A report to the New South Wales Department of Planning, Industry and Environment on the consultancy: "Design and analysis of helicopter surveys of kangaroo populations in the South East Tablelands kangaroo management zone, 2020".

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Summary

1. Helicopter surveys for kangaroos were conducted using line transect sampling in the seven survey blocks that make up the South East Tablelands kangaroo management zone. The density and abundance estimates derived from the results of these surveys were intended to be used to assess the possible impact on eastern grey kangaroos (*Macropus giganteus*) population of the bushfires that occurred in the summer of 2019-2020 within parts of this management zone. Possibly confounding the outcome of this exercise is the fact the bushfires occurred at the end of a severe drought which extended over the previous three years, 2017-2019.
2. The surveys were designed using an automated survey design algorithm of DISTANCE 7.3 (Strindberg, Buckland & Thomas 2004; Thomas *et al.* 2010). To facilitate survey design, each survey block was divided into two or three strata based upon land capabilities and kangaroo density. Those strata identified as most likely to be supporting medium to high densities of kangaroos were the strata surveyed. Low kangaroo density strata were not surveyed.
3. The surveys were designed as a scoping exercise with the intention of estimating eastern grey kangaroo numbers with a reasonably low level of precision. This was set in relation to target survey block coefficients of variation of 40% for the population estimates obtained for eastern grey kangaroos.
4. The density of eastern grey kangaroos in the management zone was estimated to be 19.6 km^{-2} which corresponded to a population estimate of 818,535 kangaroos. This compares to a population density of 43.1 km^{-2} estimated from a previous survey conducted in 2018.
5. Since the previous survey conducted in 2018, the eastern grey kangaroo population in this management zone has decreased by 55%. Prior to this sharp decline in numbers, the long-term trend in eastern grey kangaroo numbers in this management zone had been such that the population had been increasing to an annual finite rate of increase in numbers of 11% over the period 2009-2018.
6. Three other species of macropod, the common wallaroo (*Osphranter robustus*), the red-necked wallaby (*Macropus rufogriseus*) and the swamp wallaby (*Wallabia bicolor*) were recorded in this survey. There were not enough of each of these species observed for population estimates to be determined.

1. Introduction

All states and territories of the Commonwealth of Australia administer, in one form or another, macropod management plans. Commercial harvesting conducted by licensed harvesters is generally a significant component of the management of the populations of the large kangaroo species that are variously widespread and abundant throughout much of the continental Australia (Pople & Grigg 1998). The commercial harvesting of large kangaroos is undertaken in all five mainland states. Currently, it plays no part in macropod management in either the Australian Capital Territory or the Northern Territory. Further, large kangaroos are not harvested in Tasmania.

In those states where it is undertaken, the commercial harvest is limited by quotas that are set with the intention of ensuring its sustainability. It is a legislative requirement that any commercial harvesting of kangaroos be conducted on a sustainable basis (Pople & Grigg 1998). In order to set appropriate harvest quotas, it is necessary to obtain reasonably precise and accurate estimates of the sizes of the kangaroo populations proposed to be harvested. Species-specific quotas are set as proportions of these population estimates (Pople & Grigg 1998).

In New South Wales (NSW), some or all four of those species of macropod identified as large kangaroos, the red kangaroo (*Osphranter rufus*), the eastern grey kangaroo (*M. giganteus*), the western grey kangaroo (*M. fuliginosus*) and the common wallaroo or euro (*O. robustus*), are currently harvested from within 15 kangaroo management zones (Anon. 2011, 2016). Nine of these management zones are located on the inland western plains. The other six are located on the tablelands and western slopes of the Great Dividing Range.

Estimates of the sizes of the kangaroo populations in the inland management zones are obtained from aerial surveys conducted annually using fixed-wing aircraft and, more recently, the method of line transect sampling (Anon. 2016). Harvest quotas for the next calendar year following the surveys are set in relation to these population estimates. Because of the general relief of the landscape in those management zones that cover the tablelands and western slopes, the kangaroo populations there cannot be surveyed using fixed-wing aircraft. They are, instead, currently surveyed on a triennial basis using helicopters and the method of line transect sampling. Annual harvest quotas for these management zones are set for the next three successive years in relation to the population estimates obtained from these surveys (Anon. 2016). The suitability and effectiveness of helicopter line transect sampling of kangaroo populations has been demonstrated by Clancy, Pople & Gibson (1997) and Clancy (1999).

Conducting these surveys on a triennial basis is considered to be a safe option for monitoring kangaroo populations in mesic environments such as the tablelands and western slopes of NSW, as opposed to semi-arid rangeland environments (Pople 2003, 2008). According to Pople (2008), the risk of quasi-extinctions occurring in relation the setting of harvest quotas using triennial population estimates is relatively low in mesic environments.

One of the six kangaroo management zones along the Great Dividing Range is the South East Tablelands kangaroo management zone (see Fig. 1). When established and first surveyed in 2003, this zone comprised five Rural Land Protection Board (RLPB) districts (Cairns 2004, 2007). It was later expanded in size with the inclusion of a sixth RLPB district (Cairns, Lollback & Bearup 2010). These RLPB districts now no longer exist as administrative/management units, but they remain as broad strata within this kangaroo management zone for the purpose of survey design. Across NSW, clusters of RLPB districts have now been combined to form Local Land Service regions (see http://www.lls.nsw.gov.au/).

The South East Tablelands management zone has been surveyed on a triennial basis from the time of its establishment in 2003, with the most recent survey having been undertaken in September, 2018. The next scheduled survey of this management zone was planned for September, 2021. The 2018 survey had been undertaken midway through what was considered to be a particularly severe drought which extended over the period 2017-2019 (http://www.bom.gov.au/climate/drought/knowledge-centre/previous-droughts.shtml). In the spring of 2019, this drought culminated in the development of dangerous fire weather conditions; weather conditions which ultimately resulted in a period of severe bushfires in December of that year and January of the following year, 2020. These fires had a considerable impact on parts of the South East Tablelands kangaroo management zone. In light of this, rather than wait until the conduct of the scheduled 2021 survey to assess the possible impact of the fires and the drought that had preceded them on the kangaroo populations in this zone, a low precision scoping survey was planned and carried out in September and November, 2020. Usually, the precision of the surveys undertaken in this management zone were set in relation to a coefficient of variation of estimates of 20%. The present survey was planned to be undertaken in relation to an anticipated coefficient of variation of estimates of 40%. Reported here are the survey design, the description of the sampling and data analysis methods used, and the results of this low precision survey. Some discussion of the outcome of this exercise is also included.

2. Study Area: South East Tablelands Kangaroo Management Zone

The South East Tablelands kangaroo management zone (Fig. 1) surrounds the Australian Capital Territory and comprises seven survey blocks that were formerly identified as Rural Lands Protection Board (RLPB) districts: Bombala, Braidwood, Cooma, Goulburn, Gundagai, Yass and Young. The Bombala, Braidwood, Cooma, Goulburn and Yass survey blocks now comprise part of the South East Local Land Service region. The Gundagai and Young survey blocks are now part of the Riverina Local Land Service region.

Biogeographically, this management zone comprises parts of the South Eastern Highlands Biogeographic Region (IBRA) and the South Western Slopes Biogeographic Region (IBRA) (Sahukar *et al.* 2003). The Bombala, Braidwood, Cooma and Goulburn survey blocks are all within the South Eastern Highlands Biogeographic Region. The Gundagai and Yass survey blocks lie substantially within the South Eastern Highlands Biogeographic Region, with their western edges extending into the South Western Slopes Biogeographic Region. The Young survey block lies entirely within the South Western Slopes Biogeographic Region.

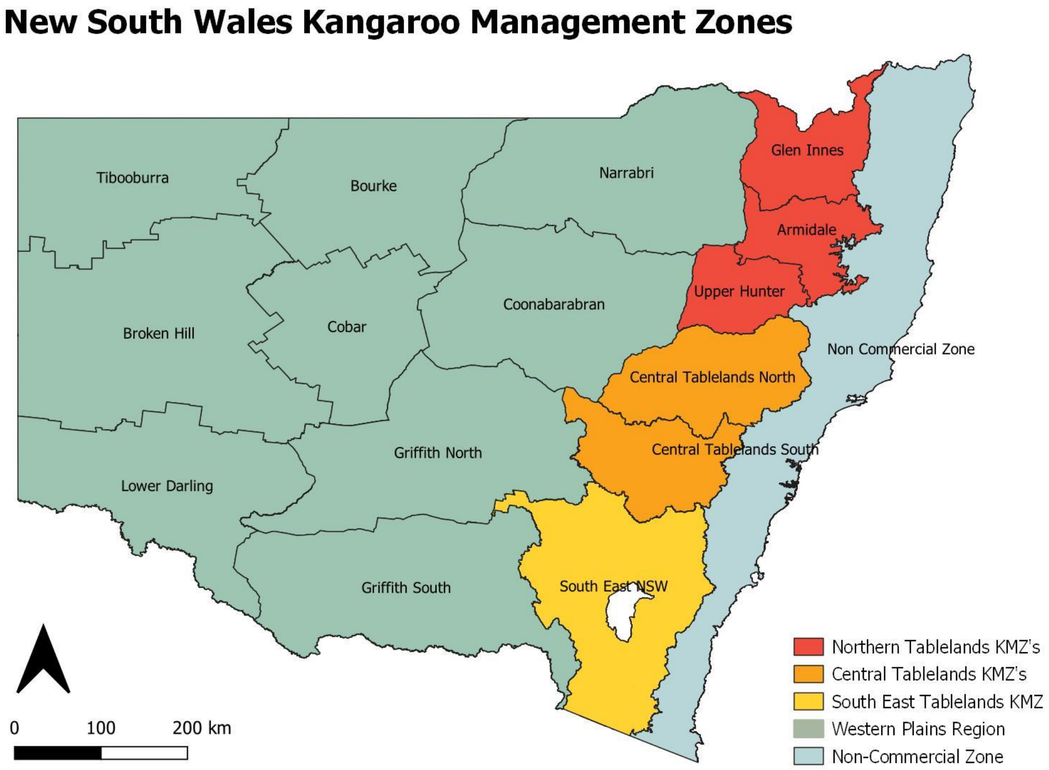

Fig. 1. The 15 kangaroo management zones administered by NSW DPIE.

The characteristic landforms of the South Eastern Highlands Biogeographic Region comprise the dissected ranges and plateau of the Great Dividing Range that are topographically lower than the Australian Alps, which lie towards the southwest of this bioregion (Sahukar *et al.* 2003). In the east, this bioregion extends to the Great Escarpment, while its western slopes comprise part of the inland drainage of the Murray-Darling basin. The topography of this bioregion comprises relatively steep, hilly and undulating terrain, giving way in the west to hilly ranges and peaks set in wide valleys. The characteristic landforms of the South Western Slopes Biogeographic Region are represented by a large area of foothills and ranges that extend from the western fall of the Great Dividing Range to the edge of the Riverina bioregion (Sahukar *et al.* 2003). The topography of the South Western Slopes Biogeographic Region also comprises relatively steep, hilly and undulating terrain, giving way towards the west to hilly ranges and peaks set in wide valleys.

For the purpose of this survey, each block was subdivided into either two or three strata based upon the suitability of the terrain for the conduct of aerial surveys and kangaroo occupancy and relative density (see Section 3.1). This subdivision was initially undertaken using information regarding landscape relief, vegetation cover, land use and anecdotal information on kangaroo densities obtained from National Parks and Wildlife Service (NPWS) and Local Land Services offices (Pople, Cairns & Menke 2003). The stratification of these blocks was later updated in relation to the results of subsequent helicopter surveys (Cairns 2004, 2007; Cairns, Lollback, & Bearup 2010, 2013). Areas of high relief were excluded from surveys. The estimated total area of the management zone was 58,043 km^2; with the estimated total area of the strata actually surveyed being 34,085 km^2 (see Table 1).

3. Survey Design

The South East Tablelands kangaroo management zone comprises seven survey blocks, each of which was stratified for the purpose of survey design. Survey design was undertaken using what is now recognised as a comparatively standard procedure (Cairns, Bearup & Lollback 2019) that utilises the automated design capabilities of the most recent version of the DISTANCE software package (Thomas *et al.* 2010); in this case DISTANCE 7.3 (http://distancesampling.org/Distance/#download-latest-version).

To design a survey using DISTANCE, GIS shape files of the survey areas are required, along with estimates of the nominal survey effort. The shape files used here were stratified and nominal survey efforts determined in relation to the precision of surveys conducted previously in the South East kangaroo management zone (see below). For each new survey conducted in each survey block, the boundaries of the strata may be redefined in relation to kangaroo density and survey count information. This option of redefining of stratum boundaries before proceeding to design a survey was considered to be consistent with the adoption of an adaptive management approach to the conduct of aerial surveys in the tablelands management zones.

3.1 Zone Stratification

To increase both the efficiency and the precision of the surveys, each survey block was divided into two or three strata. This is done using GIS shape files obtained from the NSW OEH. The initial stratification was based upon eight categories of land capability, that extended from cultivation, through to mixed farming and grazing, through to grazing only with decreasing levels of grazing intensity, through to steep, timbered country and, finally, through to rocky outcrops. The boundaries of the strata were further adjusted in relation to coincident knowledge of kangaroo densities. The kangaroo density information used for the first survey of this management zone (Cairns 2004; Pople *et al.* 2006) was anecdotal. The kangaroo densities and transect line counts used to adjust the stratum boundaries for the second survey conducted in 2006 (Cairns 2007) were taken from the results of the 2003 survey (Cairns 2004). This applied to all of the survey blocks, except the Young block, which was not incorporated into the management zone until 2009, and the Bombala block which was not added to the management zone until 2015.

