Threatened Species Recovery Hub

National Environmental Science Programme

Control and monitoring of kangaroo populations in the Mallee Parks of semi-arid Northwest Victoria

Version 2

William K. Morris, David H. Duncan and Peter A. Vesk

March 2019

THE UNIVERSITY OF MELBOURNE

Parks Victoria Healthy Parks Healthy People

Control and monitoring of kangaroo populations in the Mallee Parks of semi-arid Northwest Victoria - Version 2
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Parks Victoria Research Partners Panel Project 1516 P18, with support from the Australian Government's NationalEnvironmental Science Program through the Threatened Species Recovery Hub

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Executive Summary

This report is about the estimation, monitoring and control of kangaroo populations in the Mallee National Parks of Victoria. Kangaroo populations in the Parks are managed for two interdependent reasons: to prevent large die-offs of kangaroos during drought and because they are believed to impede the ecological restoration of degraded semi-arid woodland ecosystems, including the nationally Endangered Buloke Woodlands of the of the Murray Mallee and Riverina Depression Bioregions.

The core of our work is a detailed, model-based examination of the kangaroo monitoring and control data from the parks up to and including 2017. We also review previous modelling on the optimisation of resources used by Parks Victoria for kangaroo monitoring and management. Monitoring kangaroo populations is undertaken to inform and guide kangaroo control activities. To be of value for gauging kangaroo impacts on woodland recovery, monitoring of seedling recruitment and woodland status is also required. But monitoring can be costly and must be performed as efficiently as possible so resources that could otherwise be used on direct management are not wasted.

This report addresses the following tasks:

1. Review the current kangaroo monitoring and management strategy used in the Mallee Parks.
2. Analyse the population monitoring data collected to date.
3. Review the removal sampling methods and the population control algorithm.
4. Analyse the culling data collected to date and apply the removal sampling model to new data.
5. Assess the efficacy of the removal sampling model in light of new culling data and investigate whether the method can achieve the goal of reducing the need for the current amount of direct population monitoring.
6. In light of the above, identify shortcomings and problems with the methods and/or data that may make implementation problematic.
7. Identify aspects of the current monitoring and management strategies that could be refined to achieve better management outcomes in the future.

Between 1998 and 2016 more than 60 000 kangaroos were culled in the Mallee Parks (at Murray Sunset and Hattah-Kulkyne cull data is unavailable prior to 2004). Approximately 80% of which were western grey kangaroos and the remaining 20% red kangaroos. The number of kangaroos culled tended to increase through time as the cull program was expanded to more areas and red kangaroos were included in the program.

In the years following the implementation of the culling program, University of Melbourne researchers undertook work to bring the monitoring and management of Mallee Park kangaroos into an adaptive management framework. University of Melbourne researchers have designed and tested the application of a population control algorithm based on removal sampling. The population control algorithm had previously shown the potential to reduce the cost of monitoring and increase operational efficiency.

Though population trends provide some circumstantial evidence that the culling program is having a desired effect (at least maintaining populations at lower levels than before culling) there are multiple barriers to establishing a complete chain of cause and effect linking the culling program, kangaroo population size, grazing pressure and woodland recruitment and recovery. In some cases declines in kangaroo populations to current levels occurred before culling was implemented. Also, there is as yet no capacity to compare culled kangaroo populations with a control population of monitored but unmolested kangaroos, and gauge the true effect on population growth and size.

To address the need to increase the efficiency of kangaroo monitoring, a population control algorithm incorporating removal sampling modelling was proposed by Chee and Wintle in 2010. We undertook a painstaking review of their approach and rebuilt the models from scratch. Through this process we identified significant limitations inherent in the culling data and removal sampling model. Additionally we have identified problems with some previous applications of the model that have resulted in an overstatement of its performance and potential. Therefore, at this stage, we cannot recommend that direct monitoring is forgone with an expectation that information could be compensated for with data collected during culling.

If removal sampling is to be used with success in the future the removal sampling model and the culling data must be properly reconciled with either the removal sampling model modified to account for the idiosyncrasies of culling and data collection, or the culling and data collection process must be modified to accord with the assumptions of the removal sampling model. In addition, more information on the rate at which kangaroos are able to be removed from the population is needed to address the problem of model identifiability.

It may be possible to reduce the current level of monitoring without jeopardizing the goals of the kangaroo management program. However, the effect of any reduction in kangaroo population monitoring is difficult to predict with the information currently available. The tight coupling of monitoring and management actually confounds the ability to use the time-series of population data (in particular the longer-term data collected for Central Wyperfeld) to gauge the effect of reducing monitoring. An alternative would be to simulate the dynamics of the kangaroo population, the monitoring processes, and the management. Such an approach, known as Management Strategy Evaluation (see e.g., Boyce et al., 2012). However, the caveat applies that the uncertainties in its prediction would necessarily be large.

A Western Grey Kangaroo at Wyperfield National Park. Photo: Donald Hobern CC BY 2.0 Wikimedia Commons

Acknowledgements

Thanks to Lorraine Taylor of Parks Victoria for providing kangaroo monitoring and control data at various junctures. José Lahoz-Monfort and David Morgan (both University of Melbourne) variously shared unpublished data, analyses, expertise and unpublished documents. We received technical assistance dissecting and diagnosing previous statistical models from Yung En Chee, and earlier versions of this report were improved by comments from Brendan Rodgers, Kathryn Schneider, Lorraine Taylor, John Wright and Graeme Coulson. Figure 3 was redesigned with the assistance of Bella Vesk.

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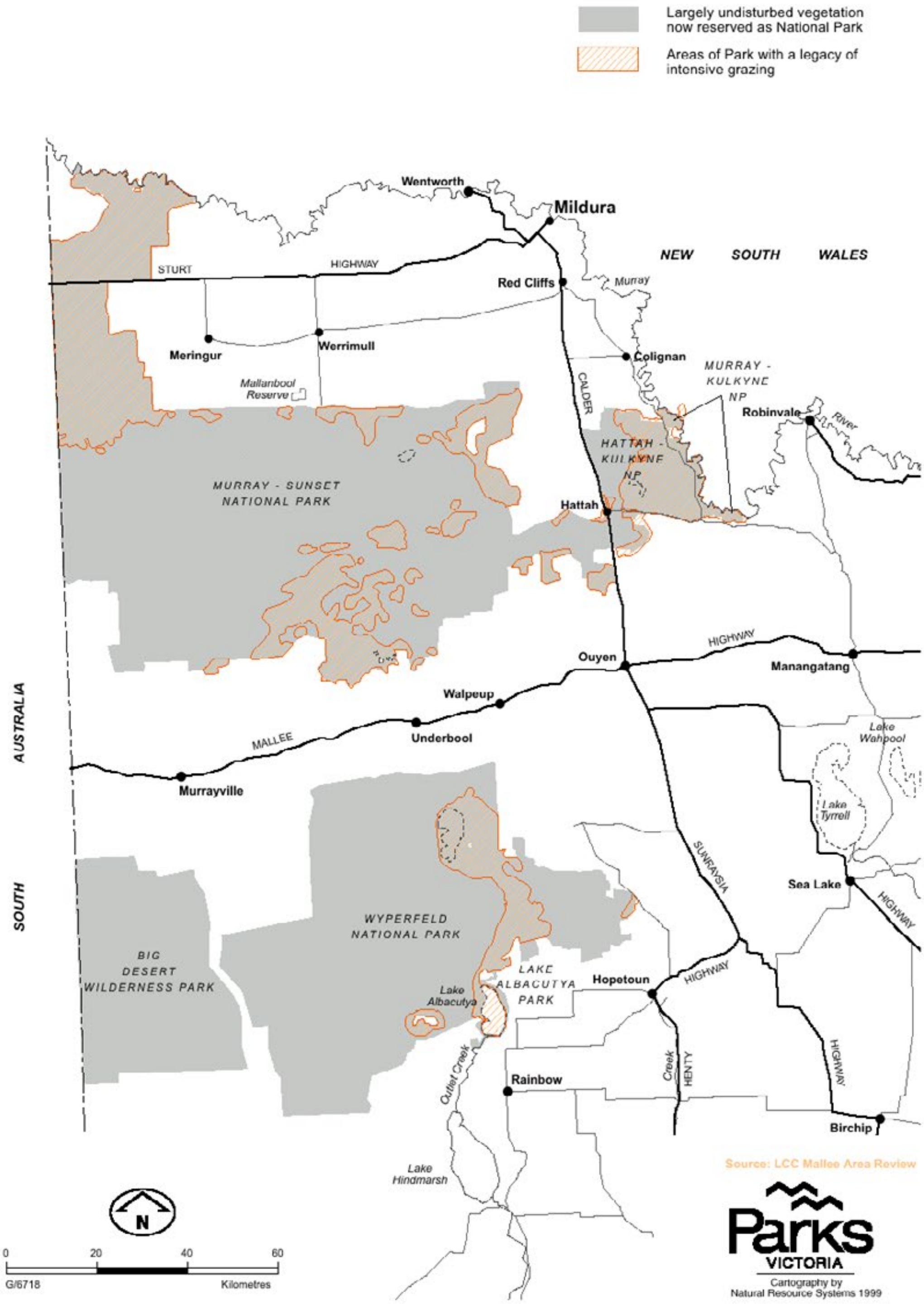
1. Introduction

This report details a review and investigation of the population estimation, monitoring and control of kangaroo populations in the Mallee National Parks. Grazing by kangaroos, alongside rabbits and goats, is a major ecological threat in the Mallee National Parks of north-western Victoria (Taylor & Pegler, 2016). The combined grazing pressure from these herbivores is assumed to impede the park management objective of restoring the highly degraded semi-arid woodland communities. Consequently, much effort and many resources have been and continue to be expended on the management of the threat from grazing by introduced and overabundant native mammals; Parks Victoria describe the management of total grazing pressure in semi-arid and riverine woodlands of the Mallee Parks as their "longest running restoration project" (Taylor & Pegler, 2016).

Kangaroo management in the Mallee Parks is inextricably linked both to the historical degradation of the semi-arid woodlands, and hopes for their future recovery. Once widespread, semi-arid woodland assemblages were preferentially cleared and converted to agriculture. What remains is now identified by Parks Victoria as key conservation asset and management priority of Mallee landscapes. Semi-arid woodlands include four plant communities listed as threatened at State Level, and Federally, the EPBC listed Threatened Ecological Community "Buloke Woodlands of the Murray Mallee and Riverina Depression Bioregions". Three of the four largest remnant areas this community are located within Victoria's Mallee National Parks (Cheal et al., 2011). While the the clearing and conversion of the semi-arid woodlands was a disaster for most native fauna and flora, it has eventually promoted population growth of kangaroos, through promoting grassy native and exotic species to feed on, and water, intended for livestock, to drink through dry periods. The historical degradation of the semi-arid woodlands set the scene for periods of prodigious population growth in western grey kangaroos, and this amplified presence of kangaroos now presents a clear impediment to the ecological restoration objectives for the woodlands.

The management approach to kangaroos in the mallee has evolved through time. Kangaroo monitoring commenced at Wyperfeld NP in 1972, later Hattah Kulkyne NP in 1983, and Murray Sunset NP in 1992 (Taylor & Pegler, 2016). An active management focus on the threat that over-abundant kangaroo populations posed to the regeneration of the woodlands came after Hattah Kulkyne was proclaimed, after stock were long gone and rabbit populations had been locally controlled (Cheal, 1986). Routine kangaroo population control of western grey kangaroos (*Macropus fuliginosus*) and red kangaroos (*Osphranter rufus*), with the dual objectives of reducing overgrazing and preventing large-scale undesirable kangaroo die-off during droughts, began in 1998 in Wyperfeld National Park (1990 and 2001 at Hattah-Kulkyne and Murray Sunset National Parks respectively). At Wyperfeld, the monitoring and control functions are now tightly linked. Each year kangaroos numbers are surveyed and from those data the population in the next year is projected with a population model that estimates population growth as a function of rainfall and population size in the immediate past. In years when kangaroos are projected to exceed a target population level, the number of kangaroos in excess of the target are shot during an annual cull, removing them from the population and reducing grazing pressure.

The monitoring and management of kangaroo populations is costly, and Parks Victoria are constantly looking to increase their cost-effectiveness and operational efficiency through the framework of adaptive management. This project continues an enduring collaboration between Parks Victoria and The University of Melbourne to that end. The design of the kangaroo monitoring and the population model was developed for Wyperfeld by Morgan (2000), who later helped to integrate the population model in the control strategy (Morgan & Pegler, 2010). Later, Chee & Wintle (2010) and Chee (2010) designed and tested the application of a population control algorithm based on removal sampling, work which indicated potential to unify kangaroo monitoring and control, thereby increasing operational efficiency. More recently Hauser & Lahoz-Monfort (2014) argued for a reframing of kangaroo control as a means to an end, a management action in the service of the desired ecological restoration outcomes (see Figure 3). They strongly emphasised the need for an ecological process model linking the grazing pressure and grazing management with restoration outcomes in semi-arid woodland in order to advance on an adaptive management footing. To that end, a number of field and modelling studies targeting knowledge gaps for restoration of semi-arid woodlands are in progress with the support of the National Environmental Science Program (Duncan, 2017).


