A report to the Biodiversity and Conservation Division, New South Wales Department of Climate Change, Energy, the Environment and Water on the consultancy: “Design and analysis of helicopter surveys of kangaroo populations in the Central Tablelands North and Central Tablelands South kangaroo management zones, 2023”.

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Summary

1. Helicopter surveys for kangaroos were conducted using line transect sampling in the Central Tablelands North and Central Tablelands South kangaroo management zones. These surveys were the fifth successive surveys conducted in these management zones for the purpose of providing estimates of kangaroo numbers for the management of the commercial kangaroo harvest. The previous surveys were conducted in spring of 2008, 2011, 2014, 2017 and 2020.
2. Each management zone was subdivided into three strata of land capabilities and increasing kangaroo density in order to facilitate the process of designing the surveys. The two strata identified as likely supporting the highest numbers of kangaroos were surveyed. The third, low kangaroo density stratum was not surveyed. The surveys were designed using an automated survey design algorithm in DISTANCE 7.5 (Thomas *et al.* 2010).
3. These surveys were designed with the aim of obtaining eastern grey kangaroo population estimates with levels of precision equivalent to coefficients of variation of no greater than 20%. The coefficients of variation for the population estimates obtained for eastern grey kangaroos from the surveys in the two management zones were of the order of 9-13%.
4. These surveys provided sufficient data to produce population estimates for eastern grey kangaroos, common wallaroos, red-necked wallabies and swamp wallabies. Only eastern grey kangaroos are harvested commercially from these two management zones.
5. Eastern grey kangaroo densities were estimated to be 35.5 km^{-2} in the Central Tablelands North management zone and 38.2 km^{-2} in the Central Tablelands South management zone. These densities correspond to estimates of population abundance of 823,840 and 721,530 kangaroos, respectively, for each of these management zones.
6. Between 2017 and 2020, the eastern grey kangaroo population in both management zones declined in abundance in response to the 2017-2019 drought. Following the end of the drought, between 2020 and 2023, numbers were found to have increased by 2% per annum in the Central Tablelands North management zone, and by 17% per annum n the Central Tablelands South management zone.

1. Introduction

All states and territories of the Commonwealth of Australia administer, in one form or another, macropod management plans that are aimed principally at the management of the four common species of large kangaroos. An integral part of a number of these kangaroo management plans is the conduct of sustainable, commercial harvesting of one or more of these species (Pople & Grigg 1999). Commercial harvesting is undertaken in Queensland, New South Wales, Victoria, South Australia, Western Australia and Tasmania. In Tasmania, however, only one of the four large species of kangaroo is endemic to the island and it is not harvested. The harvested species are two smaller species of macropod; a species of wallaby and a species of pademelon. Commercial harvesting is not currently part of kangaroo management in the Australian Capital Territory nor the Northern Territory.

In those states where it does take place, commercial harvesting is undertaken in relation to quotas that are set with the intention of ensuring harvest sustainability. It is a legislative requirement that any commercial harvesting of kangaroos be conducted on a sustainable basis (Pople & Grigg 1999). In order to set appropriate harvest quotas, it is necessary to obtain 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.

In NSW, the commercial harvesting of kangaroos is managed in relation to a number of kangaroo management zones established across the inland parts of the state, extending from the tablelands of the Great Dividing Range in the east to the South Australian border in the west (see Fig. 1). Some or all four of those species of macropod identified as large kangaroos, the red kangaroo (*Osphranter rufus*), the eastern grey kangaroo (*Macropus giganteus*), the western grey kangaroo (*Macropus fuliginosus*) and the common wallaroo (*Osphranter robustus*) are currently harvested from within 15 kangaroo management zones (Anon. 2022). Only one of these species, the eastern grey kangaroo, is harvested in the Central Tablelands and slopes regions of NSW.

In NSW, the required precise and accurate estimates of the sizes of the kangaroo populations proposed to be harvested are obtained in one of two ways. For the nine inland kangaroo management zones (see Fig. 1), annual population estimates are determined from the results of aerial surveys conducted using fixed-wing aircraft (Anon. 2022). Commercial harvest quotas are set in relation to these population estimates (Payne 2007). Because of the general relief of the landscape in those management zones that cover the tablelands and western slopes of the Great Dividing Range (see Fig. 1), the kangaroo populations found there cannot be monitored using fixed-wing aircraft surveys. Instead, these management zones are surveyed on a triennial basis using helicopters and the method of line transect sampling. The annual harvest quotas for these management zones are set retrospectively over three successive years in relation to the population estimates obtained from these surveys (Anon. 2022).

Conducting these surveys triennially is considered to be a safe option for monitoring kangaroo populations in mesic as opposed to semi-arid rangeland environments (Pople 2003; Payne 2007). The risk of quasi-extinctions occurring in relation the setting of harvest quotas using triennial population estimates is relatively low in mesic environments such as the tablelands and western slopes of NSW (Pople 2008). The suitability and effectiveness of helicopter surveys has been demonstrated by Clancy *et al.* (1997), Clancy (1999), and Southwell & Sheppard (2000).

The kangaroo management zones that are surveyed triennially include the three zones in the Northern Tablelands region (Cairns, Bearup & Lollback 2023; Anon. 2022), the two zones in the Central Tablelands region (Cairns, Bearup & Lollback 2020; Anon. 2022) and the single Southeastern NSW zone (Cairns, Bearup & Lollback 2022; Anon. 2022). The two kangaroo management zones in the Central tablelands and slopes region are identified as Central Tablelands North and Central Tablelands South (see Fig. 1).

Triennial surveys have been conducted in the two Central Tablelands management zones since 2008. For the reporting of the most recent of these, see Cairns, Bearup & Lollback (2020). Reported on here is the design of the surveys conducted in the two Central Tablelands kangaroo management zones in September 2023, the survey and data analysis methods used in the conduct of these surveys and synthesis of the results, and the estimated macropod densities and abundances obtained from these surveys. The population estimates obtained from these surveys are used to set the 2024-2026 harvest quotas for eastern grey kangaroos in the two management zones.

2. Survey Areas

The two kangaroo management zones (KMZ) in the Central Tablelands region of NSW are shown in Fig. 1 as Central Tablelands North (Zone 48) and Central Tablelands South (Zone 49).

The Central Tablelands North zone extends south from the Liverpool Range that marks its boundary with the Upper Hunter kangaroo management zone (Zone 14, Fig. 1) to its boundary with the Central Tablelands South zone which lies in a line immediately south of the central NSW township of Kandos (32º 51’ 00” S, 149º 58’ 00” E). The eastern boundary of the zone lies between the townships of Singleton (32º 32’ 27” S, 151 09’ 42” E) and Branxton (32º 39’ 22” S, 151º 21’ 15” E) in the Hunter Valley. The zone is bounded in the west by the Coonabarabran kangaroo management zone (Zone 10, Fig. 1); its western boundary being southwest of the township of Wellington (32º 33’ 20” S, 148º 56’ 35” E).

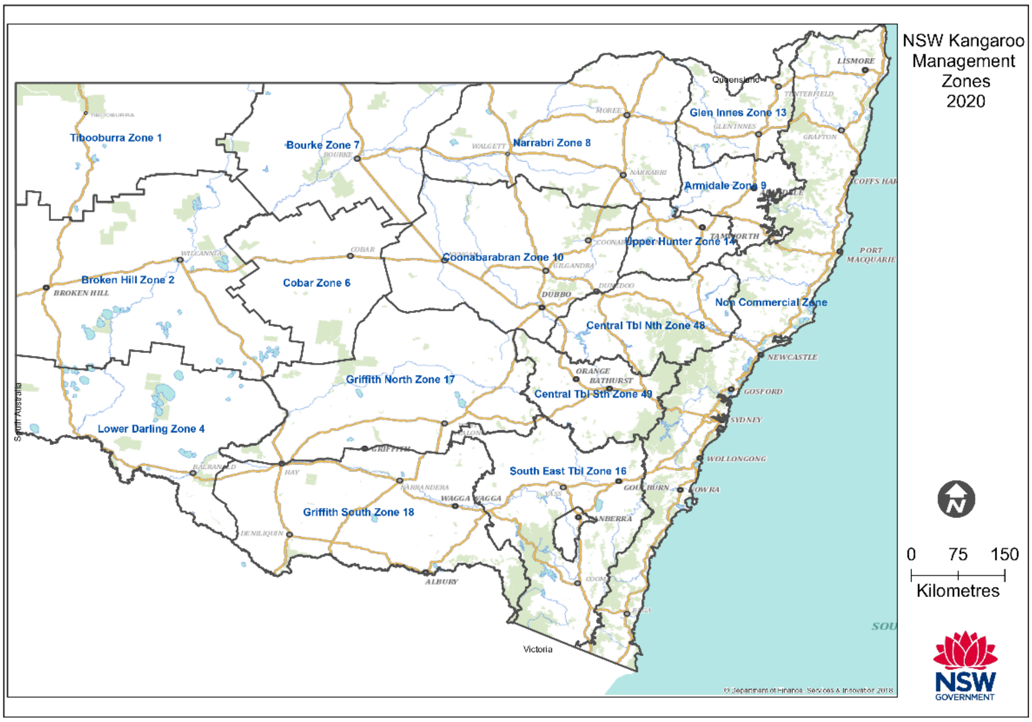

Fig. 1. The 15 kangaroo management zones administered by NSW DCCEEW. The two Central Tablelands kangaroo management zones are identified as Central Tablelands North and Central Tablelands South.

The Central Tablelands North kangaroo management zone comprises parts of four biogeographic regions. In the northeast, there is a small portion of the North Coast Biogeographic Region (IBRA), while the rest of the eastern part of the zone lies within the Hunter subregion of the Sydney Basin Biogeographic Region (IBRA) (Sahukar *et al.* 2003). In the west, it lies within the Brigalow Belt South Biogeographic Region (IBRA) towards the north and within the South Western Slopes Biogeographic Region (IBRA) towards the south (Sahukar *et al.* 2003). The characteristic landforms of this zone extend from steep, hilly and undulating ranges, to rolling hills and wide valleys. There are no particularly prominent geodiversity features present such as those found in the Northern Tablelands management zones (Cairns, Bearup & Lollback 2023).

The Central Tablelands South zone extends south from its boundary with the Central Tablelands North zone to its boundary with the South East NSW kangaroo management zone (Zone 16, Fig. 1). Its eastern boundary lies to the east of Bathurst (33º 25’ 00” S, 149º 34’ 00” E); in line with the township of Wallerawang (33º 24’ 40” S, 150º 03’ 51” E). The zone is bounded in the west by the existing Griffith North kangaroo management zone (Zone 11, Fig. 1), with its western boundary being to the east of the townships of Parkes (33º 08’ 00” S, 148º 10’ 00” E) and Forbes (33º 22’ 00” S, 148º 00’ 00” E).

