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Database records of koalas (*Phascolarctos cinereus*) in northern Sydney

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ABSTRACT

This study examined records of koalas (*Phascolarctos cinereus*) in northern Sydney held in online biodiversity databases. There were 221 unique records distributed across the Northern Beaches, Ku-ring-gai, Hornsby and Hills Shire local government areas from 1788 to 2022, with records from the Northern Beaches local government area comprising 68% of this dataset. Records from the 1970s represented 41% of the dataset (90 records), while there were only 42 records from 2000 to 2022. Post-2000 records were spread broadly, showing no major contraction in distribution compared to the spread of earlier records, but with a notable absence of more recent records on the Barrenjoey Peninsula, a previously documented species stronghold. Substantial proportions of records were found in both protected reserves and privately-owned lands, which alludes to the value of the former but also shows that koala conservation in this capital city cannot rely solely on protected reserves. The 2000–22 records were widely distributed across 15 plant community types and areas of non-native vegetation, probably reflecting breeding and dispersal movements more than specific habitat selection. Possibly due to the same influences, none of the 2000–22 records were matched to areas represented by the Koala Habitat Suitability Model, a prediction model for spatial distribution of potential koala habitat across NSW, with a high habitat suitability score (greater than 0.85). We therefore recommend systematic on-ground surveys to clarify the patterns observed from the records.

Keywords: community science, endangered species, habitat suitability, land tenure, marsupial, plant community types, Sydney metropolitan area, threatened species, urban environments.

Introduction

Urbanisation has significant impacts on wildlife populations through habitat loss and fragmentation, as well as human activities contributing to disturbances and threats to wildlife (McKinney 2002; Callaghan *et al.* 2018). Urbanised environments broadly comprise human-constructed spaces such as buildings and roads, and vegetated patches, sometimes referred to as 'green spaces' (Adams *et al.* 2006). Extensive land use change in Sydney, Australia's oldest and most populous city, has been brought on by rapid population increase and a long history of industrial activity since European settlement (Birch *et al.* 2015; Reid 2020). The Sydney metropolitan area has an estimated human population of over 5 million, residing within an area of approximately 12 367 km^2. This equates to more than 60% of the population of New South Wales (NSW), residing within an area occupying less than 2% of the state's land mass (Easthope and Randolph 2009). The modern geography of this metropolitan area ranges from heavily developed areas in the inner city to large tracts of remnant natural areas and peri-urban areas at the peripheries. There has therefore been substantial scientific interest in the capacity of indigenous wildlife to adapt and persist in such a modified landscape mosaic (Denning 2010; Major 2010; Shea 2010; Mo 2015, 2019).

In mammals, body mass appears to play a determining role in a species' capacity to exploit urban environments, with species weighing less than 10 kg having a greater likelihood of persistence (Baker and Harris 2007). The koala (*Phascolarctos cinereus*) is

an iconic Australian mammal that fits within this body mass range (6–7 kg, Ellis and Bercovitch 2011). Koalas are still found in some urban environments (Goldingay and Dobner 2014; Whisson *et al.* 2020) but they face a range of anthropogenic threats such as motor vehicle collisions (McAlpine *et al.* 2006; Lunney *et al.* 2022*a*, 2022*b*), domestic animal attacks (Rundle-Thiele *et al.* 2019; Lunney *et al.* 2022*c*) and chlamydia infection (McCallum *et al.* 2018; Quigley and Timms 2020). Fundamentally, the extensive clearing of forests to facilitate urbanisation has had immediate impacts on the viability of landscapes for koalas to persist (McAlpine *et al.* 2015). As a result, the combined koala populations of NSW, Queensland and the Australian Capital Territory (ACT) are federally listed as endangered (DCCEEW 2022), which is reflected in the species' conservation status under the NSW *Biodiversity Conservation Act 2016* (NSW TSSC 2022).