Largely undisturbed vegetation now reserved as National Park
Areas of Park with a legacy of intensive grazing
Wentworth
Mildura
NEW SOUTH WALES
STURT HIGHWAY
Red Cliffs
Murray
Meringur
Werrimull
Colignan
Mallanbool Reserve
MURRAY - KULKYNE NP
Robinvale
River
CALDER
HATTAH - KULKYNE NP
MURRAY - SUNSET NATIONAL PARK
Hattah
HIGHWAY
Ouyen
Manangatang
Walpeup
Underbool
MALLEE
Lake Wahpool
Murrayville
Lake Tyrrell
SOUTH AUSTRALIA
SUNRAYSIA
Sea Lake
HIGHWAY
WYPERFELD NATIONAL PARK
BIG DESERT WILDERNESS PARK
LAKE ALBACUTYA PARK
Lake Albacutya
Hopetoun
HIGHWAY
Outlet Creek
Creek
HENTY
HIGHWAY
Rainbow
Birchip
Lake Hindmarsh
Source: LCC Mallee Area Review
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1.1 Scope

The focus of this report is a detailed, model-based examination of the management of kangaroo populations in the Mallee Parks, including monitoring and control data up to and including 2017. The report responds to the following tasks:

- We review the context of the kangaroo monitoring and management strategy as a measure to protect and restore the semi-arid and riverine woodland communities.

Then follows the first main analysis:

- We review the work done to date to estimate kangaroo populations, and present an analysis of population trends across all of the Mallee Parks based on 45 years of accumulated monitoring data.

Monitoring of kangaroo populations is required in order to understand their contribution to total grazing pressure, and consider the impact that they may be having on regeneration and general woodland health. Nonetheless monitoring can be costly and must be performed as efficiently as possible so resources that could otherwise be used on direct management are not wasted.

With these considerations in mind Chee & Wintle (2010) devised a management approach that integrated culling and monitoring using a removal sampling model. This model was tested with data collected during culling at Wyperfeld in Chee (2010). It was subsequently tested based on cull data from 2013 by Hauser & Lahoz-Monfort (2014), who cautiously considered the results to be consistent with the promise of providing more efficient and precise population estimates. However, more robust testing was required. Thus, in the second main analysis, we apply the model to four years of culling data collected since the previous model tests, and examine whether the approach lives up to its potential to increase the efficiency of kangaroo management in the Mallee Parks. This element comprised the following tasks:

- Review Chee and Wintle's removal sampling methods and the population control algorithm.
- Analyse the culling data collected to date and apply the removal sampling model to the new data.
- Assess the efficacy of the removal sampling model in light of new culling data and investigate whether the method can achieve the goal of reducing the need for the current amount of direct population monitoring.
- In light of the above, identify shortcomings and problems with the methods and/or data that may make implementation problematic.
- Identify aspects of the current monitoring and management strategies that could be refined to achieve more optimal management outcomes in the future.

A degraded remnant of Buloke Woodland, Pine Plains, Wyperfeld National Park. Photo: David Duncan

2. Review of kangaroo management in the Mallee Parks

The need to actively control kangaroo populations in the Mallee Parks has a historical context that is important to understand. Overabundance of kangaroos, and the risk they currently pose to the conservation and regeneration of woodland communities, is a legacy of radical changes to land use and vegetation structure that accompanied occupation of the Mallee by European settlers. While the clearing and conversion of the semi-arid woodlands was a disaster for most native fauna and flora, it has eventually proved a net benefit for kangaroos, promoting grassy native and exotic species to feed on, and water, intended for live stock, to drink through hard times.

Dingoes, kangaroos and other medium-sized mammals were once common in semi-arid Northwest Victoria where indigenous people were sustained by hunting and food-gathering. Semi-arid woodland vegetation was widespread, including now-threatened pine-buloke woodlands vegetation formations (Cheal et al., 2011). In the 19th century, land-use in the region changed dramatically. Much of the pine-buloke woodlands were cleared for cropping and sheep and cattle grazing. Introduced pasture grasses, other exotic plants and feral rabbits and goats became common in the region. The indigenous people began to leave the area as hunting became less viable and water less available. Dingoes were trapped and shot, their numbers still remaining low today. From the late 19th century, damming and irrigation altered the hydrological regime and flooding in Northwest Victoria became rare (Morgan & Pegler, 2010).

Over the course of the 20th century a large proportion of public land in the Northwest, previously under pastoral lease, was gazetted as national park and other conservation reserves. The three national parks established in the area, and now managed by Parks Victoria, are Wyperfeld (1921), Hattah-Kulkyne (1960) and Murray Sunset (1991). The earliest reservations and the bulk of the parks comprised relatively intact mallee woodlands on coarse sandy soils that had never supported significant pastoral activity. The total area reserved in the three Mallee parks continued to increase through until the early 21st century as more highly utilised semi-arid woodlands and riverine plains were officially incorporated (DNRE, 1996; Durham, 2001; State of Victoria, 2007). By 1998, livestock grazing had finally been phased out of the region's national parks (Sandell et al., 2002). The active conservation management of the Mallee parks began in the 1960's, in an attempt to halt the decline and restore condition of native vegetation including pine-buloke woodlands. Management actions included active revegetation, rabbit control and weed control. As stock were removed and rabbit numbers suppressed, it became apparent that kangaroo numbers in the Mallee parks had grown particularly high and were believed to be impeding the regeneration of pine-buloke woodland and other native vegetation (Cheal, 1986).

2.1 Monitoring and managing kangaroo populations in the Mallee Parks

Monitoring of western grey kangaroos began in Central Wyperfeld in 1972, and over the next three decades surveys of kangaroo numbers expanded to include all three Mallee parks as well as red kangaroos that occur in Murray Sunset and Hattah-Kulkyne (Figure 1). Annual kangaroo monitoring, which at first were conducted during winter but now typically occur in spring, initially comprised ground-based surveys. Kangaroo densities, stratified by habitat type (mallee and non-mallee/woodland), were calculated using distance sampling methods (Morgan, 2000). Following a calibration study, aerial surveys from helicopter replaced ground survey in relatively open areas of Murray Sunset NP in 2002, but walked transects are still preferred in the more wooded locations of Wyperfeld, Hattah Kulkyne and Lindsay Island (Murray Sunset) (Taylor & Pegler, 2016).

The period 1972 to 1997 saw marked fluctuations in the Central Wyperfeld western grey kangaroo population (Figure 2). Wetter periods were followed by exponential increases in kangaroo numbers, and in the subsequent dries the population crashed in just 2–4 years. During these dry periods, feed was scarce and many animals succumbed to dehydration, starvation, hypothermia and hyperthermia. As preferred feed ran out, kangaroos began to consume relatively more palatable woody vegetation, contributing to the decline in vegetation condition and inhibiting woodland regeneration (Morgan & Pegler, 2010).

By the end of the 20th century a nearly two-hundred-year history of logging, clearing, grazing by livestock, feral rabbits and goats, and kangaroos released from predation by humans and dingoes, in combination with changes in fire and flooding regimes and the introduction of exotic plants, had degraded the condition and cover of many ecological communities in the Mallee parks. Vegetation associated with historically periodic higher water availability such as pine-buloke, red gum and black box woodlands, tended to be more impacted while dryer communities such as mallee and heathland had been less affected (Morgan & Pegler, 2010).

Despite the cessation of land clearing and stock grazing in the Mallee Parks and with some success in managing rabbits, goats, weeds and efforts to better manage the fire and hydrological regimes, the condition of vegetation, in particular pine-buloke woodland, continued to decline and there was little sign of recovery. The high density of kangaroos, thought to be due to a lack of predation by humans and dingoes, was posited to contribute to the continued decline in vegetation condition and was seen as barrier to recovery because kangaroo browsing was preventing recruitment of woody plant seedlings and damaging mature plants in dry periods when preferred forage was absent (DNRE, 1996).

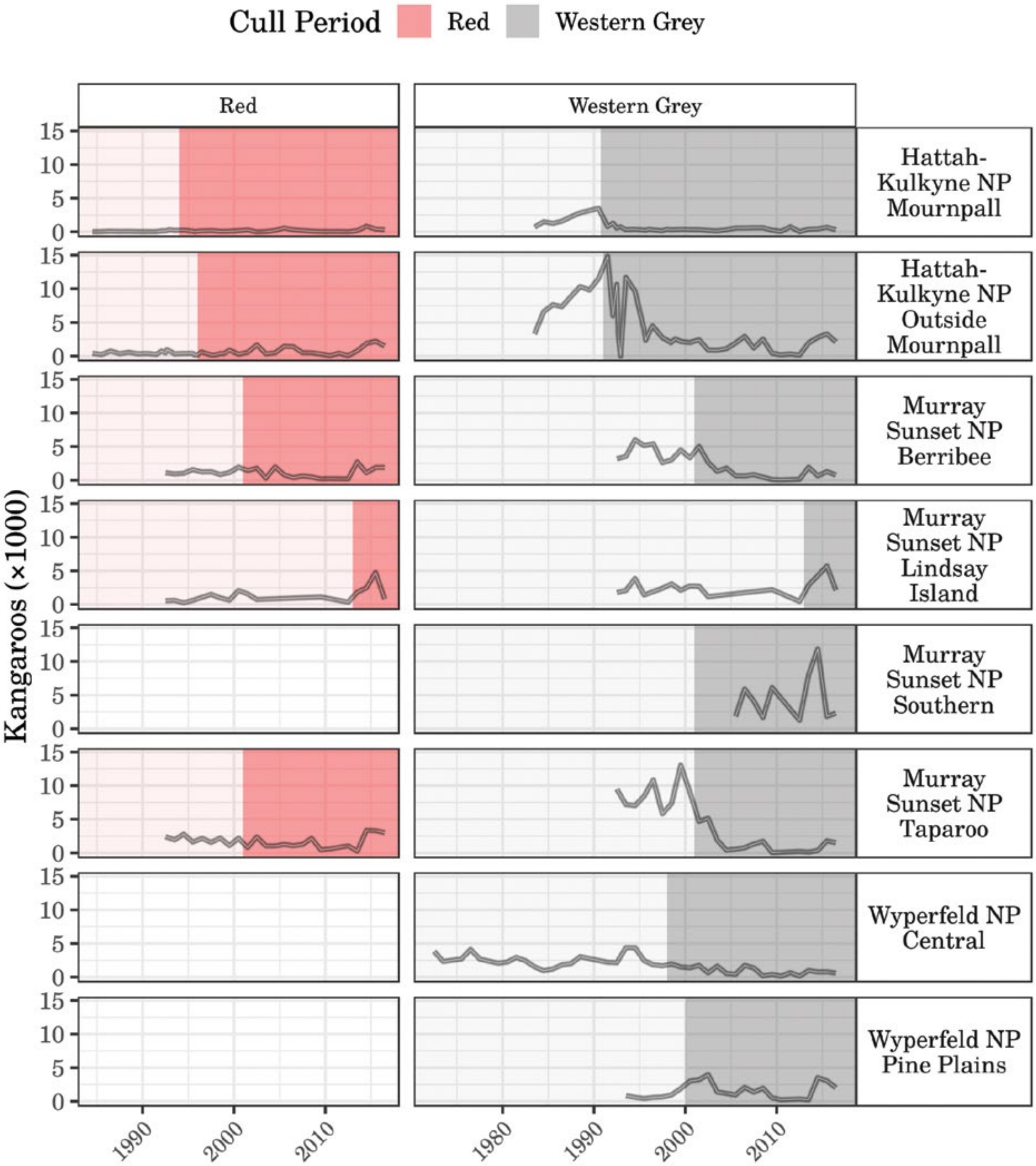

Figure 1: Mallee parks kangaroo populations 1972 to 2016. Estimated population sizes from distance sampling data for red and western grey kangaroos in the three Mallee parks (data supplied by Parks Victoria). Data on culling is considered unreliable prior to 1998.