Following the initial survey of the five original blocks (Cairns 2004; Pople *et al.* 2006), a major re-stratification was undertaken which resulted in a reduction in the number of strata within some of the blocks. In the Braidwood, Goulburn, Gundagai and Yass blocks, the original three strata were reduced to two, with the high and medium strata being combined to form single medium density stratum. Also, some changes were made to the boundaries of their respective low density strata. In the Cooma block, the high and medium density strata were combined to form a single high density stratum, while the low density stratum was redefined as a medium density stratum. These two strata were later combined into a single survey stratum (Cairns, Lollback & Bearup 2013).

A preliminary survey, conducted in the Young block in 2008 (Cairns, Lollback & Bearup 2010), provided the kangaroo density information needed to complete the stratification of this block into a low, a medium and a high density stratum. For the Bombala block, stratification was based upon land capabilities and information on kangaroo density obtained from a preliminary survey conducted in 2012 (Cairns, Bearup & Lollback 2013). This block was set up on the basis of two strata identified as being of medium and low density.

The breakdown of the survey block areas of the management zone into their constituent strata is given in Table 1. For visual representations of the stratification of the survey blocks, see Figs. 2-8.

Table 1. Areas (km^2) of the seven survey blocks (former RLPB districts) that constitute the current South East Tablelands kangaroo management zone. The survey areas do not include reserved lands such as National Parks (NPs) or State Forests (SFs), or those areas of high relief outside reserve lands that are unsuitable for aerial survey. The remaining areas are subdivided into three strata representing habitat associated with, in relative terms, high, medium and low kangaroo densities (adapted from Pople, Cairns & Menke 2003). The area surveyed comprises the high density and medium density strata.

Survey block	Bombala	Braidwood	Cooma	Goulburn	Gundagai	Yass	Young	KMZ
RLPB district	6,722	8,824	11,375	6,426	9,507	6,305	8,884	58,043
NP, SF and high relief areas	3,935	4,536	4,173	37	2,986	690	–	16,357
Survey block area	2,787	4,288	7,202	6,391	6,521	5,615	8,884	41,688
Block stratification								
High density	–	–	–	–	–	–	3,185	3,185
Medium density	2,720	3,987	7,202	4,608	5,562	4,518	2,303	30,900
Low density	67	301	–	1,783	959	1,097	3,396	7,603
Area surveyed	2,720	3,987	7,202	4,608	5,562	4,518	5,488	34,085

For this survey, only the high and medium density strata were surveyed. That the low density strata supported only trace numbers of kangaroos and did not warrant surveying had previously been confirmed for the original five survey blocks from the survey conducted in 2006 (Cairns 2007). With the exclusion of population centres, national parks, reserves and miscellaneous areas of high relief, 72% of the combined area of the seven survey blocks remained available to be surveyed. With the exclusion of the combined low density strata of each survey block, the final survey area represented 59% of the whole of the management zone.

3.2 Survey Effort

In line transect sampling, survey effort is defined as the total length of transect surveyed. Although ultimately constrained by cost, survey effort is generally determined in relation to some desired level of precision (i.e. the ratio of standard error to mean). With this essentially being a scoping survey, the nominal level of precision was set at 40%. This compares with the level of precision of 20% usually considered to be realistic and reasonably cost-effective for standard kangaroo surveys (Pople, Cairns & Menke 2003; Cairns 2007; Cairns, Bearup & Lollback 2019).

The present survey was conducted as a scoping exercise and was not part of the regular scheduled surveys conducted on a triennial basis. The target level of precision was set at 40% for all survey blocks except the Gundagai and Young blocks. For the Gundagai block, the target level of precision was set at 30% in order to ensure a reasonable level of coverage of survey transects. For the two strata within the Young block, survey effort was determined in relation to a target level of precision of 40% for the high density stratum and a target level of 50% for the medium density stratum. Overall cost was a constraining factor here.

To determine the survey effort required, the method proposed by Buckland *et al.* (2001, p. 243) was used in relation to the precision (measured by the coefficient of determination) averaged over the surveys conducted in 2018 (Cairns, Bearup & Lollback 2019). The survey efforts determined for each survey block are listed in Table 2 as the nominal survey effort. The planned total survey effort was 811 km. This compared with the total survey effort 2,278 km set for the 2018 survey.

Table 2. Areas of the proportion of each survey block (former RLPB district) surveyed, the nominal survey effort determined for the purpose of survey design and the actual survey effort applied during the survey. Note that the Young survey block comprised a high and a medium kangaroo density stratum. All the other survey areas were classed as medium density strata. All eight surveys were conducted as the systematic segmented trackline surveys.

Survey block	Survey area (km^2)	Nominal survey effort (km)	Actual survey effort (km)
Bombala	2,720	77.0	75.0
Braidwood	3,987	78.5	80.0
Cooma	7,202	95.0	105.0
Goulburn	4,608	110.0	120.0
Gundagai	5,562	86.5*	82.5
Yass	4,518	87.5	90.0
Young (high)	3,185	101.5	80.0
Young (medium)	2,303	175.0**	90.0

*Set to a level of precision of 30% rather than 40%.

**Set to a level of precision of 50% rather than 40%.

3.3 Automated Survey Design

The principal aim of designing a survey is to obtain optimal estimates of abundance, preferably with high precision and low bias. Achieving this is not straightforward, particularly when designing a survey by hand. However, taking advantage of the information that can be obtained through the use of GIS and by using automated design algorithms such as those offered by DISTANCE 7.3 (Thomas *et al.* 2010) the likelihood of obtaining an optimal design will be increased (Strindberg, Buckland & Thomas 2004).

As with the previous version of this package, DISTANCE 7.3 offers four different classes of survey design for surveys of the type to be undertaken here: parallel random sampling, systematic random sampling, systematic segmented trackline sampling and systematic segmented grid sampling (Thomas *et al.* 2010). According to Buckland *et al.* (2001) and Strindberg, Buckland & Thomas (2004), systematic designs produce smaller variation in density estimation from one realisation to the next and negate any problems associated with overlapping samplers (transects). Hence, a systematic survey design with a buffer zone around the boundary of each survey stratum was selected as the most likely appropriate design option for the present surveys. Inclusion of a buffer in the design guards against the problem arising whereby the distribution of objects from the transect line is not in general uniform out to the truncation distance if the transect line intersects the stratum boundary (Strindberg, Buckland & Thomas 2004). Based upon the outcome of previous analyses (Cairns, Lollback & Bearup 2010, 2013; Cairns, Bearup & Lollback 2016, 2019), the integrity of individual samplers (transects) was maintained in preference to using split samplers.

Three systematic sampling designs, the systematic random, the systematic segmented grid and the systematic segmented trackline designs were tested for survey coverage. For each survey, a series of 999 simulations was run in relation to a 1-km square coverage grid to assess the evenness of the coverage probability of the survey designs selected for comparison (Strindberg, Buckland & Thomas 2004; Thomas *et al.* 2010). Where it was applicable, survey designs were compared separately for the high and medium density strata of each of survey block using the nominal survey efforts given in Table 2. The outcome of this process was that the systematic segmented trackline sampling design with fixed-length samplers provided a more than adequate even coverage of the survey areas of all seven blocks. Once this was confirmed, a single realisation of the selected design was generated for each survey stratum within each survey block.

For the Bombala block, the selected survey design resulted in ten 7.5-km long transects being allocated to the survey stratum (Fig. 2). For the Braidwood block, the selected survey design resulted in sixteen 5-km long transects being allocated to the survey stratum (Fig. 3). For the Cooma block, the selected survey design resulted in fourteen 7.5-km long transects being allocated to the survey stratum (Fig. 4). For the Goulburn block, the selected survey design resulted in sixteen 7.5-km long transects being allocated to the survey stratum (Fig. 5). For the Gundagai block, the selected survey design resulted in eleven 7.5-km long transects being allocated to the survey stratum (Fig. 6). For the Yass block, the selected survey design resulted in twelve 7.5-km long transects being allocated to the survey stratum (Fig. 7). For the Young block, the selected survey design resulted in ten 10-km long transects being allocated to the high density stratum and seventeen 10-km long transects being allocated to the medium density stratum (Fig. 8). For all blocks except Young, the allocated transects were flown. For the nominal total survey efforts used in the design process along with the total survey efforts of the realised survey designs, see Table 2.

4. Survey Methods

The aerial surveys of the seven blocks were conducted in early to mid-spring during the three periods, 16-17 September (Young), 28-29 September (Braidwood, Goulburn, Gundagai and Yass) and 2-4 November (Bombala and Cooma), 2020. These surveys were conducted as helicopter surveys in accordance with the survey designs developed above (see Section 3.3), with each survey block being considered a separate entity and subdivided into two to three strata; one or two of which were surveyed. The method of line transect sampling (Buckland *et al.* 2001; Thomas *et al.* 2002) was used. In the original design for these surveys, there was a total of 107 transects to be flown across the seven survey blocks. The completed surveys comprised a total of 96 transects (see Table 2). The 11 transects not flown because of poor weather conditions and time constraints were all in the Young survey block.

All surveys were conducted within either the three-hour period following sunrise or the three-hour period before sunset. David Bearup (NPWS), Mika Saunders (NPWS) and Scott Seymour (Parks ACT) were the observers used for these surveys. The pilots used for these survey sessions were Peter Alexander, Rick Kesce, Tate Steen and Philip Treasure.

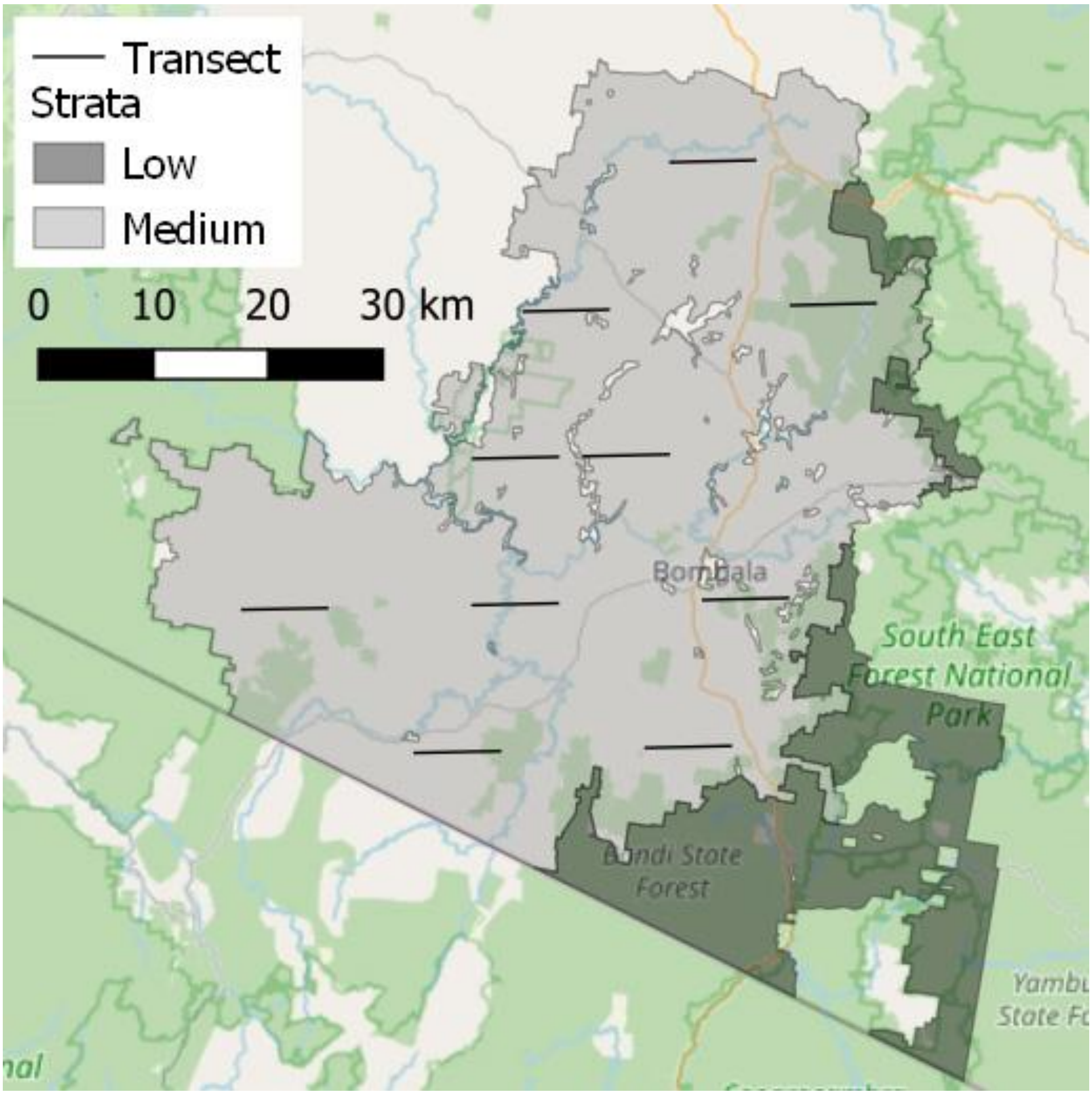

Fig. 2. The Bombala survey block of the South East Tablelands kangaroo management zone. Shown are the two survey strata, the population centres (towns) and the placement of the survey transects within the medium kangaroo density stratum. Note that no survey transects were placed into the low density stratum.

