Animal pests: distance sampling for Bennett's wallaby

Version 1.0

This specification was prepared by David M. Forsyth and Kennedy Lange in 2012.

Contents

Department of Conservation
Te Papa Atawhai

Synopsis

Figure 1. Bennett's wallaby (photo: G. Coulson).

The suitability of distance sampling to estimate the density and abundance of Bennett's wallaby (*Macropus rufogriseus*) in a 3875 ha area of montane grassland habitat in the Hunters Hills was assessed in February 2010. Distance sampling showed promise for estimating the density and abundance of Bennett's wallaby. The way that distance sampling will be employed to estimate the density and abundance of Bennett's wallaby will depend on circumstance (e.g. habitat, history of hunting/control, population density), but we recommend the following key steps:

1. **Survey objective(s) and area**
   Define the survey objective(s) and the study area. Is distance sampling the best of the available methods to address the survey objective(s) given the study area's size, terrain, and vegetation, particularly in light of the required resources? If yes, proceed to the survey design and planning stage.

2. **Survey design and planning**
   The best approach is to systematically sample the study area with transects that sample across the grain of the habitat (i.e. across gullies rather than down or up). The study area may be stratified on the basis of habitat (e.g. grassland and forest) or expected densities (e.g. as a consequence of control history). A minimum of 15–20 transects is recommended, and consideration should be given to zigzag transects to minimise time spent walking between transects. For small study areas, fewer transects can be sampled multiple times. A minimum of 60–80 observations are required to robustly estimate density using distance sampling, so consideration needs to be given to how much survey effort (i.e. number of transects and number of times each transect is walked) is required to achieve this. It may be prudent to walk a sub-sample of transects once to estimate what resources will be required for the survey in terms of people, equipment and transport, etc.

3. **Observer training**
   Careful training of observers is required, and resources need to be allocated to this task.

Observers must understand how to walk and search transects, and how to use equipment (e.g. a laser range finder and sighting compass) correctly.

4. **Data collection**
   Data should be collected as accurately as possible and entered into a standardised field sheet. Data should be checked by the field team leader after the first transects have been completed and again at the end of the field trip.

5. **Data entry and storage**
   Field sheets should be scanned and saved as *.pdf documents, and electronic and hard copies stored and archived. The data should be entered into a spreadsheet or database and archived, and imported into the latest version of DISTANCE (Thomas et al. 2009) for analysis.

6. **Analysis**
   The analyst(s) should familiarise themselves with how other macropod distance sampling studies have been analysed. First, exploratory data analysis is conducted to understand the data and identify problems. Particular problems in wallaby surveys would be too few detections close to the transect line (most usually caused by animals moving away before the observer detects them) or, as occurred in our study, a 'spike' of observations at zero (usually caused by observers rounding small angles down to zero). The second stage of analysis is model selection. Truncation (left and/or right) of data and definition of intervals/cutpoints (for histograms, goodness-of-fit and other diagnostic tests) are conducted at this stage. The third and final stage of analysis is inference from the best model(s).

7. **Reporting**
   The final report should include sufficient information so that your study could be duplicated by another person without your assistance. It would therefore be useful to report the electronic locations of the scanned field sheets, stored data and DISTANCE project. The report should also include the study objectives and design, the observers used and any training given, and a detailed summary of the three stages of analysis (i.e. exploratory data analysis, model selection and inference from the best model(s)).

Assumptions

- All animals on the transect line are detected ($p(0) = 1$), although violation of this assumption *may* be accommodated.
- Animals do not move prior to detection. A snapshot is usually obtained—all animals are detected as if stationary.
- Distances from the transect line to animals are accurately measured.
- Individuals, or clusters of individuals, are detected independently of other such sample units.
- Transects are distributed over the area of interest according to a probability-based sampling design (simple random, systematic, stratified, etc.).
- The animal population remains constant throughout the survey period.

Advantages

- If the assumptions hold, distance sampling can provide robust estimation of abundance more cheaply than mark–recapture/resight methods.
- Not all animals within the study area need be counted.
- Compared to mark–recapture methods, the modelling component is relatively straightforward (largely a software issue).
- Providing the first assumption holds, the potential for bias introduced by pooling data from observations with different detection probabilities is significantly reduced (i.e. they are 'pooling robust'). This is a very powerful feature of distance sampling.
- Unbiased population estimates can be compared across time and space.
- Analysis of distance data has been dramatically simplified by the software DISTANCE (Thomas et al. 2009).

Disadvantages

- Violation of critical assumptions may cause serious errors in density and abundance estimates. These assumptions are usually violated to some degree in most animal surveys using this method: the question is to what extent.
- Application of the method in some habitats (e.g. thick forest) can be problematic.
- Sampling design must be considered on a case-by-case basis given the topography and vegetation in the area of interest.
- The minimum number of detections required to model the detection function is relatively large. As a rule of thumb, 60 detections are required as a minimum for distance sampling surveys, and estimates tend to improve with more detections. Distance sampling is therefore unlikely to be suitable for low-density populations, particularly if it is necessary to stratify data to account for habitat and observer differences. Pooling data may alleviate this potential problem in some circumstances.
- Observer training is necessary to ensure that the key assumptions of distance sampling are, as far as is possible, met. It should be recognised that not all field staff may be competent to conduct distance sampling. Observer training is therefore a critical component of any distance sampling programme.
- The cost and effort required to obtain data suitable for unbiased and precise population estimates may exceed available funding.

