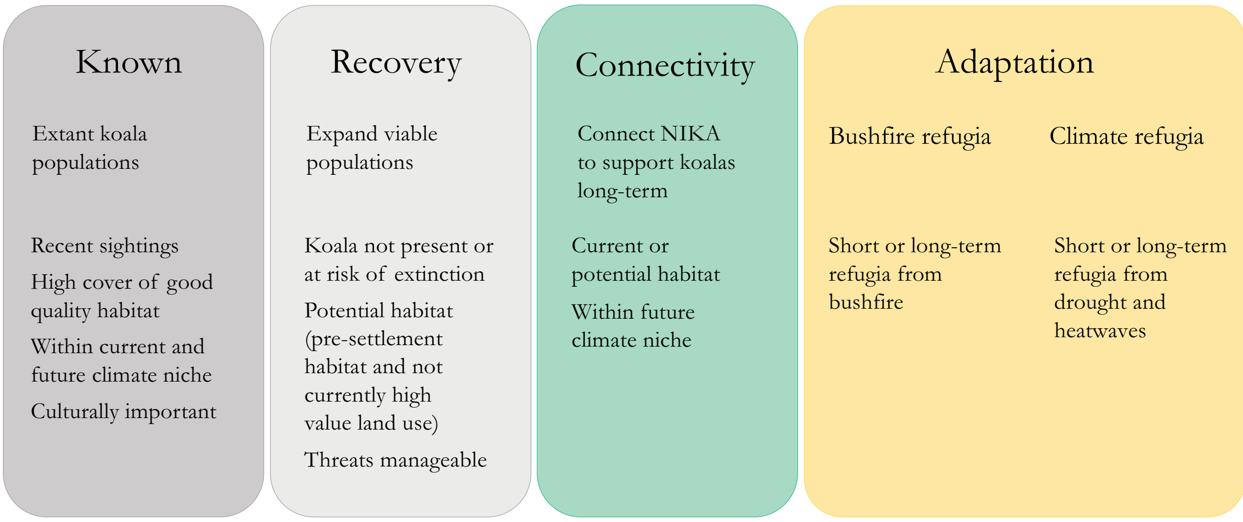

Figure 4. Schematic of Nationally Important Koala Areas under proposed approach.

7.1 Known NIKA

Known NIKA are *regions that contain nationally significant extant populations of koalas that are likely to support long-term koala populations.* Actions should be prioritised in these areas to maintain large populations of breeding koalas and sufficient genetic diversity to support long-term persistence and evolutionary processes.

A. Known NIKA should be designated in habitat in each bioregion known to be occupied by koalas.

B. Known NIKA should be of sufficient habitat quality to support breeding koalas long-term (i.e. sources not sinks). This may mean delineating fragmented and non-remnant habitat. Riparian habitat is likely to be particularly important in western areas[16].

Additional criteria may include:

C. Climatically stable. Places that are currently and predicted to remain climatically suitable for koalas and their habitat trees over the next 50 years. It is essential that recovery planning for koalas is resilient to the environmental changes currently underway across Australia. One of the largest challenges for koalas, and one that has been slow to be considered in conservation planning in general[37], is that of climate change. Models of future koala distribution predict that koalas will continue to disappear from northern and inland areas and contract to coastal areas[17,38–40].

D. Culturally important[28].

Subtypes:

Viable. Population substantial, threats manageable and within current and future climate niche.

At risk. Population small and/or threats high.

7.2 Recovery NIKA

Recovery NIKA are *regions within each bioregion that are important for expanding koala populations. Recovery NIKA might reasonably be expected to support nationally significant numbers of koala with conservation but are subject to threats including historical habitat loss and climate change such that koalas are no longer present or present in low numbers or have been insufficiently surveyed to determine the viability of koalas.* These are places where koalas are known to or likely to have occurred and where the drivers behind their disappearance are known and manageable. Actions are aimed at recovering and monitoring koala numbers in these areas and/or protecting genetic diversity.

Criteria

A. Recovery NIKA should be delineated in places which contain good habitat for koalas or would be expected with restoration to contain good habitat for koalas such that they contribute to stable or positive growth of koala numbers and/or conserve genetic diversity.

B. Koalas are not present or are at risk of extinction

C. Threats present in Recovery NIKA can feasibly be managed to facilitate stable or increasing koala numbers or protect genetic diversity

Subtypes:

Insufficiently surveyed. Areas of likely or possible koala habitat where that have not been surveyed in the past 3 generations (21 years) or where no recent opportunistic records exist.

Extinct/potentially extinct/on the way to extinction. Areas that were once known or suspected to support large koala numbers but where koalas have not been detected for 3 generations including areas that have biophysical qualities expected to support large koala numbers or where pre-clearing vegetation mapping indicates once contained high quality habitat.

7.3 Connectivity NIKA

Connectivity NIKA *include places that maintain landscape connectivity between sub-populations and/or genetic connectivity within metapopulations.* Many koala populations are small and declining. Connectivity NIKAs represent places that connect known or recovery NIKAs to ensure the connected populations are of sufficient size for long-term persistence. Landscape characteristics such as proximity to known koala populations, land use and tenure, climatic suitability, barriers to dispersal and pre-settlement habitat could all be considered in the mapping process. A number of existing tools can map corridors[41–44] and datasets of landscape connectivity exist for most of eastern Australia[45,46]. The criteria presented here are based on existing detailed guidelines for prioritising patches of habitat to increase connectivity for koalas[29].

A. Give priority to the revegetation of areas adjacent to and between large and medium sized[29] NIKA (Known or Recovery NIKA) where the natural dispersal of female koalas is unlikely.

B. Connectivity NIKA should be sufficiently wide to avoid edge effects.

C. Connectivity NIKA should maintain or restore sufficient habitat cover within that corridor to facilitate safe koala transit and/or expand the area of functional habitat in connected patches.

D. Connectivity NIKA could be comprised of intact habitat patches, isolated trees or non-remnant patches that are likely to be used by koalas in transit, and may or may not support breeding.

E. Maintain areas free from barriers to koala movement

7.4 Adaptation NIKA

Adaptation NIKA are *regions that support adaptation of koalas; and places that act as short or long-term refugia for koalas from drought, heatwaves and bushfire.* They can overlap with Known and Recovery NIKA.

We propose two types of Adaptation NIKA.

Bushfire refugia. May be places that have a low burn frequency based on historical fire history mapping or NDVI/water availability mapping[47]. The unprecedented bushfires of 2019-2020[48] raised questions of how to manage landscapes to enhance the likelihood of koala survival and resilience of their food and shelter trees. Work is currently underway to understand how to better manage fire for koalas (including NESP 8.4.5 project). This project and others currently underway will greatly improve knowledge around the specific factors that determine koala bushfire refugia in the next 12 months. As such, we do not provide criteria for bushfire refugia in this report.

Climate refugia. Places that would be expected to act as drought and heatwave refugia for koala now and in the coming decades. Such locations may have favourable microclimates, geography or geology such that vegetation retains nutrients and water availability to support koalas during drought and heatwaves[16,17,49–54]. Many of these areas are likely to be quite localised. Remote mapping may not be of sufficient resolution or accuracy to identify these important areas. Indigenous and local knowledge will be essential to identifying these areas. Several projects are currently underway to elicit key factors determining koala persistence during drought and heatwave, including projects by NSW Department of Environment and projects at ANU. Existing mapping may also prove useful (NSW habitat mapping for western region[4]). As the state of knowledge around drought and heatwave refugia mapping is likely to be much improved in the next 12 months, we do not provide criteria for climate refugia in this report.

8. Suggested technical criteria for delineating NIKA

The suggested technical criteria for NIKA delineation are summarised in Figure 5 and the ecological significance of key variables is listed in Table 3.

We have defined technical criteria for Known NIKA (Section 8.1), Recovery NIKA (Section 8.2) and Connectivity NIKA (Section 8.3). We have not defined technical criteria for Adaptation NIKA as research is underway to improve the state of knowledge around climate refugia and bushfire refugia.

We have proposed a set of Known NIKA which are included in the data package available with this report[1]. The cut-points around Known NIKA have been evaluated and are discussed in Section 8.1. The short duration of funding for NESP4.4.12 prevented our mapping a proposed set of Recovery NIKA or Connectivity NIKA. The data package includes preliminary analysis that will support delineation of Recovery NIKA and is discussed in Section 8.2.

We have aggregated a number of datasets into 100ha planning units across the koala's range in Queensland and NSW to support evaluation and delineation of NIKA. Full details of the data package can be found in Appendix 1: Datasets supporting delineation of NIKA.

