A report to the Biodiversity and Conservation Division, New South Wales Department of Planning, Industry and Environment on the consultancy: “Design and analysis of helicopter surveys of kangaroo populations in the Central Tablelands North and Central Tablelands South kangaroo management zones, 2020”.

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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 and 2017.
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 probably 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 7.3 (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 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 10-15%.
4. These surveys provided sufficient data to provide 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 31.9 km^{-2} in the Central Tablelands North management zone and 25.2 km^{-2} in the Central Tablelands South management zone. These densities correspond to population estimates of 777,350 and 488,270 kangaroos, respectively for each of these management zones.
6. Between 2017 and 2020, the eastern grey kangaroo population in the Central Tablelands North management zone declined annually by 24%, while in the Central Tablelands South management zone the population declined annually by 19%.
7. The densities of common wallaroos were 5.3 km^{-2} in the Central Tablelands North zone and 3.0 km^{-2} in the Central Tablelands South zone. The densities of the two smaller macropods, the red-necked wallabies and swamp wallabies were of the order of 0.3-1.8 km^{-2}.

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 1998). Commercial harvesting is undertaken in Queensland, New South Wales, South Australia, Western Australia and Tasmania. In Tasmania, only one of the four large species of kangaroo is endemic 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 Victoria, the Australian Capital Territory or the Northern Territory.

In those states where it occurs, 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 1998). 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 (*Macropus rufus*), the eastern grey kangaroo (*M. giganteus*), the western grey kangaroo (*M. fuliginosus*) and the common wallaroo (*M. robustus robustus*) are currently harvested from within 14 kangaroo management zones (Anon. 2016). 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 eight inland kangaroo management zones (see Fig. 1), annual population estimates are obtained from aerial surveys conducted using fixed-wing aircraft (Anon. 2016). 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. 2016).

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 (Anon. 2016; Cairns, Bearup & Lollback 2020), the two in the Central Tablelands region (Anon. 2016; Cairns, Bearup & Lollback 2018) and the single Southeastern NSW zone (Anon. 2016; Cairns, Bearup & Lollback 2019). 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 (Cairns, Bearup & Lollback 2018). Reported here are the design of the survey, the survey method and method of data analysis used, and the results of a fifth helicopter line transect survey conducted in the two Central Tablelands management zones in September, 2020.

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 and Central Tablelands South.

The Central Tablelands North zone extends south from Liverpool Range that marks its boundary with the Upper Hunter kangaroo management zone 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, 151º 9’ 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; its western boundary being southwest of the township of Wellington (32º 33’ 20” S, 148º 56’ 35” E).

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 falls within the Hunter subregion of the Sydney Basin Biogeographic Region (IBRA) (Sahukar *et al.* 2003). In the west, it falls 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 2020).

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. Its eastern boundary lays 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, 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).

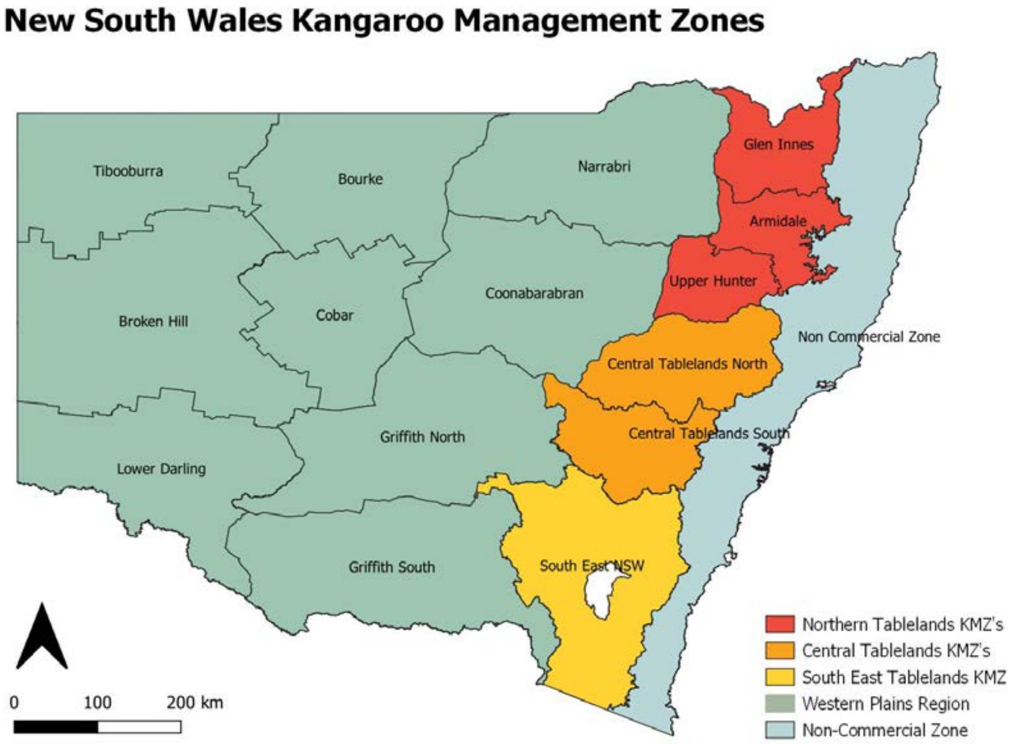

Fig. 1. The 15 kangaroo management zones administered by NSW DPIE. The two Central Tablelands kangaroo management zones are identified as Central Tablelands North and Central Tablelands South.

The Central Tablelands South zone takes in parts of two biogeographic regions. In the east, it falls within the South Eastern Highlands Biogeographic Region (IBRA), while in the west it falls 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 comprise 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.

For the purposes of designing and conducting kangaroo surveys, those parts of the two 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 survey areas. The remaining areas were divided on the basis of whether they supported medium or high densities of kangaroos. 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), and the most recent aerial surveys conducted in the Northern Tablelands kangaroo management zones (Cairns, Bearup & Lollback 2020) and the Southeastern NSW kangaroo management zone (Cairns, Bearup & Lollback 2019), 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 7.3. To facilitate this process, kangaroo density strata within each of the two management zones needed to be defined and the required survey effort 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 OEH. 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. Land capability 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 strata were modified in relation to available kangaroo density and raw count information, and redigitised to create final, simpler versions of the three density strata within each of the two zones. Stratification of the two management zones was initially undertaken for the first kangaroo surveys of these zones conducted in 2008 (Cairns, Lollback & Bearup 2009). The outcomes of the 2008 survey and the 2011 survey (Cairns & Bearup 2012) confirmed the broad basis of the stratifications.

Table 1. Areas (km^2) of the two Central Tablelands kangaroo management zones (KMZ) divided into three survey strata based upon land capability attributes and nominal high, medium and low kangaroo densities. Survey area comprises the medium and high density strata.

Stratum	Kangaroo management zone	
	Central Tablelands North	Central Tablelands South
Total zone 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

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 was divided for the purpose survey design into two sub-strata of approximately equal in area which were identified as Mudgee-medium (7,396 km^2) and Hunter-medium (7,006 km^2). A large tract of land dominated by open cast coal mining was excluded from the Hunter-medium sub-stratum. In the Central Tablelands South zone, this 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.

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 2018). 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%, while for the two medium density sub-strata the level of precision used was 22.5%. 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 22.5%. To determine the survey effort required, the method proposed by Buckland *et al.* (2001, p. 243) was used in relation to the precision (coefficient of determination) of the surveys completed in 2014 (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 strata 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.

