State-wide abundance of kangaroos in Victoria, 2020

Results from the 2020 aerial and ground survey

P.D. Moloney, D.S.L. Ramsey and M.P. Scroggie

March 2021

Arthur Rylah Institute for Environmental Research
Technical Report Series No. 324

Arthur Rylah Institute for environmental research

Victoria State Government | Environment, Land, Water and Planning

Acknowledgment

We acknowledge and respect Victorian Traditional Owners as the original custodians of Victoria's land and waters, their unique ability to care for Country and deep spiritual connection to it. We honour Elders past and present whose knowledge and wisdom has ensured the continuation of culture and traditional practices.

We are committed to genuinely partner, and meaningfully engage, with Victoria's Traditional Owners and Aboriginal communities to support the protection of Country, the maintenance of spiritual and cultural practices and their broader aspirations in the 21st century and beyond.

Arthur Rylah Institute for Environmental Research
Department of Environment, Land, Water and Planning
PO Box 137
Heidelberg, Victoria 3084
Phone (03) 9450 8600
Website: www.ari.vic.gov.au

Citation: Moloney, P.D., Ramsey, D.S.L., and Scroggie, M.P. (2021). State-wide abundance of kangaroos in Victoria: results from the 2020 aerial survey. Arthur Rylah Institute for Environmental Research Technical Report Series No. 324. Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Front cover photo: Western Grey Kangaroo in the Mallee (Museums Victoria, Mark Norman).

ISSN 1835-3827 (print)
ISSN 1835-3835 (pdf))
ISBN 978-1-76105-461-7 (pdf/online/MS word)

Accessibility

If you would like to receive this publication in an alternative format, please telephone the DELWP Customer Service Centre on 136 186, email customer.service@delwp.vic.gov.au or contact us via the National Relay Service on 133 677 or www.relayservice.com.au. This document is also available on the internet at www.delwp.vic.gov.au

State-wide abundance of kangaroos in Victoria, 2020

Results from the 2020 aerial and ground survey

P.D. Moloney, D.S.L. Ramsey and M.P. Scroggie

Arthur Rylah Institute for Environmental Research
123 Brown Street, Heidelberg, Victoria 3084

Arthur Rylah Institute for Environmental Research
Technical Report Series No. 324

Acknowledgements

We thank Peter Menkhorst who provided valuable feedback on drafts of this report. This report was commissioned by the Regulation Strategy and Design Branch, Biodiversity Division, of the Department of Environment, Land, Water and Planning. Aerial surveys were conducted by Terrestrial Ecosystem Services Pty Ltd, (www.ecoknowledge.com.au). Ground surveys were conducted by Graeme Coulson (Macropus Consulting). We thank Associate Professor Coulson for many valuable suggestions, and for the provision of personally collected data.

Contents

Tables

Figures

Summary

Context:

The Victorian Government supports ecologically sustainable commercial harvesting of wild grey kangaroo (Eastern Grey Kangaroo, *Macropus giganteus* and Western Grey Kangaroo, *M. fuliginosus*) populations in the state. In addition, both species of grey kangaroo and the Red Kangaroo (*Osphranter rufus*) can be subject to legal control under the Authority to Control Wildlife (ATCW) provisions of the *Wildlife Act 1975* (Victoria). To determine whether the total offtake of kangaroos through both regulatory mechanisms is ecologically sustainable, the State of Victoria is conducting state-wide aerial population surveys of these three species of kangaroo.

Aims:

To estimate the abundance of the three species of kangaroo in the non-forested regions of Victoria.

Methods:

Aerial surveys conducted in October 2020 were used to estimate kangaroo abundance within seven survey zones comprising 58 local government areas (LGA). These surveys update population estimates derived from an earlier program of surveys conducted in 2017 and 2018 (Moloney *et al.* 2017; Moloney *et al.* 2019) Heavily forested areas were excluded from kangaroo abundance estimates as these could not be reliably monitored using aerial surveys. As Eastern and Western Grey Kangaroos cannot be reliably distinguished from aerial surveys, concurrent ground surveys were undertaken within areas of Victoria where these two species overlap to estimate the relative proportions of each species.

Results:

Based on an analysis of the aerial and ground survey data, the overall kangaroo population in Victoria was estimated to be 1 942 000 (95% confidence interval: 1 513 000 – 2 492 000). There were an estimated 1 717 000 (1 316 000 – 2 239 000) Eastern Grey Kangaroos (EGK), accounting for the majority (88%) of Victorian kangaroos. The remaining kangaroo population was comprised of an estimated 195 000 (140 000 – 272 000) Western Grey Kangaroos (WGK) and 30 000 (13 000 – 69 000) Red Kangaroos (RK).

The Central survey zone had the highest density of EGK (54.2 kangaroos/km^2), much greater than the next highest density in the Otway zone (14.1 kangaroos/km^2). The Mallee zone had the lowest density of kangaroos (3.1 kangaroos/km^2 with all species combined).

Conclusions:

The results from the 2020 aerial survey indicate that Victoria's kangaroo population has increased since 2018. Compared to estimates from 2018, the density of grey kangaroos was similar for most survey zones except for the Central and Gippsland zones (higher in 2020 and similar to 2017 densities). The density of Red Kangaroos in the Mallee zone was marginally lower in 2020 compared with the 2018 estimate. The precision of estimates also improved for most survey zones compared with the 2018 estimates, with the exception of the North-East and Otway zones, which were lower than expected due to a high level of aggregation of kangaroos on some transects.

Recommendations:

- Continuation of the current survey frequency of every two years is recommended. If the survey frequency is reduced, conditions such as severe or prolonged drought may require the two-year survey frequency to be reinstated.
- Consideration could be given to reducing the frequency of ground surveys as the position of the Grey Kangaroo Overlap Zone (GKOZ), the area where Eastern and Western Grey kangaroos overlap, is now better understood.
- Some further targeted ground surveys may provide a better understanding of the distribution and abundance of the EGK in the Mallee zone, as estimates of the proportion of EGK in this area were markedly lower than was found previously.
- Given the high level of kangaroo aggregation seen during the aerial surveys, consideration could be given to using a model-based distance sampling approach, which could result in improved estimates of abundance for each survey zone as well as enable estimates for smaller regions.

1 Introduction

In Victoria, offtake of wild kangaroos is permitted under two regulatory mechanisms. The first mechanism is the Authority to Control Wildlife (ATCW) provisions of the *Wildlife Act 1975* (Victoria), which allows legal control of wildlife, including three species of kangaroo — Eastern Grey Kangaroo (*Macropus giganteus,* EGK), Western Grey Kangaroo (*M. fuliginosus,* WGK) and Red Kangaroo (*Osphranter rufus*, RK). The second is a commercial harvest of EGK and WGK where annually determined quotas allow for ecologically sustainable commercial use of both species of grey kangaroo.

To determine the level of offtake under both regulatory mechanisms that is ecologically sustainable, the Victorian Government is conducting state-wide aerial population surveys of these three species of kangaroo. Ecological sustainability can be defined in terms of the maximum offtake that can be sustained in the long-term, while ensuring a low risk of declines in kangaroo populations and their respective conservation status. Sustainable offtake rates of kangaroos are usually based on a fixed proportion of the estimated population size, with offtake proportions of 10–20% of the population generally considered to be ecologically sustainable (Caughley *et al.* 1987; Hacker *et al.* 2004; McLeod *et al.* 2004; Scroggie and Ramsey 2020).

Aerial surveys have been used to guide the management of kangaroo populations since the 1960's (Caughley *et al.* 1976) and in combination with line transect sampling, provide accurate estimates of population density and abundance of kangaroos (Fewster and Pople 2008; Tracey *et al.* 2008). The first comprehensive aerial and ground survey of Victoria's kangaroo population was conducted in 2017 (Moloney *et al.* 2017). That survey estimated Victoria's kangaroo population to be 1 442 000, with an overall precision (coefficient of variation, CV) of 19%. Because the precision of the population estimates for some zones were inadequate, improvements to the survey design were recommended (Moloney *et al.* 2018). These recommendations sought to establish the minimum survey effort required to estimate the population abundance of kangaroos within each of seven survey zones, with a CV of 20% or less. The seven survey zones were chosen by amalgamating local government areas to reflect the likely regional variation in the density of Victoria's kangaroo populations.

Because of the difficulty in distinguishing the two species of grey kangaroo during aerial surveys, ground surveys were undertaken to estimate the relative proportions of Eastern and Western Grey Kangaroos within the overlap zone where the two species co-occur (in the Lower and Upper Wimmera zones). These proportions were then used to derive separate estimates of the abundances of the two grey kangaroo species within the overlap zone from the overall estimates of grey kangaroo abundance derived from the aerial survey. Zone-level estimates of density for each species were then used to estimate kangaroo abundances in each of 58 non-metropolitan Local Government Areas (LGAs). Heavily forested areas in each zone or LGA were excluded from kangaroo abundance estimates because these areas could not be reliably surveyed from the air.

In this report we present the results of the third state-wide aerial survey of kangaroo populations in Victoria, based on aerial and ground surveys conducted during 2020. Updated abundance estimates (and their precision) are provided for each zone and LGA. Comparisons are made between the results from this updated survey and the previous surveys in 2017 and 2018 (Moloney *et al.* 2017; Moloney *et al.* 2019).

2 Methods

2.1 Species distribution, study area and stratification

Aerial and ground surveys using the methodology outlined in (Moloney *et al.* 2018) were conducted (with slight variation) in October 2020 to estimate the kangaroo population in Victorian LGAs. Some aerial transects that could not be flown safely in 2018 were replaced in 2020, increasing the number of transects from 145 to 150, comprising a total of 3234 km (an increase from 3182 km in 2018). The new aerial survey was a substantial increase over the 79 transects (1600 km) undertaken in the initial survey in 2017 (Moloney *et al.* 2017). The survey and estimates exclude LGAs that are entirely (or almost entirely) within highly urbanised parts of the Melbourne metropolitan area. Estimates also excluded thickly forested areas because of the unreliability of kangaroo detection from the air in those areas. The survey and the resulting population estimates were therefore restricted to the 58 non-metropolitan LGAs listed in Table 1.