The Central Tablelands South management zone takes in parts of two biogeographic regions. In the east, it lies within the South Eastern Highlands Biogeographic Region (IBRA), while in the west it lies within the South Western Slopes Biogeographic Region (IBRA) (Sahukar *et al.* 2003). The topography of both the South Eastern Highlands and the South Western Slopes Biogeographic Regions comprises the western fall of the Great Dividing Range, with relatively steep, hilly and undulating terrain giving way towards the west to hilly ranges and peaks set in wide valleys. Perhaps the most important defining feature of the geodiversity of this zone is the Canobolas volcanic field of the South Eastern Highlands Biogeographic Region (Sahukar *et al.* 2003).

Most of the land in these two kangaroo management zones is freehold; with state forests, gazetted reserves and national parks comprising only small proportions of their total areas. The principal land use is the grazing of domestic livestock, with a prominent secondary land use comprising the growing of grain and oilseed crops.

Horticulture and coal mining also feature as significant land uses in parts of both management zones (see Fig. 2).

For the purposes of designing and conducting kangaroo surveys, those parts of both management zones dominated by cultivation or mining, along with those dominated geographically by rocky outcrops and some steep, timbered country were deemed to be areas supporting zero to very low densities of kangaroos, and were therefore excluded from the areas to be surveyed. The remaining areas were divided for the purpose of proportionally allocating survey effort on the basis of land capabilities and the relative densities of kangaroos supported. For the areas of the two kangaroo management zones, see Table 1.

3. Survey Design

As has been the case with previous aerial surveys conducted in the Central Tablelands kangaroo management zones (e.g., Cairns, Bearup & Lollback 2015, 2018, 2020), and the most recent aerial surveys conducted in the Northern Tablelands kangaroo management zones (Cairns, Bearup & Lollback 2023) and the Southeastern NSW kangaroo management zone (Cairns, Bearup & Lollback 2022), this survey was designed using the automated design capabilities of the most recent version of the DISTANCE software package (Thomas *et al.* 2010); in this case DISTANCE 7.5. To facilitate this process, kangaroo density strata within each of the two management zones needed to be defined and the required survey efforts determined.

3.1 Management Zone Stratification

GIS shape files for the two Central Tablelands kangaroo management zones showing land capability attributes were obtained from NSW DCCEEW. These files contained the attributes of eight categories of land capability which extend from cultivation, through to mixed farming and grazing, through to grazing only (with decreasing levels of grazing intensity), through to steep, timbered country, through to rocky outcrops. They also contained some information on the location of state forests, gazetted reserves and national parks, all of which were excluded from the survey areas of each zone. The eight categories of land capability were merged into a smaller number of broader categories to form the initial basis of the three strata to be used in the survey design process.

Using these land-capability attributes, three kangaroo density strata were created within each management zone. Attribute Categories 1 and 2, which are representative of areas dominated by cultivation practices, were merged with Category 8, which is representative of areas dominated by rocky outcrops, and some of Category 7 (steep, timbered country) to form the basis of the likely low kangaroo density stratum within each zone. Categories 3 and 4, which are representative of areas of grazing and low intensity cropping, were merged to form the basis of the likely medium-density kangaroo stratum. Categories 5 and 6, which are representative of grazing land, and some of Category 7, were merged to form the basis of the likely high kangaroo density stratum. The boundaries of the merged attributes strata were modified in relation to available kangaroo density and raw count information, and then were re-digitised to create the final, simpler versions of the three density strata within each of the two management zones. Based on these stratifications of the two management zones an initial survey was undertaken in 2008 (Cairns, Lollback & Bearup 2009). The outcomes of the 2008 survey and of a second survey conducted in 2011 (Cairns & Bearup 2012) were used to confirm the broad basis of the stratifications of the two management zones.

The breakdowns of the areas of the two management zones into their constituent strata are given in Table 1. In the Central Tablelands North zone, 36% of the area formed the high density stratum, 59% formed the medium density stratum and the remaining 5% formed the low density stratum. The medium density stratum of this zone was divided into two sub-strata of approximately equal area for the purpose of designing the survey. These strata were labelled the Mudgee-medium (7,396 km^2) and the Hunter-medium (7,006 km^2) strata. A large tract of land dominated by open-cast coal mining was excised from the Hunter-medium sub-stratum. In the Central Tablelands South zone, the breakdown was 41% high density stratum, 56% medium density stratum and 3% low density stratum. For visual representation of the stratification of the zones, see Figs. 2 and 3.

Table 1. Areas (km^2) of the two Central Tablelands kangaroo management zones divided into three survey strata based upon a combination of nominal kangaroo densities (high, medium and low) and land capability attributes. The areas surveyed were those comprising the high and medium density strata.

Stratum	Kangaroo management zone	
	Central Tablelands North	Central Tablelands South
Total area	24,396	19,362
High density	8,783	7,974
Medium density	14,402	10,918
Low density	1,211	470
Survey area	23,185	18,892

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 preferred level of precision (i.e. the ratio of standard error to mean). In the conduct of surveys such as the one reported upon here, aiming for a general level precision of up to 20% would appear to be realistic and reasonably cost-effective (Pople, Cairns & Menke 2003; Cairns, Bearup & Lollback 2020). Some variations were made in relation to this benchmark level of precision.

For the Central Tablelands North management zone, survey effort for the high-density stratum was determined in relation to a level of precision of 17.5%. For the Mudgee-medium stratum the level of precision used was 20% and for the Hunter-medium stratum it was 15%. Similarly, for the Central Tablelands South management zone, survey effort for the high density stratum was determined in relation to a level of precision of 17.5%, while for the medium density stratum it was determined in relation to a level of precision of 20%. To determine the survey effort required, the method given by Buckland *et al.* (2001, p. 243) was used in relation to the precision (coefficient of determination) of the surveys completed in 2017 (Cairns, Bearup & Lollback 2018).

The nominal survey efforts determined for the high and medium density strata in each of the two kangaroo management zones are given in Table 2. No survey effort was allocated to the low-density stratum of either of the management zones. Low-density strata, which comprised either areas dominated by cropping, or areas of heavily timbered and rugged terrain, were thought to support only trace numbers of kangaroos.

Table 2. The nominal survey efforts determined for a specified coefficient of variation using the method of Buckland *et al.* (2001) and the actual survey efforts applied during the survey. For each survey stratum, one of either two survey design models, systematic segmented grid (SSG) sampling or systematic segmented trackline (SST) sampling were used.

Survey stratum	Sampling model	Nominal survey effort (km)	Actual survey effort (km)
Central Tablelands North			
High	SST	277.5	277.5
Mudgee-medium	SST	315.0	315.0
Hunter-medium	SST	215.0	215.0
Central Tablelands South			
High	SSG	270.0	270.0
Medium	SST	360.0	360.0

3.3 Automated Survey Design

The principal aim in designing a survey is to obtain optimal estimates of abundance, preferably with high precision and low bias (Strindberg, Buckland & Thomas 2004). Achieving this is not straightforward, particularly when designing a survey manually. However, taking advantage of GIS and using automated design algorithms such as those offered by DISTANCE 7.5 (Thomas *et al.* 2010) increases the likelihood that an optimal design will be achieved (Strindberg, Buckland & Thomas 2004).

DISTANCE 7.5 offers four different classes of 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.* 2009). According to both Buckland *et al.* (2001) and Strindberg, Buckland and Thomas (2004), systematic designs give smaller variation in density estimation from one realisation to the next and avoid any problems associated with overlapping samplers (transects).

A survey design incorporating either systematic segmented grid sampling (SSG) or systematic segmented trackline sampling (SST) with a buffer zone around the boundary of each survey stratum was selected as the most likely design option for the present surveys. Inclusion of a buffer zone in a design has the effect of guarding 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). Inclusion of a buffer zone of unspecified size (determined by the design algorithm) results in what is termed minus sampling (Thomas *et al.* 2010). The buffers in adjacent strata do not overlap. The two design options considered were tested against each other in relation to survey coverage probability. Based upon the outcomes of previous simulations, the option to maintain the integrity of the samplers (transects) was adopted in favour of the option of using split samplers.

Surveys were designed separately for each of the high and medium-density strata within each of the two kangaroo management zones using, as a broad basis for ensuring adequate survey effort, the nominal survey efforts given in Table 2. In designing each of the three surveys for the Central Tablelands North zone and the two surveys for the Central Tablelands South zone, a series of 999 simulations was run in relation to a 1-km square coverage grid to compare the coverage of the survey designs selected for comparison (Strindberg, Buckland & Thomas. 2004; Thomas *et al.* 2010). Once a particular design had been selected as being the most suitable for a survey stratum, then a single realisation of that design was generated to be used for the survey of that stratum.

The selected designs for the three strata in the Central Tablelands North management zone, the ones considered to provide the best coverage probability, were based upon systematic segmented trackline (SST) sampling. The selected designs for the two strata in the Central Tablelands South management zone, were based upon systematic segmented grid (SSG) sampling in the high-density stratum, and based upon systematic segmented trackline (SST) sampling in the medium-density stratum. All selected designs comprised fixed length rather than split samplers. The survey efforts for the realised survey designs are given in Table 2.

