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WILDLIFE RESEARCH

Insights and inferences on koala conservation from records of koalas arriving to care in South East Queensland

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ABSTRACT

Context. Records collected when sick, injured or dead animals arrive at wildlife care facilities have potential to offer insights into population declines and identify key threatening processes for conservation and management intervention. **Aims.** Records compiled from a centralised Queensland Government database of koala (*Phascolarctus cinereus*) arrivals to care facilities across South East Queensland were analysed to explore long- and short-term trends in arrivals in terms of seasonality, causes, outcomes and spatial distribution, with a particular focus on insights hospital records could provide into the potential role of disease in koala population declines. **Methods.** Analysis was conducted on over 22 years of records of koalas arriving at care facilities collated by the Queensland Government. We summarised causes of hospital arrivals and outcomes. We utilised time-series methods to explore short-term cyclic dynamics in the data, and spatial tools to document changes in the distribution of koala arrivals. **Key results.** In the long term, koala hospital arrivals increased modestly from 1997 to 2014, before falling into decline by 2018. Long-term changes are dwarfed by short-term fluctuations, including clear annual cyclic dynamics associated with car strike and dog attack, which peak from August to October each year, likely coinciding with the onset of the koala breeding season. Seasonality is also detected in disease-associated arrivals. Known severe declines in wild koala populations in South East Queensland, an area of intensive urbanisation and associated loss of koala habitat, are not reflected in the overall koala hospital arrival numbers. Our analysis suggests that severe local declines in wild koala abundance have been obscured by increases in the catchment areas from which koalas are entering the hospital network. **Conclusions.** Koala hospital records provide an extensive dataset that can be mined for insights into koala population dynamics and threatening processes. However, interpretation of our findings must consider limitations and biases inherent in data collection. **Implications.** Despite acknowledged shortcomings in terms of bias and data quality, retrospective analysis of records from care facilities can provide important insights for guiding conservation efforts. For example, our findings with respect to seasonality in koala hospital arrivals mirror results reported for other locales, suggesting that cyclic dynamics are not a local phenomenon, but occur more broadly across the species range, with implications for seasonal delivery of conservation actions.

Keywords: anthropogenic impacts, conservation biology, endangered species, koala, mortality, *Phascolarctos cinereus*, wildlife care, wildlife management.

Introduction

Records of wildlife treated at care facilities can provide novel insights into population declines, allowing the detection of trends in population abundance, or identification of key threatening processes for conservation and management (Mazaris *et al.* 2008; Holderness-Roddam and McQuillan 2014; Schenk and Souza 2014). For example, analysis of records of small birds and mammals admitted to a care facility in Virginia, USA, allowed the identification of species most at risk of predation by free-roaming cats, and provided insights into potential interventions to reduce cat-related mortality (Mcruer *et al.* 2017).

Similarly, records of turtles entering care in North Carolina have highlighted the importance of trauma related to vehicle strike, garden equipment and fishing equipment as sources of mortality in wild turtle populations (Stranahan *et al.* 2016), while otter fatality records in the UK have highlighted the significance of road mortality and informed management to improve road-crossing design (Philcox *et al.* 1999). Records of wildlife carers have been analysed to demonstrate the effectiveness of rehabilitation, and highlight threats to wild flying fox populations (Mo *et al.* 2021). The use of care records to inform conservation and management is especially appropriate for charismatic species with high reporting rates and established facilities for care, such as the koala (*Phascolarctus cinereus*) (Tisdell and Nantha 2007).

The koala is an arboreal marsupial endemic to the eastern coast of Australia. Koala populations in Queensland, New South Wales and the Australian Capital Territory (ACT) were listed as Endangered under the *Environmental Protection and Biodiversity Conservation Act* in February 2022, following evidence of significant declines in abundance (Department of Agriculture Water and the Environment 2022). In South East Queensland (SEQ), a former stronghold for koala populations undergoing rapid urbanisation, a 2015 study concluded that two key populations (the Koala Coast and Pine Rivers) had declined by 80.3% and 54.3% respectively between 1996 and 2014 (Rhodes *et al.* 2015).

Numerous contributors to koala population declines have been recognised, including habitat loss, car strike, dog attack, disease, bushfire and drought (Griffith *et al.* 2013; McAlpine *et al.* 2015; Gonzalez-Astudillo *et al.* 2017). A 2011 study analysed a radio-tracking data set and population density and abundance estimates for the Koala Coast population to quantify mortality rates due to dog attacks, vehicle strikes and disease; the authors concluded that koala population declines were multifactorial, and any conservation actions that focussed solely on one cause of mortality would not halt them (Rhodes *et al.* 2011).

In recent years, the role of infectious disease in driving wildlife population dynamics has been recognised (McCallum 2012). Koalas can often be infected by bacteria in the family *Chlamydiaceae*, in particular *Chlamydia pecorum* and *C. pneumonia* (associated with urogenital, ocular and respiratory disease; Weigler *et al.* 1988; Hulse *et al.* 2021), retroviruses (KoRVs; Denner and Young 2013), trypanosomes (McInnes *et al.* 2011) and herpesviruses (Vaz *et al.* 2011, 2012). More recent work has suggested that co-infection by *C. pecorum* with high detected loads of a particular KoRV subtype (KoRV-B) may be associated with disease (Waugh *et al.* 2017), demonstrating the complexities of disease in koalas. However, the role of infectious disease in actually driving koala population dynamics is still controversial (McCallum *et al.* 2018), with a recognised lack of studies examining the population-level impacts of disease on koalas (Grogan *et al.* 2017, 2018).