Table 1. Local government areas and zones included in the survey and estimates.

Survey zone	LGA
Central	Ballarat
	Brimbank
	Hepburn
	Hume
	Macedon Ranges
	Melton
	Mitchell
	Moorabool
	Mount Alexander
	Murrindindi
	Nillumbik
	Whittlesea
	Yarra Ranges
Gippsland	Bass Coast
	Baw Baw
	Cardinia
	Casey
	East Gippsland
	Latrobe
	Mornington Peninsula
	South Gippsland
	Wellington
Lower Wimmera	Ararat
	Central Goldfields
	Gannawarra
	Glenelg
	Loddon
	Northern Grampians
	Pyrenees
	Southern Grampians
North East	Alpine
	Benalla
	Campaspe
	Greater Bendigo
	Greater Shepparton
	Indigo
	Mansfield
	Moira
	Strathbogie
	Towong
	Wangaratta
	Wodonga
Otway	Colac Otway
	Corangamite
	Golden Plains
	Greater Geelong
	Hobsons Bay
	Moyne
	Surf Coast
	Warrnambool
	Wyndham
Upper Wimmera	Buloke
	Hindmarsh
	Horsham
	Swan Hill
	West Wimmera
	Yarriambiack
Mallee	Mildura

Three kangaroo species are widely distributed over parts of Victoria. RK is restricted to the far north-west of the state. EGK inhabit most of the state, apart from the far north-west of the state. WGK inhabit only the west and north-west. The range of EGK and WGK overlap in a broad band across the west of the state, known as the Grey Kangaroo Overlap Zone, GKOZ (Caughley *et al*. 1984). To account for the different kangaroo distributions and potential differences in density, Moloney *et al*. (2018) subdivided Victoria into seven survey zones by amalgamating ecologically similar LGAs (Figure 1).

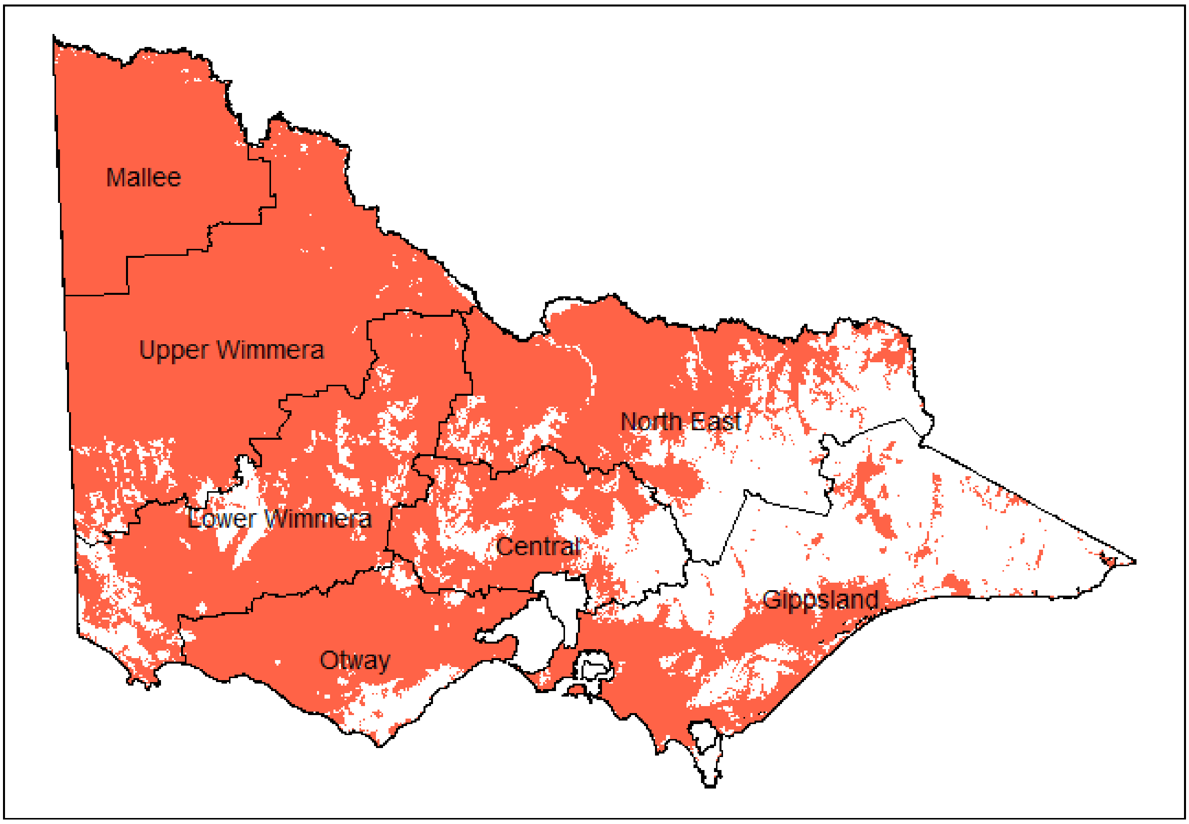

Figure 1. Map of the stratification scheme used for the state-wide kangaroo survey. Each survey zone was formed by aggregating several ecological similar and geographically proximate LGAs. Coloured shading corresponds to open or lightly forested areas and mallee vegetation types that are included in the survey and estimates. Unshaded areas are heavily forested, highly urbanised, or kangaroo-free areas that were excluded from survey and estimates.

2.2 Aerial surveys

Aerial surveys and line-transect distance sampling (Buckland *et al.* 1993) were used to estimate kangaroo densities across Victoria. Aerial surveys were conducted by Terrestrial Ecosystem Services in October 2020 using a Bell LongRanger helicopter, using similar methods as were undertaken in 2017 and 2018 (Lethbridge and Stead 2017). A total of 3234 km of transects were flown within three hours of sunrise or sunset in an easterly or westerly direction (flying away from the sun) at a height of 200 feet (about 60 m) above ground level, at a speed of 50 knots (about 90 km/h) (priority 1 and 2 transects in Figure 2). A few of these transects had to be substituted with backup (contingency) transects because of the presence of obstructions such as power lines that precluded the safe operation of the aircraft. Backup transects were selected from the contingency pool transects for that survey zone (Figure 2). A five-zone survey pole was used on either side of the aircraft, allowing observed kangaroos to be placed into one of five distance classes (0–20 m, 20–40 m, 40–70 m, 70–100 m and 100–150 m). The species, size and distance class of the first observation of each group of kangaroos was recorded. Because of difficulties in accurately determining the difference between EGK and WGK from the air, only RK and an aggregated ‘grey kangaroo’

(GK) (representing both EGK and WGK combined) were recorded. For further details of the aerial surveys methodology see Lethbridge and Stead (2017).

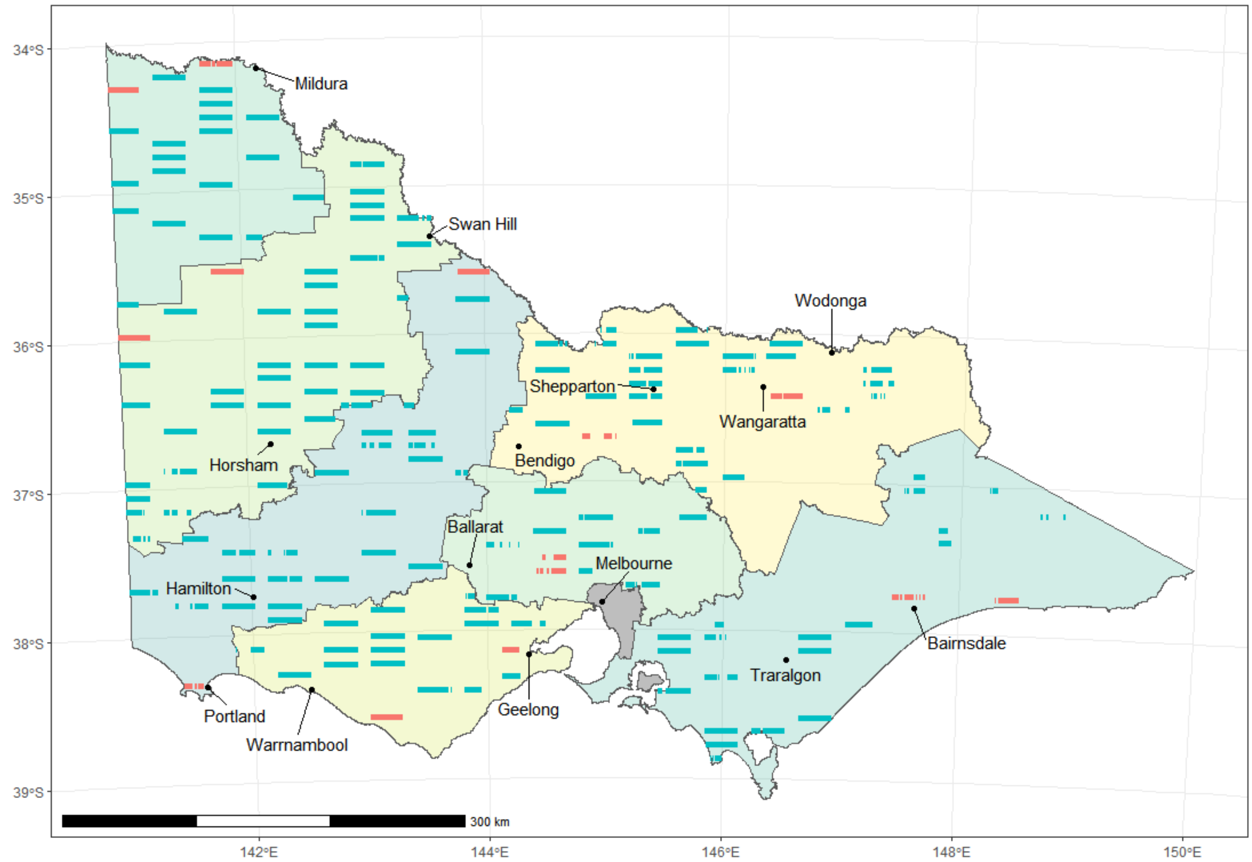

Figure 2. Map of transects flown in the 2020 kangaroo aerial survey.
Priority transects (blue) were surveyed with contingency transects (red) substituted in the event that priority transects could not be safely flown. Shading indicates different survey zones.

