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WILDLIFE RESEARCH

An 8-year long retrospective analysis identifies the major causes of morbidity and mortality in rescued koala joeys

Harsh Pramila Pahuja[A,*] and Edward Jitik Narayan[A,*]

For full list of author affiliations and declarations see end of paper

*Correspondence to:
Harsh Pramila Pahuja
School of Agriculture and Food Sciences, Faculty of Science, University of Queensland, St Lucia, Qld 4072, Australia
Email: uqhpahu1@uq.edu.au;
Edward Jitik Narayan
School of Agriculture and Food Sciences, Faculty of Science, University of Queensland, St Lucia, Qld 4072, Australia
Email: e.narayan@uq.edu.au

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ABSTRACT

Context. Wildlife rescue and rehabilitation centres aid millions of species worldwide. The clinical databases from these wildlife rehabilitation centres are increasingly being recognised as valuable scientific resources that have the potential to yield information on animal biology and inform conservation efforts. Although orphaned koala joeys constitute a substantial proportion of wildlife rescues in Australia, the causes of morbidity and mortality, specifically in rescued young koalas, remain largely unexplored. **Aims.** The primary aim of this study is to analyse the trends in causes and outcomes of koala joeys admitted for rehabilitation at the Adelaide Koala Wildlife Centre (AKWC). **Methods.** We analysed the hospital records of koala joeys admitted to the AKWC over an 8-year period (2014–2021) to identify the major causes of morbidity and mortality, and analysed the trends in arrivals in terms of season, sex and release rate. **Key results.** Our examination indicates that the top five major reasons for admission and mortality in koala joeys are as follows – renal disease, heat stress, chlamydiosis, animal attack and vehicle collision. A significant increase in the proportion of heat stress, renal disease and chlamydiosis cases can be observed over the study period. Of the major causes of mortality, the most distinctive feature is the exceptionally high mortality rate of koala joeys with renal disease. Over the study period, the overall positive outcome for all joeys increased up to two-fold, and the mortality rate also declined slightly. **Conclusion.** Despite the significant increase in positive outcome, it is evident that renal disease, chlamydiosis and heat stress are increasing at a rapid rate. Renal disease poses a major threat to rehabilitating koala joeys due to its severely high mortality rate. **Implication.** This is the first study identifying the key drivers of morbidity and mortality of rescued koala joeys, and the rapid increase of renal disease, chlamydiosis and heat stress warrant the attention of future conservation policy developers. Furthermore, the severely high mortality rate of koala joeys due to renal disease warrants improving treatment protocols and any measures that can help reduce the mortality rate of this disease in koala joeys.

Keywords: aetiology, chlamydiosis, heat stress, koala joey rescue, mortality, oxalate nephrosis, renal disease, retrospective analysis, vehicle collision.

Introduction

Rescue and rehabilitation of wildlife is a growing noble service across the globe, aiding millions of wildlife species worldwide (Tribe and Brown 2000; Wimberger *et al.* 2010; Barnes 2017; Pyke and Szabo 2018*a*; Romero *et al.* 2019; Cope *et al.* 2022). Wildlife rescue refers to attending to an injured animal and/or getting an animal out of danger, whereas rehabilitation refers to the treatment and care of injured, orphaned or sick animals, with the ultimate aim of releasing them back into the wild (Tribe and Brown 2000; Pyke and Szabo 2018*a*; Cope *et al.* 2022). Although the role of rehabilitated and released wildlife in conservation of a particular species is arguable (Saran *et al.* 2011; Hernandez 2019), it is well established that wildlife rescue and rehabilitation centres contribute substantially to supplementation and maintenance of existing populations (Ridgeway 2018; Romero *et al.* 2019). Furthermore, wildlife centres have the potential

to serve as excellent education and fundraising tools by garnering the attention of the media (Tisdell and Nantha 2006; Mo *et al.* 2021; Cope *et al.* 2022).

Every rescue represents an encounter with an individual of a particular species, sex and age at a particular location, date and time, with a particular cause for rescue (Tribe and Brown 2000). These data are generally noted for each case and form the database of a particular wildlife rescue and rehabilitation organisation. Wildlife rescue databases serve as an important tool in identifying the negative impacts of anthropogenic activities [e.g. vehicle collision (Englefield *et al.* 2018), pet attack (Rasmussen *et al.* 2021), lawn mowing (Scheelings 2015)] on wildlife, and for recommending potential measures to improve urban planning to ameliorate the negative consequences of such activities (Taylor-Brown *et al.* 2019). The vast wealth of information contained in wildlife rescue databases is increasingly being recognised as a valuable scientific resource that has the potential to yield information on animal biology and reform conservation efforts (Molina-López *et al.* 2011; Griffith *et al.* 2013; Gonzalez-Astudillo *et al.* 2017; Pyke and Szabo 2018*b*; Narayan and Vanderneut 2019; Taylor-Brown *et al.* 2019; Charalambous and Narayan 2020; Lunney *et al.* 2022*a*; Schlagloth *et al.* 2022). Although there are notable issues with bias and accuracy of this information, records from wildlife care facilities can provide a wealth of information to reform conservation and management practices (Kerlin *et al.* 2023). For example, Griffith *et al.* (2013) conducted a retrospective analysis of 30 years of arrival records to demonstrate an increasing relative risk to koalas from vehicle collisions, and argued to reform future conservation policy development for koalas.