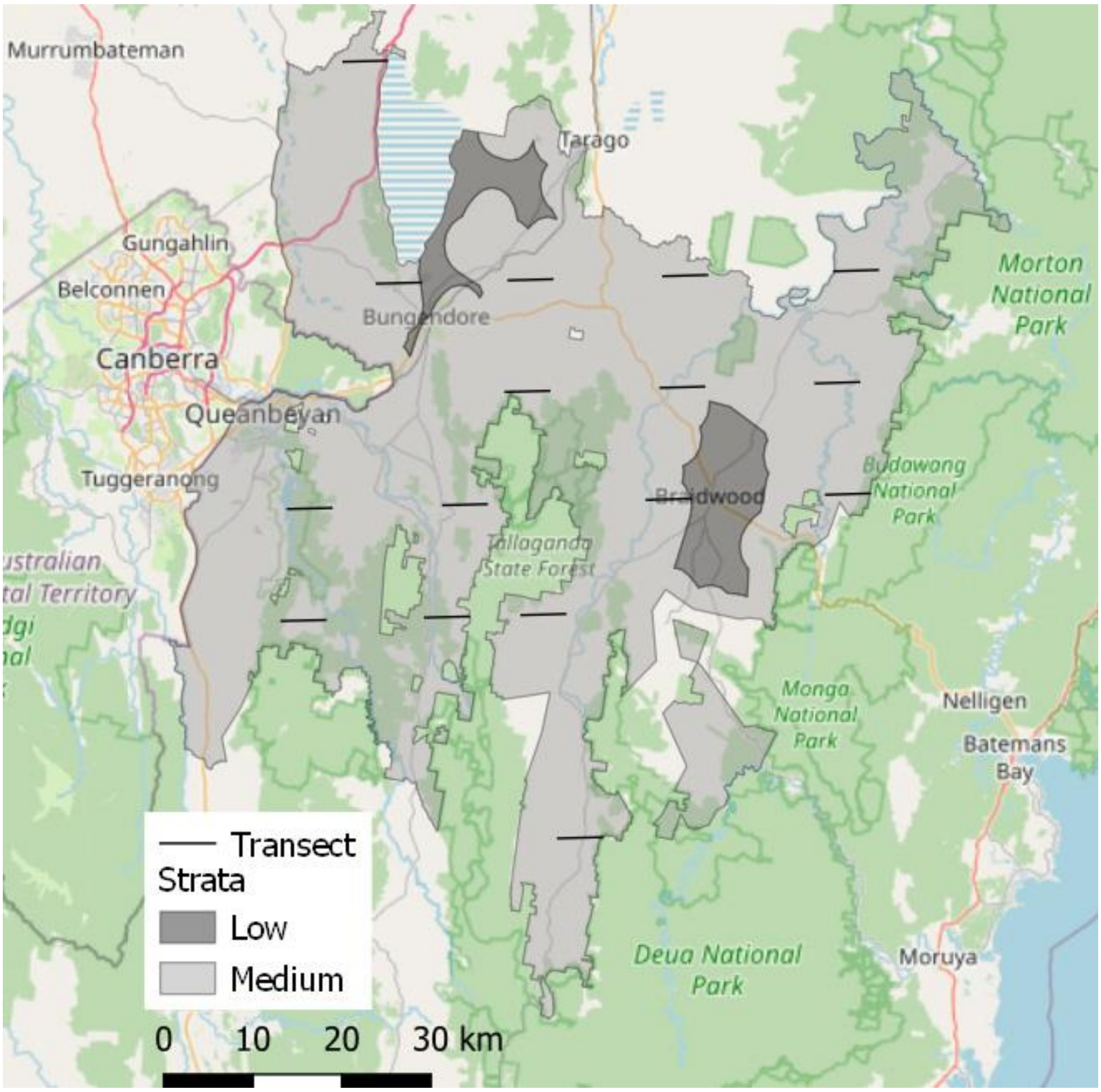

Fig. 3. The Braidwood survey block of the South East Tablelands kangaroo management zone. Shown are the two survey strata, the population centres (towns) and the placement of the survey transects within the medium kangaroo density stratum. Note that no survey transects were placed into the low density stratum.

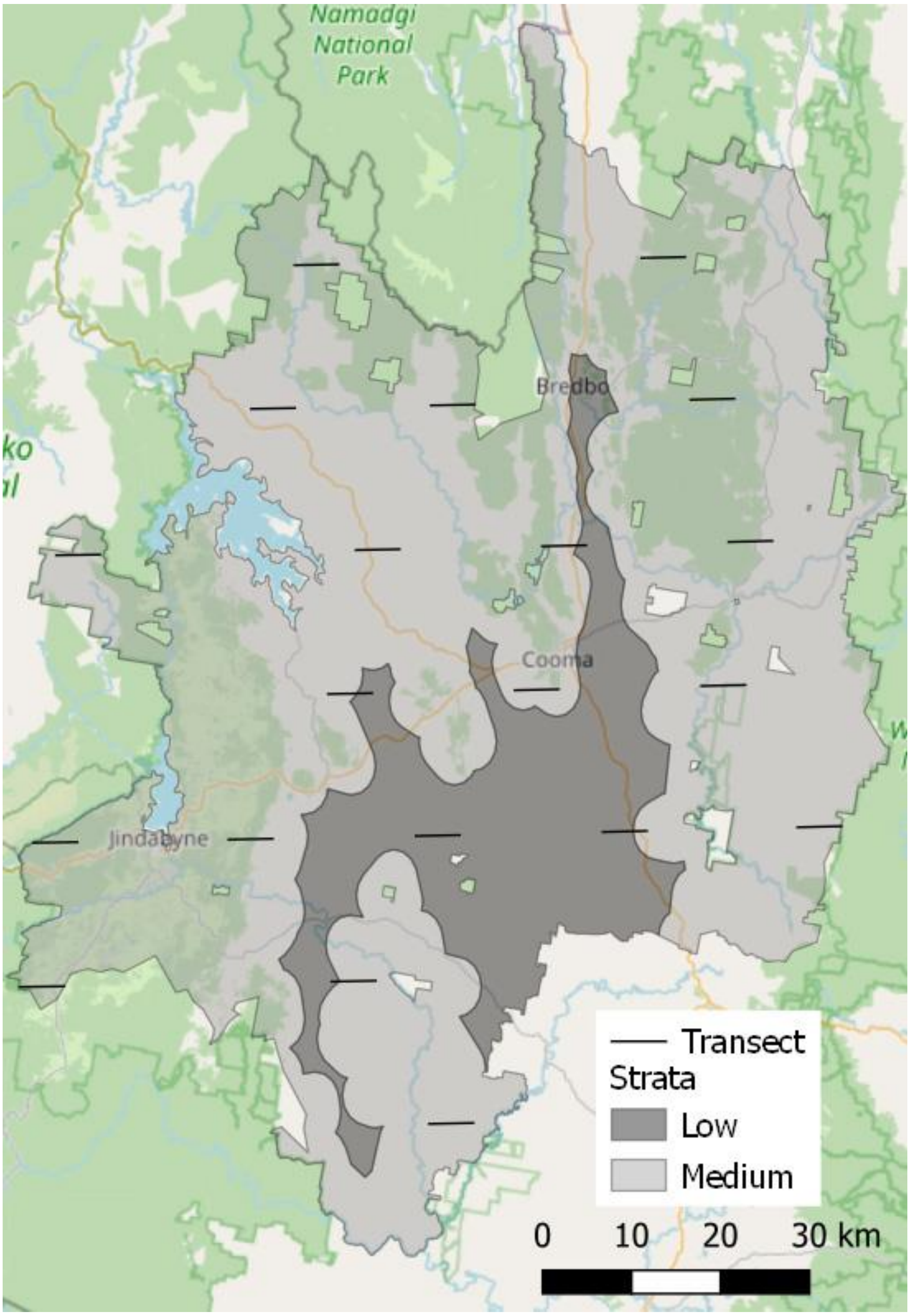

Fig. 4. The Cooma survey block of the South East Tablelands kangaroo management zone. There is no stratification of this block. The whole area is considered to be equivalent to a medium kangaroo density stratum.

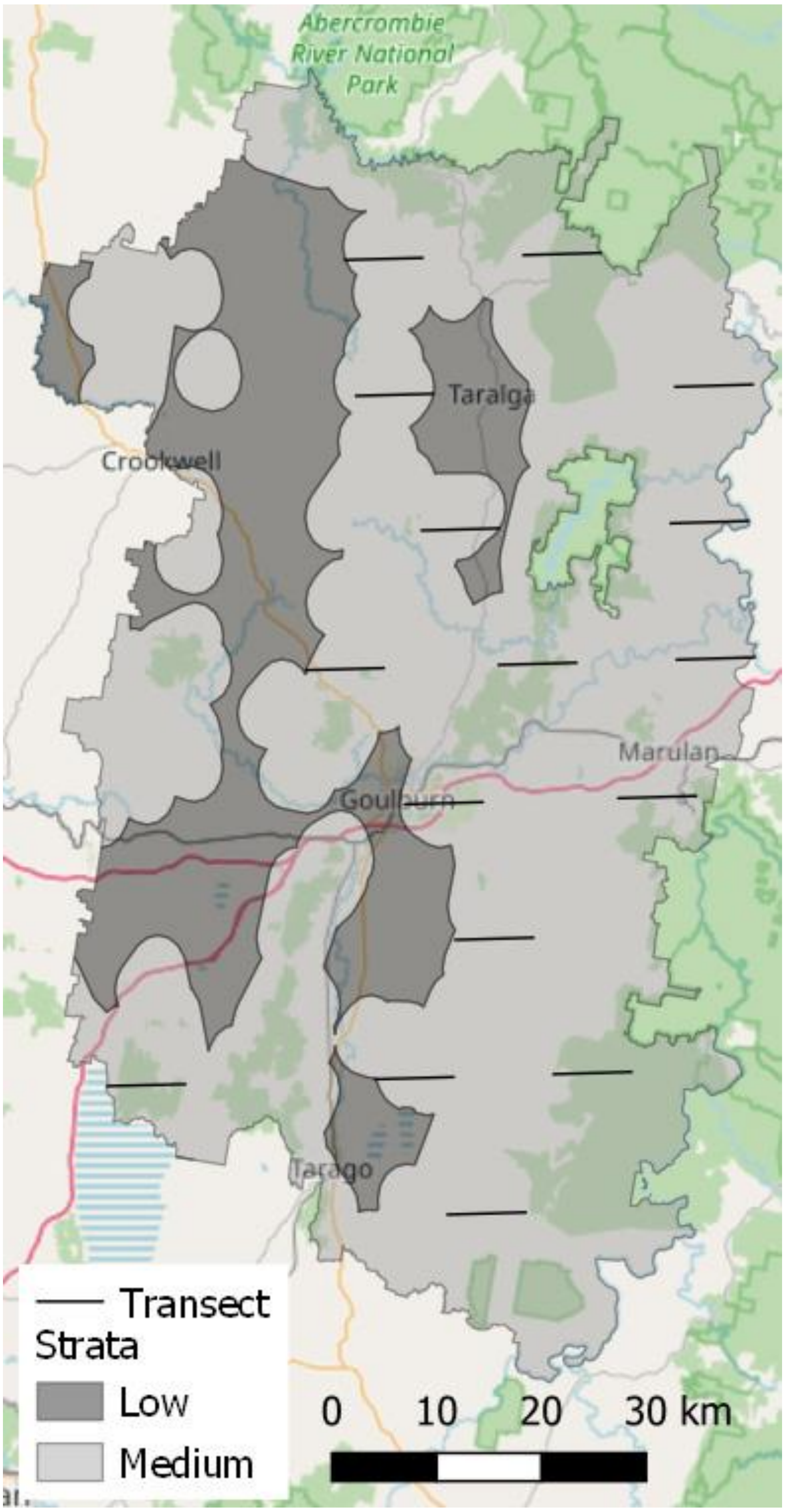

Fig. 5. The Goulburn survey block of the South East Tablelands kangaroo management zone. Shown are the two survey strata, the population centres (towns) and the placement of the survey transects within the medium kangaroo density stratum. Note that no survey transects were placed into the low density stratum.