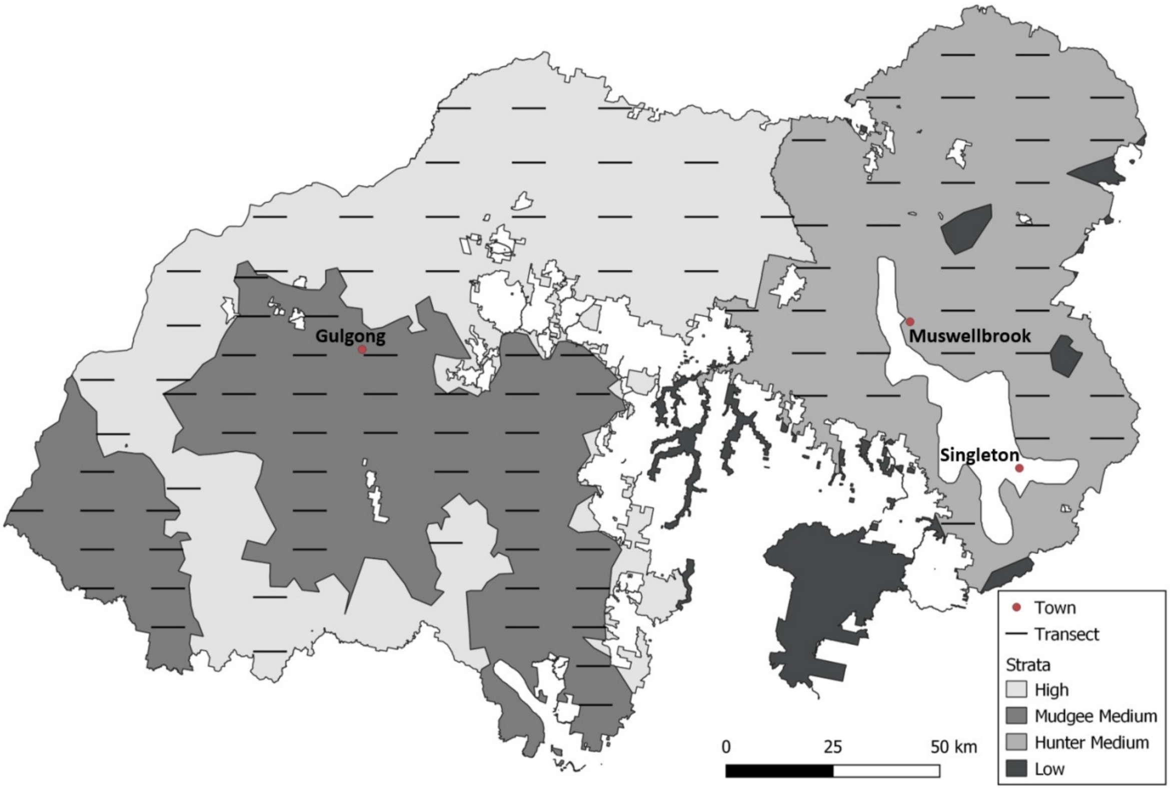

Fig. 2. The Central Tablelands North kangaroo management zone. Shown are the three survey strata; the medium kangaroo density stratum in this case being divided two sub-strata: Mudgee-medium in the central and western parts of the zone (left) and Hunter-medium in the east of the zone (to the right). 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.

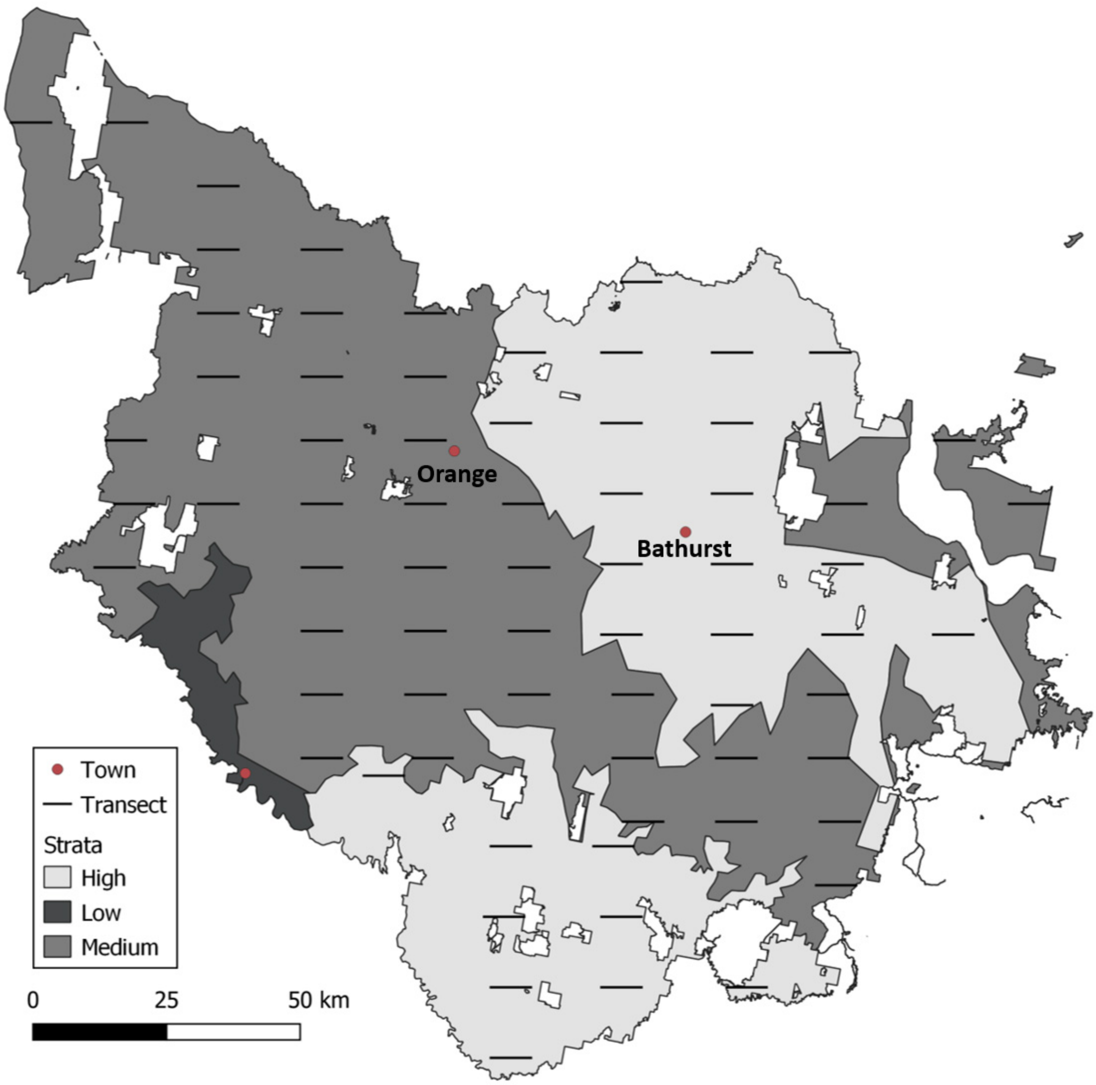

Fig. 3. The Central Tablelands South kangaroo management zone. Shown are the three survey strata, the population centres (towns) and the placement of the survey transects within the high and medium kangaroo density strata. Note that no survey transects were placed into the low density stratum.

Table 2. The nominal survey efforts determined for a specified coefficient of variation using the method give in Buckland *et al.* (2001) and the actual survey efforts applied during the survey.

Survey stratum	Nominal survey effort (km)	Actual survey effort (km)
<u>Central Tablelands North</u>		
High	217.5	210.0
Mudgee-medium	330.0	330.0
Hunter-medium	262.5	247.5
<u>Central Tablelands South</u>		
High	202.5	210.0
Medium	322.5	315.0

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 7.3 (Thomas *et al.* 2010) increases the likelihood that an optimal design will be achieved (Strindberg, Buckland & Thomas 2004).

DISTANCE 7.3 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 Buckland *et al.* (2001) and Strindberg, Buckland & 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 or systematic segmented trackline sampling 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 in a 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). Inclusion of a buffer 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 of 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 these five surveys, a series of 999 simulations was run in relation to a 1-km square coverage grid to assess the coverage probability 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, the ones considered to provide the best coverage probability, were, in all instances, designs based upon systematic segmented grid sampling. All selected designs comprised fixed length rather than split samplers. The actual survey efforts of the realised survey designs are given in Table 2.

For each stratum to be surveyed, all samplers (transects) were of a fixed 7.5 km in length. For the Central Tablelands North zone, the selected survey designs comprised 29 transects in the Mudgee-high stratum, 44 transects in the Mudgee-medium stratum and 35 transects in the Hunter-medium stratum (Fig. 2). For the Central Tablelands South zone, the selected survey designs comprised 28 transects in the high density stratum and 44 transects in the medium density stratum (Fig. 3). Corresponding map representations of the survey designs shown in Figs. 2-3 are shown in Appendix 1, Figs. A1.1-1.2.

4. Survey Methods

The aerial surveys of the Central Tablelands North and Central Tablelands South kangaroo management zones were conducted as helicopter surveys during the period 8-16 September, 2020. 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.

For logistical reasons, not allocated transects were flown during the survey. In the Central Tablelands North zone (KMZ 48), 28 of the allocated 29 transects were flown in the high density stratum, all 44 allocated transects were flown in the Mudgee-medium stratum and 33 of the allocated 35 transects were flown in the Hunter-medium stratum. In the Central Tablelands South zone (KMZ 49), the 28 allocated transects were all flown in the high density stratum, while 42 of the 43 allocated transects were flown in the medium density stratum.

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. Tate Steen was the pilot.

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 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.

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 from the helicopter 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. 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.

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, $0 \leq x \leq w$ and $g(0) = 1$) needs to be modelled and evaluated at $x = 0$, directly on the transect line (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 horses in this instance, should be 60-80 for reliable modelling of the detection function.

The survey results from each kangaroo management zone were analysed separately. 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 *et al.* 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 model and, hence, which were the most likely and accurate estimates of population density and abundance. 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, 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 (s) are independent of distance from the transect line (i.e. if *g(x)* does not depend upon *s*), then the sample mean cluster size is taken as an unbiased estimator of the mean size of the *n* 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 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, using only the CDS analysis engine.

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 stratum was assumed to support fewer than trace numbers of kangaroos and was, 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), 28 comprising 210 km of survey effort were flown across the high density stratum. A total of 691 eastern grey kangaroos were counted on these transects, along with 54 wallaroos. Of the other species of macropod present, there were 11 red-necked wallabies (*Macropus rufogriseus*) and nine swamp wallabies (*Wallabia bicolor*) counted. Forty-four transects comprising 330 km of survey effort were flown across the Mudgee-medium stratum. A total of 1,070 eastern grey kangaroos were counted on these transects, along with 48 wallaroos, 28 red-necked wallabies and 18 swamp wallabies. Thirty-three transects comprising 247.5 km of survey effort were flown across the Hunter-medium stratum. A total of 1,145 eastern grey kangaroos were counted on these transects, along with 125 wallaroos, 50 red-necked wallabies and 34 swamp wallabies. As well as the macropods counted across these three strata, there were also 393 feral goats (*Capra hircus*), 148 feral pigs (*Sus scrofa*) and 109 deer counted. With regard to the macropods, this raw survey information is summarised in Table 3.