Koalas (*Phascolarctos cinereus*) are arguably one of the most iconic marsupial species in Australia. Despite rampant public concern and care, the International Union for Conservation of Nature (IUCN) status of koala has been updated from 'Vulnerable' (Woinarski and Burbidge 2020) to 'Endangered' in February 2022 (DCCEEW 2022). The Australian Koala Foundation (AKF) report highlights a decline of 37%, 41%, 16% and 31% in koala population across Queensland (Qld), New South Wales (NSW) Victoria (Vic.) and South Australia (SA) respectively, with not even a single region reflecting an upward trend in koala population (AKF 2021). Given the charismatic nature of the koala, sick and/or injured animals are frequently reported when sighted by the public, resulting in increased care of sick and/or injured individuals (Kerlin *et al.* 2023). Wildlife retrospective studies from Qld, NSW and Vic. highlight that over the years, more and more koalas are being rescued and admitted to wildlife hospitals for veterinary attention (Griffith *et al.* 2013; Burton and Tribe 2016; Gonzalez-Astudillo *et al.* 2017; Taylor-Brown *et al.* 2019). The study by Taylor-Brown *et al.* (2019) highlights that koalas are more frequently rescued and brought into care than any other wildlife species. The continuous increase in koala rescues is a result of several synergistic factors, ranging from habitat clearance and fragmentation (Seabrook *et al.* 2003; Gordon *et al.* 2006), to disease (Speight *et al.* 2016; Grogan *et al.* 2018; McCallum *et al.* 2018), to dog attacks and vehicle collisions (Charalambous and Narayan 2020; Schlagloth *et al.* 2022). Furthermore, the key results from these studies highlight that the clinical outcome for the majority of koalas admitted at wildlife hospitals is that they either succumb to their injuries and/or debilitating diseases, or have to be humanely euthanased due to their critical condition (Burton and Tribe 2016; Gonzalez-Astudillo *et al.* 2017; Taylor-Brown *et al.* 2019). High mortality of adult koalas results in increased rescues of young orphans that require intensive care and/or hand-rearing. For example, a study by Taylor-Brown *et al.* (2019) on the impact of human activities on Australian wildlife indicated that 'orphaned' individuals were the second-leading reason for admission among wildlife. Marsupials alone contributed >50% to this category, and among marsupials, koalas were the second-largest group (after possums) that were rescued as orphans. Even though orphaned koala joeys constitute a large proportion of wildlife rescues, the major reasons for joey admission are unknown. Furthermore, as highlighted by Gipp (2004), a large proportion of koala joeys admitted as orphans die while in care, but the reasons for such high rates of mortality are unknown. These factors pose a substantial knowledge gap that warrants detailed scientific investigation. To our knowledge, retrospective evaluation of the causes of morbidity and mortality in rescued koala joeys has not been conducted before.

The primary aim of this retrospective study is to use the information from the Adelaide Koala Wildlife Centre rescue database to identify trends in koala joey rehabilitation in the Adelaide vicinity of South Australia. The key objectives surrounding this research study are to: (1) identify the major reasons (and trends over time) for admission of koala joeys; (2) determine major causes of mortality (and trends over time) of koala joeys while in care; and (3) identify miscellaneous trends with respect to the season, sex, release rate, and if their rescues are influenced progressively by year.

Materials and methods

Animal ethics

Because this research is a desktop-based study involving analysis of the retrospective database, animal ethics was not required.

Study site

The clinical database of rescued wildlife was obtained from the Adelaide Koala and Wildlife Centre (AKWC) (34°96′39.2″S, 138°55′35.0″E). AKWC is a non-profit

organisation (inaugurated in the year 2014) that relies solely on magnanimous financial support and in-kind public donations. AKWC is located in Plympton, which is an inner city suburb of Adelaide. We added the co-ordinates (latitude and longitude) for each koala joey rescue location in the database to visualise the primary study area and to represent the localities covered by the AKWC in a spatial context (Fig. 1).

Data collection

The clinical database of wildlife pertaining to rescued admissions between 1 January 2014 and 31 December 2021 was obtained from AKWC. The database was then restructured to include the clinical data pertaining only to koala joeys rescued throughout the aforementioned period of interest of study. Data pertaining to koala joeys were segregated by using the search function 'joey', and age measure estimates (reported by the veterinarians) were used to exclude all individuals >12 months of age (Gipp 2004). The data were then systematically organised into Microsoft Excel™ with additional information such as sex (male/female/unknown), reason for admission and clinical outcome (died in care/euthanised/released into care/released into the wild/unknown). Clinical outcomes following admission were also grouped into either 'mortality' (died in care and/or euthanised) or 'positive outcome' (release into the wild and/or released into care). Other potentially useful information such as weight on admission, approximate age of the joey, number of days in the hospital, body condition score, etc., were not recorded consistently and were thus not included in the analysis.

Analysis of reason for admission

Reason for admission was initially broadly classified into 'Orphaned (Healthy)', 'Trauma', 'Disease', 'Heat stress' and 'Unknown' categories. Orphaned category refers to joeys that were diagnosed healthy (with no injury and/or disease) and were rescued without the mother and/or whose mother was deceased. Trauma category refers to joeys that were rescued and diagnosed with injuries. Disease category refers to joeys that were rescued and diagnosed with illnesses associated with specific symptoms. Heat stress category refers to joeys that were rescued and diagnosed with reduced food and water uptake resulting in emaciation and dehydration. These categories were then segregated into sub-categories as follows: trauma sub-categories identified in the database include trauma due to animal attack, vehicle collision, burns (potentially due to bushfires) and idiopathic trauma (i.e. trauma caused due to unidentified/unknown reasons); disease sub-categories identified in the database include gastro-intestinal tract (GIT) infection, chlamydiosis, mange, idiopathic disease (i.e. unidentified/unknown disease) and renal disease. GIT infection was associated mainly with examination notes of diarrhoea, bloating and tender