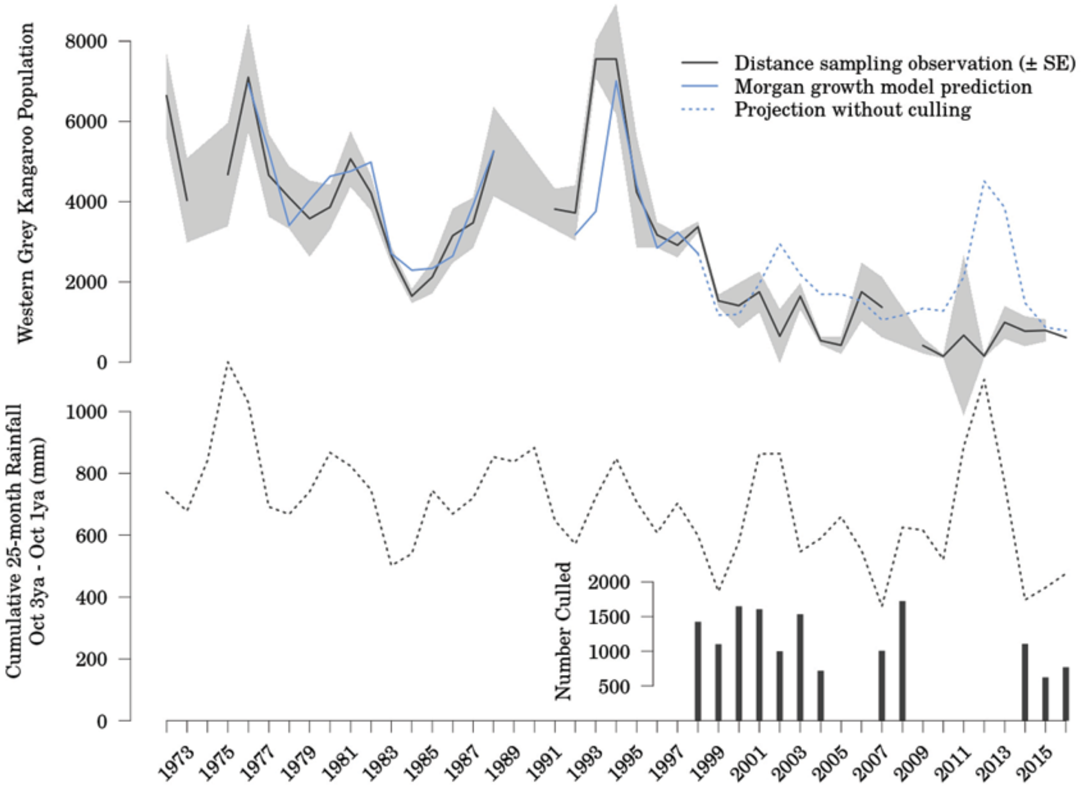

Figure 2: Central Wyperfeld western grey kangaroo population 1972 to 2016. Top panel shows the observations from distance sampling (solid black lines; grey ribbon is one standard error). Solid red line shows the prediction from the Morgan growth model during the pre-culling period. Dashed red line shows the projection of the population without culling according to the Morgan growth model. Bottom panel shows the cumulative 25 month (October to October) rainfall and the number of kangaroos culled in each year.

Western grey kangaroos bound across a cleared plain at Pine Plains, Wyperfeld National Park. Image: Cindy Hauser

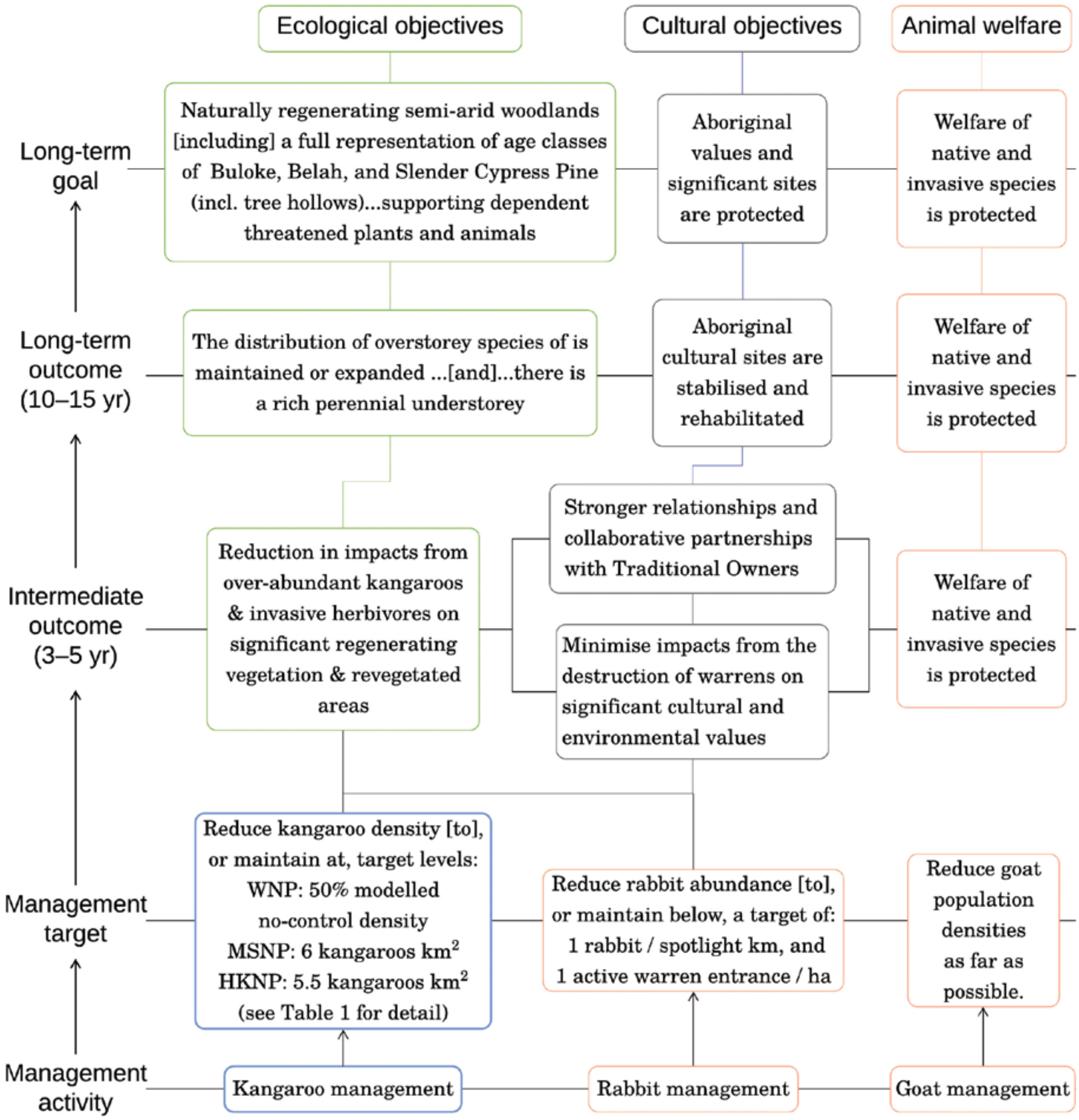

Figure 3: Objectives Framework for the Mallee Parks Total Grazing Management Plan (2016–2021), (after Taylor & Pegler, 2016). This figure emphasises that management of kangaroos has a broader context and purpose, which is the restoration of semi-arid woodlands ecosystems. Management of kangaroos and other vertebrate herbivores is an activity that has its own explicit activity targets that are means objectives to contribute to quantifiable ecological, animal welfare and cultural outcomes over the medium and longer term.

Increasingly concerned with poor vegetation condition and regeneration failure on the one hand, and the repeated instances of mass kangaroo die-off caused by food shortages in dry periods on the other, Parks Victoria began investigating how to best control kangaroo populations. Shooting was, and is, considered the most humane and cost-effective way to cull or harvest kangaroos (Olsen & Low, 2006). The current culling program began in 1990 (after an earlier attempt at culling in Hattah-Kulkyne was abandoned due to public disapproval). The program was intended to allow regeneration of the semi-arid woodland and floodplain vegetation communities through regulating the kangaroo population by substituting culling for the now-absent predation by dingoes and humans. Both western grey and red kangaroos (though not both species in all parks at all times) were culled during the summer, with the number of animals shot a function of the estimated density obtained from field survey, and a target density that varied by location and species (Table 1). In Wyperfeld, the target density varies from year to year according to a model that simulates predator–prey dynamics and incorporates the effect of rainfall (Morgan & Pegler, 2010), while at other locations the target is fixed at a constant density, itself devised to maintain biomass above a critical threshold of 400 kg (dry weight) per hectare (Coulson & Norbury, 1988).

Table 1: Kangaroo population density targets in the Mallee Parks.

Park	Management site	Area (km^2)	Target (Kangaroos/km^2)	
Hattah Kulkyne	Mournpall Outside Mournpall	55 273	0.5	5
Murray Sunset	Berribee Lindsay Island	293 161	2	4
	Southern Taparoo	446 525	na 1	6 5
Wyperfeld	Central Pine Plains	98 122	na na	variable variable

2.2 Developing an integrated kangaroo management and monitoring strategy

Parks Victoria has consulted with researchers since the beginning of the kangaroo culling program and researcher input has helped shape the implementation of kangaroo management and monitoring. At the outset of the culling in Wyperfeld, a program of western grey kangaroo management was enacted seeking to replicate the effects of past predation by humans and dingoes long absent from the Mallee Parks. With this program, the cull rate was allowed to vary from year to year, simulating the natural dynamics of a predator–prey relationship rather than simply employing a static target kangaroo population (Morgan, 2000).

2.2.1 Morgan growth model

In 1998, David Morgan of the University of Melbourne constructed a dynamic population model, based on annual observations of western grey kangaroo densities in Central Wyperfeld from 1972 to 1997 (Chee & Wintle, 2010; Morgan & Pegler, 2010). Morgan had been involved with collection and analysis of the survey data from the program's inception. The model relates the population growth rate from one time to another, $r_t = \log(N_t/N_{t-1})/l_t$ (where N_t is the population size and l_t is the number of years between $t - 1$ and t), to the average population density, $\bar{d}_t = (N_{t-1} + N_{t-2})/2A_t$ (where A_t is the area occupied by the population), of the two years prior to the end of the growth period and the cumulative rainfall, p_t, over a 25 month period from the previous October (before the beginning of growth period) to the October two years previous to that. To distinguish it from other models in this report we refer to this as the Morgan growth model. We refit this model to the growth rates over the period 1972 to 1997 to confirm the following equation for calculating the growth rate of given period:

$$r_t = 1.6p_t - 0.024\bar{d}_t - 0.56, \qquad (1)$$

where p_t is expressed in meters of rain[1] and $\bar{d}_t$ in kangaroos per kilometre squared.

[1]In the original model Morgan & Pegler use rainfall in mm. The measure was rescaled here to simplify the equation.

For the period of time (1972–1997) on which dynamic population model was based, the model explained 64% of variance in population growth rate and predicted plausible values in all except one aberrant year (Morgan, 2000). However, note that all population projections for Wyperfeld NP referred to as "pre-culling" from this point forward are derived from a model trained on these, 1972–1997 observations. Annual kangaroo surveys continue, but while those data do inform the annual cull targets, they are not used to update the population model itself.

While the Morgan growth model has shown some aptitude for predicting population dynamics at Central Wyperfeld during the pre-culling era, it is less clear that it provides skilled predictions outside this period and location. The estimates at Pine-Plains are certainly less predictive (figure 4), but is difficult assess whether the model is able predict the population dynamics of kangaroos subjected to ongoing culls as well as it does for the non-culled populations the model was based on. Indeed, in the future, there may be scope to improve the model to include the effects of culling and spatial variation, as more data have become available since the time the model was first proposed.

