Kangaroo harvest quotas for Victoria, 2020

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

December 2019

Arthur Rylah Institute for Environmental Research
Technical Report Series No. 308

Arthur Rylah Institute for environmental research

VICTORIA State Government | Environment, Land, Water and Planning

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: Scroggie, M.P. and Ramsey, D.S.L. (2019). *Kangaroo harvest quotas for Victoria, 2020*. Arthur Rylah Institute for Environmental Research Technical Report Series No. 308. Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Front cover photo: Western Grey Kangaroo (Source: Lindy Lumsden).

Edited by Organic Editing

ISSN 1835-3827 (print)
ISSN 1835-3835 (pdf))
ISBN 978-1-76077-915-3 (print)
ISBN 978-1-76077-916-0 (pdf/online/MS word)

Kangaroo harvest quotas for Victoria, 2020

M.P. Scroggie[1] and D.S.L. Ramsey[1]

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

Arthur Rylah Institute for Environmental Research
Technical Report Series No. 308

Arthur Rylah Institute for Environmental Research
Department of Environment, Land, Water and Planning
Heidelberg, Victoria

Acknowledgements

We thank the participants in the Department of Environment, Land, Water and Planning (DELWP) kangaroo harvesting program workshop for sharing their expertise during the early stages of this project. We thank Elizabeth Coluccio (Biodiversity Division) and Paul Moloney (Arthur Rylah Institute) for helpful comments on drafts of this report. This work was funded by the Biodiversity Division, DELWP.

Contents

Tables

Figures

Summary

Context:

The Victorian Government has adopted a policy of supporting ecologically sustainable commercial harvesting of wild Eastern and Western Grey kangaroo populations in the state. To support the implementation of this policy, there is a requirement to develop a means of setting ecologically sustainable harvesting quotas in order to avoid overexploitation of kangaroo populations.

Aims:

We aimed to develop a simple stochastic harvest model for Victorian kangaroo populations that can be used to explore the effects of different harvesting rates and assumed demographic parameters on the ecological risks associated with the proposed harvest program.

Methods:

Given the paucity of demographic data available for kangaroo populations in Victoria, information was obtained from population studies elsewhere in Australia to support the development of a simple stochastic population model. This model was used to investigate the ecological risks associated with a range of harvesting rates of between zero and 30% per annum.

Results:

Conditional on the assumptions of the stochastic model, harvesting rates of up to 10% per annum were found to be of very low ecological risk. The relative risks of alternative harvesting rates were sensitive to the assumed value of the maximum rate of kangaroo increase $r_{\max}$. Harvesting rates higher than 20% per annum had unacceptably high ecological risks.

Conclusions and implications:

Based on a risk analysis using this model, it is recommended that a maximum harvest rate of 10% per annum be currently adopted for Victorian kangaroo populations. Somewhat higher harvest rates may be justifiable in the future, but current uncertainties about the demographic rates of Victorian kangaroo populations mean that potential ecological risks associated with rates greater than 10% per annum remain unacceptable. The recommended 10% maximum rate includes all sources of culling mortality (i.e. not just commercial harvest), so policy mechanisms would be needed to apportion the total annual quota between commercial harvest and culling under the Authority to Control Wildlife provisions of the *Wildlife Act 1975* (Victoria).

Recommendations:

- Over the near term (e.g. 2020–2025), a harvest fraction of 10% of the population is recommended. Raising the harvest fraction to a higher percentage such as 15% may be possible in the future, but would require detailed analysis of additional monitoring and harvest data to ensure that overexploitation of kangaroos did not occur.
- For the 2020 calendar year, a total quota of 137,800 grey kangaroos is recommended as the maximum sustainable offtake. This includes kangaroos culled by both commercial harvesting and the Authority to Control Wildlife (ATCW) permit process.
- Aerial surveying of the kangaroo population should be undertaken at least every 3 years, using the methods presented in Moloney et al. (2018). If a harvest fraction greater than 10% is desired, then an increase in the frequency of monitoring to once a year, or once every second year is recommended.
- Accurate and detailed harvest records, including the location, species, sex, and age class of all harvested kangaroos should be maintained. These harvest statistics will provide valuable information for future population modelling and analysis to support quota setting and management in the future.

1 Introduction

Following termination of the Kangaroo Pet Food Trial (KPFT) in 2019, the Victorian Government adopted a policy supporting the commercial harvest of kangaroos in Victoria. To ensure the ecological sustainability of the program, it is essential that the maximum number of kangaroos that are permitted to be harvested each year is determined based on clear ecological criteria, with administrative and regulatory controls in place to ensure that the populations are not overexploited.

Scroggie et al. (2019) developed interim harvest quotas for the final quarter of calendar year 2019 based on a policy of allowing a maximum harvest fraction of 10% of the estimated kangaroo population in each calendar year. As these interim quotas were intended to apply for only a 3-month period, the nominal 10% annual harvest quota was divided by four to arrive at recommended interim quotas. Proportional harvest quotas of 10% were recommended for both kangaroo species for which harvest is permitted in Victoria (Eastern Grey Kangaroo, *Macropus giganteus* and Western Grey Kangaroo, *M. fuliginosus*), with the total quota further divided between seven harvest management zones based on the proportions of the total statewide population located in each zone. Legal culling of kangaroos takes place both through the commercial harvest program, as well as via the Authority to Control Wildlife (ATCW) provisions of the *Wildlife Act 1975* (Victoria). For the purposes of this report, no distinction is made between these two mechanisms for permitting culling. Regulatory frameworks will need to include mechanisms for apportioning the total ecologically sustainable harvest between these two categories. Scroggie et al. (2019) suggested various management options for determining this apportionment.