The public appeal of the koala leads to high public reporting rates when sick and injured animals are sighted, and has resulted in the care of sick and injured koalas with government, private sector and charitable funding for koala 'ambulance' services and specialised treatment facilities ('koala hospitals'), in addition to local veterinarian clinics and carers. Records of koalas arriving at hospitals and other care facilities have the potential to be interrogated to provide insights into koala population dynamics. For example, a retrospective analysis of koala arrivals to a hospital in coastal New South Wales examined 30 years of arrival records to demonstrate an increasing relative risk to koalas from vehicle strike, with the authors arguing that such insights can be used to inform future conservation policy development (Griffith *et al.* 2013).

In SEQ, records of koalas arriving at koala hospitals and other care facilities are submitted to the State Government in line with the *Nature Conservation (Koala) Conservation Plan 2006 and Management Programme 2006–2016*. Prior to 2014, records were collated into what is colloquially known as the 'Moggill Koala Hospital Database' by the state government agency implementing the plan (at the time of writing, the Queensland Department of Environment and Science). Since 2014, a majority of the older records from the Moggill Koala Hospital Database were ported across to a new system, 'KoalaBASE' (www.koalabase.com.au). Following a transition period, new records are now uploaded directly to KoalaBASE. Subsets of these records, limiting the years analysed or number of koalas assessed, or omitting records with missing data, have been examined for various purposes, such as, for example, to quantify rescue and rehabilitation outcomes (Burton and Tribe 2016). They have also been utilised to examine aetiologies associated with hospital arrivals and identify spatiotemporal hotspots where koalas were at high risk of injury or disease (Gonzalez-Astudillo *et al.* 2017). A related study has reported results of 519 necropsies of koalas passing through this system and has provided increased understanding of the role of disease and comorbidity in hospital arrivals (Gonzalez-Astudillo *et al.* 2019).

Rather than focusing on subsets, we elected to examine all available data, that is, over 22 years of records of koalas arriving at care facilities, as provided by the Queensland Government (January 1997–June 2019), including problematic records. We first report causes of hospital arrivals and outcomes, allowing comparison with existing studies. We then use time-series and spatial methods to explore long-term changes in the distribution of koalas entering the care system. Trends in the rapidly urbanising SEQ region are of interest in comparison to changes in koala populations in coastal New South Wales as reported by Griffith *et al.* (2013). Further, given significant reported declines in koala population abundance in South East Queensland (Rhodes *et al.* 2015), and current interest in the role of infectious diseases in driving these declines (McCallum *et al.* 2018), we were particularly interested in any insights koala hospital records could provide into declines and the potential role of disease in driving these declines.

Methods

This analysis examined 29 442 records for koala arrivals (including dependent pouch young arriving with mothers) to South East Queensland treatment facilities from 1 January 1997 to 27 June 2019. These records were compiled from three extracts of the older Moggill Koala Hospital Database, plus one extract from the new KoalaBASE database; records were cleaned and cross-checked to remove duplication. Although more recent records would be welcome, there are issues with data collection and compilation that limited analysis to 2019. It is important to note that data quality is inconsistent, as might be expected for records collected over 22 years. Records are for koala arrivals to four major facilities (Australia Zoo Wildlife Hospital, Moggill Koala Hospital, Currumbin Wildlife Sanctuary and Royal Society for the Prevention of Cruelty to Animals (RSPCA) animal care centres), and a number of veterinary practises and wildlife carers. Note also that although this dataset includes further records from veterinarians and wildlife carers in addition to wildlife hospitals, we will use the term 'hospital arrival' to denote arrivals to any of these facilities.

The date and circumstances of each hospital arrival were recorded. Information such as sex, size (adult, subadult or joey), and presence or absence of pouch young, were generally included in each record. Other potentially useful information such as weight and tooth wear (of use in ageing koalas; Gordon 1991) was not consistently recorded, so was not considered further.

Not all arrivals received veterinary assessments, and it is not necessarily clear from records which animals received assessments, nor whether any assessments that are recorded were conducted by veterinarians. The explicit cause of hospitalisation was not recorded; instead a number of indicative associations (disease, car strike, dog attack, wasting, injured and other cause) were attributed to arriving koalas. A single individual could be hospitalised with multiple associations. The exact nature of any 'injury' was typically not specified in records, but could be due to car strike or dog attack, or from falls or attacks from other animals (e.g. birds, cows). Similarly, the nature of any 'disease' was not specified, but in most cases, can be assumed to refer to chlamydial disease with observed clinical signs, including conjunctivitis, urinary and reproductive tract disease, and rhinitis/pneumonia (Blanshard and Bodley 2008; Polkinghorne *et al.* 2013). Wasting generally refers to animals with poor body condition; this may be associated with reduced nutrient uptake (i.e. starvation through failure to successfully forage) and/or increased nutrient loss (i.e. associated with infection, or high energy expenditure because of increased foraging effort).

For records prior to November 2015, outcomes for each koala arrival were noted. Koalas may have arrived dead (dead-on-arrival) or died while in hospital. Alternatively, a koala could be released without treatment, treated, or euthanised.