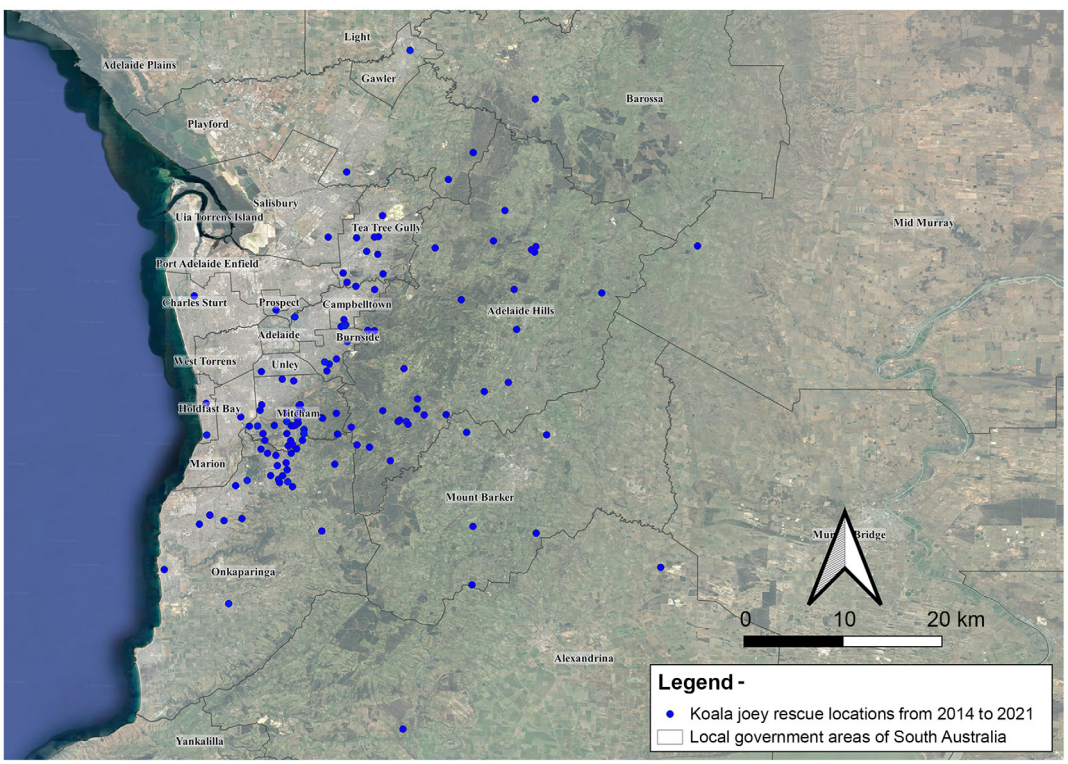

Fig. 1. Spatial representation of koala joey rescues conducted by the AKWC between 2014 and 2021.

abdomen. Preliminary findings from Phillips *et al.* (2018) suggest that *Chlamydia pecorum* is capable of infecting the GIT of koalas, but we could not find any diagnostic and/or examination comments to confirm this finding. Chlamydiosis is a common infectious disease that has a detrimental impact on koala populations throughout Australia (Quigley and Timms 2020). The disease is primarily associated with ocular and/or urogenital infection (Polkinghorne *et al.* 2013). The clinical symptoms associated with ocular chlamydiosis include keratoconjuctivitis, corneal inflammation and ocular discharge (Griffith and Higgins 2012). Urogenital chlamydiosis displays clinical symptoms of cystitis, incontinence and urine scald, colloquially termed as 'wet bottom' (Blanshard and Bodley 2008). Mange outbreaks in South Australian koala populations are associated with the clinical signs of severe hyperplastic and hyperkeratotic dermatitis, thickening and crusting of the skin and deep fissures into the dermis (Canfield *et al.* 1992; Speight *et al.* 2017). These changes can be observed all over the body (including the face, sternum, ventral thorax and the abdomen), but are more prominent in the distal and interdigital areas of the limbs (Speight *et al.* 2017). Renal disease is associated with the insufficient functioning of the kidney, and displays clinical symptoms of weight loss, polydipsia, polyuria and renal deposition of calcium oxalate (oxalate nephrosis), and in extreme cases results in renal failure (Haynes *et al.* 2004). The disease is prevalent in South Australian koala populations (Speight *et al.* 2013*a*, 2019), but is only a minor contributor to poor health in other Australian states (Blanshard and Bodley 2008).

The sub-categories of reason for admission were standardised by following the protocol from Lunney *et al.* (2022*a*) so that there was only one term used for each reason for admission. For example, '*car hit*', '*Hit by car* (*HBC*)', and '*motor vehicle collision*' were all converted and categorised under 'Vehicle collision'. Similarly, 'Animal attack' category comprises both injuries identified as dog and/or cat injuries, and injuries that could not be confirmed as a dog, cat, cow or goanna, but were diagnosed by veterinarians as injuries caused due to some sort of animal attack. The AKWC database included records of examination notes, along with the primary diagnosis of admission. The examination notes were not recorded in a standardised manner, and there was no record of whether blanks in this field represented absence of comorbidity or that it was not assessed. We therefore predominantly based our analysis only on the primary reason for admission, with only supporting information from secondary conditions as mentioned above.

Statistical analysis

Data were imported into Graph Pad Prim v 9.3.1 and reformatted where necessary. Data were assessed for normal/non-normal distribution prior to parametric or non-parametric inferential analyses. To determine the temporal trends across the major reasons for admission and the clinical outcome of rescued joeys, trend lines were generated using simple linear regression with the years on the x-axis and proportion (%) of rescues per year on the y-axis. For data with normal distribution, we calculated the Pearson correlation coefficient, and for data with non-normal distribution, we calculated the Spearman correlation coefficient and used a statistical significance level of 0.05. We performed unpaired t-tests to identify sex-based differences across major admission reasons (parametric) and clinical outcome (non-parametric; Mann–Whitney U-test) of rescued koala joeys.

Ethics approval

This is a desktop only study without any interaction with animals.

Results

Dataset

We studied a total of 214 koala joey admissions to the AKWC and the outcomes of those admissions, from January 2014 to December 2021. Over the study period, the year 2021 accounted for highest number of koala joey rescues (n = 44); however, these numbers are similar to koala joey rescues from the years 2015 (n = 42) and 2016 (n = 41) (Fig. 2*a*). Koala joey rescues were significantly higher (Mann–Whitney U = 702; P = 0.006) from October to March, relative to April to September (Fig. 2*b*). Over the period of time covered by these records, male and female koala joeys were presented in roughly similar numbers (n = 92 and n = 110 respectively, with n = 12 arrivals with unknown/no sex recorded).

Trends associated with clinical outcome

Consistent with the overall increase in admissions over time, the positive outcome of admitted joeys increased substantially between 2014 and 2021. There was a significant positive relationship (r = +0.64; P = 0.043) between the years and the positive outcome of the rescued joeys. A positive caveat to note is that, simultaneous to the increase in positive outcome, the mortality rate of joeys also indicated a slight decline between 2014 and 2021 (Fig. 3). There was a negative correlation between the years and the mortality rate of the rescued joeys (r = −0.31), but the relationship was not significant (P = 0.220). There were no sex-based differences in the clinical outcome of rescued koala joeys (Mann–Whitney U = 6938; P = 0.725).

Reason for admission

The major categories under which koala joeys were rescued during the study period are summarised in Fig. 4*a*.