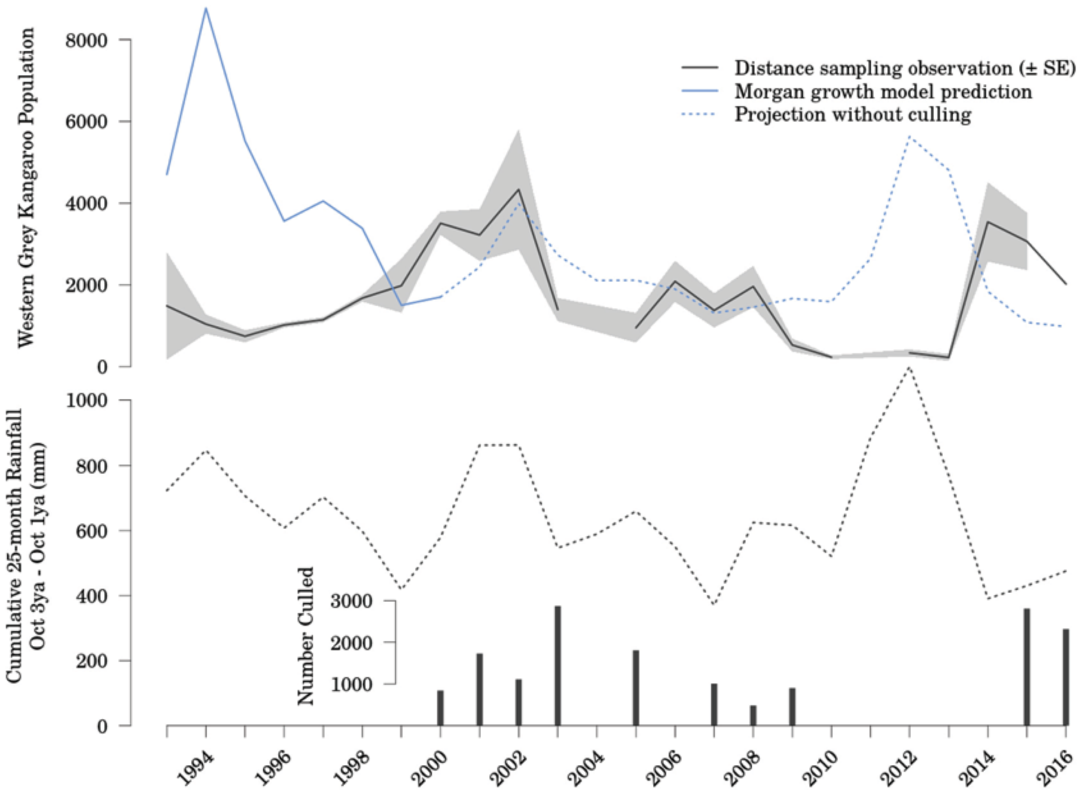

Figure 4: Pine Plains western grey kangaroo population 1993 to 2016. Top panel shows the observations from distance sampling (solid black lines; grey ribbon is ± one standard error). Solid red line shows the prediction from the Morgan growth model during the pre-culling period. Dashed red line shows the projection of the population without culling according to the Morgan growth model. Bottom panel shows the cumulative 25 month (October to October) rainfall and the number of kangaroos culled in each year.

2.2.2 Using the Morgan growth model to set target populations in Wyperfeld

Parks Victoria have used the Morgan growth model to set target populations and cull quotas at Central Wyperfeld since 1998 and at Pine Plains since 2000. The target population at both these sites is set at 50% of the population size that would be expected in the absence of predation. To estimate the expected population size, in the absence of predation for a given year ahead of a cull, the Morgan growth model was used to project a population trajectory through time, initialised with the 1996 and 1997 density observations in Central Wyperfeld and updated each November with the previous 25 months total rainfall. The whole population projections can be seen in the red dashed lines in top panels of figures 2 and 4 and woodland targets and populations are shown in figure 5. For any given year, t, the projected population, $\hat{N}_t$, was calculated as

$$\hat{N}_t = N_{t-1} e^{l_t r_t}, \tag{2}$$

where l_t and r_t are as defined above (section 2.2.1). In 1998, the $\bar{d}_t$ component of equation 1 was the average of the observed densities of Central Wyperfeld in 1996 and 1997, while in 1999 $\bar{d}_t$ was the average of the density observed in 1997 and the projected density, $\hat{N}_t/A_t$, in 1998, and from 2000 onwards $\bar{d}_t$ was the average of the previous two projected densities.

The target population is calculated as

$$\text{Target}_t = \frac{\hat{N}_t}{2m_{t-1}}, \tag{3}$$

where m_{t-1} is the ratio of the observations of total population to the woodlands population at the last survey.

2.2.3 Setting cull quotas

A cull quota is set in each year that the population observed in the woodlands at the previous survey is greater than the target population (Figure 6). At Central Wyperfeld the observations of woodland kangaroos were augmented by the assumption that half the population observed in the surrounding mallee would migrate into the woodlands where feed was preferred. This mallee 'buffer' area was an area somewhat greater than the area of mallee in which the annual surveys occur. In each year a cull quota was set, the number to be culled was the difference between the number of kangaroos observed in the previous year (including assumed migrants) and the target. In parks other than Wyperfeld the target was fixed across all years (Table 1).

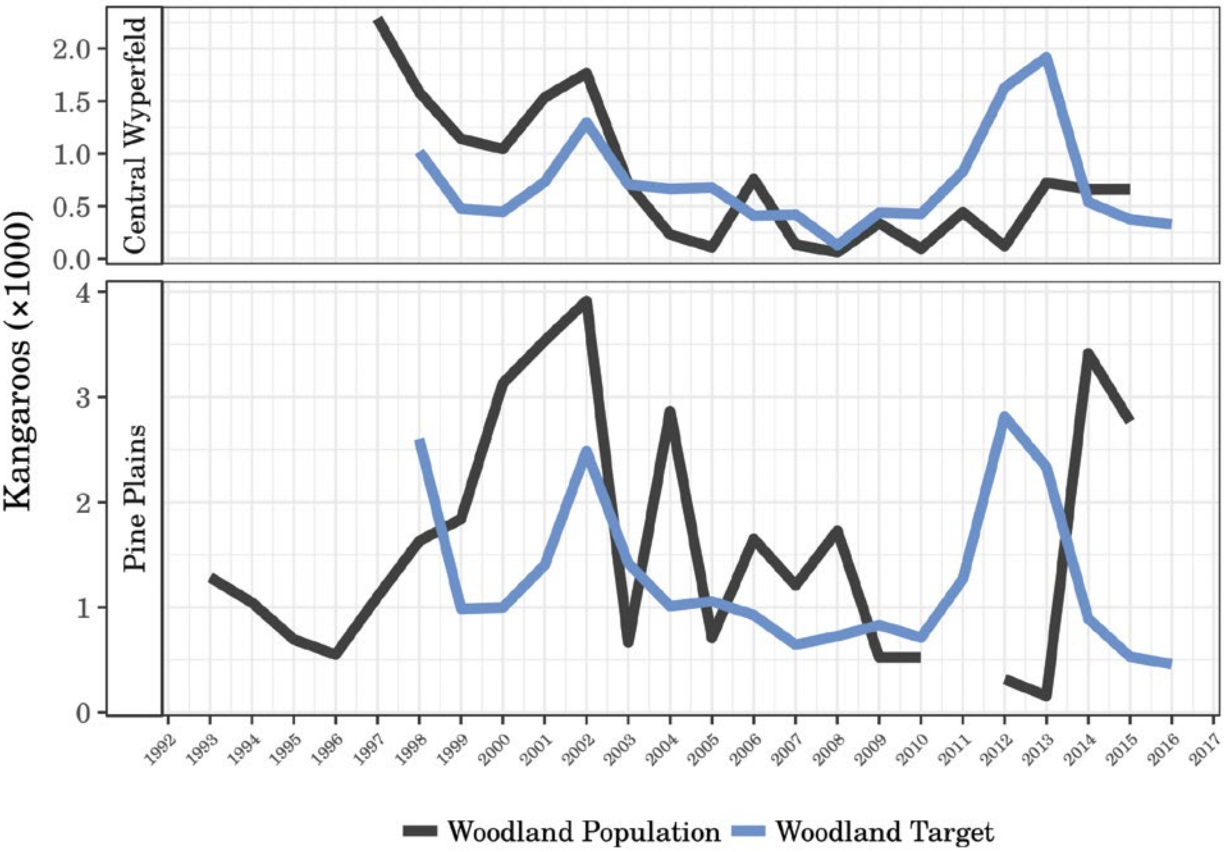

Figure 5: Comparison of the woodland components of the Central Wyperfeld and Pine Plains western grey kangaroo populations to their corresponding target populations during the period 1993–2016.

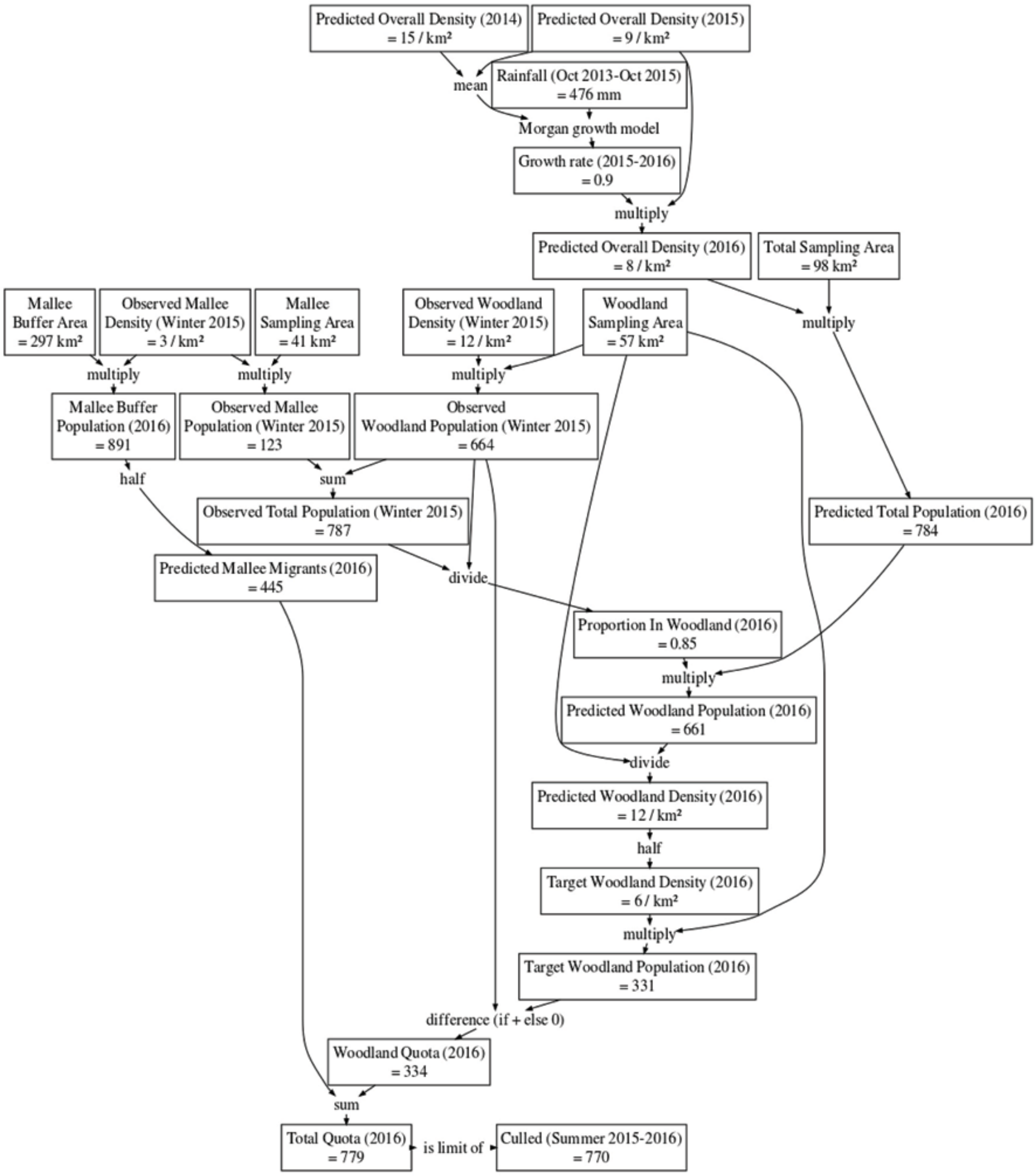

Figure 6: The process used for setting the cull quota for Central Wyperfeld summer 2015–2016.

2.2.4 Kangaroo culling in the Mallee Parks

The first cull of kangaroos in the Mallee Parks occurred in Hattah-Kulkyne in 1984 when 787 western grey kangaroos were shot in the Mournpall management block (Cheal, 1986; Coulson & Norbury, 1988). That cull was the first in National Parks anywhere in Australia (Caughley & Shepherd, 1987) and the controversy and opposition it generated rendered the use of culling politically unpalatable for some years after. Culling recommenced in 1990 in the Mournpall block and the following year more widely in the park. Between 1990 and 1994 over 15,000 western grey kangaroos were shot in Hattah-Kulkyne (Coulson, 2001). Between 1998 and 2016 more than 60,000 kangaroos were culled in the Mallee Parks (at Murray Sunset and Hattah-Kulkyne cull data is not available prior to 2004). Approximately 80% of which were western grey kangaroos and the remaining 20% red kangaroos. The number of kangaroos culled tended to increase through time as the cull program was expanded to more areas and red kangaroos were included in the program. The increase was however, not monotonic. The cull peak was 8,872 in 2013 and several years (2006 and 2010–2012) had no kangaroos culled due to persistent drought. The culling level varied between the eight culling sites (Figure 7).