Based on long experience of quota setting for harvesting kangaroo populations in other Australian jurisdictions, harvest quotas of 15–20% are routinely applied to populations of kangaroos in Queensland, New South Wales and South Australia (Hacker et al. 2004; McLeod et al. 2004), and the 10% quota recommended by Scroggie et al. (2019) could be considered conservative. However, the apparently conservative Victorian interim quotas reflect the much less extensive available data on kangaroo population dynamics that were available from Victoria in comparison with other states. Most available data and analysis pertinent to setting kangaroo harvest quotas has been collected from populations of Red Kangaroos (*Osphranter rufus*), Western Grey Kangaroos and Euros (*Macropus robustus*) inhabiting arid and semi-arid ecosystems, including rangeland ecosystems in New South Wales, Queensland and South Australia. Several authors have used available long-term population density and abundance data from these systems to construct stochastic population models for assessing the ecological risks associated with harvest policies for arid-zone kangaroo populations (e.g. McCarthy 1996; Jonzen et al. 2005; Chee and Wintle 2010). Such models use time-series observations of abundance or density of kangaroos, alongside harvest statistics, and data on presumed drivers of kangaroo demography (such as rainfall and pasture availability), to infer relationships between the rate at which kangaroo populations increase, and spatially and temporally varying factors such as density dependence, resource availability and harvest offtake.

The lack of comparable time-series abundance data for kangaroo populations in Victoria means that development of such models for Victorian kangaroo populations must rely on ecological and demographic information collected from kangaroo populations elsewhere. Much of Victoria has a mesic climate, with higher and more consistent rainfall and pasture growth than is the case in more arid systems, so it is likely that the demography of Victorian kangaroo populations will differ markedly from those in other states. As harvest and abundance monitoring data accumulate, models based on Victorian data can gradually replace those based on semi-arid systems, leading to greater model realism, and greater confidence when using the models for management decision-making such as quota-setting. In the interim, a conservative approach to quota-setting should be retained until adequate local monitoring data and management experience can be used to inform and validate more robust stochastic models for Victorian kangaroo populations.

The purpose of this report is to present additional analysis supporting the setting of quotas for the commercial harvest of kangaroos in Victoria for the 2020 calendar year. To this end, a preliminary stochastic model of kangaroo population dynamics for Victoria was developed to explore the effects of varying harvest proportions, as well as demographic and environmental variation, on the sustainability of the annual harvest of kangaroos. The outcomes of this initial modelling were then used to determine an annual harvest quota that balances the competing objectives of maximising long-term cumulative harvest while ensuring ecological sustainability of the kangaroo population. This preliminary model precedes the development of a more comprehensive model of kangaroo population dynamics and harvest, which will be detailed in a separate report.

2 Methods

2.1 Background

For the purpose of constructing models for each species and harvest management zone, the most recent kangaroo density estimates for Victoria (Moloney et al. 2018) were used. These estimates were of kangaroo density and abundance, apportioned between the three species for each of seven management zones. Separate estimates are available for Eastern and Western Grey Kangaroos (hereafter, EGK and WGK) (Table 1). The harvest management zones were formed by merging groups of ecologically similar local government areas (Figure 1). These harvest management zones are also aligned with the survey strata used for estimating the abundances of kangaroos in Victoria from aerial survey data.

Table 1. Estimates of abundance for Eastern and Western Grey kangaroos in seven harvest zones covering the non-forested part of Victoria.

These are derived from local government area–level estimates tabulated in Moloney et al. (2018). Blank cells in the table denote absence (or near absence) from a harvest zone.

Harvest zone	Eastern Grey Kangaroo	Western Grey Kangaroo	Grey kangaroos combined
Mallee	5,808	41,682	47,490
Upper Wimmera	43,593	48,722	92,315
Lower Wimmera	364,300	38,199	402,499
Central	274,953		274,953
Otway	182,537		182,537
North east	288,098		288,098
Gippsland	90,711		90,711
Statewide total	**1,250,000**	**128,603**	**1,378,605**