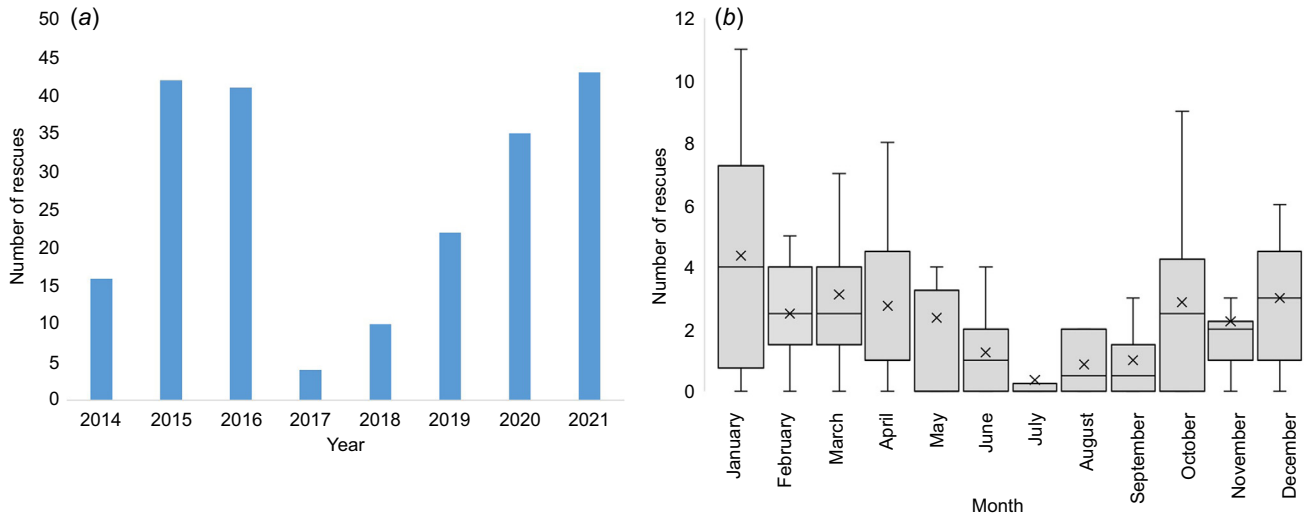

Fig. 2. (*a*) Number of koala joeys admitted at the AKWC per year from 2014 to 2021. (*b*) Box-plot representation of average number of koala joeys admitted at the AKWC per month between 2014 and 2021.

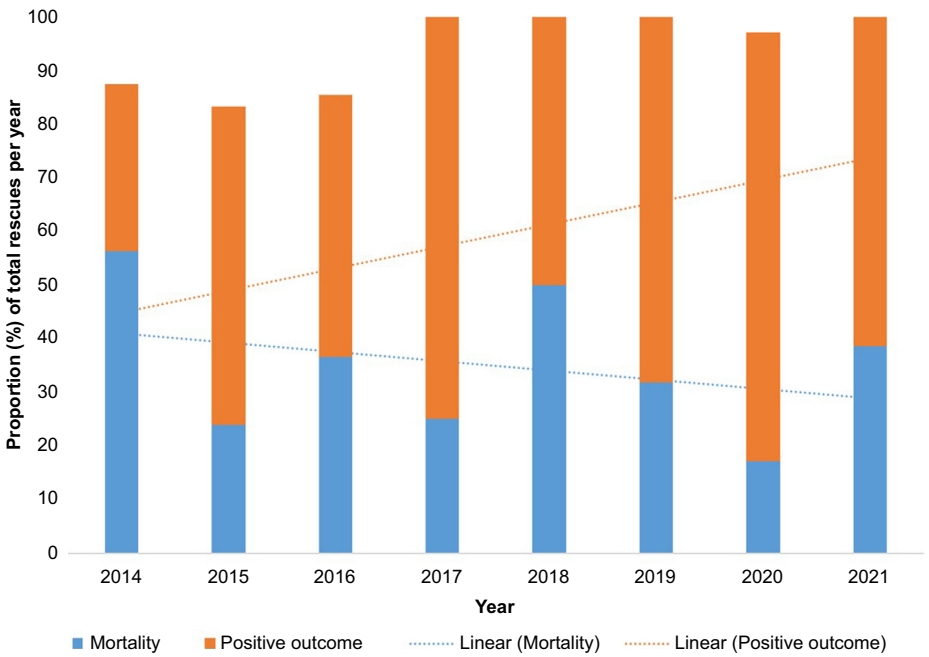

Fig. 3. Trends in the clinical outcome of koala joeys admitted at the AKWC between 2014 and 2021. Proportion (%) of positive outcome refers to individuals that were released into the wild and/or released into care, whereas proportion of mortality encompasses individuals that died in care and/or were euthanised based on welfare grounds. Trend lines are included to highlight the increasing disparity between positive outcome and mortality over the study period.

The majority of koala joeys were rescued as healthy individuals (28.5%) because they were orphaned and needed foster care. The second major category was disease, accounting for 23.8% of all rescues. More than half of the rescues under the disease and infection category were due to renal disease (56.9%). Chlamydiosis was the second leading reason for admission under the disease category, accounting for 23.5% of all rescues (Fig. 4*b*). Trauma was the third major category, accounting for 17.8% of all koala joey rescues. Within the trauma category, koalas were rescued mainly because of idiopathic trauma (i.e. trauma caused due to unknown reasons), accounting for 44.7% of all trauma cases. This was followed by trauma due to animal attack and vehicle collision, which accounted for 26.3% and 23.7% of all

