A report to the Biodiversity and Conservation Division, New South Wales Department of Planning and Environment on the consultancy: “Design and analysis of helicopter surveys of the kangaroo populations of the Northern Tablelands kangaroo management zones, 2022.”

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Summary

1. Helicopter surveys of the kangaroo populations in the three Northern Tablelands kangaroo management zones (see Fig. 1) were first conducted in October 2001 and May 2002, and then subsequently on a triennial basis in September from 2004. The population estimates obtained from these surveys have been used to set harvest quotas for eastern grey kangaroos (*Macropus giganteus*) and common wallaroos (*Osphranter robustus robustus*) from within these management zones.
2. The most recent of these triennial surveys were conducted in September 2022. As was the case on the six previous occasions, these surveys were designed using an automated survey design algorithm (Strindberg *et al.* 2004). To do this, each management zone was subdivided into three strata of increasing relative kangaroo density in order to facilitate the design process.
3. The surveys were designed with the aim of obtaining eastern grey kangaroo population estimates with a level of precision of better than 20% and wallaroo population estimates with a level of precision of better than 30%. Overall, this aim was readily achieved.
4. The results of the surveys were such that there were estimated to be 439,220 eastern grey kangaroos in the Glen Innes management zone, 446,700 in the Armidale management zone, and 260,650 in the Upper Hunter management zone. These population estimates equated to densities of 23.81 km^{-2}, 28.26 km^{-2} and 18.61 km^{-2}, respectively, in these three management zones.
5. It was also estimated that there were 116,620 wallaroos in the Glen Innes management zone, 136,010 in the Armidale management zone, and 112,980 in the Upper Hunter management zone. These population estimates equated to densities of 6.32 km^{-2}, 8.60 km^{-2} and 8.07 km^{-2}, respectively, in these three management zones.
6. Both the eastern grey kangaroo and wallaroo populations in the Glen Innes and Armidale management zones have effectively remained unchanged in comparison with the estimated sizes of these populations obtained from surveys conducted in 2019. In contrast to this, the populations of both these species in the Upper Hunter management zone increased significantly in comparison with the estimated sizes of these populations obtained from surveys conducted in 2019.

1. Introduction

All states and territories of the Commonwealth of Australia administer, in one form or another, macropod conservation and management plans. As part of some of these plans, commercial harvesting conducted by licensed field processors is often a significant component of the management of the populations of the large kangaroo species that are variously widespread and abundant throughout much of the continental Australia (Pople & Grigg 1995). Commercial harvesting of large kangaroos is undertaken in Queensland, New South Wales, Victoria, South Australia and Western Australia. Currently, it plays no part in macropod management in the Australian Capital Territory, nor the Northern Territory. Also, large kangaroos are not harvested in Tasmania.

In those states where it does occur, commercial harvesting is undertaken in accordance with quotas that are set with the intention of ensuring both harvest sustainability and regional population viability. It is a legislative requirement that any commercial harvesting of kangaroos be conducted on a sustainable basis (Pople & Grigg 1995). In order to set appropriate harvest quotas, it is necessary to obtain reasonably precise and accurate estimates of the sizes of the kangaroo populations intended for harvest. Species-specific quotas are set as proportions of these population estimates (Pople & Grigg 1995).

In New South Wales (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 west from the tablelands of the Great Dividing Range through to the South Australian border (see Fig. 1). Some or all four of those species of macropod identified as large kangaroos, the red kangaroo (*Osphrantor rufus*), the eastern grey kangaroo (*Macropus giganteus*), the western grey kangaroo (*Macropus fuliginosus*) and the common wallaroo (*Osphrantor robustus*) are currently harvested from within some or all of 15 kangaroo management zones (Anon. 2016, 2022). Two of these species, the eastern grey kangaroo and the eastern subspecies of the common wallaroo (*O. r. robustus*) are harvested in the Northern Tablelands region of northern 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 obtained from aerial surveys conducted using fixed-wing aircraft (Anon. 2016, 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. 2016, 2022).

Conducting these surveys on a triennial basis is considered to be a safe option for monitoring kangaroo populations in mesic environments such as the tablelands and western slopes of NSW, as opposed to semi-arid rangeland environments (Pople 2003; Payne 2007). According to Pople (2008), the risk of quasi-extinctions occurring in relation to the setting of harvest quotas using triennial population estimates is relatively low in mesic environments.

In 1989 and1990, a series of ground surveys were conducted to estimate the densities of macropods in an area of northeastern NSW that included the three the Northern Tablelands kangaroo management zones (Southwell *et al.* 1995). In the years subsequent to the conduct of these surveys, harvest quotas for eastern grey kangaroos and wallaroos in these zones were set broadly in relation to these 1989-1990 population estimates. This practice of setting quotas using these population estimates continued until 2001, when the first helicopter surveys of the kangaroo populations in the Northern Tablelands management zones were successfully undertaken (Cairns 2003). The change to using helicopter surveys and the method of line transect sampling (Thomas *et al.* 2002) overcame a major problem associated with managing kangaroo populations in tablelands environments; that of ensuring that regular population surveys were undertaken. To have conducted regular ground surveys similar to those carried out by Southwell *et al.* (1995) would have been logistically cumbersome and prohibitively costly. Furthermore, helicopter surveys conducted using the method of line transect sampling had been demonstrated to be a reasonably effective method for estimating both eastern grey kangaroo and wallaroo numbers on a small to medium scale in other parts of Australia (Clancy *et al.* 1997; Clancy 1999; Southwell & Sheppard 2000).

The initial helicopter survey of the Northern Tablelands was structured around the use of monitor blocks placed within each of the three kangaroo management zones (see Fig. 1) in such a way as to give what was thought to be the best possible coverage of the representative landscape of each zone (Cairns 2003). The outcome of this survey was considered successful from the perspective of providing what were thought to be reasonable estimates of eastern grey kangaroo numbers. However, comparison between the estimates of the wallaroo numbers obtained from this survey and those obtained by ground surveys conducted by Southwell *et al.* (1995) led to the conclusion that, in future, an overall better designed survey would be required (Cairns 2003). The result of this was that subsequent surveys of the three Northern Tablelands management zones were designed using the automated survey design capabilities of the analysis program DISTANCE (Thomas *et al.* 2010). As part of this process, each management zone was stratified on the basis of land capabilities and relative kangaroo densities. The automated survey design engine in DISTANCE is GIS-based and incorporates a range of algorithms that can be used for the development of line transect surveys (Strindberg, Buckland & Thomas 2004; Thomas *et al.* 2010). The last six surveys that have been conducted in the Northern Tablelands kangaroo management zones have all been designed using this method (Cairns 2004, 2007; Cairns, Lollback & Bearup 2011; Cairns, Bearup & Lollback 2013, 2017, 2020).

Since the undertaking of the initial, preliminary helicopter surveys conducted in 2001 and 2002 (Cairns 2003), the kangaroo populations in the Northern Tablelands kangaroo management zones have been surveyed regularly, every three years, beginning in 2004. Reported on here is the design of the surveys conducted in the three Northern Tablelands kangaroo management zones in September 2022, the survey and data analysis methods used in relation to the conduct of these surveys, and the estimated macropod densities and abundances obtained from these surveys. The population estimates obtained from these surveys will be used to set the 2023-2025 harvest quotas for eastern grey kangaroos and common wallaroos in the three Northern Tablelands kangaroo management zones.

2. Survey Areas

The three kangaroo management zones (KMZ) in the Northern Tablelands region of NSW are shown as Zone 9 (Armidale), Zone 13 (Glen Innes) and Zone 14 (Upper Hunter) in Fig. 1. These management zones extend south from the Queensland border to the Liverpool Range, north of the Hunter Valley. The two northernmost zones (Glen Innes and Armidale) straddle the New England Tablelands Biogeographic Region (IBRA) in the east and extend into the Nandewar Biogeographic Region (IBRA) in the west (Sahukar *et al.* 2003). The Upper Hunter zone straddles these two biogeographic regions, with its western edge extending into the Brigalow Belt South Biogeographic Region (IBRA) (Sahukar *et al.* 2003).

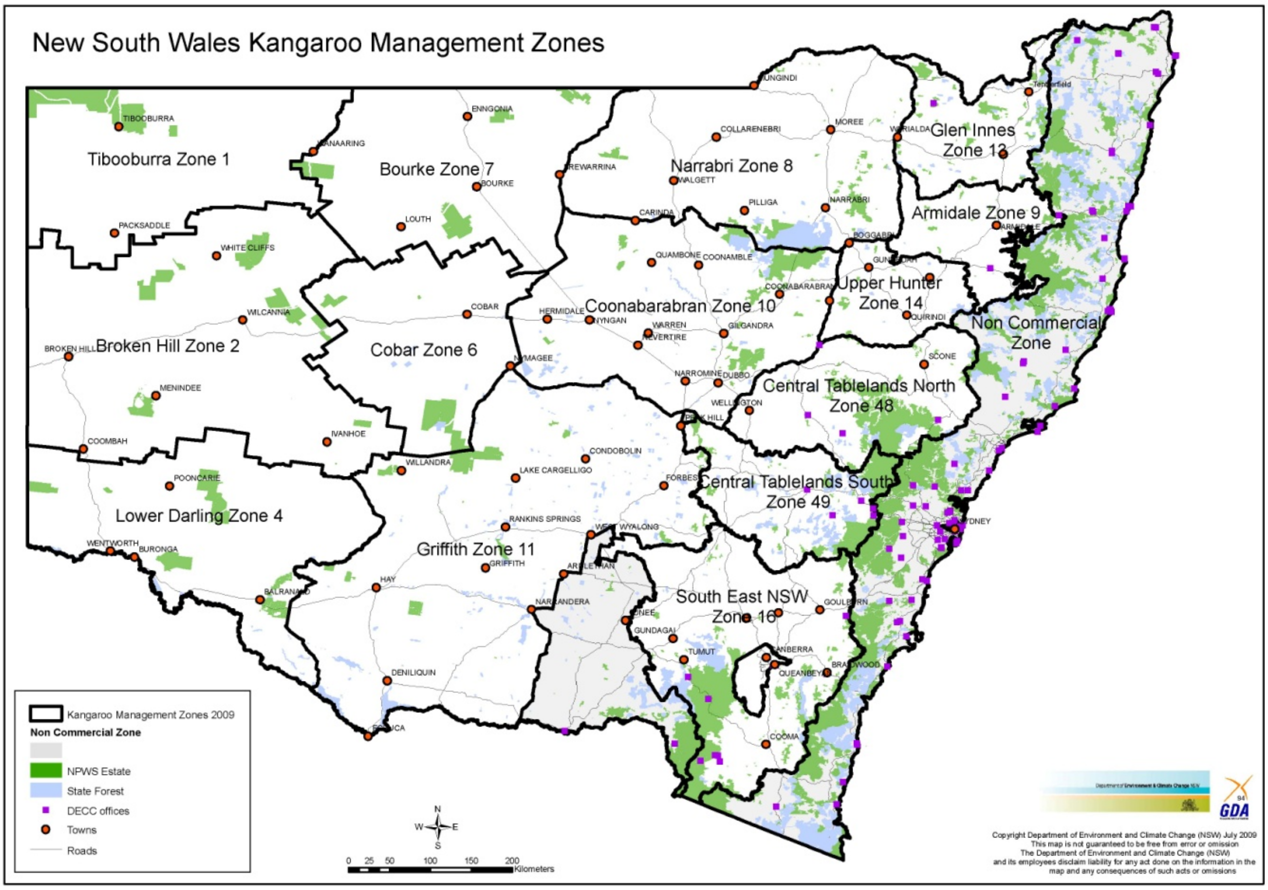

Fig. 1. The 15 kangaroo management zones administered by NSW Dept of Planning and Environment. The three Northern Tablelands kangaroo management zones are identified as Zones 9, 13 and 14.

In the eastern parts of the Armidale and Glen Innes management zones, which fall into the New England Tablelands Region, the topography comprises a stepped plateau of hills and plains, with elevations of between 600 m and 1500 m. Important defining features of the geodiversity of the New England Tablelands are, in the east, the Great Escarpment, which is characterised by deep rugged gorges such as the Apsley Gorge and Hillgrove Gorge, and, in the south, the Moonbi Range. In the central and western parts these two zones, which fall into the Nandewar Region, the topography comprises a hilly landscape that is characteristically warmer and drier than that of the tablelands to the east. A major feature of the geodiversity of the Nandewar Region is the volcanic landform of Mt Kaputar. In the Brigalow Belt South Region, which forms the western and southwestern edges of the Upper Hunter zone, the topography is, for most parts, one with gentle relief. The major feature of the geodiversity in this part of the Brigalow Belt South Region is the Liverpool Range.

Most of the land in the three kangaroo management zones is freehold, with some state forests, gazetted reserves and national parks comprising small proportions of the total areas. The principal land use practiced in these management zones is the grazing of domestic livestock. However, in the southwestern part of the Glen Innes zone and in a large part of the Upper Hunter zone, reasonably sizeable areas of land have been given over to broadacre cultivation. Only a small proportion of the Armidale zone is given over to cultivation. For the purpose of conducting kangaroo surveys, those parts of each of the three management zones dominated by cultivation and those parts dominated by steep, timbered country and rocky outcrops have been deemed to be areas that supported zero to very low densities of kangaroos. In order to maintain cost-effectiveness, these areas were defined as low density areas and excluded from the survey designs. For the areas of the three kangaroo management zones, see Table 1.

3. Survey Design

As has been the case with the previous six aerial surveys conducted in the Northern Tablelands kangaroo management zones (see Cairns, Bearup & Lollback 2020a) and the most recent aerial surveys conducted in the Southeastern NSW kangaroo management zone (Cairns, Bearup & Lollback 2022) and the two Central Tablelands kangaroo management zones (Cairns, Bearup & Lollback 2020b), this survey was designed using the automated design capabilities of a recent version of the DISTANCE software package (Thomas *et al.* 2010); in this case DISTANCE 7.3. The survey areas of each management zone were divided into three strata. Separate surveys were designed for the high and medium density strata within each management zone. The low density strata were not surveyed.