We conducted analysis of these records using the R statistical software package ver. 3.6.1 (R Core Team 2014). Koala arrivals were aggregated by month for analysis, using the R package 'zoo' (Zeileis and Grothendieck 2005) and we conducted basic comparisons using Chi-squared tests and linear regression. We decomposed arrival data for time-series analysis using a smoothed spline, with the number of knots used equal to the number of years in the time series, to identify long-term and seasonal trends. Disease- and wasting-associated arrival data were similarly detrended for subsequent wavelet analysis. Alternative de-trending methods (e.g. moving averages) did not significantly alter the results. Wavelet analysis was conducted using the R package 'WaveletComp' (Roesch and Schmidbauer 2014).

Owing to Queensland Government concerns over privacy, the location where koalas were found was not provided to us for analysis. Instead, data were analysed spatially by aggregating by postcode. Aggregating by post code allowed us to examine changes in hospital arrival numbers at a finer spatial scale, to see whether patterns detected in our analysis were true across the entire area from which koalas entered the hospital network. The postcode location from which koalas entered the hospital system was recorded for only 44% of arrivals. We created spatial plots to examine spatiotemporal changes in postcode areas from which koalas enter the hospital network, using the 'tmap' package in R. We aggregated data into the following four time periods: 1997–2002; 2003–2008, 2009–2014 and 2015–2019; note that records were available only until June 2019.

Results

Disease was the leading association noted as present for koala hospital arrivals in South East Queensland, being associated with 48% of arrivals, followed by injury (27.3%), car strike (26.9%), wasting (26.4%), and dog attack (8.9%).

Individual koalas were frequently associated with multiple causes of hospitalisation (Fig. 1). These generally clustered into two groups, namely, arrivals associated with disease and wasting versus arrivals associated with trauma (dog attacks, car strikes and injury). Disease and wasting were highly associated (87.6% of 7769 koalas classified as wasted were also classified as suffering disease, and 48.2% of 14 131 disease admissions were also classified as wasted). There was a minimal overlap between arrivals associated with dog attack and and those with car strike; only 0.46% of 2615 dog attack-associated arrivals were also associated with car strike. Other associations were of interest; 2.8% of disease-associated

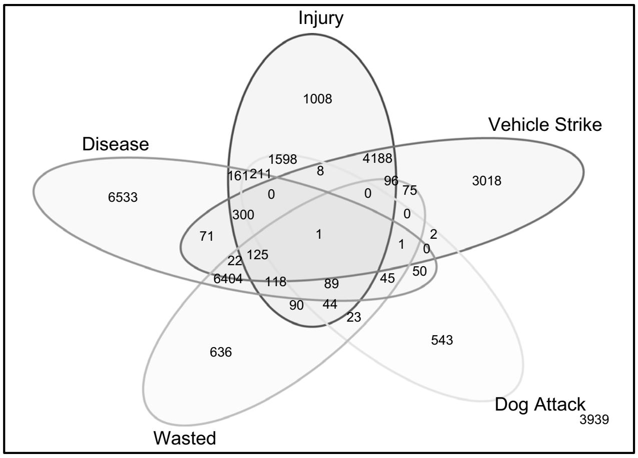

Fig. 1. Venn diagram representation of cause of hospitalisation. Individual koalas were frequently associated with multiple causes of hospitalisation.

arrivals were also associated with dog attack, whereas 3.7% of disease-associated arrivals were also associated with car strike. Conversely, 15.2% of dog-associated arrivals, and only 6.6% of car-associated arrivals were also associated with disease. Only 6.6% of dog-associated arrivals, and 4% of car-associated arrivals were also associated with wasting. In total, 3939 koalas arriving at hospital had no recorded cause of hospitalisation (13.4%).

Over the period of time covered by these records, male and female koalas presented in roughly similar numbers (12 660 and 11 935 respectively, with 4827 arrivals with no gender recorded). The proportion of females arriving at hospital associated with disease (0.525) was significantly ($\chi^2 = 221.72$, d.f. = 1, $P < 0.001$) higher than that of males (0.43). Similarly, a significantly ($\chi^2 = 41.2$, d.f. = 1, $P < 0.001$) greater proportion of females (0.25) than males (0.218) arrived described as wasted. Conversely, a higher proportion of males arrived at hospital as a result of car strike (0.318 vs 0.221; $\chi^2 = 294$, d.f. = 1, $P < 0.001$) and injury (0.319 vs 0.25; $\chi^2 = 163.69$, d.f. = 1, $P < 0.001$). There were no significant differences in the proportion of males or females arriving at the hospital because of dog attack (0.091 vs 0.096; $\chi^2 = 1.462$, d.f. = 1, $P = 0.227$).

With respect to long-term trends in koala hospital arrivals (Fig. 2*a*), arrivals rose modestly, from an average of 93.3 hospital arrivals per month in 1997 to an average of 124.6 per month in 2011 (116.3% of 1997 arrivals), before falling back down to 89.3 per month in 2018 (83.3% of 1997 levels). This year-to-year variation in arrivals is dwarfed by observed intra-annual variation in arrivals (Fig. 2). Linear models, using year (continuous) and month (categorical) to predict koala arrivals, suggest that year is not a significant predictor ($F_{1,257} = 2.66$, $P = 0.1$), whereas month is a significant predictor ($F_{11,257} = 52.04$, $P < 0.001$).