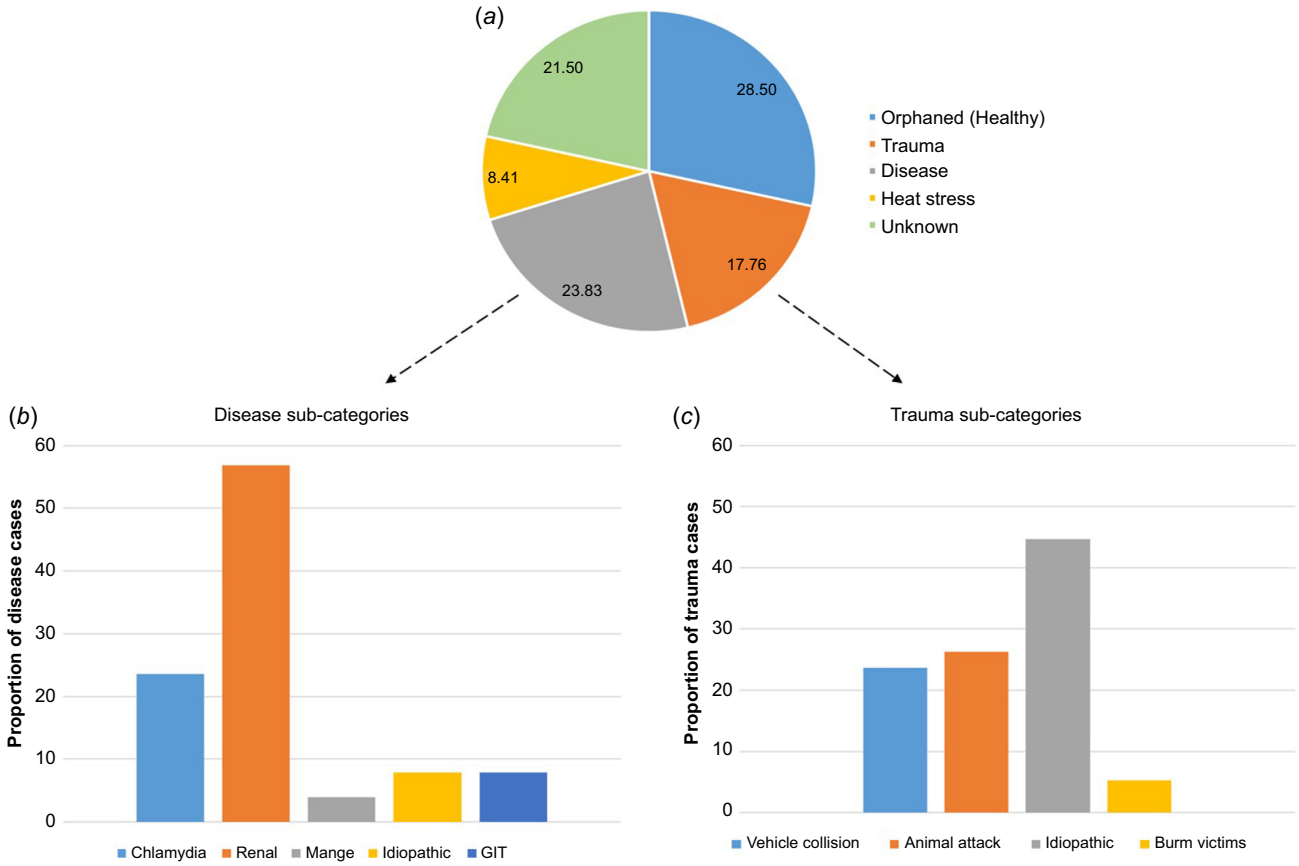

Fig. 4. (*a*) Major categories of cause of admission of koala joeys admitted at the AKWC between 2014 and 2021. (*b*) Proportion (%) of disease sub-categories of koala joeys admitted at the AKWC between 2014 and 2021. (*c*) Proportion (%) of trauma sub-categories of koala joeys admitted at the AKWC between 2014 and 2021.

trauma cases respectively (Fig. 4*c*). The final category of admission was heat stress, which mainly included dehydrated and emaciated joeys. Heat stress category accounted for 8.7% of all koala joey rescues. Note that 21.5% of all koala joeys arriving at the hospital were categorised as 'Unknown', having no recorded cause of hospitalisation. The top five major reasons for admission of koala joeys (after excluding healthy admissions and unknown/idiopathic causes) in descending order were as follows: (1) renal disease; (2) heat stress; (3) chlamydiosis; (4) animal attack; and (5) vehicle collision (Fig. 5). There were no sex-based differences in the major admission reasons of rescued koala joeys ($t(10) = 0.192$; $P = 0.512$)

Trends associated with the reason for admission

Of the top five major reasons for admission, the proportion of vehicle collision had a weakly positive correlation that was non-significant ($r = +0.11$; $P = 0.396$), whereas animal attack admissions had a weakly negative correlation that was also non-significant ($r = -0.17$; $P = 0.349$) over the years between 2014 and 2021 (Fig. 6). On the contrary, the proportions of heat stress ($r = +0.69$; $P = 0.028$), renal disease ($r = +0.88$; $P = 0.013$) and chlamydiosis ($r = +0.74$; $P = 0.025$) all had a significantly positive correlation over the years between 2014 and 2021 (Fig. 6).

Causes of mortality and release rates

The overall mortality rate was 32.7%, which included joeys that were dead on arrival, euthanised on a welfare basis and joeys that died in care. Of the major causes of mortality, the most distinctive feature was the exceptionally high mortality rate of koala joeys with renal disease, at 93.1% (Fig. 7). This was followed by mortality caused due to vehicle collision, at 55.5%. Mortality caused by animal attack was also substantially high, at 40.0%. Another important caveat to note is that the clinical outcome for 58.3% of chlamydiosis admissions was not recorded (Fig. 7).

The overall release rate for koala joeys was 59.8%, which includes joeys released into the wild and/or released into care. Release rate for healthy orphaned joeys was the highest at 98.3% (Fig. 7). Heat-stressed joeys had a high positive outcome rate (61.1%) relative to other causes of admission.

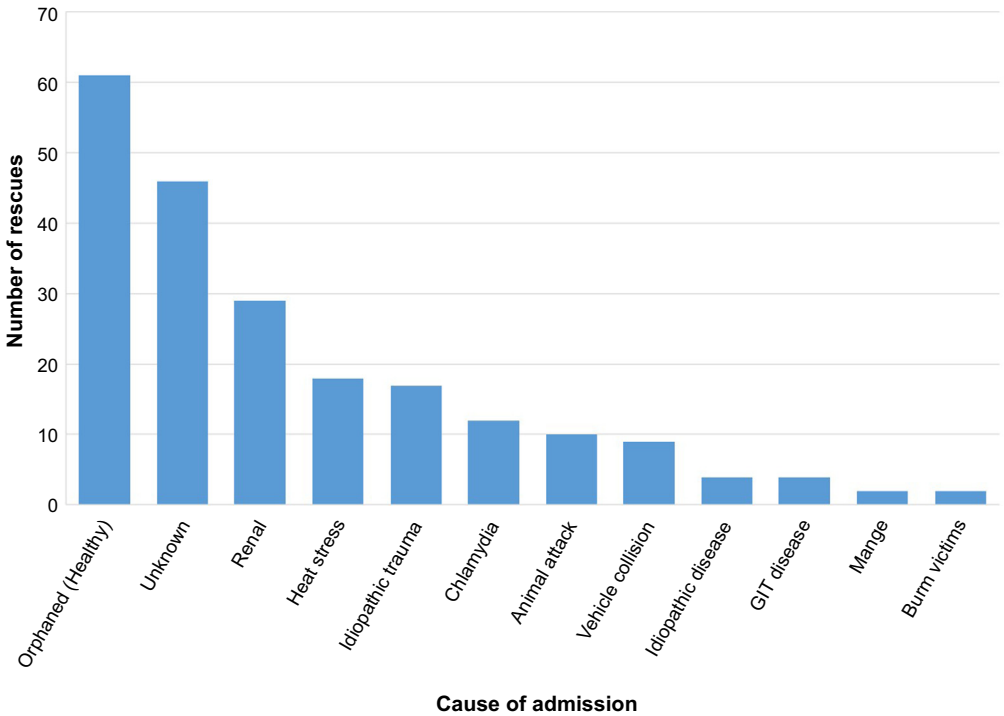

Fig. 5. Causes of admission of koala joeys at the AKWC between 2014 and 2021.