3.1 Management Zone Stratification

GIS shape files for the three Northern Tablelands kangaroo management zones showing land capability attributes were previously obtained from NSW OEH (Cairns 2004). These shape files identified eight categories of land capability which extended broadly from cultivation, through mixed farming and grazing, through decreasing levels of grazing intensity, through to steep, timbered country, through to rocky outcrops. These files also contained information on the locations of state forests, gazetted reserves and national parks; all of which were excluded from the survey areas.

Using these land capability attributes three kangaroo density strata were created within each management zone. The eight land capability categories were merged into three broad land-use classes to form the basis of this stratification. Land capability categories 1 and 2, which are representative of areas dominated by cultivation practices, were merged with category 8, which is representative of rocky outcrops, to form the basis of a likely low kangaroo density stratum within each management zone. Categories 3 and 4, which are representative of areas of grazing and low intensity cropping, were merged to form the basis of a likely medium kangaroo density stratum. Categories 5, 6 and 7, which are representative of grazing land, were merged to form the basis of a likely high kangaroo density stratum. In finalising the three survey strata, owing to the steepness of the terrain, some parts of category 7 were merged into the low density stratum rather than being retained within the high density stratum. This transfer of some category 7 landform areas from the high to the low density stratum was done in relation to the Nandewar Range in the Armidale management zone and the Moonbi Range in the Upper Hunter management zone.

Taking into account initially available knowledge of the density distributions of eastern grey kangaroos and wallaroos within the three management zones (Southwell *et al.* 1995; Cairns 2003), the boundaries of the merged strata were redigitised to create final, simpler versions of the three density strata within each of the management zones. Further successive adjustment have been made to these boundaries in relation to known kangaroo density and survey count information obtained from previous surveys (Cairns 2004, 2007; Cairns, Lollback & Bearup 2011). Although no adjustments were deemed necessary in relation to the design of the present surveys, this process of redefining the density strata before proceeding to design a survey is consistent with taking an adaptive management approach to the conduct of aerial surveys.

Table 1. Partitioning of the areas (km^2) of the three Northern Tablelands kangaroo management zones. Kangaroo harvesting is precluded from National Parks (NP), State Forests (SF) and areas of urban consolidation (UC). The remaining area suitable for the conduct of helicopter surveys is divided into three strata representative of areas of nominally high, medium and low kangaroo density.

Area partitioning (km^2)	Kangaroo management zone Glen Innes	 Armidale	 Upper Hunter
Total area	20,941	16,331	14,590
NP, SF and UC	2,492	522	586
High density	4,774	9,078	3,552
Medium density	12,467	5,945	4,431
Low density	1,208	786	6,021
Survey area	18,449	15,809	14,004

The breakdowns of the areas of the three kangaroo management zones into their constituent strata are given in Table 1. In the Glenn Innes zone, the survey area, before stratification, covers 88% of the total area. Twenty-six percent of this survey area comprises the high kangaroo density stratum, 68% comprises the medium density stratum, and the remaining 6% comprises the low density stratum. In the Armidale zone, the survey area covers 97% of the total area. Fifty-seven percent of this survey area comprises the high kangaroo density stratum, 38% comprises the medium density stratum, and the remaining 5% comprises the low density stratum. In the Upper Hunter zone, the survey area covers 96% of the total area. Twenty-five percent of this survey area comprises the high kangaroo density stratum, 32% comprises the medium density stratum and 43% comprises the low density stratum, which is mostly land under cultivation, but also includes parts of the Moonbi Range in the east.

3.2 Survey Effort

In line transect sampling, survey effort is defined as the total length of transect surveyed and is generally determined in relation to some desired level of precision (i.e. the ratio of standard error to the sample mean of an estimate). The selection of the level of precision is modulated to some extent by cost constraints, which were relevant to deciding on the level of precision used in relation to the medium density stratum in the Upper hunter management zone. In the conduct of surveys such as the one reported upon here, aiming for a general level of precision of up to 20% would appear to be realistic and reasonably cost-effective (Pople, Cairns & Menke 2003; Cairns 2004, 2007). This target level of precision was used to determine the nominal survey effort for the two survey strata in the Glen Innes and Armidale management zones, and for the high density stratum of the Upper Hunter zone. A level of precision of 30% was used in relation to the medium density stratum of the Upper Hunter zone. To determine the survey effort required, the method proposed in Buckland *et al.* (p. 243; 2001) was used in relation to the precision of the surveys completed in 2016 (Cairns, Bearup & Lollback 2017).

The nominal survey efforts determined for the high and medium density strata in each of the three kangaroo management zones are given in Table 2. No survey effort was allocated to the low density strata of any of the management zones. Low density strata, which comprised either areas dedicated to cropping or areas of heavily timbered and rugged terrain, were thought to support only trace numbers of kangaroos (Southwell *et al.* 1995; Cairns 2003).

Table 2. The nominal survey efforts determined using the method of Buckland *et al.* (2001) and the actual survey efforts applied during the survey. One of either two survey design models were considered, systematic segmented grid (SSG) sampling and systematic segmented trackline (SST) sampling, with the latter being selected for all surveys.

Survey stratum	Sampling model	Nominal survey effort (km)	Actual survey effort (km)
Glen Innes (high)	SST	265.0	265.0
Glen Innes (medium)	SST	330.0	322.5
Armidale (high)	SST	550.0	550.0
Armidale (medium)	SST	247.5	247.5
Upper Hunter (high)	SST	355.0	355.0
Upper Hunter (medium)	SST	310.0	295.0

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 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 or systematic segmented trackline sampling with a buffer zone around the boundary of each survey stratum was selected as the most likely appropriate design option for the present surveys. Inclusion of a buffer in 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. As well as this, the option of maintaining the integrity of individual samplers (transects) was tested against the option of using split samplers. Samplers that were 5 km, 7.5 km and 10 km in length were tested in these designs to determine whether either of the shorter two gave better coverage than did the 10 km sampler.

Surveys were designed separately for each of the high and medium density strata of each of the three 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 six 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 giving the best coverage of a survey stratum, then a single realisation of that design was generated for the survey of that stratum.

The selected designs for all six survey strata, the ones considered to provide the best coverage probability, were all designs based upon systematic segmented trackline sampling (Table 2). All selected designs comprised fixed length rather than split samplers. Split samplers were rejected mainly because there were potential logistical problems associated with their use. The actual survey efforts of the realised survey designs are also given in Table 2.

For the Glen Innes management zone, the selected survey designs allocated 53 transects, each 5 km in length, to the high density stratum and 44 transects, each 7.5 km in length, to the medium density stratum (Fig. 2). For the Armidale zone, the selected survey designs allocated 55 transects, each 10 km in length, to the high density stratum and 33 transects, each 7.5 km in length, to the medium density stratum (Fig. 3). For the Upper Hunter zone, the selected survey design allocated 71 transects to the high density stratum and 62 transects with to the medium density stratum (Fig. 4). These transects were all 5 km in length.

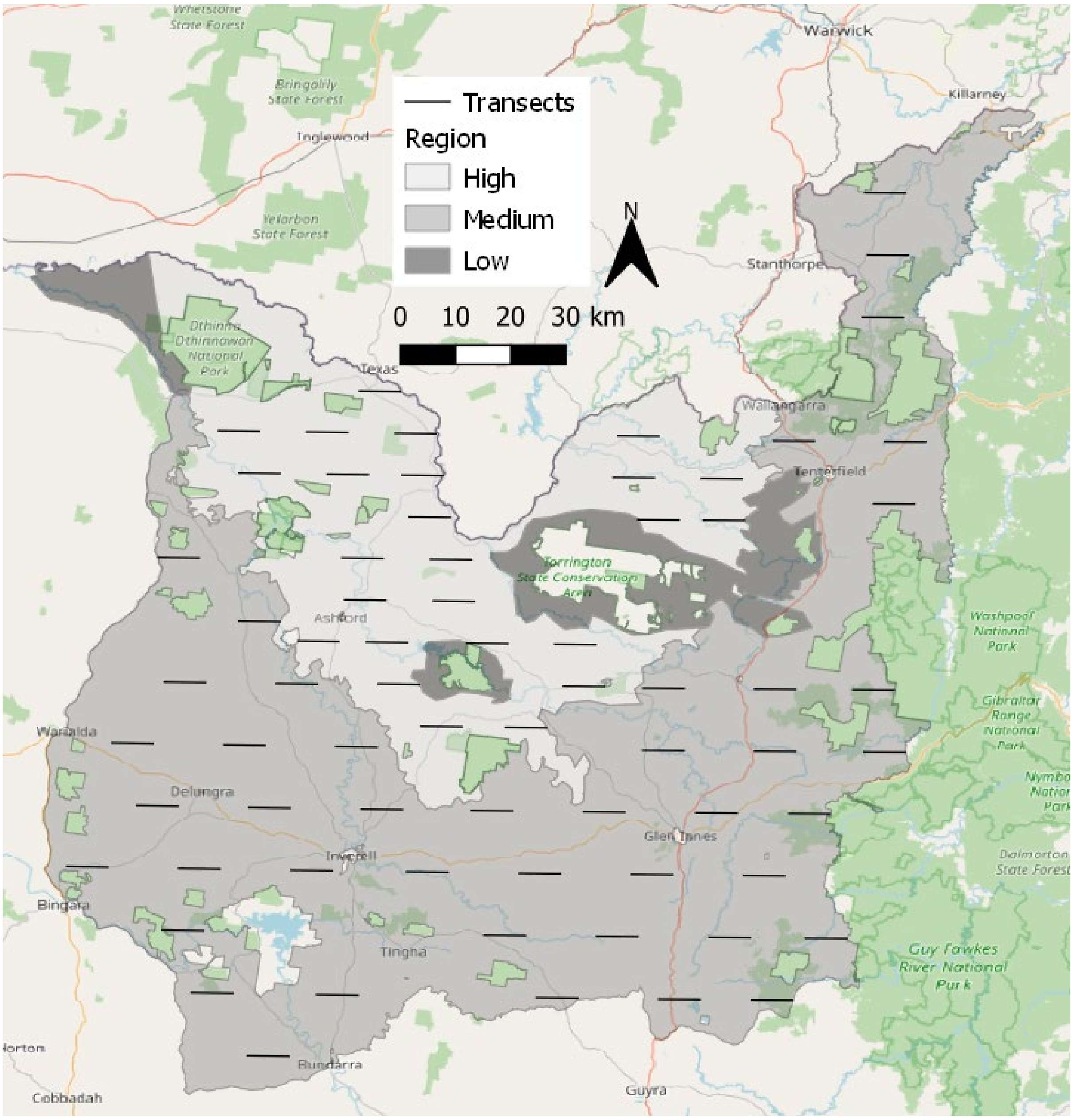

Figure 2. The Glen Innes kangaroo management zone (KMZ 13). Shown are the three survey strata (see legend), national parks, state forests and urban consolidations not considered as part of the survey area (white), population centres (towns) and the placement of the survey transects in the high and medium kangaroo density strata.

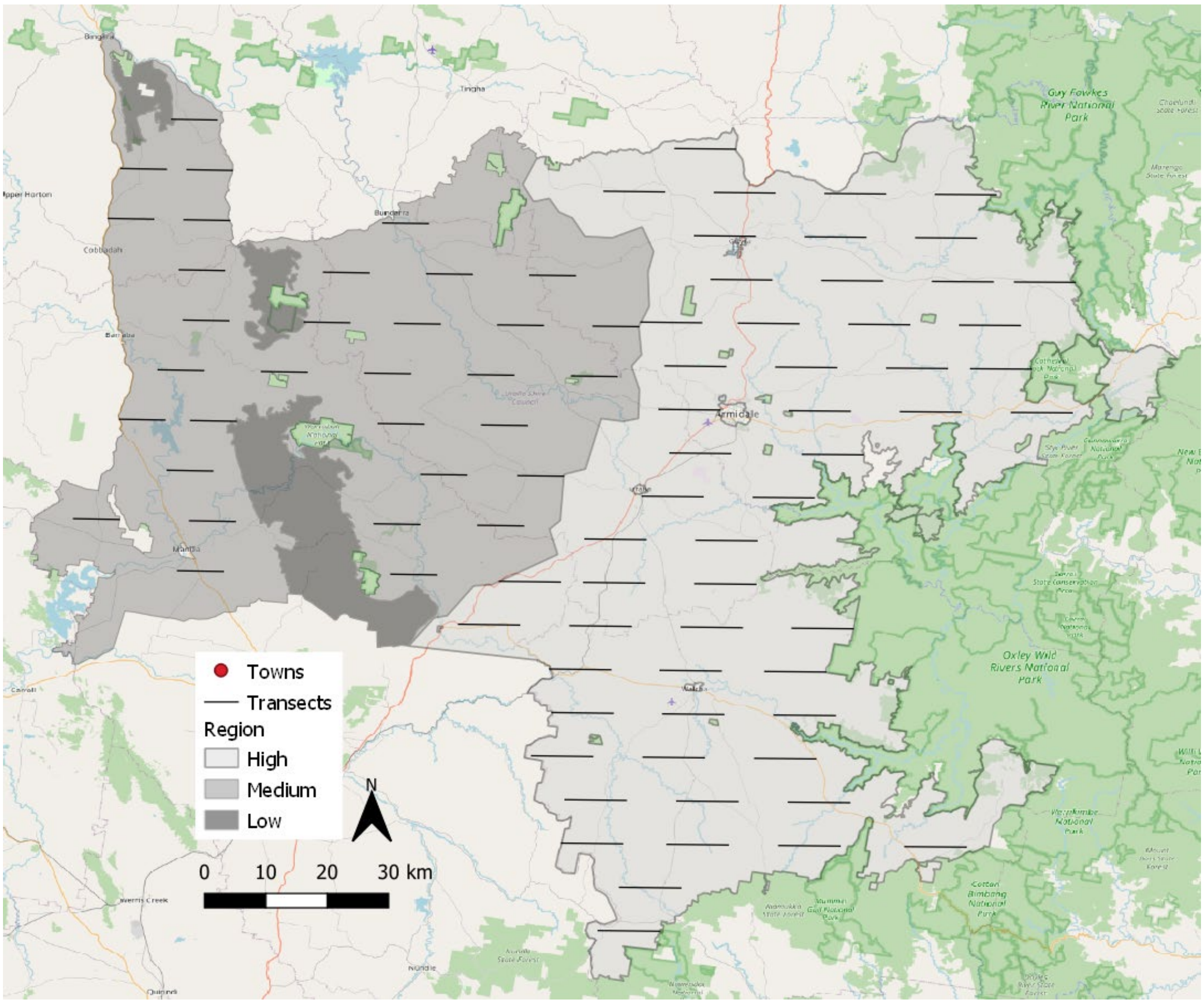

Figure 3. The Armidale kangaroo management zone (KMZ 9). Shown are the three survey strata (see legend), national parks, state forests and urban consolidations not considered as part of the survey area (white), population centres (towns) and the placement of the survey transects in the high and medium kangaroo density strata.