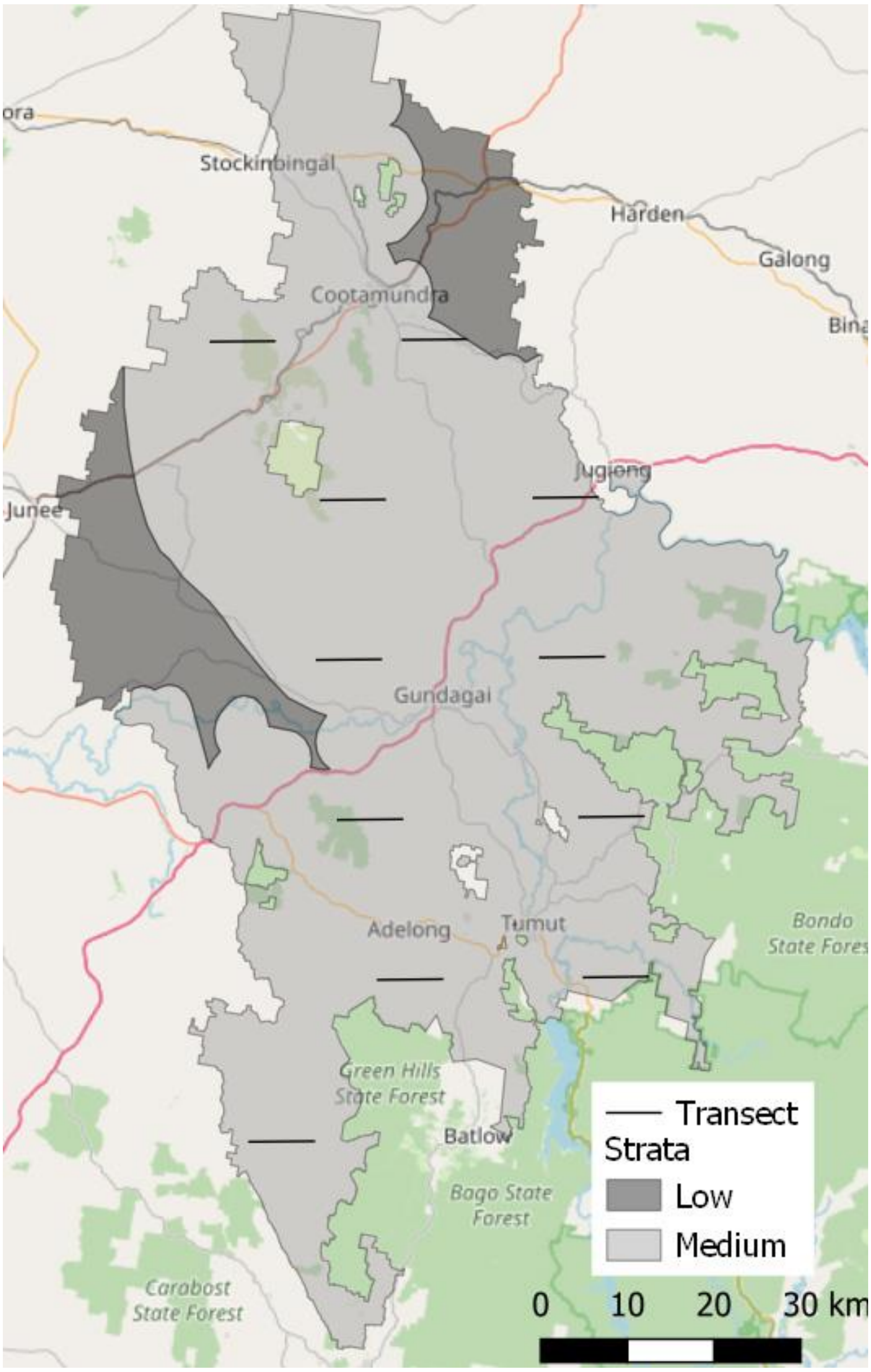

Fig. 6. The Gundagai survey block of the South East Tablelands kangaroo management zone. Shown are the two survey strata, the population centres (towns) and the placement of the survey transects within the medium kangaroo density stratum. Note that no survey transects were placed into the low density stratum.

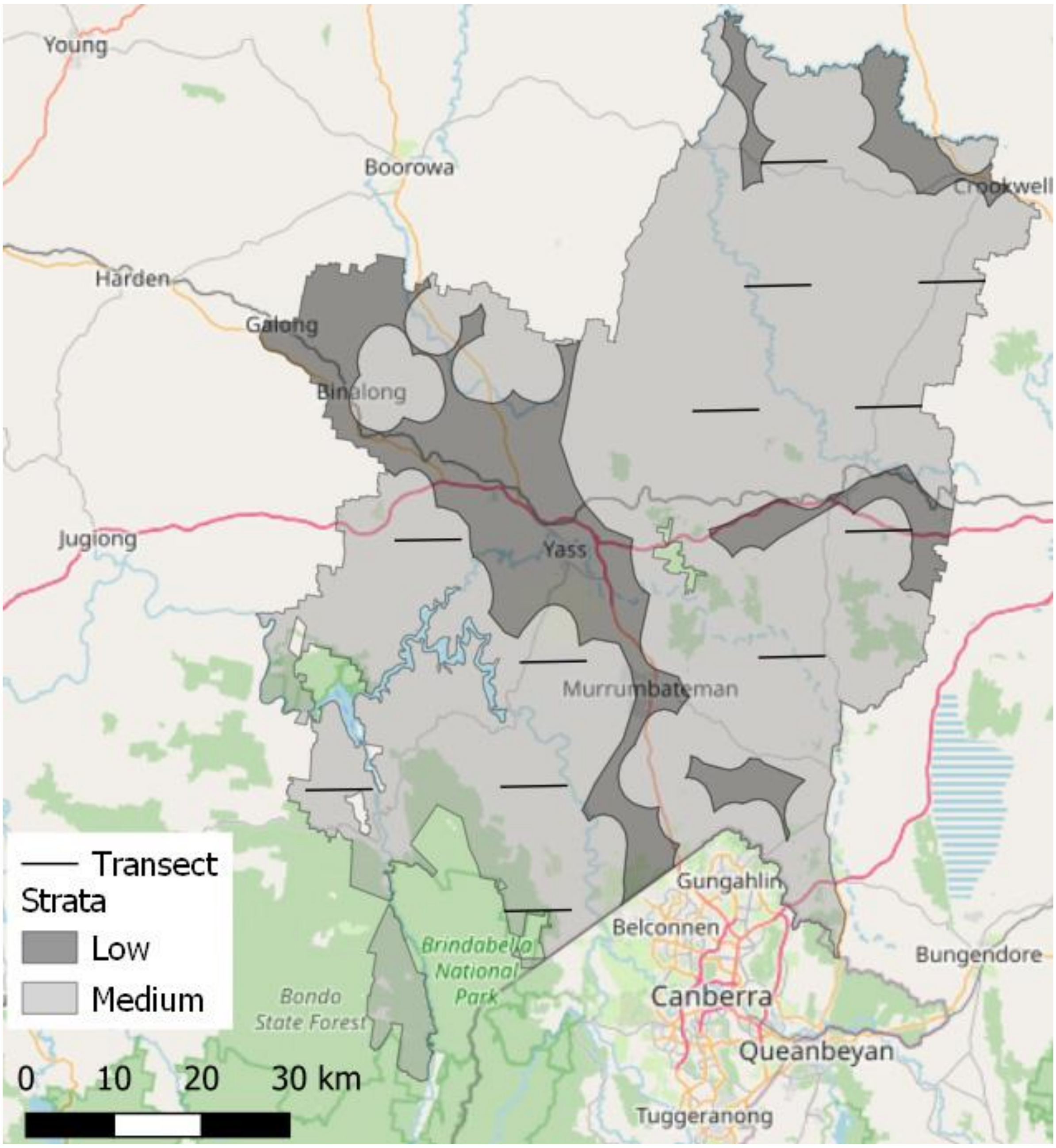

Fig. 7. The Yass survey block of the South East Tablelands kangaroo management zone. Shown are the two survey strata, the population centres (towns) and the placement of the survey transects within the medium kangaroo density stratum. Note that no survey transects were placed into the low density stratum.

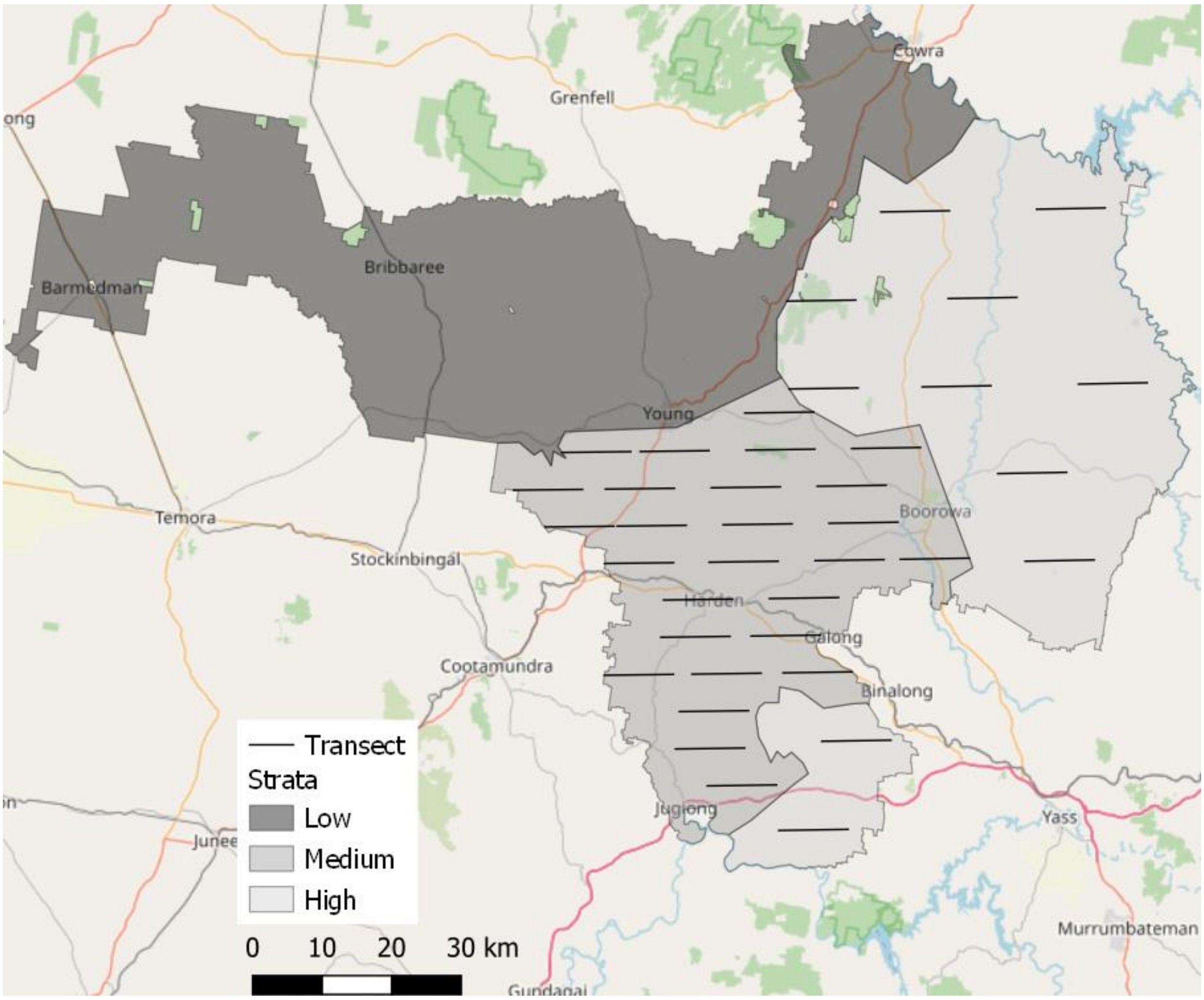

Fig. 8. The Young survey block of the South East Tablelands kangaroo management zone. Shown are the three survey strata, the population centres (towns) and the placement of the survey transects within the high and medium kangaroo density strata. Note that no survey transects were placed into the low density stratum.

4.1 Helicopter Line Transect Surveys

In conducting the surveys, the aircraft, a Eurocopter AS350 Écureuil (*Squirrel*) single-engine light helicopter with the two rear doors open was flown along each transect line at a ground speed of 93 km h^{-1} (50 kts) and at a height of 61 m (200 ft) above ground level. Navigation was by a global positioning system (GPS) receiver. The two observers occupying the rear seats of the helicopter counted kangaroos seen on either side of the aircraft. The seating of the observers in relation to the left-hand and right-hand side of the aircraft was allocated randomly for each survey session. Sightings of kangaroos were recorded into the 0-20 m, 20-40 m, 40-70 m, 70-100 m and 100-150 m distance classes, perpendicular to the transect centreline. The distance classes were delineated on metal booms extending from either side of the helicopter (Fig. 9).

Data in the form of the numbers of clusters (groups of one or more individuals) of eastern grey kangaroos, common wallaroos (*M. r. robustus*), red-necked wallabies (*M. rufogriseus*) and swamp wallabies (*Wallabia bicolor*) observed in the different delineated distance classes on the nominal survey strip were voice-recorded. The presence of other, non-target species was noted. Voice-recorded information was transcribed at the end of each survey session.

Fig. 9 Distance boom mounted on the left-hand side of the Eurocopter AS350 Écureuil helicopter used in the survey. The distance bins used in the surveys (0-20 m, 20-40 m, 40-70 m, 70-100 m and 100-150 m) are indicated by the black bands on the boom.

4.2 Data Analysis

The analysis of distance sampling data such as those collected here first involves the estimation of the detection probability of animals within the covered area (usually a designated survey strip), then the estimation of the density of animals within the covered area given this detection probability and, finally, the estimation of the number of animals in the survey region given the density of animals in the covered area (Borchers & Burnham 2004). With a properly designed survey, inferences can be safely made about the survey region using information obtained from sample units (Thompson 2002). Density ($\widehat{D}$) in the covered area is estimated from:

$$\widehat{D} = \frac{n_a \hat{E}(c)}{2wLP_a} \qquad \text{eqn. 1}$$

where, n_a is the number of clusters observed, $\hat{E}(c)$ is the expected cluster size (see later), L is the survey effort (total transect length) and P_a is the probability of detecting a cluster of the animals within w, the half-width of the designated survey strip (Buckland *et al.* 2001).

In order to estimate the probability (P_a) of detecting a cluster of the animals within w, the detection function g(x), the probability that a cluster of animals at perpendicular distance x from the survey transect centreline is detected (where, $0 \le x \le w$ and $g(0) = 1$) needs to be modelled and evaluated at x = 0, directly on the transect centreline (Thomas et al. 2002). To do this, the sampling data, the counts of clusters of animals (kangaroos) within each of the five distance bins used in these surveys, were analysed using DISTANCE 7.3 (Thomas et al. 2010). Basing the analysis on the sightings of clusters in preference to the sightings of individual animals has been found to ensure against overestimation of the true variances (Southwell & Weaver 1993).