2.3 Ground surveys

Both EGK and WGK occur in Victoria, and to enable effective management, separate population estimates are required for the two species. WGK are confined to the west and north-west of the state, but there is a broad zone (the GKOZ) in the Mallee, Upper Wimmera and Lower Wimmera zones where the geographic ranges of the two species overlap (Caughley *et al.* 1984). Since it is not possible to reliably distinguish the two species of GK during aerial surveys, distance sampling estimates derived from the aerial surveys are for the aggregate 'species', GK. In zones occupied only by EGK (North East, Central, Otway, and Gippsland) the estimates of total GK abundance equates to the number of EGK. However, in the GKOZ it was necessary to apportion the total population estimate between the two species. This apportionment was based on an analysis of available distributional data for the two species, including data derived from targeted ground surveys across the GKOZ.

Ground surveys intended to enable an estimate of the ratio of EGK to WGK in western Victoria have been conducted across much of the Victorian portion of the GKOZ during 2017, 2018, and 2020 (Coulson 2017; Coulson 2018; Coulson 2020). Additional unpublished observations from adjacent parts of the GKOZ in South Australia and New South Wales, collected during other fieldwork undertaken during 2019, were also generously provided for this report by Graeme Coulson (unpublished data).

Kangaroos were observed from a slow-moving vehicle while driving road transects that traversed the GKOZ around dawn and dusk. All macropods that were encountered on, or close to the road were identified to species level wherever possible. This included identification of road-killed and other dead kangaroos. Only animals that could confidently be identified to species were considered further. Some kangaroos encountered during 2018 were identified using genetic analysis of tissue samples obtained from badly damaged carcasses that could not otherwise have been identified (Graeme Coulson, pers. comm.). The resulting confirmed records for both species of grey kangaroo are shown in Figure 3.

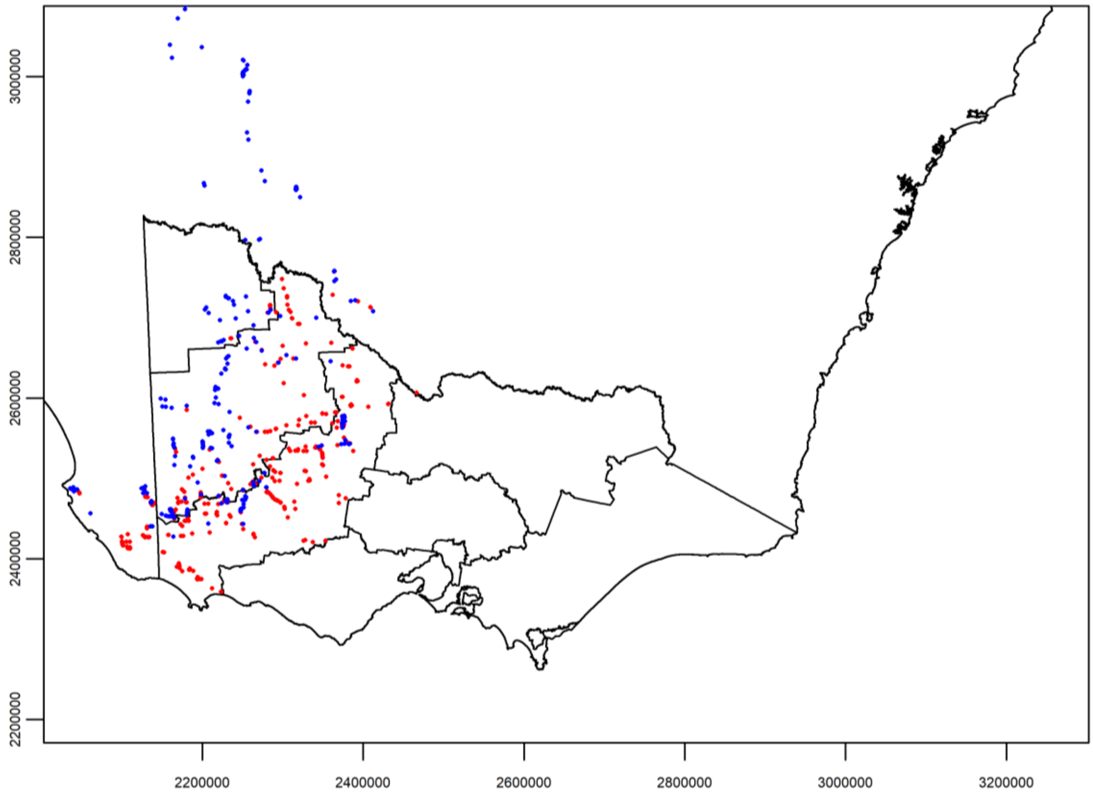

Figure 3. Survey records of Eastern Grey Kangaroo (red) and Western Grey Kangaroo (blue) from across the grey kangaroo overlap zone collected between 2017 and 2020.
Polygons are the survey zones used for the design and analysis of the aerial surveys. The map coordinate system is VicGrid.

2.4 Proportions of Eastern and Western Grey Kangaroos in the overlap zone

We used the records from the ground surveys in combination with a comprehensive set of biodiversity atlas data to estimate the proportion of EGK and WGK in different parts of the GKOZ and, more specifically, for each LGA within each of the three relevant survey zones. WGK inhabit only the west and north-west of the state, so it was explicitly assumed that the proportions of WGKs in the Otway, North East, Central and Gippsland zones were zero. Hence, estimation focused on the survey zones in the west and north-west (Mallee, Upper Wimmera and Lower Wimmera) known to be occupied by both species of GKs. This assumption was supported by a complete lack of recent, reliable records of WGK outside the three zones where their occurrence is well documented. However, the possibility of small numbers of WGK in parts of the Otway, Central and Northeast zones close to their respective boundaries with the Lower Wimmera zone cannot be entirely discounted.

Additional records for EGK and WGK in south-eastern Australia (covering Victoria, South Australia and New South Wales) were obtained from the Atlas of Living Australia database (Atlas of Living Australia 2021a; Atlas of Living Australia 2021b). The atlas records spanned the period 1940–2020, and were limited to those records with positional accuracy better than 2000 m. As there is some evidence that the location of the GKOZ within Victoria had moved over time (Moloney *et al*. 2019), it was necessary to account for possible movement of the GKOZ when analysing the various sources of distributional data (Atlas of Living Australia data and ground survey data collected between 2017 to 2020). Accordingly, a space-time Generalised

Additive Model (GAM) with a Bernoulli error distribution was fitted to the set of location/year data, which allowed the model to estimate the direction and scale of any movement in the width or location of the GKOZ.

The space–time GAM uses observations of the two species in space and time to estimate the probability that a randomly observed kangaroo will be an EGK, conditional on location (geographic coordinates) and the year of observation. The model includes smooth terms for the temporal trend, a spatial smoothing surface, and a tensor-product interaction between the temporal trend and the spatial smooth, to allow for spatial variability in the temporal trend. The model was fitted to the data using the R package `mgcv` (Wood 2017). A soap-film smoothing approach (Wood *et al.* 2008) was applied to the spatial component of the model to allow for the effects of the edges (i.e. coastline) of the modelled area and to prevent unrealistic smoothing of the spatial surface around peninsulas and other coastal features. Predictions of the model (expressed as probabilities that a random grey kangaroo was an EGK) were generated for the whole of the south-eastern Australian mainland on a grid resolution of 5 km. Although the model can make predictions for any given time, we restricted our attention to the year 2020 so that our predictions of the ratio of EGK:WGK at any given point on the map would be contemporaneous with the timing of the aerial surveys that were used to estimate the abundances of kangaroos.

We used the fitted GAM to estimate the expected proportion of EGK within each of the Mallee, Upper Wimmera and Lower Wimmera survey zones during 2020. This was calculated by taking the mean of the estimated probability that a random grey kangaroo was an EGK at all points on the 5 km prediction grid that fell within the bounds of each zone polygon. Uncertainty in the proportions for each zone was estimated using a parametric bootstrap procedure (Wood 2017). A sample of 250 random values were drawn from the multivariate normal distribution describing the sampling distribution of the parameters of the GAM (including the covariances between parameters), and for each resulting set of parameters a new prediction surface was generated. By computing the mean of the estimated proportions of EGK in each zone for each set of randomly generated parameters, a sample of 250 estimates of the proportion of EGK for each zone could be computed along with estimates of uncertainty around the point estimates (standard deviation and confidence intervals). The estimates of the proportions of WGK are simply the complement of the proportion of EGK in each zone or LGA across the entire study area. The resulting estimates for each zone were then used to apportion the total population estimates for GK in each zone and LGA (obtained from the analysis of the aerial survey data) between the two species.

We also estimated uncertainty in the current location of the midline of the GKOZ by calculating the location of the 50% probability contour on each of the 250 replicate estimates of the prediction surface. A random sample of 50 of these contours was overlaid on a map p(EGK) to visualise our uncertainty in the location of the GKOZ midline.