In the Central Tablelands South zone (Zone 49, Fig. 1), 28 transects comprising 210 km of survey effort were flown across the high density stratum. A total of 803 eastern grey kangaroos were counted on these transects, along with 42 wallaroos, 9 red-necked wallabies and 10 swamp wallabies. Forty-two transects comprising 315 km of survey effort were flown across the medium density stratum of this zone. A total of 916 eastern grey kangaroos were counted on these transects, along with 41 wallaroos, five red-necked wallabies and six swamp wallabies. As well as the macropods counted across these two strata, there were also 261 feral goats, 19 feral pigs and 23 deer counted. With regard to the macropods, this raw survey information is summarised in Table 3.

Table 3. Number of transects flown, total survey effort (km) and 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	28	210.0	691	54	11	9
Mudgee-medium	7,396	44	330.0	1,070	48	28	18
Hunter-medium	7,006	33	247.5	1,145	125	50	34
Central Tablelands South							
High	7,974	28	210.0	803	42	9	10
Medium	10,917	42	315.0	916	41	5	6

5.2 Line Transect Analysis

To estimate the population densities and abundances of kangaroos and wallabies, the counts of clusters of the various species were grouped into the five distance categories set on the survey booms (Fig. 4). The method of analysis used to determine densities and abundances conformed to a general and well-understood framework for analysing distance sampling data, as presented in Buckland *et al.* (2001). Key to the analysis is the modelling of the detection of clusters of kangaroos (macropods) in relation to at least one covariate, the perpendicular distance from the 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 AIC statistics (see Section 4.2). Where feasible, the data were analysed in relation to each survey stratum within the two kangaroo management zones and the results combined to produce whole-zone population and then density estimates. Otherwise, the data were analysed on a whole management zone basis; the survey stratification being discounted. Population estimates were determined for eastern grey kangaroos, wallaroos, red-necked wallabies and swamp wallabies in the both the Central Tablelands North management zone and Central Tablelands South zone.

With these analyses, the most parsimonious (specific) detection function model was selected principally on the basis of it being the one that yielded the smallest value of the AIC statistic. The overall model selection process is comparative. 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 it being on unknown interval scale that lacks a true zero (Burnham & Anderson 2002). For a given model, the value of the AIC is only comparative, relative to other AIC values in the model set tested. Hence, it is the AIC differences (ΔAIC) that are important. In comparing any two models, when $\Delta AIC > 2$, the interpretation is that there is increasing 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 of this is that when $\Delta AIC < 2$, then it can be thought that there is 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. For further information on the use of AICs 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. In the Central Tablelands North management zone, a model with separate detection functions for each of the three strata surveyed proved to be a better option than a model with a global detection function (ΔAIC = 5.81). By way of further comparison, the difference between the final CDS-derived model and an MCDS-derived model was quite substantial (ΔAIC = 11.86). The final model option selected points to landscape-specific differences in sightability of eastern grey kangaroos across the strata of the management zone, which would not be the case with a global detection function model.

In the Central Tablelands South management zone, an MCDS-derived model with global Half-normal detection function and a single observer covariate proved to be a far better option than a model with separate CDS-derived detection functions for each of the two survey strata (ΔAIC = 35.35). The selection of this model implies a consistent, but observer-specific, sightability of eastern grey kangaroos across the landscapes of this management zone. The general forms of the detection functions for eastern grey kangaroos in the two management zones are shown in Appendix 2, Figs. A2.1-A2.4. Although not shown in Fig. A2.4, it should be noted that the inclusion of observer as a covariate in a model 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 the encounter rates (n/L), probabilities (P_a) that a randomly selected cluster of kangaroos in the nominal survey strip (150 m) will be detected and the associated effective strip (half-) widths (μ). The encounter rate, the number of clusters of kangaroos detected per unit (km) of survey effort is, in some respects, a more informative statistic than is n itself (Buckland *et al*. 2001). Encounter rate variance usually dominates the overall variance of object (kangaroo) density. While P_a is required as part of the estimation process, both these statistics can be viewed as indicators of the interaction between the subjects of the survey, the landscape

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). MCDS is the multiple covariates distance sampling analysis engine. The detection functions have either been determined globally across the survey strata of a KMZ or, alternatively, separately for each stratum. Given also are the encounter rate (n/L), the probability that a cluster of kangaroos present on the survey strip is detected (P_a) and the effective strip width (μ).

KMZ/stratum	n	Analysis engine	Detection function	Model	Covariates	n/L	P_a	μ (m)
Central Tablelands North								
High	224	CDS	Stratified	Half-normal/Cosine	–	1.07	0.32	48.3
Mudgee-medium	295	CDS	Stratified	Half-normal/Cosine	–	0.89	0.30	45.5
Hunter-medium	447	CDS	Stratified	Half-normal/Cosine	–	1.81	0.32	48.0
Central Tablelands South								
High	261	MCDS	Global	Half-normal	Observer	1.24	0.31	47.0
Medium	270	MCDS	Global	Half-normal	Observer	0.86	0.36	53.8

they occupy and the observers and conditions on the survey platform. They would therefore have some comparative value.

Although the encounter rates were generally higher in the high density strata than in the medium density strata, the Hunter-medium stratum in the eastern, more developed part of the Central Tablelands North management zone had by far the highest encounter rate for eastern grey kangaroos. The probability (P_a) that a cluster of eastern grey kangaroos in the survey strip will be detected showed little variation across the two management zones; being in the range 0.30-0.36, with a median value of 0.32. These probabilities were higher than they were for the 2017 survey, where they were in the range 0.24-0.29 (Cairns, Bearup & Lollbeck 2018) but lower than they were for the surveys conducted in these two management zones in 2011 (Cairns & Bearup 2012) and 2014 (Cairns, Bearup & Lollback 2015). The associated statistic, the effective strip width (μ), is interpreted as the perpendicular distance from the transect centreline (i.e. the half-strip width) for which as many animals (kangaroos) are detected beyond that distance as remain undetected within that distance (Buckland *et al.* 2001). Hence, a line transect survey can be thought of as effectively covering a survey strip of a total area of 2Lμ, for some value of $\mu \leq W$ and length L (Borchers and Burnham 2004). Another way of interpreting this is: if all the animals on the survey strip were to be detected, this could only be possible if the width of the survey strip (W) was equivalent to the effective strip width (μ) on either side of the transect centreline. By virtue of the way μ is determined ($\mu = W \times P_a$; where W is the nominal strip width of the survey transect), the higher the value of P_a, the wider will be the effective strip width. The effective strip widths determined in relation to the results of these surveys ranged from 46 m to 54 m; wider than the effective strip widths from previous survey (Cairns, Bearup & Lollbeck 2018).

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 (specific) 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 Half-normal/Cosine model, is given along with its associated statistics in Table 5. The general forms of the Half-normal/Cosine detection function for wallaroos is shown in Appendix 2, Fig. A2.5.

Table 5. The survey effort, number of sightings of clusters of animals (n), DISTANCE 7.3 analysis engine used (see text), the detection function model, the encounter rate (n/L), the probability that a randomly-selected cluster of animals in the survey strip is detected (P_a) and the effective strip width (ESW) 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.

Kangaroo management zone	Effort (km)	n	Analysis engine	Model	n/L	P_a	ESW
Central Tablelands North	787.5						
Wallaroos		120	CDS	Half-normal/Cosine	0.15	0.32	47.6
Red-necked wallabies		65	CDS	Hazard-rate/Cosine	0.08	0.21	32.0
Swamp wallabies		52	CDS	Hazard-rate/Polynomial	0.07	0.25	37.5
Central Tablelands South	525.0						
Wallaroos		38	CDS	Half-normal/Cosine	0.07	0.32	47.6
Red-necked wallabies		10	CDS	Hazard-rate/Cosine	0.02	0.21	32.0
Swamp wallabies		15	CDS	Hazard-rate/Polynomial	0.03	0.25	37.5

In relation to the detection function model for wallaroos given in Table 5, are also estimates of encounter rates (n/L), the probability that a randomly selected cluster of wallaroos in the nominal survey strip will be detected (P_a) and the associated effective strip (half-) widths (μ). The encounter rates for wallaroos were 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 similar to those determined for eastern grey kangaroos, as were the corresponding values of the effective strip width (see Table 4).

As was the case for wallaroos, with too few sighting to allow separate analyses for each of the two management zones, global detection function models were fitted to the combined survey results for red-necked wallabies and swamp wallabies. The most parsimonious detection function model for red-necked wallabies was a Hazard-rate/Cosine model, while the most parsimonious model for swamp wallabies was a Hazard-rate/Polynomial model, respectively (Table 5). The forms of the detection function models are shown in Appendix 2, Figs. A2.6 and A2.7. Encounter rate for both these species was low, as were the estimates of P_a and the associated ESW (Table 5).