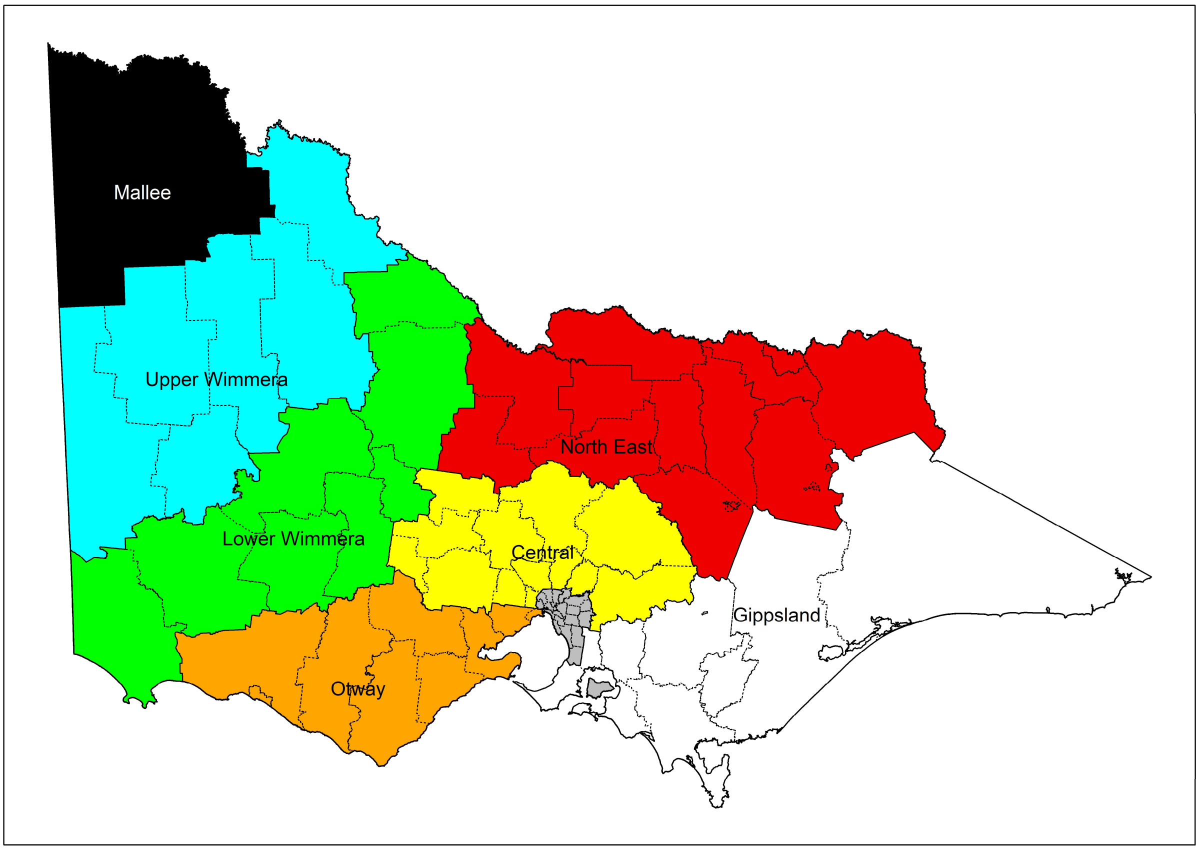

Figure 1. Kangaroo harvest management zones in Victoria. Each zone is formed by amalgamating groups of ecologically similar local government areas. The grey shaded area is not subject to harvest. Colour-coding of the harvest management areas matches that of the tags attached to carcasses during commercial harvesting operations.

2.2 Stochastic harvest model

A stochastic population model was constructed in terms of the density of kangaroos (individuals per km^2) occurring in each harvest zone at each annual time step (D_t). Transitions between time steps occur in proportion to the rate of increase (r_t):

$$D_t = D_{t-1}\exp(r_t) \quad (1)$$

The rate of increase (r_t) during a given year varies, with the maximum possible value ($r_{\max}$) ultimately determined by the reproductive biology of kangaroos. This quantity represents the maximum rate at which a kangaroo population could plausibly increase, given infinite resources (e.g. food) and no effect of intra- or inter-specific competition on reproduction and survival. Observational data from populations of kangaroos in other states suggest that values of $r_{\max}$ > 0.5 are unlikely, except in exceptional cases where populations have become heavily female-biased (for example, due to heavy male-biased harvesting) immediately prior to periods of rapidly increasing pasture availability (Bayliss 1985a, 1985b; Cairns and Grigg 1993). An $r_{\max}$ value of 0.5 corresponds to around a 65% increase in abundance per year, which in a population of kangaroos with a sex ratio close to unity is at the upper end of biological plausibility.

Under realistic conditions, actual rates of increase will always be less than $r_{\max}$, with the reduction depending on both density-dependent and density-independent factors. Density-dependence describes the phenomenon whereby the rates of increase vary inversely with population density due to processes such as increased competition for resources when densities are high (Sinclair and Pech 1996). Density dependence is expressed in our model by relating the rate of increase to the density of kangaroos at the previous time step (D_{t-1}). Furthermore, there is additional density-independent year-to-year variation in the rate of increase, which is ultimately explained by inter-annual variation in factors such as rainfall (McCarthy 1996; Jonzen et al. 2005). For some kangaroo populations elsewhere in Australia, there are well-established empirical relationships between rainfall and rates of increase, which are presumably caused by the effects of rainfall on the availability and quality of pasture for kangaroos (Bayliss 1985a; Jonzen et al. 2005). At high rainfall, these relationships lead to the rate of increase approaching $r_{\max}$. Unfortunately, empirical relationships between rainfall and/or pasture availability and rates of increase have not been established for Victorian kangaroo populations, so it is not currently possible to construct models that explicitly model the relationship between rates of increase and rainfall or pasture availability. As an alternative to explicit modelling of pasture availability or rainfall, we instead included random temporal fluctuations in resource availability in the model to account for density-independent temporal variation in the rate of increase, (environmental stochasticity).

Placing each of the above mechanisms together leads to an equation for the rate of increase that depends on the maximal rate of increase ($r_{\max}$), antecedent density (D_{t-1}), random environmental stochasticity, and the annual removal of a harvested fraction of the population (h):

$$r_t = r_{\max} + bD_{t-1} + \varepsilon_t - hD_{t-1} \qquad 2$$

The parameter b represents the strength of the density dependence, with negative population growth occurring when the density exceeds $-r_{\max}/b$, which can be considered the long-term carrying capacity of the population in the absence of harvesting (K). The parameter h is the harvest fraction, with the parameter ε_t indicating environmental stochasticity, which was characterised as normally distributed random noise, with the amount of temporal variation determined by the standard deviation (σ):

$$\varepsilon_t \sim N(0, \sigma)$$

Demographic stochasticity in the population dynamics was accommodated using a Poisson approximation to recalculate the abundance at each time step. The influence of demographic stochasticity was expected to be small, relative to other influences, because population sizes within harvest management zones are quite large (tens to hundreds of thousands). Demographic stochasticity typically has significant impacts on population viability only at low absolute population sizes (Melbourne and Hastings 2008).