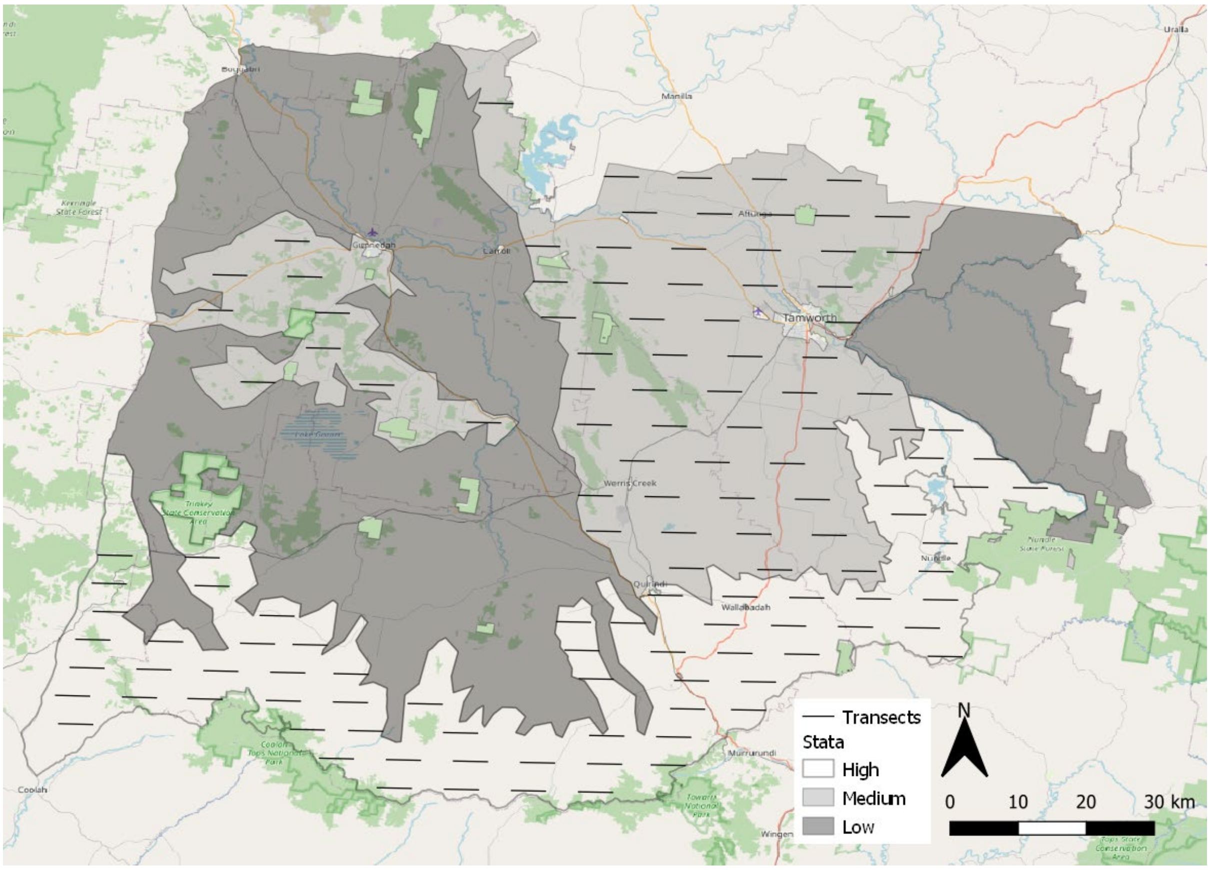

Figure 4. The Upper Hunter kangaroo management zone (KMZ 14). Shown are the three survey strata (see legend), national parks, state forests and urban consolidations not considered as part of the survey area (white), population centres (towns) and the placement of the survey transects in the high and medium kangaroo density strata.

4. Survey Methods

The aerial surveys of the three Northern Tablelands kangaroo management zones were conducted as helicopter surveys during the period 6-18 September, 2022. The surveys were carried out in accordance with the survey designs developed above (see Section 3.3), with each kangaroo management zone being considered a separate entity subdivided into three strata based principally upon assumed and known kangaroo densities, and modulated in relation to land use capability. The strata identified as supporting high and medium densities of eastern grey kangaroos were the strata surveyed. The method of line transect sampling (Buckland *et al.* 2001; Thomas *et al.* 2002) was used. In the original design for these surveys, there was a total of 318 transects to be flown across the three management zones. The completed surveys comprised a total of 314 transects (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), Mika Saunders (NPWS) and Neil Marks (QNPWS) were the observers. Brigid Coley (Park Air) and Hugh Johnson (Park Air) were the pilots. Ben James (NSW NPWS) and Lindsay Wauchope (NSW NPWS) were the ground crew.

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 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 (Fig. 5).

Data in the form of the numbers of clusters (groups of one or more individuals) of eastern grey kangaroos (*M. giganteus*), common wallaroos (*O. 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. 5 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 as:

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

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 centreline (Thomas *et al.* 2002). To do this, the sampling data, the counts of clusters of animals (kangaroos) within each of the five distance bins used in these surveys, were analysed using DISTANCE 7.3 (Thomas *et al.* 2010). Basing the analysis on the sightings of clusters in preference to the sightings of individual animals has been found to ensure against 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 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, clusters of kangaroos in this instance, should be at least in the range 60-80 for reliable modelling of the detection function.

For all four species of macropod, the survey results from each management zone were analysed separately. Where there were enough observations, 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.

DISTANCE 7.3 has three different analysis engines that can be used to model the detection function (Thomas *et al.* 2010). Two of these, the conventional distance sampling (CDS) analysis engine and the multiple-covariate distance sampling

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

The analysis protocol followed was such that the results of the analyses conducted using detection function model options available within both the CDS and MCDS analysis engines were compared serially in order to determine which was the most parsimonious (suitable) model and, hence, which were the most likely and accurate estimates of population density and abundance determined in relation to this detection function. The model with the lowest value for a penalised log-likelihood in the form of Akaike's Information Criterion ($AIC = -2 \times \text{log-likelihood} + 2[p + 1]$; 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, habitat cover at point of detection, survey aspect and cloud cover. 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 line (i.e. if $g(x)$ does not depend upon c), then the sample mean cluster size is taken as an unbiased estimator of the mean size of the n_a clusters observed in the study area. If, however, the observed sizes of detected clusters are found to be dependent upon the perpendicular distance from the transect line, then, the sample mean cluster size is replaced by a value determined using a regression of this relationship (Buckland *et al.* 2001).

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

The survey results were analysed to determine separate kangaroo density and population estimates for the high and medium density strata, and for the whole of each kangaroo management zones; with density being determined in relation to all three strata. While the eastern grey kangaroo and common wallaroo counts were analysed at the level of survey stratum within management zone, the counts of the incidental species of macropod, red-necked wallabies and swamp wallabies, were pooled across strata and analysed at the level of management zone.

5. Results and Discussion

5.1 Survey Data Summaries

Each of the three Northern Tablelands kangaroo management zones was subdivided into three strata based upon land capability and the relative densities of eastern grey kangaroos (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 of each zone was assumed to support no more than trace numbers of eastern grey kangaroos and common wallaroos, and was, therefore, along with national parks, state forests and gazetted reserves, not surveyed.

Ninety-six transects comprising 587.5 km of survey effort were flown across the two survey strata of the Glen Innes kangaroo management zone (Fig. 2). A total of 2,205 eastern grey kangaroos were counted on these transects, along with 300 common wallaroos. Of the other species of macropod present, 84 red-necked wallabies (*Macropus rufogriseus*) and 103 swamp wallabies (*Wallabia bicolor*) were also counted on these transects. As well as the macropods counted on these transects, 62 emus (*Dromaius novaehollandiae*), 560 feral goats (*Capra hircus*), 263 feral pigs (*Sus scrofa*) and 79 deer (*Dama* sp. and *Cervus* sp.) were also counted. Eighty-eight transects comprising 797.5 km of survey effort were flown across the two survey strata of the Armidale zone (Fig. 2). A total of 3,088 eastern grey kangaroos were counted on these transects, along with 405 wallaroos, 88 red-necked wallabies and 58 swamp wallabies. There was also one emu, 152 feral goats, 264 feral pigs and 50 deer counted on these transects. One-hundred and thirty transects comprising 650.0 km of survey effort were flown across the two survey strata of the Upper Hunter zone (Fig. 3). A total of 2,537 eastern grey kangaroos were counted on these transects, along with 469 wallaroos, 173 red-necked wallabies and 105 swamp wallabies. There were also 204 feral goats, 380 feral pigs and 228 deer counted on these transects. With regards to the macropods, this raw survey information is summarised in relation to survey strata in Table 3.

Table 3. Number of transects flown, total survey effort (km) and raw counts of macropods for each of the two survey strata within the three kangaroo management zones.

Kangaroo management zone	Number of transects	Survey effort (km)	Raw counts			
			Eastern grey kangaroos	Common wallaroos	Red-necked wallabies	Swamp wallabies
Glen Innes						
High	53	265.0	1,192	196	33	61
Medium	43	322.5	1,013	104	51	42
Armidale						
High	55	550.0	2,081	208	76	39
Medium	33	247.5	1,007	197	12	19
Upper Hunter						
High	71	355.0	1,650	351	134	75
Medium	59	295.0	887	118	39	30

5.2 Line Transect Analysis

To estimate the population densities and abundances of kangaroos, wallaroos and wallabies, the counts of clusters of these macropods obtained during the surveys were grouped as recorded into the five distance categories set on the survey booms mounted on the helicopter (Fig. 5). 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) using both the CDS and the MCDS analysis engines of DISTANCE 7.3 (Thomas *et al.* 2010).

Key to analysing distance sampling data is the modelling of the detection of objects (clusters of macropods) in relation to at least one covariate, the perpendicular distances of the objects from the survey transect centreline. To do this, a set of candidate detection function models was fitted to the survey data from which the single most parsimonious (specific) model was selected (see Section 4.2). The model selection process is comparative, being based upon the difference between the AIC statistics for competing models (ΔAIC), with the most parsimonious (specific) detection function usually being selected on the basis of it being the one that yields the smallest value of the AIC statistic. In comparing any two models, when ΔAIC >2.00, 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 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. For further information on the use of AIC in model selection, see Burnham and Anderson (2002).

Eastern grey kangaroo density and abundance estimates were determined separately for each management zone, with the results from the two strata surveyed being incorporated into a stratified analysis based upon either the determination of a global detection function or separate detection functions for each survey stratum. The densities and abundances of common wallaroos were similarly determined. The densities and abundances of red-necked wallabies and swamp wallabies were determined on the basis of each of the three management zones, with the survey results for the two strata surveyed in each zone being combined.

In analysing the results of surveys such as those undertaken here, it is important that the recommended minimum sample sizes of both transect lines and observations are at least attained. According to Buckland *et al.* (2001), the recommended minimum number of samplers (replicate transect lines) should be at least in the range 10-20 in order to ensure reasonably reliable estimation of the variance of the encounter rate. The recommended number of observations, of clusters of macropods in this instance, should be at least in the range 60-80 for reliable modelling of the detection function. The required minimum number of replicate transects was easily attained for each survey stratum. For eastern grey kangaroos, the required minimum numbers of replicate observations were also easily obtained for each survey stratum (Table 4). For wallaroos, the required minimum numbers of replicate observations were obtained for all survey strata except the medium density stratum in the Glen Innes management zone (Table 5). For red-necked wallabies and swamp wallabies, the required minimum number of replicate observations were obtained for the Glen Innes and Upper Hunter management zones, but fell a little short for the Armidale management zone (see Table 11).

The most parsimonious detection function models fitted to the results of the surveys of eastern grey kangaroos in the three kangaroo management zones are given in Table 4. For the Glen Innes and Upper Hunter management zones, the detection function models were global MCDS-derived models that incorporated the covariate of habitat cover at point-of-detection. For the Armidale management zone, the detection function model was a global MCDS-derived model that incorporated the covariate of observer. The key functions for all these models were the Half-normal function. There were two types of habitat at point-of-detection recorded during the surveys, namely open habitat and habitat dominated by tree cover. Three observers were used in rotation during these surveys.

Table 4. The number of sightings of clusters of kangaroos (n), the DISTANCE 7.3 analysis engine used (see text), the detection function and model (including covariate) for the surveys of the eastern grey kangaroo populations in the three Northern Tablelands kangaroo management zones (KMZ). MCDS is the multiple covariate distance sampling analysis engine. The detection functions have been determined globally across the two survey strata of each KMZ. Given also is the encounter rate (n/L) and the probability that a cluster of eastern grey kangaroos present on the survey strip is detected (P_a).

KMZ/stratum	n	Analysis engine	Detection function	Model	Covariate	n/L	P_a
<u>Glen Innes</u>							
High	491	MCDS	Global	Half-normal	Cover	1.85	0.43
Medium	355	MCDS	Global	Half-normal	Cover	1.10	0.46
<u>Armidale</u>							
High	643	MCDS	Global	Half-normal	Observer	1.17	0.37
Medium	351	MCDS	Global	Half-normal	Observer	1.42	0.37
<u>Upper Hunter</u>							
High	488	MCDS	Global	Half-normal	Cover	1.37	0.35
Medium	291	MCDS	Global	Half-normal	Cover	0.97	0.35

With the final MCDS-derived models for all three management zones, the differences between these models and the nearest corresponding CDS-derived models were all quite substantial: Glen Innes (ΔAIC = 54.67), Armidale (ΔAIC = 76.99) and Upper Hunter (ΔAIC = 39.44). The general forms of the detection functions for eastern grey kangaroos in the three management zones are shown in Appendix 1, Figs. A1.1-A1.3. For both the Glen Innes and Upper Hunter zones, two models are shown in relation to habitat cover at point-of-detection. For the Armidale zone, where observer was major covariate, only a single model is shown. Although not shown in this graphic, it should be noted that inclusion in the model of the covariate of observer has the effect of altering the scale of the detection function, but not its general form (Marques & Buckland 2004). This is similarly the case with the inclusion in a model of habitat cover at point-of-detection as a covariate.