Suitability for inventory

The expense of distance sampling is not usually justified for inventory.

- Specialist skills for design and analysis are also likely to be in short supply and expensive.
- Costs (labour and money) can be large and the results obtained often beyond that required for simple inventory.

Suitability for monitoring

- If the critical assumptions listed above can be met (or at least not grossly violated) and sufficient resources are available, distance sampling can provide robust and unbiased estimates of density and abundance.
- Comparison of density/abundance estimates over time and across space is possible and this is an advantage for monitoring programmes in which the primary objective is to estimate absolute density and/or population size. However, the relative merits of absolute density estimates and indices for describing trend depend on their relative sampling variance (including the effect of operational overheads on sample size), the level of uncontrollable variation in detectability, and the intended audience.
- Distance sampling is less suitable for monitoring low density animal populations simply because obtaining the *minimum* number of observations (60) is likely to be prohibitive in terms of time, labour and cost. However, if the detection function is known from a previous survey (e.g. a pre-control survey when the population was at a higher density) then program DISTANCE can be used to estimate density using fewer than 60 observations (this application is not discussed further here).

Skills

Those responsible for survey design must:

- Be familiar with the relevant design issues pertinent to the use of distance sampling methods for animal populations. Buckland et al. (2001, 2004) devote many chapters to survey design and field methods. These issues include the critical assumptions and their impact on appropriate sampling design, definition of the sampling frame and sampling unit, the number of transects (and their length) and distribution of transects over the sampling frame.
- Have an understanding of the target species' spatial distribution (e.g. clumped or territorial) and potential for stratification. This understanding is also extremely useful and can markedly improve the precision of abundance estimates. A pilot study is strongly recommended (Thompson et al. 1998) because it will provide useful information on the precision resulting from a given level of labour and cost. It will also provide an idea of the expected encounter rate and detection function from which the transect length required to reach predetermined levels of precision can be estimated.

Field observers must be:

- Familiar with the target species (identification, behaviours, etc.)
- Able to consistently follow the designated sampling design and make accurate distance and bearing measurements
- Able to identify violations of assumptions and understand the consequences for density and abundance estimates (see Borchers et al. 2002, p. 160)

Those responsible for analysis must have:

- Specialist statistical skills and familiarity with the program DISTANCE.

Resources

Distance sampling is usually more expensive than obtaining indices of relative abundance despite the relatively small amount of additional information collected in the field. This is particularly true if the species of interest is at low to moderate density, as more intensive sampling and/or more transects are required for reasonable precision. Forethought is required when designing the sampling programme to ensure the critical assumptions underlying distance sampling are met and sufficient data are collected. Additional sampling infrastructure is often required to ensure that transects are sufficiently well defined to minimise measurement error (e.g. marker poles, tags, etc.). All sampling programmes utilising distance sampling will require a significant training component to ensure observer competence in the data collection methods, equipment use and species identification. Consider testing of potential observers' visual acuity—use only those who reach a set standard. If training and checks are not done, an additional cost will be the bias introduced by the violation of underlying assumptions.

This method requires the following resources:

- Suitably trained people
- Maps of the study area and transects to be sampled
- Marked transects
- GPS to assist with navigating to/from and along transects
- Range finder to measure distance
- Compass to measure bearing
- Data sheets and notebook
- Suitable means of moving between plots (e.g. walk, drive, helicopter)
- Appropriate communication, safety and first-aid equipment

Minimum attributes

Consistent measurement and recording of these attributes is critical for the implementation of the method. Other attributes may be optional depending on your objective. For more information refer to 'Full details of technique and best practice', Buckland et al. (2001) and Thomas et al. (2009).

DOC staff must complete a 'Standard inventory and monitoring project plan' (docdm-146272).

In the field, record data on the field sheet, preferably printed on waterproof paper.

Minimum attributes to record:

- Metadata, including observer's name and contact details, date of survey, time over which survey conducted (start/finish times) and relevant weather details
- Location (eastings and northings and/or polygons) of survey area, sample area, lines or points and strata (if required)
- Habitat variables associated with line/point and stratum
- Line length and sample effort (number of times line walked or point visited)

- Number of individuals (or group of individuals, termed 'cluster') of the target species seen from the transect line
- Distance (to nearest metre) or distance interval from the transect line to each individual or cluster
- Bearing (to nearest degree) from the transect line to each individual or cluster
- Covariates that may help explain density (e.g. treatment, non-treatment, vegetation type)