With the backdrop of an ever-growing interest in wildlife persistence in urban areas and the koala as a charismatic species, koalas occurring in the Sydney metropolitan area have been of particular scientific, public and political interest. A significant volume of scientific literature is devoted to the study of koalas in southern Sydney (Ward 2002; Lee *et al.* 2010; Karas 2018), especially the Campbelltown area (Phillips and Callaghan 2000; Sluiter *et al.* 2001; Ward and Close 2004; Lunney *et al.* 2010*a*, 2010*b*). Koalas occurring in northern Sydney have received less attention in the scientific literature (Strahan and Martin 1982; Curtin and Lunney 1995; O'Brien 1995; Lott *et al.* 2022), though there was an extensive study of koalas in the former Warringah Shire (Smith and Smith 1990; now incorporated into the Northern Beaches local government area). Koalas in this area were once regarded as the largest population in the Sydney metropolitan area (Williamson 1975; Strahan and Martin 1982; Lee and Martin 1988), but it has been reported as extirpated by at least one author (Lott *et al.* 2022). Without further study, the current distribution and abundance of koalas in northern Sydney remains unknown, especially whether recent sightings represent individuals dispersing from adjoining regions or individuals originating from a remnant population. A recent genetic study found that two koalas sampled in 1950 from the Northern Beaches local government area were more closely related to Queensland and South Australian populations, which suggests that some koalas in this area were derived from captive-sourced individuals (Lott *et al.* 2022).

The aim of this study was to examine the distribution of koalas in northern Sydney based on occurrence records lodged in online biodiversity databases relative to mapped protected areas, land tenure, plant community type and habitat suitability. Our study area comprised the Hills Shire, Hornsby Shire, Ku-ring-gai, Northern Beaches, Willoughby, Mosman, North Sydney, Lane Cove, Hunters Hill, Ryde and Parramatta local government areas. We were particularly interested in the distribution of reported sightings of koalas within the study area during 2000–22 and how this spread would compare to reported locations prior to 2000. The study provides a baseline for further research into the ecology and conservation needs of koalas prone to the effects of urban development.

Materials and methods

Data extraction and cleaning

We established a spatial dataset of koala occurrence records within our study area by downloading occurrence records from three online biodiversity databases: NSW BioNet (http://www.bionet.nsw.gov.au), Atlas of Living Australia (https://www.ala.org.au) and iNaturalist (https://inaturalist.ala.org.au). Data were extracted on 1 July 2022. We excluded records of occurrence outside our study area.

We excluded records from BioNet that were flagged by the application as invalid (i.e. quarantined, suspect or rejected records; OEH 2019) and excluded records from the iNaturalist database that were not classified as research grade (iNaturalist classifies records as verifiable if the observation is georeferenced, dated, has photograph/s or audio recording/s, and is of a free-living animal, i.e. not a captive animal, and as research grade when a majority of at least three application users agree on species identity). We excluded records extracted from the Atlas of Living Australia that had been transferred from BioNet and iNaturalist to remove duplicate data.

We conducted all spatial analyses in ArcGIS 10.4. For all spatial overlay analyses, we constrained the sample size to only records with positional accuracy within 500 m to minimise the probability of false classifications of records.

Spatial and temporal distribution of koala sightings

To examine the spatial and temporal distribution of koala occurrence within the study area, we categorised and mapped records to time periods of 1930–49, 1950–59, 1960–69, 1970–79, 1980–89, 1990–99, 2000–09 and 2010–22. The selection of these time periods was based on the records available. Records with no temporal data and those attributed to date ranges greater than 9 years were excluded. We also examined the seasonal frequency (months) of sightings with known observation dates.

Koala sightings relative to land tenure

We investigated the land tenure of locations of koala sightings in two stages. With an interest in how many sightings occurred within protected bushland, we first examined the distribution of all records on land currently protected as reserves managed by the NSW National Parks and Wildlife Service (NPWS). This was done through spatial overlay analysis with mapped NPWS reserve boundaries. We

included records made prior to 2000 in this assessment on the assumption that locations that are currently NPWS reserves would have been natural habitat at the time sightings were recorded. With a broader interest in what land tenure other sightings occurred on, we then determined the land tenure of records from 2000 to 2022. We restricted this assessment due to expected changes to land tenure and associated land use over time. Records occurring within NPWS reserves were determined through the previous assessment. Records that were on Crown land were determined through spatial overlay analysis with mapped Crown land boundaries. Land tenure of the remaining 2000–22 records were determined through a spatial overlay analysis with a Lot Ownership spatial layer maintained by the NSW Department of Planning and Environment, which is based on land ownership records held by the Land Titles Office. This enabled us to manually interrogate ownership information to determine whether records resided on council-owned land, lands owned by other government agencies or lands owned by private individuals or corporations.