Given in relation to each of the detection function model in Table 4, are estimates of the encounter rate (n/L) and probability (P_a) that a randomly selected cluster of kangaroos in the nominal survey strip (150 m) will be detected. The encounter rate, the number of clusters of macropods detected per unit (km) of survey effort is considered a more informative statistic than is n itself (Buckland *et al.* 2001). That the encounter rate variance usually dominates the overall variance of object (kangaroo) density is indicative of the importance of this statistic. While P_a is required as part of the estimation process, it also has some comparative value. It can be viewed as an indicator of the interaction between the macropods, the landscape they occupy, the conditions of the survey and the observers on the survey platform.

The encounter rates were within a reasonably narrow range (0.97-1.85) across the survey strata of the three management zones and were indicative of the ubiquity of the eastern grey kangaroo throughout the Northern Tablelands of NSW (Table 4). In relation to this, it could be noted that the variances of these encounter rates were also, proportionally, reasonably similar. The probability that a randomly selected cluster of eastern grey kangaroos in the survey strip will be detected (P_a) showed some variation across survey strata, ranging from 0.35 to 0.46, with a median value of 0.37 (Table 4). Overall, this probability has shown some, but not a great deal, of variation in relation to past surveys conducted in these management zones. For the surveys conducted in 2019, the value of P_a determined across the survey strata was found to have a wider range than for the present surveys, ranging from 0.30 to 0.41 (Cairns, Bearup & Lollback 2020a). However, for the surveys conducted in these management zones in 2016, the value of P_a determined across the survey strata was found to have a narrower range than this, ranging from 0.38 to 0.45 (Cairns, Bearup & Lollback 2017).

Although the variation in P_a probably reflects the extent of the variation in the general sightability of eastern grey kangaroos in relation to the differing broad landscapes of the constituent parts of the survey areas, it also reflects the possible influence of general weather conditions and light on sightability. Separating the influence of these factors would be somewhat difficult, although the covariates included in some of the detection function models could be pointers to this. The overall relatively low values of P_a in relation to the nominal survey half-width of 150 m are indicative of the necessity and effectiveness of the use of line transect sampling as opposed to strip transect sampling for estimating the abundance of macropods under the conditions of these surveys.

For common wallaroos, the most parsimonious detection function models fitted to the results of the surveys of the three kangaroo management zones are given in Table 5. For all three management zones, the detection function models were MCDS-derived models that incorporated one covariate. The key function for these models was the Half-normal function; the single incorporated covariate was that of habitat cover at point-of-detection. All models were fitted globally using the combined data from the two survey blocks within each management zone.

With the final MCDS-derived models, the differences between the selected models and the nearest corresponding CDS-derived models were reasonably substantial for the analysis of the survey: Glen Innes (ΔAIC = 7.31), Armidale (ΔAIC = 6.09) and Upper Hunter (ΔAIC = 7.96). The general forms of the detection functions for common wallaroos in the three management zones are shown in Appendix 1, Figs. A1.4-A1.6.

The probability that a randomly selected cluster of wallaroos in the survey strip will be detected (P_a) showed some variation across survey strata, ranging from 0.28 to 0.40, with a median value of 0.37 (Table 5). Overall, this probability has shown some variation in relation to past surveys conducted in these management zones. For the surveys conducted in 2019, P_a was determined as being somewhat higher and less variable across the three management zones than it was for the present surveys, ranging from 0.34 to 0.45 (Cairns, Bearup & Lollback 2020a). For the surveys conducted in these management zones in 2016, the value of P_a determined across the survey strata was found to be in the range 0.34-0.45 (Cairns, Bearup & Lollback 2017).

Table 5. The number of sightings of clusters of wallaroos (n), the DISTANCE 7.3 analysis engine used (see text), the detection function and model (including covariate) for the surveys of the common wallaroo populations in the three Northern Tablelands kangaroo management zones (KMZ). MCDS is the multiple covariate distance sampling analysis engine. The detection functions have been determined globally across the two survey strata of each KMZ. Given also is the encounter rate (n/L) and the probability that a cluster of common wallaroos present on the survey strip is detected (P_a).

KMZ/stratum	n	Analysis engine	Detection function	Model	Covariate	n/L	P_a
Glen Innes							
High	108	MCDS	Global	Half-normal	Cover	0.41	0.39
Medium	56	MCDS	Global	Half-normal	Cover	0.17	0.40
Armidale							
High	108	CDS	Global	Half-normal	Cover	0.20	0.38
Medium	97	CDS	Global	Half-normal	Cover	0.39	0.36
Upper Hunter							
High	150	MCDS	Global	Half-normal	Cover	0.42	0.29
Medium	61	MCDS	Global	Half-normal	Cover	0.21	0.28

In general, there were enough sightings of clusters of red-necked wallabies and swamp wallabies across the three management zones to allow population estimates of these two incidental species to be determined (see Table 11). The most parsimonious detection function models for red-necked wallabies were all CDS-derived models with a Half-normal key function and a Cosine series adjustment. For swamp wallabies, it was a Half-normal key function with a Cosine series adjustment for the Glen Innes and Armidale management zones, and a Hazard-rate key function with no series adjustments for the Upper Hunter management zone. For red-necked wallabies, the values of P_a were in the range 0.22-0.33. For swamp wallabies, the values of P_a were in the range 0.24-0.29. The forms of the detection function models for these two minor species are shown in Appendix 1, Figs. A1.7-A1.9.

5.3 Population Estimates

The densities of clusters of eastern grey kangaroos along with the corresponding population densities within the two survey strata of each kangaroo management zone are given in Table 6. These density estimates are also given in Table 7, along with the corresponding population abundances for each kangaroo management zone.

In the Glen Innes management zone, the density of eastern grey kangaroos was found to be some 40% higher in the high density survey stratum than in the medium density stratum (Table 6; z = 1.96; P = 0.049). This outcome differed from that of the survey of this management zone conducted in 2019 (Cairns, Bearup & Lollback 2020a), when the densities of eastern grey kangaroos in the two survey strata were found not to be different (z = 0.21; P = 0.971). It was, however, similar in pattern to the outcome of the survey conducted in 2016 (Cairns, Bearup & Lollback 2017) when the density of eastern grey kangaroos in the high density stratum was estimated to be some 60% higher than it was in the medium density stratum (z = 2.63; P = 0.008). The 2019 survey was conducted at the end of the 2017-2019 drought (http://www.bom.gov.au/climate/drought/knowledge-centre/previous-droughts.shtml), the impact of which could well have been responsible for a relative decline in the numbers of eastern grey kangaroos in the high density survey stratum as a result of mortality, restricted recruitment and a possible movement of animals south out of this stratum and into the larger medium density stratum (Fig. 2). This situation could have been assumed to have been redressed by the time of the 2022 survey, which was conducted some three years after the end of the drought.

Table 6. Results of the helicopter line transect surveys of eastern grey kangaroos conducted in the high and medium density strata of the three Northern Tablelands kangaroo management zones (KMZ) in September, 2022. Given along with the areas of the two strata surveyed in each management zone are the densities of clusters of kangaroos sighted (D_s) and kangaroo population densities (D). Given in association with the two density estimates are the empirically-estimated and bootstrap-estimated coefficients of variation (cv %), and the bootstrap confidence intervals. Details of the most parsimonious detection function models used to determine these densities are given in Table 4. Densities are rounded to two decimal places.

KMZ/stratum	Area (km^2)	Cluster density (km^{-2})				Kangaroo density (km^{-2})			
		D_s	cv (%)	95% bootstrap confidence interval	cv$_{boot}$ (%)	D	cv (%)	95% bootstrap confidence interval	cv$_{boot}$ (%)
Glen Innes									
High	4,774	14.23	11.3	11.49-17.13	10.5	32.27	11.6	25.08-40.00	11.8
Medium	12,467	8.02	12.2	6.31-10.01	11.0	22.87	13.1	16.70-28.55	14.0
Armidale									
High	9,078	10.63	10.2	8.68-12.72	9.8	29.95	10.6	23.13-37.19	11.9
Medium	5,945	12.64	9.8	10.78-15.05	8.3	29.40	10.4	23.70-36.27	10.7
Upper Hunter									
High	3,552	13.03	11.3	10.18-16.11	11.5	41.45	11.7	31.34-52.21	13.1
Medium	4,431	9.48	16.7	6.52-12.48	15.8	25.48	17.1	16.34-36.14	18.9

Table 7. The eastern grey kangaroo population densities (D) and abundances (N) for the two strata surveyed in each of the three Northern Tablelands kangaroo management zones (KMZ). Given in association with the estimates are bootstrap confidence intervals. The abundances and confidence intervals given in bold are the combined, whole-zone estimates. Densities are rounded to two decimal places.

KMZ/stratum	D (km^{-2})	95% bootstrap confidence interval	N	95% bootstrap confidence interval
Glen Innes				
High	32.27	25.08-40.00	154,050	119,740 – 190,970
Medium	22.87	16.70-28.55	285,170	206,300 – 355,980
			439,220	353,300 – 518,770
Armidale				
High	29.95	23.13-37.19	271,900	209,950 – 337,630
Medium	29.40	23.70-36.27	174,800	140,870 – 215,640
			446,700	380,620 – 526,770
Upper Hunter				
High	41.45	31.34-52.21	147,220	111,320 – 185,470
Medium	25.48	16.34-36.14	113,430	72,390 – 155,710
			260,650	208,170 – 317,040

In the Armidale management zone, the densities of eastern grey kangaroos in the two survey strata were found to be quite similar (Table 6; z = 0.21; P = 0.835), which was also the case with the result of the 2019 survey (z = 0.34; P = 0.736). Before the onset of the 2017-2019 drought, the result of the 2016 survey had been such that the density of eastern grey kangaroos in the medium density stratum was, surprisingly, estimated to be some 80% higher than it was in the high density stratum (z = 2.79; P = 0.005). The 2016 result was the opposite of the results of the surveys conducted previously back to 2004, and would have to be considered to be unusual and somewhat counter-intuitive. With regard to the two survey strata in this management zone (Fig. 3), the high density stratum is on the eastern fall of the Northern Tablelands and has higher average rainfall than does the medium density stratum which is on the western fall of the tablelands. With the higher rainfall in the high density stratum has usually come higher densities of macropods; eastern grey kangaroos, at least.

In the Upper Hunter management zone, the density of eastern grey kangaroos in the high density survey stratum was found to be some 60% higher than it was in the medium density stratum (Table 6; z = 2.45; P = 0.014). This was similar to the situation in 2019, when the density of eastern grey kangaroos in the high density stratum was estimated to be some 70% higher than it was in the medium density stratum (z = 1.97; P = 0.048). These two results were also similar to that of the survey of this management zone conducted in 2016, when the density of eastern grey kangaroos in the high density stratum was also estimated to be some 67% higher than it was in the medium density stratum (z = 2.22; P = 0.027).

The consistent difference in the eastern grey kangaroo (and wallaroo) numbers between survey strata in the Upper Hunter management zone can probably be explained by the fact that the landscape of high density stratum is hilly, tending towards being steep, and managed principally for livestock grazing. It extends into the foothills and slope of the Liverpool Range. The medium density stratum comprises a more even landscape and is managed for some mixed cropping along with livestock grazing. The large low density stratum in this management zone (Fig. 4) is, in the main, dominated by cropping and is, from a landscape and habitat perspective, not particularly amenable for supporting kangaroo populations. Unlike the situations in the other two management zones where the 2017-2019 drought may have had some effect on the relative densities of kangaroos within survey strata, it would appear that, this was not the case here, even though it had an effect on changes in total numbers.

The densities of clusters of common wallaroos along with the corresponding population densities within the two survey strata of each kangaroo management zone are given in Table 8. These density estimates are also given in Table 9 along with the corresponding population abundances for each kangaroo management zone.

Table 8. Results of the helicopter line transect surveys of common wallaroos conducted in the three Northern Tablelands kangaroo management zones (KMZ) in September, 2022. Given along with the areas of the two strata surveyed in each zone, are the densities of clusters of wallaroos sighted (D_s) and wallaroo population densities (D). Given in association with the density estimates are the empirically-estimated and bootstrap-estimated coefficients of variation (cv %), and the bootstrap confidence intervals. Details of the most parsimonious detection function models used to determine these densities are given in Table 5. Densities are rounded to two decimal places.

KMZ/stratum	Area (km^2)	Cluster density (km^{-2})				Wallaroo density (km^{-2})			
		D_s	cv (%)	95% bootstrap confidence interval	cv_{boot} (%)	D	cv (%)	95% bootstrap confidence interval	cv_{boot} (%)
Glen Innes									
High	4,774	3.47	20.5	2.32-4.91	18.3	6.27	21.3	3.88-8.83	20.7
Medium	12,467	1.43	23.8	0.88-2.09	21.0	2.66	25.7	1.41-3.94	25.2
Armidale									
High	9,078	1.72	17.3	1.18-2.32	16.8	3.28	18.3	2.10-4.68	20.4
Medium	5,945	3.63	27.4	2.20-5.53	24.2	7.38	27.9	4.00-11.27	26.4
Upper Hunter									
High	3,552	4.84	18.4	3.47-6.31	15.1	11.33	24.0	7.77-15.07	16.6
Medium	4,431	2.43	24.0	1.47-3.67	23.1	4.70	24.7	2.80-7.14	23.5

Table 9. The common wallaroo densities (D) and abundances (N) for the two strata surveyed in each of the three Northern Tablelands kangaroo management zones (KMZ). Given in association with the estimates are bootstrap confidence intervals. The abundances and confidence intervals given in bold are the combined, whole-zone estimates. Densities are rounded to two decimal places.