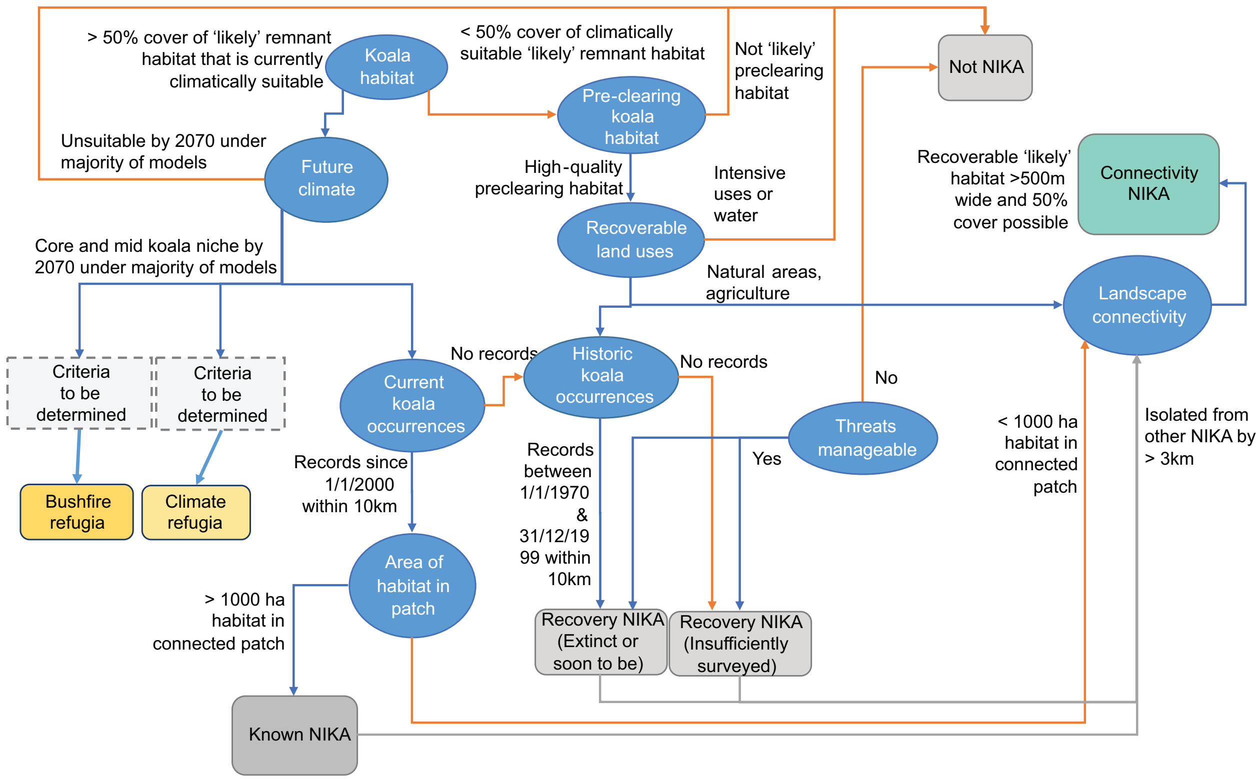

Figure 5. Decision tree summarising NIKA delineation criteria.

Table 1 Summary of areas delineated for koala

Variable	Ecological significance	Dataset
Koala habitat coverage	There appear to be thresholds of the amount of habitat in a landscape below which koala decline. These range from 10-60%, depending on the particular landscape[29].	Harmonised koala habitat mapping[2].
	Koalas prefer certain tree species (predominantly but not solely *Eucalyptus*) for foraging and resting, and are more likely to occur in areas where conditions remain within their thermal tolerance[55].	With the exception of western NSW, the habitat map used incorporates information on preferred tree species. Lists of tree species can be found in[3–5] and current climate niche in[17]
	Koalas prefer older trees (higher dbh)	Remnant vegetation mapping[56] underpins the habitat dataset.
Future climate niche	Koalas have limited tolerance to heat, and are especially susceptible to hot weather during drought conditions when leaf water availability is low. The climate niche of koalas is rapidly contracting coastward and to the south.	Briscoe 2016[17]
Current koala occurrences	Climate change and other threats are already affecting koala distributions. Recent records can help map where koalas currently occur.	Wildnet[57] and Bionet[58]
Historical koala occurrences	Historic records offer opportunities to identify potential koala habitat.	Wildnet[57] and Bionet[58]
Koala birth and mortality rates & trajectory in different types of habitat	Higher quality habitat will support higher birth rates, but is often located in places with higher mortality (e.g. in urbanised coastal areas). Uncleared areas may not support koalas above replacement.	Not assessed.
Landscape connectivity	Koala habitat is fragmented, and patches may no longer be functionally connected.	National Connectivity Index[45] Connectivity Potential[46]
Genetic metapopulations	Koalas are thought to exist within four genetic metapopulations, originating from Plio-Pleistocene biogeographic barriers[21].	Not yet available nationally.
Cultural significance	Some koala populations will be culturally important, regardless of the likelihood or cost of successful conservation of that population. Koalas closer to urban and periurban areas are valued by many people[28]. Indigenous values for koalas have yet to be mapped.	Not yet available nationally.
Bushfire refugia	Koalas prefer older trees, which are found in places that burn less frequently AND/OR prefer habitat that maintains leaf water availability, which might be expected to burn less frequently AND/OR populations may become locally extinct after fire.	Datasets include Historical fire data[59] and datasets related to 2019-2020 bushfires[48,60,61] but specific criteria are yet to be developed.
Climate refugia	Koalas require habitat that maintains high leaf water availability during drought and heatwaves.	Datasets include plant available water[62], hydrology[63] and NDVI. Work defining refugia is underway.

8.1 Technical criteria for Known NIKA

We have delineated a set of suggested Known NIKA (Figure 6). First, we split the koala's range into 100ha (approximately 1km) planning units. We then assessed whether planning units met all of the following technical criteria:

A. where koalas have been recorded within 10km within the past 3 generations (since 01/01/2000),

B. contain high coverage of the best quality koala habitat ('likely' habitat >50% coverage, equivalent to 50ha of habitat in any configuration in each 100ha planning unit), and

C. are predicted fall within the mid and core climate niche for koalas in 2070 under the majority of climate models (7 of 12 models 95% threshold).

Planning units meeting these criteria were clumped by merging adjacent planning units meeting those criteria into larger polygons ('patches'). The area of each patch is indicated by colour in Figure 6. A description of the datasets used to define Known NIKA can be found in Appendix 1: Datasets supporting delineation of NIKA.

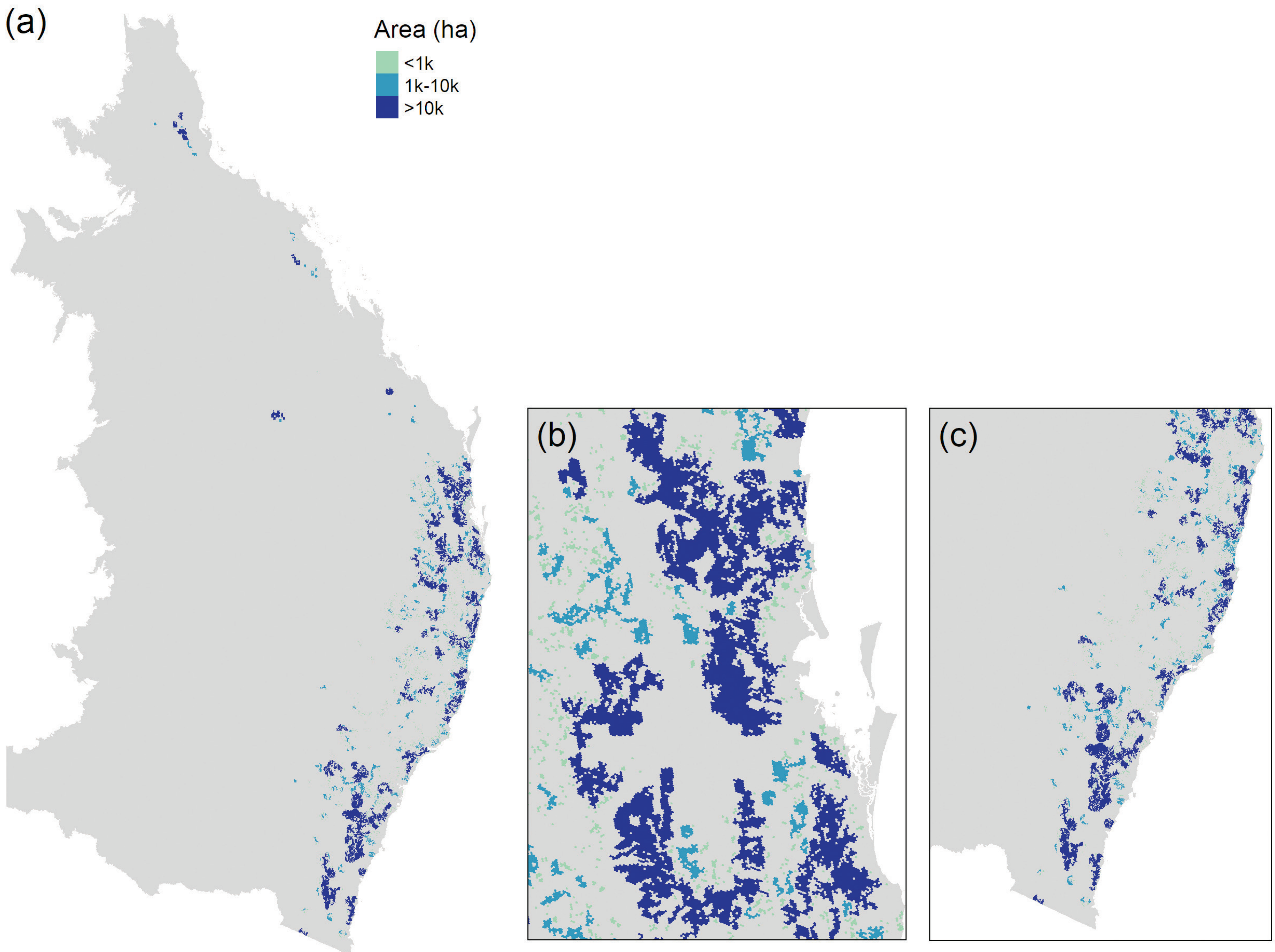

Figure 6. Known NIKA (a) across the koalas range (b) south-east Queensland (b) eastern NSW. Patches are coloured by the area of habitat in a contiguous patch. To meet criteria, 50% of the planning unit must consist of koala habitat in any configuration; koala must have been recorded within 10 km of the planning unit in the past 3 generations; and the planning unit must fall within the mid-range of likely koala habitat under the majority of climate models. Colour indicates the area of habitat (ha) in contiguous planning units meeting NIKA criteria.