Koala sightings relative to plant community types

We assessed the distribution of 2000–22 records by the Department of Planning and Environment's eastern NSW plant community type classification version 1.1 (DPE 2022) and examined whether records were concentrated within any particular plant community types.

Comparison of recent records of koala occurrence with the Koala Habitat Suitability Model

The Koala Habitat Suitability Model using the program MaxEnt was developed as part of the NSW Koala Habitat Information Base (DPIE 2019) to predict the probability of suitable koala habitat occurring at specific locations across NSW between values of 0 to 1 (Mitchell *et al.* 2021). We examined habitat prediction at a local scale using the Koala Habitat Suitability Model and extracted the suitability scores for the locations of each koala sighting between 2000 and 2022.

Results

We found 221 unique records of koalas within our study area; 205 unique records in BioNet, 13 unique records in the Atlas of Living Australia and three unique records in iNaturalist (see Supplementary material). Of these, 130 had specific sighting dates, 82 had date ranges from 3 days to 162 years (wider date ranges were generally historical data with speculative temporal information) and nine records with no dates. An exact year of sighting was attributable to 194 records and a further seven records were attributable to a period within 4 years (e.g. 1967–70 or 1974–75).

Demographical information was only available for 24 records, representing approximately one-tenth of the dataset. There were six records denoting adult individuals, three of which also denoted male individuals, and one further record that also denoted a male individual with no information on age category. These records were sightings between 2006 and 2017. There were 12 records denoting juvenile individuals, all of which were sightings between 1970 and 1975.

Spatial and temporal distribution of koala sightings

A large proportion of records were sightings during the 1970s. There were 90 unique records during this decade, comprising 41% of our dataset. Since 1960, there has been a minimum of nine unique records lodged in the biodiversity databases in each decade. There were 42 records from 2000 to 2022, which constitutes 19% of our dataset.

There were 130 records with known observation dates, of which there were higher numbers of sightings for the months of October (21 records), November (20 records), December (20 records) and January (16 records). The dataset contained less than 10 records for other months, ranging from three (April) to eight records (June).

Records were distributed across four local government areas (Fig. 1). The largest proportion of records were sightings within the Northern Beaches local government area (150 records), representing 68% of our dataset, of which 16 were 2000–22 records. There was also a large proportion of records within the Hornsby local government area (40 records), representing 18% of our dataset, of which 10 were 2000–22 records. The remainder of records were within the Hills Shire (22 records) and Ku-ring-gai local government area (nine records), representing 10 and 4% of our dataset respectively. Of these, 12 and four records respectively were sightings during 2000–22. There were no records within the Willoughby, Mosman, North Sydney, Lane Cove, Hunters Hill, Ryde and Parramatta local government areas.

Koala sightings relative to land tenure

Of the total 221 records, 71 records were within a positional accuracy within 500 m. Of these, 24 records were sightings within protected reserves managed by NPWS, with two records in Berowra Valley National Park (1990–99), one record in Cattai National Park (2010–19) and 21 records in Ku-ring-gai Chase National Park (one during 1960–69, 12 during 1970–79, one during 1990–99, four during 2000–09, one during 2010–19, two during 2020–22), equating to one-third of this sample size. Of note, there were 41 records attributed with a positional accuracy of 1000 m in which geographical coordinates reported were within the boundaries of protected reserves, including a further two