KMZ/stratum	D (km^{-2})	95% bootstrap confidence interval	N	95% bootstrap confidence interval
Glen Innes				
High	6.27	3.88-8.83	29,910	18,520-42,160
Medium	2.66	1.41-3.94	33,130	17,600-49,170
			63,040	42,540-83,370
Armidale				
High	3.27	2.10-4.68	29,720	19,140-42,490
Medium	7.37	4.00-11.27	43,800	23,780-66,980
			73,520	49,410-99,360
Upper Hunter				
High	11.33	7.77-15.07	40,250	27,590-53,530
Medium	4.70	2.80-7.14	20,820	12,420-31,650
			61,070	45,590-79,500

In the Glen Innes management zone, the density of wallaroos in the higher density survey stratum was found to be some 2.35X higher than it was in the medium density stratum (Table 8: z = 2.94; P = 0.003). This outcome was contrary to that of the survey conducted in this management zone in 2019, when it was found that there was no difference in wallaroo densities between the two survey strata (z = 0.35; P = 0.724). Prior to that, the survey conducted in 2016 found that the density of wallaroos in the high density stratum was estimated to be 2.27X higher than it was in the medium density stratum (z = 3.17; P = 0.002).

In the Armidale management zone, density of wallaroos in the medium density (western) stratum was estimated to be some 2.25X higher than that it was in the high density (eastern) stratum (Table 8; z = 1.92; P = 0.056). This was similar to the outcome of the 2019 survey, when it was found that the density of wallaroos in the medium density stratum was estimated to be some 3.67X higher than that it was in the high density stratum (z = 2.91; P = 0.004). This was also comparable to the outcome of the 2016 survey, when the density of wallaroos in the medium density stratum was estimated to be some 3.48X higher than it was in the high density stratum (z = 3.96; P = 0.000). The landscape of the medium density (western) stratum would appear to be more suitable for wallaroos than the landscape of the high density (eastern) stratum.

In the Upper Hunter management zone, the density of wallaroos in the higher density survey stratum was found to be some 2.71X higher than it was in the medium density stratum (Table 8; z = 5.23; P = 0.001). In 2019, the density of wallaroos in the high density stratum was some 1.90X higher than was found in the medium density stratum (z = 2.52; P = 0.012). In 2016, the density of wallaroos in the high density stratum was some 2.77X higher than it was in the medium density stratum (z = 2.95; P = 0.003). The steeper landscape of the high density stratum presents particularly suitable habitat for wallaroos. In regions such as the Northern Tablelands of NSW, wallaroos have a preference for rocky and hilly habitat (Taylor 1985).

The densities and abundances of wallaroos are presented in two forms, uncorrected (Tables 8 and 9) and corrected (Table 10). 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 from walked line transect sampling. Supportive of this was the outcome of a similar study conducted in the Barrier Ranges in 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 from walked line transect surveys (S. C. Cairns, A. R. Pople & J. Gilroy, *unpubl. data*).

The population estimates and corresponding whole-zone densities of eastern grey kangaroos and wallaroos in the three kangaroo management zones are given in Table 10. For eastern grey kangaroos, the population estimates were determined by summing the population estimates for the two strata of each zone that were surveyed (Table 7). For wallaroos, these population estimates were determined by summing the abundances for the two strata surveyed in each zone (Table 9) and multiplying this total by a correction factor of 1.85. The densities given in Table 10 differ from those for eastern grey kangaroos given in Table 7, and those for wallaroos given in Table 9 because they have been determined from the population abundance estimates in relation to the total area of the three survey strata in each management zone. In relation to the conduct of these surveys, the low density stratum of each management zone was assumed to support, at the most, only trace numbers of kangaroos, and was therefore not surveyed.

Table 10. Estimated whole-zone total abundances (N) and population densities (D) of eastern grey kangaroos and common wallaroos in the three Northern Tablelands kangaroo management zones (KMZ). 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 adjusted by a correction factor of 1.85 (see text). Densities are rounded to two decimal places.

KMZ		Eastern grey kangaroos		Common wallaroos	
	Area (km^2)	N	D (km^{-2})	N	D (km^{-2})
Glen Innes	18,449	439,220	23.81	116,620	6.32
Armidale	15,809	446,700	28.26	136,010	8.60
Upper Hunter	14,004	260,650	18.61	112,980	8.07

Helicopter line transect surveys of the form reported on here were first undertaken in the three Northern Tablelands kangaroo management zones in 2004 (Cairns 2004). For the purpose of comparison, these surveys produced baseline density estimates of eastern grey kangaroos of 8.8 km^{-2}, 7.8 km^{-2} and 5.1 km^{-2} for each of the Glen Innes, Armidale and Upper Hunter management zones, respectively. These surveys were conducted at a time during the more severe part of the Millennium drought, which had extended over the period 1997-2009 (http://www.bom.gov.au/climate/drought/knowledge-centre/previous-droughts.shtml). These baseline densities were lower than previous density estimates available for the Northern Tablelands region that were obtained from walked line transect surveys conducted by Southwell *et al.* (1997) over the period 1987-1992 (13.2-22.0 km^{-2}), which was well before the beginning of the Millennium drought. In relation to this, it could be expected that, free of drought conditions, eastern grey kangaroo densities in the Northern Tablelands would usually be higher than these baseline estimates.

Over the 12-year period extending from 2004 through to 2016, the eastern grey kangaroo populations in these three management zones were found to have increased in size by a factor of ~3.5X (Cairns, Bearup & Lollback 2017). This upward trend in population sizes peaked in 2016, prior to the beginning of the 2017-2019 drought, which appeared to have the effect of curtailing further population increases (Cairns, Bearup & Lollback 2020a).

Although the impact of the 2016-2019 drought was considered as being particularly severe in some parts of NSW, its effect on the eastern grey kangaroo populations in the Northern Tablelands was variable. In relation to the results of the 2019 surveys, the drought appeared not to have had a great deal of effect on the eastern grey kangaroo populations in the northern (Glen Innes zone) and middle (Armidale zone) parts of the Northern Tablelands, but did have a substantial impact on the population in southern part of the broader region (Upper Hunter zone). Between 2016 and 2019, the eastern grey kangaroo populations in the Glen Innes and Armidale management zones registered only marginal declines in numbers (Cairns, Bearup & Lollback 2020a). Compared to this though, the population in the Upper Hunter zone declined by some 36% over this period. In relation to this, further appraisal of the post-drought changes that occurred in the eastern grey kangaroo and wallaroo populations in the Northern Tablelands management zones follows, beginning with the results of the 2022 surveys (Table 10).

The size of the eastern grey kangaroo population in the Glen Innes management zone in 2022 was estimated to be 439,220 individuals. This compared to a 2019 population estimate of 547,840 kangaroos. The apparent decline in population size was, however, not significant ($z = 1.24$; $P = 0.215$), therefore indicating that there was effectively no change in the size of the eastern grey population in this management zone over the period 2019-2022. In comparison with this, there had, similarly, been no significant change in the size of this population over the period 2016-2019 (Cairns, Bearup & Lollback 2020a). Prior to 2016 and, therefore prior to the onset of the 2017-2019 drought, numbers had increased by some 57% over the three-year period leading up to the 2016 survey (Cairns, Bearup & Lollback 2017).

In the Armidale management zone, there was an apparent, but not significant ($z = 0.33$; $P = 0.740$) increase in the size of the eastern grey kangaroo population, from 416,660 individuals in 2019 to 446,700 in 2022. Similar to this, there had also been no significant change in numbers over the previous three-year period, 2016-2019. Prior to that, the eastern grey kangaroo population in this management zone had increased by some 60% over the preceding three-year period, 2013-2016.

In contrast to the Glenn Innes and Armidale management zones, in the Upper Hunter management zone the eastern grey kangaroo population was found to have increased significantly ($z = 2.57$; $P = 0.010$) by a factor of 1.56X, from 166,510 individuals in 2019 to 260,650 in 2022. In comparison with this, numbers had previously declined by a significant 36% over the period 2016-2019. This recorded decline had followed a doubling in numbers over the previous three-year period, 2013-2016. That increase had followed a previous decline of some 25% in the size of the population over the period 2010-2013.

In the Glen Innes and Armidale management zones, a pattern of increasing eastern grey kangaroo numbers from 2004 through until 2016 was followed, in association with the occurrence of the 2017-2019 drought, by an extended period over which the sizes of these two populations effectively remained steady. However as outlined above, the trend in eastern grey kangaroo numbers in Upper Hunter management zone contrasted sharply over the last three survey periods (2013-2022) with the trends found in the other two management zones.

Compared to eastern grey kangaroos, the wallaroo populations in the Northern Tablelands are relatively small (Table 10). For the purpose of comparison, the baseline densities of wallaroos estimated from the surveys conducted in 2004 were 2.5 km^{-2}, 3.9 km^{-2} and 4.4 km^{-2} for the Glen Innes, Armidale and Upper Hunter management zones, respectively. Over the 12-year period from 2004 to 2016, these wallaroo populations increased in size by some ~2-3X (Cairns, Bearup & Lollback 2017).

Between the 2019 and 2022, the wallaroo population in the Glen Innes management zone registered an apparent, but not significant ($z = 0.65$; $P = 0.515$), decrease in size from a population of 136,820 individuals in 2019 to one of 116,620 in 2022. In comparison with this, no change in wallaroo numbers had been found to have occurred between 2016 and 2019 (Cairns, Bearup & Lollback 2020a). Prior to this, the wallaroo population in this management zone had increased by a factor of ~2.67X between 2013 and 2016 (Cairns, Bearup & Lollback 2017).

Between the 2019 and 2022, the wallaroo population in the Armidale management zone registered an apparent but not significant ($z = 0.57$; $P = 0.569$) increase in size from a population of 117,290 individuals in 2019 to one of 136,010 in 2022. In comparison with this, there was no change found to have occurred in the size of the population between 2016 and 2019. This apparent stability for the extended period of 2016-2022 had followed a doubling in numbers over the previous three-year period, 2013-2016.

In contrast to the Glenn Innes and Armidale management zones, the wallaroo population in the Upper Hunter management zone had been found to have increased significantly ($z = 3.82$; $P < 0.001$) by a factor of ~2.5X, from 45,080 individuals in 2019 to 112,980 in 2022. In comparison with this, numbers had declined by a significant 67% over the period between the 2016 and 2019 surveys. This decline followed an extraordinary apparent ~8.25X increase in numbers over the previous three-year period (2013-2016), which had, in turn, followed a decline in numbers by some 67% over the three-year period before that (Cairns, Bearup & Lollback 2013). These apparent erratic changes in wallaroo numbers in this management zone contrasted sharply over the last three survey periods with the trends found in the other two management zones.

The surveys of the three kangaroo management zones were designed with the intention of providing population estimates with coefficients of variation of 20% for eastern grey kangaroos and possibly 30% for wallaroos. This aim was essentially achieved with the present surveys. Examination of the bootstrap coefficients of variation for the estimates of eastern grey kangaroo numbers that are given in Table 6 shows that, within the survey strata of each management zone, they fall into the range 11-19%. Examination of the bootstrap coefficients of variation for the estimates of wallaroo numbers that are given in Table 8 shows that they fall into the range 17-26%. In previous surveys, the anticipated level of precision has generally been achieved with regard to the eastern grey kangaroo population estimates, but this has not always been the case with regard to the wallaroo population estimates.

Table 11. Results of the helicopter line transect surveys of red-necked wallabies (RNW) and swamp wallabies (SW) conducted in the three Northern Tablelands kangaroo management zones (KMZ) in September, 2019. Given are the numbers of sightings (n), the densities of clusters of wallabies sighted (D_s) and wallaby population densities (D). Given in association with these estimates are the empirically-estimated and bootstrap-estimated coefficients of variation (cv %), and the bootstrap confidence intervals. Densities are rounded to two decimal places.

KMZ	Cluster density (km^{-2})					Wallaby density (km^{-2})			
	n	D_s (km^{-2})	cv (%)	95% bootstrap confidence interval	cv_{boot} (%)	D (km^{-2})	cv (%)	95% bootstrap confidence interval	cv_{boot} (%)
<u>Glen Innes</u>									
RNW	100	2.82	14.1	2.03-3.92	16.7	3.93	14.7	2.77-5.51	17.2
SW	70	2.72	17.3	1.81-3.49	16.8	3.03	17.6	1.98-3.85	17.0
<u>Armidale</u>									
RNW	19	0.58	23.0	0.33-0.88	23.5	0.77	25.1	0.39-1.21	25.6
SW	29	1.22	26.6	0.56-1.93	28.9	1.30	27.0	0.51-1.93	29.9
<u>Upper Hunter</u>									
RNW	23	0.65	27.1	0.36-1.10	22.2	1.06	28.9	0.45-1.65	29.9
SW	30	1.17	26.4	0.63-1.75	25.7	1.26	28.2	0.71-2.14	28.5

Regarding the two incidental species of macropod observed in these surveys, the red-necked wallaby and swamp wallaby, population density estimates across the three management zones are given in Tables 11. Overall, the densities of both these species were similarly low compared to those of eastern grey kangaroos and wallaroos. Both these species were more abundant in the Glen Innes management zone than in the Armidale and Upper Hunter zones. The precision of the estimates for both species were quite reasonable; being comparable to the precision of the estimates of eastern grey kangaroos and wallaroos (Tables 6 and 8). Although both these species of wallaby occur in quite low numbers, they, nevertheless, should, from an ecological perspective, be considered as being significant components of the macropod communities of the Northern Tablelands of NSW.

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As with any project, the job is never completed without the support of others who either wittingly or unwittingly are drawn in to provide assistance. Co-authors David Bearup and Greg Lollback both provided invaluable GIS support, without which projects such as this would have foundered. As well as filling the role of a very able observer during the conduct of the surveys, co-author David Bearup also provided invaluable support with regard to day-to-day management and survey planning. Mika Saunders, Neil Marks and Steve Chapple more than ably filled seats as observers, along with David Bearup. The flight and ground crews provided excellent and obliging service with the helicopter. Their attention to OH&S issues was well appreciated.