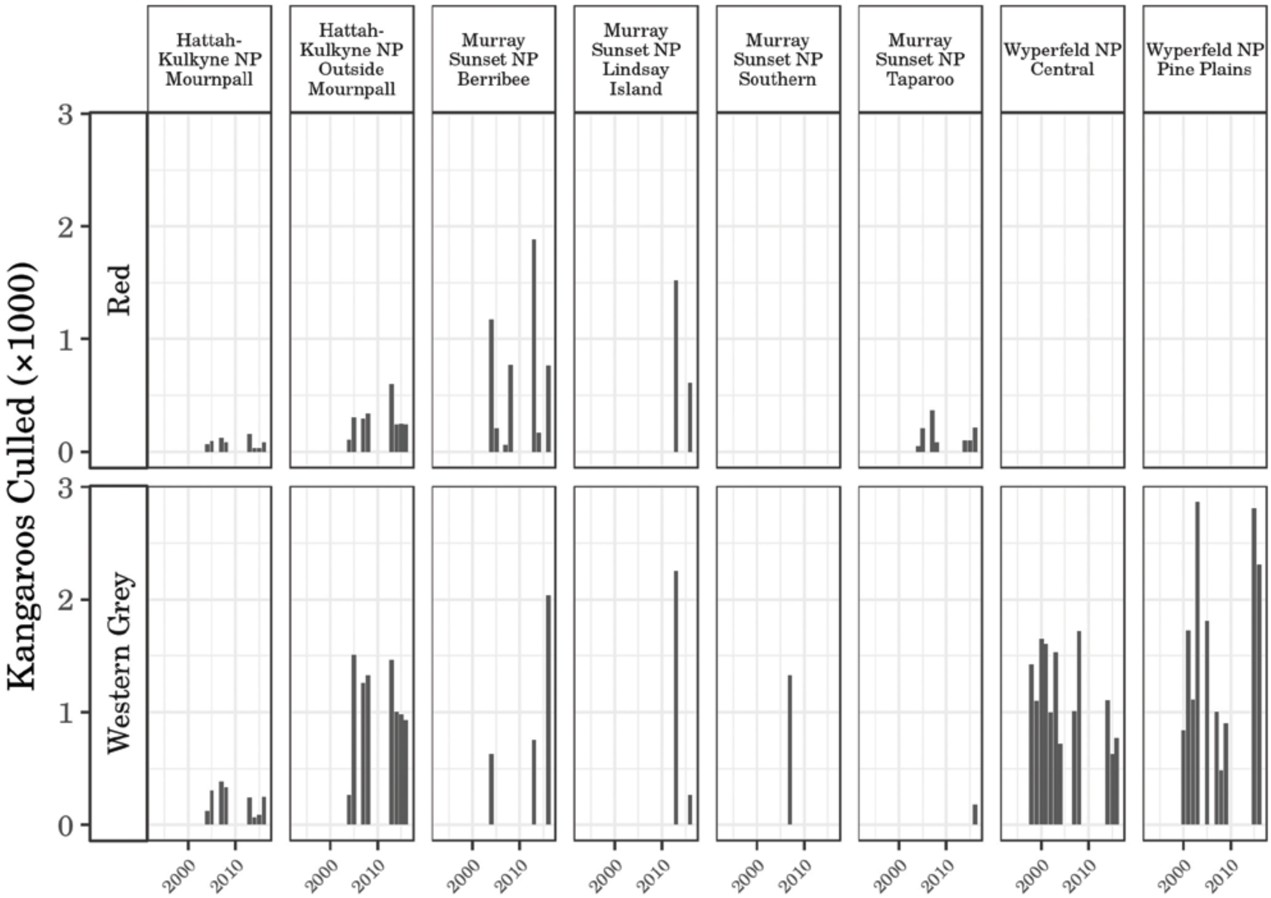

Figure 7: Recorded number of red and western grey kangaroos culled in the Mallee Parks during the period 1998–2016

2.3 Towards adaptive management of kangaroo populations in the Mallee Parks

Consultation with researchers at the University of Melbourne continued after the adoption of the Morgan growth model used to help manage kangaroo populations in Wyperfeld. In the years following the implementation of the culling program University of Melbourne researchers undertook work to bring the monitoring and management of Mallee Park kangaroos into an adaptive management framework.

2.3.1 Chee population growth/removal sampling model

Using the Morgan growth model as a base, Chee and Wintle developed a new multi-component model integrating the kangaroo population and culling observations (see Chee, 2010 and Chee & Wintle, 2010, for details). The new model consisted of combining an updated version of the Morgan growth model with a removal sampling model. The aim was to learn about the population size from the removal sampling (recording of culling activity), thereby getting more rapid feedback and to seek to relieve some of the cost burden of population surveys. Whereas the growth model applied to the distance sampling data, collected yearly during winter/spring, the removal sampling model component applied to data on the number of kangaroos removed from the population in a given period of time (or unit of culling effort) and collected during culling in the intervening summers. While the growth component was based on the Morgan growth model, the removal sampling component was adapted from the removal sampling/catch per unit effort models of Wyatt (2002) and Mäntyniemi et al. (2005). Both model components were implemented using Bayesian methods. Predictions made of population size using the growth model component were used as Bayesian priors and subsequently updated using the cull data and removal sampling model. We refer to this combined population and removal sampling model as the Chee growth/removal model.

The growth component of the Chee growth/removal model relates the kangaroo density, $D_t = N_t/A_t$, in a given year to the cumulative rainfall, p_t (as above), and the density in the previous year (as opposed to the average of the previous two surveyed densities, $\bar{d}_t$, used in the Morgan growth model). Here kangaroo density is modelled as Poisson[2] distributed with the following probability model:

$$\begin{aligned} D_t &\sim \text{Poisson}\ (D_{t-1}e^{g_t}) \\ g_t &\sim \text{Normal}\ (a + bD_{t-1} + cp_t, \sigma) \\ a &\sim \text{Normal}\ (0, 10^6) \\ b &\sim \text{Normal}\ (0, 10^6) \\ c &\sim \text{Normal}\ (0, 10^6) \\ \sigma &\sim \text{Uniform}\ (0, 1), \end{aligned} \tag{4}$$

where the growth rate, g_t, is normally distributed having a standard deviation, σ, with a uniform prior, and mean, a linear function of D_{t-1} and p_t, with intercept a and coefficients b and c having vague normal priors (standard deviation = 10^6).

The removal sampling component relates the number of kangaroos culled in a given year, t, sub-setted into a sequence of removals (x_j for $j = 1, \ldots, J$) of equal effort, to the estimated population size, $\hat{N}_{t,j}$, the expected proportion ofthe population culled in a single removal, μ, and the rate at which the proportion culled declines with successive removals, η, with the following binomial probability model:

$$\begin{aligned} x_j &\sim \text{Binomial}\left(\hat{N}_{t,j} - x_{j-1}, \frac{\mu e^{\eta}}{e^{\eta} + j - 1}\right), \text{ for } j = 1, \ldots, \text{J} \\ \hat{N}_{t,1} &\sim \text{Negative-binomial}\ (\alpha, \beta) \\ \mu &\sim \text{Beta}\ (1, 1) \\ \eta &\sim \text{Uniform}\ (0, 30), \end{aligned} \tag{5}$$

where $x_0 = 0$, μ has a vague beta prior and η has a uniform prior. The prior for the pre-cull population size, $\hat{N}_{t,1}$, follows a negative-binomial distribution and links the two components of the Chee growth/removal model. The prior parameters, α and β (the shape and rate of the negative-binomial) are derived from the posterior predictive distribution for the population in a given year

$$\tilde{N}_t \sim \text{Poisson}\ (D_{t-1}A_t e^{g_t}), \tag{6}$$

where $\alpha = \text{E}\ (\tilde{N}_t)^2/\text{Var}(\tilde{N}_t)$ and $\beta = \text{E}(\tilde{N}_t)/\text{Var}(\tilde{N}_t)$.

[2]Note that a Poisson likelihood typically only applies to non-negative integers, and is de fined as $\Pr(x; \lambda) = e^{-\lambda}\frac{\lambda^x}{x!}$ for $x = 0, 1, \ldots; \lambda \geq 0$, Chee however, uses an alternative definition which applies to all real non-negative numbers, $\Pr(x; \lambda) = e^{-\lambda}\frac{\lambda^x}{\Gamma(x+1)}$ $x, \lambda \geq 0$

2.3.2 Aims of the Chee growth/removal model

The Chee growth/removal model was constructed with two aims in mind. The first aim was to use the model in a dynamic control process, whereby a population could be monitored "live" during a cull. The idea being, that if the initial estimate of population size ($\tilde{N}_t$ the posterior predictive estimate from equation 6) exceeded a desired level then culling would occur (in stages), ceasing when the culled population estimate ($\hat{N}_{t,j}$ from equation 5) was at the desired level (Chee & Wintle, 2010).

The second aim of this new model was to take advantage of the population information in the culling data and replace an appropriate proportion of direct and costly monitoring (the distance sampling) with the indirect indication of population dynamics arising from cull data.

2.3.3 Application of the Chee growth/removal model

Chee & Wintle (2010) devised simulations to demonstrate two aspects of applying the Chee growth/removal model to kangaroo control. First, they ran a set of simulations to show how iterative removal estimation proceeds and performs in a single management year. They found that the estimates of population size increased in both accuracy and precision when using the removal sampling method.

Another set of simulations was used to investigate how a population control algorithm (Figure 8), based on the Chee growth/removal model, could perform over a 20-year management horizon in a virtual world. The second set of simulations accounted for, in addition to demographic and environmental stochasticity, uncertainty and inaccuracy in estimates of key model parameters. The goal of the control algorithm was to keep the kangaroo population within predetermined lower, L, and upper, U, limits. For the simulation, L was fixed at 5, and U took the value 20 kangaroos per km^2. The simulation, using the steps outlined in figure 8, was run with 27 different parameterisations (and 10 replications for 270 total simulations) that were combinations of different values for three uncertain parameters: initial population density (D_{t-1}), density dependence (b) and effect of rainfall (c). The 27 alternative model parameterisations were used to test the effect of imperfect knowledge on management with only one of the 27 parameterisations coinciding with those the virtual managers were using to predict the initial population density at the beginning of each culling year. A second set of simulations without culling was run in parallel to the simulations using the population control algorithm for comparison. Without culling, less than 10% of the 270 simulations stayed in the control limits for 10 or more out of the 20 years of management. When the population control algorithm was used only 3 of the 270 simulations were outside of the control limits for more than 10 years and 86% of simulations were in control for at least 15.

Chee (2010) tested the application of the Chee growth/removal model to actual cull data collected during summer 2006–2007 at Pine Plains. They found that using the growth/removal model for a sequence of removals attained by dividing the cull into 3 person-hour blocks improved the precision of the esti mate of initial population size. Hauser & Lahoz-Monfort (2014) again tested the application of the Chee growth/removal model with data collected during the summer 2013–2014 at Central Wyperfeld. These authors also found that the precision of the estimate of final population size was improved but that the removal sampling model indicated that the distance-sampling based estimate of initial population size was an underestimate according to the information present in culling data.

Degraded pine-buloke woodland formation showing the signs of past clearing and pastoral use, a state maintained by herbivores including kangaroos. Very few mature trees remain, and the understorey is very sparse and highly simplified. Recruitment of ***Pittosporum angustifolium*** *can be seen in the mid-ground. Photo: David Duncan*