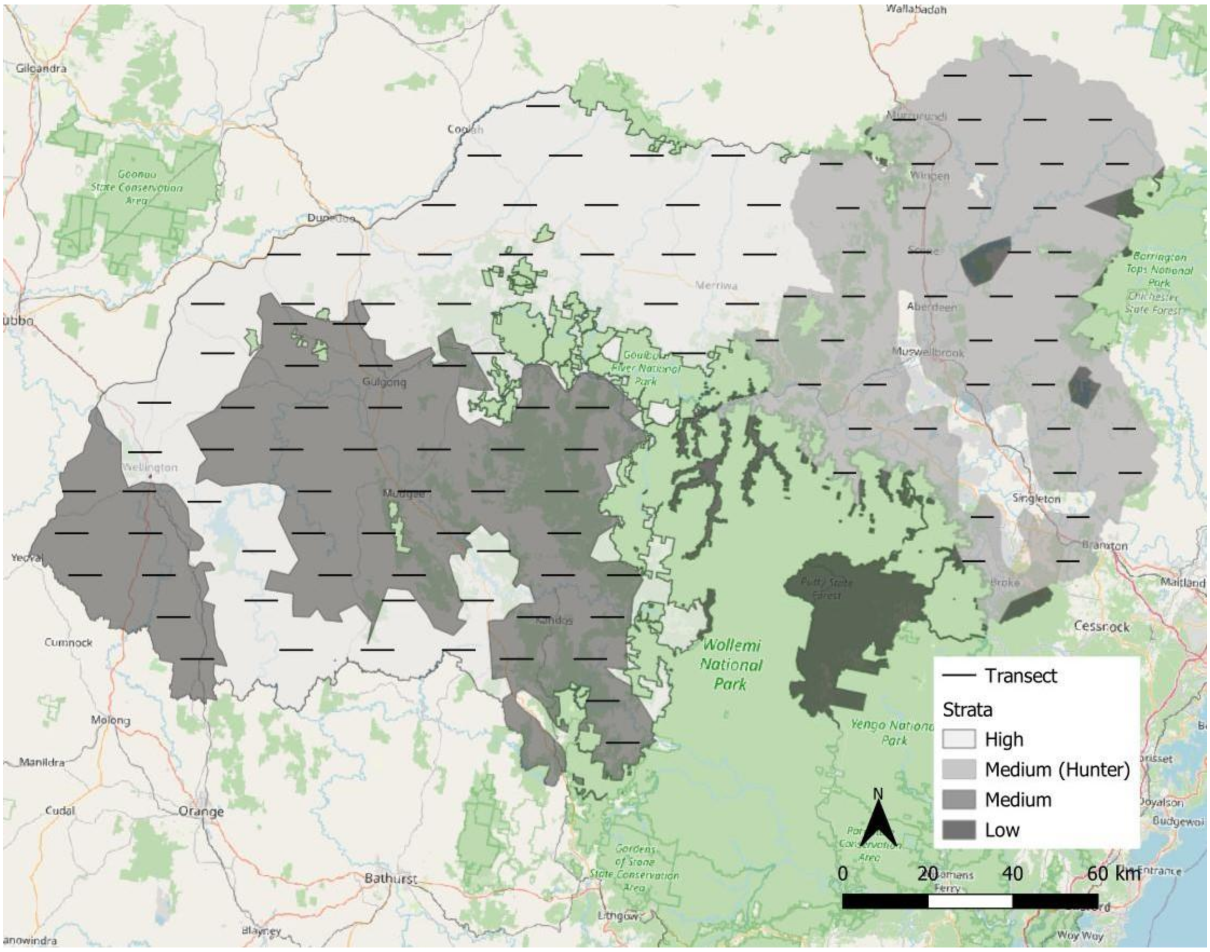

Fig. 2. The Central Tablelands North kangaroo management zone. Shown are the population centres (town) and the three survey strata; the medium kangaroo density stratum in this case being divided into two sub-strata: Mudgee-medium in the central and western parts of the zone (left) and Hunter-medium in the east of the zone (to the right). The open-cast coal mining area of the Hunter Medium sub-stratum (white) was not considered as part of the survey area. Shown also are the placement of the survey transects within the high and the two medium kangaroo density strata. Note that no survey transects were placed into the low density stratum.

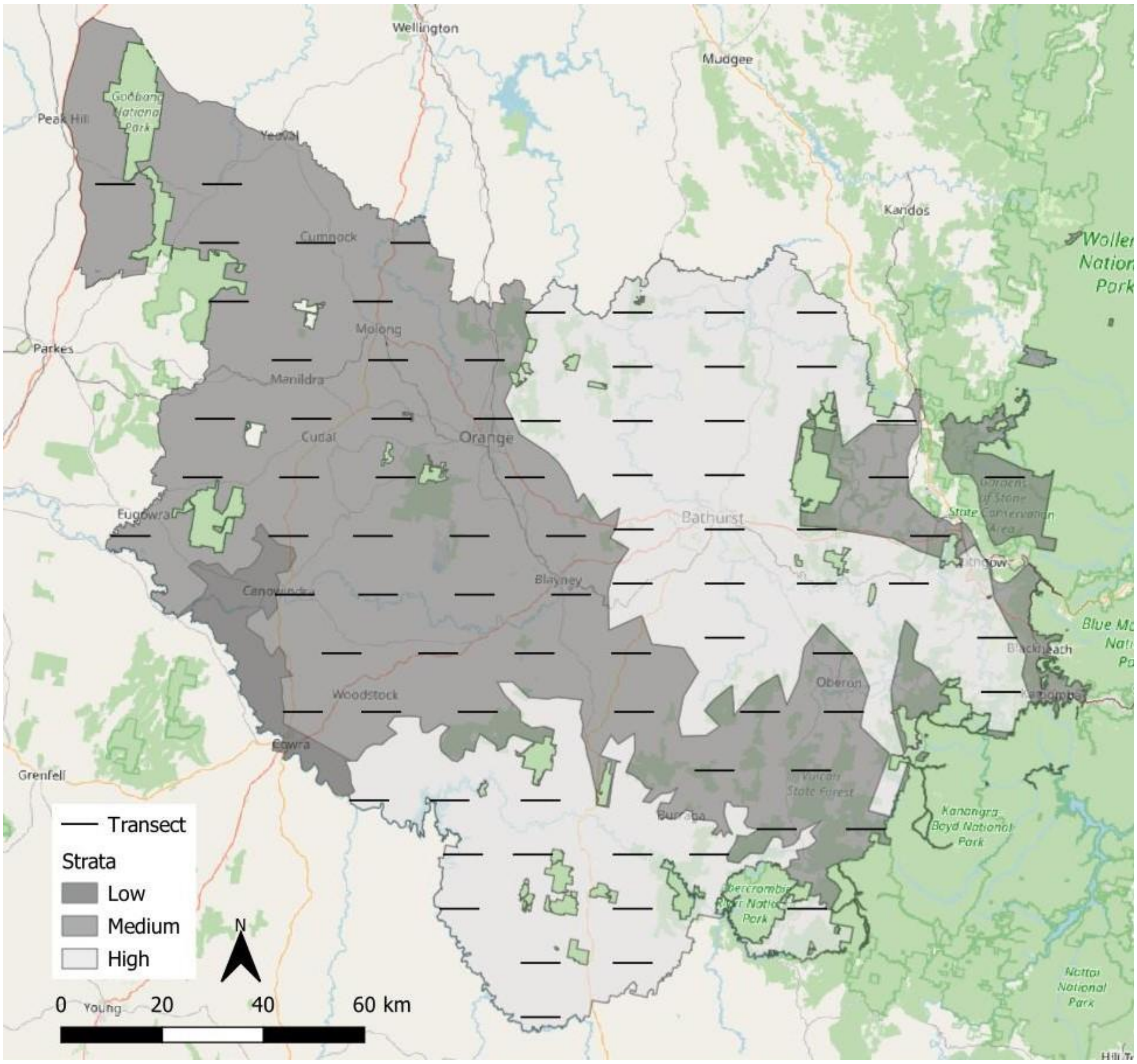

Fig. 3. The Central Tablelands South kangaroo management zone. Shown are the three survey strata, the population centres (towns) and the placement of the survey transects within the high and medium kangaroo density strata. Note that no survey transects were placed into the low density stratum.

For the Central Tablelands North zone, the selected survey designs comprised 37 transects in the Mudgee-high stratum, 42 transects in the Mudgee-medium stratum and 43 transects in the Hunter-medium stratum (Fig. 2). For the Central Tablelands South zone, the selected survey designs comprised 36 transects in the high-density stratum and 48 transects in the medium-density stratum (Fig. 3). For the Hunter-medium stratum in the Central Tablelands North zone, the samplers (transects) were a fixed 5 km in length. For the other two strata in this management zone, and for the two survey strata in the Central Tablelands South zone, the samplers were a fixed 7.5 km in length.

4. Survey Methods

The aerial surveys of the Central Tablelands North and Central Tablelands South kangaroo management zones were undertaken by helicopter during the period 7-14 September, 2023. They were conducted in accordance with the survey designs outlined in Section 3.3; with each management zone being considered a separate entity and subdivided into three strata based principally upon land-use capability, and modulated in relation to known general levels of kangaroo density. The two of the three strata within each management zone that were identified as supporting high and medium densities of eastern grey kangaroos, respectively, were surveyed. The method of line transect (distance) sampling (Buckland *et al.* 2001; Thomas *et al.* 2002) was used. In the original design for these surveys, there was a total of 206 transects to be flown across the two management zones. All these transects were flown to complete the surveys (see Table 3).

All surveys were conducted within either the two to three-hour period following sunrise or the two to three-hour period before sunset. David Bearup (NPWS), Steve Chapple (NPWS), and Scott Seymour (ACT Emergency Services) were the observers. Paul Caristo and Peter Franks were the pilots. Rod Clarke was an air safety observer. Doug Sandry and Sheridan Maher (NSW DCCEEW) provided technical and ground support.

4.1 Helicopter Line Transect Surveys

In conducting the survey, 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 91 m (300 ft) above the ground. 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. 4).

Fig. 4 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.

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

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 area covered during the survey is estimated as:

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

where, n_a is the number of clusters of animals 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 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, $0 \leq x \leq w$ 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 7.5 (Thomas *et al.* 2010). Basing the analysis on the sightings of clusters in preference to the sightings of individual animals has been found to insure against the 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 >10 in order to ensure reasonably reliable estimation of the variance of the encounter rate, and the recommended number of observations, clusters of kangaroos in this instance, should be, if possible, >60 for reliable modelling of the detection function.

For eastern grey kangaroos, the survey results from each management zone were analysed separately. Stratification was incorporated into the analyses, with the option 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. For the other three macropod species, to ensure the required threshold number of observations for the reliable modelling of the detection function, the data from the two management zones were pooled for analysis.

DISTANCE 7.5 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 will 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 ($AIC = -2ln(L) + 2[k + 1]$; where, L is the maximised value of the likelihood function for the model and k is the number of parameters in the model: Burnham & Anderson 2002) 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 centreline, 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, habitat cover at point-of-detection, survey aspect and cloud cover. These covariates were all factor covariates. To avoid over-parameterisation, only single covariates were included in the models tested. Two key functions are available with the MCDS analysis engine: the Half-normal and the Hazard-rate 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 centreline (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 centreline, 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 were determined empirically, the upper and lower confidence limits (UCL and LCL), and the associated coefficients of variation (cv%) for these estimates were determined from bootstrapping the data. The data were bootstrapped 999 times in relation to all model options in the analysis engine used and not just the model selected to determine the empirical estimates. It was expected that bootstrapping the data in this way would improve the robustness of the estimation of these statistics (Buckland *et al.* 2001). The 95% confidence limits given with the empirical estimates were the 2.5% and 97.5% quantiles of the respective bootstrap estimates. Bootstrapping the data was necessary in order to estimate confidence intervals for management zone estimates based on combining estimates determined at the survey stratum level when using the MCDS analysis engine.