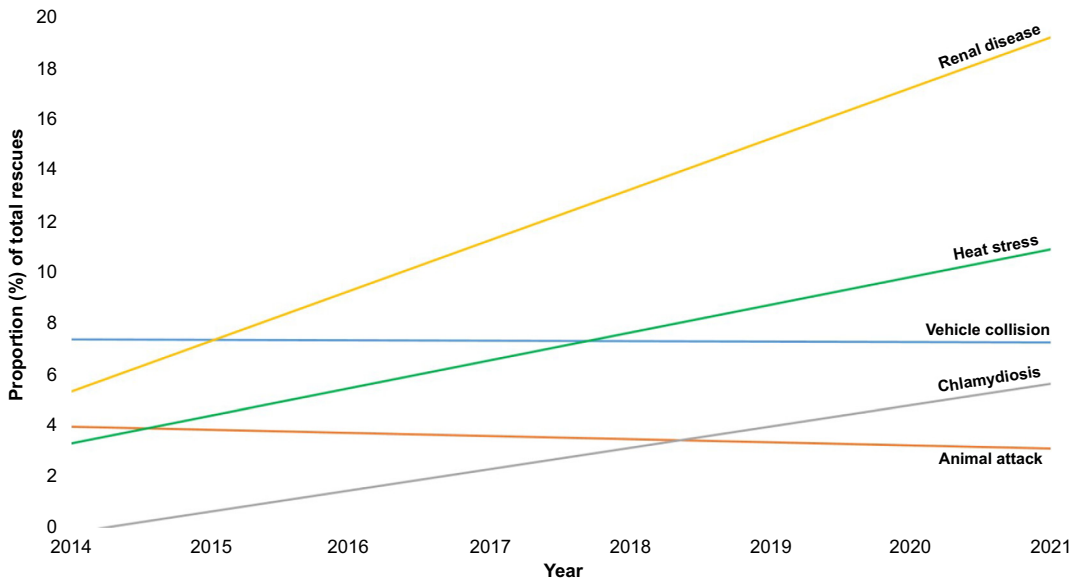

Fig. 6. Trends in major causes of admission of koala joeys admitted at the AKWC between 2014 and 2021.

Discussion

In the past, several studies have conducted long-term retrospective analyses of the causes and fates of koalas admitted for rehabilitation; however, the primary focus of previous research has been on adult koalas, conducted mainly in Qld and NSW (Griffith *et al.* 2013; Burton and Tribe 2016; Gonzalez-Astudillo *et al.* 2017; Charalambous and Narayan 2020; Lunney *et al.* 2022*a*; Kerlin *et al.* 2023), except for one study on Kangaroo Island in South Australia during the 2019–2020 bushfires (Dunstan *et al.* 2021). Furthermore, to our knowledge there has not been any retrospective evaluation of the causes of morbidity and mortality in koala joeys. Our examination of the trends in reasons for

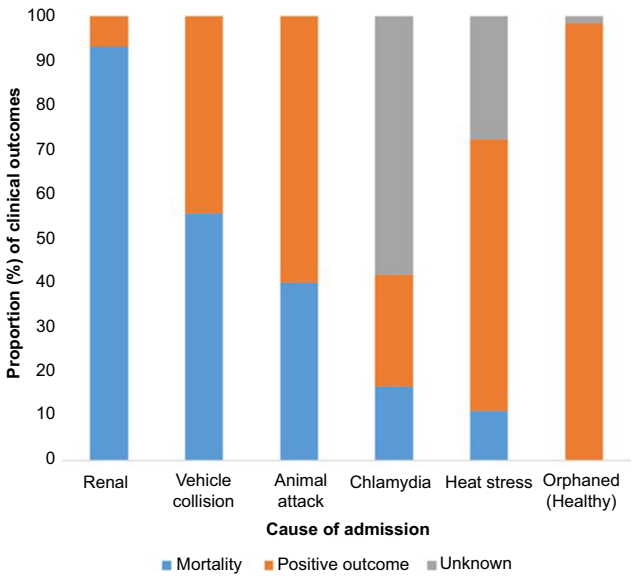

Fig. 7. Clinical outcome of the major causes of admission of koala joeys admitted at the AKWC between 2014 and 2021. Proportion (%) of positive outcome includes individuals that were released into the wild and/or released into care, whereas proportion (%) of mortality refers to individuals that died in care and/or were euthanised based on welfare grounds.

admission and mortality of koala joeys admitted for rehabilitation at AKWC in South Australia indicated that the release rate of rescued koala joeys increased significantly ($P = 0.043$) up to two-fold between 2014 and 2021, with the mortality rate simultaneously decreasing slightly during this period. Renal disease, along with chlamydiosis and heat stress, displayed an increase in frequency from 2014 to 2021. The leading reason for admission of koala joeys was orphaned individuals that needed foster care (followed by renal disease and heat stress), and the leading cause of mortality was renal disease (followed by trauma caused by vehicle collisions and animal attack).

Impact of anthropogenic-induced trauma

In our study, trauma admissions for koala joeys mainly included trauma caused by collision with vehicles and trauma caused by attack by other animal species. These results are similar to a study by Griffith *et al.* (2013), which concluded that vehicle collision (21.2%) was the primary reason for admission for koalas in the Port Macquarie region of NSW, and when combined with animal attack (19.8%), contributed to 41% of trauma admissions. Both vehicle collision and animal attack are well-recognised threats to koalas in Australia (Beyer *et al.* 2018; Charalambous and Narayan 2020; Lunney *et al.* 2022*b*; Melzer and Black 2022; Schlagloth *et al.* 2022; Kerlin *et al.* 2023). Trauma caused by vehicle collision and animal attack were among the top five major reasons for admission for koala joeys in our study. As highlighted by Lunney *et al.* (2022*a*), the figures for trauma caused by vehicles and other animal species may be well under-represented in hospital databases because these databases only account for cases admitted to the hospital, not for sightings of animals that are already deceased from these causes. This is even more prevalent for animal attack cases; in cases of motor vehicle collision, the driver is present to report the case to the respective authorities, but it is more likely for an 'animal attacked' koala joey to go unnoticed. Animal attacks were more common than vehicle collisions (Fig. 5), but the mortality rate caused by vehicle collisions was higher than that of animal attacks (Fig. 7). As concluded by (Lunney *et al.* 2022*a*), vehicular collisions serve as an immediate death threat to koalas: of the 1140 koalas in the Friends of the Koala hospital database, 544 (47.71%) were sightings of road-killed koalas, and of the remaining 596 admissions, a further 405 (68%) were not released. In our study, these figures are also reflected for young koalas, which indicate a 55.55% mortality rate. However, unlike other studies that report an evident cyclicity in car- and animal attack-associated admissions (peak between August and October) (Griffith *et al.* 2013; Gonzalez-Astudillo *et al.* 2017; Kerlin *et al.* 2023), we could not observe any cyclic dynamics for specific admission reasons of koala joeys in our study, but there was a significant ($P = 0.004$; Fig. 2*b*) increase in the overall koala admissions from September through to March, with a peak in admission in January. Considering the koala's breeding season (between August and October), and a short gestation period of approximately 1 month (Gifford *et al.* 2002), an increase in young koala admissions from September fits well with the growth and pouch emergence (26–28 week old) of joeys (Tobey *et al.* 2006).