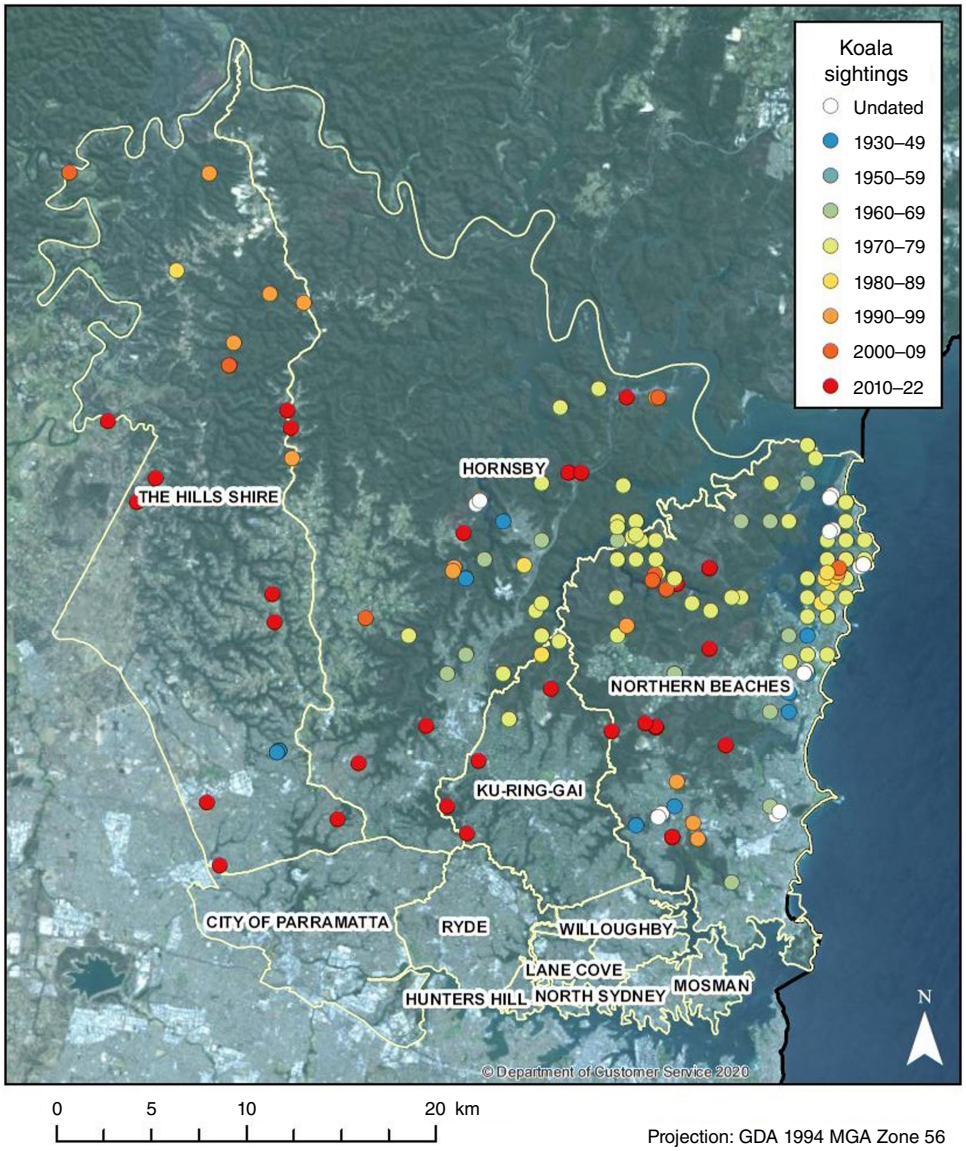

Fig. 1. Spatial and temporal distribution of 221 unique records of koalas in northern Sydney local government areas.

protected reserves, Garigal National Park (one record) and Muogamarra Nature Reserve (three records).

From the 42 records from 2000 to 2022, spatial information for 35 records were within a positional accuracy of 500 m. We matched these records to seven broad categories of land tenure, with approximately half of these sightings occurring on government-owned lands (17 records) and the remaining half on privately-owned land (18 records). Specifically, there were eight records in protected reserves managed by the NSW National Parks and Wildlife Service, four on Crown land, two on lands owned by other state government organisations (Sydney Water and the Transport Asset Holding Entity), three on council-owned land (two within Ku-ring-gai Council and one within Hornsby Shire Council), two on Local Aboriginal Land Council properties, 12 on properties owned by private individuals, and four on properties owned by private corporations.

Koala sightings relative to plant community types

Of the 35 records from 2000 to 2022 with a positional accuracy within 500 m, we matched 23 records to 15 plant community types recognised by the eastern NSW plant community type classification across nine vegetation classes and eight vegetation formations (Table 1). The remaining 12 records were within areas mapped as non-native vegetation. The vegetation formation with the largest number of sightings were dry sclerophyll forests (shrubby sub-formation), with four records matched to three plant community types under the Sydney coastal dry sclerophyll forests vegetation class and three records matched to two plant community types under the Sydney hinterland dry sclerophyll forests vegetation class (Table 1). These koala sightings were distributed across the four local government areas but all occurred within protected

Table 1. Distribution of 2000–22 records of koalas with positional accuracy within 500 m across the eastern NSW plant community type classification ($n = 35$).