Known NIKA are predominantly identified in coastal regions from south-east Queensland south, but several areas in northern and central Queensland have been identified as meeting Known NIKA criteria (Figure 6a). These northern and central NIKA will become increasingly isolated under climate change, and are likely to hold high and unique genetic diversity (Figure 7). Much historical koala habitat within these climate niches has already been lost or fragmented by urbanisation and agriculture, particularly along the east coast. In essence, the koala's range is being squeezed south-eastwards by climate change, and westward by urbanisation. Intact patches of habitat along the Great Dividing Range will become increasingly important as koala strongholds. A key question is whether koalas can retain sufficient densities and fecundities in these relatively less fertile places to maintain long-term persistence.

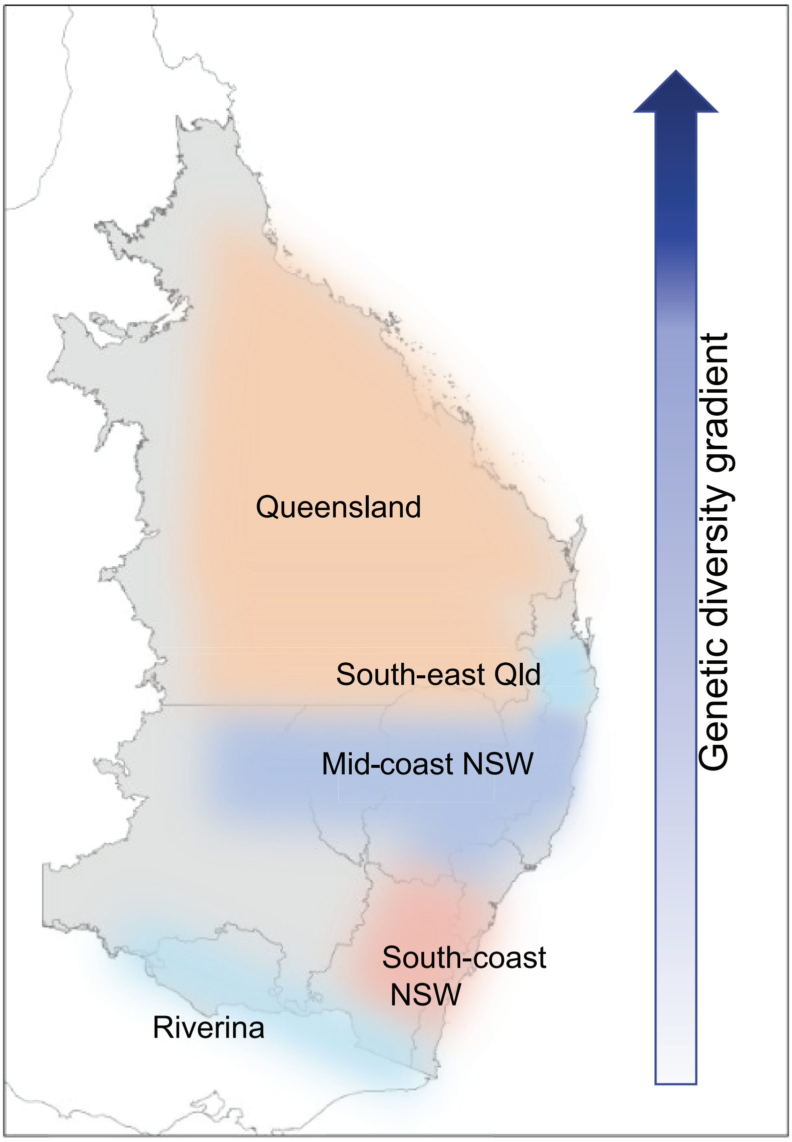

Figure 7. Koala genetic grouping, adapted from Lott et al (unpublished)[21].

Though based in ecological knowledge (Table 3), the technical cut-points for delineating Known NIKA delineation are arbitrary. The following sections explore the uncertainty around the suggested criteria.

8.1.1 Uncertainty around habitat mapping

The Known NIKA conceptual criteria suggests 'Known NIKA should be of sufficient habitat quality to support breeding koalas long-term'. The habitat mapping we use in NIKA delineation is the best currently available, but uncertainty exists around both the mapping of habitat, and what quality and coverage of habitat is sufficient to support breeding koalas. Figure 8 illustrates the uncertainty around choosing cut-points for habitat coverage (Figure 8a) and habitat quality (Figure 8b) in NIKA delineation. We chose 50% coverage as this threshold appears to support stable koala numbers in a variety of landscapes[29]. Habitat loss has selectively impacted higher fertility koala habitat more greatly[32], and it is possible that in applying this threshold Known NIKA could be biased towards more intact, less fertile habitat.

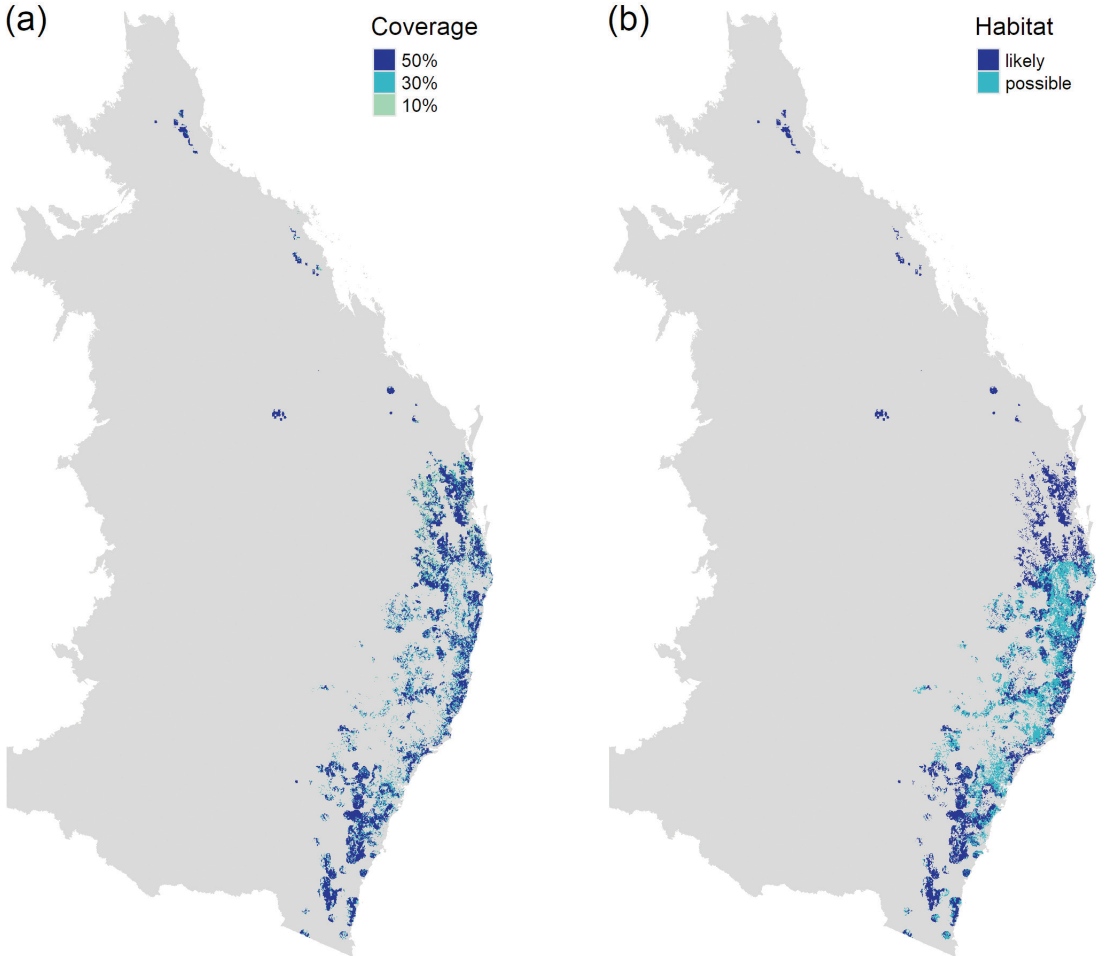

Figure 8. Known NIKA delineated considering a) different cutoffs for habitat coverage in a planning unit (10%, 30% and 50% habitat coverage in a planning unit, equivalent to 10ha, 30ha and 50ha of habitat in each 100ha planning unit) and b) a comparison of NIKA delineated using 50% coverage of likely habitat (dark blue) and additional NIKA delineated using 50% coverage of possible habitat (teal).