5.3 Population Estimates

The densities of clusters and corresponding population densities of eastern grey kangaroos within the survey strata of each of the two kangaroo management zone are given in Table 6. Bootstrap confidence intervals and coefficients of variation have been determined in relation to these densities. The precision of the estimates across the survey strata, as indicated by the coefficients of variation, were all considered to be near to or better than the overall target level of precision of 20%. Combining the strata estimates improved the precision of the estimates considerably (see Table 7). The density and abundance estimates for the eastern grey kangaroos in each of the survey strata of the two management zones, along with combined, whole-zone abundance estimates, are given in Table 7.

Table 6. Results of the helicopter line transect surveys of eastern grey kangaroos conducted in the Central Tablelands kangaroo management zones (KMZ) in September, 2020. 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 (%)
Central Tablelands North							
Mudgee-high	8,783	11.04	7.34 – 15.68	18.2	34.06	21.03 – 46.21	19.8
Mudgee-medium	7,396	9.84	6.52 – 13.72	19.8	24.71	16.38 – 35.94	19.4
Hunter-medium	7,006	18.80	13.86 – 23.63	13.6	42.17	30.96 – 52.95	13.9
Central Tablelands South							
High	7,974	13.23	8.93 – 18.02	17.8	33.14	21.50 – 47.25	19.9
Medium	10,917	7.97	5.28 – 11.53	19.4	20.52	13.30 – 30.10	20.7

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	D (km^{-2})	95% bootstrap confidence interval	N	95% bootstrap confidence interval	CV (%)
Central Tablelands North					
High	34.06	21.03 – 46.21	299,160	184,680 – 405,870	19.8
Mudgee-medium	24.71	16.38 – 35.94	182,770	121,130 – 260,010	19.4
Hunter-medium	42.17	30.96 – 52.95	295,420	216,930 – 370,960	13.9
			777,350	613,870 – 920, 250	10.3
Central Tablelands South					
High	33.14	21.50 – 47.25	264,050	171,450 – 396,930	19.9
Medium	20.52	13.30 – 30.10	224,050	145,240 – 328,660	20.7
			488,270	359,770 – 639,560	14.7

In the Central Tablelands North zone, the highest eastern grey kangaroo density was in the Hunter-medium stratum. Relative densities in the three strata of this management zone show a degree of fluidity, with the highest density in 2017 occurring in the Mudgee-medium stratum (Cairns, Bearup & Lollback 2018) and in the high density stratum in 2014 (Cairns, Bearup & Lollback 2015). In the Central Tablelands South zone the density of eastern grey kangaroos in the high density stratum was similar to that of the density in the medium density strata. In 2017, the density of kangaroos in the high density stratum was broadly twice that in the medium density stratum. This was similar to what was previously found with the 2014 survey.

In comparison with the population estimates for 2017, which were particularly high, the number of eastern grey kangaroos in the Central Tablelands North zone showed a significant 55% decrease ($z = 3.50$; $P < 0.001$) over the three years to

2020. This decline in numbers has followed on from a previous estimated 60% increase in numbers between 2014 and 2017, which had compounded earlier increases of a substantial 95% between 2011 and 2014,and 40% between 2008 and 2011 (Cairns, Lollback & Bearup 2009; Cairns & Bearup 2012; Cairns, Bearup & Lollback 2015, 2018).

In the Central Tablelands South zone, the eastern grey kangaroo population showed a similar, significant 48% decrease in numbers (z = 2.66; P = 0.008) over the three year period from 2017 to 2020. This decline in numbers has followed on from an estimated 30% increase between 2014 and 2017, which had compounded earlier increases in numbers of a substantial 130% between 2011 and 2014. (Cairns & Lollback 2009; Cairns & Bearup 2012; Cairns, Bearup & Lollback 2015, 2018). This sequence of increases had followed on from a 35% decline in numbers that had occurred between 2008 and 2011 (Cairns & Bearup 2012). At the level of individual survey stratum, these proportional changes in numbers were particularly variable when determined across the three successive survey periods.

Another way of understanding the broader dynamics of the changes in eastern grey kangaroo numbers that have occurred in these management zones over the 12-year period since aerial surveys were first undertaken in 2008 is to consider them in terms of the their finite rates of population increase (λ). Considered on an annual basis, this statistic is a compound multiplier that represents the rate at which a population would increase each year (Krebs 1994).

From the results of the four successive surveys that have been conducted in the two Central Tablelands management zones over the period 2008-2017, the rates increase (λ) for eastern grey kangaroo populations appeared to be quite different, both spatially and temporally. However, further analysis shows that, statistically, there is no difference between the rates of increase of the populations in the two management zones ($F_{1,5}$ = 3.06; P = 0.14). 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, for every individual present in a given year, there will be 1.151 individuals present the following year. At this rate of increase, these two populations currently have a doubling time of approximately five years. This almost certainly represented a trajectory that would be, in the long run, unsustainable.

By way of comparison, this annual finite rate of increase was 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 2016). However, both rates of population increase are considered to be 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 the tablelands of NSW.

Between 2017 and 2020, the populations in the two management zones declined sharply (see above). The annual finite rate of increase (decrease) for two eastern grey kangaroo 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 represent successive annual declines in numbers of 23% and 19%, respectively. In relation to this, it should be noted that most of NSW, including the Central Tablelands and Hunter regions, had been in continuing drought since mid-2017 until early this year. This event might well have contributed substantially to marked decline in the eastern grey kangaroo populations in these two kangaroo management zones through its effect on the herbivore resource base.

The densities of wallaroos within the survey strata of each of the two kangaroo management zones are given in Table 8. The precision of estimation was somewhat lower in the Central Tablelands South zone than in the Central Tablelands North zone, where it was comparable to the precision of the estimates of eastern grey kangaroo numbers (Table 6). In both these management zones, the wallaroo densities were substantially lower than were the estimates obtained from the surveys conducted in 2017 (Cairns, Bearup & Lollback 2018); being down by up to 75%.

The sightability of wallaroos in relation to helicopter line transect surveys has been reported to be lower than it is for eastern grey kangaroos. 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 (*M. 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, the subsequent estimates of whole-zone wallaroo densities and abundances are corrected (x1.85) estimates. The population abundances of wallaroos in the two management zones are given in Table 9.

Table 8. The number of sightings (n), density of clusters of animals sighted (D_s) and population density (D).for 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 two density estimates are the bootstrap confidence intervals and coefficients of variation (CV %). Details of the most parsimonious detection function models used to determine these densities are given in Table 7.

Kangaroo management zone	Kangaroo and wallaby densities (km^{-2})					
	D_s	95% bootstrap confidence interval	CV (%)	D	95% bootstrap confidence interval	CV (%)
Central Tablelands North						
Wallaroos	1.60	1.04 – 2.30	19.9	3.04	1.86 – 4.12	20.9
Red-necked wallabies	1.29	0.83 – 2.00	26.3	1.76	1.09 – 2.56	25.6
Swamp wallabies	0.88	0.52 – 1.34	23.4	1.07	0.59 – 1.62	24.5
Central Tablelands South						
Wallaroos	0.76	0.37 – 01.25	30.1	1.66	0.70 – 2.83	33.2
Red-necked wallabies	0.30	0.13 – 0.53	34.3	0.32	0.13 – 0.57	37.3
Swamp wallabies	0.38	0.21 – 0.57	25.0	0.41	0.22 – 0.62	25.7

The sightability of wallaroos in relation to helicopter line transect surveys has been reported to be lower than it is for eastern grey kangaroos. 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 (*M. 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, the subsequent estimates of whole-zone wallaroo densities and abundances are corrected (x1.85) estimates. The population abundances of wallaroos in the two management zones are given in Table 9.

Table 9. Estimated whole-zone total abundances (N) and population densities (D) of eastern grey kangaroos and common wallaroos in the Central Tablelands North and Central Tablelands South kangaroo management zones. Given in association of these estimates are the combined areas of the three survey strata within each kangaroo management zone. The numbers for common wallaroos have been corrected by a multiple of 1.85 (see text).

Kangaroo management zone	Area (km^2)	Eastern grey kangaroos N	Eastern grey kangaroos D (km^{-2})	Common wallaroos N	Common wallaroos D (km^{-2})
Central Tablelands North	24,396	777,350	31.86	130,390	5.34
Central Tablelands South	19,361	488,270	25.22	58,020	3.00

The densities of both red-necked wallabies and swamp wallabies were substantially lower than those of wallaroos, which, in turn, were again substantially lower than those of eastern grey kangaroos (see Table 6). 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 whole-zone population estimates of abundances and densities of eastern grey kangaroos and wallaroos in the two management zones are given in Table 9. Management zone densities were determined in relation to the area of all three 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 support larger, higher density populations of eastern grey kangaroos than do the three Northern Tablelands management zones (see Table 10, Cairns, Bearup & Lollback 2020) and the South East NSW management zone (see Table 7, Cairns, Bearup & Lollback 2019).

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 10-21% (Table 7), this aim was easily achieved with the surveys designed for each of the two management zones. For wallaroos, a species that is not harvested commercially in either of the Central Tablelands management zones, the attained levels of precision were relatively low, with coefficients of variation of 21-33% (Table 8).