In analysing the results of surveys such as those undertaken here, it is important that the recommended minimum sample sizes of both transect lines and observations are at least attained. According to Buckland *et al.* (2001), the recommended minimum number of samplers (replicate transect lines) should be in the range 10-20 in order to ensure reasonably reliable estimation of the variance of the encounter rate, and the recommended number of observations, of clusters of kangaroos in this instance, should be 60-80 for reliable modelling of the detection function.

The results from each survey block were analysed separately. Where required, stratification was incorporated into the analyses, with the two options of either fitting a common (global) detection function to the data for the two survey strata within each management zone, or fitting separate detection functions to the high and medium density strata, respectively.

DISTANCE 7.3 has three different analysis engines that can be used to model the detection function (Thomas *et al.* 2010). Two of these, the conventional distance sampling (CDS) analysis engine and the multiple-covariate distance sampling (MCDS) analysis engine were used here. In analysing survey results using the CDS analysis engine, there is no capacity to include any covariates other than the perpendicular distance of a cluster of animals from the transect centreline in the modelling process. Hence, an assumption is made of pooling robustness, i.e. it is assumed that the models used yield unbiased (or nearly unbiased) estimates when distance data collected under variable conditions are pooled (Burnham, Anderson & Laake 1980). If the MCDS analysis engine is used, additional covariates can be included in the analysis. This can help to relax to some extent (but not entirely) reliance on the assumption of pooling robustness (Burnham *et. al.* 2004).

The analysis protocol followed was such that the results of the analyses conducted using detection function model options available within both the CDS and MCDS analysis engines were compared serially in order to determine which was the most parsimonious (suitable) model and, hence, which were the most likely and accurate estimates of population density and abundance determined in relation to this detection function. The model with the lowest value for a penalised log-likelihood in the form of Akaike's Information Criterion (AIC= -2 x log-likelihood + 2[p +1]; where p is the number of parameters in the model) was, as is generally the case, selected as the most likely detection function. In selecting the most parsimonious model, along with comparing AIC values, some secondary consideration was given to goodness-of-fit and the shape criterion of the competing detection functions; with any model with an unrealistic spike at zero distance, rather than a distinct 'shoulder' near the transect line, being likely to be rejected. Although available as an option to improve goodness-of-fit, no manipulation of the grouping intervals was undertaken.

For analyses using the CDS analysis engine, comparisons were made amongst a suite of four detection function models. Each of these models comprised a key function that, if required, can be adjusted by a cosine or polynomial series expansion containing one or more parameters (Buckland *et al.* 2001). The different models considered were a Half-normal key function with an optional Cosine or Hermite Polynomial series expansion, and a Hazard-rate key function with an optional Cosine or Simple Polynomial series expansion. The number of adjustments incorporated into the model was determined via the sequential addition of up to three terms.

The MCDS analysis engine allows for the inclusion in the detection function model of covariates other than the perpendicular distance from the line (Thomas *et al.* 2010). These can be either factor (qualitative or categorical) or non-factor (continuous) covariates and have the effect of altering the scale but not the shape of the detection function (Thomas *et al.* 2010). The covariates used in these analyses were related to individual detections of clusters of kangaroos and were identified as observer, survey aspect and cloud cover. To avoid over-parameterisation, only single covariates were included in the analyses separately. Two key functions are available with the MCDS analysis engine: the Half-normal and the Hazard-rate functions. Cosine, Simple Polynomial and Hermite Polynomial series expansions were available be used in relation to these two key functions.

In estimating kangaroo densities using these two analysis engines, if the observed sizes of detected clusters (c) are independent of distance from the transect line (i.e. if g(x) does not depend upon c), then the sample mean cluster size is taken as an unbiased estimator of the mean size of the n_a clusters observed in the study area. If, however, the observed sizes of detected clusters are found to be dependent upon the perpendicular distance from the transect line, then, the sample mean cluster size is replaced by a value determined using a regression of this relationship (Buckland et al. 2001).

While densities and abundances, and their associated statistics of variation were determined empirically, confidence limits (LCL and UCL) and coefficients of variation (cv%) were also determined by bootstrapping the data. The data were bootstrapped 999 times in relation to all model options in the analysis engines and not just the model selected to determine the empirical estimates. This was expected to improve the robustness of the estimation of these statistics (Buckland *et al.* 2001). The 95% confidence limits presented were the 2.5% and 97.5% quantiles of the respective bootstrap estimates.

The data were analysed to determine separate eastern kangaroo density and abundance estimates for each management zone. Counts of common wallaroos and the smaller, less common species, red-necked wallabies and swamp wallabies were too low to allow density estimates to be obtained for these species.

5. Results and Discussion

5.1 Survey Data Summaries

Five of the seven survey blocks listed in Table 1 were subdivided into two strata based on land capability and knowledge of eastern grey kangaroo densities (see Section 3.1). The Young survey block was subdivided into three strata. The Cooma block was not stratified; the whole of its area generally supporting comparatively high and even densities of kangaroos. Only those strata identified as supporting high and medium densities of kangaroos were surveyed. These comprised a single stratum in all blocks except Young, in which two strata were surveyed.

In the Bombala survey block, ten transects were flown in the medium density stratum (Fig. 2), on which 62 clusters of eastern grey kangaroos were observed. In the Braidwood block, 16 transects were flown in the medium density stratum (Fig. 3), on which 101 clusters of eastern grey kangaroos were observed. The Cooma block was surveyed as a single stratum. Fourteen transects were flown across the block (Fig. 4), on which 156 clusters of eastern grey kangaroos were observed. In the Goulburn block, 16 transects were flown in the medium density stratum (Fig. 5), on which 112 clusters of eastern grey kangaroos were observed. In the Gundagai block, 11 transects were flown in the medium density stratum (Fig. 6), on which 46 clusters of eastern grey kangaroos were observed. In the Yass survey block, 12 transects were flown in the medium density stratum (Fig. 7), on which 81 clusters of eastern grey kangaroos were observed. The Young block was subdivided into a low, a medium and a high density stratum (Fig. 8). Eight transects were flown in the high density stratum on which 76 clusters of eastern grey kangaroos were observed. Nine transects were flown in the medium density stratum on which 29 clusters of eastern grey kangaroos were observed. The survey effort originally allocated to both strata in the Young block was higher than the actual total length of transect flown (Table 2). Poor weather and time constraints precluded the full allocation of transect from being flown.

As well as eastern grey kangaroos, sightings were also made of common wallaroos, red-necked wallabies and swamp wallabies on these survey blocks. A summary of the raw individual counts of the four species of macropods found in the survey areas is given in Table 3.

Table 3. Number of transects flown, total survey effort (km) and raw counts of macropods for each of the seven survey blocks. Note that the Young block comprises two survey strata.

			Raw counts			
Survey block	No. of transects	Effort (km)	Eastern grey kangaroos	Common wallaroos	Red-necked wallabies	Swamp wallabies
Bombala	10	75.0	292	–	6	3
Braidwood	16	80.0	495	–	4	6
Cooma	14	105.0	582	–	9	2
Goulburn	16	120.0	428	3	11	11
Gundagai	11	82.5	131	1	–	–
Yass	12	90.0	317	3	1	3
Young						
Young (high)	8	80.0	304	5	1	7
Young (medium)	9	90.0	117	–	–	–

5.2 Line Transect Analysis

To estimate the population densities and abundances of kangaroos, the counts of clusters of kangaroos observed during line transect sampling were grouped into the five distance categories set on the survey booms mounted on the helicopter (Fig. 9). The method of analysis used conformed to a general and well-understood framework for analysing distance sampling data, as outlined in Buckland et al. (2001). Key to distance sampling analysis is the modelling of the detection of objects (clusters of kangaroos) in relation to their perpendicular distances from the survey transect centreline. Analyses involved the use of both the CDS and the MCDS analysis engines of DISTANCE 7.3 (Thomas et al. 2010), with the most parsimonious (specific) detection function model being selected principally on the basis of comparison of the AIC statistic (see Section 4.2). Eastern grey kangaroo density and abundance estimates were determined separately for each survey block. For analysis for the Young block, the survey results for the two survey strata were incorporated into a single stratified analysis. The density and abundance estimates obtained for the seven survey blocks were combined to provide estimates for the SE NSW kangaroo management zone. The densities and abundances of common wallaroos, red-necked wallabies and swamp wallabies were not estimated because of the low counts of these three species.

For each analysis, the most parsimonious (specific) detection function model, global or stratified, was selected principally on the basis of it being the one that yielded the smallest value of the AIC statistic (see Section 4.2). With regard to the calculation of the AIC for a particular model, it should be noted that an individual AIC value is, by itself, not interpretable due to the unknown interval scale to which it is related (Burnham & Anderson 2002). Hence, for a given model, the value of the AIC is only comparative, relative to other AIC values in the set of models tested. It is the AIC differences (ΔAIC) that are important. In comparing any two models, when ΔAIC >2.00, the interpretation is that there is mounting evidence that it is increasingly less plausible that the fitted model with the larger AIC could be considered the better of the two models, given the data. The converse to this is that when ΔAIC ≤2.00, it can then be thought that, in this instance, there is some level of empirical support for the model with the larger AIC as well as for the model associated with the smaller AIC, given the data. For further information on the use of AIC in model selection, see Burnham & Anderson (2002).

In analysing the results of surveys such as those undertaken here, it is important that the recommended minimum sample sizes of both transect lines and observations are at least attained. According to Buckland et al. (2001), the recommended minimum number of samplers (replicate transect lines) should be at least in the range 10-20 in order to ensure reasonably reliable estimation of the variance of the encounter rate, and the recommended number of observations, of clusters of horses in this instance, should be at least in the range 60-80 for reliable modelling of the detection function. The numbers of replicate transects flown across the survey strata of the seven survey blocks are given in Table 3 and the replicate numbers of clusters of eastern grey kangaroos observed are given in Table 4. This present survey was designed as a low precision survey aimed at scoping the possible impact of the 2019-2020 bushfires and, possibly, the 2017-2019 drought on the kangaroo populations in the South East Tablelands management zone. The numbers of replicate transect lines flown on each survey block exceeded the recommended minimum numbers of samplers. With the exception of the Gundagai survey block, the replicate numbers of clusters of kangaroos also exceeded the recommended numbers of observations.

Table 4. The number of sightings of clusters of eastern grey kangaroos (n), analysis engine used, detection function model (including covariates), and the probability that a cluster of kangaroos in the survey strip is detected (P_a) for the surveys of the eastern grey kangaroo populations in the seven survey blocks. CDS is the conventional distance sampling engine and MCDS is the multiple-covariate distance sampling engine.

Survey block	n	Analysis engine	Model	Covariates	P_a
Bombala	62	CDS	Hazard-rate	–	0.28
Braidwood	101	MCDS	Half-normal	ASPECT	0.40
Cooma	156	MCDS	Half-normal	OBSERVER	0.45
Goulburn	112	MCDS	Half-normal	CLOUD	0.26
Gundagai	46	CDS	Half-normal	–	0.44
Yass	81	CDS	Hazard-rate	–	0.38
Young	105	MCDS	Half-normal	OBSERVER	0.45

The most parsimonious detection function models fitted to the results of the surveys of eastern grey kangaroos in the seven survey blocks are given in Table 4. For the Bombala, Gundagai and Yass blocks, robust CDS-derived models without the inclusion of any covariates proved to be the most parsimonious models of those tested. These models were of either Half-normal or Hazard-rate in form. For the other four survey blocks, the detection function models were MCDS-derived models, each incorporating one of the three covariates used in the analysis: observer, aspect and cloud cover The key function of the models fitted to the survey data from each of these four blocks was the Half-normal function (Table 4).

With the final MCDS-derived models, the differences between the selected models and the corresponding CDS-derived models were sometimes, but not always, substantial ($0.57 \leq \Delta AIC \leq 14.00$). Where the difference was substantial, the inclusion of covariates proved important to the modelling process. Where the difference was less than substantial ($\Delta AIC \leq 2.00$), then, if preferred, a case could be made for alternatively considering a robust, CDS-derived model as the detection function model. The general forms of the detection functions for the seven survey blocks are shown in Appendix 1, Figs. A2.1-A2.7. Although not shown in these graphics, it should be noted that where covariates are included in the models, they have the effect of altering the scale of the detection function, but not its general form (Marques & Buckland 2004).

Given in relation to each of the detection function models in Table 4, are estimates of the probability (P_a) that a randomly selected cluster of kangaroos in the nominal survey strip (150 m) will be detected. While P_a is required as part of the estimation process, this statistic can be viewed as an indicator of the interaction between the subjects of the survey, the landscape they occupy, the prevailing conditions of the survey and the observers on the survey platform. Given this, P_a therefore has some comparative value.

The probability that a randomly selected cluster of eastern grey kangaroos in the survey strip will be detected (P_a) showed some variation across survey strata, ranging from 0.26 to 0.45, with a median value of 0.40. The variability in this statistic is comparable to that found across these survey block in relation to previous surveys, where the value of P_a has been estimated to have ranged from as low as 0.21 to as high as 0.54 (Cairns, Lollback & Bearup 2010; Cairns, Bearup & Lollback

2013, 2016, 2019). No pattern exists across the survey blocks which supports the suggestion that each estimate of P_a is a function of the conditions and circumstances associated with the conduct of each survey.