2.3 Model parameterisation

As insufficient kangaroo population data are currently available for inferring the parameters of the stochastic harvest model for Victorian kangaroo populations, plausible ranges of parameter values were determined using values taken from comparable models published in the peer-reviewed scientific literature. As mentioned above, $r_{\max}$ values greater than 0.5 were considered biologically implausible. At the other end of the spectrum, values of $r_{\max}$ < 0.2 (equivalent to around a 22% annual increase in abundance under ideal conditions) were also considered implausible. Therefore, a range of 0.2–0.5 was used for the values of $r_{\max}$ in the stochastic model.

We have no local data on which to base estimates of the strength of the density dependence parameter b. However, the equilibrium density K (in the absence of harvesting) and our knowledge concerning prevailing population densities of kangaroos in Victoria, along with values for $r_{\max}$ derived from studies elsewhere, provide some basis for developing a range of plausible values for this parameter. Taking the highest and lowest assumed values for $r_{\max}$ (0.5 and 0.2, respectively), along with a broad range of equilibrium kangaroo densities (between 2 and 25 kangaroos per km^2), leads to range of values for the density dependence parameter b from –0.1 to –0.02.

Finally, it was necessary to develop assumptions regarding the amount of environmental stochasticity (σ). We somewhat arbitrarily assumed that values between 0 and 0.2 would apply, as the upper end of this range entails a very high degree of population volatility. Precise estimation of environmental stochasticity parameters of biological populations generally requires a very long-term series of data, so in the interim a wide range of plausible values have been considered.

Victorian kangaroo habitats span a wide climatic gradient, so it likely that different population parameters within the assumed broad ranges specified above will apply for populations in different parts of the state. Populations in the north-west (Mallee and adjacent areas) may well be approximated by model parameters derived from studies of kangaroo populations in arid and semi-arid Australia. In contrast, populations in southern and eastern Victoria may diverge quite significantly, although critical data are currently lacking. Kangaroo populations in the mesic environments of southern and eastern Victoria may have a higher $r_{\max}$, may be less affected by density dependence, and may experience less environmental stochasticity (smaller σ) than populations in semi-arid parts of the state. Similarly, there is insufficient available data to specify different stochastic models for each of the harvested kangaroo species, so in the interim the model has been applied to grey kangaroos as a group.

To explore the sensitivity of various measures of ecological risk to different assumed parameter values, we ran 1000 replicate runs of the stochastic model using a large number (2250) of combinations of parameter values and assumed harvest fractions. All models were run for 50 years. We assumed a scenario starting with a density of 5.0 kangaroos per km^2, applied to a hypothetical harvest management zone with an area of 25,000 km^2. The specified area and density imply an initial population of 125,000 kangaroos at the initial time step. The area of 25,000 km^2 was chosen as it is approximately equal to the mean area of the seven harvest management zones, and the starting density of 5.0 kangaroos per km^2 was chosen to represent typical kangaroo densities (Moloney et al. 2018). The ranges of parameters values used in the stochastic harvest model are given in Table 2.

Table 2. Assumed parameter ranges for the stochastic harvest model for kangaroos. Step size is the spacing of the increments within the parameter range at which the stochastic model was evaluated.

Parameter	Meaning	Range	Step size
$r_{\max}$	Maximum rate of increase	0.2, 0.5	0.05
b	Density dependence	–0.1, –0.02	0.01
σ	Environmental stochasticity	0, 0.2	0.05
h	Harvest fraction	0, 0.3	0.05
area	Area of harvest zone	25,000 km^2	Fixed
D_1	Density at time 1	5.0 kangaroos per km^2	Fixed
N_1	Abundance at time 1	125,000 kangaroos	Fixed

2.3.1 Harvest and monitoring policies

Harvest fractions between 0% (i.e. no harvesting) and 30% were considered. It was assumed that the numerical harvest quota was reset every 3 years (immediately after a statewide aerial survey was conducted to determine kangaroo density). This monitoring interval was chosen to match the recommended frequency of future aerial surveys in Victoria. Future model development will be able to incorporate alternative monitoring policies, such as more frequent monitoring, or adaptive monitoring that is undertaken at varying intervals depending on kangaroo abundance, actual harvest, rainfall, or pasture resource availability information (Hauser et al. 2006).

The stochastic model was coded using R (R Core Team 2019), and 1000 replicate simulations of each parameter combination and harvest rate were run for a 50-year period. For each simulated run, two measures of risk were calculated. First, we recorded whether the density of kangaroos fell below a threshold level of 0.25 kangaroos per km^2; then by averaging across all 1000 replicate simulations we were able to estimate the probability of a population with these assumed parameter values dropping below this density (i.e. a ‘quasi-extinction probability’, Ginzburg et al. 1982). The threshold of 0.25 kangaroos per km^2 is somewhat arbitrary, but was taken to represent an unacceptably low density of kangaroos from a conservation point of view. More generally, while the choice of threshold matters for determining absolute ecological risks, it is somewhat irrelevant if the intention is to compare the relative risks associated with alternative management scenarios and parameter values. For this reason, the quasi-extinction probability provides a useful relative measure of ecological risk for each scenario.