8.1.2 Uncertainty around future climate suitable areas

We tested a range of criteria for aggregating model predictions into predictions of future climate suitability for koalas. Figure 9 shows the uncertainty around different choices of threshold and model aggregation on the area to which koalas will contract. The area predicted as core climatically suitable for koala under all models (Figure 9a teal) is considerably smaller than that predicted as mid suitable under the majority of models (Figure 9a dark blue). Much of this different arises from a single model that predicts koala distribution using a low value for leaf water availability. Models do not account for spatial variation in leaf water availability across the koala's range[17].

While predictions fairly consistently show that coastal and southern areas will remain climatically suitable for koala, there is uncertainty around where the western and northern climatic limits of koala distribution will fall. Predictions vary at the fine scale, depending on the climate trajectory and weather variables chosen, expectations of leaf water availability, and assumptions over future *Eucalyptus* distribution[17,50]. A conservative approach to identifying future climate suitable areas could be to choose the locations that are predicted to offer moderate-high habitat suitability under all models[17] (e.g. Fig.4d in Briscoe 2016[17]; Figure 9 core 100%). The criteria we propose delineates climate suitability under the majority of a set of models, and we illustrate uncertainty around these criteria in Figure 9 and Figure 10 and Figure 11.

To capture uncertainty in future climate predictions, we chose to use published climate models based on two very different types of species model, two diverging climate models (GCMs) and predicted to low abatement climate futures (representative climate pathway RCP8.5).

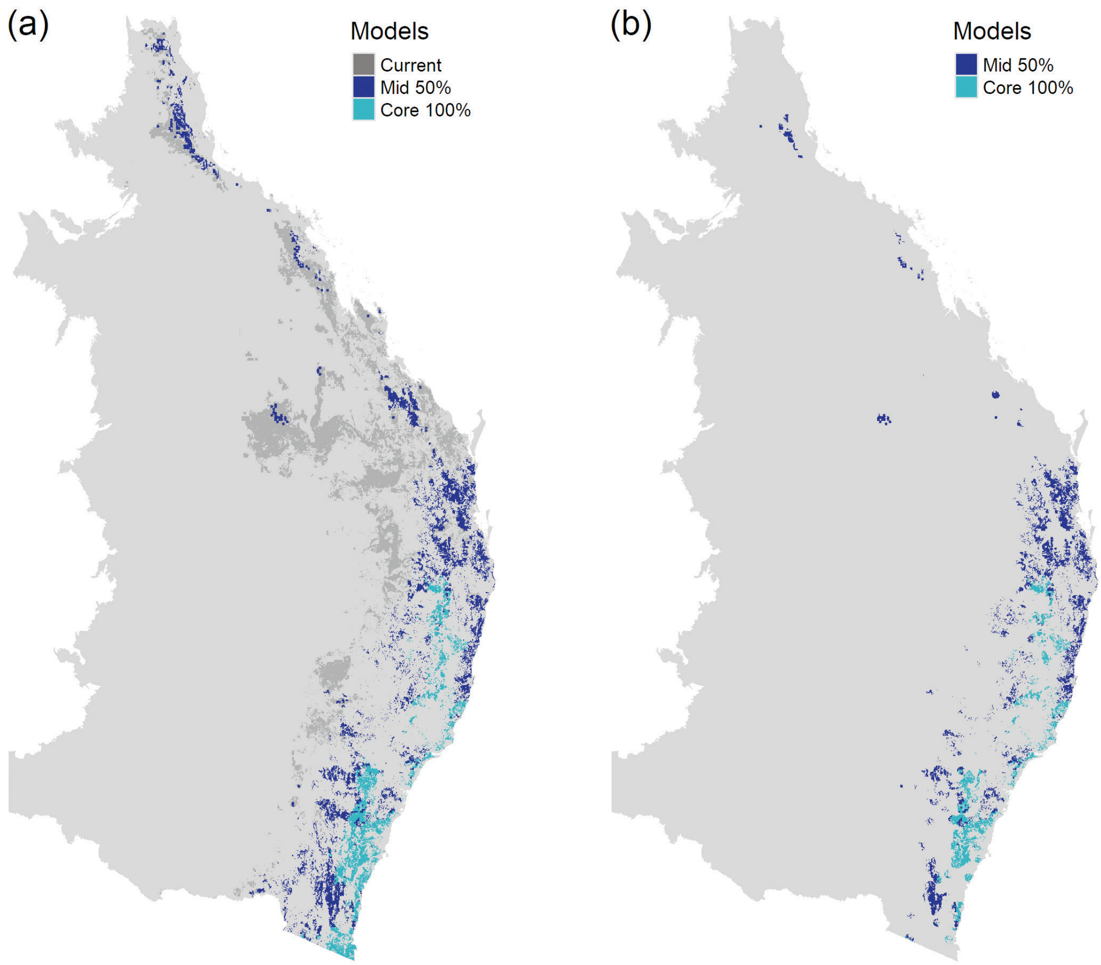

Figure 9. Uncertainty in climate projections for koalas a) Habitat predicted to be suitable by 2070. Current climate suitable habitat is shown in grey, habitat predicted to fall within the mid climate niche under 50% of models is shown in dark blue, and habitat predicted to fall within core climate niche under 100% of models is shown in teal. b) Known NIKA delineated under conservative climate predictions (teal: core niche under 100% of models) and less restrictive climate predictions (dark blue: mid niche under 50% of models). Climate models are drawn from Briscoe et al. 2016[17]

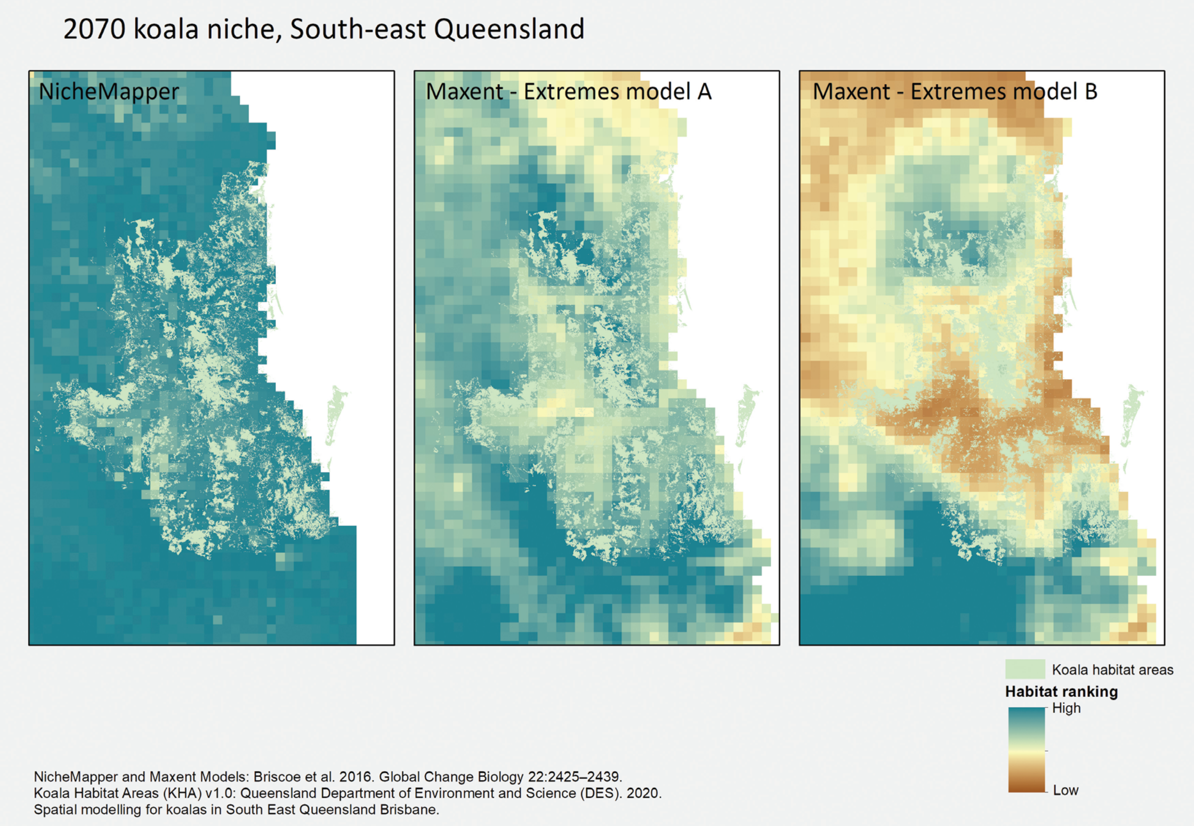

Figure 10. Comparison of predictions of 2070 climate suitability under a selection of climate models underlying NIKA categorisation (NicheMapper, Maxent Extremes model A, Maxent Extremes model B)[17], overlaid with current Koala Habitat Areas for south-east Queensland[5].