5.3 Population Estimates

The baseline population estimates for eastern grey kangaroos obtained from the analyses of the survey results are given in Table 5. These estimates are densities of the clusters of kangaroos observed and corresponding population densities determined at the level of survey stratum. Empirical and bootstrap coefficients of variation and bootstrap confidence intervals are given with these estimates. In relation to these densities, average cluster size was in the range 2.5-4.0 kangaroos. There was a tendency for the smaller clusters to be found in the southern survey blocks of the management zone, namely Bombala, Cooma and Gundagai.

The survey was designed as one with a relatively low target level of precision of 40% for each survey block/stratum. The precision of the estimates of both cluster density and kangaroo density, as indicated by the respective coefficients of variation, were such that this low target level of precision was easily attained for all survey blocks except Bombala and, perhaps, Gundagai (Table 5). Compared to this, the levels of precision attained for the 2018 survey were higher, with coefficients of variation <25% (see Table 8). The 2018 survey was planned for an overall target level of precision of at least 20% (Cairns, Bearup & Lollback 2019).

Population abundances for each survey block derived using the densities given in Table 5 are given in Table 6. Using these abundances, whole-block density estimates were determined for each survey block and the management zone (Table 7). These densities were determined, where applicable, in relation to the combined areas of the high, medium and low density strata. Recall that any low density strata were not surveyed and, based on the outcome of surveys conducted in 2006 (Cairns 2007), were assumed to support at the most only trace numbers of kangaroos. As well as the block densities, a single management zone density of eastern grey kangaroos was also determined.

Table 5. Survey stratum area, density of clusters of eastern grey kangaroos sighted (D_s) and kangaroo population density (D). Given also are empirical and bootstrap coefficients of variation (CV), and bootstrap confidence intervals for each of these two density statistics.

		Cluster density (km^{-2})				Kangaroo density (km^{-2})			
Survey block	Area (km^2)	D_s	CV (%)	95% bootstrap confidence interval	CV_{boot} (%)	D	CV (%)	95% bootstrap confidence interval	CV_{boot} (%)
Bombala	2,720	6.43	37.3	3.03-11.15	52.0	20.45	40.2	5.66-51.12	58.5
Braidwood	3,987	10.43	31.2	5.65-16.91	28.0	40.13	32.8	17.35-70.35	34.0
Cooma	7,202	11.02	24.0	6.85-15.78	21.0	30.12	24.9	15.28-50.02	29.7
Goulburn	4,608	6.81	24.8	3.34-11.09	28.0	22.40	26.6	10.01-40.13	34.1
Gundagai	5,562	4.25	27.7	2.54-8.72	31.5	10.78	29.5	4.81-24.69	41.5
Yass	4,518	7.92	27.2	4.22-11.58	24.6	31.00	32.9	12.95-51.50	33.2
Young									
High	3,185	6.42	24.0	3.87-9.00	20.7	17.42	28.6	11.66-25.67	19.5
Medium	2,303	5.15	26.1	1.44-7.14	38.4	11.90	40.5	4.69-20.65	35.7

Table 6. The areas of the survey strata within the seven survey blocks, and the densities (D) and abundances (N) of eastern grey kangaroos in these strata. Given also are the bootstrap confidence intervals and coefficients of variation (CV) for each of these estimates.

Survey block	Area (km^2)	D (km^{-2})	95% bootstrap confidence interval	N	95% bootstrap confidence interval	CV_{boot} (%)
Bombala	2,720	20.45	5.66-51.12	55,610	15,390-138,990	58.5
Braidwood	3,987	40.13	17.35-70.35	159,980	69,160-280,050	34.0
Cooma	7,202	30.12	15.28-50.02	216,920	110,080-360,240	29.7
Goulburn	4,608	22.40	10.01-40.13	103,230	46,130-184,910	34.1
Gundagai	5,562	10.78	4.81-24.69	59,940	26,730-137,300	41.5
Yass	4,518	30.98	12.95-51.50	139,950	58,490-232,660	33.2
Young						
High	3,185	17.43	11.66-25.67	55,511	37,130-81,740	19.5
Medium	2,303	11.90	4.69-20.65	27,394	10,800-47,550	35.7
Pooled	5,488	15.11	10.71-21.25	82,905	58,750-116,610	18.0

This current survey of the South East Tablelands kangaroo management zone was conducted outside the triennial sequence of surveys scheduled for this management zone. The most recent survey conducted in this sequence was carried out in September, 2018. The next survey in this scheduled sequence was due to be conducted in September, 2021. The reason for conducting the current survey was due to concern that the bushfires that occurred within parts of the management zone during the summer of 2019-2020 (Anon. 2020) might have had a substantial detrimental impact on the broader kangaroo population within the zone. However, in relation to this, the likelihood of there being any detrimental effect of the fires on the kangaroo population would be confounded by the possible effect of the 2017-2019 drought which had dominated the landscape in the lead up to the bushfires. This drought was characterised by its impact mainly through the cooler months (April-

September) of each of the three years it lasted, with rainfalls for these periods being registered in the category of lowest on record (http://www.bom.gov.au/climate/drought/knowledge-centre/previous-droughts.shtml). Hot conditions at the end of the spring of 2019 combined with the dry landscape and strong prevailing winds to produce the dangerous fire weather conditions of December 2019 and early January 2020.

Table 7. The total area, total number (N) and density (D) of eastern grey kangaroos for each of the survey blocks and the whole SE NSW kangaroo management zone.

Survey block	Area (km^2)	N	D (km^{-2})
Bombala	2,787	55,610	19.95
Braidwood	4,288	159,980	37.31
Cooma	7,202	216,920	30.12
Goulburn	6,391	103,230	16.15
Gundagai	6,521	59,940	9.19
Yass	5,615	139,950	24.92
Young	8,884	82,905	9.33
SE NSW zone	41,688	818,535	19.64

In total, there was estimated to be 818,535 eastern grey kangaroos in the South East Tablelands kangaroo management zone in 2020. The regional breakdown of this estimate is given in Table 7 and comparisons of these regional abundances with those obtained from the 2018 survey are given in Table 8. In 2018, there was estimated to be a total of 1,807,510 eastern grey kangaroos in the management zone. The 2020 estimate represented a significant 55% decline in numbers from the 2018 population estimate. It is of note that the 2018 estimate was for a population that had already been exposed to the effects of the first half of the 2017-2019 drought. However, with the population having increased in size from 2015 to 2018 (Cairns, Bearup & Lollback 2019), any negative impact of the first half of the drought would appear not to have been apparent. The negative demographic response to the onset of drought in semi-arid and arid regions is fairly rapid and well-defined (Bayliss 1985; Cairns & Grigg 1993; Cairns *et al.* 2000). However, in more mesic environments such as the South East Tablelands kangaroo management zone, such demographic responses are thought to be somewhat lagged (Pople 2003, 2008).

Table 8. The 2018 and 2020 estimates of the eastern grey kangaroo population abundances (N) in the survey blocks within the SE NSW kangaroo management zone. The differences between the two estimates given for each block are tested using a Z statistic test. The P-values are two-tailed levels of significance associated with testing the null hypothesis of equality of abundance between successive surveys (H_o: $N_{2018} = N_{2020}$).

Survey block	N_{2018}	$cv\%_{2018}$	N_{2020}	$cv\%_{2020}$	Z	P-value
Bombala	131,050	21.1	55,610	58.5	1.767	0.077
Braidwood	218,840	22.2	159,980	34.0	0.808	0.420
Cooma	587,700	22.0	216,920	29.7	2.566	0.010
Goulburn	362,400	24.9	103,230	34.1	2.676	0.007
Gundagai	126,960	14.7	59,940	41.5	2.155	0.031
Yass	170,550	21.6	139,950	33.2	0.516	0.607
Young	210,010	21.1	82,905	18.0	2.718	0.007
SE NSW Zone	1,807,510	9.8	818,535	13.6	4.711	0.000

Consistent with the overall decline in total population between 2018 and 2020 was that there were no regional increases in numbers as has often been recorded in relation to previous surveys (Cairns, Bearup & Lollback 2016, 2019); increases that can often reflect regional movement of animals within the larger area of the management zone. However, the regional breakdown of the overall population estimate showed that in some of the survey blocks there had been no significant changes in numbers since 2018, while in others, such a Cooma, Goulburn, Gundagai and Young, the declines in numbers between 2018 and 2020 have been both significant and substantial (Table 8).

Since 2009, following the end of the millennium drought, the eastern grey kangaroo population in this management zone had increased at an annual rate of 11.2% (Cairns, Lollback & Bearup 2019). More specifically, in the three-year period between 2015 and 2018, prior to and leading into the first half of the 2017-2019 drought, the eastern grey kangaroo population in the South East management zone increased by 32%. This increase would probably have occurred in association with the two particularly wet and productive years that preceded the decline into drought in 2017. This sequence of annual population increases was presumably halted and later reversed by the onset and then continuation of the drought. What impact the bushfires might have had on the population cannot really be separated from that of the drought.

By way of comparison, the population decline estimated to have occurred in the two-year period between 2018 and 2020 in the South East Tablelands kangaroo management zone was broadly comparable to the declines in eastern grey kangaroo numbers estimated to have occurred in the two Central Tablelands management zones (Fig. 1) between 2017 and 2020 (Cairns, Bearup & Lollback 2020).

With the continuation of the drought through the second half of 2018 and on to the end of 2019, as well as the advent of the 2019-2020 summer bushfires, some decline in eastern grey kangaroo numbers in the South East Tablelands management zone would have been expected. This decline has been estimated here to be quite substantial. A regular, full survey of this management zone is scheduled for September 2021. The outcome of this survey will no doubt confirm that there has been a decline in numbers from a peak in 2018. Whether the extent of the decline that will be determined in relation to a more comprehensive survey will correspond to the one registered here is yet to be seen.

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7. References

Anon. (2016). *New South Wales Commercial Kangaroo Management Plan 2017-2021*. Department of Environment and Conservation. 32 pp.

Anon. (2020). *NSW Fire and Environment 2019-20 Summary: Biodiversity and landscape data and analyses to understand the effects of the fire events.* NSW Environment, Energy and Science Department of Planning, Industry and Environment. 20 pp.

Bayliss, P. (1985). The population dynamics of red and western grey kangaroos in arid New South Wales, Australia. II. The numerical response. *Journal of Animal Ecology* **54**: 127-135.

Borchers, D.L & Burnham, K. P. (2004). General formulation for distance sampling. In: *Advanced Distance Sampling* (eds. S. T. Buckland, D. A. Anderson, K. P. Burnham, J. L. Laake and L. Thomas). Pp. 6-30.

Buckland, S. T., Anderson, D. R., Burnham, K. P., Laake, J. L., Borchers, D. L. & Thomas, L. (2001). *Introduction to Distance Sampling: Estimating abundance of biological populations*. Oxford University Press, Oxford.

Burnham, K. P & Anderson, D. A. (2002). *Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach*. Springer, New York.

Burnham, K. P., Anderson, D. R. and Laake, J. L. (1980). Estimation of density from line transect sampling of biological populations. *Wildlife Monographs* **72**: 1-202.

Burnham, K. P., Buckland, S. T., Laake, J. T., Borchers, D. L., Marques, T. A., Bishop, J. R. B. and Thomas, L. (2004). Further topics in distance sampling. In: *Advanced Distance Sampling* (eds. S. T. Buckland, D. A. Anderson, K. P. Burnham, J. L. Laake and L. Thomas). OUP, Oxford. Pp. 307-392.

Cairns, S. C. (2004). *A report to the New South Wales National Parks & Wildlife Service on the consultancy: Kangaroo Monitoring – South East New South Wales Helicopter Survey.* Unpublished report to New South Wales National Parks and Wildlife Service, Dubbo, NSW. 19 pp.

Cairns, S. C. (2007). *A report to the New South Wales Department of Environment and Climate Change on the consultancy: Kangaroo Monitoring – South East New South Wales Helicopter Survey.* Unpublished report to New South Wales Department of Environment and Climate Change, Dubbo, NSW. 30 pp.

Cairns, S. C., Bearup, D. & Lollback, G. W. (2016). *A report to the Office of Environment and Heritage (NSW) on the contract: "Design and analysis of helicopter surveys in the South East New South Wales kangaroo management zone, 2015".* Unpublished report to the Office of Environment and Heritage (NSW), Dubbo, NSW. 53 pp.

Cairns, S. C., Bearup, D. & Lollback, G. W. (2019). *A report to the Office of Environment and Heritage (NSW) on the contract: "Design and analysis of helicopter surveys in the South East New South Wales kangaroo management zone, 2018".* Unpublished report to the Office of Environment and Heritage (NSW), Dubbo, NSW. 49 pp.

Cairns, S. C., Bearup, D. & Lollback, G. (2020). *A report to the New South Wales Department of Planning, Industry and Environment on the consultancy: Design and analysis of helicopter surveys of the kangaroo populations in the Central Tablelands kangaroo management zones, 2020.* Unpublished report to New South Wales Department of Planning, Industry and Environment, Dubbo, NSW. 46 pp.

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**: 444-458.

Cairns, S. C., Grigg, G. C., Beard, L. A., Pople, A. R. & Alexander, P. (2000). Western grey kangaroos (*Macropus fuliginosus*) in the South Australian pastoral zone: populations at the edge of their range. *Wildlife Research* **27**: 309-318.

Cairns, S. C., Lollback, G. W. & Bearup, D. (2010). *A report to the New South Wales Department of Environment, Climate Change and Water on the consultancy: "Kangaroo Monitoring – South East NSW Commercial Harvest Zone Redesign and*

Analysis of Helicopter Survey". Unpublished report to New South Wales Department of Environment, Climate Change and Water, Dubbo, NSW. 55 pp.