Impact of disease

The trends in both the numbers admitted and the high mortality rate for renal disease show that this disease has a severe impact on affected individuals. As highlighted by (Speight *et al.* 2013*a*), renal disease is not a common cause of morbidity and mortality in Qld and NSW. However, oxalate nephrosis-associated renal disease is the most prevalent disease in koala populations near Adelaide (Narayan and Williams 2016). Although previously identified mainly in adult koalas (Narayan and Williams 2016), the results of our study are consistent with these findings even in young koalas. It was previously believed that the causative factor of oxalate nephrosis in koalas was high amount of dietary oxalate (Canfield and Dickens 1982); however, subsequent studies concluded that *Eucalyptus* leaves did not contain sufficient amounts of oxalate to be the primary cause of oxalate nephrosis-associated renal disease (Speight *et al.* 2013*b*). In the wild, the possibility that koalas consume leaves containing oxalate cannot be ruled out completely because an extensive study identifying all the plant species

consumed by koalas has not been conducted. However, the prevalence of renal disease in rehabilitating koala joeys, as observed in this study [and in Speight (2013)], that do not have access to oxalate-containing plants (because they are in captive conditions), implies there are other potential causes of this disease. The review by Narayan and Williams (2016) suggests that high levels of glucocorticoids in the mother during foetal development may cause continued nephron loss and low glomerular number in joeys. As a result, young koalas may be inheriting renal disorders due to maternal stress that progressively deteriorates as they grow older.

Isolated koala populations with decreased genetic diversity could be susceptible to Alanine–glyoxylate aminotransferase (AGT) (essential enzyme for metabolising glyoxylate to oxalate) dysfunction (Speight *et al.* 2013*b*). Although AGT activity was found to be normal in koala populations with decreased genetic diversity, AGT functioning could still be ineffective due to intracellular mistargeting (Speight 2013). Low water intake could also be a possible cause because dehydration is a key risk factor for renal calcium oxalate deposition (Speight 2013; Speight *et al.* 2019). It is impossible to pin-point a single factor responsible for renal disease in young koalas (and koalas in general); however, inherited pathogenesis of oxalate nephrosis (in isolated populations of decreased genetic diversity), maternal stress (in captive and wild populations) and water deprivation (in wild populations only) may all be contributing towards the high prevalence of renal disease in South Australian koala populations. What is important to note is that over the years, renal disease has been increasing at a rapid rate for koala joeys, and this is consistent with the reports from wildlife staff showing that renal disease is being seen more frequently in South Australian koala joeys (P. Hutt, pers. comm.). This is also reflected in our study by a four-fold increase in renal disease from 5% in 2014 to 20% in 2021 ($P = 0.013$; Fig. 6) in young koalas. The severely high mortality rate of renal disease raises concerns regarding the early diagnosis of this disease, improving treatment once diagnosed and any preventive measures that can help reduce the mortality rate of this disease.

As seen with the trends of renal disease, a significant ($P = 0.025$; Fig. 6) increase in chlamydiosis admissions of koala joeys can also be observed in our study between 2014 and 2021. The primary mode of transmission of chlamydiosis (particularly of *C. pecorum*) is through sexual contact, and thus sexually immature individuals were believed to be free of chlamydiosis. However, subsequent studies by several scientists (Nyari *et al.* 2017; Russell *et al.* 2018) reported that koala joeys were also vulnerable to the infection. The study by Nyari *et al.* (2017) was conducted on free-ranging koalas, and concluded that the infection in joeys could be transmitted through the pap of already infected mothers and/or be due to close contact between the mother and the joey. On the other hand, the study by Russell *et al.* (2018) was conducted on rescued orphaned joeys, and thus the possibility of transmission due to handling of the infected mother and the joey by the same animal handler cannot be completely ruled out. In either case, it can be confirmed that joeys (<12 month old) are also acquiring Chlamydial infections through vertical (close contact non-sexual transmission) routes, potentially through dam-to-joey transmission (in the wild) and/or handling by the carers (during rehabilitation) (Quigley and Timms 2020). The detrimental impact of chlamydiosis on koala populations is well documented in other studies across Australia (Polkinghorne *et al.* 2013; Patterson *et al.* 2015; Fabijan *et al.* 2019; Charalambous and Narayan 2020; Lunney *et al.* 2022*a*). There is a large proportion of chlamydiosis cases without the clinical outcome recorded (58.3%) in our study, so it would be erroneous to conclude that this disease contributes significantly to the mortality of koala joeys, as observed in adult koala populations in other parts of Australia.

Impact of heat stress

Heat stress was the second-most common reason for admission of rescued koala joeys in our study. Heat stress is not a prevalent cause of hospitalisation for koalas in other Australian states except South Australia (Kerlin *et al.* 2023). Consistent with the results of our study, heat stress was reported as the key environmental stressor for koalas in South Australia (Narayan and Williams 2016). Heat-stressed koala joeys in our study were often associated with dehydration as the secondary comorbidity. As highlighted by Narayan and Williams (2016), heat-stressed koala admissions were primarily associated with suburban fringes and temperatures exceeding 40°C. During extreme drought and heatwave events, young koalas in particular are likely to be dominated out of riparian habitats by older animals (Gordon *et al.* 1988). Exclusion from optimal habitat and the dearth of free-standing water in unsuitable habitats are plausible causes of dehydration and heat stress in young koalas. Furthermore, because the primary source of water for the koala joeys is the mother's milk, they could be inherently more vulnerable to heat stress when orphaned. Although heat stress was a major reason for admission, the mortality of heat-stressed koala joeys was substantially low (11.11%) relative to other causes. The low mortality of heat stress in our study could possibly be associated with less severe heatwaves relative to those noted by Gordon *et al.* (1988) in south-western Qld. The public appeal of koalas, resulting in early reporting to the wildlife rescuers (Kerlin *et al.* 2023), could also have contributed to the better survival chances of koalas.