Second, we also calculated the cumulative number of kangaroos harvested over 50 years for each replicate simulation run. When kangaroo densities are low, the absolute number of kangaroos harvested is reduced under a proportional harvest policy, which may affect the commercial viability of the kangaroo harvesting program. In this sense, the cumulative number of harvested kangaroos represents an (inverse) measure of commercial risk. However, as the number of kangaroos harvested from an overexploited population will also be low, cumulative total harvest also represents an inverse measure of ecological risk. Hence, cumulative harvest may be used to identify harvest regimes that would result in low harvest offtake, as well as those resulting in kangaroo populations being suppressed to densities that are unacceptably low from a conservation point of view.

After identifying harvest fractions with acceptably low ecological risks (see results below), annual quotas for the three commercially exploited kangaroo species were developed by multiplying the harvest fraction by the most recently available estimates of kangaroo abundances (Moloney et al. 2018) for each of the seven harvest management zones.

3 Results

3.1 Stochastic harvest model simulations

The behaviour of the stochastic simulation model for kangaroos is illustrated in Figure 2, which shows an example of a model run using typical parameter values for 200 replicates. Under these assumed parameter values, the abundance of kangaroos fluctuated two-fold, but essentially remained within bounds centred on a density of approximately 3 kangaroos per km^2. For these parameter values, there was a very low estimated probability of quasi-extinction, with none of the 200 replicate simulations dropping below a density of 0.25 kangaroos per km^2 over the course of the 50-year simulation. This example serves to illustrate the general behaviour of the stochastic model, which was run for a wide variety of alternative parameter values spanning the plausible ranges specified in Table 2.

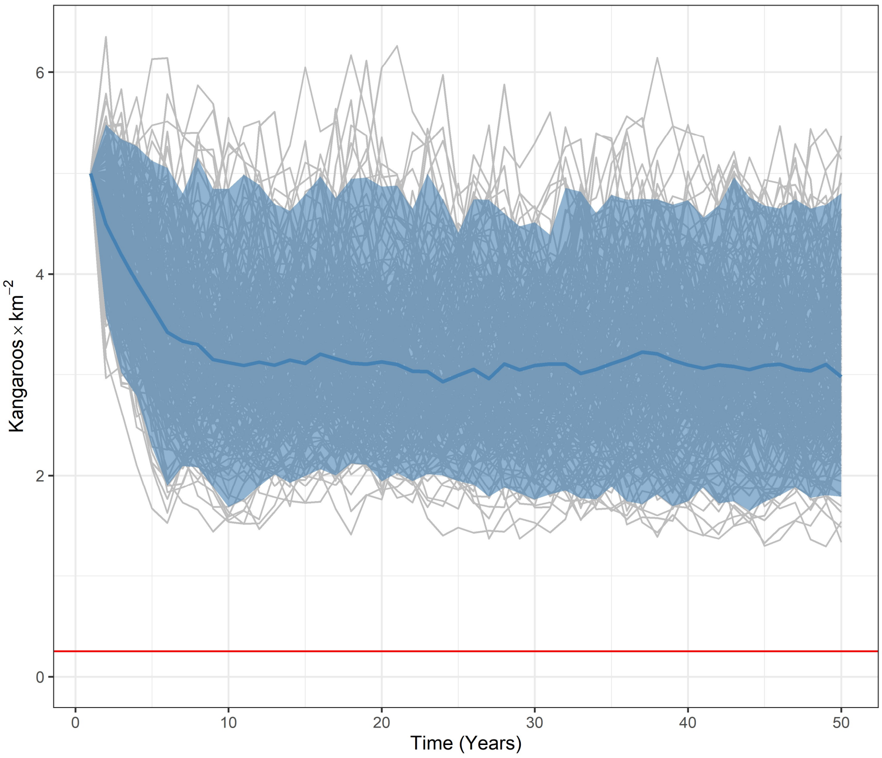

Figure 2. Example of the stochastic simulation model with assumed parameters r_{max} = 0.3, b = –0.05, σ = 0.1, h = 0.15 and D_1 = 5 kangaroos per km^2. The individual grey lines are the replicate simulation trajectories (200 in this example). The blue shaded area is the empirical 95% confidence interval for the density of kangaroos expected at each time step. The solid blue line is the median density. The red horizontal line is the quasi-extinction threshold of 0.25 kangaroos per km^2 used in the risk analyses. The proportion of trajectories going below the red line is equal to the quasi-extinction probability.

The ecological risks associated with this wide range of parameter values are illustrated in Figure 3, which shows the probability of quasi-extinction and the expected mean annual harvest, respectively, across the full range of plausible parameter values and harvest fractions. For harvest fractions of 10% or less, the risks of quasi-extinction were always low, except under very high levels of environmental stochasticity (σ > 0.15) (Figure 3). In contrast, when harvest fractions exceeded 20%, much higher risks (>10%) of quasi-extinction were evident for a broader range of parameter values (Figure 3).