Koala hospital arrivals showed a clear cyclic pattern, with a period of 12 months (Fig. 3*a*). Cyclic dynamics were primarily driven by increased arrivals of koalas associated with car strike and dog attack (Fig. 3*b*, *c*). As expected, because of the degree of co-association between these causes of

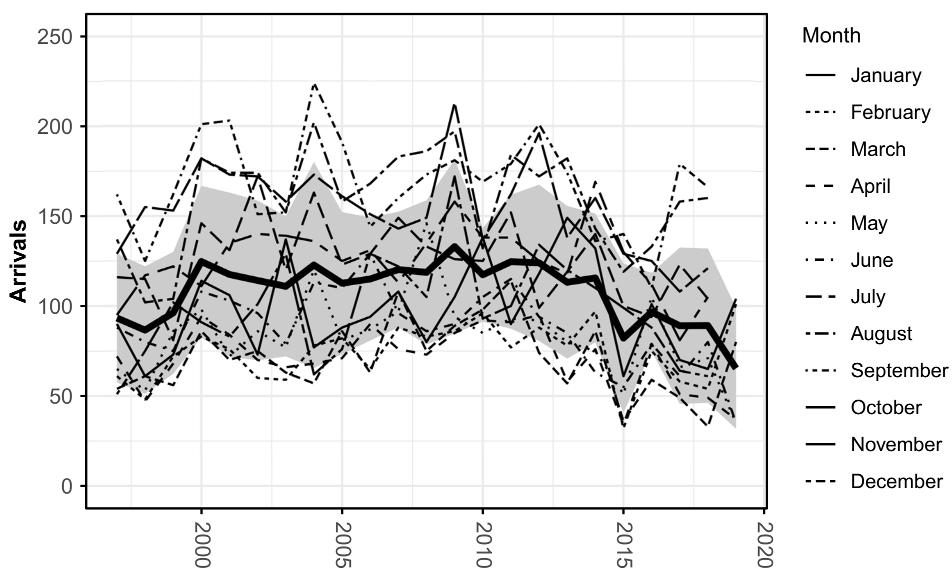

Fig. 2. Long-term changes in koala hospital arrivals. Monthly variation in hospital arrivals dwarfs annual changes, both in terms of average arrivals per month (thick black line), and on a monthly basis. Shaded area represents average ± s.d. Note that the decline in average arrivals per month in 2019 is biassed by the absence of data following June, including the typical annual peak of koala arrivals.

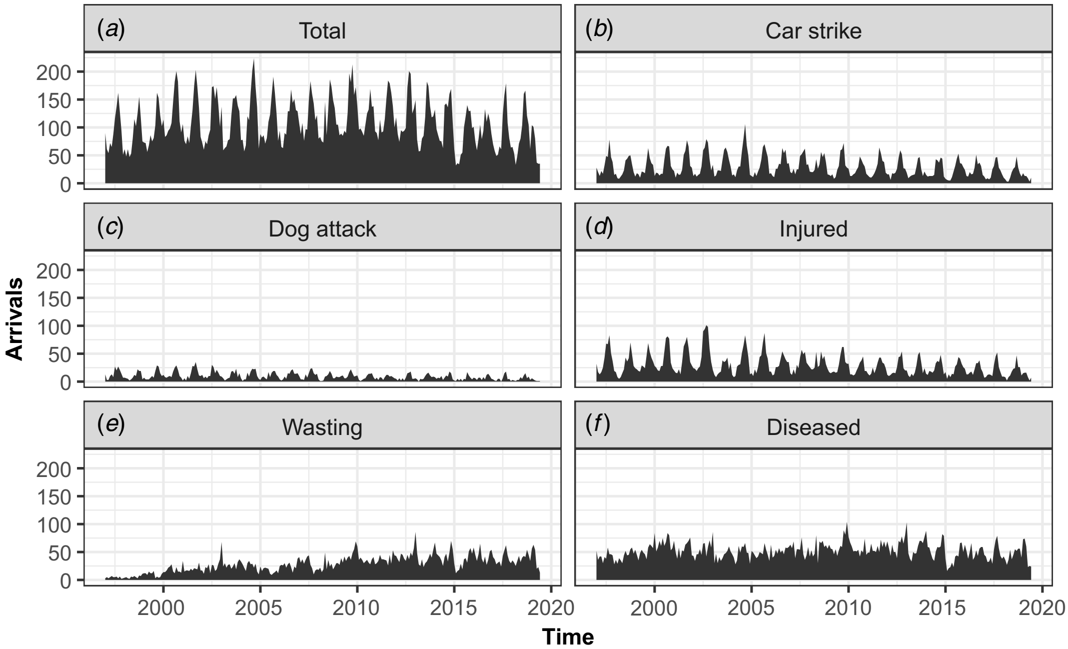

Fig. 3. Koala hospital arrivals 1 January 1997 to 27 June 2019: (*a*) total arrivals, (*b*) car strike-associated arrivals, (*c*) dog attack-associated arrivals, (*d*) injury-associated arrivals, (e) wasting-associated arrivals, and (*f*) disease-associated arrivals. Individual koalas were frequently associated with multiple causes of hospitalisation.

hospitalisation, these cycles are mirrored in injury-associated hospital arrivals (Fig. 3*d*). Arrivals associated with wasting did not display cyclic dynamics, instead exhibiting a steady increase through time (Fig. 3*e*).

Arrivals associated with disease did not, *prima facie*, suggest cyclic dynamics (Figs 3*f*, 4*a*). However, wavelet analysis confirmed the presence of annual cyclic dynamics in disease-associated koala hospital arrivals from September 2000 to December 2004 and from June 2007 to August 2019 (Fig. 4*b*). The cycles had a period of 9–14 months (autocorrelation with a lag of 12 months: $r^2 = 0.306$, d.f. = 256, $P < 0.001$; Fig. 4*c*). These cycles were also apparent in disease-associated arrivals when arrivals also associated with dog attack and/or car strike were omitted (i.e. these cycles were not simply a product of co-associations with trauma-associated arrivals). Arrivals associated with wasting exhibited a steady increase through time, but time series analysis on detrended wasting arrival data again detected weak cycles with a period of 11–12 months (autocorrelation on detrended data with a lag of 12 months: $r^2 = 0.153$, d.f. = 256, $P = 0.014$).