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7. References

Anon. (2016). *New South Wales Commercial Kangaroo Management Plan 2017-2021*. Department of Environment and Conservation. 32 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., 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. & Bearup, D. (2012). *A report to the New South Wales Office of Environment and Heritage on the consultancy: Design and analysis of helicopter surveys of kangaroo populations in the Central Tablelands North and South management zones.* Unpublished report to the Office of Environment and Heritage (NSW), Dubbo, NSW. 46 pp.

Cairns, S. C., Bearup, D. & Lollback, G. (2015). *A report to the New South Wales Office of Environment and Heritage (NSW) on the consultancy: Design and analysis of helicopter surveys of the kangaroo populations in the Central Tablelands kangaroo management zones, 2014.* Unpublished report to New South Wales Department of Environment and Climate Change, Dubbo, NSW. 50 pp.

Cairns, S. C., Bearup, D. & Lollback, G. (2018). *A report to the New South Wales Office of Environment and Heritage (NSW) on the consultancy: Design and analysis of helicopter surveys of the kangaroo populations in the Central Tablelands kangaroo management zones, 2017.* Unpublished report to New South Wales Department of Environment and Climate Change, Dubbo, NSW. 42 pp.

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

Cairns, S. C., Bearup, D. & Lollback, G. (2020). *A report to the Biodiversity and Conservation Division, New South Wales Department of Planning, Industry and Environment on the consultancy: "Design and analysis of helicopter surveys of the kangaroo populations of the Northern Tablelands kangaroo management zones, 2019* Unpublished report to New South Wales Department of Environment and Climate Change, Dubbo, NSW. 51 pp.

Cairns, S. C. & 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. and 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. (2009). *A report to the New South Wales Office of Environment and Heritage on the consultancy: Kangaroo Monitoring: Hunter and Central Tablelands Zones Design and Analysis of Helicopter Survey.* Unpublished report to New South Wales Department of Environment, Climate Change and Water, Dubbo, NSW. 43 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. and Gibson, L. A. (1997). Comparison of helicopter line transects with walked line transects for estimating densities of kangaroos. *Wildlife Research* **24**: 397-409*.*

Krebs, C. J. (1994). *Ecology: the experimental analysis of distribution and abundance*. 4th edition. Harper Collins

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.

Payne, N. (2007). *Population Monitoring Methods for the NSW Kangaroo Management Program.* Department of Environment and Conservation, NSW. 17 pp.

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. and Grigg, G. C. (1998). *Commercial harvesting of kangaroos in Australia.* Environment Australia, Canberra. Retrieved in February 2017 from http://www.environment.gov.au/node/16685

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

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., & Sheppard, N. (2000). Assessing harvested populations of the euro (*Macropus robustus erubescens*) in the Barrier Ranges of western NSW. *Australian Mammalogy* 21: 165-171.

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. & Stringberg, S. (2002). Distance sampling. In: *Encyclopaedia of Environmentrics* (eds. A. H. El-Shaarawi and W. W. Piegorsch). Volume 1, pp. 544-552.

Thomas, L., Laake, J.L., Rexstad, E., Strindberg, S., Marques, F.F.C., Buckland, S.T., Borchers, D.L., Anderson, D.R., Burnham, K.P., Burt, M.L., Hedley, S.L., Pollard, J.H., Bishop, J.R.B. & Marques, T.A. (2009). Distance 6.0. Release 2. Research Unit for Wildlife Population Assessment, University of St. Andrews, UK. http://www.ruwpa.st-and.ac.uk/distance/

Thomas, L., Buckland, S. T., Rexstad, E. A., Laake, J. L., Strindberg, S., Hedley, S. L., Bishop, J. R. B., Marques, T. A. & 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

Map representations of the stratification and the designs of the helicopter line transect surveys conducted in the two Central Tablelands kangaroo management zones.

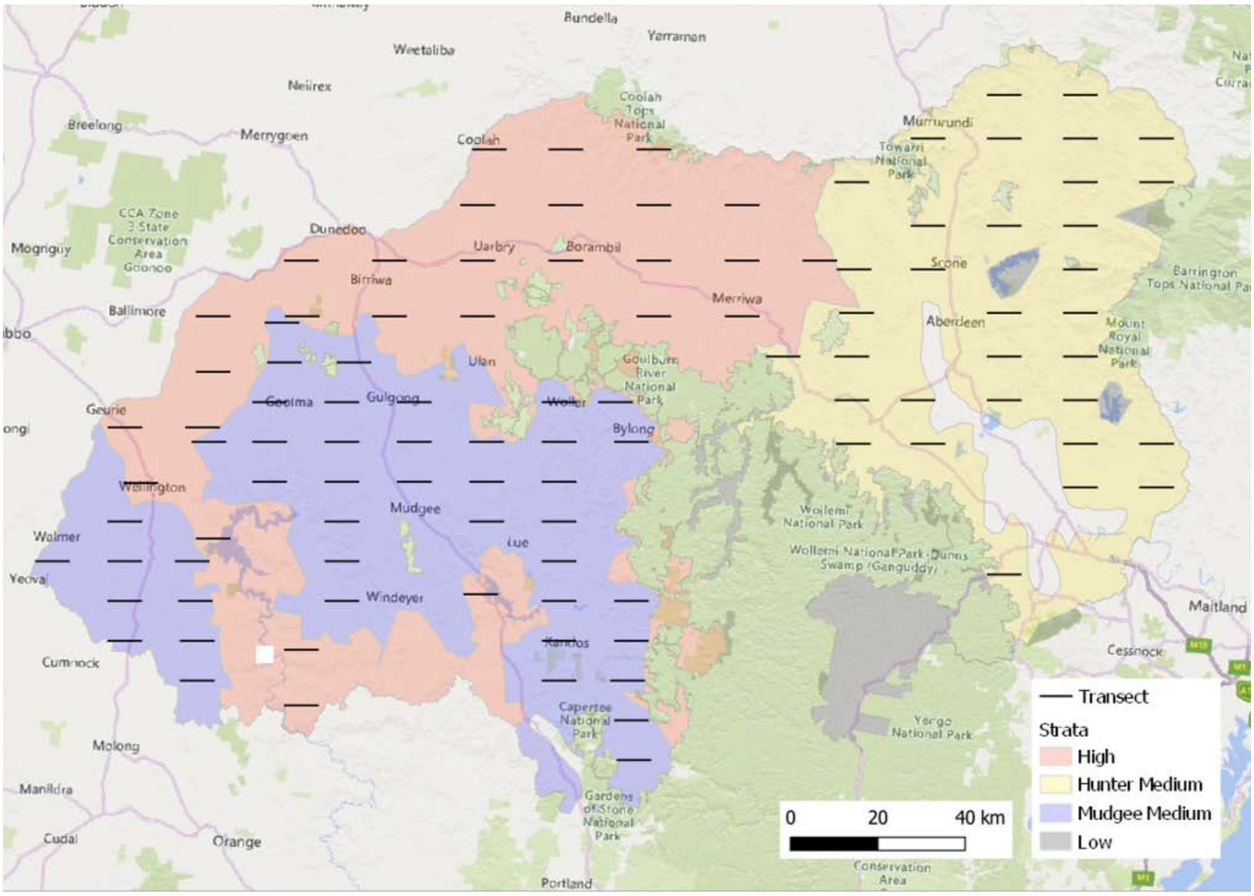

Fig. A1.1. The Central Tablelands North kangaroo management zone (KMZ 48). Shown are the four survey strata (see legend), national parks, state forests and urban consolidations not considered as part of the survey area, population centres (towns) and the placement of the survey transects in the high and medium kangaroo density strata.