2.5 Kangaroo abundance estimates for each LGA

The density of GK and RK (kangaroos/km^2) was estimated for each zone using standard line-transect distance sampling techniques (Buckland *et al.* 1993). Half-normal and hazard-rate detection functions with potential second and third order cosine adjustment terms were considered, with the model with the lowest Akaike's Information Criterion (AIC; Burnham and Anderson 2002) used for the final inferences. Kangaroo abundance estimates for each LGA were then calculated by multiplying the zone density estimates for each kangaroo species by the area (in square kilometres) of habitat (i.e. non-forested) in each LGA. In LGAs outside the GKOZ, GK can be assumed to be either EGK or WGK and densities can be estimated directly from the distance sampling model. However, within the GKOZ the density of GK needed to be assigned to EGK and WGK. This was done by multiplying the relevant density estimates by the modelled proportion of GK in that LGA that were EGK and WGK, respectively. Bootstrapping, based on 10,000 replicate samples, was used to estimate the standard error and confidence intervals of the EGK and WGK densities within the GKOZ (Efron and Tibshirani 1993). The analysis was carried out using the statistical program `R` (R Development Core Team 2020), with the `Distance` package (Miller 2017) used to estimate the distance sampling model.

3 Results

3.1 Kangaroo density estimates for each survey zone

A total of 6268 grey kangaroos (GK) and 102 Red Kangaroos (RK) were observed along the 3234 km of transects during the aerial survey. Studies have shown that at least 80 distance observations are required to provide a reasonable estimate of the detection function, which is necessary to estimate density with acceptable precision and accuracy (Buckland *et al*. 1993). Since there were only 50 RK clusters observed (and therefore, only 50 distance observations for the RK individuals), a single detection function was fitted for all kangaroos, with the assumption that the distance detection function for GK and RK was identical. A hazard rate detection function with second order cosine adjustments was selected after comparing the fit of the half-normal and hazard rate distance functions, with up to fourth order cosine adjustments (Table A1). The monotonicity assumption was not violated, with the estimated detection function decreasing as distance from the transect increased (Figure 4). There were insufficient degrees of freedom to conduct a goodness-of-fit test for the model.

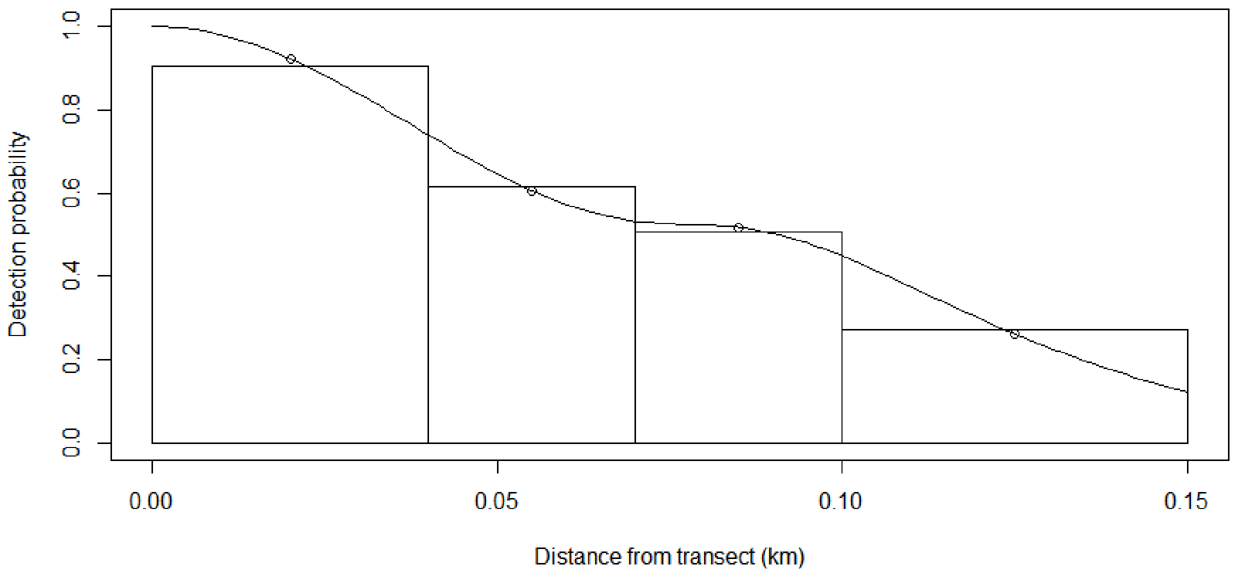

Figure 4. Estimated probability of detection of kangaroos with distance from the transect during the 2020 kangaroo aerial survey.
Bars indicate the relative number of kangaroos observed in that distance category. The horizontal axis denotes distance from the helicopter flight line, measured in km (0.15 km = 150 m).

The distance sampling model was used to estimate the density of GK and RK (kangaroos/km^2) for each of the seven kangaroo survey zones (Table 2). The highest density was estimated to be for GK in the Central zone (54.2/km^2, 95% confidence interval (CI): 34.3 – 85.8), more than triple the density of the next highest zone, Otway (14.1/km^2, 95% CI: 5.5 – 36.2). The north-west of Victoria (Mallee and Upper Wimmera) had the lowest densities of GK. Because all of the observed RK were in the Mallee zone, RK density and abundance estimates were provided only for that zone.

The estimated density of grey kangaroos in the Mallee, Lower Wimmera and North East survey zones were consistent from 2017 to 2020, while in the Central and Gippsland the estimates were lower only in 2018 (Figure 5). However, in the Upper Wimmera and Otway zones the estimated density trended higher from 2017 to 2020 (Figure 5). The density of RK in the Mallee zone has varied over the surveys, with the 2020 estimate being between the 2017 and 2018 density estimates (Figure 5). In most survey zones the precision of GK density estimates was acceptable, but was again low for the North East and Otway zones (Table 2 and Figure 5). Large aggregations of kangaroos on some transects most likely led to the lower precision of estimates for these zones. For example, transect NE09 in the North East, between Mount Samaria State Park and Mansfield, had a single mob of 92 kangaroos, which was 40% of all kangaroos detected in the

North East zone. In the Otway zone, transect OT12, between Dunkeld and Mortlake, had a single mob of 57 kangaroos, which was 40% of all kangaroos detected in the Otway zone.

Based on the density estimates for each zone derived from the distance sampling analysis, and the known surveyable areas of each zone, the overall kangaroo population in Victoria was estimated to be 1 942 000 (95% CI: 1 513 000 – 2 492 000). That is a 36% increase from the 2017 and 2018 estimates of 1.4 million kangaroos (Moloney *et al.* 2017; Moloney *et al.* 2019).

Table 2. Kangaroo density (kangaroos/km^2) estimates and their precision (coefficient of variation) by survey zone for grey and red kangaroos.

Lower and upper bounds indicate the 95% confidence intervals.

Species	Survey zone	Density estimate	Standard error	Coefficient of variation	Lower bound	Upper bound
GK	Mallee	1.7	0.34	0.2	1.1	2.6
GK	Upper Wimmera	3.4	0.86	0.25	2.1	5.6
GK	Lower Wimmera	13.7	3.09	0.23	8.6	21.7
GK	Otway	14.1	6.58	0.47	5.5	36.2
GK	Central	54.2	11.23	0.21	34.3	85.8
GK	North East	9.7	4.17	0.43	4.2	22.7
GK	Gippsland	10.9	3.14	0.29	6	19.7
RK	Mallee	1.4	0.57	0.41	0.6	3.2

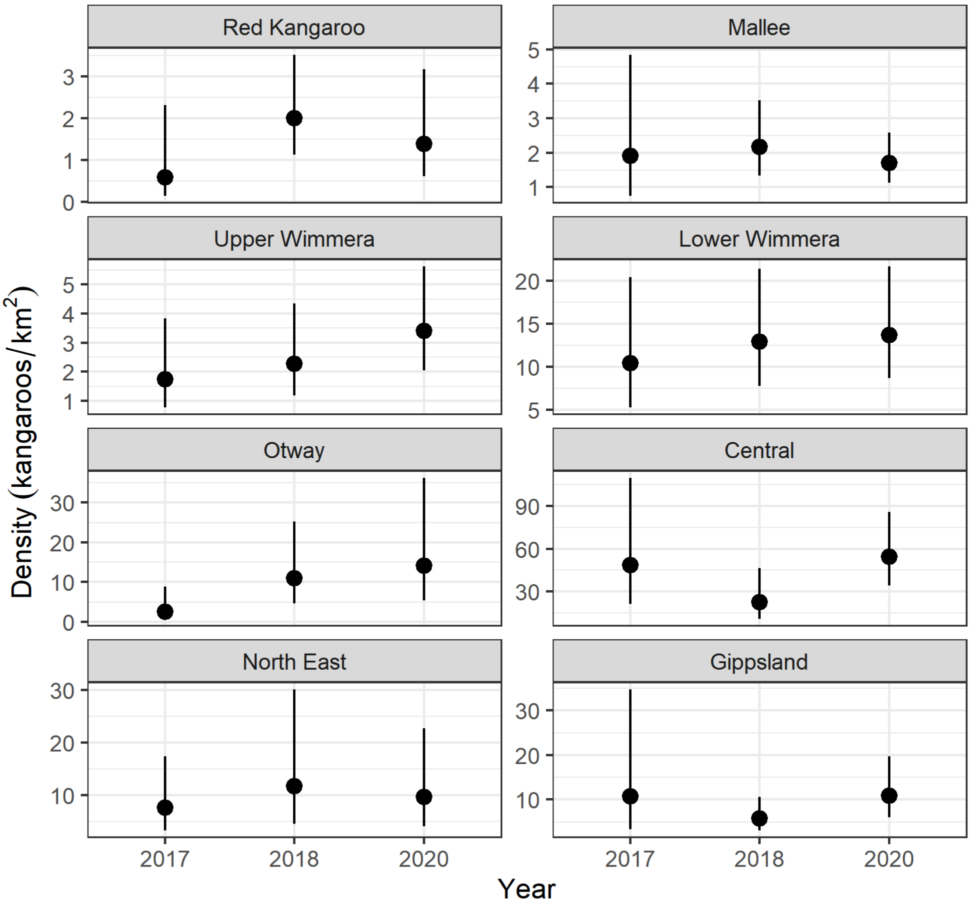

Figure 5. Comparison of survey zone density estimates in 2017, 2018 and 2020. Density is kangaroos per square kilometre. Red Kangaroo is only for the Mallee zone. All other survey zone estimates are for the aggregated grey kangaroos. Error bars are 95% confidence intervals. Note the density scale differs among survey zones.