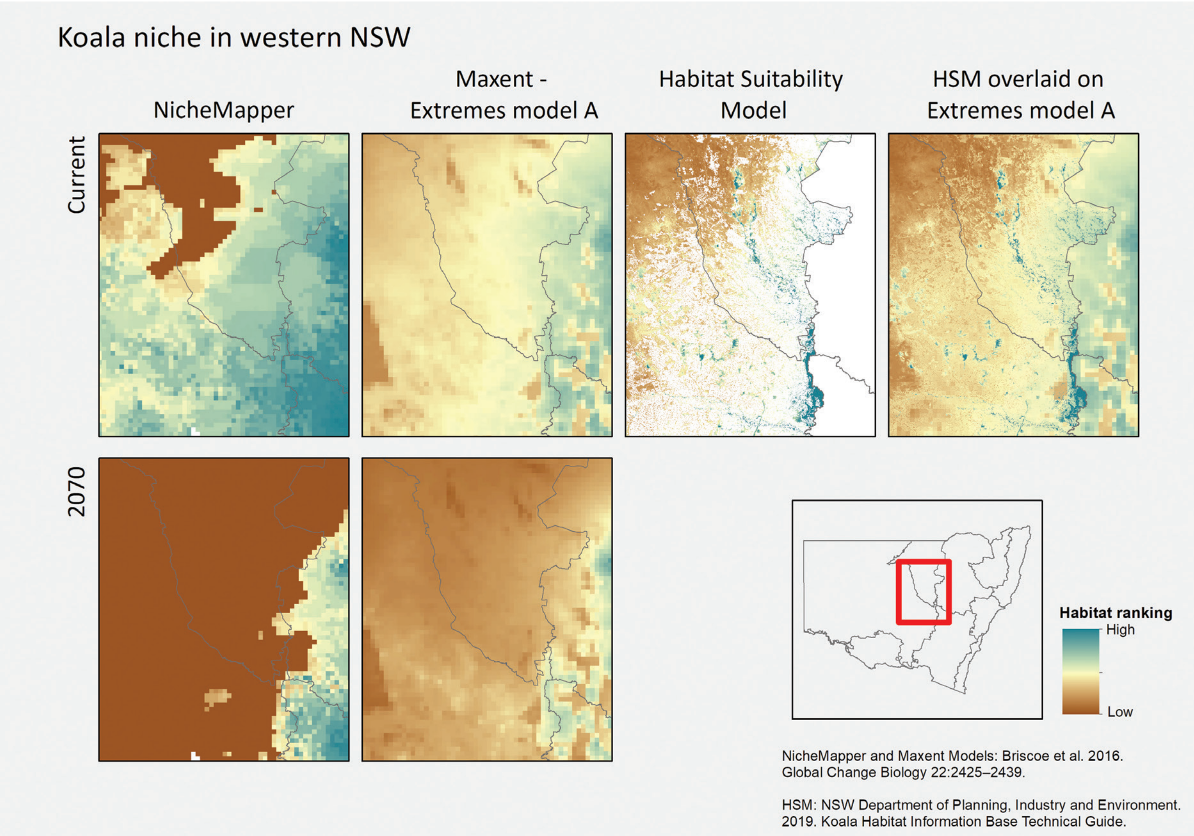

Figure 11. Comparison of climate models underlying NIKA categorisation (NicheMapper, Maxent Extremes model A, Maxent Extremes model B)[17], overlaid with current predictions of koala habitat suitability (Habitat Suitability Model, HSM)[4] for western NSW. The top row compares predictions of current climate suitability, the bottom row shows 2070 predictions.

8.2 Technical criteria for Recovery NIKA

We suggest the following technical criteria for Recovery NIKA (Figure 5).

A. Planning unit contains recoverable habitat, defined as >10% and <50% coverage of current likely habitat, is predicted to have contained any area of 'likely' koala habitat pre-clearing, and is in a recoverable land use, namely conservation or production from natural areas or agricultural land uses.

B. Koalas are not present or are at risk of extinction

Additional criteria for subcategory *Extinct* or soon to be:

Bi. Koala were historically present but have not been recorded in the past 3 generations

Additional criteria for subcategory *Insufficiently surveyed*:

Bii. No current or historical koala records within patch and no surveys of the patch within the past 3 generations.

C. Threats manageable (definition outside scope of this project).

As the time available to this project was limited, we did not analyse the full set of criteria for delineating Recovery NIKA. We have undertaken some preliminary analysis to support Recovery NIKA delineation. This can be found in section 9 and consists of:

- maps of areas that meet Criteria B (likely to be lost to climate change) and
- areas where koalas are no longer present or present in low numbers (Criteria B) or
- areas where koalas may have been insufficiently surveyed to determine the presence of koala populations (Criteria B)

Range-wide mapping of preclearing koala habitat is not available at this time, but would aid in identifying areas that once supported high quality koala habitat, and might with restoration, support high quality habitat once again. Maps of pre-clearing vegetation are available[56,64] and methods for mapping pre-clearing koala habitat have already been developed[5].

8.3 Technical criteria for Connectivity NIKA

Existing detailed guidelines for prioritising patches of habitat to increase connectivity for koalas are available[29]. Due to the limited time available to this project, we did not analyse criteria for delineating Connectivity NIKA. However, we suggest the following technical criteria:

A. Give priority to the revegetation of areas adjacent to and between large and medium sized NIKA (Known or Recovery NIKA) that are separated more than 3km[29] (a common dispersal distance for female koalas);

B. Connectivity NIKA should be at least 500m wide to avoid edge effects; and

C. Connectivity NIKA should maintain or restore habitat cover within corridors to at least 50%[29].

9. Koalas and habitat at risk under climate change

Modelling from a variety of sources indicates that the koala's distribution is constrained by climatic suitability, and particularly influenced by summer temperatures, humidity and water availability[53]. The main threat to koalas from climate change is from acute physiological stress during heatwaves, especially where combined with drought65.

Table 4 shows the area of koala habitat likely to be climatically suitable for koala by 2070, the percentage loss of koala habitat from current (pre-2019) estimates, and uncertainty around those estimates. Several bioregions holding substantial koala populations are likely to be almost completely unsuitable for koalas within the next 50 years (Brigalow Belt, Mitchell Grass Downs, Mulga Lands, Desert Uplands, Darling Riverine Plains). Koala habitat was drawn from the Harmonised Koala Habitat Map[2] and bioregions were drawn from IBRA766 and modified to be consistent with the boundaries used for the 2012 koala population estimates[30]. Climate predictions are drawn from Briscoe et al. 2016[17] and modified as per section 17.3.

Figure 12 shows habitat and koala populations likely to be lost under climate change by 2070 under conservative (core niche under 100% of models) and less conservative predictions (mid niche under majority of models). These at risk areas are based, in part, on a dataset that considers any area that becomes physiologically unsuitable for koalas for a two-week period as unsuitable for koala persistence[17]. Koalas may survive in small pockets outside this area, where microclimates such as caves, cliffs or dense vegetation provide refuge from heat and where the presence of perennial water means leaf water availability remains high.

Table 4. Estimates of koala habitat loss by 2070, by bioregion and state. The estimate is the area of habitat that is predicted to remain within the mid koala niche by 2070 under the majority (7 or more) of the 12 models. The percent loss was calculated from the habitat estimates using the Harmonised Koala Habitat Map as a baseline. Upper and lower bounds to these estimates are shown in parentheses. The lower bounds of the area estimates is the area of habitat (hectares) that is predicted to remain within the mid koala niche by 2070 under all 100% of 12 predictive models. The upper bounds describe the area predicted to remain habitat under any one (1 or more) of the models. Conversely the lower bounds to percentage loss describes the area predicted to be unsuitable for koalas by 100% of models and the upper bounds the percentage lost is the area that is not predicted to be suitable under all 100% of models. Estimates do not account for other causes of habitat loss (e.g. do not include land use change or bushfires).

	State	Current area of habitat (ha)	Area of habitat 2070 (ha)	% habitat loss by 2070
Listed range (Qld, NSW, ACT)		20.39×10^6	7.73×10^6 (3.03×10^6, 15.05×10^6)	62.1 (26.2-85.1)
Queensland		13.20 x106	2.76×10^6 (0.095×10^6, 9.14×10^6)	79.1 (30.8-99.3)
New South Wales		7.22 x106	4.99×10^6 (2.94×10^6, 5.92×10^6)	30.9 (17.9-59.3)
Bioregion				
Australian Alps	NSW	33067	33067 (412,33067)	0 (0,98.8)
Cobar Peneplain & Riverina	NSW	14800	0 (0,8100)	100 (45.3,100)
Darling Riverine Plains	NSW	283390	0 (0,0)	100 (100,100)
Mulga Lands	NSW	500	0 (0,0)	100 (100,100)
Murray Darling Depression	NSW	300	0 (0,0)	100 (100,100)
New England Tablelands	NSW	612524	611601 (460987,612524)	0.2 (0,24.7)
NSW North Coast	NSW	1171490	1098252 (614531,1127638)	6.3 (3.7,47.5)
NSW South Western Slopes	NSW	541189	158924 (17775,480929)	70.6 (11.1,96.7)
South Brigalow & Nandewar	NSW	1563728	198312 (8243,721191)	87.3 (53.9,99.5)
South East Corner	NSW	431775	416212 (402144,416212)	3.6 (3.6,6.9)
South Eastern Highlands	NSW	1551965	1532744 (802706,1547899)	1.2 (0.3,48.3)
Sydney Basin	NSW	921725	860387 (625915,890958)	6.7 (3.3,32.1)
Brigalow Belt North	QLD	1623969	55083 (0,948210)	96.6 (41.6,100)
Brigalow Belt South	QLD	6191802	333880 (0,3061897)	94.6 (50.5,100)
Central Mackay Coast	QLD	621847	93600 (0,610173)	84.9 (1.9,100)
Darling Riverine Plains	QLD	14387	0 (0,0)	100 (100,100)
Desert Uplands	QLD	67098	0 (0,0)	100 (100,100)