Cyclic dynamics in koala hospital arrivals displayed a peak roughly occurring between August and October each year. A corresponding, but less marked peak was observable in disease-associated hospital arrivals, which lagged behind the peak in car-associated and dog-associated hospital arrivals by 1 month (maximum cross-correlation occurs with a lag of 1 month: $r^2 = 0.377$, d.f. = 267, $P < 0.001$ and $r^2 = 0.355$, d.f. = 267, $P < 0.001$ respectively).

Outcomes for koala hospital arrivals could be identified for 24 379 arrivals prior to December 2015. In total, 29% of arrivals were either dead-on-arrival (including animals dead when found, but sent to a koala hospital for post-mortem analysis) or died before release. An additional 38.3% of arrivals were euthanised in care, 22.5% of arrivals received veterinary treatment, and 8.7% were released without treatment, often after a veterinary assessment.

In comparison with females, a significantly higher proportion of male arrivals resulted in mortality (including dead-on-arrival, and dead before treatment; 0.113 vs 0.083; $\chi^2 = 127.3$, d.f. = 1, $P < 0.001$) or treatment (0.258 vs 0.178; $\chi^2 = 236.93$, d.f. = 1, $P < 0.001$). Conversely, a significantly higher proportion of female arrivals resulted in euthanasia than for males (0.443 vs 0.3; $\chi^2 = 551.67$, d.f. = 1, $P < 0.001$). Euthanasia was the predominant outcome for disease-associated hospital arrivals, with 62.5% of all disease-associated arrivals ending in euthanasia. In comparison, only 20% of car-associated, and 27.4% of dog-associated arrivals resulted in euthanasia (18% of car-associated, and 19.7% of dog-associated arrivals resulted in dead-on-arrival, and dead before treatment outcomes). In total, 78.5% of all euthanasia events were recorded for animals associated with disease.

Wasting- and disease-associated koala arrivals were strongly linked, as noted above. Wasting-associated koalas arriving into care were likely to also be associated with disease (odds ratio = 12.7, $P < 0.001$). The reverse did not hold; whereas the majority of wasting-associated koala arrivals were also associated with disease, disease-associated

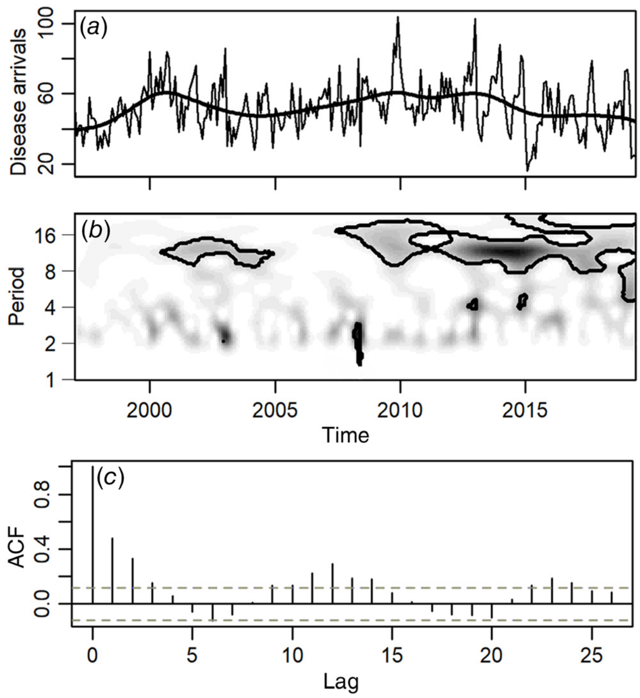

Fig. 4. Disease-associated koala hospital arrivals show evidence of cyclic dynamics: (*a*) monthly time-series plotted with fitted spline depicting long-term changes in arrivals; (*b*) wavelet analysis detected annual cycles (period of ~12 months) from October 1999 to December 2004 and from July 2007 to June 2019; (*c*) a positive auto-correlation was observed, with a lag of 11–14 months.

koalas were far less likely to also be associated with wasting (odds ratio = 0.079, $P < 0.001$). Koalas that arrived at hospital associated with both disease and wasting were significantly more likely to arrive dead, die prior to treatment, or be euthanised following examination, than were those arriving with a disease association but without a wasting association (odds ratio = 3.9, $P < 0.001$). However, this was true for the bulk of wasting-associated arrivals. Irrespective of whether disease-associated or not, 89% of wasting-associated arrivals arrived dead, died prior to treatment, or were euthanised (70.9% are euthanised).

Female disease-associated hospital arrivals were less likely to have arrived with a joey than were non-disease-associated female arrivals (odds ratio = 0.03; $P < 0.001$); 27.5% of female koala arrivals that were not associated with disease were recorded to have a joey, and 8.1% of female koala arrivals associated with disease had a joey. In all, 385 orphaned joeys were included in arrival records. However, outcomes following hospital arrival were recorded only for 58 joeys; 37 died in care, five were euthanised, 13 were released and three were sent to wildlife carers (ultimately one died and two were released).