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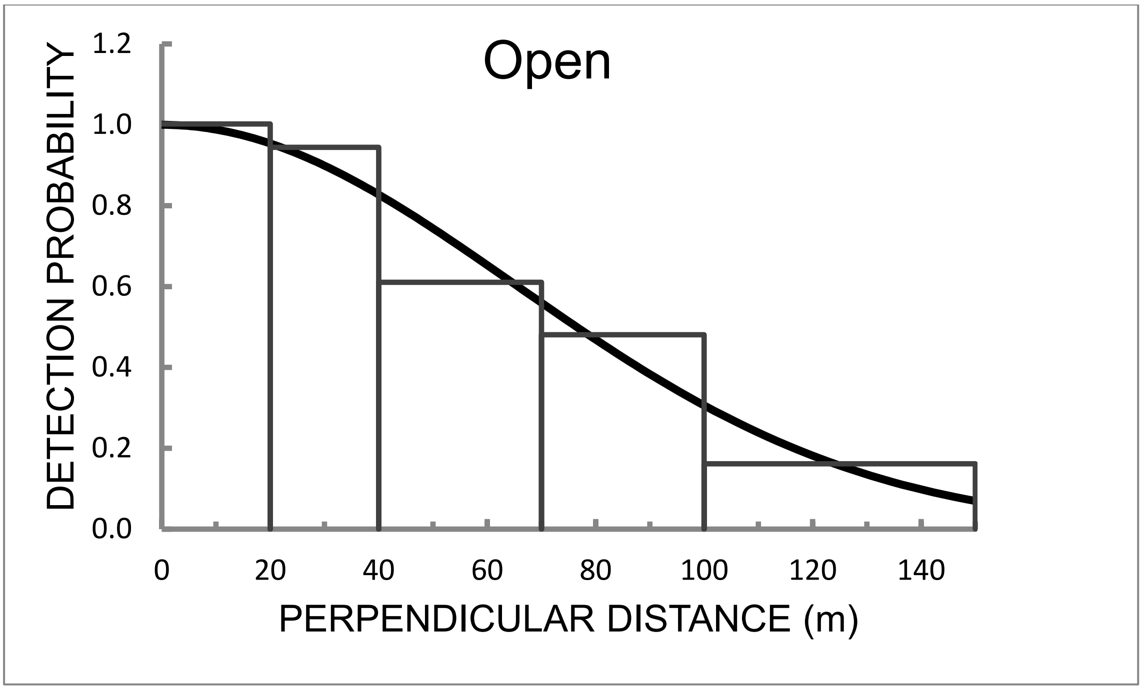
Appendix 1

Figs. A1.1-A1.9

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 three Northern Tablelands kangaroo management zones.



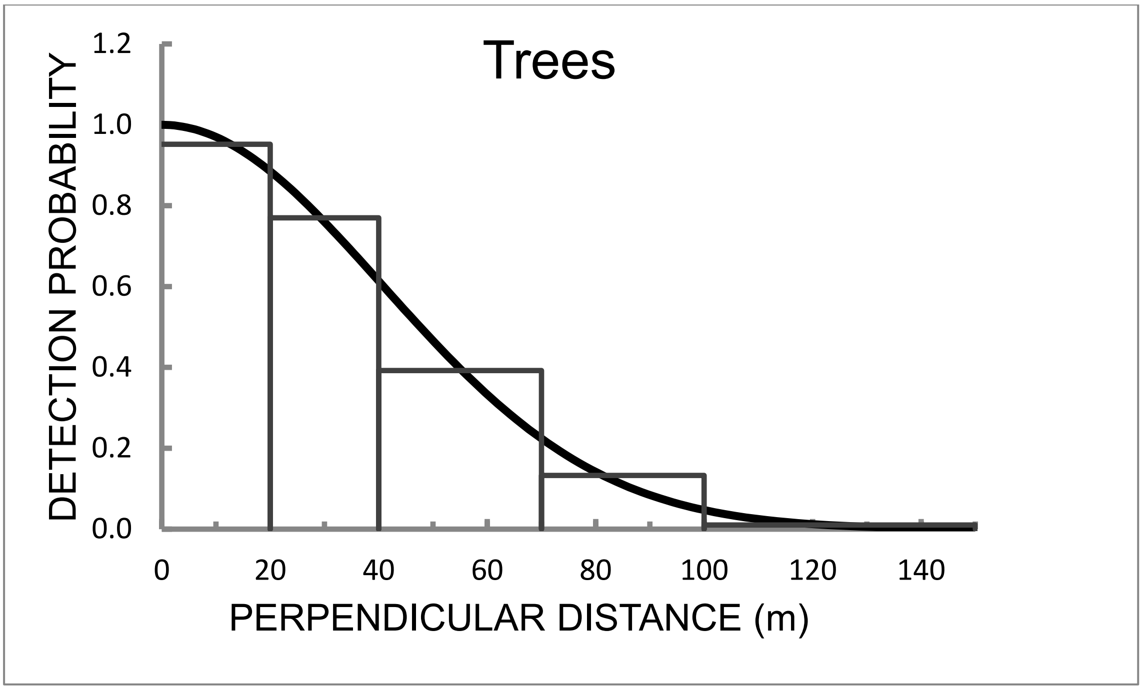


Fig. A1.1. The Half-normal detection functions for eastern grey kangaroos in the Glen Innes kangaroo management zone. For details of the model fitted using the MCDS analysis engine with Cover at point-of-detection as a covariate, see text and Table 4.

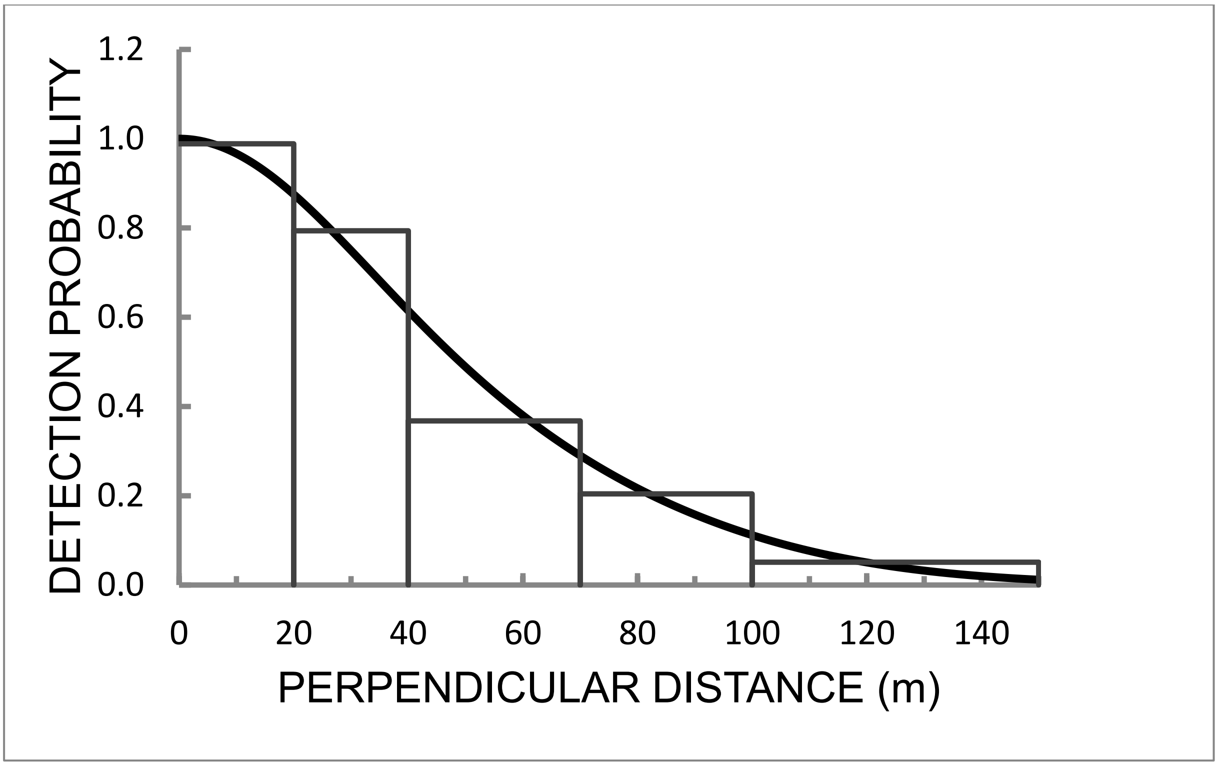
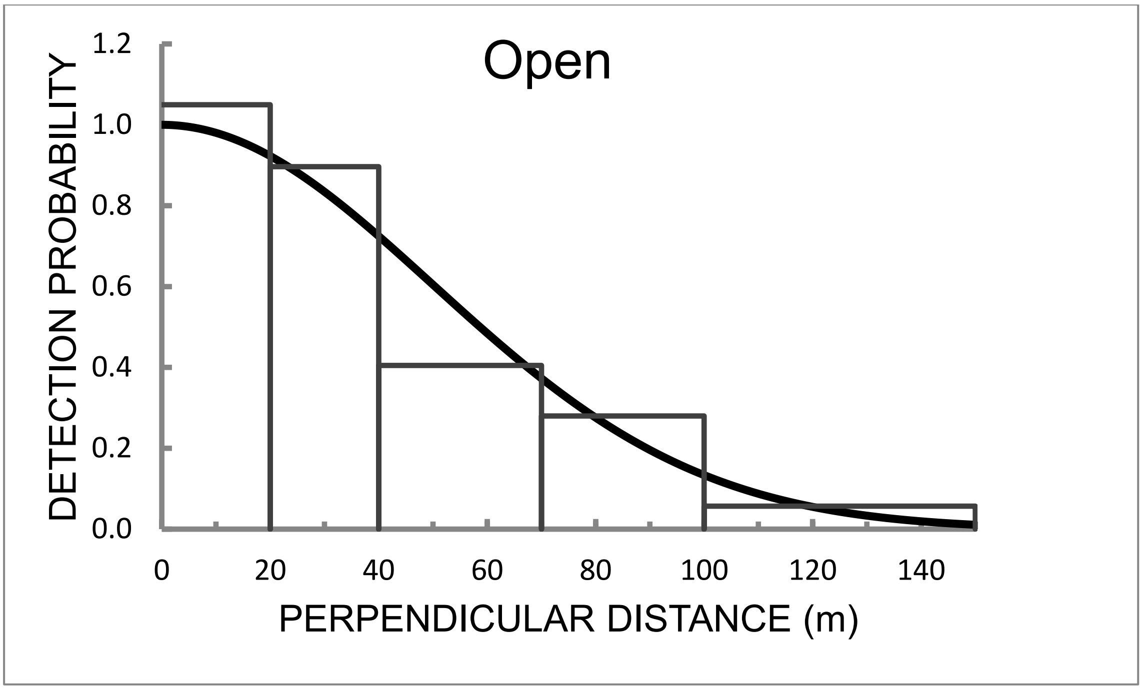


Fig. A1.2 The Half-normal detection function for eastern grey kangaroos in the Armidale kangaroo management zone. For details of the model fitted using the MCDS analysis engine with Observer as a covariate, see text and Table 4.



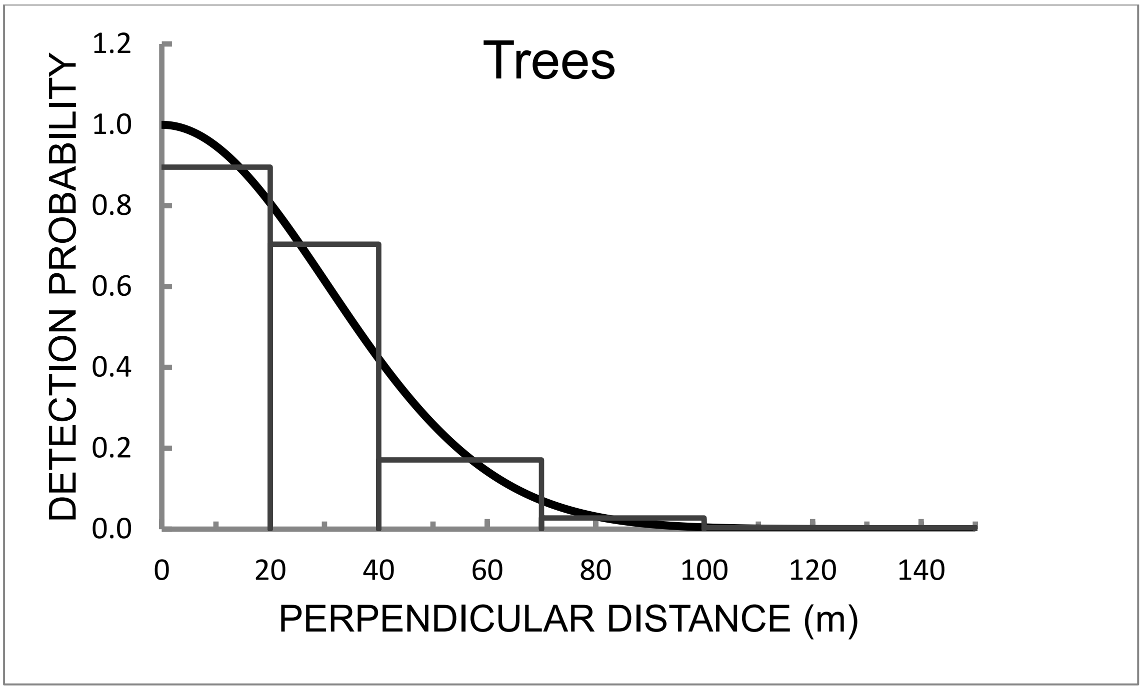


Fig. A1.3. The Half-normal detection functions for eastern grey kangaroos in the Upper Hunter kangaroo management zone. For details of the model fitted using the MCDS analysis engine with Cover at point-of-detection as a covariate, see text and Table 4.