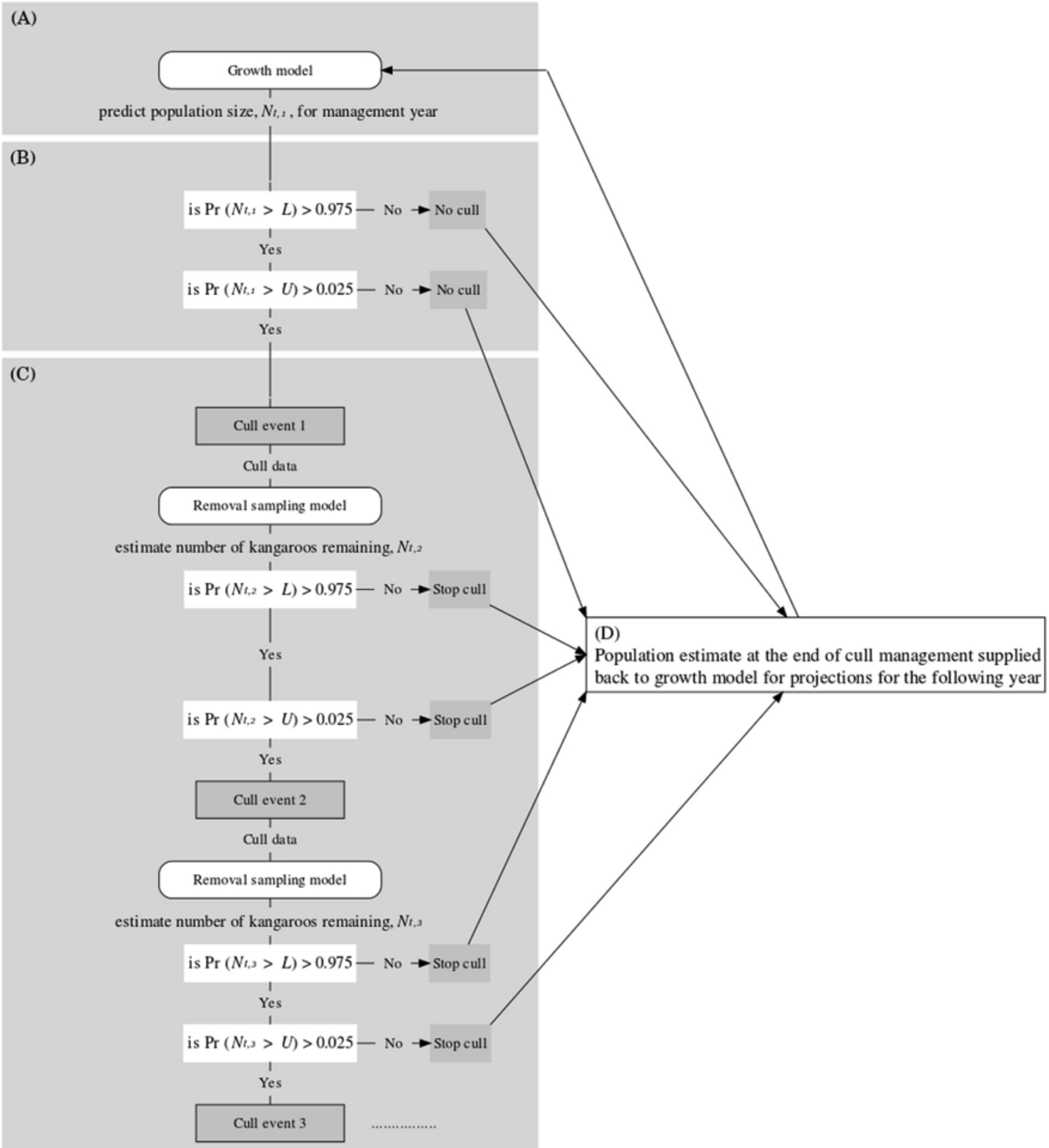

Figure 8: Population control algorithm for kangaroos in the Mallee Parks (Chee & Wintle, 2010). (A) Using the population estimate of the previous year and the most recent rainfall data, a new population size is predicted for the current management year. (B) If the probability that the population size exceeds the lower limit, L, is greater than 0.975 and the probability that the population size exceeds the upper limit, U, is greater than 0.025, then culling is implemented for that year. If one or both of these conditions is not met then no culling occurs during the current management year. (C) Culling is implemented in increments. After a culling event, the removal sampling model is applied to the cull data generated and a new estimate of the population size is produced. The conditions, as stated in section A, are reassessed and if both are satisfied the process is repeated; if not, culling is ended for the current management year. (D) After culling has ended, or if no culling occurs, the last population size estimated is supplied back into the growth model when the next set of rainfall data is available and the initial population size for the next management year is predicted.

3 Findings and options for management

3.1 Trends in Mallee Parks kangaroo populations before and after culling

Figure 1 shows the population changes in red and western grey kangaroos in the Mallee Parks for the years these populations have been monitored. Population sizes varied between parks, sites, species, and through time. For western grey kangaroos, both the population size and its variation over time were generally lower after culling was implemented. However, there is some indication that the opposite is true for red kangaroos. The reason being perhaps, is that reduced competition from western grey kangaroos (after culling) have enabled their populations to increase despite the limited culling of red kangaroos that also occurred.

3.2 Population levels and targets

At Wyperfeld, where the Morgan growth model was applied, the western grey kangaroo populations have tended to stay below the without-culling projections of the model (Figures 2 and 4). Though this is less so for Pine Plains than it is for Central Wyperfeld. Moreover, while at Central Wyperfeld the western grey kangaroo population observed in the woodlands has tended to remain at or below the target population since culling was introduced, the observed woodland population at Pine-Plains has more often than not been at levels above the target population (Figure 5). At Hattah-Kulkyne, kangaroo populations have usually been above their target levels since culling began. Inside the Lake Mournpall fence, the observed population has tended to be much closer to the target than the observations of kangaroos for both species outside the fenced area (Figure 9). At Murray Sunset, western grey kangaroos have tended to stay below their target population level, except at Lindsay Island—although culling of western grey kangaroos has been limited in the park generally (Figure 7). Red kangaroos, culled more frequently than western grey kangaroos in this park, have been at levels above their target a majority of the time.

3.3 Is culling working?

Though the population trends provide some circumstantial evidence that the culling program is having a desired effect (at least maintaining populations at lower levels than before culling) there remain multiple barriers to declaring a direct causal link between the culling program, kangaroo population size, grazing pressure and woodland recruitment and recovery (Hauser & Lahoz-Monfort, 2014). In some cases declines in populations to current levels occurred before culling was implemented (Murray Sunset Berribee and Taparoo). Also, there is little capacity to compare culled kangaroo populations with a control population of monitored but unmolested kangaroos, and gauge the true effect on population growth and size.

And, moreover, whilst a program of periodic assessments of the condition of semi-arid woodlands in the Mallee Parks exists (see Sunraysia Environmental, 2011; Kenny et al., 2012), it is not designed to reveal whether the culling program is contributing to the fundamental objective of the management program it forms a part of.

*Hattah-Kulkyne National Park - dunes and swathes of Poached egg daisy, **Polycalymma stuartii**. Photo: Peter Neaum CC BY 3.0 Wikimedia Commons*

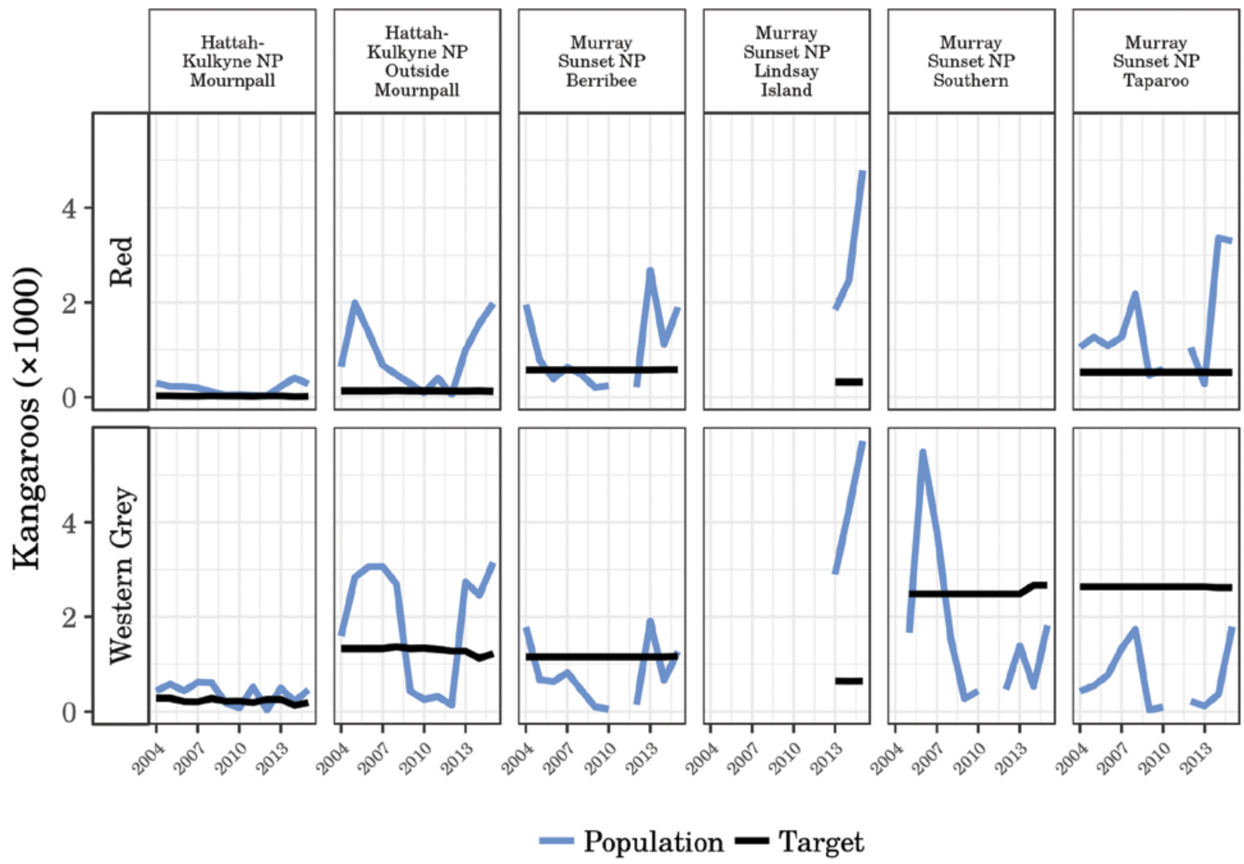

Figure 9: Comparison of Hattah-Kulkyne and Murray Sunset red and western grey kangaroo populations to the their corresponding target populations during the period 2004–2015. Where the (Fixed) target lines shift it corresponds to a change in the area over which the cull was applied.

3.4 Does culling data and a removal sampling model improve estimates of kangaroo population size?

3.4.1 Problems with the removal sampling model

Unfortunately, during this current round of review of the removal sampling methods, flaws were identified in some of the previous analyses. While the underlying model and technique was sound, mistakes made in the implementation of the removal sampling model invalidated the results reported in Chee & Wintle (2010) and Chee (2010). Both the analysis of simulated and real removal sampling data and the simulation of the population control algorithm contain important technical flaws (note however that the errors were not made in Hauser & Lahoz-Monfort, 2014 and the results in their report are correct).

First, in the analysis of simulated and real removal sampling data, estimates of the population size and removal rate from each iterated application of the Bayesian model to a sequence of removals were overly precise. This is because the data from all previous removals were used in successive application of the model to later bouts of removal within a yearly cull program. This is akin to having duplicated data and so leads to overconfidence in the estimates of population size and removal rate. This overconfidence was propagated through the population control simulation leading to optimistic picture of the effectiveness of the method under the conditions of kangaroo control in Wyperfeld.

In combination, these errors lead to an overstatement of the usefulness of removal sampling data for estimating kangaroo population size. Whereas Chee and Wintle concluded that the removal sampling model and culling data could considerably improve the precision and accuracy of the estimate of initial populations, in light of the error in implementing the methods, these findings can no longer be considered accurate. Indeed, precision may decrease (as measured on some scales) when adding the information from culling data, and accuracy will not increase under all circumstances. The primary reason for this apparent contradiction is that the removal-sampling model suffers from a paucity of identifiability (see Reichert & Omlin, 1997, for discussion of identifiability and overparameterization).

This model is unidentifiable because it seeks to estimate two unknown parameters (the size of the population, and the rate at which kangaroos are removed from the population via culling) for which the uncertainty is effectively interchangeable. Non-identifiability is common in models of complex ecological systems, particularly when we want to predict outcomes of a known process for which we have insufficient data to statistically resolve. Thus, it is not an error per se, and in some circumstances is necessary or even desirable that models retain non-identifiable parameters (Reichert & Omlin, 1997). In the case of the kangaroo removal sampling model, however, it reflects a fundamen

tal limitation that the currently available data and culling approach place on the objective of simultaneously estimating and controlling kangaroo populations. Figure 10 demonstrates the problem at hand, showing that when the removal rate is fixed, the sequence of removals expected from different population sizes is more easily distinguished than when the removal rate varies. This problem is exacerbated when there are relatively few removals and the overall proportion of the population removed is low.

To ameliorate the issue of identifiability for the kangaroo removal sampling model would require substantive knowledge of one or other or the model parameters in play. That is, it would require knowledge, ahead of time, on either the initial population size or the expected proportion of the population that could be removed with a given unit of effort. In the case of the former, knowing the population size is the ultimate aim of the removal sample modelling and possessing such knowledge would make the model redundant. Knowing the latter on the other hand, would require a good sense of how culls of this kind operate in general, and how the rate of population removal can vary with conditions such as weather and terrain. This might require formal experimental culls on closed and well-known kangaroo populations, which may or may not be logistical and/or financially feasible.