3.2 Geographic variation in the Proportion of Eastern and Western Grey Kangaroos

The space-time GAM model fitted to the ground survey and atlas data indicated both the space and time terms in the model and their interactions were significant, with the model explaining 94% of the overall space-time variation in the proportions of the two GK species. The significant time and space-time interaction terms were consistent with the hypothesis that the GKOZ had moved over recent decades, with predictions over time suggesting a complex pattern of movement of the zone with expansion of WGK in the northern part of the GKOZ, and corresponding retraction of WGK in the southern part of the zone, most notably in far south-western Victoria and adjacent parts of South Australia.

The predictions of the space-time GAM model as of 2020 are shown in Figures 6–8, with all recent atlas and ground survey records for the period 2015–2020 overlaid. (The coordinate system for all maps is VicGrid). Overall, the fitted model coincides well with our existing knowledge of the current position and extent of the GKOZ. Estimated proportions of EGK in the Mallee, Upper Wimmera and Lower Wimmera zones ranged from 2.5 to 83% (Table 3). These estimates were used to apportion the total estimates of GK abundance between the two species in the three survey zones spanning the Victorian portion of the GKOZ.

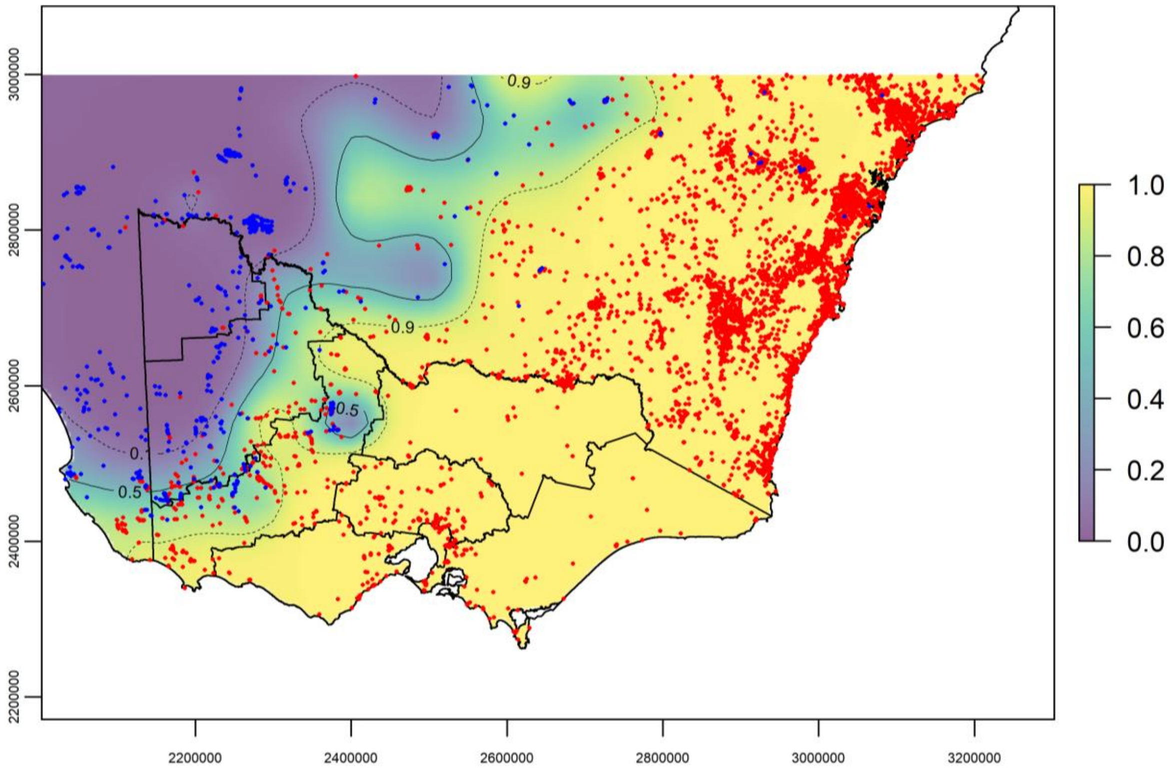

Figure 6. Spatial variation in the estimated proportion of EGK across the study area, as predicted by the space-time Generalized Additive Model. Predictions are for the year 2020.
Overlaid points are observations of Eastern (red points) and Western (blue points) Grey Kangaroos between 2015 and 2020, including records from the ground surveys described in the text as well as records obtained from the Atlas of Living Australia. Overlaid contour lines are 10, 50 and 90 percent iso-probability lines.

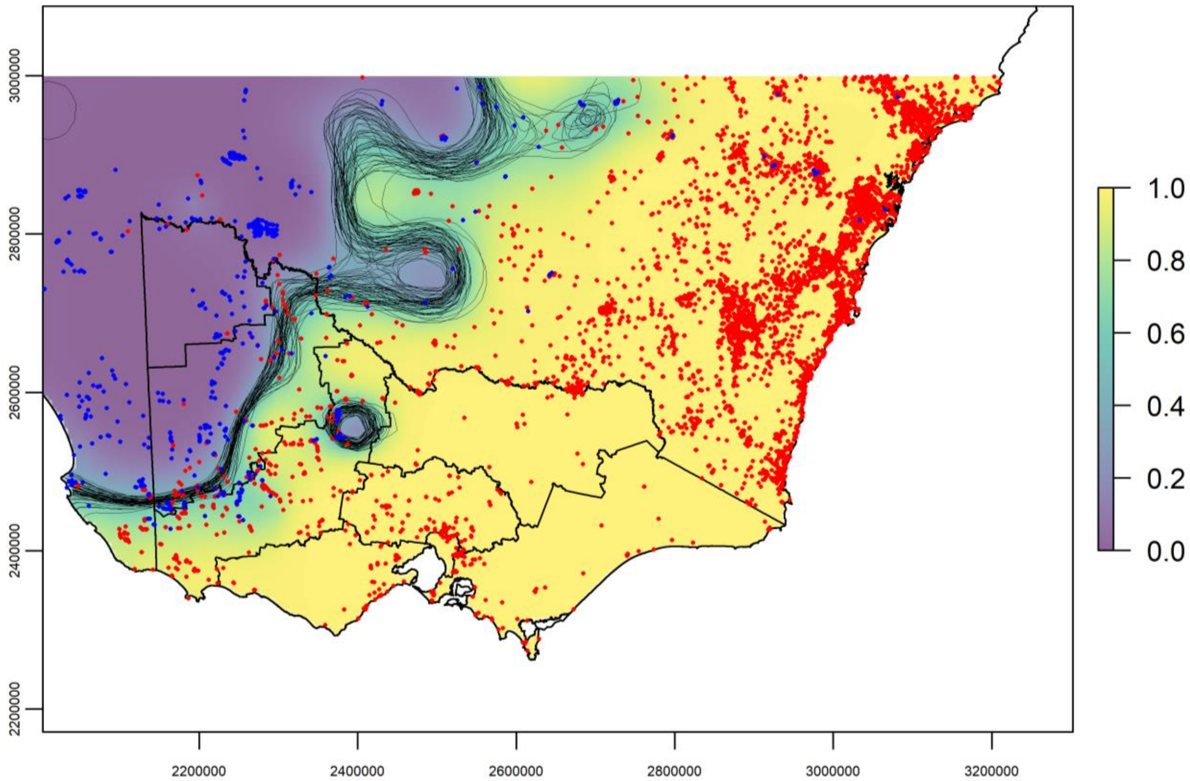

Figure 7. This map displays the same information as Figure 6, except that the multiple overlaid contours represent uncertainty as to the present (2020) location of the midline of the Grey Kangaroo Overlap Zone.

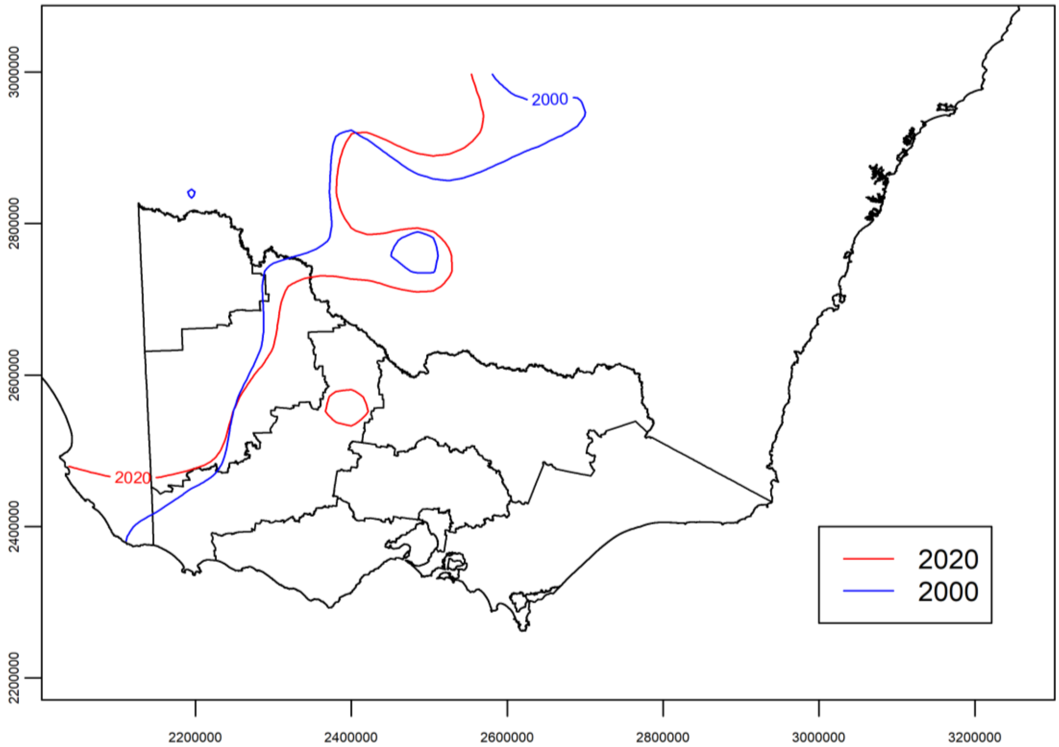

Figure 8. Estimated change in the location of the 50% iso-probability line between 2000 and 2020.