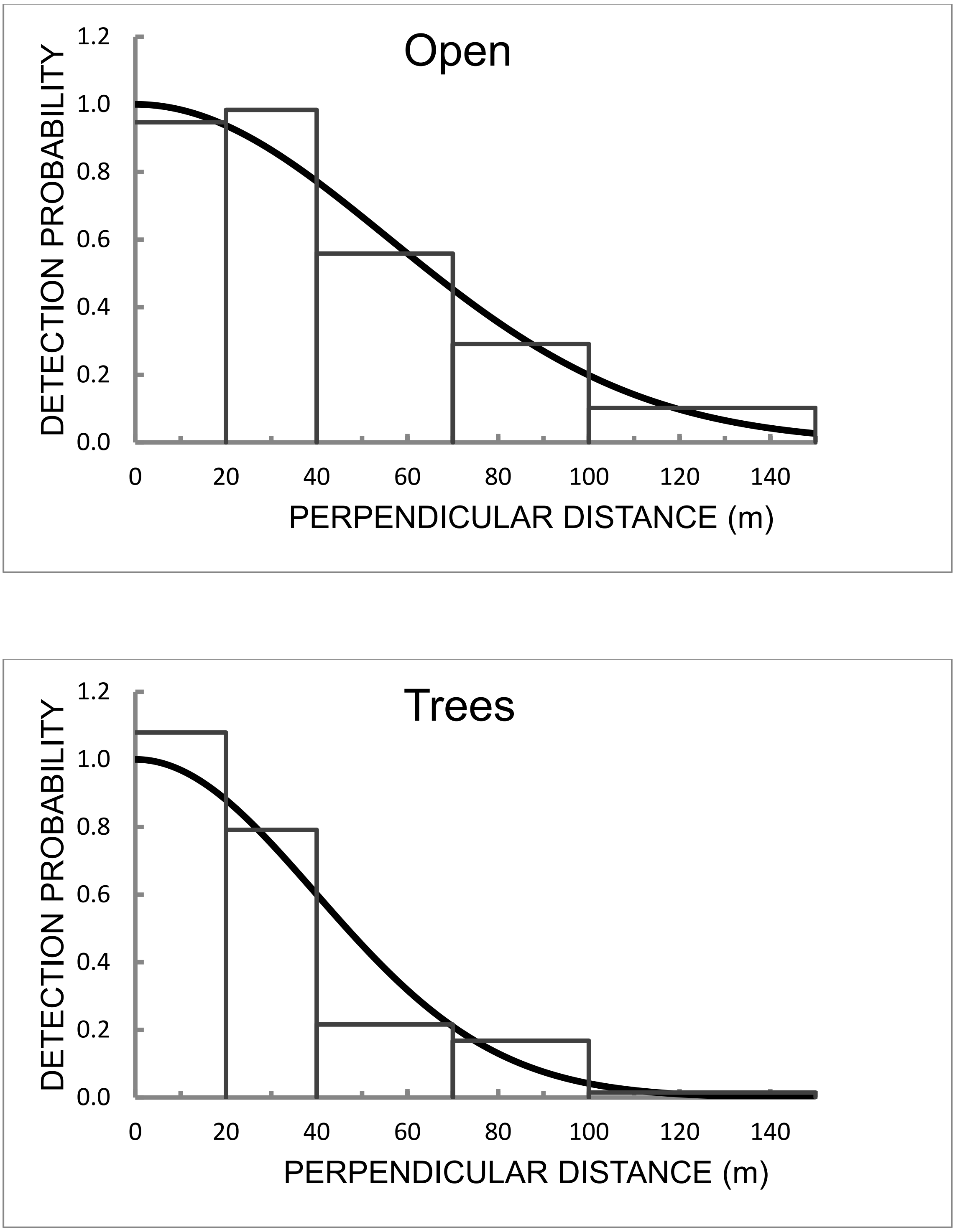


Fig. A1.4. The Half-normal detection functions for common wallaroos in the Glen Innes kangaroo management zone. For details of the model fitted using the MCDS analysis engine with Cover at point-of-detection as a covariate, see text and Table 5.

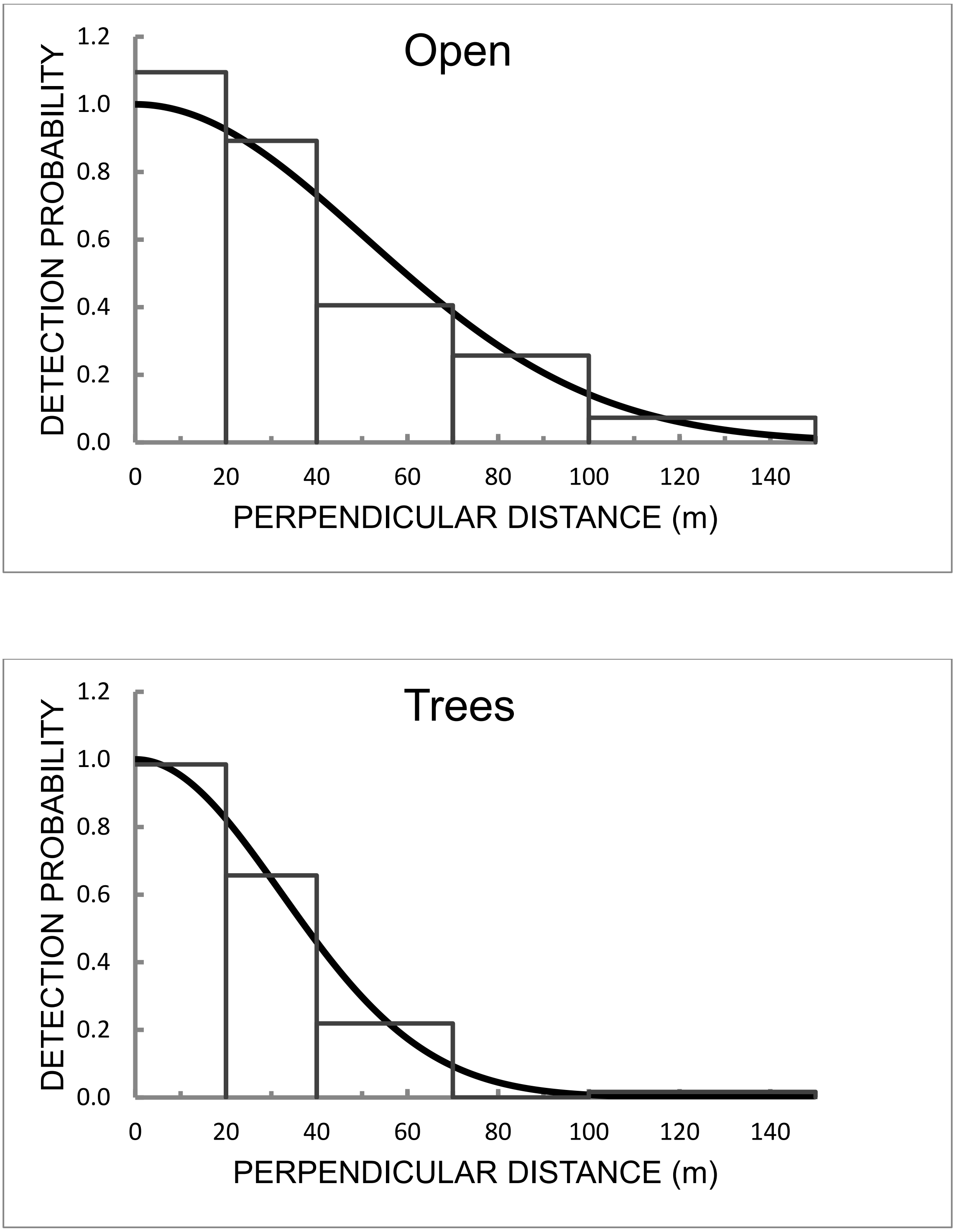
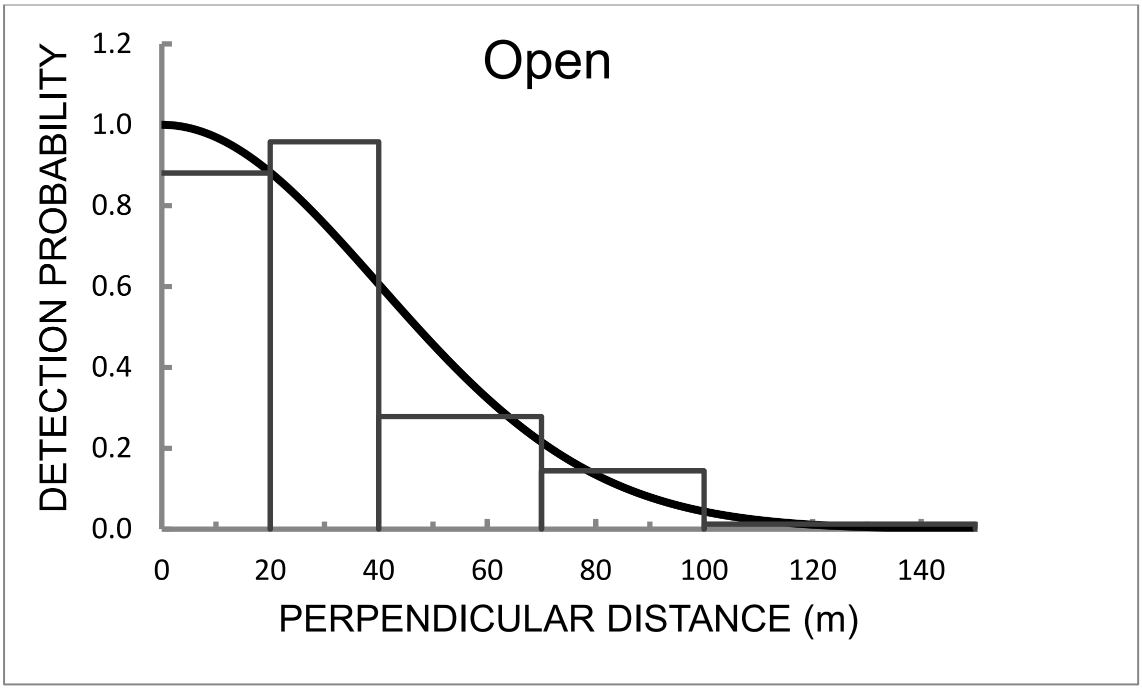


Fig. A1.5. The Half-normal detection functions for common wallaroos in the Armidale kangaroo management zone. For details of the model fitted using the MCDS analysis engine with Cover at point-of-detection as a covariate, see text and Table 5.



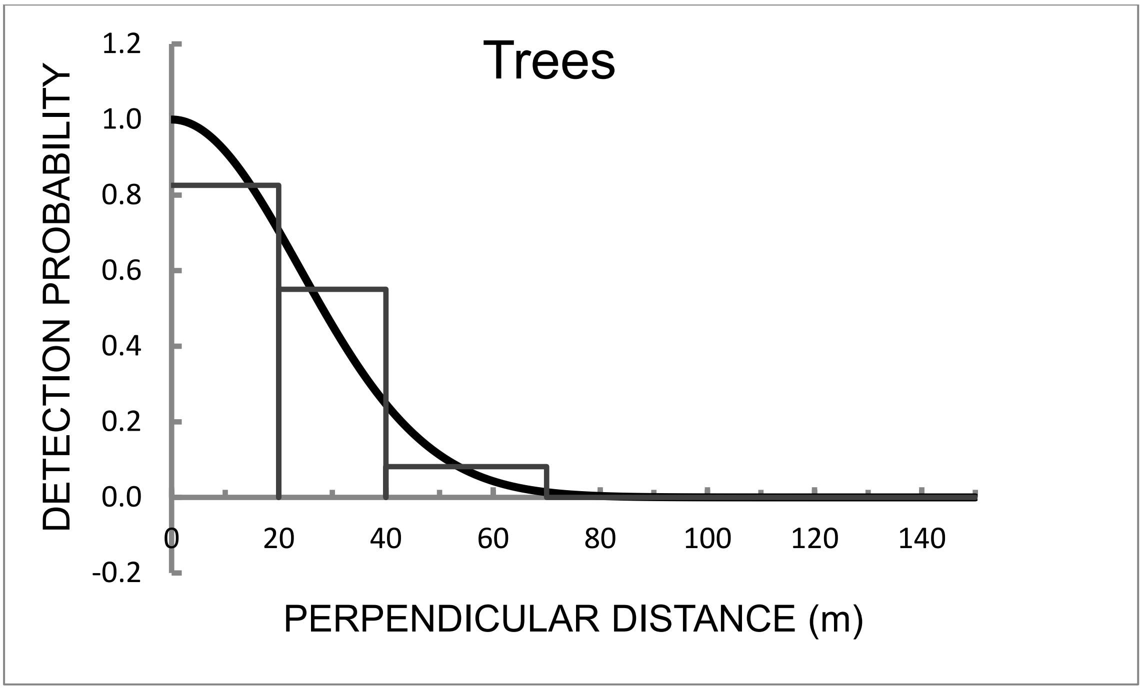
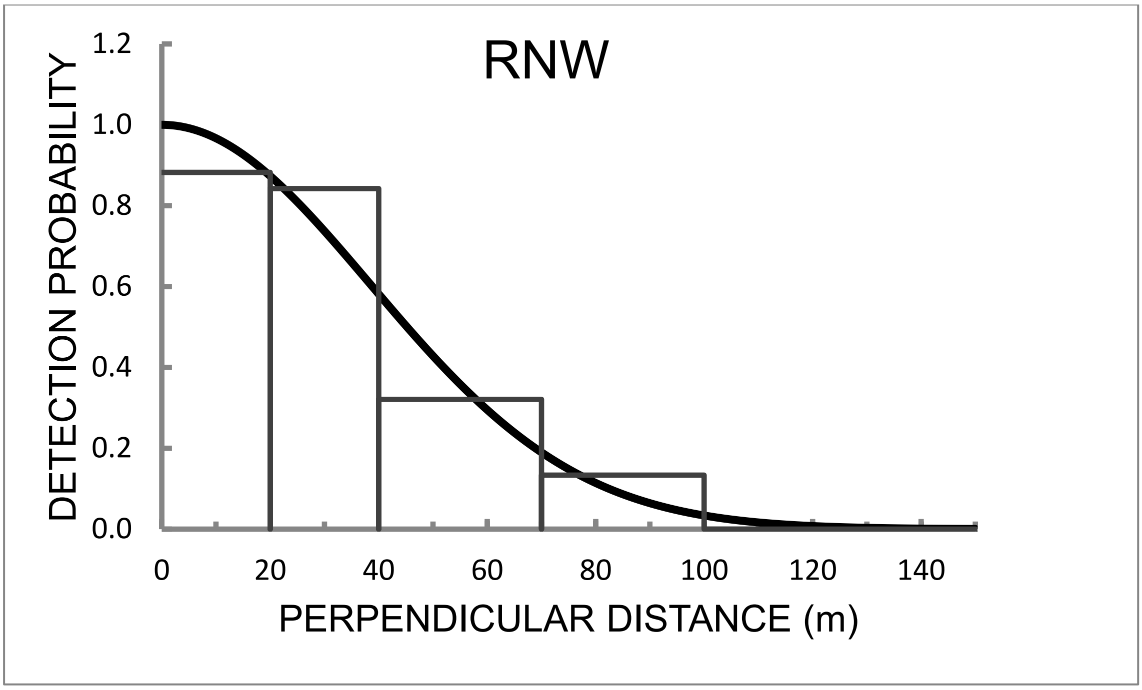


Fig. A1.6. The Half-normal detection functions for common wallaroos in the Upper Hunter kangaroo management zone. For details of the model fitted using the MCDS analysis engine with Cover at point-of-detection as a covariate, see text and Table 5.