The data were analysed to determine separate kangaroo density and abundance estimates for the high and medium density strata of each management zone, and for the whole of each kangaroo management zones; with an overall density being determined in relation to all three strata, including the low density stratum which was not surveyed. Eastern grey kangaroo counts were able to be analysed at the level of survey stratum within management zone, using both the CDS and MCDS analyses engines. Common wallaroos and the smaller, less common species, red-necked wallabies and swamp wallabies, were analysed at the level of survey area within each management zone.

5. Results and Discussion

5.1 Survey Data Summaries

Each of the two kangaroo management zones surveyed was subdivided into three strata based upon land capability and relative eastern grey kangaroo densities (see Section 3.1). Of the three strata within each zone, only the high and medium kangaroo density strata were surveyed. The low density strata were assumed to support, at the most, trace numbers of kangaroos and were, therefore, not surveyed. The medium density stratum in the Central Tablelands North management zone was recast as two sub-strata, namely the Mudgee-medium and Hunter-medium strata. Doing this was reflective of the higher level of human occupancy, and industrial and agricultural activity that takes place in the Hunter region.

In the Central Tablelands North kangaroo management zone (Zone 48, Fig. 1), 37 transects comprising 277.5 km of survey effort were flown across the high density stratum. A total of 1,817 eastern grey kangaroos were counted on these transects, along with 76 common wallaroos. Of the other species of macropod present, there were 20 red-necked wallabies (*Macropus rufogriseus*) and 21 swamp wallabies (*Wallabia bicolor*) counted. Forty-two transects comprising 315 km of survey effort were flown across the Mudgee-medium stratum. A total of 1,538 eastern grey kangaroos were counted on these transects, along with 69 wallaroos, 27 red-necked wallabies and 23 swamp wallabies. Forty-three transects comprising 215 km of survey effort were flown across the Hunter-medium stratum. A total of 973 eastern grey kangaroos were counted on these transects, along with 74 wallaroos, 75 red-necked wallabies and 45 swamp wallabies. As well as the macropods counted across these three survey strata, there were 509 feral goats (*Capra hircus*), 213 feral pigs (*Sus scrofa*) and 141 introduced deer also counted. With regard to the macropods, this raw survey information is summarised in Table 3.

In the Central Tablelands South management zone (Zone 49, Fig. 1), 36 transects comprising 270 km of survey effort were flown across the high density stratum. A total of 1,881 eastern grey kangaroos were counted on these transects, along with 29 wallaroos, 10 red-necked wallabies and 46 swamp wallabies. Forty-eight transects comprising 360 km of survey effort were flown across the medium density stratum of this zone. A total of 1,838 eastern grey kangaroos were counted on these transects, along with only 24 wallaroos, two red-necked wallabies and 11 swamp wallabies. As well as the macropods counted across these two strata, there were 439 feral goats, 113 feral pigs and 55 introduced deer also counted. With regard to the macropods, this raw survey information is summarised in Table 3.

Table 3. The numbers of transects flown, the survey efforts (km) these comprise and the raw counts of individual macropods for each of the survey strata within the two Central Tablelands kangaroo management zones.

				Raw counts			
Kangaroo management zone	Area (km^2)	Number of transects	Survey effort (km)	Eastern grey kangaroos	Common wallaroos	Red-necked wallabies	Swamp wallabies
Central Tablelands North							
High	8,783	37	277.5	1,817	76	20	21
Mudgee-medium	7,396	42	315.0	1,538	69	27	23
Hunter-medium	7,006	43	215.0	973	74	75	45
Central Tablelands South							
High	7,974	36	270.0	1,881	29	10	46
Medium	10,917	48	360.0	1,838	24	2	11

5.2 Line Transect Analysis

To estimate the population densities and abundances of eastern grey kangaroos, wallaroos and wallabies, the counts of clusters of these macropods obtained during the surveys were recorded in relation to the five distance categories set on the survey booms mounted on the helicopter (Fig. 4). These results were then analysed as distance sampling data using a method conforming to a general and well-understood framework as outlined in Buckland *et al.* (2001).

Key to the analysis is the modelling of the detection of clusters of kangaroos in relation to at least one covariate, the perpendicular distance from the transect centreline as defined by the boundaries of the five distance classes on the survey booms. Analyses involved the use of both the CDS and the MCDS analysis engines of DISTANCE 7.5 (Thomas *et al.* 2010), with the most parsimonious (preferred) detection function model being selected from a number of candidate models principally on the basis of the comparison of AIC statistics (see Section 4.2). Where feasible, the data were analysed in relation to each of the survey strata within each of the two kangaroo management zones, and the results combined to produce whole-zone population density and abundance estimates. If this was not able to done, the data were analysed on a whole survey area basis; the survey stratification being discounted. For details of this, see Section 4.2.

With the model selection process, a number of candidate detection function models were fitted to the data and compared, with the preferred model being selected as the one that yields the smallest value of the AIC statistic. In comparing any two models, where the difference between the two AIC values (ΔAIC) increases beyond the nominal value of 2.00, it can be concluded that there is evidence that it is becoming increasingly less plausible that the fitted model with the larger AIC could be considered the more likely of the two models, given the data. The converse of this is that when ΔAIC <2.00, then it can be thought that there can be some level of empirical support for the model with the larger AIC in comparison with the one associated with the smaller AIC, given the data. Such ambiguity could be dealt with using model averaging. For further information on the use of AIC in model selection, see Burnham & Anderson (2002).

The most parsimonious detection function models fitted to the results of the surveys of eastern grey kangaroos in the two kangaroo management zones are given in Table 4. For the Central Tablelands North management zone, the preferred model was a global, MCDS-derived model that incorporated the covariate of vegetation cover at point-of-detection. For the Central Tablelands South management zone, the preferred model was a global, MCDS-derived model that incorporated the covariate of observer. The key functions for both these models were the Half-normal function. There were two types of habitat vegetation cover at point-of-detection recorded during the surveys. These identified either open habitat and habitat with tree cover. Three observers were used in rotation during these surveys.

Table 4. The number of sightings of clusters of eastern grey kangaroos (n), analysis engine used (see text), detection function and model for the survey of the eastern grey kangaroo populations in the two Central Tablelands kangaroo management zones (KMZ) conducted in September, 2023. MCDS is the multiple covariates distance sampling analysis engine. The detection functions have been determined globally across the survey strata of a KMZ. Given also are the encounter rate (n/L) and the probability that a cluster of kangaroos present on the survey strip is detected (P_a).

KMZ/stratum	n	Analysis engine	Detection function	Model	Covariates	n/L	P_a
Central Tablelands North							
High	467	MCDS	Global	Half-normal	cover	1.68	0.42
Mudgee-medium	426	MCDS	Global	Half-normal	cover	1.35	0.44
Hunter-medium	355	MCDS	Global	Half-normal	cover	1.65	0.42
Central Tablelands South							
High	626	MCDS	Global	Half-normal	observer	1.95	0.45
Medium	483	MCDS	Global	Half-normal	observer	1.34	0.44

In relation to the preferred models derived for each of the two management zones, the differences (ΔAIC) between these models and the others tested were quite substantial. For the analysis of the Central Tablelands North survey results, $\Delta AIC > 52.24$, while for the analysis of the Central Tablelands South results, $\Delta AIC > 21.77$. The general forms of the preferred detection functions for eastern grey kangaroos in the two management zones are shown in Appendix 1, Figs. A1.1-A1.2. For the Central Tablelands North zone, two forms of the preferred model are shown in relation to the type of vegetation cover at point-of-detection. For the Central Tablelands South zone, three forms of the preferred model are shown in relation to each of the three observers. In relation to the models shown in each of these figures, it should be noted that inclusion in the model of a covariate has 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 encounter rates (n/L) and probabilities (P_a) that a randomly-selected cluster of eastern grey kangaroos in the nominal survey strip will be detected. The encounter rates were within a reasonably narrow range (1.34-1.95) across the survey strata of the two management zones and were indicative of the ubiquity of the eastern grey kangaroo throughout the Central Tablelands of NSW (Table 4). As would be expected, the higher encounter rates were for the high density survey strata. The probabilities of detection (P_a) were found to be similar across the survey strata of the two management zones even though in some instances it was influenced by vegetation cover at point-of-detection and in others by the different observers.

The encounter rate, the number of clusters of kangaroos detected per unit (km) of survey effort is considered, in some respects, a more informative statistic than is n itself (Buckland *et al*. 2001). As well as the encounter rate itself, the precision of its estimation is also important. High precision associated with the encounter rate points to low variability between the detections of clusters of kangaroos on individual transects. This can usually be considered as an indicator of how well a survey has been designed. In these surveys, the precision of the encounter rates was relatively high, with coefficients of variation (cv) in the range 13-14% in the Central Tablelands

North zone, and 10-15% in the Central Tablelands South zone. In distance sampling, encounter rate variance is usually the dominant component of the overall variance of object (kangaroo) density. Low variance in the encounter rate can be taken as an indicator of low bias in a density estimate; indicating its closeness to the true density.

While P_a is required as part of the estimation process, it can also be viewed as a broad indicator of the interaction between the objects of the survey, the landscape they occupy, and the observers and conditions on the survey platform. It therefore has some limited comparative value. Ranging from 0.42 to 0.45, P_a showed some, but not much variation across the survey strata. This relative consistency perhaps points to the broad similarities in the landscapes of the two management zones and the adjusted similarity in performance of the observers. Comparisons of the P_a estimates from these surveys with those obtained from the previous surveys conducted in these two management zones cannot be meaningfully made because the current surveys were conducted at a height of 91 m, which amounted to an increase of some 50% in survey height in relation to previous surveys, all of which had been conducted at a height of 61 m.

For common wallaroos a single, global detection function model was fitted to the combined data for the two management zones. This was done because of the relative low count of clusters of wallaroos in the Central Tablelands South zone (Table 5). The most parsimonious detection function model was selected using the method outlined in Section 4.2. The detection function model fitted to the combined wallaroo survey data, a CDS-derived Hazard-rate model, is given along with its associated statistics in Table 5. The general form of the detection function for wallaroos is shown in Appendix 1, Figs. A1.3. The encounter rates for wallaroos were at least an order of magnitude lower than those determined for eastern grey kangaroos. The overall probability that a randomly selected cluster of wallaroos in the survey strip will be detected (P_a) was some two-thirds of those determined for eastern grey kangaroos (see Table 4).

Table 5. The survey effort, number of sightings of clusters of animals (n), DISTANCE 7.5 analysis engine used (see text), the detection function model, the encounter rate (n/L) and the probability that a randomly-selected cluster of animals in the survey strip is detected (P_a) for common wallaroos, red-necked wallabies and swamp wallabies in the Central Tablelands North and Central Tablelands South kangaroo management zones. CDS is the conventional distance sampling engine and MCDS is the multiple covariate distance sampling engine.