Two noteworthy trends can be drawn from a spatial analysis of the available data (Fig. 5). The number of postcode areas from which koalas entered hospitals rose from 145 in 1997–2002, to 176 in 2003–2008 and 192 in 2009–2014, before falling to 181 postcode areas in 2015–2019. At the same time, the average number of koalas from each postcode area fell, from 51.4 koalas in 1997–2002, to 44.4 in 2003–2008, 43.2 in 2009–2014, and 25.8 in 2015–2019. The majority of koala hospital arrivals come from urban areas close to Brisbane. Trends in arrivals for two key koala populations, the Koala Coast and Pine Rivers (as identified in Rhodes *et al.* 2015), are noteworthy; in the Koala Coast, arrivals are high in 1997–2002 and 2003–2008, but fall noticeably in 2009–2014 and 2015–2019; in Pine Rivers, arrivals are not high initially (1997–2002), but increase (2003–2008 and 2009–2014) before falling in 2015–2019 (Fig. 5, insets).

Discussion

Koalas arrive at South East Queensland koala hospitals for a variety of reasons. These have been classified as disease, car strikes, dog attacks, injury and wasting. There has been little long-term change in the broad numbers of koalas arriving at hospital facilities since 1997, especially relative to the significant annual cyclic dynamics observed in the data. In light of reported declines in koala populations throughout South East Queensland, in particular reported declines of 80.3% and 54.3% in two key populations (Rhodes *et al.* 2015), this initial result appears surprising. However, analysis of the data at finer spatial scales shows clear evidence of localised declines.

Cyclic dynamics in car- and dog-associated arrivals are readily apparent in hospital statistics, with an observed peak corresponding to the koala breeding season in August to October (Lee and Martin 1988). The result matches prior observations of increases in hospital arrivals during the breeding season, both in the same population (Gonzalez-Astudillo *et al.* 2017) and in New South Wales koala hospital arrivals (Griffith *et al.* 2013). During this time, koalas (males in particular) are increasingly mobile because they search for mating opportunities. Increased mobility is likely to expose koalas to more frequent encounters with vehicular traffic and dogs (Griffith *et al.* 2013), resulting in increased hospital arrivals.

Increased activity of koalas during the breeding season and therefore increased encounter/detection rates may also be responsible for observed cyclic fluctuations in disease-associated arrivals. Koalas with clinical signs of disease may be more likely to be spotted and reported when on the move. Alternatively, a link between stress and clinical manifestation of chlamydial disease in koalas has long been postulated, although the direction of this link is open to conjecture (McAlpine *et al.* 2017; McCallum *et al.* 2018; Narayan 2019).