Cairns, S. C., Lollback, G. W. & Bearup, D. (2013). *A report to the Office of Environment and Heritage (NSW) on the contract: "Design and analysis of helicopter surveys in the South East New South Wales kangaroo management zone, including the former Bombala Rural Lands Protection Board".* Unpublished report to the Office of Environment and Heritage (NSW), Dubbo, NSW. 61 pp.

Clancy, T. F. (1999). Choice of survey platforms and technique for broad-scale monitoring of kangaroo populations. *Australian Zoologist* **31**: 367-274.

Clancy, T. F., Pople, A. R. & Gibson, L. A. (1997). Comparison of helicopter line transects with walked line transects for estimating densities of kangaroos. *Wildlife Research* **24**: 397-409*.*

Marques, F. F. C. & Buckland, S. T. (2004). Covariate models for the detection function. In: *Advanced Distance Sampling* (eds. S. T. Buckland, D. A. Anderson, K. P. Burnham, J. L. Laake and L. Thomas). Pp. 31-47.

Pople, A. R. (2003). Harvest Management of Kangaroos during Drought. Unpublished report to New South Wales National Parks & Wildlife Service, Dubbo, NSW. 27 pp.

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

Pople, A. R., Cairns, S. C. & Menke, N. (2003). "Monitoring Kangaroo Populations in Southeastern New South Wales." Unpublished report to New South Wales National Parks and Wildlife Service, Dubbo, NSW. 24 pp.

Pople, A. R., Cairns, S. C., Menke, N. & Payne, N. (2006). Estimating the abundance of eastern grey kangaroos (*Macropus giganteus*) in south-eastern New South Wales, Australia. *Wildlife Research* **33**: 93-102.

Pople, A. R. & Grigg, G. C. (1998). *Commercial harvesting of kangaroos in Australia.* Environment Australia, Canberra. Retrieved in May 2016 from http://www.environment.gov.au/resource/commercial-harvesting-kangaroos-australia

Sahukar, R., Gallery, C., Smart, J. & Mitchell, P. (2003). *The Bioregions of New South Wales: their biodiversity, conservation and history*. National Parks and Wildlife Service (NSW).

Southwell, C. J. & Weaver, K. E. (1993). Evaluation of analytical procedures for density estimation from line-transect sampling data: data grouping, data truncation and the unit of analysis. *Wildlife Research* **20**: 433-444.

Strindberg, S., Buckland, S. T. & Thomas, L. (2004). Design of distance sampling surveys and Geographic Information Systems. In: *Advanced Distance Sampling* (eds. S. T. Buckland, D. A. Anderson, K. P. Burnham, J. L. Laake and L. Thomas). Pp. 190-228.

Thomas, L., Buckland, S. T., Burnham, K. P., Anderson, D. R., Laake, J. L., Borchers, D. L. & Strindberg, S. (2002). Distance sampling. In: *Encyclopaedia of Environmentrics* (eds. A. H. El-Shaarawi and W. W. Piegorsch). Volume 1, pp. 544-552.

Thomas, L., Buckland, S. T., Rexstad, E. A., Laake, J. L., Strindberg, S., Hedley, S. L., Bishop, J. R. B., Marques, T. A. and Burnham, K. P. (2010). Distance software: design and analysis of distance sampling surveys for estimating population size. *Journal of Applied Ecology* **47**: 5-14.

Thompson, S. K. (2002). *Sampling*. 2nd edition. John Wiley & Sons, Inc., New York.

Appendix 1

The detection function models for eastern grey kangaroos (*M. giganteus*) in the seven survey blocks in the South East Tablelands kangaroo management zone.

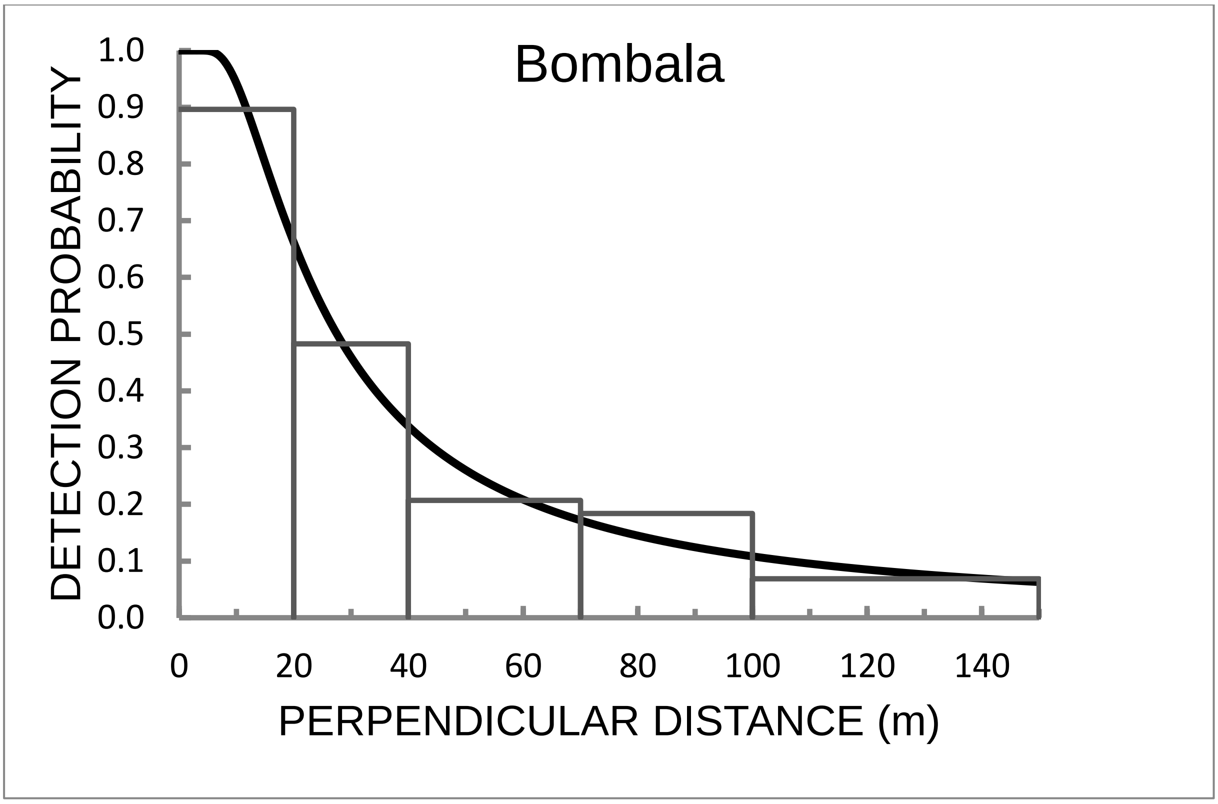

Fig. A2.1. The Hazard-rate detection function for eastern grey kangaroos in the Bombala survey block. This detection function was derived using the CDS analysis engine of DISTANCE 7.3 (for further details, see Table 4).

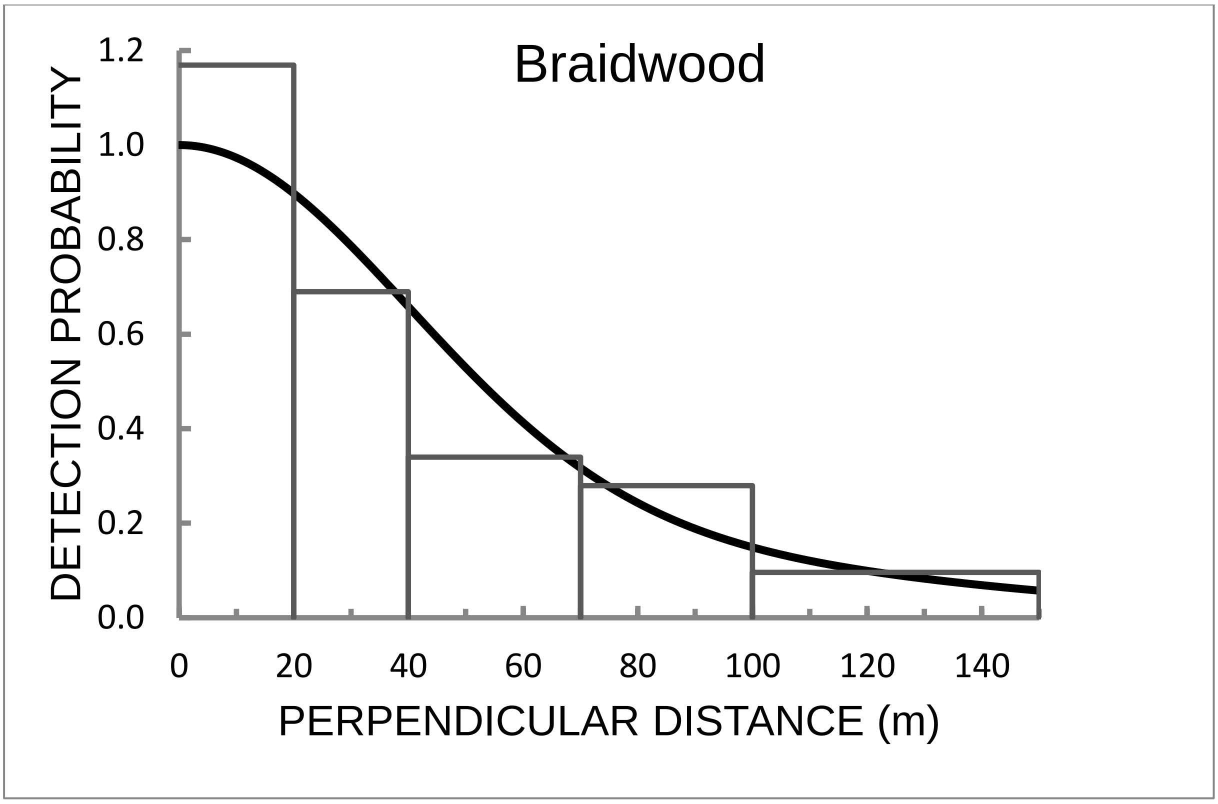

Fig. A2.2. The Half-normal detection function for eastern grey kangaroos in the Braidwood survey block. This detection function was derived using the MCDS analysis engine of DISTANCE 7.3 (for further details, see Table 4).

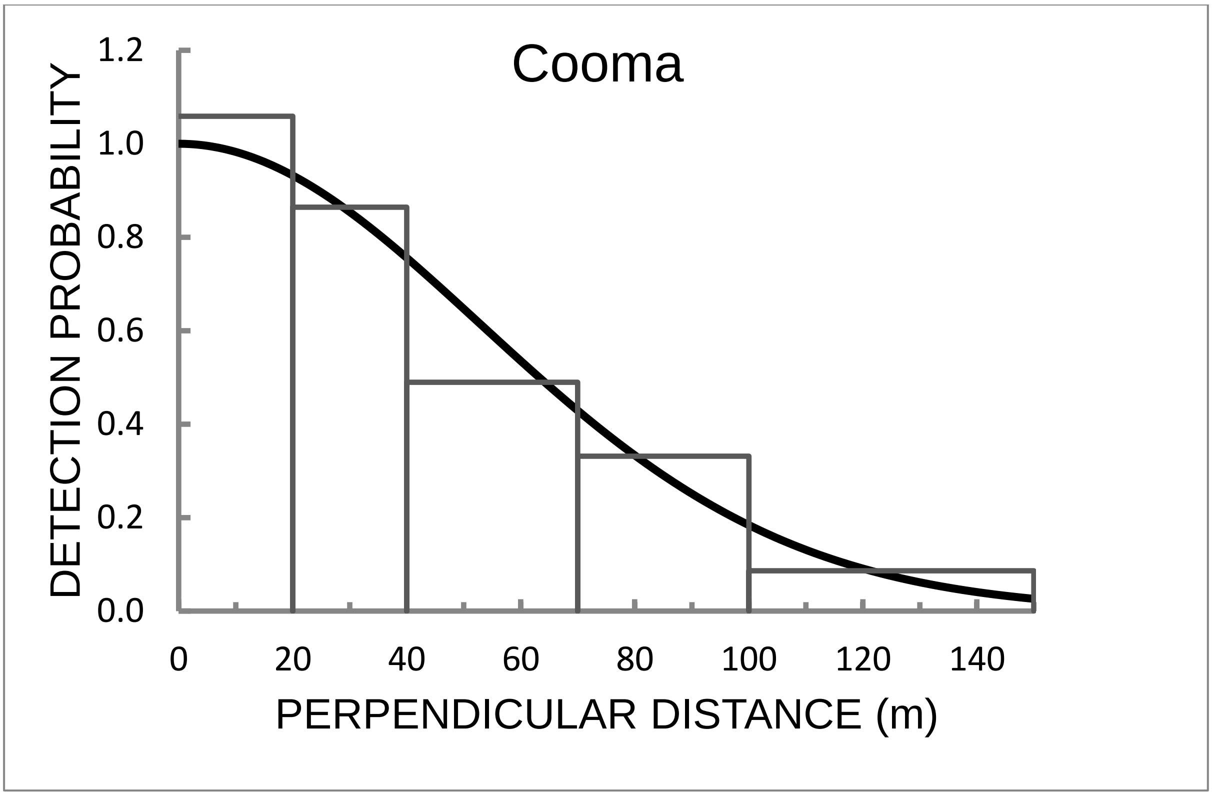

Fig. A2.3. The Half-normal detection function for eastern grey kangaroos in the Cooma survey block. This detection function was derived using the MCDS analysis engine of DISTANCE 7.3 (for further details, see Table 4).