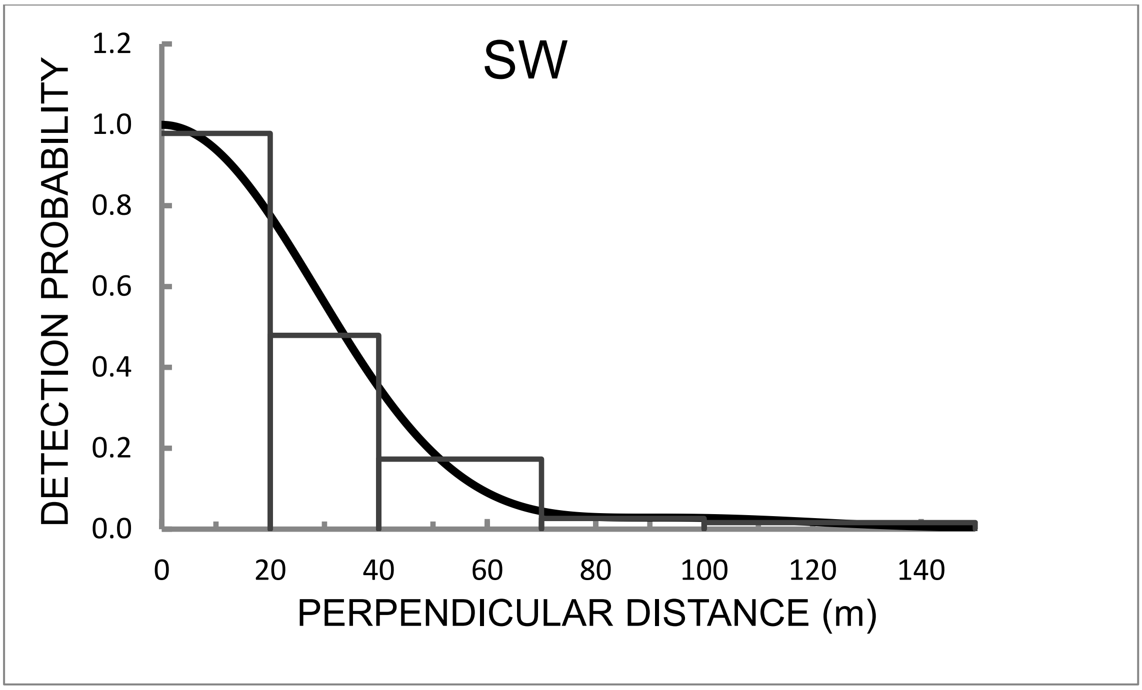
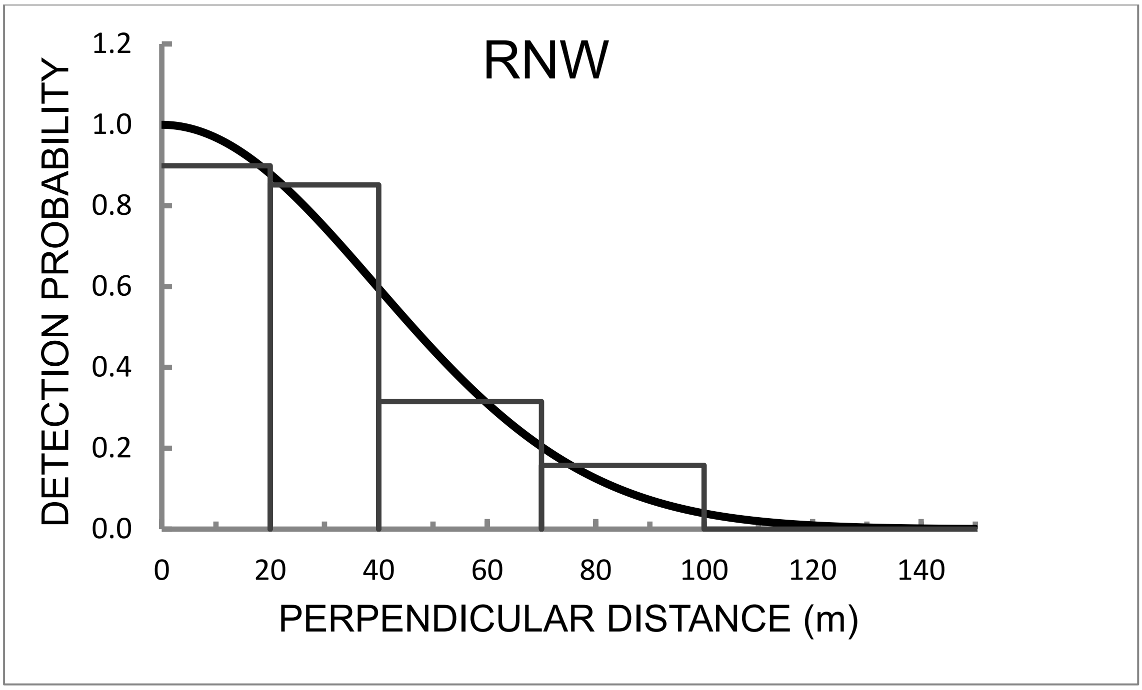


Fig. A1.7. The Half-normal/Cosine detection function for red-necked wallabies (RNW) and swamp wallabies (SW) in the Glen Innes kangaroo management zone. For details of the model fitted using the CDS analysis engine, see text.



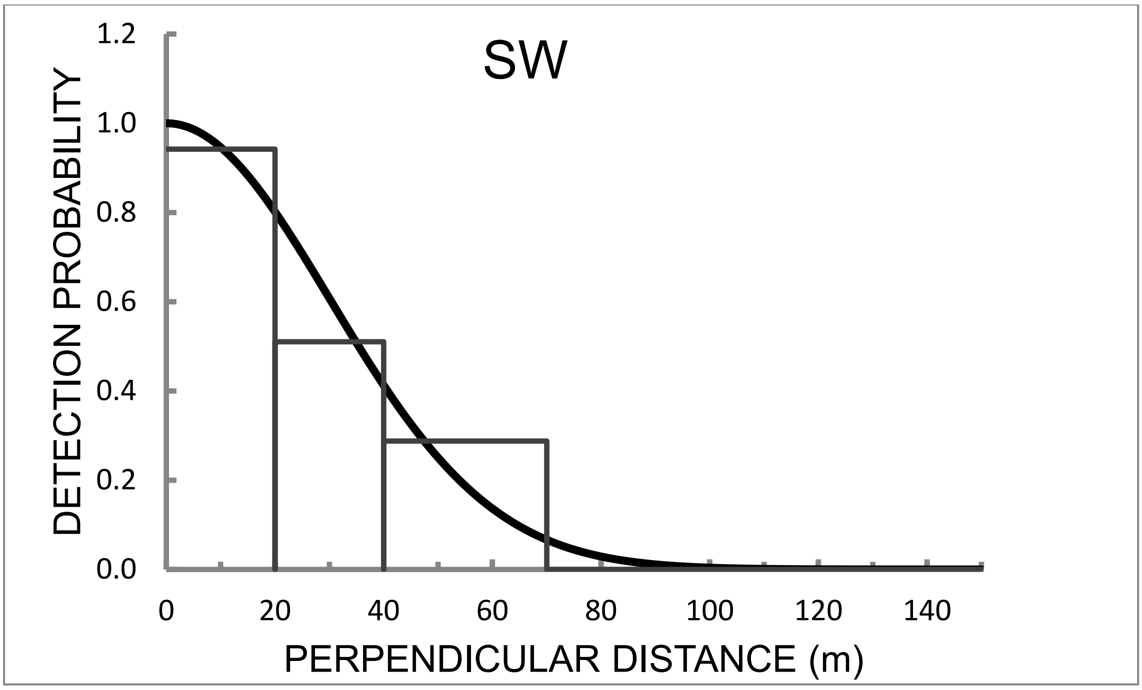
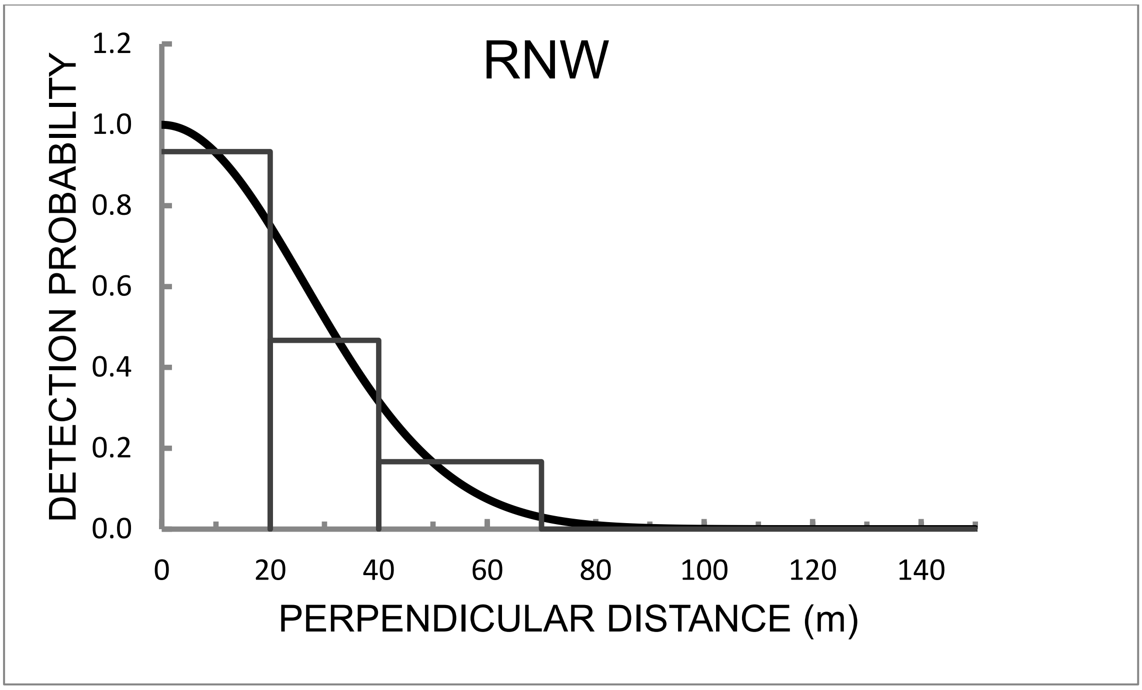


Fig. A1.8. The Half-normal/Cosine detection function for red-necked wallabies (RNW) and swamp wallabies (SW) in the Armidale kangaroo management zone. For details of the model fitted using the CDS analysis engine, see text.



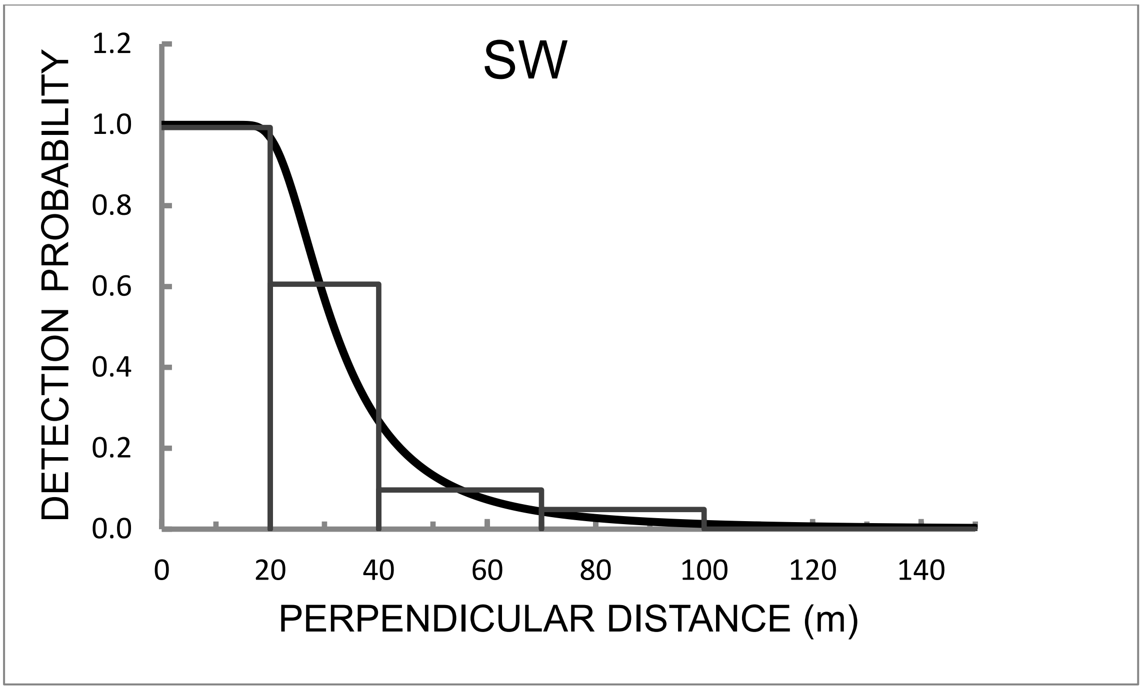


Fig. A1.9. The half-normal/Cosine detection function for red-necked wallabies (RNW) and the Hazard-rate detection function for swamp wallabies (SW) in the Upper Hunter kangaroo management zone. For details of the model fitted using the CDS analysis engine, see text.