Kangaroo management zone	Effort (km)	n	Analysis engine	Model	Covariate	n/L	P_a
<u>Central Tablelands North</u>	807.5						
Common wallaroos		114	CDS	Hazard-rate	–	0.14	0.30
Red-necked wallabies		82	MCDS	Hazard-rate	aspect	0.10	0.29
Swamp wallabies		80	MCDS	Half-normal	observer	0.10	0.22
<u>Central Tablelands South</u>	630.0						
Common wallaroos		31	CDS	Hazard-rate	–	0.05	0.30
Red-necked wallabies		12	MCDS	Hazard-rate	aspect	0.02	0.32
Swamp wallabies		51	MCDS	Half-normal	observer	0.08	0.23

As was the case for wallaroos, with too few sightings to allow separate analyses for each of the two management zones, single global detection function models were fitted to the combined survey results for the minor species, red-necked wallabies and swamp wallabies. The most parsimonious detection function model for red-necked wallabies was a Hazard-rate model with survey aspect as a covariate, while the most parsimonious model for swamp wallabies was a Half-normal model with observer as a covariate (Table 5). The forms of the detection function models are shown in Appendix 1, Figs. A1.4 and A1.5. Encounter rates for both these species were low, as were the estimates of P_a.

5.3 Population Estimates

The densities of clusters of eastern grey kangaroos along with the corresponding population densities within each of the survey strata of the two kangaroo management zone are given in Table 6. Bootstrap confidence intervals and corresponding coefficients of variation are given in relation to these density estimates. As indicated by the coefficients of variation (cv), these density estimates were all obtained with a level of precision better than the threshold level of 20%. Combining stratum estimates to obtain management zone estimates improved the precision of estimation considerably (see Table 7).

The population densities and corresponding estimates of abundance of eastern grey kangaroos in each of the survey strata, along with the total abundance estimates for each management zone, are given in Table 7. Bootstrap confidence intervals and corresponding coefficients of variation are given in relation to both these estimates.

Table 6. Results of the helicopter line transect surveys of eastern grey kangaroos conducted in the Central Tablelands kangaroo management zones (KMZ) in September, 2023. Given are the areas of the survey strata, the densities of clusters of kangaroos sighted (D_s) and kangaroo population densities (D). Given in association with the two density estimates are the bootstrap confidence intervals and bootstrap coefficients of variation (cv %). Details of the most parsimonious detection function models used to determine these densities are given in Table 4.

KMZ/stratum		Kangaroo densities (km^{-2})					
	Area (km^2)	D_s	95% bootstrap confidence interval	cv (%)	D	95% bootstrap confidence interval	cv (%)
<u>Central Tablelands North</u>							
High	8,783	13.32	10.21-17.51	13.4	44.50	32.13-57.61	15.3
Mudgee-medium	7,396	10.32	7.76-14.43	13.9	31.25	23.09-40.83	14.8
Hunter-medium	7,006	13.25	10.02-17.61	14.1	28.81	20.32-38.38	16.0
<u>Central Tablelands South</u>							
High	7,974	14.48	11.43-18.36	11.6	42.95	31.24-56.42	15.1
Medium	10,917	10.25	7.16-13.68	17.0	34.72	22.61-50.65	20.1

Table 7. The eastern grey kangaroo population densities (D) and abundances (N) for the strata surveyed within the Central Tablelands North and Central Tablelands South kangaroo management zones (KMZ). Given in association with the estimates are bootstrap confidence intervals and bootstrap coefficients of variation (cv%). The abundances given in bold are the combined, whole-zone estimates.

KMZ/stratum	Area (km^2)	D (km^{-2})	95% bootstrap confidence interval	N	95% bootstrap confidence interval	cv (%)
Central Tablelands North						
High	8,783	44.50	32.13-57.61	390,880	282,220-505,940	15.3
Mudgee-medium	7,396	31.25	23.09-40.83	231,090	170,080-302,000	14.8
Hunter-medium	7,006	28.81	20.32-38.38	201,870	142,390-268,920	16.0
				823,840	682,110-976,740	9.2
Central Tablelands South						
High	7,974	42.95	31.24-56.42	342,450	249,080-449,920	15.1
Medium	10,917	34.72	22.61-50.65	379,080	246,800-553,030	20.1
				721,530	551,190-932,880	13.3

In the Central Tablelands North management zone, the highest density of eastern grey kangaroos was recorded in the designated high density stratum. Over time, the relative eastern grey kangaroo densities in the three survey strata of this management zone have shown a degree of fluidity. In 2020, the highest density was recorded in the Hunter-medium stratum (Cairns, Bearup & Lollback 2020), while before that, in 2017, it was recorded in the Mudgee-medium stratum (Cairns, Bearup & Lollback 2018). In the Central Tablelands South zone the density of eastern grey kangaroos in the high density stratum was greater than it was in the medium density stratum. In 2020, the density of eastern grey kangaroos in the high density stratum was similar to that in the medium density stratum, while in 2017, the difference was substantial, with the density of kangaroos in the high density stratum being approximately twice that in the medium density stratum. Enveloped within the six-year period over which these three surveys were conducted was a period of severe drought, which officially extended from January 2017 through to December 2019 (http://www.bom.gov.au/climate/drought/knowledge-centre/previous-droughts.shtml). It could be safely assumed that this drought would have had an influence on the temporal changes in the relative densities of kangaroos within these two management zones.

In the Central Tablelands North management zone, despite the noted internal changes in density distributions, the eastern grey kangaroo population showed no significant change in abundance from that estimated in relation to the survey conducted in 2020 ($z = 0.31$; $P = 0.756$). Compared to this, a significant change had previously occurred between 2017 and 2020, when the particularly large population recorded in this zone in 2017 (see Table 6, Cairns, Bearup & Lollback 2018) had, by the time of the 2020 survey, declined in numbers by a significant 55% ($z = 3.50$; $P < 0.001$). This was almost certainly in response to the drought that occurred in that intervening period. The decline in numbers between 2017 and 2020 had followed on from a previously estimated 60% increase in numbers between 2014 and 2017, an increase which compounded earlier increases of the order of a substantial 95% between 2011 and 2014, which had followed an increase of 40% between 2008 and 2011 (Cairns, Lollback & Bearup 2009; Cairns & Bearup 2012; Cairns, Bearup & Lollback 2015, 2018).

In the Central Tablelands South management zone, the eastern grey kangaroo population was found to have increased in size over the three years since the 2020 survey by a near significant 48% (z = 1.95; P = 0.051). Compared to this, the high population recorded in 2017 (see Table 6, Cairns, Bearup & Lollback 2018) had, by the time of the 2020 survey, decreased in size by a significant 48% (z = 2.66; P = 0.008). Again, this was no doubt in response to the drought that occurred in that intervening period. This decline in numbers has followed on from an estimated 30% increase in numbers between 2014 and 2017, which had compounded earlier increases in numbers of a substantial 130% between 2011 and 2014 (Cairns, Lollback & Bearup 2009; Cairns & Bearup 2012; Cairns, Bearup & Lollback 2015, 2018). The successive increases in numbers that occurred between 2011 and 2020 had followed on from an earlier 35% decline in numbers that had occurred between 2008 and 2011 (Cairns & Bearup 2012). As noted above, at the individual survey stratum level, these proportional changes in numbers were particularly variable when compared across the four successive survey periods (2008-2017) leading up to and including the onset of the drought.

Both the eastern grey kangaroo populations defined by the two management zones increased in numbers over an extended period up to the onset of the 2017-2019 drought, before declining substantially between 2017 and 2020, and then recovering to some extent between 2020 and 2023. Another way of understanding these changes in numbers is to consider within the context of population dynamics, through an examination of annual finite rates of population increase (λ). Simply defined, this statistic is a compound multiplier that represents the rate at which a population would increase each year (Krebs 1994).

From 2008 through until 2017 in the early stages of the drought, eastern grey kangaroo numbers had increased over the successive survey periods. From the results of the four successive surveys that have been conducted in the two management zones over this period, when calculated separately the rates of increase (λ) of the populations within each of the two management zones appeared to be quite different, both spatially and temporally. However, further analysis showed that, statistically, there was no difference between the trends in the rates of increase of these populations over this period ($F_{1,5}$ = 3.06; P = 0.14). In terms of the compounding changes in numbers, the overall annual finite rate of increase for eastern grey kangaroo populations across both management zones was 1.151 per individual per year for the period 2008-2017. In other words, these two kangaroo populations had increased annually over this period at a rate of 15% per annum.

By way of comparison, this annual finite rate of population increase was found to be higher than that estimated for the eastern grey kangaroo populations in the Northern Tablelands management zone over the period 2004-2016 (λ = 1.102; Cairns, Bearup & Lollback 2017). Further, both these estimated rates of population increase for eastern grey kangaroos could be considered comparable to the rates of increase estimated for other species of large kangaroo (Bayliss 1985; Cairns & Grigg 1993; Cairns *et al.* 2000); rates of increase determined for populations in semi-arid to arid environments, rather than the mesic environment that is characteristic of the tablelands of NSW.

As noted above, the populations in the two management zones declined sharply between 2017 and 2020. The annual finite rate of increase (decrease) for two populations were 0.766 in the Central Tablelands North management zone and 0.806 in the Central Tablelands South management zone. These rates of increase (decrease) represent successive annual declines in numbers over this period of 23% and 19%, respectively. Between 2020 and 2023, following the end of the drought, both populations recorded increases in numbers at a low rate of 2% per annum (λ = 1.020) in the Central Tablelands North management zone and a much greater rate of17% per annum (λ = 1.172) in the Central Tablelands South management zone.

For the purpose of comparison, whole-zone population density estimates were determined for the eastern grey kangaroo in each of the two management zones. These were found to be 35.53 km^{-2} for the Central Tablelands North management zone and 38.19 km^{-2} for the Central Tablelands South management zone. These densities were determined in relation to the area of all three survey strata from the estimates of total abundance determined in relation to those strata actually surveyed. Both of the Central Tablelands kangaroo management zones are larger than the three Northern Tablelands management zones, but each is equal in size to about three-quarters the area of the current South East NSW management zone (Fig. 1). Both management zones currently support larger, higher density populations of eastern grey kangaroos than do each of the three Northern Tablelands management zones (see Table 10, Cairns, Bearup & Lollback 2023). However, densities in the Southeastern NSW zone are generally higher than those in both of the Central Tablelands management zones (see Table 8, Cairns, Bearup & Lollback 2022).