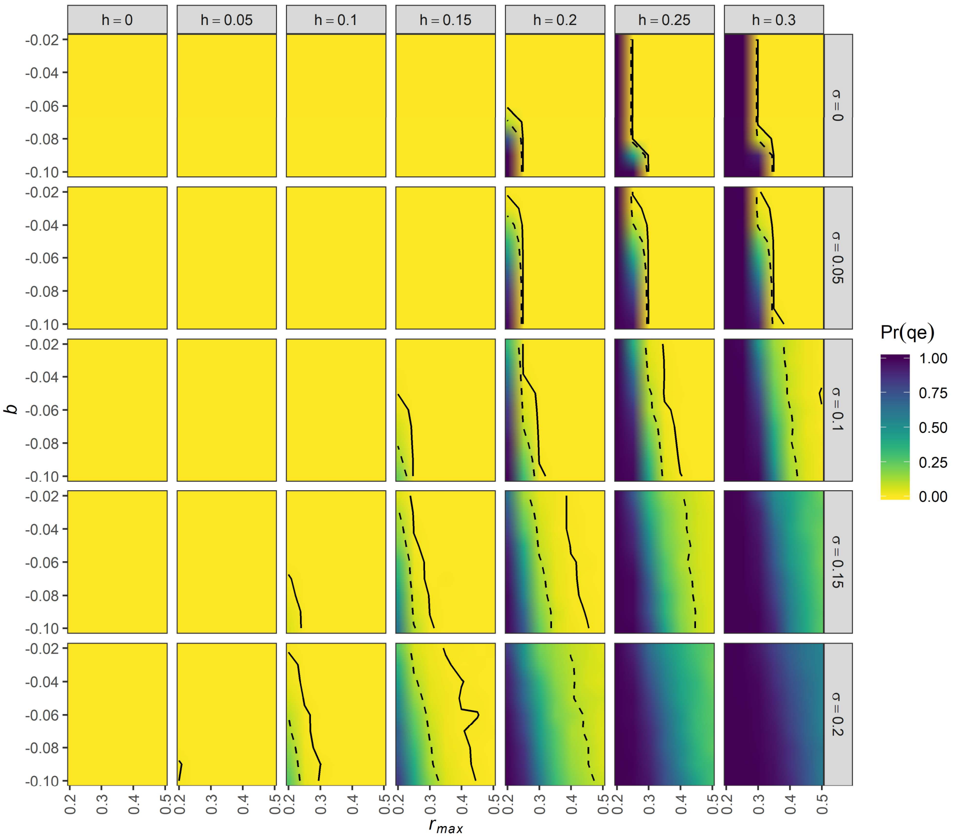

Figure 3. Estimates of quasi-extinction probability [Pr(qe)] (i.e. the probability of kangaroo densities going below 0.25 kangaroos per km^2 over 50 years) for Victorian kangaroo populations inhabiting a hypothetical 25,000 km^2 harvest zone under a range of parameter values ($r_{\max}$, *b*, *σ*) and for harvest fractions (*h*) varying between zero and 30% per annum. Blue shaded areas imply greater risk of quasi-extinction. The solid and dashed lines delimit parameter combinations with 1% and 10% probability of quasi-extinction, respectively.

Plots of quasi-extinction risk against mean annual harvest also demonstrated the high sensitivity of the ecological risks and the expected mean annual harvest to the assumed values of $r_{\max}$ (Figure 4). High risks of quasi-extinction combined with comparatively low mean annual harvest were nearly always associated with low values of $r_{\max}$. Whenever $r_{\max}$ was >0.3, risks of quasi-extinction were markedly lower, and the expected mean annual harvest was higher than otherwise (Figure 4). This strong sensitivity of two measures of risk and performance for the harvest program to the assumed values of $r_{\max}$ suggests that reducing uncertainty in the value of $r_{\max}$ by further modelling and data collection may help to provide greater certainty as to the true ecological risks inherent in the harvest program.