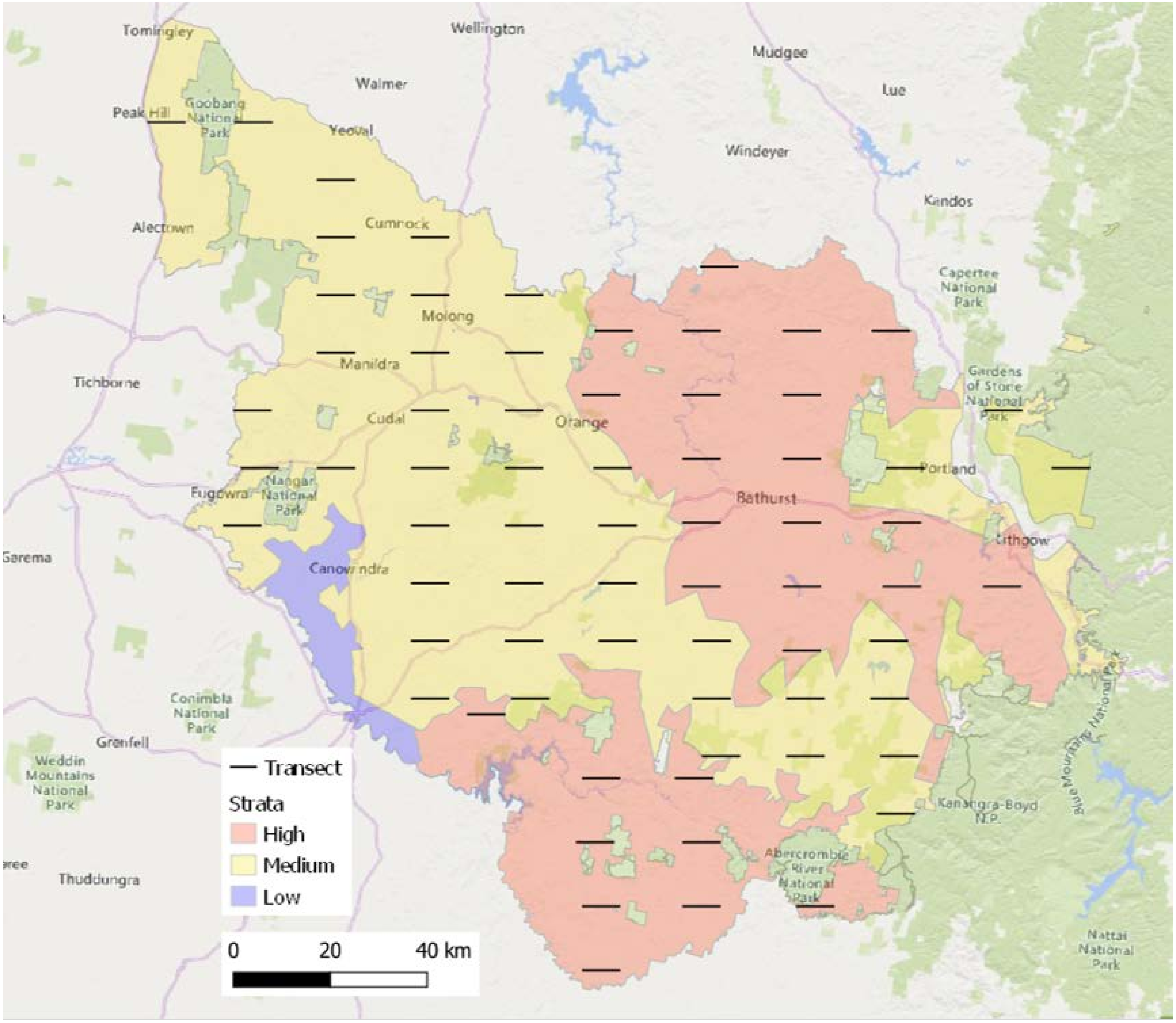

Fig. A1.2. The Central Tablelands South kangaroo management zone (KMZ 49). Shown are the three survey strata (see legend), national parks, state forests and urban consolidations not considered as part of the survey area, population centres (towns) and the placement of the survey transects in the high and medium kangaroo density strata.

Appendix 2

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

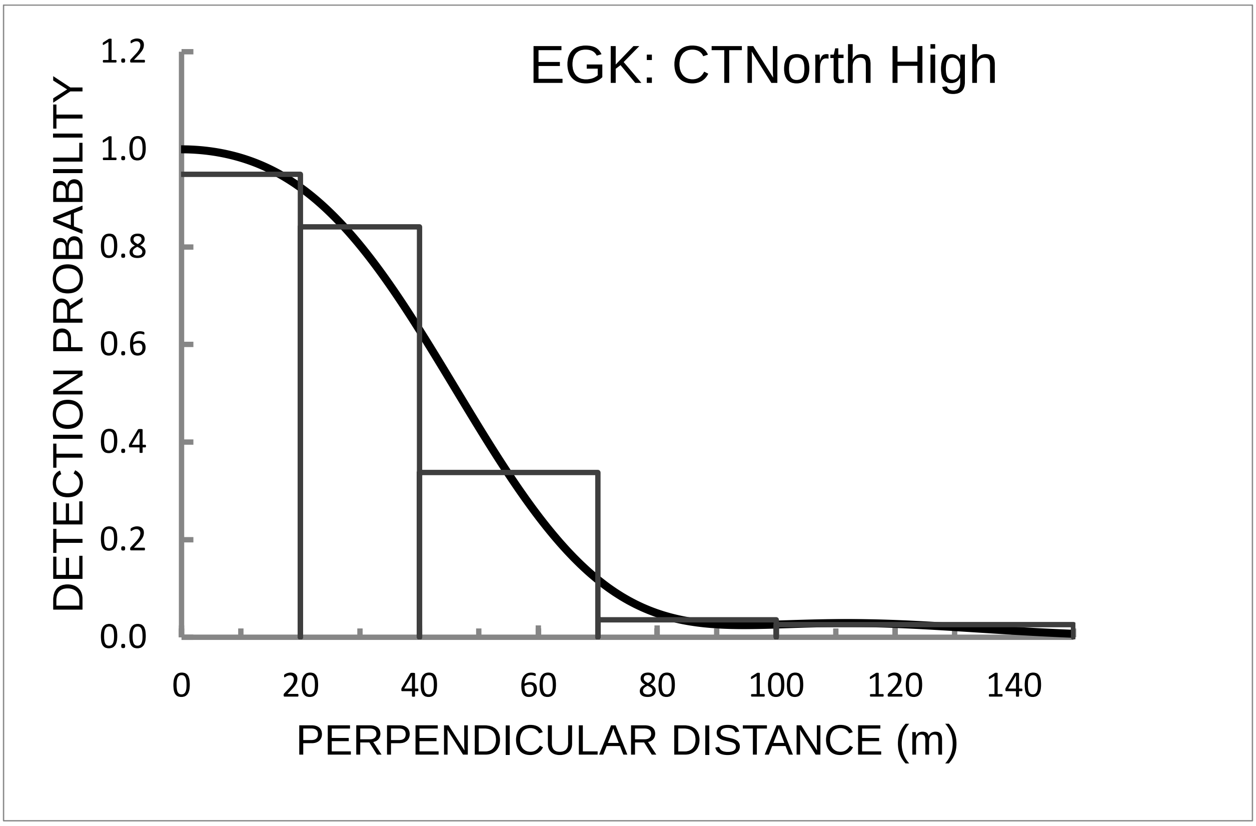

Fig. A2.1. The Half-normal/Cosine detection function for eastern grey kangaroos in the high density stratum of the Central Tableland North kangaroo management zone. For details of the model fitted using the CDS analysis engine, see text.

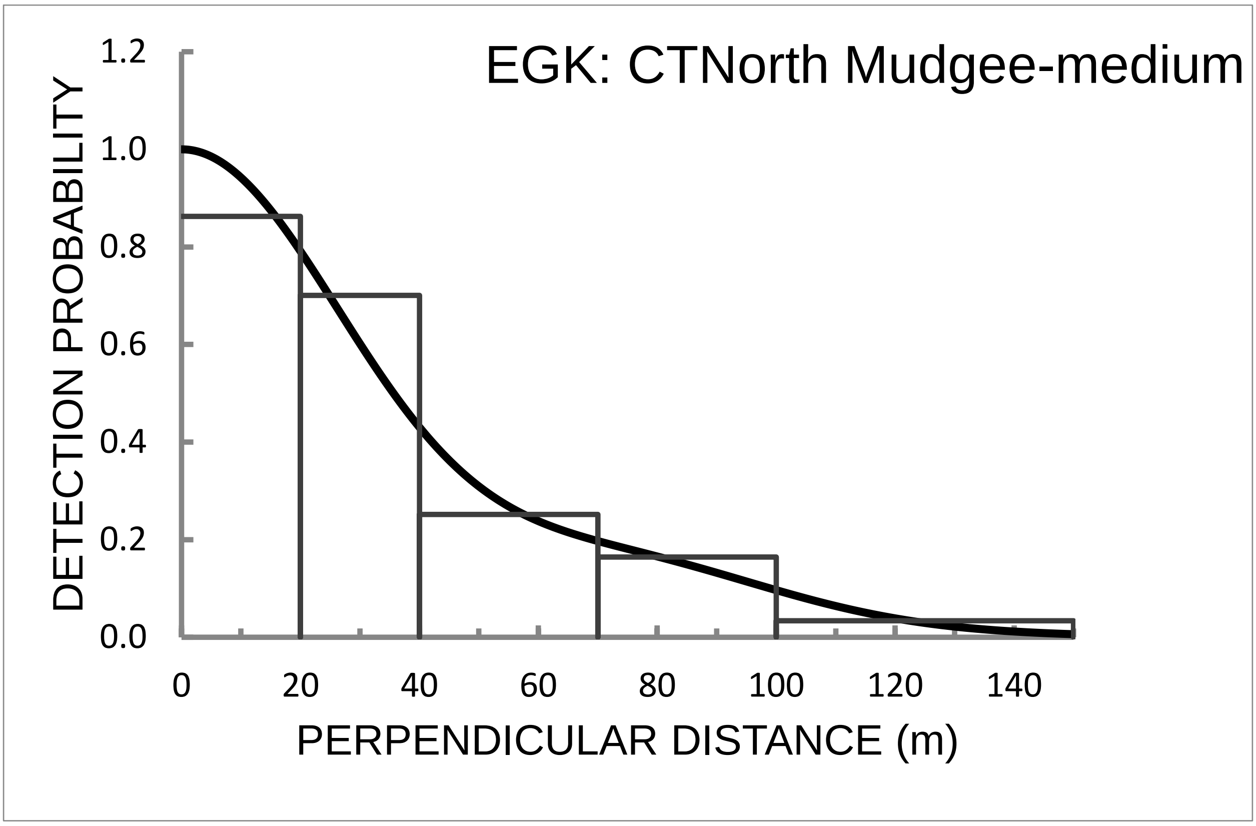

Fig. A2.2. The Half-normal/Cosine detection function for eastern grey kangaroos in the Mudgee medium density stratum of the Central Tableland North kangaroo management zone. For details of the model fitted using the CDS analysis engine, see text.