	State	Current area of habitat (ha)	Area of habitat 2070 (ha)	% habitat loss by 2070
Einasleigh Uplands & Wet Tropics	QLD	1501560	571737 (0,1474761)	61.9 (1.8,100)
Mitchell Grass Downs	QLD	9738	0 (0,0)	100 (100,100)
Mulga Lands	QLD	22778	0 (0,0)	100 (100,100)
Nandewar	QLD	226343	142193 (23205,212155)	37.2 (6.3,89.7)
New England Tablelands	QLD	77263	77263 (67979,77263)	0 (0,12)
South Eastern Queensland	QLD	2822345	1476050 (1887,2745619)	47.7 (2.7,99.9)

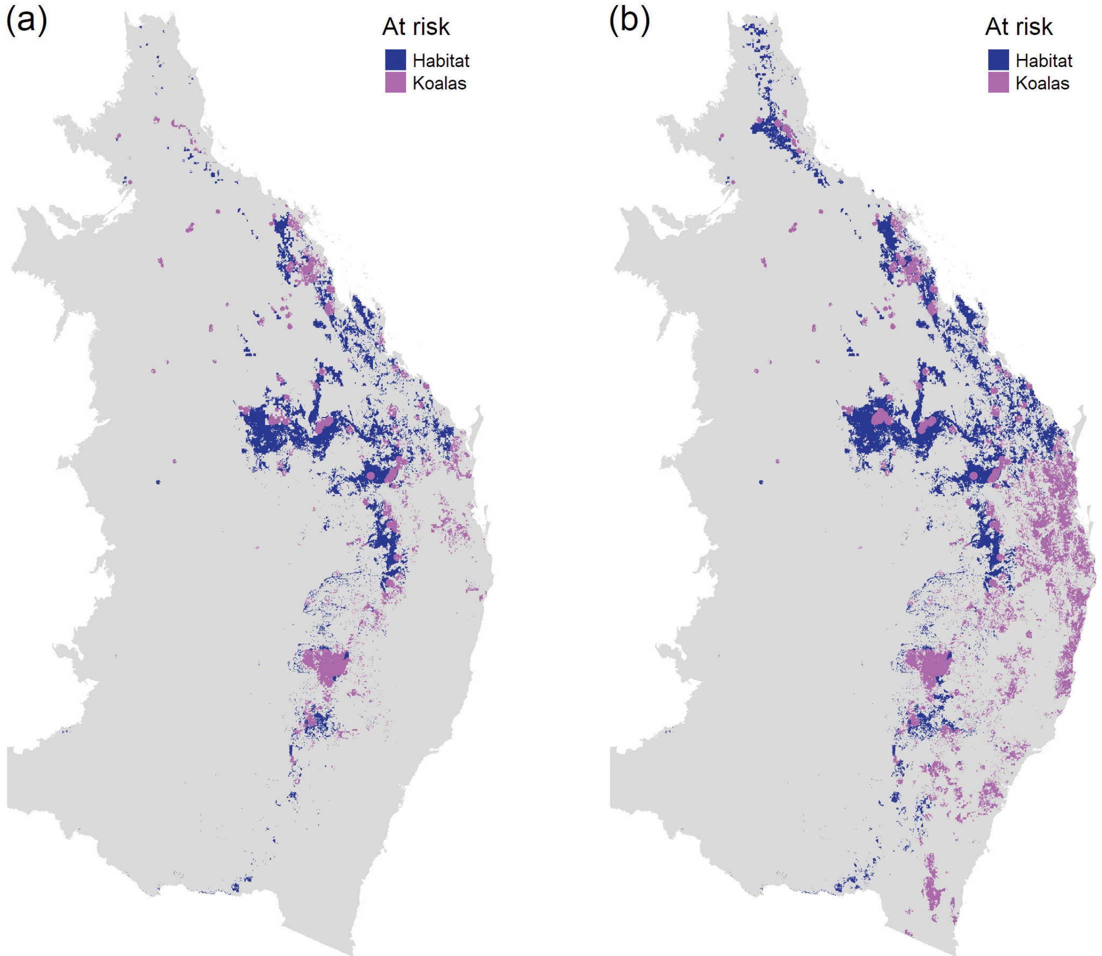

Figure 12. Koala habitat and populations at risk from climate change. Some of these populations may have already been lost. a) Habitat and populations likely to be lost by 2070 under mid-range predictions (mid koala niche, >50% of models), and b) habitat and populations likely to be lost by 2070 under conservative predictions (core koala niche 100% of models). Climate models are drawn from[17].

9.1 Potentially extinct koala populations

Figure 13a show areas where historical koala populations are recorded, but have not been recorded in the past 3 generations (since 01/01/2000). Figure 13b illustrates the sampling bias in koala records. Survey effort in western areas is low, and some of these populations may be extant. Koala records were drawn from WildNet[57] and BioNet[58]. We are aware of additional survey records not available in these datasets. Due to licensing issues we were unable to access these.

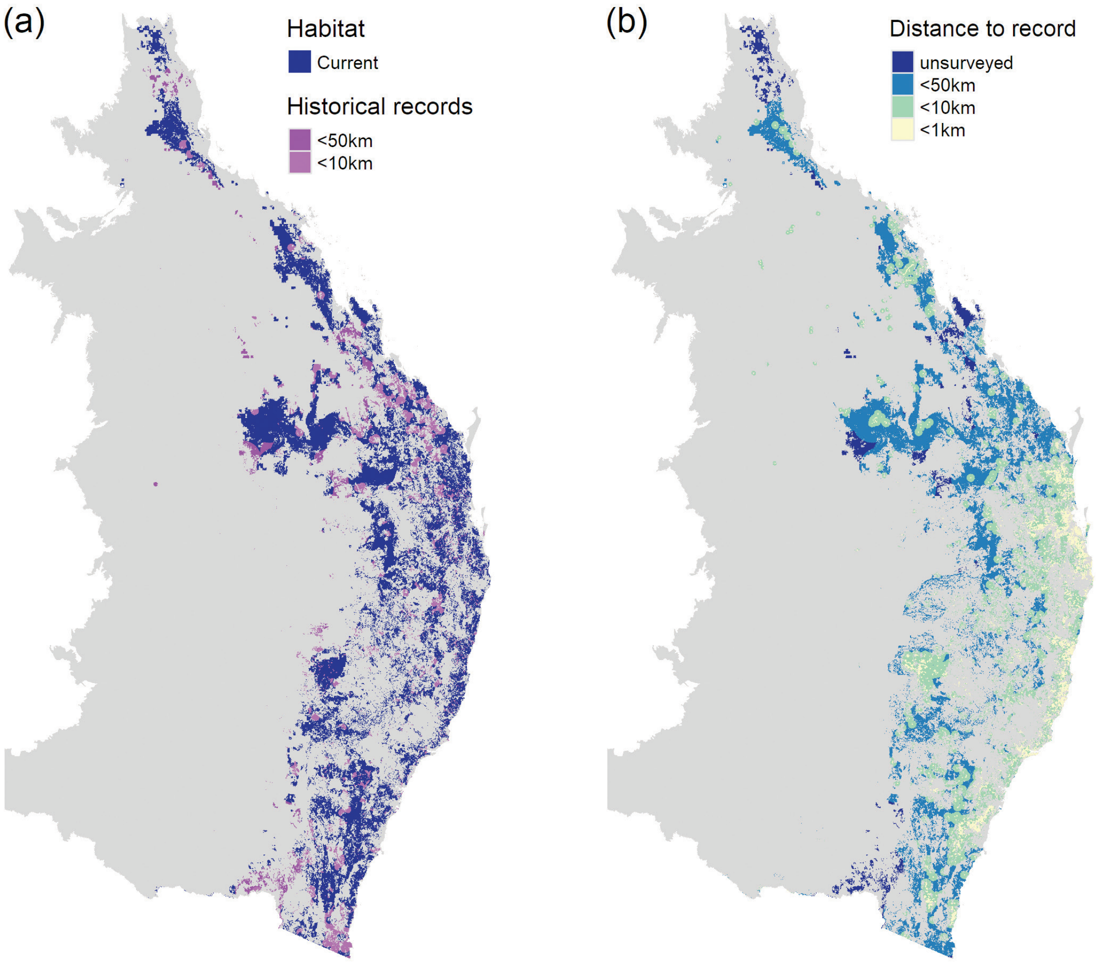

Figure 13. (a) Potentially extinct koala populations. Sites where koala were recorded after 1970, but that have not been recorded in the past 3 generations (since 2000) within 10 and 50km of the historical sightings are shown in pink and dark pink respectively). Current koala habitat is shown in dark blue. (b) Many of these populations may be extant, but have not been surveyed to confirm their presence recently. The map shows koala habitat with the distance to the nearest recent koala record shown by the colour scale (within 3 generations, since 01/01/2000). Records are drawn from WildNet[57] and BioNet[58].

10. Application of research

This research was conducted to support national koala recovery planning. As such, it is designed to support identification and conservation of nationally important koala habitat rather than all koala habitat. We anticipate that the findings and datasets will provide guidance for many interested parties and stakeholders, from national managers to local conservation groups. The recommendations around climate change planning, local and indigenous participation, genetic diversity and landscape connectivity will be of general interest to many stakeholders.