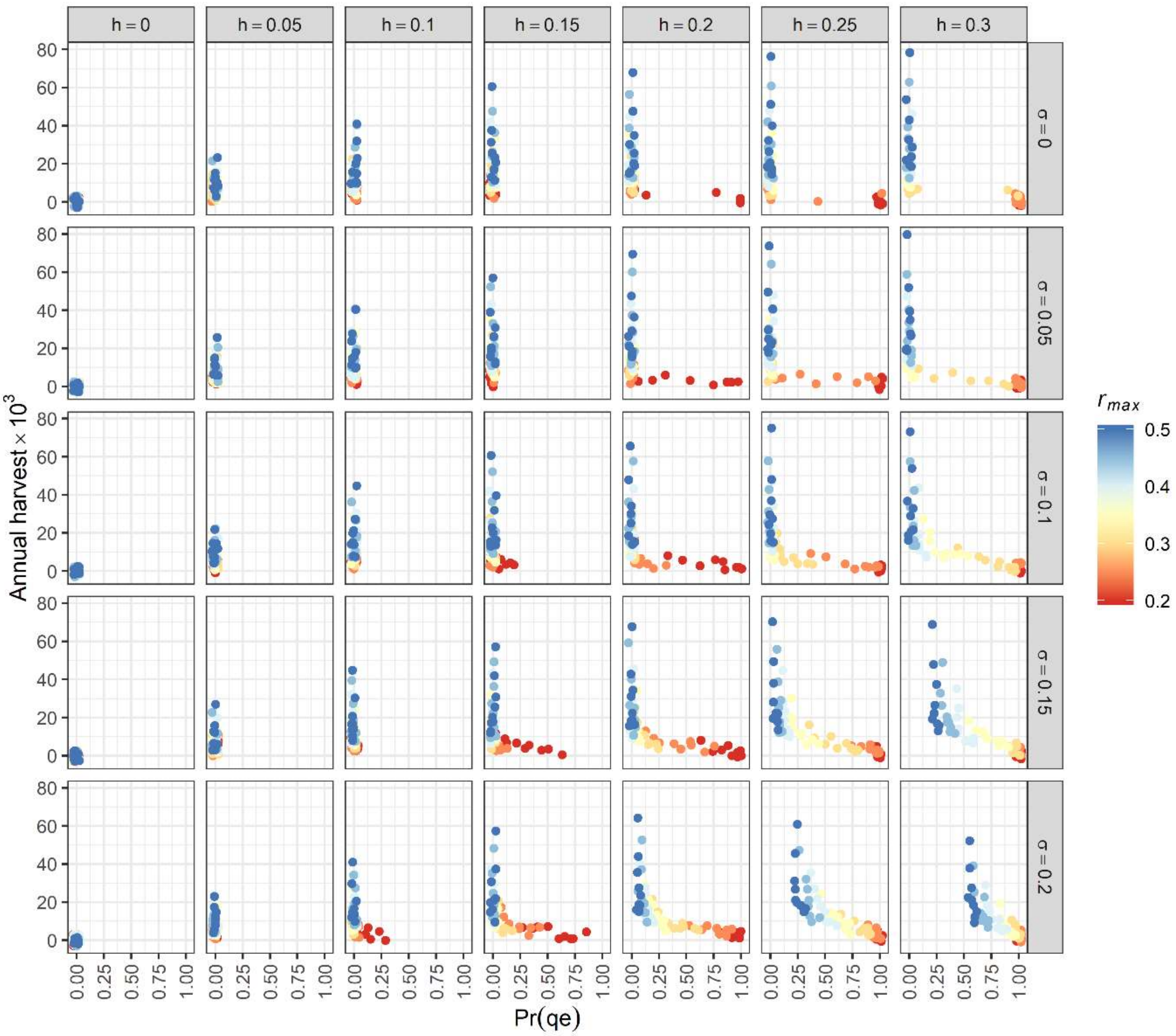

Figure 4. Relationship between quasi-extinction probability [Pr(qe)] and expected mean annual harvest (in thousands of kangaroos) for all parameter combinations considered in the simulation model for a hypothetical kangaroo harvest management zone of 25,000 km^2. Colouring of the plotted points is related to the assumed value of the maximum population rate of increase, $r_{\max}$. Higher risks of quasi-extinction (>0.1) are nearly always associated with low values of $r_{\max}$, demonstrating the sensitivity of ecological risk to assumptions regarding this parameter. Points are randomly jittered to allow overlapping points to be seen.

3.2 Setting harvest quotas

Based on the risk analysis above, a conservative harvest quota of 10% per annum was recommended over the near term (i.e. 2020–2025). Higher quotas may be considered in future, but current uncertainty regarding the dynamics of Victorian kangaroo populations means that under some circumstances, risks may be higher than would be considered ecologically acceptable. Accordingly, the quotas have been determined from the population estimates given in Moloney et al. (2018), with a harvesting rate of 10%. The resulting quotas are given in Table 3, with the quotas for each species/harvest management zone being rounded to the nearest 100 kangaroos. Quotas are given separately for the two grey kangaroo species (EGK and WGK), as well as for both species combined. The overall total recommended quota for the calendar year 2020 is therefore 137,800 kangaroos.

Table 3. Recommended harvest quotas for Eastern and Western Grey Kangaroos and both species combined (rounded to the nearest 100). Totals include all intended culling under both ATCW and commercial culling allocations for the period 1 January to 31 December 2020. Maximum harvest rates are set at no more than 10% of the population per annum

Harvest zone	Eastern Grey Kangaroo	Western Grey Kangaroo	Grey Kangaroos combined
Mallee	600	4,200	4,700
Upper Wimmera	4,400	4,900	9,200
Lower Wimmera	36,400	3,800	40,200
Central	27,500		27,500
Otway	18,300		18,300
North East	28,800		28,800
Gippsland	9,100		9,100
Statewide total	**125,100**	**12,900**	**137,800**

4 Discussion

Simulation of Victorian kangaroo populations using the stochastic harvest model suggests that, based on the currently available knowledge regarding plausible demographic parameters for Victorian kangaroo populations, harvest fractions of up to 10% per annum can be considered to involve very low risk, and therefore can be expected to be ecologically sustainable in the long term. Higher harvest fractions (in the region of 15–20%) will only be of low ecological risk under a limited range of assumed population parameters. In particular, the risk of quasi-extinction is sensitive to the value of the population's maximum rate of increase ($r_{\max}$). Where $r_{\max}$ is greater than 0.3, risks of quasi-extinction are usually low for 15% or 20% harvest fractions, unless density dependence and or environmental stochasticity are at the upper ends of their plausible ranges.

Harvest fractions greater than 20% were found to be generally unsustainable under all but the most restrictive assumptions regarding kangaroo population dynamics. This finding is in general accordance with data from other Australian jurisdictions, where quotas of between 10% and 20% have typically been applied. (Hacker et al. 2004).

As monitoring and harvest statistics accumulate over time, it is proposed that a more complex and realistic model structure be adopted and used to predict kangaroo population dynamics over space and time. As data accrue, it should be possible to infer the parameter values of the model from the observational data, rather than relying on values borrowed from harvested kangaroo populations elsewhere. Such a model structure may incorporate features such as migration, resource (pasture) productivity, harvest sex ratios, and age structure in a spatially explicit framework. This will allow predictions of kangaroo population dynamics at a much finer scale than those of the harvest management zone currently used. Such a model should more faithfully represent the complex spatial and temporal dynamics of a kangaroo populations impacted by the Victorian commercial kangaroo harvest system. The initial development of the proposed spatial kangaroo harvest model will be detailed in a separate report.