Classification[A]	No. records
Dry sclerophyll forests (shrubby sub-formation)	7
Sydney coastal dry sclerophyll forests	4
Sydney coastal enriched sandstone forest	1
Sydney coastal sandstone bloodwood shrub forest	2
Sydney coastal sandstone gully forest	1
Sydney hinterland dry sclerophyll forests	3
Sydney hinterland grey gum transition forest	2
Sydney hinterland turpentine-apple gully forest	1
Forested wetlands	1
Coastal floodplain wetlands	1
Coastal alluvial bangalay forest	1
Freshwater wetlands	1
Coastal freshwater lagoons	1
Southern lower floodplain freshwater wetland	1
Grassy woodlands	5
Coastal valley grassy woodlands	5
Cumberland shale-sandstone ironbark forest	5
Heathlands	2
Sydney coastal heaths	2
Woronora Plateau heath-mallee	2
Rainforests	2
Northern warm temperate rainforests	2
Sydney coastal coachwood gallery rainforest	2
Wet sclerophyll forests (grassy sub-formation)	4
Northern hinterland wet sclerophyll forests	4
Central Coast escarpment moist forest	1
Northern foothills blackbutt grassy forest	1
Sydney coastal shale-sandstone forest	1
Sydney turpentine ironbark forest	1
Wet sclerophyll forests (shrubby sub-formation)	1
North Coast wet sclerophyll forests	1
Sydney enriched sandstone moist forest	1
Non-native vegetation	12

[A]Classification follows the NSW vegetation classification hierarchy: vegetation formation (unindented), vegetation class (first indentation), plant community type (second indentation).

reserves managed by NPWS or on private land within 3 km of NPWS reserve boundaries.

The plant community type matched to the largest number of koala sightings was Cumberland shale-sandstone ironbark forest, a type of grassy woodland (five records, or one-seventh of the 35 records; Table 1). These koala sightings all occurred in the Hills Shire local government area, two sightings on a property owned by a Local Aboriginal Land Council and three sightings on lands owned by private individuals. No other plant community type was attributed to more than three records (see Table 1 for other plant community types attributed to records).

Comparison of recent records of koala occurrence with the Koala Habitat Suitability Model

Our matching of the 2000–22 records with the Koala Habitat Suitability Model found that locations of sightings ranged in suitability scores from 0 to 0.85, with no records situated at locations with suitability scores between 0.90–1 (Fig. 2, Table 2). The 14 sightings at locations with suitability scores greater than 0.50 only made up 40% of the 35 records. Only 20% of the 35 records occurred in locations with suitability scores greater than 0.70 (seven records). In comparison, a large proportion of sightings occurred in locations within the suitability score ranges of 0.30–0.39 (six records) and 0.40–0.49 (eight records), which combined represented 40% of the 35 records.

Discussion

We consider the current volume of reported koala sightings in northern Sydney to be small relative to the accessibility of the study area. Nevertheless, our examination of records showed that koala sightings in northern Sydney extend into recent decades, albeit not at the reporting rate of the 1970s. This study showed that koala sightings in northern Sydney across time have occurred across four local government areas, most prominently in the Northern Beaches local government area. This supports the inferences of Smith and Smith (1990) that this area has been a particular stronghold for koalas in the Sydney metropolitan area, especially the Ku-ring-gai Chase National Park and historically the Barrenjoey Peninsula. Despite there being fewer records during 2000–22, these limited recent sightings were broadly distributed as far as the southern parts of the Northern Beaches, Ku-ring-gai and Hornsby local government areas and near the western boundaries of the Hills Shire local government area. Based on this, recent sightings during 2000–22 show no major contraction in distribution compared to earlier records.