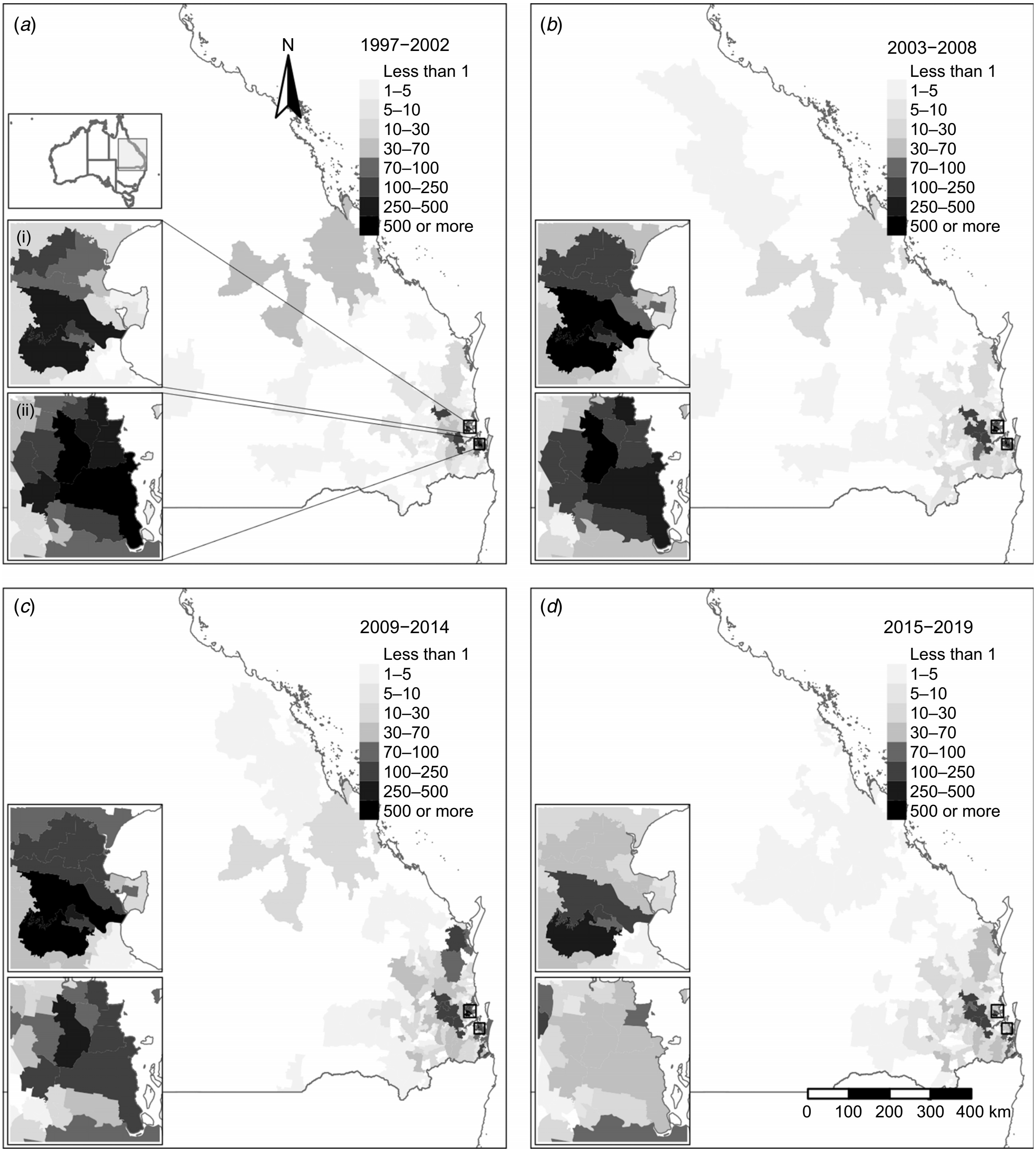

Fig. 5. Koala hospital admissions by post-code area from (*a*) 1997–2002, (*b*) 2003–2008, (*c*) 2009–2014, and (*d*) 2015–2019. Inset maps highlight changes in (i) the Pine Rivers region, and (ii) the Koala Coast region.

Chlamydia is widespread in koala populations and individuals can be infected without exhibiting signs of clinical disease (Polkinghorne *et al.* 2013). Additionally, the relationship between clinical signs of disease and intensity of infection can be poor (Wan *et al.* 2011). While limited evidence of a link between stress and clinical disease has thus far been reported (McAlpine *et al.* 2017), cyclic dynamics in koala hospital arrivals are consistent with a hypothesis that stress exacerbates disease progression in koalas. Increased metabolic demands during the breeding season may reduce immune function in infected koalas, leading to the transition of subclinical infection into clinical disease during periods of increased reproductive activity. An alternative hypothesis, namely that disease-associated hospital arrivals exhibit cyclic dynamics because of co-associations with increased car-strike and dog-attack arrivals during the breeding season, is less plausible, given the presence of cyclic dynamics in koalas arriving without such co-associations.

While arrivals associated with car strike and dog attack drop off substantially outside the breeding season, disease-associated arrivals remain comparatively high throughout the year, and predominate arrivals outside of the breeding season. However, complicating the interpretation of these results is the absence of any data relating to disease severity; koalas arriving at hospital with mild disease, or even subclinical infections (where tested), are recorded the same as koalas arriving with debilitating disease. We therefore do not at present have the data necessary to determine whether average disease severity was greater during periods of reproductive stress (the breeding season). The lack of accurate data on the age of presenting animals also reduces any inferences we can make about the role of disease in koala population dynamics (koalas are currently reported only as juveniles, subadults and adults).

In contrast with other associations, arrivals associated with wasting exhibit a marked increase over the period for which records were available. An explanation may be changes in record keeping; increased records of wasting animals may reflect a developing recognition from record keepers that wasting was an important concern. Increased wasting may, alternatively, be driven by reduced food availability through time. South East Queensland has been an area of significant human population growth and urban development (Spearritt 2010; State of Queensland Department of Infrastructure 2017). Rapid urban growth has expanded into surrounding areas, leading to what one commentator has dubbed the '200-kilometre city' (Spearritt 2010), and resulting in a significant loss of habitat and food resources for koalas. Pointedly, wasting-associated arrivals have the poorest outcomes, with very few koalas being indicated as receiving treatment and release.

Wasting may be associated with more severe disease, but it is difficult to draw such conclusions with certainty from the present data. However, the strong co-association of wasting and disease in koalas arriving into care may be suggestive of synergies, namely, disease can mediate wasting because of decreased nutrient uptake (i.e. interference with foraging) or increased nutrient loss. Alternatively, nutritional stress and wasting owing to habitat loss and fragmentation may exacerbate infection and shift subclinical infections towards clinical disease.

It is difficult to determine whether the co-association of wasting and disease is indicative of increased disease severity. Koalas arriving into care associated with both disease and wasting are more likely to arrive dead, die prior to treatment, or be euthanised following examination than are those koalas arriving associated with disease but not wasting. However, this is unsurprising, because wasting has poor outcomes, irrespective of disease status. Additionally, body condition can be an important criterion in euthanasia decision algorithms in koala hospitals. For example, koalas with evidence of ovarian cysts and a poor body condition score may be euthanised, even in the absence of other clinical signs of disease (Loader 2010). This decision is largely driven by Qld Government legislation, which requires that 'koalas that cannot make a contribution to the ongoing reproductive success of the species' are not released following treatment (*Nature Conservation (Koala) Conservation Plan 2006 and Management Programme 2006–2016*).

Although koala numbers in Queensland are in obvious decline (Rhodes *et al.* 2015; Department of Agriculture Water and the Environment 2022), that decline has not been reflected in the overall SEQ-wide koala hospital arrival numbers, as would be expected. Between 1997 and 2014, there was an increase in the total 'catchment' from which koalas entered in SEQ koala hospital records, suggesting that hospital arrivals were being maintained by bringing in koalas from wider geographic areas. This could be driven by expansion of habitat loss and destruction for the development of new suburbs, but is also likely to be a result of operational changes whereby more areas have started sending sick and injured koalas to the major koala hospitals around Brisbane. This trend appears to have been reversed in more recent years, with the catchment in 2014–2019 shrinking, and some suggestion that hospital arrivals have been falling since 2015. In particular, koala arrivals from the Koala Coast region, a former stronghold of koalas in South East Queensland, severely diminished in 2014–2019, with arrivals from the Pine Rivers region following a similar trajectory, reflecting reported declines in those areas. This suggests a need to consider koala hospital data at an appropriate scale. Increases in the catchment from which koalas enter the hospital network have meant new sources of koalas entering the system; the addition of koalas from these new areas have offset the reduction of koala hospital arrivals from original strongholds. From a broad overview of the koala hospital data (looking at total hospital arrivals), changes in catchment size have obscured fine-scale changes in local koala population dynamics. Severe declines at a local scale may be offset by increased arrivals from an expanding catchment. Continuing analysis of future records, with greater consideration of issues of scale, may help shed light on long-term trends in this population.