Table 3. Estimated proportions of EGK in each survey zone within the GKOZ during 2020, along with corresponding estimates of uncertainty.

Proportions are derived from the predictions of the space–time Generalised Additive Model fitted to the ground survey data and available Atlas of Living Australia records for the two species (see methods).

SD = standard deviation; lower and upper bounds = 95% confidence interval.

Survey Zone	Estimate	SD	Lower bound	Upper bound
Mallee	0.024	0.008	0.014	0.047
Upper Wimmera	0.377	0.024	0.331	0.423
Lower Wimmera	0.838	0.021	0.791	0.870

3.3 Kangaroo abundance estimates for each LGA

Estimates of the number of EGK, WGK and RK in each LGA are provided in the Appendix (Tables A2, A3 and A4 respectively). A visual summary of those results for EGK and WGK are shown in Figures 9 and 10. The overall estimates from 2020 were generally larger than those from 2017 and 2018 (Moloney *et al.* 2017; Moloney *et al.* 2019). Approximately 70% of LGA estimates increased in 2020. The overall estimate for 2020 was relatively more precise (Table 5 and Figure 11).

As in 2018, the majority (88%) of kangaroos were EGK, although the population estimate for that species in 2020 was larger than 2017 and 2018. The estimated population of RK was lower in 2020 than 2018. However, none of these changes are significant (Figure 11). The estimated population of WGK increased in each survey since 2017, with the difference in 2017 to 2020 being significant. This increase is partly a result of the change in WGK proportion across the GKOZ with the estimated 50% iso-probability contour for the EGK–WGK boundary moving south-east over that time in the northerly part of the Upper Wimmera zone and adjacent part of the Mallee zone (Figure 8).

The precision of abundance estimates increased for most survey zones compared with the corresponding estimates in 2017 and 2018 (Table 4). North East and Otway zones (EGK) and the Mallee zone (RK) all had relatively low precision, with coefficients of variation over 40%.

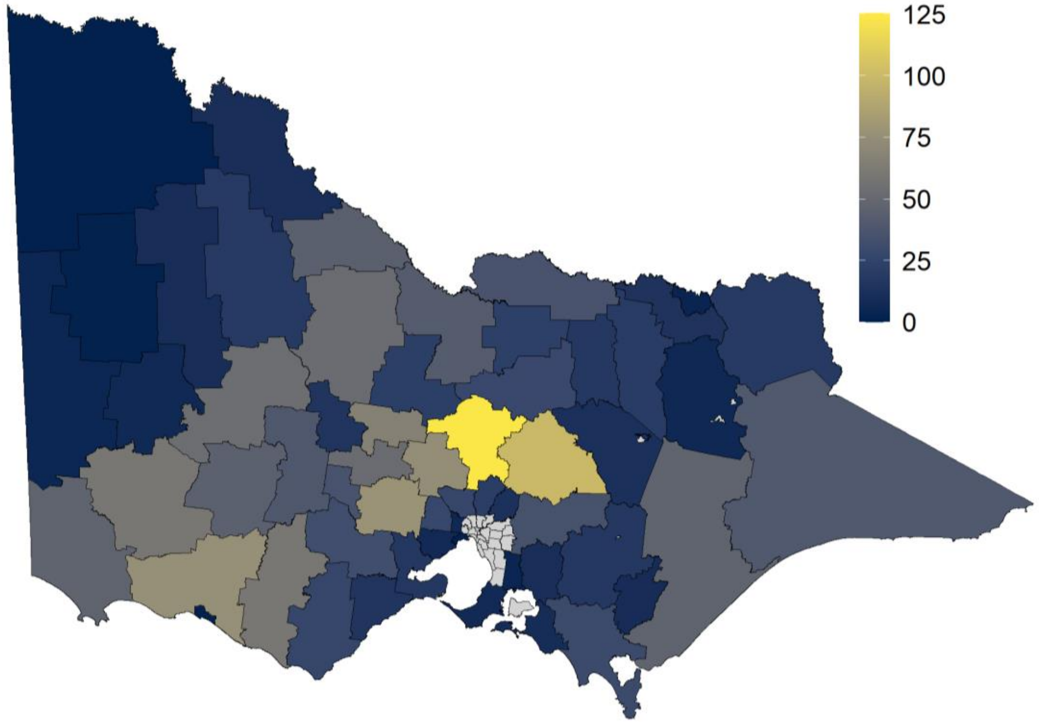

Figure 9. EGK abundance estimates by LGA.
Scale is in thousands of kangaroos. LGAs shaded grey were not surveyed and were excluded from the analysis.

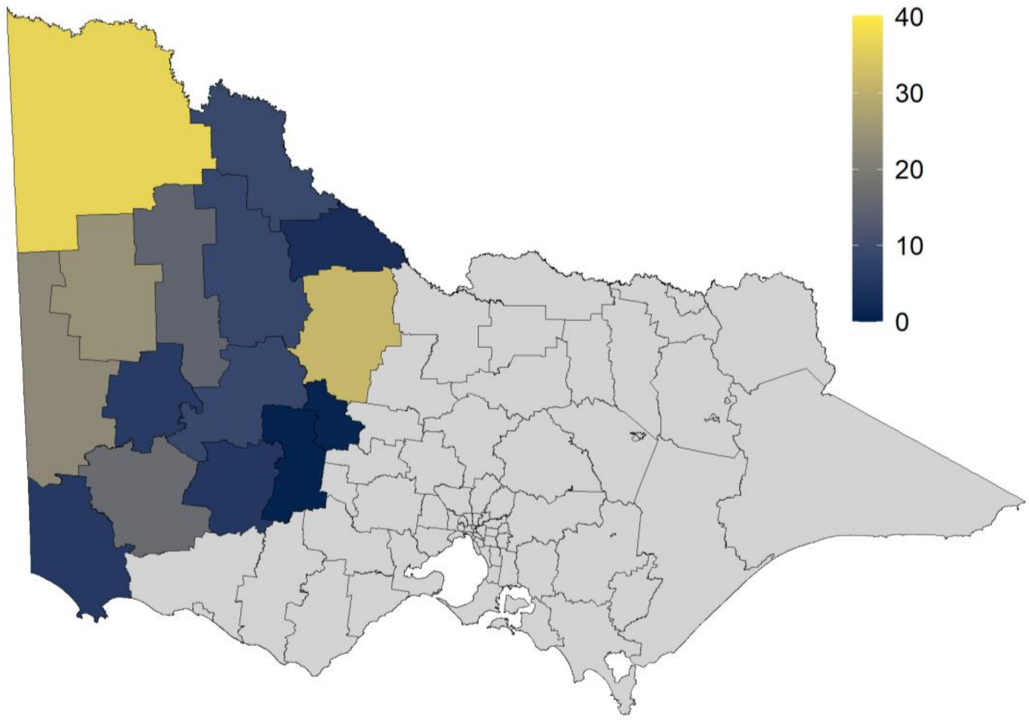

Figure 10. WGK abundance estimates by LGA.
Scale is in thousands of kangaroos. LGAs shaded grey were excluded from the analysis as Western Grey Kangaroos are known to be absent from these areas.

Table 4. Relative precision (coefficient of variation) of kangaroo abundance estimates as a percentage for various populations of kangaroos across Victoria in 2017, 2018 and 2020.

Lower values indicate higher precision.

		Coefficient of variation (%)		
Region	**Species**	**2017**	**2018**	**2020**
Mallee	RK	67	25.9	40.9
Mallee	EGK	43	23.4	20.2
Upper Wimmera	EGK	39	32.8	25.2
Lower Wimmera	EGK	32	24.9	22.6
Otway	EGK	54	41.2	46.7
Central	EGK	35	31.4	20.7
North East	EGK	40	48.2	43.0
Gippsland	EGK	53	30.2	28.8
Victoria-wide	EGK	19.6	17.6	13.6
Victoria-wide	WGK	28.8	18.2	17.1
Victoria-wide	RK	67.0	25.9	40.9
Victoria-wide	All species	18.8	15.7	12.5