Three other species of macropod were observed during the current surveys. The estimates of population density and abundance for these three species in the two kangaroo management zones are given in Table 8. The most abundant of these three species is the common wallaroo. With the estimation of the numbers of this species, the attained level of precision could be considered acceptable given that the surveys were designed principally to estimate eastern grey kangaroo numbers. In comparison with the results of the 2020 survey, no change was found to have occurred in wallaroo numbers in either the Central Tablelands North zone or Central Tablelands South zone ($z < 1.35$; $P > 0.175$). In both these management zones, the wallaroo numbers had been found to be substantially lower in 2020 than were the estimates obtained from the surveys conducted in 2017 (Cairns, Bearup & Lollback 2020), having declined in abundance by up to 75%.

With regard to helicopter surveys of the type conducted here, the sightability of wallaroos has been reported to be lower than it is for eastern grey kangaroos which mean that the population estimates obtained will be underestimates and need to be acknowledged as such. In surveys conducted in southeastern Queensland, Clancy *et al.* (1997) found that helicopter line transect surveys of wallaroos were likely to underestimate wallaroo numbers by a factor of 1.85 when compared with the results of walked line transect sampling. Supportive of this was the outcome of a similar study conducted in the Barrier Ranges of western NSW in 1998 from which it was found that helicopter line transect sampling underestimated euro (*O. r. erubescens*) numbers by a factor of 1.50 in undulating terrain and 1.88 in steep terrain, when compared with the results of walked line transect surveys (S. C. Cairns, A. R. Pople & J. Gilroy, *unpubl. data*). Taking this into account, if there was a need for wallaroo numbers to be estimated for the purpose of setting harvest quotas, then it would be reasonable to apply a correction factor (x1.85) to the abundance estimates obtained from these helicopter line transect surveys.

Table 8. The densities (D) and abundances (N) of common wallaroos, red-necked wallabies and swamp wallabies in the Central Tablelands North and Central Tablelands South kangaroo management zones. Given in association with the estimates are bootstrap confidence intervals and coefficients of variation (cv%).

Kangaroo management zone	D (km^{-2})	95% bootstrap confidence interval	N	95% bootstrap confidence interval	cv (%)
Central Tablelands North					
Common wallaroos	3.04	2.09-4.32	70,530	48,470-100,190	18.8
Red-necked wallabies	1.71	0.91-2.16	39,540	21,040-50,020	22.9
Swamp wallabies	1.66	1.07-2.34	38,450	24,860-54,270	18.9
Central Tablelands South					
Common wallaroos	0.94	0.47-1.41	17,830	8,880-26,700	26.4
Red-necked wallabies	0.20	0.07-0.35	3,750	1,310-6,640	38.1
Swamp wallabies	1.31	0.86-1.81	24,730	16,290-34,260	19.4

In the Central Tablelands North management zone, densities of both red-necked wallabies and swamp wallabies were found to be substantially lower than those of wallaroos (Table 8), which, in turn, were again substantially lower than those of eastern grey kangaroos (see Table 6). In the Central Tablelands South management zone, the swamp wallaby was found to be more abundant than the other two minor macropod species. With regard to red-necked wallabies and swamp wallabies, it is possible that, as is the case with wallaroos, that the population estimates obtained from these surveys these species could also be underestimates. At present, this is untested. Although both these species of wallaby occur in quite low numbers, they, nevertheless, from an ecological perspective, comprise significant components of the macropod communities of the Central Tablelands and Hunter regions of NSW.

The aerial surveys conducted in these two kangaroo management zones were designed with the intention of providing reasonably precise population estimates for eastern grey kangaroos; estimates with coefficients of variation of ≤20%. With coefficients of variation of 10-20% (Table 7), this aim was easily achieved with the surveys designed for each of the two management zones.

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Appendix 1

Figs. A1.1-A1.5

The detection function models for eastern grey kangaroos (*M. giganteus*) common wallaroos (*O. r. robustus*), red-necked wallabies (*M. rufogriseus*) and swamp wallabies (*W. bicolor*) in the two Central Tablelands kangaroo management zones.

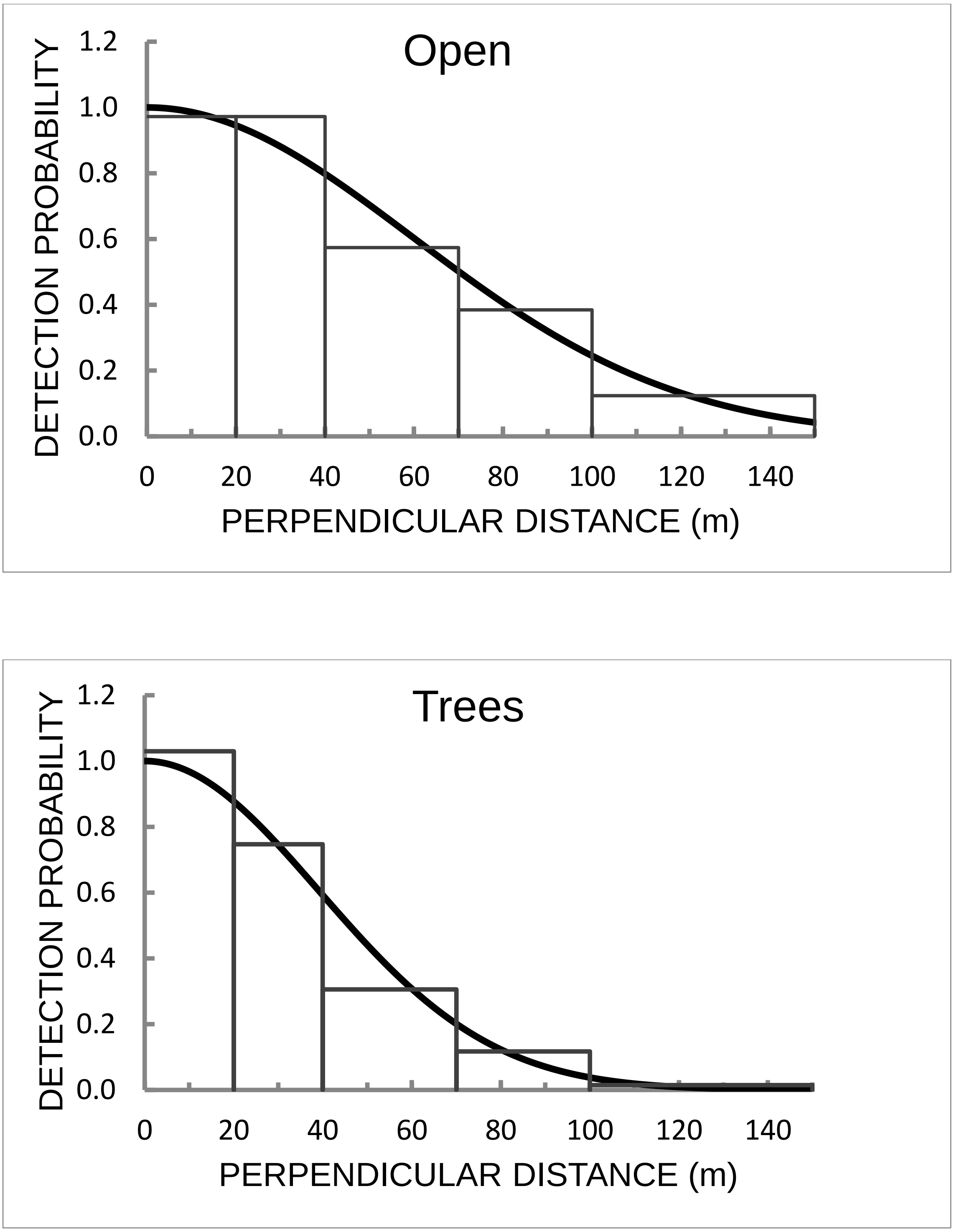
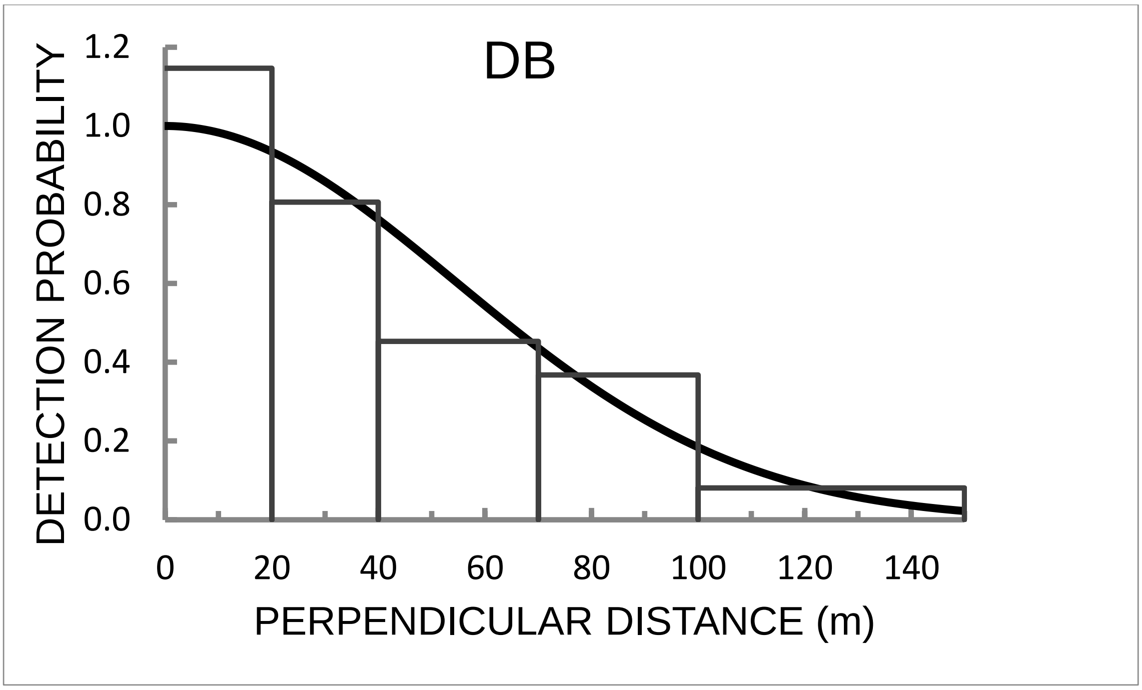
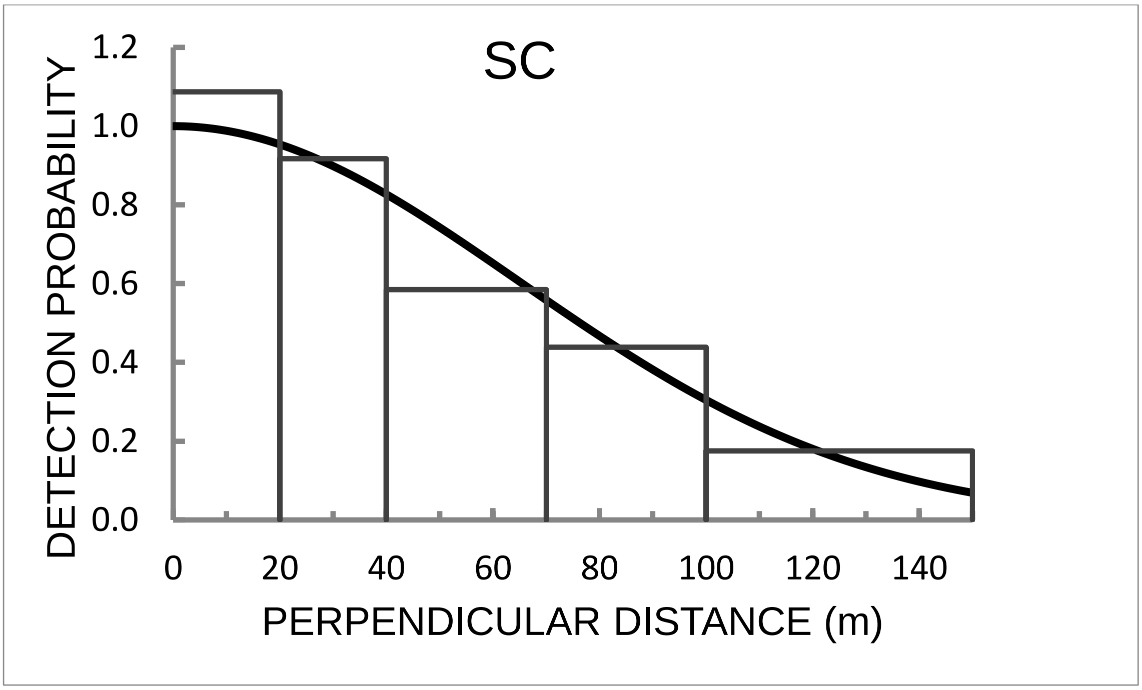