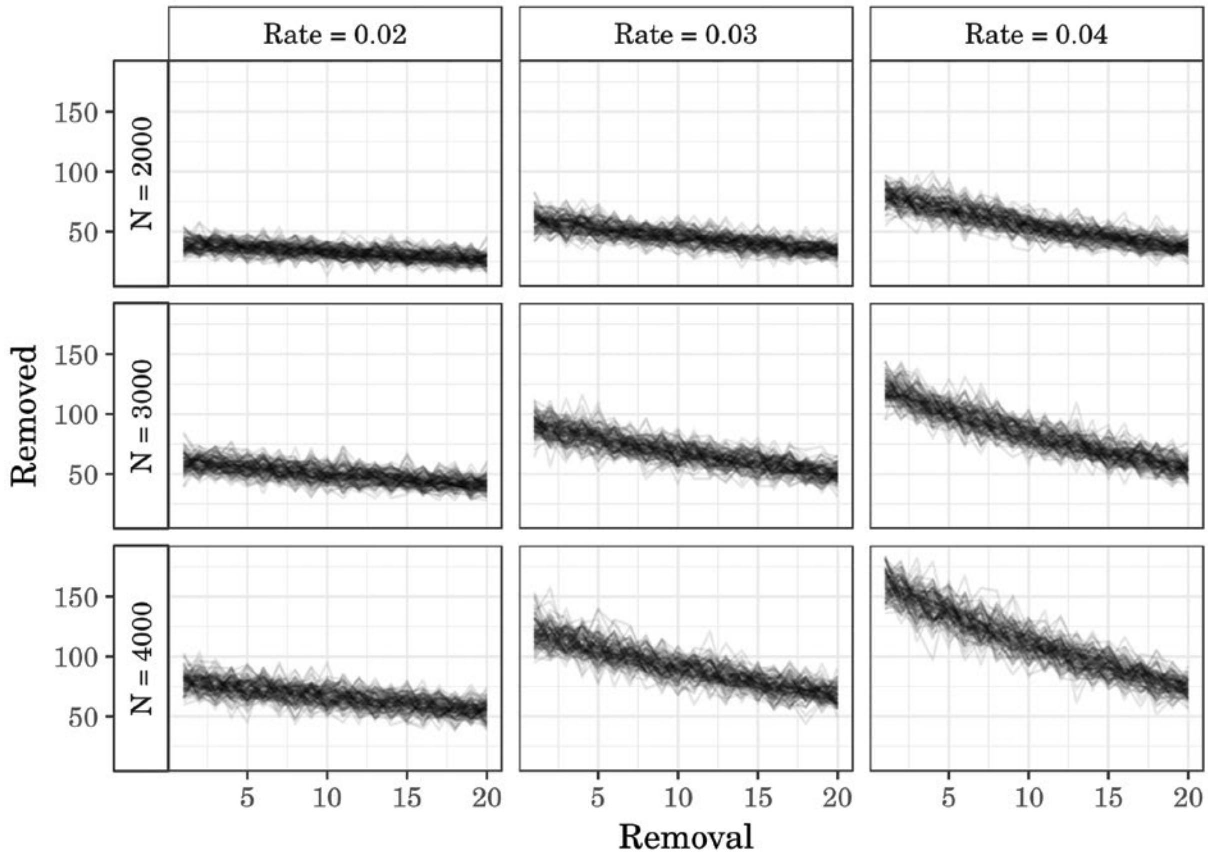

Figure 10: Simulated removal sampling data. Each panel shows a set of 100 simulated removal time-series (20 consecutive removals from a population without replacement) for fixed initial population size (increasing from top to bottom) and removal rate (increasing from left to right) as transparent black lines. For any given removal there is a spread across simulations due to random binomial variation. Note that if the ratio of removal rate to initial population size changes (moving up and down, left and right or diagonally top-left to bottom-right) the trajectory of removals is relatively easy to distinguish. However, if this ratio remains the same (moving diagonally bottom-left to top-right) then the number removed through time is relatively similar. Moreover the fewer the total number of removals the harder the time-series would be to distinguish.

3.4.2 Problems with the culling data

Next, we address the cull data and what it tells us about the applicability of the removal sampling method. The assumptions of the removal sampling include constant cull effort, random interception, perfect and instantaneous mixing of the population and linear decline in catchability. In this report we collate the raw culling data for Wyperfeld for the years 2014 to 2016. Raw culling data included the dates and location of the hunt, the identity of the hunters, start and end times of hunting nights, time and duration of during-hunting-night hunter breaks, and the time each individual kangaroo was killed. Errors were found in the raw cull data—the most common being that reported break times did not coincide with breaks in kangaroos being shot. To remedy these inconsistencies the break times were either shifted to when there was a corresponding absence of reported kangaroo shooting immediately before or after the break was supposed to occur, or if no such absence could be found, then the break was ignored, and it was assumed not to have happened. The raw culling data was aggregated into three hour duration person-hour blocks accounting for between and within hunt-night breaks (Figure 11). For example, if two hunters shot 30 kangaroos each, in an hour and forty minutes and both took a ten minute break during that time, this would constitute a single block of hunting with 60 kangaroos culled.

Figure 12 displays the cumulative cull against person-hours expended. Contrast this with the simulated cull of 2500 kangaroos in figure 13. It highlights significant issues with the culling data and indicates its incompatibility with the assumptions of the removal sampling model. In a majority of cases the catch rate is approximately constant (about one kangaroo every three minutes at Pine Plains and one every four minutes at Central Wyperfeld). The model however, predicts that catch rate should decline over time as the population is depleted and kangaroos become harder to find. In 2014 at Central Wyperfeld (data also analysed in Hauser & Lahoz-Monfort, 2014) there is some indication of a declining catch rate but this may actually be due to the hunters approaching their target and reigning back their effort towards the end of the cull.

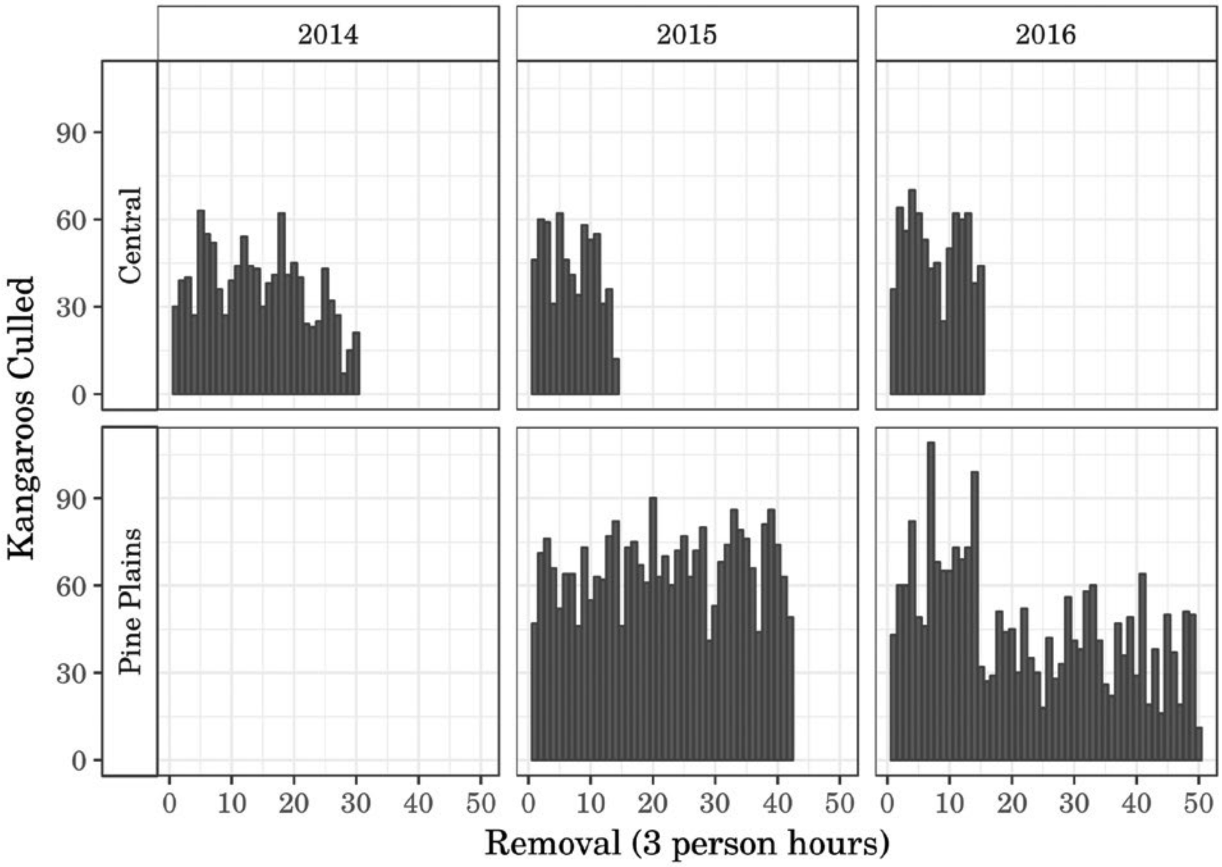

Figure 11: Western grey kangaroo culling in Wyperfeld 2014 to 2016. Bars show the number of kangaroos shot in blocks of three person-hours of effort. Note that the effort in the final bar of each panel is something less than three person-hours of effort and these blocks were not used in analyses.

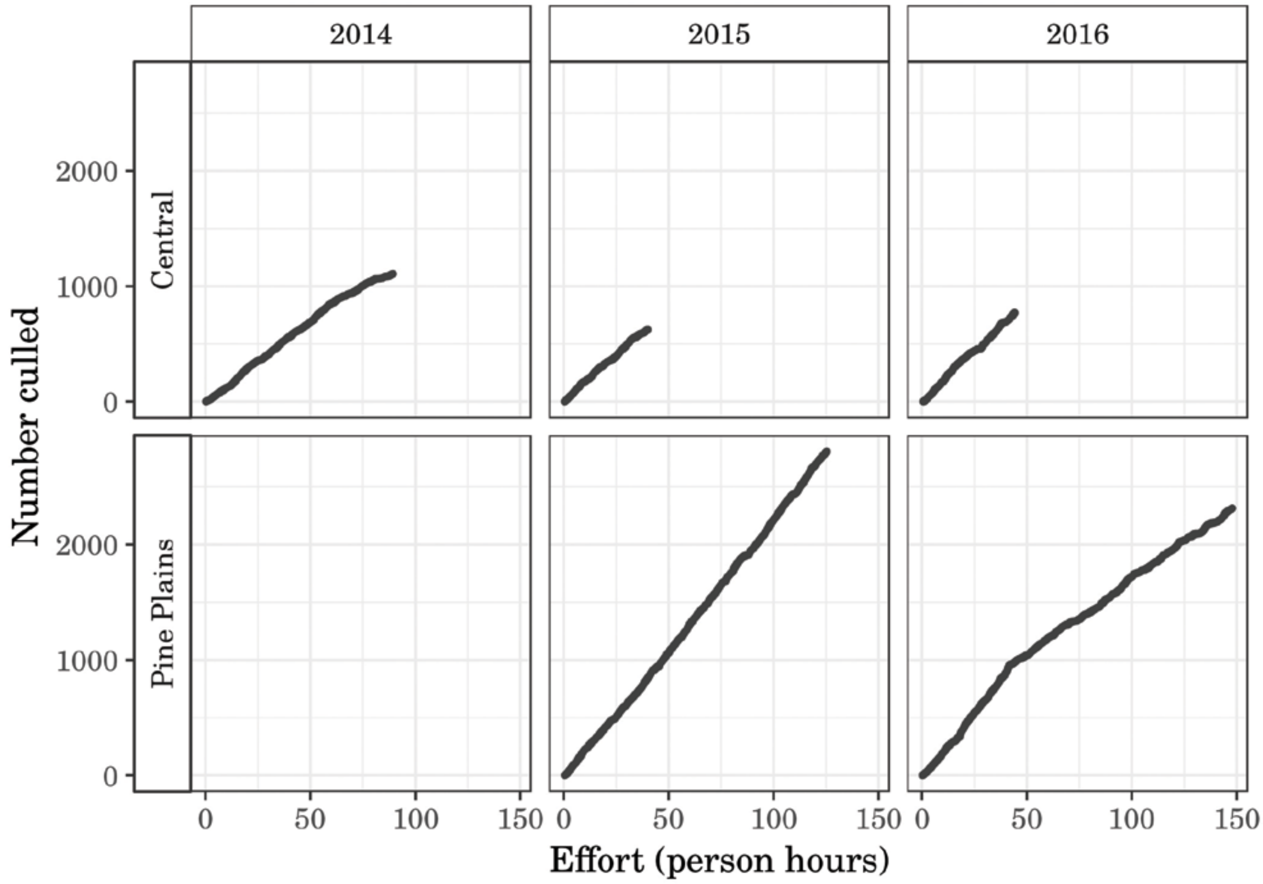

Figure 12: Western grey kangaroo culling in Wyperfeld 2014 to 2016. Lines show the cumulative cull as a function of cull effort (in person-hours).