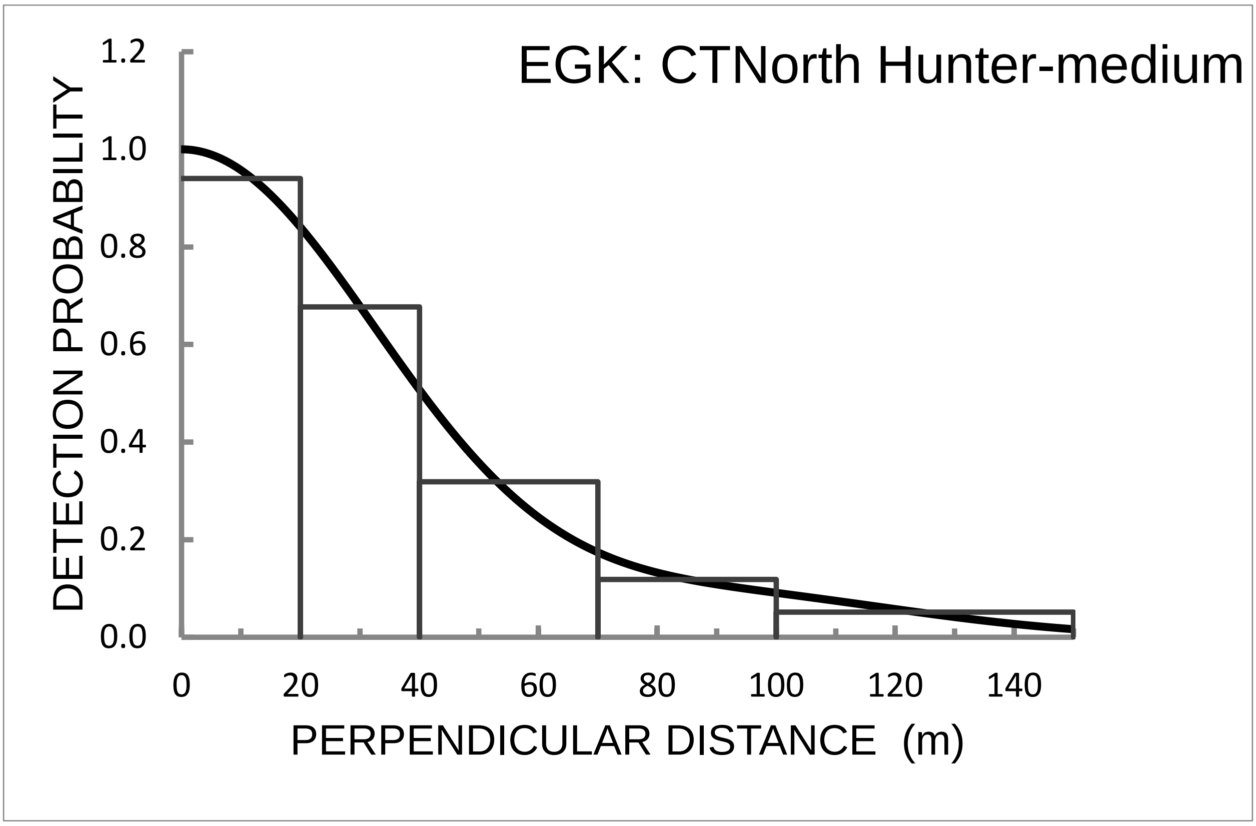

Fig. A2.3. The Half-normal/Cosine detection function for eastern grey kangaroos in the Hunter medium density stratum of the Central Tableland North kangaroo management zone. For details of the model fitted using the CDS analysis engine, see text.

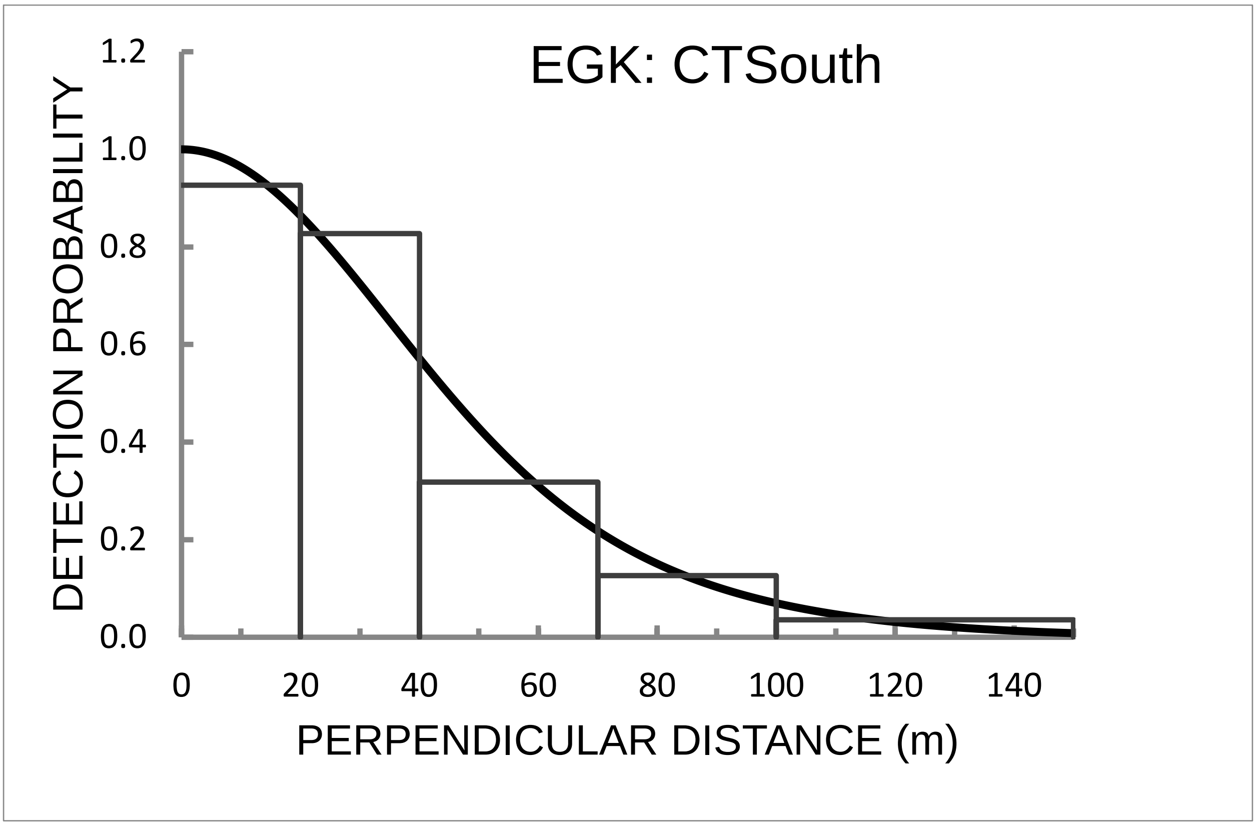

Fig. A2.4. The Half-normal detection functions for eastern grey kangaroos in the Central Tablelands South kangaroo management zone. For details of the model fitted using the MCDS analysis engine with Observer as a covariate, see text.