One aspect of the approach to commercial harvesting of kangaroos in Victoria can be expected to further contribute to the expected low ecological risks of the proposed harvest quotas. The population estimates provided by Moloney et al. (2018) do not include large areas of forested habitat in the state. These areas contain a significant, but unknown additional number of kangaroos. As these kangaroos are not included in the calculation of the harvest quota, the maximum proportion of kangaroos that can be harvested under the recommended quotas will always be less than the specified rate (i.e. <10%). This factor adds an additional margin of safety to the process of allocated harvest quotas, which will further contribute to the already low ecological risks that the stochastic model has helped to identify.

The total harvest fraction considered in this report included all types of culling, not only the commercial harvest of kangaroos. Regulatory mechanisms will need to be developed to allow apportionment of the total harvest quota between the commercial harvest, and other culling undertaken under the ATCW provisions of the Wildlife Act.

4.1 Recommendations

- Over the near term (e.g. 2020–2025), a harvest fraction of 10% of the population is recommended. Raising the harvest fraction to a higher percentage such as 15% may be possible in the future, but would require detailed analysis of additional monitoring and harvest data to ensure that overexploitation of kangaroos did not occur.
- For the 2020 calendar year, a total quota of 137,800 grey kangaroos is recommended as the maximum sustainable offtake. This includes kangaroos culled by both commercial harvesting and the ATCW permit process.

- Aerial survey of the kangaroo population should be undertaken at least every 3 years using the methods presented in Moloney et al. (2018). If a harvest fraction greater than 10% is desired, then an increase in the frequency of monitoring to once a year, or once every second year is recommended.
- Accurate and detailed harvest records, including the location, species, sex and age class of all harvested kangaroos, should be maintained. These harvest statistics will provide valuable information for future population modelling and analysis to support quota setting and management in the future.

5 References

Bayliss, P. (1985a). The population dynamics of Red and Western Grey Kangaroos in arid New South Wales, Australia. I. Population trends and rainfall. *Journal of Animal Ecology* **54**, 111–125. doi:10.2307/4624

Bayliss, P. (1985b). The population dynamics of Red and Western Grey Kangaroos in arid New South Wales, Australia. II. The numerical response function. *Journal of Animal Ecology* **54**, 127–135. doi:10.2307/4625

Cairns, S.C. and Grigg, G.C. (1993). Population dynamics of Red Kangaroos *(Macropus rufus)* in relation to rainfall in the South Australian pastoral zone. *Journal of Applied Ecology* **30**, 444. doi:10.2307/2404185

Chee, Y.E. and Wintle, B.A. (2010). Linking modelling, monitoring and management: an integrated approach to controlling overabundant wildlife. A wildlife population control algorithm. *Journal of Applied Ecology* **47**, 1169–1178. doi:10.1111/j.1365-2664.2010.01877.x

Ginzburg, L.R., Slobodkin, L.B., Johnson, K. and Bindman, A.G. (1982). Quasiextinction probabilities as a measure of impact on population growth. *Risk Analysis* **2**, 171–181. doi:10.1111/j.1539-6924.1982.tb01379.x

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, Australian Capital Territory.

Hauser, C.E., Pople, A.R. and Possingham, H.P. (2006). Should managed populations be monitored every year? *Ecological Applications* **16**, 807–819.

Jonzen, N., Pople, A.R., Grigg, G.C. and Possingham, H.P. (2005). Of sheep and rain: large-scale population dynamics of the red kangaroo. *Journal of Animal Ecology* **74**, 22–30.

McCarthy, M.A. (1996). Red Kangaroo *(Macropus rufus)* dynamics: effects of rainfall, density dependence, harvesting and environmental stochasticity. *Journal of Applied Ecology* **33**, 45. doi:10.2307/2405014

McLeod, S., Hacker, R. and Druhan, J. (2004). Managing the commercial harvest of kangaroos in the Murray–Darling Basin. *Australian Mammalogy* **26**, 9. doi:10.1071/AM04009

Melbourne, B.A. and Hastings, A. (2008). Extinction risk depends strongly on factors contributing to stochasticity. *Nature* **454**, 100–103. doi:10.1038/nature06922

Moloney, P.D., Ramsey, D.S.L. and Scroggie, M.P. (2018). *State-wide abundance of kangaroos in Victoria: results from the 2018 aerial survey*. Arthur Rylah Institute for Environment Research Technical Report Series No. 296. Arthur Rylah Institute for Environmental Research, Heidelberg. https://www.wildlife.vic.gov.au/__data/assets/pdf_file/0030/415596/Statewide_kangaroo_report_2018_FINAL.pdf (accessed 26 August 2019).

R Core Team. (2019). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Scroggie, M.P., Moloney, P.M. and Ramsey, D.S.L. (2019). *Interim harvest quotas for kangaroos in Victoria October–December 2019*. Unpublished report to Biodiversity Division, DELWP, Arthur Rylah Institute for Environmental Research, Heidelberg, Victoria.

Sinclair, A.R.E. and Pech, R.P. (1996). Density dependence, stochasticity, compensation and predator regulation. *Oikos* **75**, 164. doi:10.2307/3546240

www.delwp.vic.gov.au

www.ari.vic.gov.au