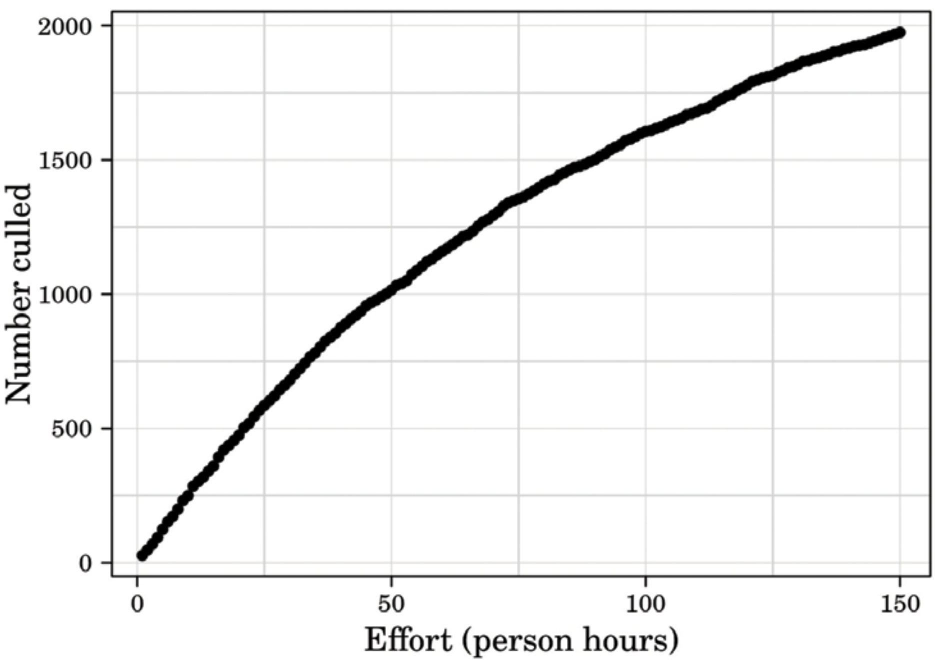

Figure 13: A simulation of a cull that does not violate the assumptions of the removal sampling model. In this case the initial population size is 2500 kangaroos and culling occurs at a rate of 1% per person hour. Note the concave shape of the relationship. If culling rate is allowed to decline over time (in this case it does not) then the relationship would be even more concave.

Assuming that the cull data do not violate the assumptions of the model, then the mildly declining or near constant catch rates of Central Wyperfeld (2014–2016) and Pine Plains (2014–2015) can only be explained by an improbably high initial kangaroo population, such that the depletion of kangaroos during culling has only a negligible effect on kangaroo density over the duration of the cull. However, this assumption cannot explain the culling pattern at Pine Plains during 2016. In this instance there is clear evidence of a change in catch effort after 48 hours of effort was expended, which does not accord with the assumption of constant effort and a linear decline in catchability of the model. Based on the culling data collected to date we think it is unlikely that culling is ever occurring with constant effort applied during the cull, and this would therefore confound the results of analyses using these data.

If culling is indeed occurring with non-constant effort, it is not immediately clear why. One plausible explanation is that the kangaroo shooters, having been assigned a target number of kangaroos to kill and an allotted amount of time in which to shoot them, pace themselves such that they are shooting kangaroos at a constant rate rather than with constant effort.

Another possibility is that the clustering of kangaroos into mobs plays a role. With kangaroos remaining in groups during a cull the time it takes to locate the next kangaroo to shoot may not decline through time as the model expects as the time to find or relocate a mob of kangaroos is not related to (or at least not proportional to) the number of kangaroos removed from the population so far.

There are certainly many other possible reasons that these data are not conforming with the modelling assumptions, many will be mutually inclusive and could have compounding effects.

3.5 Updating Wyperfeld population estimates

Applying the removal sampling model to the cull data collected in Wyperfeld in recent years as outlined in section 2.3.1 (Figures 14 & 15) updates estimates of population size. In most cases the improvement in estimate precision is minimal (note that the estimates are displayed on the logarithmic scale and precision appears greater than it is in reality) and in many cases (particularly for estimates at Pine Plains) the posterior estimates include implausibly large population sizes, the exception being Central Wyperfeld in 2015. For comparison, the observed population sizes were approximately 600–800 kangaroos at Central Wyperfeld and 2000–3000 kangaroos at Pine Plains during these periods.

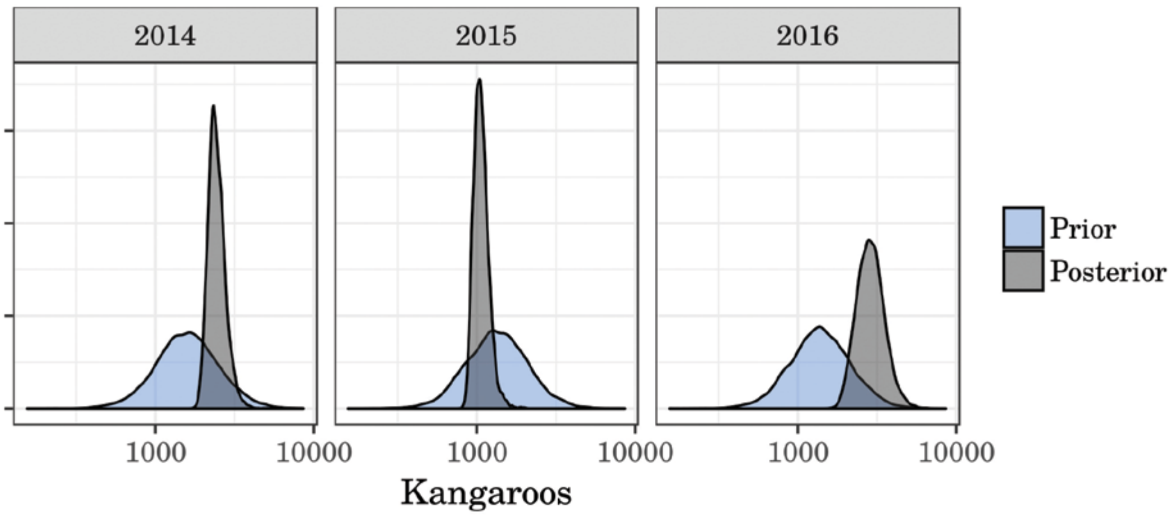

Figure 14: Central Wyperfeld western grey kangaroo population estimates 2014–2015. Density plots show the probability distribution of the prior and posterior estimates of kangaroo population size for each year derived from MCMC sampling. The prior estimate is the posterior predictive distribution from the Chee model growth component conditioned on the previous year's estimated kangaroo density (distance sampling observation) and the 25 month (October to October) cumulative rainfall. The posterior distribution is the same quantity as the prior, updated via Bayesian inference, with the removal sampling data.

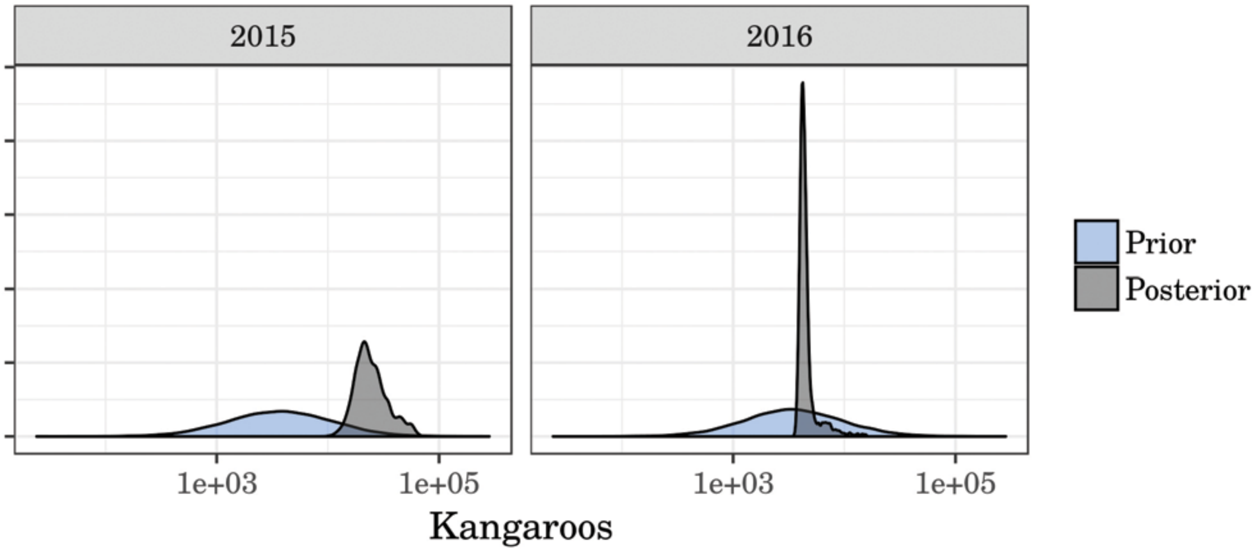

Figure 15: Pine Plains western grey kangaroo population estimates 2015–2016. Density plots show the probability distribution of the prior and posterior estimates of kangaroo population size for each year derived from MCMC sampling. The prior estimate is the posterior predictive distribution from the Chee model growth component conditioned on the previous year's estimated kangaroo density (distance sampling observation) and the 25 month (October to October) cumulative rainfall. The posterior distribution is the same quantity as the prior, updated via Bayesian inference, with the removal sampling data.

Direct seeding lines curving through the skeletal remains of semi-arid woodland structure. Direct seeding is an expensive measure made necessary by chronic failure to regenerate the woodland structure. Photo: Emily Baldwin

3.6 Can direct monitoring be substituted by removal sampling?

We have identified significant shortcomings in the culling data, the removal sampling model and problems with some previous applications of the model. Therefore, at this stage, we cannot recommend that direct monitoring is forgone with the expectation that this information could be compensated with data collected during culling.

Table 2: Aspects of kangaroo control activity with scope for improvement.

Aspect	Problem	Options	Feasibility
Population monitoring	Population monitoring is resource intensive	Reduce monitoring effort. Some combination of fewer sites and/or alternating yearly measurement, etc.	Easily implemented, but potentially detrimental as limits certainty of population estimates and projections
Population model	Model oversimplifies population dynamics	Build more complex population model. Include culling explicitly, and data from sites other than Central Wyperfeld	Somewhat feasible. Though there is a trade-off between model complexity and accuracy, and model estimate uncertainty
Removal sampling	Removal sampling data violates assumptions of model	Collect more detailed culling data. Handling time, search time, etc. Further restrict shooter activity to facilitate random encounters with kangaroos and uniform effort applied during hunt as is assumed by model	Potentially onerous for staff and/or shooters Would decrease efficiency of cull and hamper shooters efforts to reach target
Removal sampling model	Removal sampling data violates assumptions of model Identifiability. Model is attempting to estimate population and catch rate simultaneously	Reformulate model to account for idiosyncrasies of culling data Conduct experiment on a known, closed population of kangaroos to estimate catch rate prior to culling in the open populations of the Mallee Parks	Difficult at present as no clear picture exists on how exactly culling data is violating the current removal sampling model Limited feasibility Would incur a potentially high logistic and financial cost

3.7 Prospect for using removal sampling in the future

If removal sampling is to be used with success in the future, the issues raised above will need to be addressed in some way. First, the removal sampling model and the culling data must be reconciled. That is, either the removal sampling model must be modified to account for the idiosyncrasies of culling and data collection, or the culling and data collection process must be modified to accord with the assumptions of the removal sampling model. Second, the issue of model identifiability must be overcome. To do so would require more information on the rate at which kangaroos are able to be removed from the population, for which further study is needed.

For example, a study could be conducted to estimate the intrinsic removal rate of kangaroos for a given culling regime and its dependence on habitat, weather or other factors. This might be done in an enclosed section of park with a reliable kangaroo population estimate in a tightly controlled set of circumstances. Then assuming the estimated removal rate(s) is applicable outside of the experiment, it could be used to overcome the problem of identifiability in the removal-sampling model. Whether this is practicable, we do not know.

3.8 Reducing monitoring and predicting its effect

It may be possible to reduce the current level of monitoring (yearly at all sites) and reduce costs without jeopardizing the goals of the kangaroo management program. However, the effect of any reduction in kangaroo population monitoring is difficult to predict with information currently available. The tight coupling of monitoring and management confounds the ability to use the time-series of population data (in particular the longer-term data collected for Central Wyperfeld) to gauge the effect of reducing monitoring. For any given year we can project how a cull target would change if monitoring did not occur and a predicted population was used in place of an observed. Extending this idea beyond a single year is fraught because how many kangaroos are observed in any given year depends on what was culled in the previous year.

An alternative investigation would be to simulate the dynamics of the kangaroo management and monitoring. Such a simulation would be possible with the caveat that the uncertainties in its prediction would necessarily be large.

A Western Grey Kangaroo at Wyperfield National Park. Photo: Donald Hobern Flickr CC by 2.0

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Further information:

http://www.nespthreatenedspecies.edu.au/

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