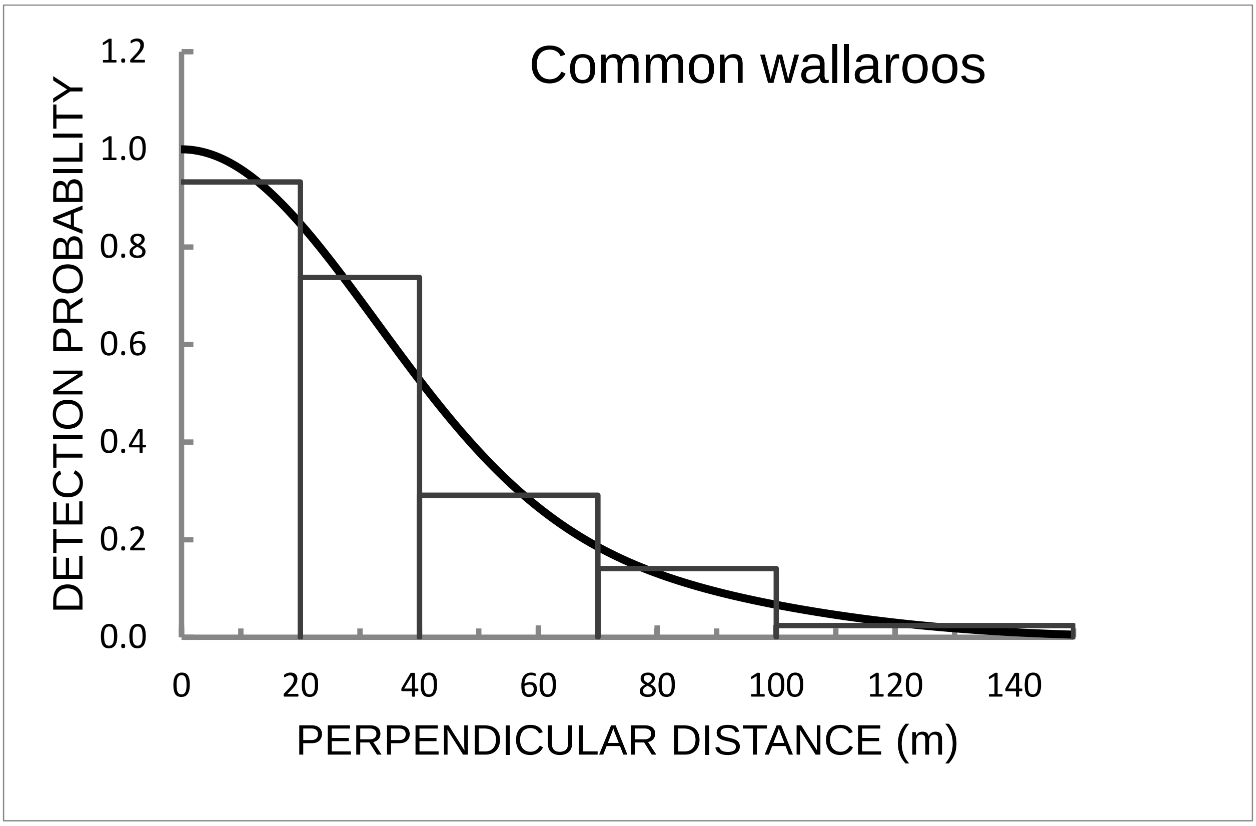

Fig. A2.5 The Half-normal/Cosine detection function for common wallaroos in the Central Tablelands North and Central Tableland South kangaroo management zones. For details of the model fitted using the MCDS analysis engine with Observer as a covariate, see text.

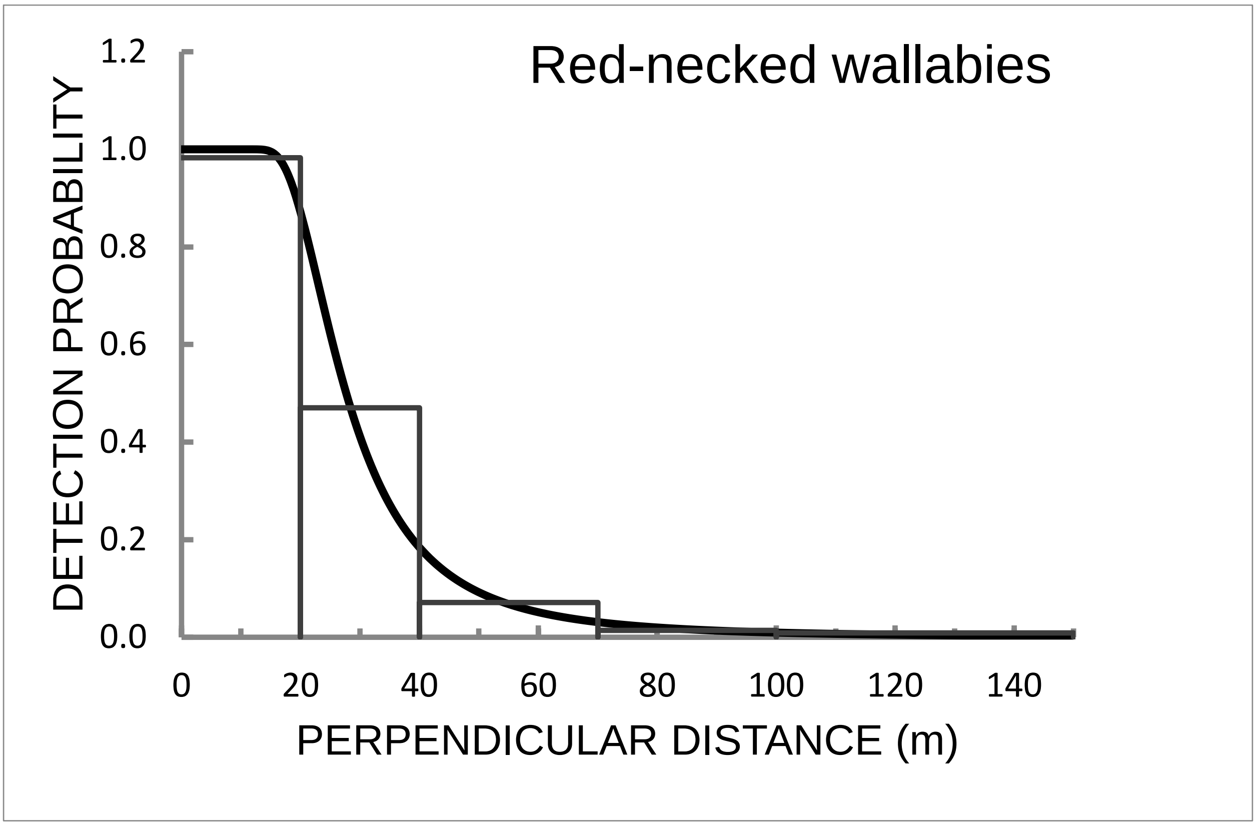

Fig. A2.6 The Hazard-rate/Cosine detection function for red-necked wallabies in the Central Tablelands North and Central Tableland South kangaroo management zones. For details of the model fitted using the MCDS analysis engine with Observer as a covariate, see text.

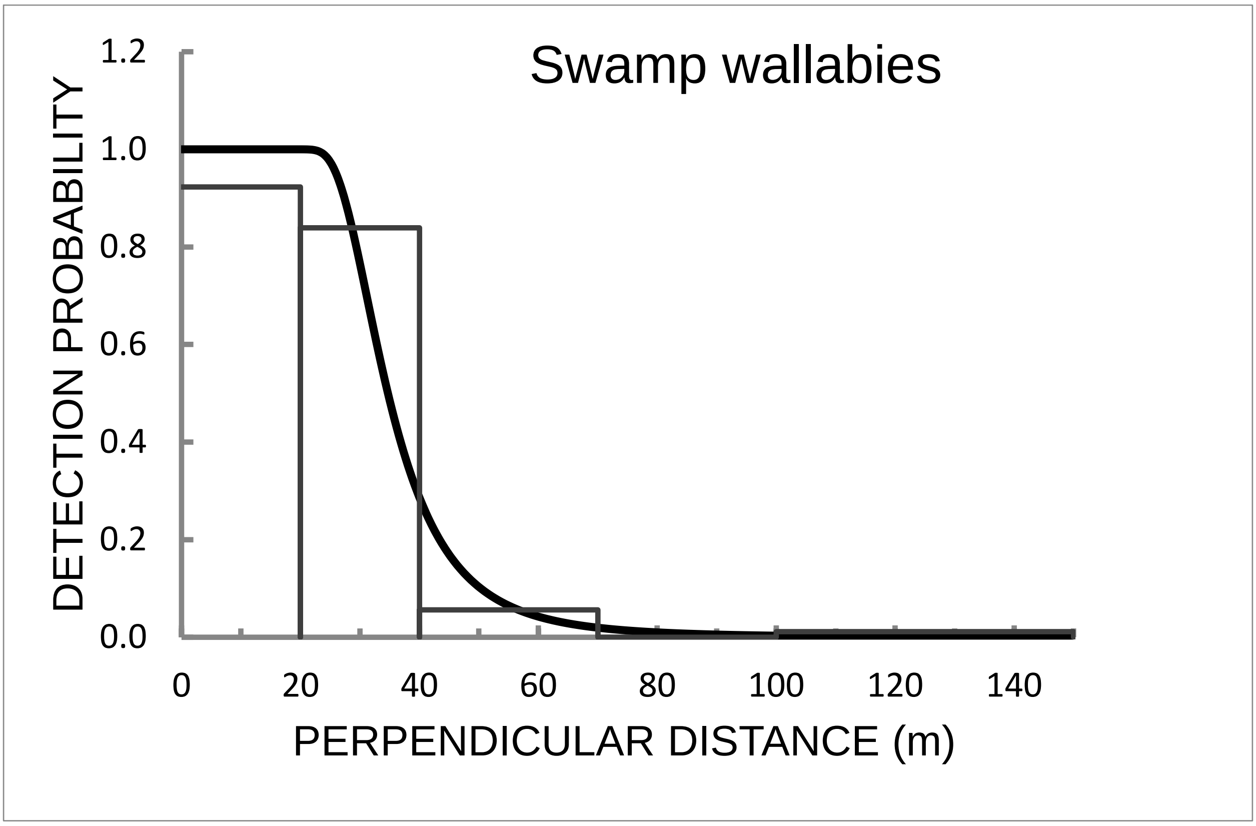

Fig. A2.7 The Hazard-rate/Polymonial detection function for swamp wallabies in the Central Tablelands North and Central Tableland South kangaroo management zones. For details of the model fitted using the MCDS analysis engine with Observer as a covariate, see text.