Fig. A1.1. The Half-normal detection functions for eastern grey kangaroos in the Central Tablelands North kangaroo management zone. For details of the model fitted using the MCDS analysis engine with cover at point-of-detection as a covariate, see text and Table 4.


DB
DETECTION PROBABILITY
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
140
PERPENDICULAR DISTANCE (m)


SC
DETECTION PROBABILITY
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
140
PERPENDICULAR DISTANCE (m)

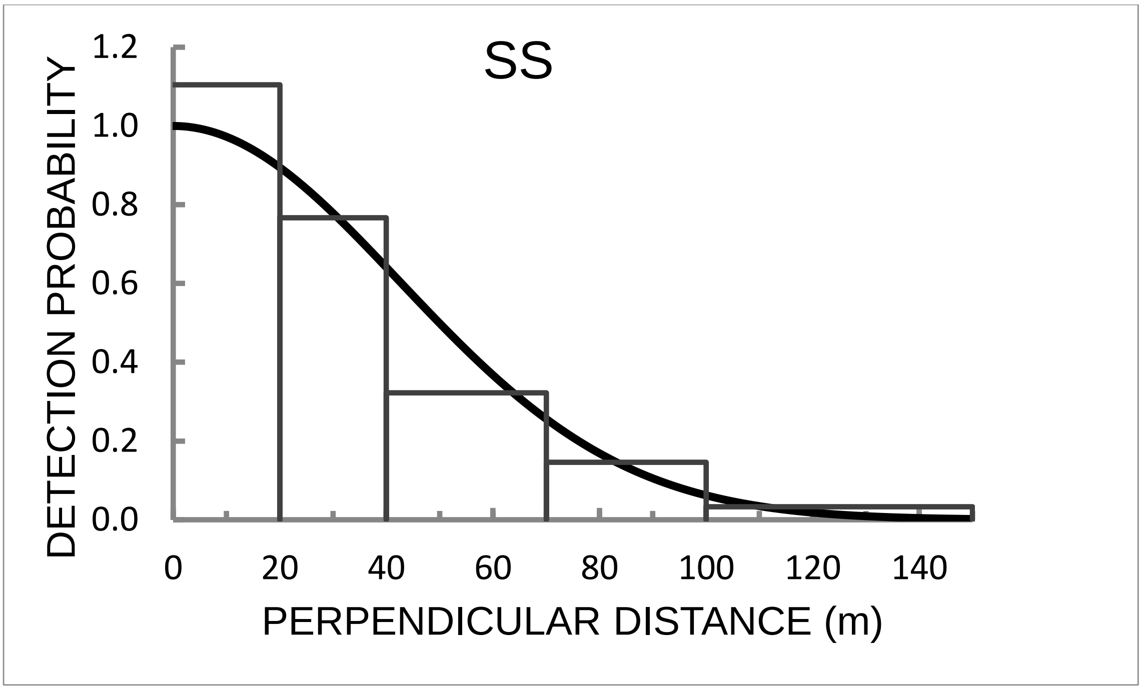


Fig. A1.2. The Half-normal detection functions for eastern grey kangaroos in the Central Tablelands South kangaroo management zone. For details of the model fitted using the MCDS analysis engine with observer as a covariate, see text and Table 4.

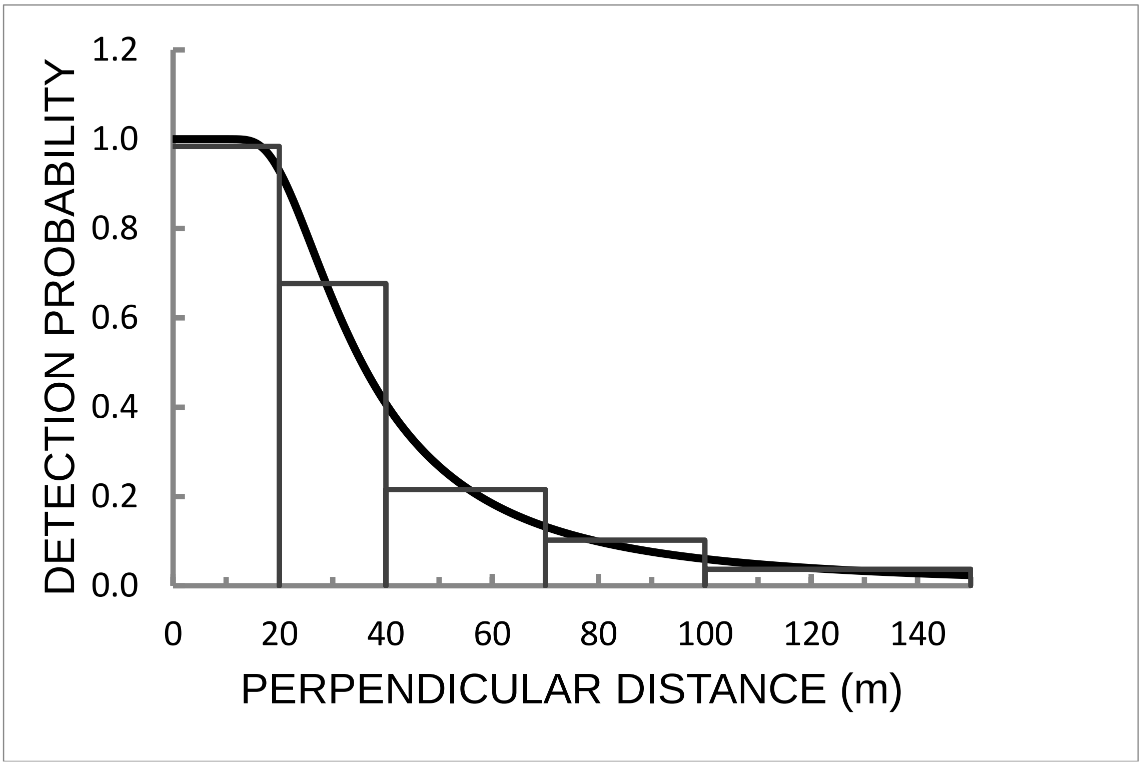
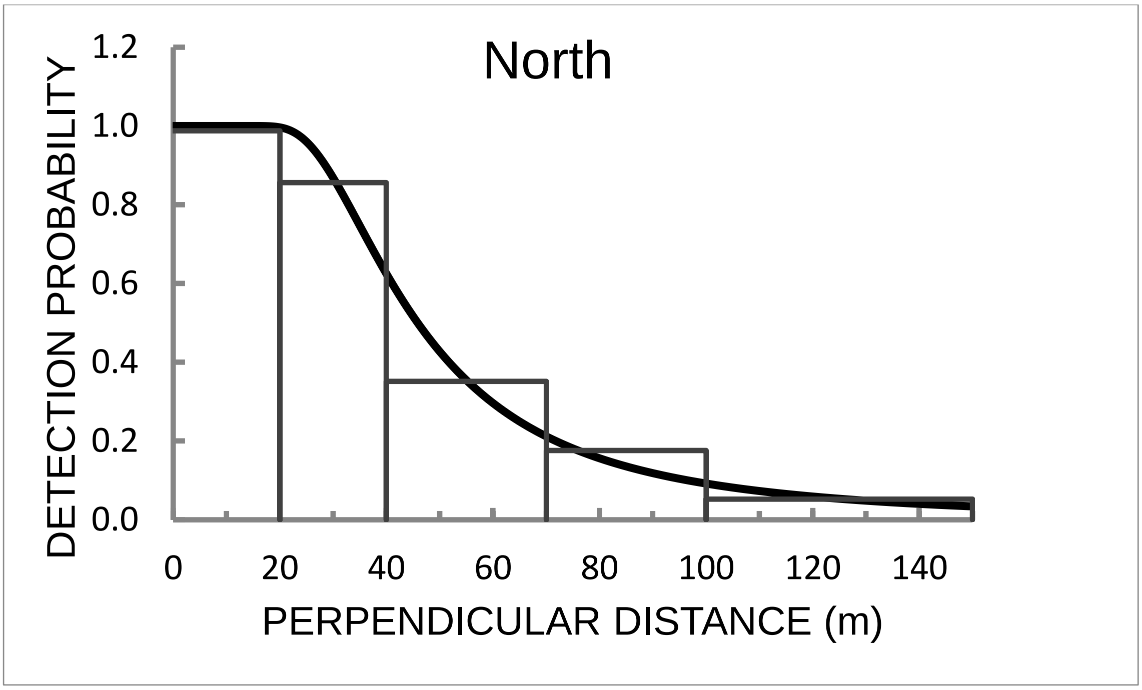


Fig. A1.3. The Hazard-rate detection function for common wallaroos in both the Central Tablelands North and Central Tablelands South kangaroo management zones. For details of the model fitted using the MCDS analysis engine with observer as a covariate, see text.