Applications include:

- Assessing climate suitability of habitat for restoration and conservation
- Developing priority areas for koala conservation
- Identifying sentinel sites for koala monitoring including under climate change

This research was not specifically designed to support regulatory activities for koalas, though we do not preclude this use.

11. Impact of research

This research supports the 2021 National Recovery Plan for Koala and Reassessment of Listing Assessment for Listed Koala. The data generated during this project will be used to inform an updated model of koala distribution and used in spatial query tools that support environmental impact assessments, recovery planning and other spatial analysis in the Commonwealth Department of Agriculture, Water and the Environment (DAWE).

12. Broader implications

Many species, across Australia and globally will be affected by the challenges arising from climate change and habitat loss. The conceptual framework that we have outlined that delineates habitat and defines sets of areas that harbour essential resources can be readily adapted to other species, including migratory and marine species.

One of the challenges in the spatial mapping of conservation areas, particularly under climate change, is that it often requires management units to be delineated across ecological gradients and with uncertain data. This means thresholds must be chosen to transform probabilistic predictions of habitat or climate suitability into binomial predictions (habitat/not-habitat, suitable/not suitable); and can involve harmonising or aggregating mapping across multiple datasets[67]. These decisions are often based on management criteria, rather than ecology. This research demonstrates practical methods for evaluating the decisions made in thresholding, aggregating, and harmonising datasets, and code associated with the project is available at https://doi.org/10.5281/zenodo.4305356. These methods can be translated to other species and regions and may be useful for the development of technical criteria for spatial mapping conservation areas.

13. Future research priorities

The main challenges and issues to be addressed moving forward are:

1. **Participation of experts, stakeholders, local and Indigenous people in NIKA delineation and criteria.** Many of the **technical decisions for NIKA delineation are arbitrary**, there isn't and isn't likely to be the ecological knowledge available to parameterise quantitatively. We emphasise that the criteria we suggest are management decision points rather than ecological decision points, and are designed to be operationally effective. We provide sensitivity analysis around these choices and recommend these be reviewed by an expert group, and that local and Indigenous knowledge and values be captured early in the planning and delineation process, and certainly before implementation. We recognise that engagement can take a long time, and suggest engagement be balanced alongside the need for timely action to prevent ongoing declines of at-risk koala subpopulations.
2. **Assess and prioritise NIKA for future conservation activity** that considers the contribution of that site to meeting koala population goals (e.g. habitat quality, connectivity, climate refugia), probability of success (e.g. current and future threats arising from urbanisation, agriculture and resource extraction, bushfire risk), and cost. Existing frameworks[68–70] including INFFER[71] may be useful for this.

3. **Define nationally important koala populations and critical habitat.** This was outside the scope of this project to define. The mapping presented in this report highlights that 'koala populations' as distinct entities exist only in a few rare cases and the ecological basis for delineating populations is slim. Rather, populations are a construct of management and policy, and may be defined at different scales.
4. **Predict koala population trajectories in different types of habitat.** A key challenge for koala recovery planning is determining whether the existing protected area estate and remnant habitat will be sufficient to recover koala populations. Much of the habitat that historically supported high densities of koalas has been lost, and koalas are declining precipitately even in protected areas[24,49]. Due to the very limited published data on the status, densities and trends, and in some regions the locations, of koalas the products we will deliver are defined around koala habitat rather than densities or population dynamics. This is a limitation of this approach. We strongly support the development of a national koala monitoring program that i) is designed to answer key management questions72,73, ii) is linked to management triggers in the National Recovery Plan for Koala[73], iii) includes funding for analysis of the data collected, and iv) harnesses citizen science[74]. In the meantime, sufficient survey data may exist in grey literature and unpublished surveys to support estimation or modelling of the potential and actual density and birth rates of koalas in different types of habitat. **This information will be important to successful long-term recovery of koalas.**
5. **Guidelines on what constitutes a koala drought refugia.** Research is underway by a number of groups including by groups at ANU, NSW Environment department and Central Queensland University that may be able to provide guidance on drought and heatwave refugia and conservation actions for koala[50]. It is possible that the qualities that define koala refugia vary across regions, and that refugial areas may have to be identified locally or in each bioregion or NRM region. Indigenous and local knowledge should play a part in identifying these areas.
6. **Guidelines for identifying koala fire refugia** and how the increased intensity of bushfires, combined with urbanisation and forestry changes the location or prevalence of these areas. Lack of guidance on conservation action that can be undertaken to increase the prevalence or utility of these areas. Following the 2019-2020 bushfires, research is underway to provide guidance for better management of fire, including upcoming NESP project 8.4.5.
7. **Generate a national dataset mapping the presence of pre-clearing or restorable koala habitat.** Data exists in SEQ and NSW that could be used to map areas that might be suitable for koala habitat restoration. The approach used to map restorable koala habitat in SEQ could be extended to the rest of Queensland drawing on the Queensland Habitat Mapping[3].
8. **Improve koala habitat mapping with stakeholder input**, including a regional elicitation of expert and Indigenous knowledge on use of regional ecosystem and tree species by koalas.
9. **Koalas and people**. Questions on how NIKA and the National Recovery Plan for Koala might be implemented across scales remain, and these will require input from Indigenous peoples and research from the social sciences and humanities:
   - Which koala populations are important to Indigenous peoples across the koala's range and how are they important?
   - Which conservation actions are acceptable and unacceptable to different communities, both Indigenous and non-Indigenous? How might these values be reconciled and cultural processes expressed around conservation actions relating to climate-driven local extinction and assisted migration?
   - How can trust and engagement be maintained between government and local groups given national priorities for koala management (persistence of species) may not align with public expectations for koala management (persistence of individual koalas)?
   - How can koala managers engage local groups and citizens in actions that support national priorities for koala monitoring and management?

14. Datasets

NESP4.4.12 has developed several spatial datasets to support the identification and implementation of NIKA. These are available at https://doi.org/10.5281/zenodo.4305157.

Proposed criteria for delineating nationally important koala areas (NIKA) and associated analysis of criteria (this report)

Proposed set of known NIKA and associated input files (GeoPackage)

Map of koala habitat and populations at risk from climate change (GeoPackage)

Map of under-surveyed koala habitat (GeoPackage)

Map of potentially extinct koala populations (GeoPackage)

Dataset available at https://doi.org/10.5281/zenodo.4305167

Harmonised koala habitat map for the entire region spanning NSW & Qld (GeoPackage, Harmonised_koala_habitat_v1.gpkg) and associated report describing methods2

Dataset available at https://doi.org/10.5281/zenodo.4305179

Queensland koala habitat mapping (GeoPackage, Qld_habitat_rank_100ha_v2.gpkg), associated files & report describing methods3

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16. Ethics statement

This research used existing datasets and ethics approval was not required.

17. Appendix 1: Datasets supporting delineation of NIKA

The set of variables used to classify planning units can be found in Table 5. A description of the processing and provenance of each variable follows.

Data processing and analysis was conducted using ArcGIS[75] and R[76] using packages 'tidyverse'[77], 'raster'78, 'sf'[79], and 'slga'[80].

Table 5. Variables that have been extracted for 100ha planning units in dataset NIKA_inputs.gpkg

	Variable name	Short description	Range of values and units
Koala records	current_koala	Number of koala observations recorded in the planning unit since 01/01/2000	0-3027
	dist2curr_koala	Distance to nearest sighting of koalas since 01/01/2000	< 10 km, 10-50km, 50-100km, >100km
	historic_koala	Number of koala observations recorded in the planning unit between 01/01/1970 and 31/12/1999.	0-1384
	dist2hist_koala	Distance to nearest sighting of koalas recorded between 01/01/1970 and 31/12/1999.	< 10 km, 10-50km, 50-100km, >100km
Current climate envelope	climate_Current _core	Number of models that predict the planning unit is currently climatically suitably for koala. Thresholds between suitable and unsuitable were chosen to represent low uncertainty tolerance.	0-6 models
	climate_Current _mid	Number of models that predict the planning unit is currently climatically suitably for koala. Thresholds between suitable and unsuitable were chosen to represent medium uncertainty tolerance.	0-6 models
	climate_Current _periphery	Number of models that predict the planning unit is currently climatically suitably for koala. Thresholds between suitable and unsuitable were chosen to represent high uncertainty tolerance.	0-6 models
Future climate envelope	climate_2070 _core	Number of models that predict the planning unit will be climatically suitably for koala in 2070. Thresholds between suitable and unsuitable were chosen to represent low uncertainty tolerance.	0-12 models
	climate_2070 _mid	Number of models that predict the planning unit will be climatically suitably for koala in 2070. Thresholds between suitable and unsuitable were chosen to represent medium uncertainty tolerance.	0-12 models
	climate_2070 _periphery	Number of models that predict the planning unit will be climatically suitably for koala in 2070. Thresholds between suitable and unsuitable were chosen to represent high uncertainty tolerance.	0-12 models
Region	nsw_eastern	Planning unit falls within eastern region of NSW (value =1)	0,1
	nsw_western	Planning unit falls within western region of NSW (value =1)	0,1
	qld_seq	Planning unit falls within south-east Queensland (value =1)	0,1
	qld_notseq	Planning unit falls within Queensland, excluding SEQ (value =1)	0,1
Land use	intact_area_ha	Area of land that contains intact vegetation or is currently under conservation tenure	0-100 ha
	Recoverable_area_ha	Area of land that is suitable for restoration i.e. agriculture or forestry.	0-100 ha
	Unrecoverable_area_ha	Area of land that is unsuitable for restoration i.e. under intensive use or is water.	0-100 ha
Habitat summary	habitat_ha_likely	Area of likely habitat within planning unit	0-100 ha
	habitat_ha_possible	Area of likely and possible habitat within planning unit	0-100 ha
	Habitat_present_likely	Planning unit assigned as likely habitat	0,1
	Habitat_present_possible	Planning unit assigned as likely or possible habitat	0,1