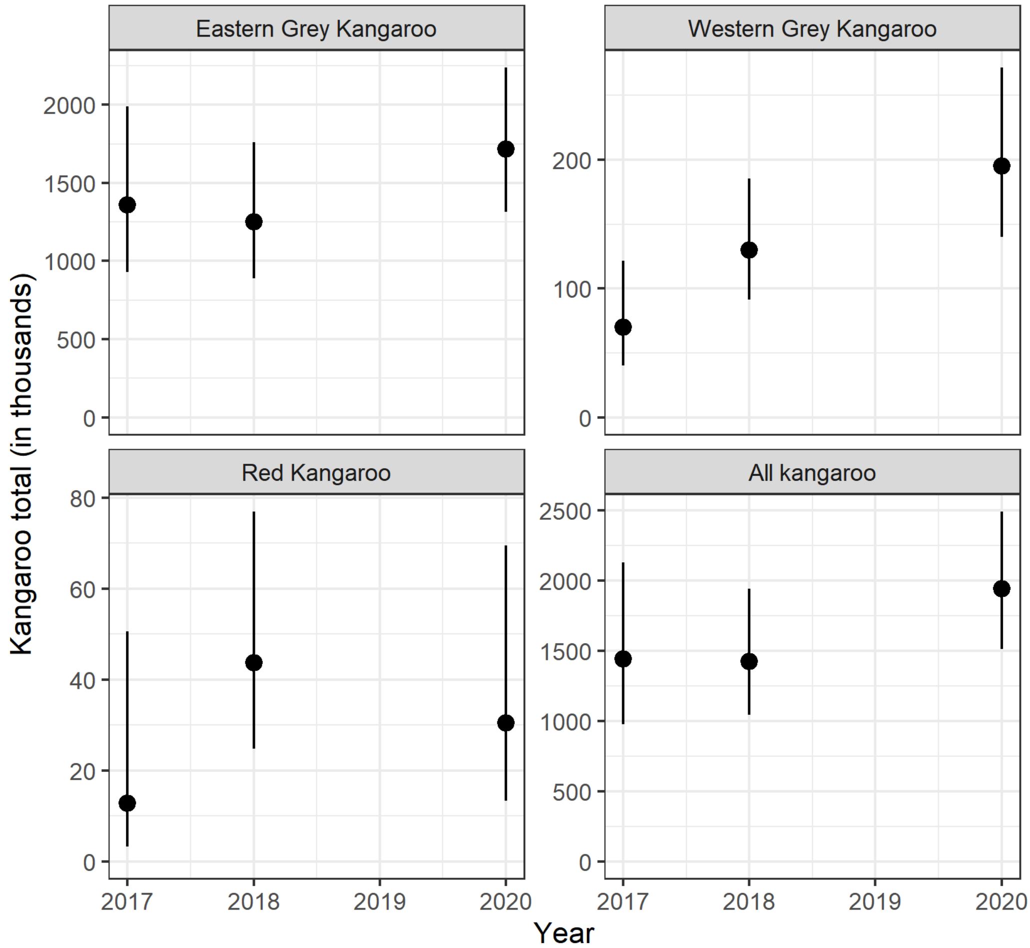

Figure 11. Comparison of Victorian-wide abundance estimates for the three species of kangaroos between 2017 and 2020.
Scales are in thousands of kangaroos. Error bars are 95% confidence intervals.

4 Discussion

Based on our analysis of the aerial survey data, we estimated that the overall kangaroo population in Victoria was 1 942 000 (95% confidence interval: 1 513 000 – 2 492 000). There were an estimated 1 717 000 (1 316 000 – 2 239 000) EGK, accounting for the overwhelming majority (88%) of Victorian kangaroos. The remaining part of the total kangaroo population was comprised of an estimated 195 000 (140 000 – 272 000) WGK and 30 000 (13 000 – 69 000) RK. The overall kangaroo estimate for 2020 (1 440 000: Figure 11) was larger than the estimates from the 2017 and 2018 surveys, but the changes in abundance from 2018 to 2020 are not statistically significant. However, the estimated WGK abundance seems to be increasing over time, and the difference between the 2017 and 2020 estimates is significant (Figure 11).

The Victoria-wide estimate of the kangaroo population met the precision goal, having a precision (expressed as the coefficient of variation, CV) of 12.5%, which was less than the target CV of 20% identified in the sampling design (Moloney *et al.* 2018). The precision of abundance estimates for each GK species has improved over time (Table 5), but the precision for the RK estimate decreased compared to 2018 but was still better than the 2017 precision. The precision of abundance estimates for individual zones ranged from 20.2% (Mallee zone for GK) to 46.7% (Otway zone for EGK). While the precision of the abundance estimates for individual zones had generally improved since the 2017 survey, the level of improvement was less than expected in some zones. The main reason for this was the high level of aggregation of kangaroos within some zones. Transects in the North East and Otway zones were subject to the chance sampling of large numbers of kangaroos on some transects, which formed a large proportion of the totals seen in these zones. Large aggregations of kangaroos inflate the transect-level variance for the zone, leading to decreased precision. Although population estimates with high precision (CV < 25%) are generally required for most management objectives (Skalski and Millspaugh 2002), population estimates with a relative precision over 50% can increase the risk of over-harvesting (Pople 2008). The CV for EGK for the North East and Otway zones and RK for the Mallee zone is marginally below this 50% threshold, but all other zones are clearly below the 50% threshold. Hence the levels of precision reached for the estimates from the 2020 survey are considered to be suitable for the setting of sustainable harvest quotas.

The space–time GAM model continues to provide an effective means of apportioning the population estimates for GKs derived from the aerial survey between the two species (EGK and WGK). This approach allows the estimation of spatial variation in the proportions of the two species to be based on systematically collected ground survey data as well as historic occurrence records derived from the Atlas of Living Australia. This means that all relevant data can inform our estimates of EGK:WGK ratios for both survey zones and other relevant geographic aggregations such as local government areas. Previously noted uncertainty in the location of the GKOZ has been somewhat resolved by this analysis. Across much of the GKOZ, the location of the 50% iso-probability line is known with a high degree of certainty (Figure 6). This means that relatively little of the uncertainty in the separate abundance estimates for EGK and WGK for the Mallee, Upper and Lower Wimmera zones will be attributable to uncertainty in the assignment of the total kangaroo population estimates to the two species.

Estimates of the proportion of EGK in the Mallee zone were markedly lower than estimates from a previous analysis using the same methodology (Moloney *et al.* 2019). This finding probably needs to be interpreted cautiously, as it is based on a relatively small number of recent observations of EGK in and around the Mallee zone. It is conceivable that this finding is therefore partly a statistical artefact. Collection of additional ground survey data on the distribution and abundance of EGK within the Mallee zone would be prudent, as the size of the EGK population in this zone is relatively small and therefore vulnerable to overharvesting.

The results from the 2020 aerial survey indicate that Victoria's kangaroo population has increased since 2018, although uncertainty in the successive estimates of abundance means that the size of the relative change between years is difficult to interpret. Although high levels of kangaroo aggregation in some zones continue to hamper the precise estimation of density and abundance, the level of precision obtained can be considered adequate for the setting of sustainable harvest quotas. Alternatively, given the high level of kangaroo aggregation observed during the aerial surveys, consideration could be given to using a model-based distance sampling approach (Camp *et al.* 2020). This would allow the data collected previously and, in the future, to be included in a single model that could account for fine scale (e.g. 1–5 km) differences in abundance across the landscape as well as changes over time. Model-based approaches (where densities would be related to geographical and environmental conditions at the transect)may provide increased precision compared with the existing design-based approach (where densities are assumed consistent across a zone), with the trade-off that estimates may have increased bias. However, a preliminary model-based approach using the 2018 aerial survey data (Scroggie and Ramsey 2020) indicated that this approach has merit, and could be further investigated now that three years of aerial survey data have accumulated. Furthermore, a model-based distance sampling approach could incorporate distance sampling from other sources, such as the line-transect kangaroo surveys undertaken in the Mallee by Parks Victoria (Mackenzie 2017).

Given the level of precision achieved with the current survey, and the need to use the resulting estimates in the setting of sustainable harvest quotas, continuation of the current survey frequency of once every two years is advised. Although studies have shown that surveys every three years greatly reduce the long-term survey costs without substantially increasing the risk of over-harvesting or inappropriate control measures (Pople 2008), more frequent surveys are recommended here. This is because of the relatively small number of surveys that have been undertaken in Victoria to date. Regular, more frequent surveys will allow the trends in kangaroo abundance over time to be more accurately established. This, in turn, will allow the impacts of various level of kangaroo offtake or the impacts of severe or prolonged drought, to be more accurately assessed. More frequent and more precise surveys of abundance are also prudent if high overall rates of harvest are intended, as risks of overharvesting and subsequent population decline will be exacerbated if uncertain population estimates inadvertently result in higher than intended rates of harvesting.

4.1 Recommendations

- Continuation of the current survey frequency of every two years is recommended. If the survey frequency is reduced, conditions such as severe or prolonged drought may require the frequency to be increased back to every two years.
- Consideration could be given to reducing the frequency of ground surveys as the position of the Grey Kangaroo Overlap Zone (GKOZ), the area where Eastern and Western Grey kangaroos overlap, is now better understood.
- Some further targeted ground surveys may provide a better understanding of the distribution and abundance of the EGK in the Mallee zone, as estimates of the proportion of EGK in this area were markedly lower than was found previously.
- Given the high level of kangaroo aggregation seen during the aerial surveys, consideration could be given to using a model-based distance sampling approach, which could result in improved estimates of abundance for each survey zone as well as enable estimates for smaller regions.

5 References

Atlas of Living Australia (2021a). Records of Eastern Grey Kangaroo. Atlas of Living Australia, accessed 29 Jan 2021 doi: 5762f951-7b01-4ecf-afd9-4631233d753c.

Atlas of Living Australia (2021b). Records of Western Grey Kangaroo. Atlas of Living Australia, accessed 29 Jan 2021 doi: ala.9eb5fa7a-145e-461b-a415-8aa7f464cbfb.

Buckland, S. T., Anderson, D. R., Burnham, K. P., and Laake, J. (1993). 'Distance sampling: estimating abundance of biological populations'. (Chapman & Hall: London.)

Burnham, K. P., and Anderson, D. R. (2002). 'Model selection and multimodel inference: a practical information-theoretic approach'. (Springer-Verlag, New York: New York.)

Camp, R. J., Miller, D. L., Thomas, L., Buckland, S. T., and Kendall, S. J. (2020). Using density surface models to estimate spatio-temporal changes in population densities and trend. *Ecography* **43**, 1079–1089. doi:10.1111/ecog.04859

Caughley, G., Brown, B., Dostine, P., and Grice, D. (1984). The grey kangaroo overlap zone. *Wildlife Research* **11**, 1–10.

Caughley, G., Shepherd, N., and Short, G. (1987). 'Kangaroos, their ecology and management in the sheep rangelands of Australia'. (Cambridge University Press: Cambridge.)

Caughley, G., Sinclair, R., and Scott-Kemmis, D. (1976). Experiments in Aerial Survey. *The Journal of Wildlife Management* **40**, 290–300. doi:10.2307/3800428

Coulson, G. (2017). Ground survey of grey kangaroos in Victoria, September 2017. Macropus Consulting report to the Department of Environment, Land, Water and Planning, Victoria.

Coulson, G. (2018). Ground surveys of grey kangaroos in Victoria, September 2018. Macropus Consulting report to the Department of Environment, Land, Water and Planning, Victoria.