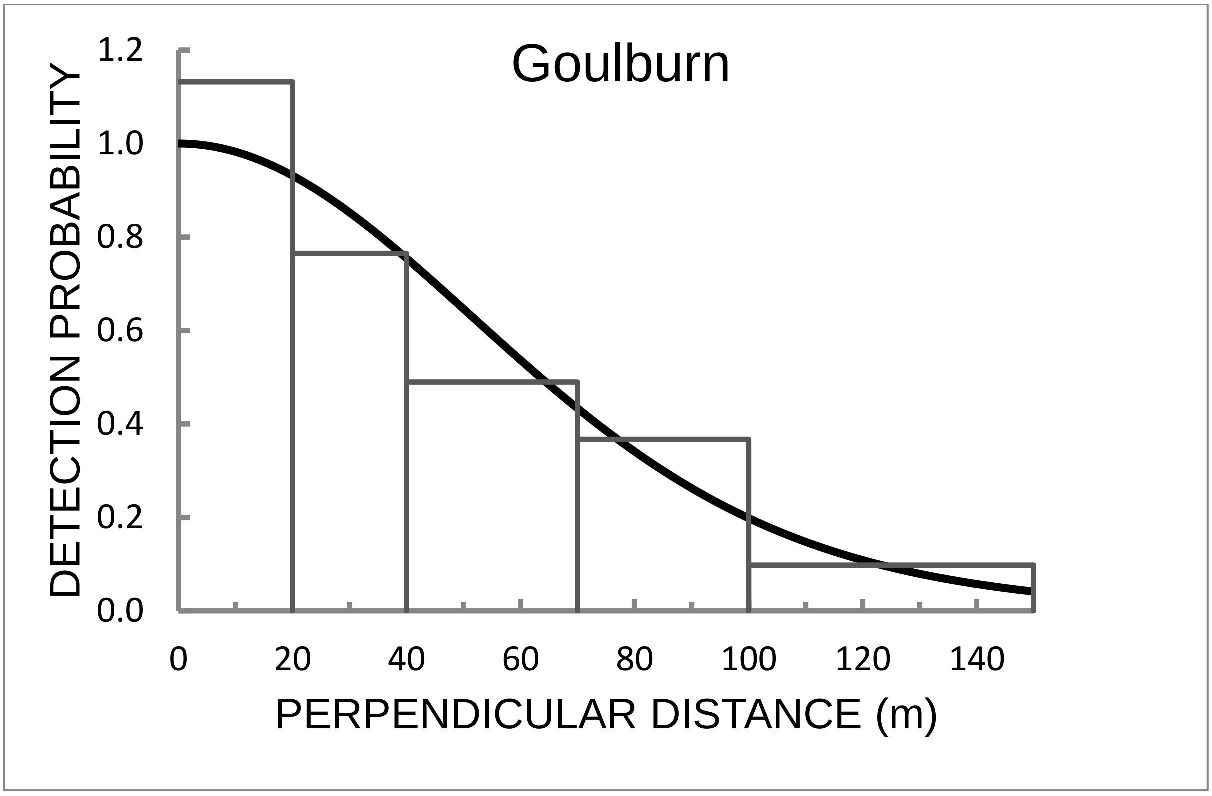

Fig. A2.4. The Half-normal detection function for eastern grey kangaroos in the Goulburn survey block. This detection function was derived using the MCDS analysis engine of DISTANCE 7.3 (for further details, see Table 4).

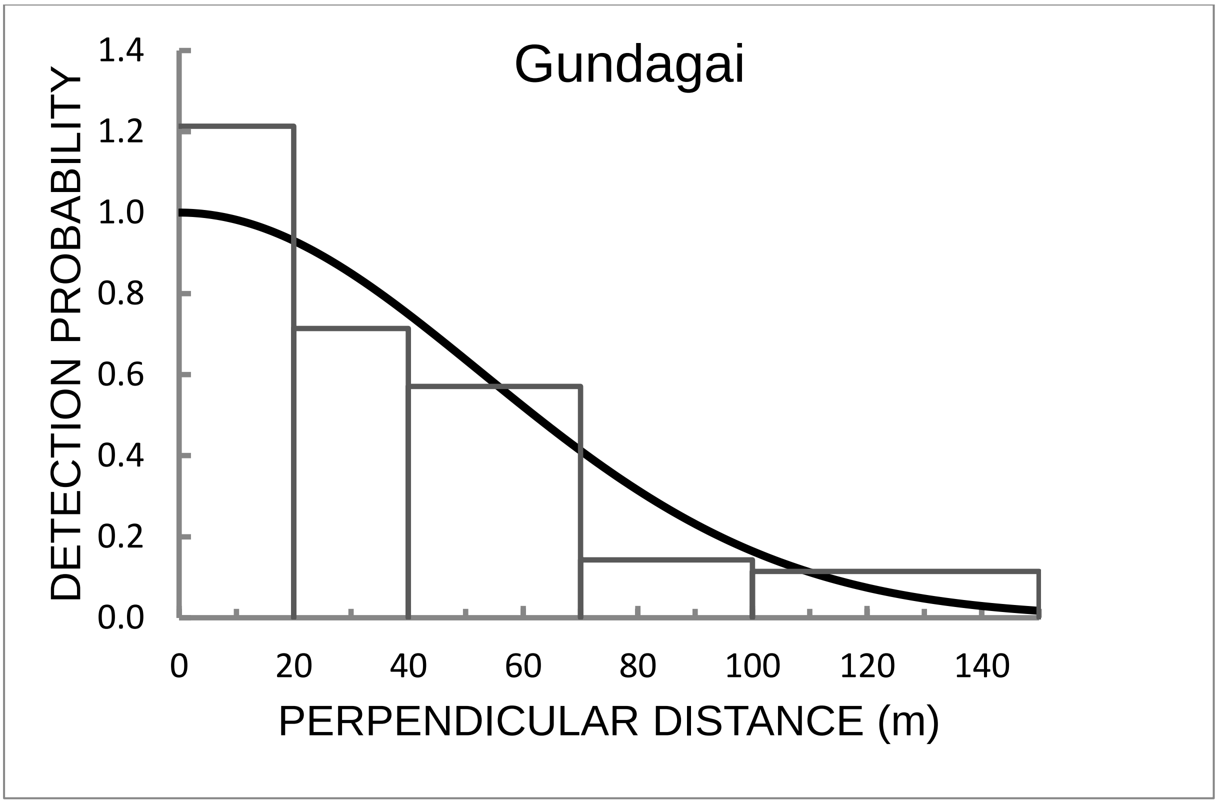

Fig. A2.5. The Half-normal detection function for eastern grey kangaroos in the Gundagai survey block. This detection function was derived using the CDS analysis engine of DISTANCE 7.3 (for further details, see Table 4).

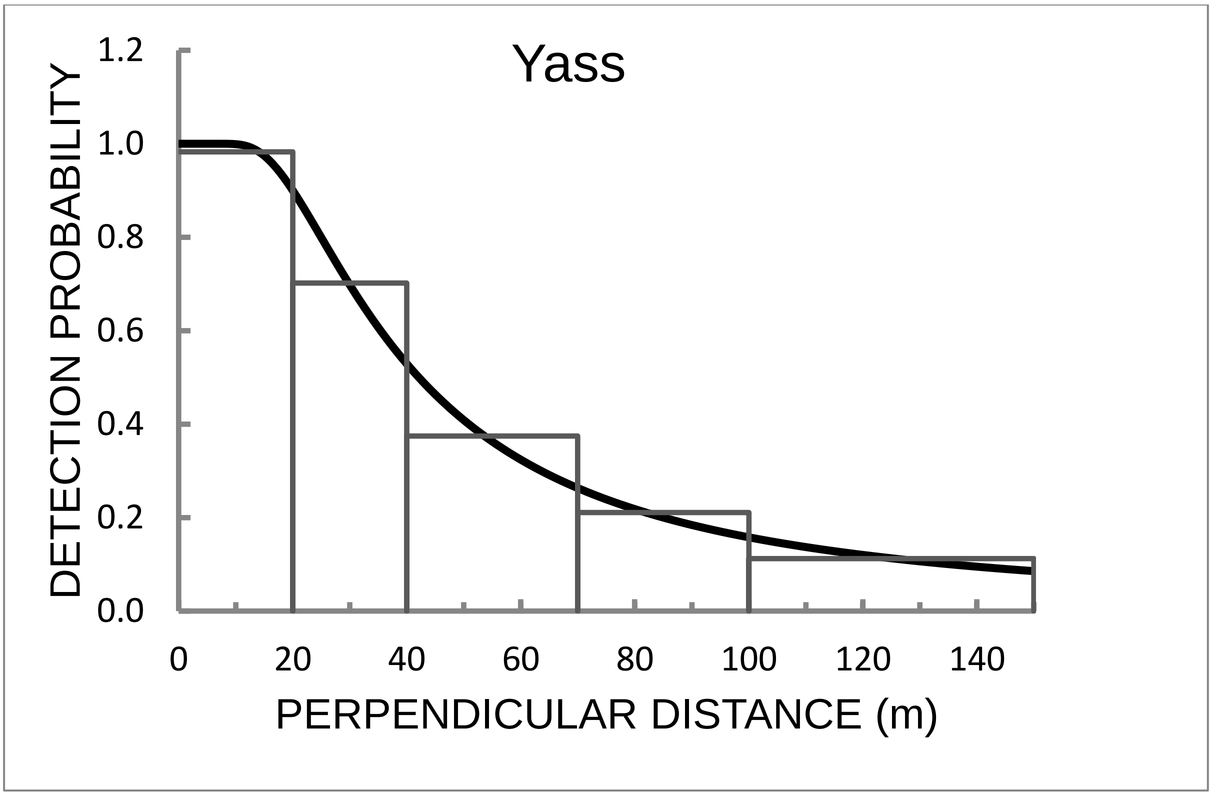

Fig. A2.6. The Hazard-rate/Cosine detection function for eastern grey kangaroos in the Yass survey block. This detection function was derived using the CDS analysis engine of DISTANCE 7.3 (for further details, see Table 4).

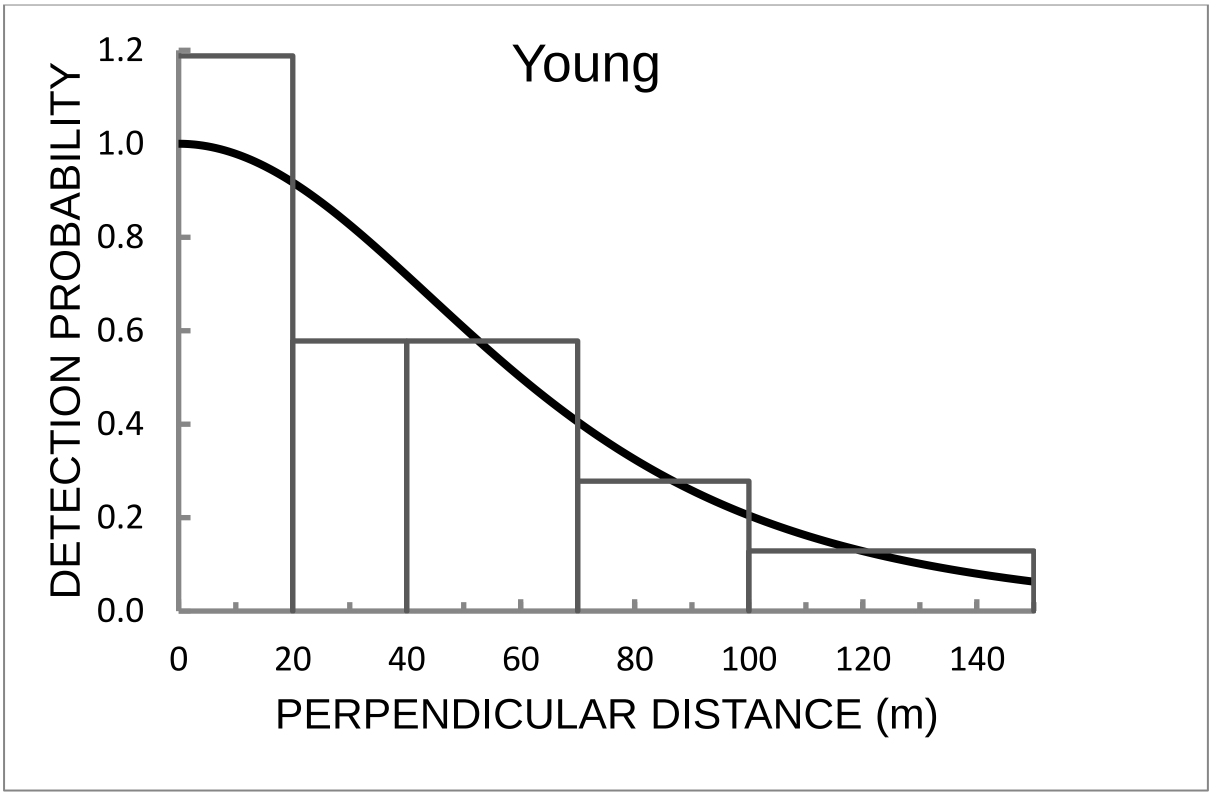

Fig. A2.7. The Half-normal detection function for eastern grey kangaroos in the Young RLPB district. This detection function was derived using the MCDS analysis engine of DISTANCE 7.3 (for further details, see Table 4).