Records of wildlife arriving at care facilities can provide important insights into population dynamics and drivers of population declines. However, careful consideration must be given to inherent biases and quality issues of such data. The most obvious potential cause of bias in this dataset is that records of hospital arrivals may not reflect the broader situation for koalas in the wild. For instance, the frequency of dog attack (9.2% of arrivals) is likely to be under-represented in the koala hospital database. Unlike car strike, where a human driver is present and able to report any incidents, dog (particularly wild dog) attacks may happen in the absence of humans, and thus may be less likely to be reported. Long-term monitoring of a radio-collared koala population in the northern suburbs of Brisbane between May 2013 and June 2016, as reported in a June 2016 update, suggests that 121 of 281 koala deaths were the result of dog attack, with a further 38 deaths being categorised as 'suspected wild dog predation' (Queensland Department of Transport and Main Roads 2016). That would represent a mortality of 43–57% owing to dogs (if we assume the suspected attacks were actual dog attacks), which is significantly higher than that inferred from analysis of hospital records. Whereas hospital data may provide insights into threatening processes, it is important to consider how such biases in arrivals and data collection may skew results.

Another obvious difficulty in using hospital data to infer population trends is the question of data quality. The 2014 migration to KoalaBASE triggered a review of koala record management (Gonzalez-Astudillo *et al.* 2017). However, incomplete and inconsistent records remain an issue. Useful data such as weight, tooth wear, and the outcomes of hospitalisation were unfortunately not available for a sizeable number of records. More notable, recorded associations attached to koala arrivals at hospital do not necessarily indicate the actual cause of hospitalisation and/or death. For instance, one koala in this dataset arrived associated with car strike, dog attack, injury, wasting and disease. The notes on this individual confirm 'injuries consistent with being hit by car as well as dog attack', as well as evidence of cystitis and wasting. The actual cause of death was not recorded; any one of these may have been the true cause of death.

Typically, determination of the cause of death would require post-mortem examination by a veterinary pathologist. However, for many records it is unclear whether a veterinary assessment was provided. Additionally, few of the koalas included in this dataset were given a post-mortem examination and so there are obvious concerns about the attribution of a cause of death. Outcomes of post-mortem examinations were, if available at all, summarised in a few words, and there was no recorded grading of disease severity, so we have no capacity to discriminate between mild and severe cases of clinical disease. No data were recorded on koala body condition (beyond simply an indication of 'wasting'), such as a body condition score (Jackson 2007), or other metrics that might allow calculation of body condition (e.g. weight, head and/or body length), despite recognition of the importance of body condition for disease status, rehabilitation and management (Gonzalez-Astudillo 2018). Limited diagnostics were conducted to determine the species/strain of chlamydia present, or to test for the presence of KoRV subtypes or other disease agents.

Although there are notable issues with bias and accuracy, records from wildlife care facilities can provide a wealth of information to inform conservation and management. For instance, this analysis has reaffirmed the significant increase in hospitalisation and mortality of koalas from car strike and dog attack during the breeding season. Given this phenomenon appears to be a universal problem in areas where urbanisation infringes on koala habitat, increased public education at this time, and increased action to actively reduce car strike and dog attack could have profound benefits for koala populations. This analysis has also detected cyclic disease dynamics, perhaps suggestive of stress mediating the onset of clinical disease. Co-associations between disease and wasting also provide new questions for researchers and conservation managers to address.

Importantly, our analysis has further shown some limitations in the use of hospital data to monitor wildlife populations. In this case, koala hospital arrivals do not adequately reflect declines in wild koala populations observed from field studies, unless careful consideration is given to issues of scale. Changes in the catchment from which koalas enter the records obscure changes in population abundance, because the addition of arrivals from further afield offset diminishing numbers closer to Brisbane.

Our analysis would be significantly strengthened by improved data collection, in particular to help address the impact of disease on koala populations. Increased reporting of disease severity and body condition (including weight, and head and/or body length), along with potential measures of koala age (such as tooth wear), would significantly strengthen inferences from hospital arrival data and may also provide insights into the role of stress in the onset of chlamydial disease. Additional useful information would include definitive records of which animals received veterinary assessments, post-mortem results (adding definitive cause of death), and outcomes of hospital arrival. Although there may be budgetary constraints, given the current interest in the potential role of KoRV infection in koala disease dynamics, routine use of diagnostic procedures to determine the species, strain and/or subtype of disease agents would also greatly increase our knowledge of the role of these pathogens in driving koala population dynamics.

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Data availability. Data used for analysis in this study were collated by the State of Queensland, Australia, through the Department of Environment and Science. An extract of the data is available at https://www.data.qld.gov.au/dataset/koala-hospital-data. This analysis used a more complete data set obtained through a data licencing agreement with the Department of Environment and Science.

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