Mortality and release rates

Of all the koala joey admissions to AKWC during our study period, the overall mortality rate was 32.7% and the overall release rate was 59.8%. As mentioned by Lunney *et al.* (2022*a*),

the overall rate of mortality and release could mask the trends over time and misrepresent the comparison between different rehabilitation organisations due to a vast variation in these rates over time. Therefore, it is important to identify trends in mortality and release rates within a narrow band of years to make this comparison informative. Because there is no scientific literature available specifically on causes and outcomes of koala joeys, these rates cannot be compared for specific causes. A comparison of release rates for healthy orphaned koala joeys by Taylor-Brown *et al.* (2019) has been discussed above. Overall, in our study, the positive outcome for joeys increased up to two-fold ($P = 0.043$; Fig. 3) between 2014 and 2021. Simultaneously, the mortality rate for admitted joeys also indicated a slight decline during this period. These trends are markedly different from those reported by Lunney *et al.* (2022*a*), who report a substantial decline in the release rate of koalas admitted at the Friends of the Koala hospital in NSW over 31 years. Whether the increasing positive outcome and decreasing mortality over the years in our study [relative to Lunney *et al.* (2022*a*)] is a result of less severe admission cases, of improving rehabilitation protocols, or merely an artefact of a narrow study period, is open to further investigation.

Rehabilitation of healthy orphaned koala joeys

Rehabilitating koala neonates is extremely difficult due to the complexity of their dietary needs and environmental requirements Koalas are an altricial species, so neonate joeys are intrinsically dependent on the mother for acquiring immunity, and the death of the mother could plausibly affect the survival of the joey. If joey survival were to be attributed to mortality of the mother, the survival rate of joeys inside the pouch is 78.8%, being on the mother's back is 84.8% and off the mother's back until independence is 88.9% (Beyer *et al.* 2018). It can be noted that in the wild, the survival of the joeys is lowest while they are still in the pouch. This highlights the vulnerable nature of koala joeys in the early months of pouch life. As a result, koala joeys weighing <120 g are not considered to be ideal candidates for rehabilitation – success in these animals is minimal (NSW 2020*a*). The AKWC database did not have the weight recorded on admission so we could not confirm this in our study. Generally, however, high infant mortality in koala joeys (both in-care and in the wild) is prevalent, and commonly attributed to 'pouch death syndrome' by some wildlife organisations; however, there is no scientific literature to support this claim. In our study, the release rate of healthy orphaned joeys was 98.3% and the clinical outcome for the rest was unknown. These numbers are markedly different from those of Taylor-Brown *et al.* (2019), who report a release rate of 64.5% and a mortality rate of 35.5% for healthy orphaned koala joeys. As rightly pointed out by Lunney *et al.* (2022*a*), comparing the mortality and release rates across different koala rehabilitation organisations is of considerable interest from a wildlife management perspective. This is even more important when rehabilitating koala joeys (or any other orphaned species) because organisations with a high release rate can discuss their rehabilitation protocols to help mitigate the issue of high mortality rates faced by other organisations when rehabilitating joeys. The current state of koala rehabilitation varies across different states of Australia based on the differences in government policies and guidelines and the conservation status of koala in different states. Although the NSW Government has laid specific Koala Rehabilitation Training Standards for volunteers, including a clear outline standard for the 'Rehabilitation of koala joeys' [see NSW (2020*b*)], other states still rely on a general wildlife rehabilitation permit for rehabilitating koala joeys. As a general rule of thumb, across all government guidelines, long-term care and rehabilitation of orphaned joeys must only be undertaken by experienced carers, and all carers must abide by the relevant animal welfare standards (NSW 2018; VSG 2021; DES 2022; DEW 2022). To what extent these guidelines are followed by the wildlife care organisations is not assessed in the scientific literature.

Limitations and conclusion

It is important to mention that descriptive studies from wildlife rescue databases such as this are associated with some bias due to a lack of randomisation of sampled data and the potential for overrepresentation of certain threats. For example, a review by Ashman *et al.* (2019) found that disease cases were disproportionately high in all threat-based research on koalas. Similar over- and under-representation of disease and animal attack cases (respectively) have been discussed above. Despite the notable issues with bias and accuracy of the information contained in the records of wildlife care facilities, these databases serve as an important tool in identifying the major causes of concern on wildlife, and are increasingly being recognised as a valuable scientific resource for recommending potential measures to reform conservation and management practices (Kerlin *et al.* 2023). Our analysis would be significantly strengthened by improved data collection, but incomplete and inconsistent records of useful data such as approximate age, weight, tooth wear, head length and secondary comorbidities were unfortunately not available for a sizeable number of records. This issue is common and has been reported in a large number of retrospective studies conducted previously. The overarching lesson from our study is that there is a synergy of threats operating in South Australia that are affecting rescued koala joeys, which implicates the need to follow a standardised procedure for recording secondary comorbidities at admission and improving data recording in general.

To our knowledge, data of this comprehensive nature on the causes of morbidity and mortality in rescued koala joeys were previously unavailable in the published scientific domain. Our retrospective study of koala joey admissions to AKWC clearly indicates that renal disease is the primary cause of mortality in rescued koala joeys undergoing rehabilitation in South Australia. The severely high mortality rate of renal disease raises concerns regarding the early diagnosis of this disease, improving treatment once diagnosed and any preventive measures that can help reduce the mortality rate of this disease. The impact of Chlamydiosis is well documented in adult koalas, but further research is needed to understand its transmission to sexually immature individuals. Anthropogenic threats such as vehicle collisions may be minimised by incorporating biological corridors for safe passage of young koalas between fragmented habitats. This also emphasises the need for strategic habitat restoration and defragmentation. Furthermore, animal attack incidents (particularly pet attack) will be minimised by educating general public regarding thoughtful pet ownership – along with wildlife-friendly driving habits. On a positive note, the increase in positive outcome and the decrease in mortality rate of rescued koala joeys over the years reflects well on the rehabilitation protocols followed by the AKWC.

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Author affiliation
[A]School of Agriculture and Food Sciences, Faculty of Science, University of Queensland, St Lucia, Qld 4072, Australia.