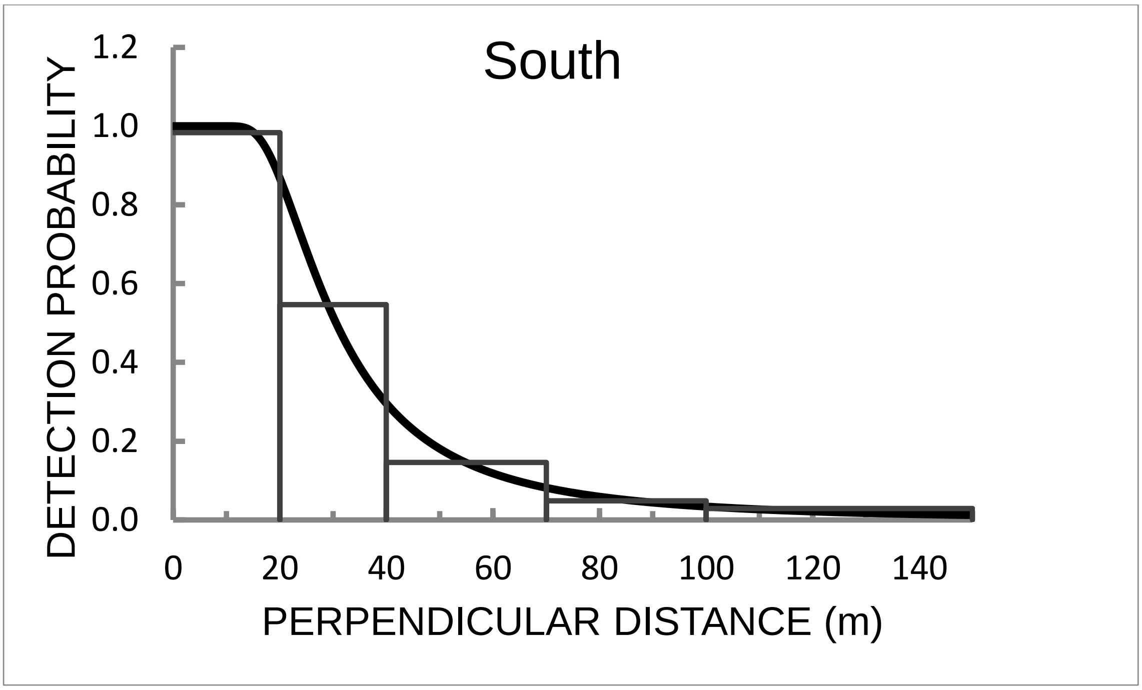
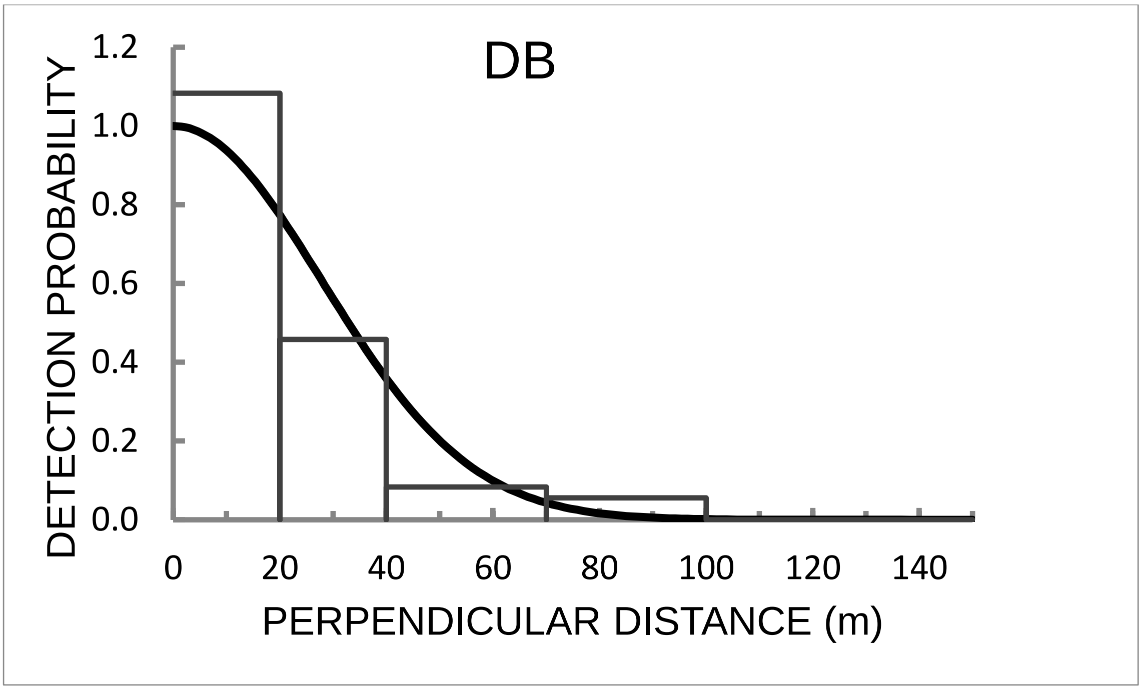
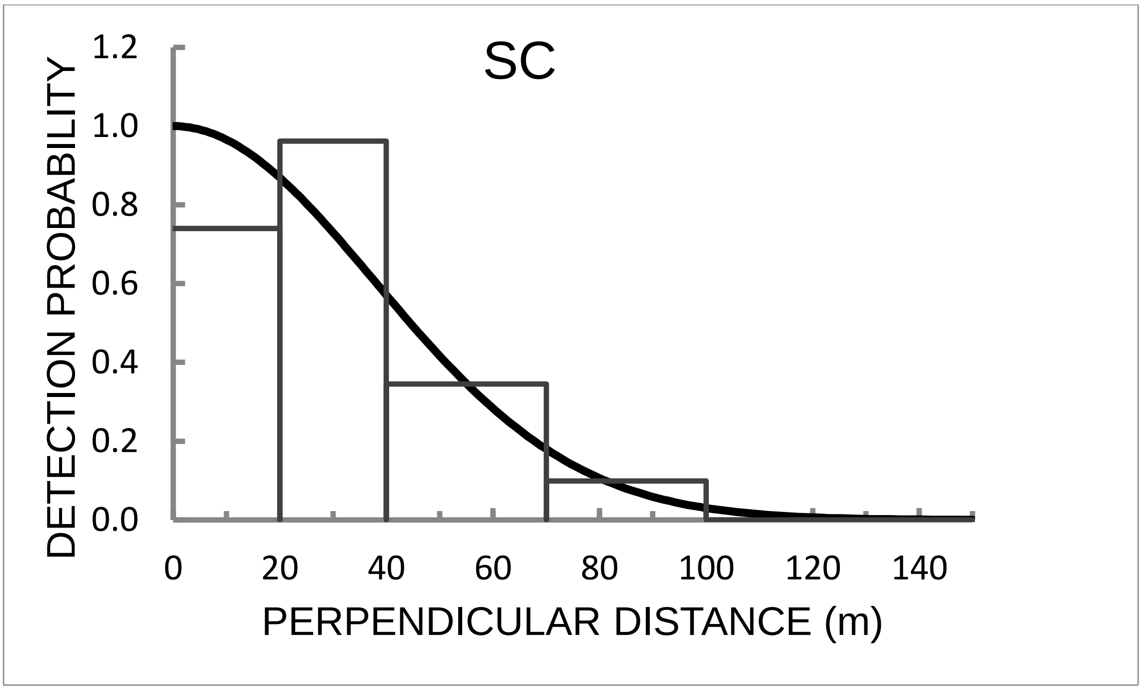


Fig. A1.4. The Hazard-rate detection functions for red-necked wallabies in the Central Tablelands North and Central Tablelands South kangaroo management zones. For details of the model fitted using the MCDS analysis engine with survey aspect as a covariate, see text.


DB
DETECTION PROBABILITY
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
140
PERPENDICULAR DISTANCE (m)


SC
DETECTION PROBABILITY
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
140
PERPENDICULAR DISTANCE (m)

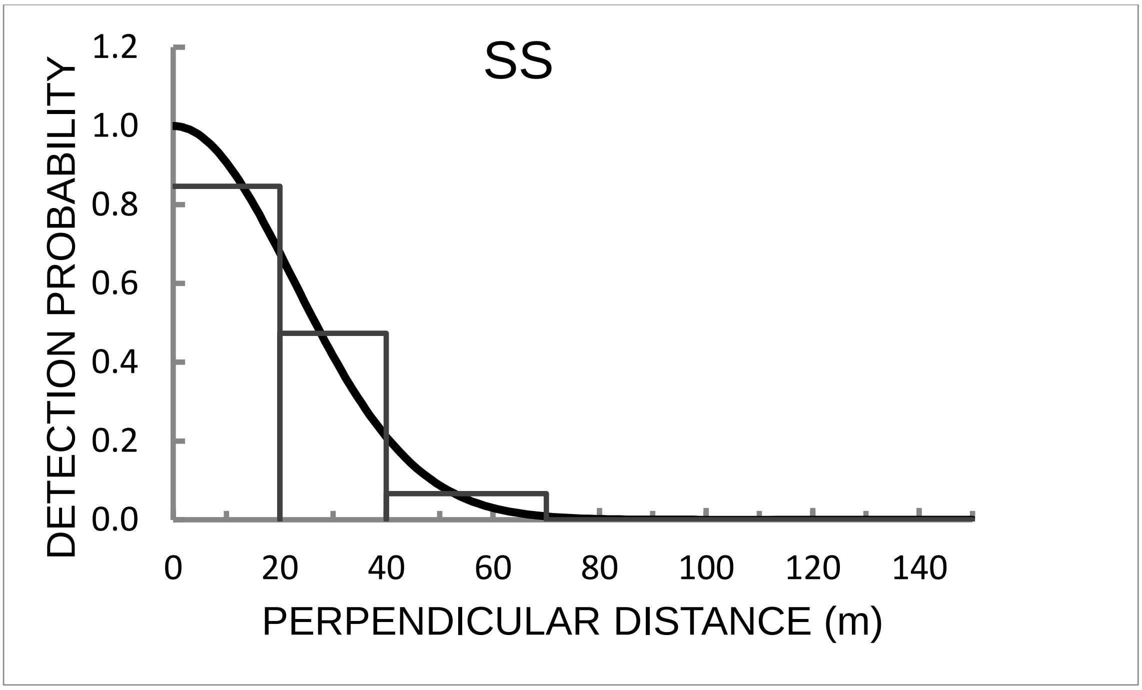


Fig. A1.5. The Half-normal detection functions for swamp wallabies in the Central Tablelands North and Central Tablelands South kangaroo management zones. For details of the model fitted using the MCDS analysis engine with observer as a covariate, see text.