During the 1970s, when there was the largest number of reported sightings, koalas in one part of the Northern Beaches local government area, the Barrenjoey Peninsula were estimated at over 123 individuals (Smith and Smith 1990). Records across the Northern Beaches local government area were substantially fewer in the 1980s and 1990s,

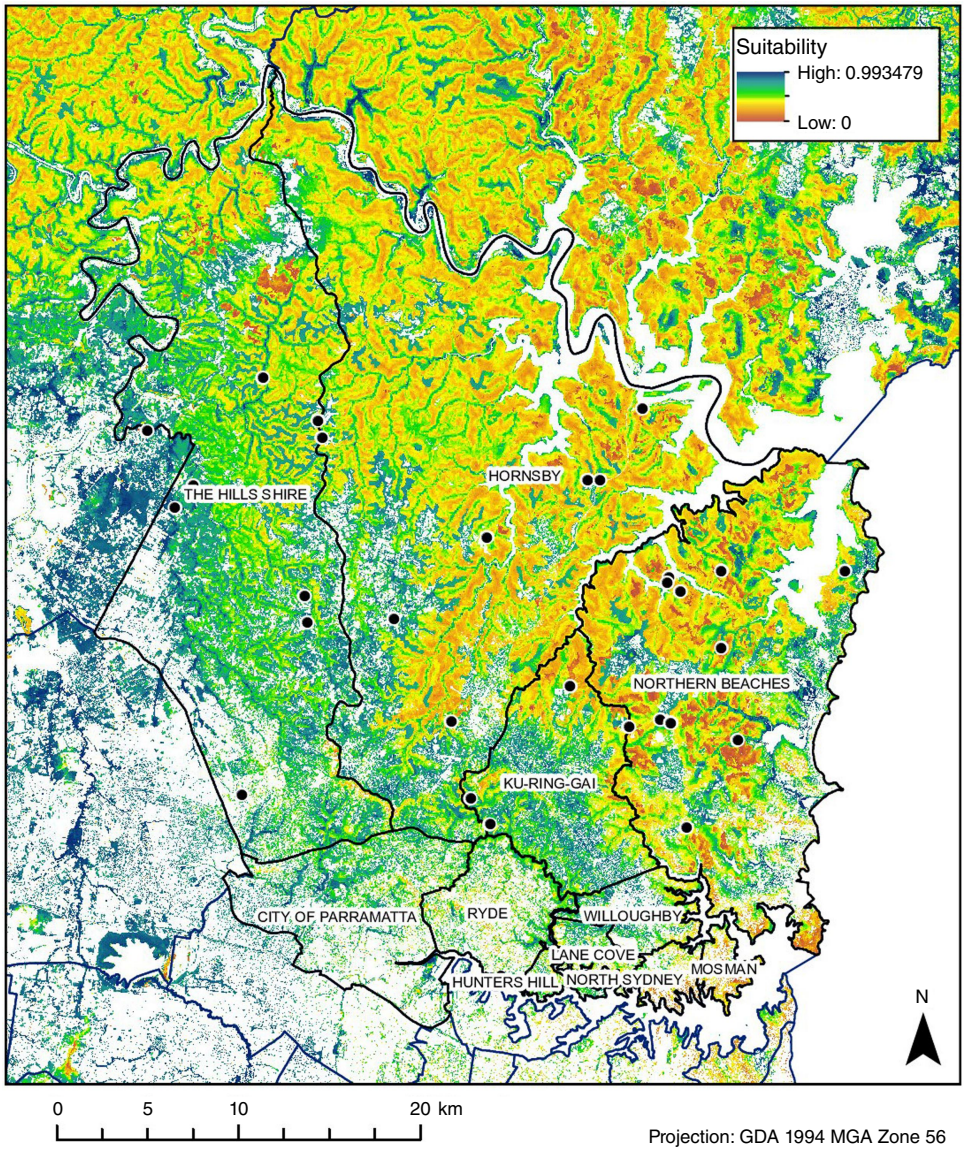

Fig. 2. Records of koalas lodged during 2000–22 with positional accuracy within 500 m overlaid with the Koala Habitat Suitability Model.

Table 2. Distribution of 2000–22 records of koalas with positional accuracy within 500 m across suitability scores of the Koala Habitat Suitability Model (n = 35).