Coulson, G. (2020). Ground surveys of grey kangaroos in Victoria, spring 2020. Macropus Consulting report to the Department of Environment, Land, Water and Planning, Victoria.

Efron, B., and Tibshirani, R. J. (1993). 'An introduction to the bootstrap'. (Chapman and Hall: London, UK.)

Fewster, R. M., and Pople, A. R. (2008). A comparison of mark-recapture distance-sampling methods applied to aerial surveys of eastern grey kangaroos. *Wildlife Research* **35**, 320–330.

Hacker, R., Mcleod, S., Druhan, J., Tenhumberg, B., and Pradhan, U. (2004). Kangaroo management options in the Murray-Darling Basin. Murray-Darling Basin Commission, Canberra, Australia.

Lethbridge, M., and Stead, M. (2017). Victorian aerial kangaroo population survey: Insights and learnings from Victoria's first state-wide kangaroo aerial survey. Report to the Department of Environment, Land, Water and Planning, Victoria.

Mackenzie, D. I. (2017). Distance analysis of Mallee parks kangaroo census data 2017. Report for Parks Victoria, Proteus Client report 1., Proteus, Outram, New Zealand.

McLeod, S. R., Hacker, R. B., and Druhan, J. P. (2004). Managing the commercial harvest of kangaroos in the Murray-Darling Basin. *Australian Mammalogy* **26**, 9–22.

Miller, D. L. (2017). Distance: Distance Sampling Detection Function and Abundance Estimation. Available at: https://cran.r-project.org/package=Distance

Moloney, P. D., Ramsey, D. S. L., and Scroggie, M. P. (2017). A state-wide aerial survey of kangaroos in Victoria. Arthur Rylah Institute for Environmental Research Technical Report Series No. 286, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Moloney, P. D., Ramsey, D. S. L., and Scroggie, M. P. (2019). State-wide abundance of kangaroos in Victoria: Results from the 2018 aerial survey. Arthur Rylah Institute for Environmental Research Technical Report Series No. 296, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Moloney, P. D., Scroggie, M. P., and Ramsey, D. S. L. (2018). Revisiting the Victorian kangaroo aerial survey design. Unpublished Client Report. Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Pople, A. R. (2008). Frequency and precision of aerial surveys for kangaroo management. *Wildlife Research* **35**, 340–348. doi:10.1071/WR07066

R Development Core Team (2020). R: A language and environment for statistical computing. Available at: http://www.r-project.org

Scroggie, M. P., and Ramsey, D. S. L. (2020). 'A Spatial Harvest Model for Kangaroo Populations in Victoria'. (Arthur Rylah Institute for Environmental Research Technical Report Series No. 315: Department of Environment, Land, Water and Planning, Heidelberg, Victoria.)

Skalski, J. R., and Millspaugh, J. J. (2002). Generic variance expressions, precision, and sampling optimization for the sex-age-kill model of population reconstruction. *Journal of Wildlife Management* **66**, 1308–1316.

Tracey, J. P., Fleming, P. J. S., and Melville, G. J. (2008). Accuracy of some aerial survey estimators: Contrasts with known numbers. *Wildlife Research* **35**, 377–384. doi:10.1071/WR07105

Wood, S. N. (2017). 'Generalized additive models: an introduction with R' 2nd ed. (CRC Press, Taylor and Francis Group: Boca Raton, Florida.)

Wood, S. N., Bravington, M. V., and Hedley, S. L. (2008). Soap film smoothing. *Journal of the Royal Statistical Society, Series B* **70**, 931–955.

Appendix

Table A1. Akaike's Information Criterion (AIC) for detection function models considered in the analysis of the distance sampling data.

Models with lower AIC values (ΔAIC) are better supported by the data.

Model	AIC	ΔAIC
Hazard-rate with second order cosine adjustments	4306.3	
Half-normal with second and third order cosine adjustments	4306.7	0.4
Half-normal with second order cosine adjustments	4308.6	2.3
Half-normal with second to fourth order cosine adjustments	4308.7	2.4
Half-normal	4311.1	4.8
Hazard-rate	4315.2	8.9

Table A2. Abundance estimates for Eastern Grey Kangaroo by LGA to the nearest 100.

SE = standard error; lower and upper bounds = 95% confidence interval.

LGA name	Survey zone	Area (km^2)	Estimate	SE	Lower bound	Upper bound
Alpine	North East	607	5900	2800	2700	13300
Ararat	Lower Wimmera	3649	44700	10500	28700	69900
Ballarat	Central	659	35700	7500	23900	53300
Bass Coast	Gippsland	846	9200	2700	5300	15900
Baw Baw	Gippsland	1530	16700	5000	9600	29400
Benalla	North East	1727	16800	7800	7400	37700
Brimbank	Central	123	6700	1400	4500	10000
Buloke	Upper Wimmera	7991	18500	5100	11000	30900
Campaspe	North East	4267	41400	19400	18600	93200
Cardinia	Gippsland	967	10500	3100	6100	18300
Casey	Gippsland	391	4300	1300	2400	7400
Central Goldfields	Lower Wimmera	1159	14900	3400	9500	22900
Colac Otway	Otway	1907	26800	13700	11100	64200
Corangamite	Otway	4230	59500	30200	24600	141600
East Gippsland	Gippsland	3617	39400	11900	22600	68900
Gannawarra	Lower Wimmera	3490	44400	10500	28600	69200
Glenelg	Lower Wimmera	3816	46500	10700	30000	71200
Golden Plains	Otway	2295	32300	16700	13500	77300

LGA name	Survey zone	Area (km²)	Estimate	SE	Lower bound	Upper bound
Greater Bendigo	North East	2268	22000	10200	10000	49000
Greater Geelong	Otway	1220	17200	8800	7300	41100
Greater Shepparton	North East	2317	22500	10700	10100	51400
Hepburn	Central	965	52300	11100	35100	78300
Hindmarsh	Upper Wimmera	7523	1200	500	500	2600
Hobsons Bay	Otway	65	900	500	400	2200
Horsham	Upper Wimmera	3844	6900	1900	4200	11400
Hume	Central	503	27300	5800	18300	40900
Indigo	North East	1421	13800	6400	6200	30800
Latrobe	Gippsland	880	9600	2900	5500	17100
Loddon	Lower Wimmera	6119	52300	13400	31500	84400
Macedon Ranges	Central	1372	74400	15900	49300	111900
Mansfield	North East	1205	11700	5400	5200	26200
Melton	Central	508	27500	5800	18500	41100
Mildura	Mallee	21875	1000	400	400	1900
Mitchell	Central	2278	123500	26100	82800	185600
Moira	North East	3651	35500	16800	15700	81600
Moorabool	Central	1431	77600	16600	51500	116200
Mornington Peninsula	Gippsland	644	7000	2100	4000	12100
Mount Alexander	Central	1223	66300	14100	43900	99000
Moyne	Otway	5387	75800	39000	30900	179700
Murrindindi	Central	1832	99400	20800	66600	147200
Nillumbik	Central	225	12200	2600	8100	18300
Northern Grampians	Lower Wimmera	4564	53700	12500	34100	82600
Pyrenees	Lower Wimmera	2891	38900	9000	25300	60100
South Gippsland	Gippsland	2686	29300	9000	16800	51600
Southern Grampians	Lower Wimmera	5552	59500	14000	38000	92700
Strathbogie	North East	2901	28200	13400	12300	63600
Surf Coast	Otway	1063	15000	7800	6400	36200
Swan Hill	Upper Wimmera	5903	11000	3100	6300	18600
Towong	North East	1871	18200	8500	8100	40400
Wangaratta	North East	2059	20000	9400	9100	44900
Warrnambo ol	Otway	120	1700	900	700	4100

LGA name	Survey zone	Area (km^2)	Estimate	SE	Lower bound	Upper bound
Wellington	Gippsland	4277	46700	14000	27100	80900
West Wimmera	Upper Wimmera	8054	4800	1300	2900	8100
Whittlesea	Central	392	21300	4500	14300	31900
Wodonga	North East	403	3900	1900	1700	8900
Wyndham	Otway	542	7600	4000	3300	18500
Yarra Ranges	Central	638	34600	7200	23300	51400
Yarriambiac k	Upper Wimmera	7320	9900	2800	5800	16700

Table A3 Abundance estimates for Western Grey Kangaroo by LGA to the nearest 100.

SE = standard error; lower and upper bounds = 95% confidence interval.

LGA name	Survey zone	Area (km^2)	Estimate	SE	Lower bound	Upper bound
Ararat	Lower Wimmera	3649	5300	2100	2400	10800
Buloke	Upper Wimmera	7991	8600	2800	4700	15400
Central Goldfields	Lower Wimmera	1159	1000	500	300	2400
Gannawarra	Lower Wimmera	3490	3400	1800	1200	8300
Glenelg	Lower Wimmera	3816	5700	1700	3200	9800
Hindmarsh	Upper Wimmera	7523	24300	6500	14900	40200
Horsham	Upper Wimmera	3844	6100	1700	3600	10100
Loddon	Lower Wimmera	6119	31500	9300	17500	53800
Mildura	Mallee	21875	36300	7600	24500	54400
Northern Grampians	Lower Wimmera	4564	8800	2600	5000	15200
Pyrenees	Lower Wimmera	2891	700	400	200	1900
Southern Grampians	Lower Wimmera	5552	16500	4400	9900	27100
Swan Hill	Upper Wimmera	5903	9100	2700	5200	15900
West Wimmera	Upper Wimmera	8054	22600	5900	14000	36800
Yarriambiack	Upper Wimmera	7320	14900	4000	8900	24500

Table A4. Abundance estimates for Red Kangaroo by LGA to the nearest 100.

SE = standard error; lower and upper bounds = 95% confidence interval.

LGA name	Survey zone	Area (km^2)	Estimate	SE	Lower bound	Upper boun d
Mildura	Mallee	21875	30400	12500	12300	69500

www.delwp.vic.gov.au

www.ari.vic.gov.au