Table 6. Additional columns included in NIKA_inputs_extended.gpkg

	Variable name	Short description	Range of values and units
Whole of range SDM	snes_likely habitat_ha	Planning unit mapped as 'Species known to occur' and 'Species likely to occur' in SNES 2020 revision.	0,1
	snes_maybe habitat_ha	Planning unit mapped as 'Species may occur' in SNES 2020 revision.	0,1
	complexsdm_value	Habitat suitability value at centroid of planning unit. Derived from 'complex whole of range model' (details below)	0-1
	env_suitable	'Likely' = snes_likely=1 OR complexsdm_value > 0.444 OR climate_current_mid > 3	Likely, possible, not suitable
Regional habitat area	habitat_ha_nsw_likely	'Possible' = snes_possible=1 OR complexsdm_value > 0.3925 OR climate_current_periphery > 3	0-100 ha
	habitat_ha_nsw_possible	Not suitable = not 'likely' or 'possible'	Likely, possible, not suitable
	habitat_ha_nsw_likely	Area of habitat (eastern NSW only) ranked as high to very high in each planning unit, from thresholded regional koala habitat suitability models (NSW KHSM).	0-100 ha
	habitat_ha_nsw_possible	Area of habitat (eastern NSW only) ranked as medium to very high in each planning unit, from thresholded regional koala habitat suitability models (NSW KHSM).	0-100 ha
	habitat_ha_nsw_likely	Presence of habitat (western NSW only) ranked as likely in each planning unit, from thresholded regional koala habitat suitability models (NSW KHSM complex model, > 0.444 equal sensitivity and specificity value). Values taken from cell centroid.	0-1
	habitat_ha_nsw_possible	Presence of habitat (western NSW only) ranked as likely or possible habitat in each planning unit, from thresholded regional koala habitat suitability models (NSW KHSM complex model > 0.3925 max kappa value). Values taken from cell centroid.	0-1
	habitat_ha_seq	Area (SEQ only) of each planning unit overlapping areas delineated as core koala habitat.	0-100 ha
	habitat_ha_qld_likely	Area of habitat (Qld excluding SEQ) ranked as suitability 8-10.	0-100 ha
	habitat_ha_qld_possible	Area of habitat (Qld excluding SEQ) ranked as suitability 4-7.	0-100 ha
Water availability	pawc_mean	Mean plant available water capacity of soil underlying planning unit	0-283
	soildepth_mean	Mean depth of soil profile underlying each planning unit (A & B horizons)	0-1000 mm
	permanent_water_area_ha	Area of perennial water sources occurring within each planning unit	0-100 ha
Fire	firefreq_88to15	Frequency of bushfires recorded within planning unit between 1988 and 2015.	1-18 fires (NA=0 fires)

17.1 Datasets and data processing

Study region boundaries were drawn by selecting IBRA7 bioregions[66] that intersected Commonwealth koala distribution maps[81]. Cape York and Gulf bioregions were excluded, and the eastern portions of Mitchell Grass Downs were included as per[30].

The study region was projected to GDA94 Australian Albers projection (EPSG:3577) and divided into ***100 ha hexagonal planning units***. A total of 1,730,652 planning units were defined, each approximately 1km in diameter.

17.2 Harmonising koala habitat across regions

A harmonised map of ***likely and possible koala habitat*** was developed for the region encompassing Queensland, New South Wales (NSW) and the Australian Capital Territory (ACT). The area (ha) and presence of koala habitat in 100ha planning units across this region was mapped by harmonising existing regional habitat mapping and range-wide and regional species distribution models. Models of koala habitat were developed for regions where existing datasets were not available. As the area of each planning unit is 100ha, the area of habitat is equivalent to the percent coverage of habitat in each planning unit.

Models that integrate information on environmental variables and koala habitat trees exist for eastern NSW[4] and south-east Queensland (SEQ)[5]. We used these without modification. For the rest of Queensland, we generated habitat maps[3] by integrating vegetation mapping[56], koala records[57],and range-wide koala distribution models[4,17,82]. In western NSW koala habitat was mapped from koala distribution models[4] and no information on tree species was included.

This dataset was developed to inform broad-scale conservation planning associated with the National Recovery Plan for Koala. The spatial resolution is 1km (100ha). It is not intended for identifying habitat at a fine scale, nor for use in environmental assessments or regulatory activities. The dataset has not been ground-truthed. Some areas identified as potential habitat may be too degraded or contain insufficient resources for koalas to occupy. Koalas may be present outside the areas identified as potential habitat.

Further information on this dataset can be found in NESP 4.4.12 report 'Harmonised koala habitat mapping'[2] and the dataset can be found at https://doi.org/10.5281/zenodo.4305167.

17.3 Climate envelopes and refugia

The ***current and future climate suitability*** of each planning unit for koala was determined from an existing dataset [17]. This dataset maps climatic suitability for koala at approximately 5km resolution (0.05 degree) under a set of six models: three correlative species distribution models generated using climatic variables, and three bioenergetics models. These six models had then been projected onto a) current climate conditions to generate 6 predictions of current climate suitability for koala; and b) future climate conditions drawn from two diverging general circulation (i.e. climate) models using the RCP 8.5 scenario for 2070 to generate a set of 12 predictions of future climate suitability.

Next, each of these 18 maps (6 current, 12 future) was thresholded to generate binomial maps (0 = not climatically suitable, 1 = climatically suitable). Thresholds were chosen to represent different tolerances of uncertainty in the mapping process. These were calculated from the value within which 90, 95 and 99 % of post-2000 koala records fall, with 90% representing the core climate niche, 95% representing the mid climate niche, and 99% representing the peripheral climate niche and a higher level of within-model uncertainty. Koala records were first spatially thinned by random sampling a single record from within each 1km grid cell.

Finally, we summed across the binomial maps in the given time period, with equal weighting given to all models. The resulting values represent the number of climate scenarios where that planning unit is predicted to be climatically suitable for koala. Values range from 0-6 for current climate and 0-12 for future (2070) climate, and were calculated for each threshold (90, 95 or 99% of koala records). A value of 6 under current and 12 under 2070 conditions represents an area that is predicted as suitable across all models.

17.4 Koala records

The number of recent and historic koala occurrence records within each planning unit was calculated by buffering koala records to 1km and calculating the number of buffered records that intersected each planning unit. 1km was chosen to match the uncertainty in the spatial accuracy of the koala records used. Records for Queensland were obtained from WildNet[57] and for NSW from BioNet[58] on 19 May 2020. Records with spatial accuracy greater than 1000m were excluded as were records with > 12 months uncertainty around the sighting date. Records falling outside Queensland and NSW land borders, museum or voucher records, and duplicates were excluded. Records were split into recent koala occurrences (any record from 01 Jan 2000; 73526 records) and historic koala occurrences (any record from 01 Jan 1970 to 31 Dec 1999; 26835 records).

17.5 Land use and recovery potential

The total ***area (ha) of recoverable, intact and unrecoverable land*** in each planning unit was estimated from the land use and land cover (LULC) overlapping each planning unit. LULC was extracted from the Catchment scale land use of Australia[83], 50m resolution. Land uses were reclassified as recoverable (suitable for restoration), unrecoverable (not suitable for restoration) and intact (native vegetation intact, or area is under conservation tenure) based on the Australian Land Use and Management Classification Version 8[84]. Primary classes 'Conservation and Natural Environments' and 'Production from Relatively Natural Environments' were assigned as 'intact'. Classes 'Production from Dryland Agriculture and Plantations' and 'Production from Irrigated Agriculture and Plantations' were assigned as 'recoverable' and 'Intensive Uses' and 'Water' assigned as unrecoverable. Total area in a given planning unit was estimated from the number of cell centres overlapping each planning unit. Area across recoverable, non-recoverable and intact cover classes ranges from 0 to 100 ha.

17.6 Soil and water characteristics

The ***mean plant available water capacity*** of soil (PAWC) underneath each planning unit was calculated from[85]. The resolution of this dataset is 0.025 degrees (approximately 250m) and units are mm/m summed across 0-1m depths of soil.

The ***mean depth of soil (mm)*** underneath each planning unit was extracted from Soil and Landscape Grid of Australia[62] using package 'slga'[80]. The resolution of this dataset is 3" arc seconds (approximately 90m) and units are m summed across the A & B soil horizons up to 1m.

The ***area of perennial water (ha)*** within each planning unit was calculated from polygons of perennial water bodies[63].

17.7 Bushfire history

The ***maximum frequency of bushfires*** in each planning unit across the koala distribution was drawn from[59], with the value being the number of fires during the period 1988 to 2015. The resolution of this dataset is 0.01 degrees (approximately 1km) and values range from 0-18 in the study region.

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Koala. Image: Dan KB, Unsplash

Further information:

http://www.nespthreatenedspecies.edu.au

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