Suitability score range	No. records	Accumulative no. records (%)
0.80–0.89	2	2 (5.7)
0.70–0.79	5	7 (20.0)
0.60–0.69	4	11 (31.4)
0.50–0.59	3	14 (40.0)
0.40–0.49	8	22 (62.9)
0.30–0.39	6	28 (80.0)
0.20–0.29	1	29 (82.9)
0 or not applicable	6	35 (100.0)

which corroborates findings of previous studies that suggest that there has been a decline in koala numbers locally during these decades, potentially to less than 10 individuals (Smith and Smith 1990; P. Higgs and D. Campbell, unpubl. data). This corresponds with the listing of koalas in the former Pittwater local government area (now incorporated into the Northern Beaches local government area) as an endangered population under NSW environmental legislation (NSW Scientific Committee 1998) between 1998 and 2022, prior to the current listing of koalas as endangered throughout NSW (NSW TSSC 2022). Notably, despite Smith and Smith (2000) reporting a sighting of an adult with a joey on the Barrenjoey Peninsula from February 2000, we only found a single post-2000 record from this area, which was from 2006 (record identity SRJC07121116; see Supplementary material). There is the potential that an extirpation has occurred on the Barrenjoey Peninsula

(P. Smith, pers. comm.). In contrast, for the second significant site identified by Smith and Smith (1990), the Ku-ring-gai Chase National Park, there have been nine post-2000 records, including two records from 2020.

The present study showed that one-third of records within the study area occurred within protected reserves managed by NPWS, which alludes to the value of these protected reserves for koalas in northern Sydney. However, we should also acknowledge a possible bias towards the number of records occurring within NPWS reserves due to NPWS staff and reserve visitors specifically searching for wildlife within this land tenure. The number of koala records outside of protected reserves is also of interest and calls attention to the need for targeted surveys throughout the study area to properly understand the distribution of koalas between land tenures. The disproportionate number of records from privately-owned land and other land tenures in the presently available data suggests that conserving this species cannot rely solely on protected reserves. This also highlights the importance of integrating community engagement into koala conservation, such as undertaking social marketing to encourage canine owner efforts to reduce koala-dog interactions (David *et al.* 2019; Rundle-Thiele *et al.* 2019) and signposting roads frequented by koalas (Harris and Goldingay 2003). Given the dense human population in Sydney and the koala being well known to the public, we would expect that sightings would be reported whether in or outside of a NPWS reserve.

Our assessment of plant community types at the locations of the 2000–22 records was limited by the small sample size after we excluded records attributed to a positional accuracy greater than 500 m. In our assessment, records were distributed across a broad range of plant community types and non-native vegetation, though this may be more a reflection of breeding and dispersal movements in koalas (Dique *et al.* 2003; Davies *et al.* 2013) rather than their specific habitat selection. Unfortunately, demographical information in the records was sparse, with only three records specifically denoting adult males. There was a higher representation of dry sclerophyll forests and grassy woodlands in the presently available data but additional records in the future would contribute to a larger sample size that would allow clarification of these patterns and whether they are statistically significant. Our matching of the Koala Habitat Suitability Model with the 2000–22 records was also limited by the sample size. This assessment found that few records were in locations attributed to habitat suitability scores greater than 0.50, which we attribute in part to the model being purposed for state-wide assessment and thus having limited applicability at a local scale. These results are also likely to be influenced by breeding and dispersal movements (Dique *et al.* 2003; Davies *et al.* 2013).

Koalas occurring in northern Sydney are fitting candidates for further research given that they occur in a capital city that has ongoing residential and infrastructure development and that present koala densities in this area still represent a knowledge gap. These factors are likely to bring political and social influences on how koala conservation in this region is prioritised, especially with the recent change in the legal status of koalas in NSW from vulnerable to endangered (NSW TSSC 2022) and increased public awareness of the threats koalas face in urban areas (McAlpine *et al.* 2006, 2015; Lunney *et al.* 2022*a*, 2022*b*). There is some evidence that koala populations can function at very low densities (Close *et al.* 2017) and that koalas probably occurred in low densities in the now Sydney metropolitan area during early settlement, making them difficult to detect (Lunney *et al.* 2010*a*). However, the ability for koalas to persist at low densities is believed to be predicated on sufficient bushland being retained and populations occurring across a wide distribution, allowing for dispersal movements to facilitate re-colonisation where local extinctions occur (Close *et al.* 2017). The present study contributes important baseline information with potentially substantial ramifications for land use planning and approvals, but it should be followed up by systematic on-ground surveys to clarify patterns observed in the existing records.

Supplementary material

Supplementary material is available online.

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