Data storage

- Copies of completed field sheets should be forwarded to the survey administrator, photocopied or scanned, then entered into an Excel spreadsheet as soon as possible after returning from the field. The key steps here are data entry, storage and maintenance for later analysis, coupled with copying and data backup for security. If data storage is designed well at the outset, it will make the job of analysis and interpretation much easier. Before storing data, check for missing information and errors, and ensure metadata are recorded.
- Storage tools can be either manual or electronic systems (or both, preferably). They will usually be summary sheets, other physical filing systems, or electronic spreadsheets and databases. Use appropriate file formats such as .xls, .txt, .dbf or specific analysis software formats. Copy and/or backup all data, whether electronic, data sheets, metadata or site access descriptions, preferably offline if the primary storage location is part of a networked system. Store copies at a separate location for security purposes.
- Completed data sheets and/or field note books can be scanned and saved as a pdf with a self-explanatory file name and stored, along with the entered data, in multiple physical locations to guard against potential loss of data from server failure and natural disasters.
- Our preference is to have one data sheet containing all the information collected in the field (and also including transect beginning and end eastings and northings) and have a separate figure (map) showing the layout of transects, but separate worksheets or files could contain that information and any other explanatory material.
- Not all of the data entered in the spreadsheet is imported into the DISTANCE software, and our preference is to create another worksheet ('Distance data') containing those data. That worksheet is then saved as a text file (i.e. *.txt) and imported into DISTANCE using the Import Data Wizard (Thomas et al. 2009). The imported data and associated analyses and output can be stored as 'Distance Projects' (Thomas et al. 2009).

Analysis, interpretation and reporting

The user of DISTANCE is directed to the software's user guide[1] (Thomas et al. 2009) where the more complex mechanics of this analysis programme are explained in detail. Buckland et al. (2001, pp. 48–50) suggest a useful strategy for the analysis of data sets and this is summarised below.

[1] http://www.ruwpa.st-and.ac.uk/distance/

Exploratory phase

During this initial phase, the analyst should critically examine the data collected. Take particular care to code effort (the number of times a sample unit has been surveyed) correctly to avoid pseudoreplication (Thomas et al. 2009). Identify and correct any data entry errors and other anomalies. Plot the data as histograms in a variety of groupings so the data can be examined in detail. These histograms can be used to identify outliers, as well as potential violation of assumptions caused by the presence of 'heaping' and 'spiking' (distances rounded to certain distances) and evasive movement (see Westbrooke et al. 2003). Data can be grouped to reduce these impacts. Buckland et al. (2001, p. 151) recommend truncation of larger distances to reduce the impact of outliers and improve model fit.

Model selection

Once a dataset has been prepared, several robust models describing the detection function should be considered. Program DISTANCE provides several useful models or 'key functions' and associated adjustment terms (or 'series expansions') used to 'shape' detection functions to fit the data. Likelihood ratio tests, goodness-of-fit tests and Akaike's information criterion (AIC) are all available as aids to objective model selection. Often the need for additional exploratory work becomes apparent at this point. Changes, such as altering truncation point, regrouping distance intervals or pooling data across surveys, might improve the fit of one or more of the candidate models. It is common to find there are several competing models, some of which appear to perform poorly relative to other models (and can be discarded) and others that perform equally well. Model averaging can then be used to account for model selection uncertainty (Burnham & Anderson 2002).

Final analysis and inference

Selection of the model(s) believed to be the best fit for the data can now occur. Once a single model (or subset of models) has been selected, estimates of density and precision of these estimates can be made (along with relevant tables and graphs) and then discussed in relation to any perceived failures of critical assumptions. Improved variance estimates can be obtained using bootstrapping routines and, if necessary, including a variance component to reflect model-selection uncertainty.

Case study A

There is no case study available for this method.

Full details of technique and best practice

Objective

The objective of the monitoring must be explicitly stated. The objective of our study was:

- To estimate the density and abundance of wallabies in a 3875 ha area of the Hunters Hills prior to control being undertaken

Sampling design

The boundary of the study area needs to be delineated on a map (e.g. with a GIS). The boundary of our study area was defined by Raukapuka Area Office staff based on local knowledge and the intention to conduct wallaby control there during winter 2010 (Fig. 2).

The sampling design needs to be determined, and many options are available (see Buckland et al. 2001, 2004). The sampling design used in our study consisted of 16 line transects arranged parallel (i.e. systematically) to sample *across* the grain of the terrain (i.e. from ridge down across the gully to the opposite ridge) (Fig. 2). Sixteen was the practical minimum number that could be walked once by the field staff in the available time to ensure a *minimum* 60 observations of Bennett's wallaby. The length of the transects (estimated with a GIS) varied from 1202 m to 3594 m, and the surface area of the study area was 3875 ha.

Prior to going into the field, staff were briefed in the office on the study's objective and design, the theory of distance sampling and the need to accurately record sighting distances and bearings, and were shown how to use the laser range-finders (Leupold® TX™-II 6×32 Digital Range Finder) and sighting compass (Suunto KB-series).

The transects were not marked. Rather, field observers were provided with a map and a GPS unit (Garmin CSx 60) with the transects loaded, and field sheets printed on waterproof paper. Observers were also provided with a compass and a sheet with the end coordinates and compass bearings for each transect.

Staff who had not conducted distance sampling before were accompanied on their first transect by an experienced observer. Observers therefore walked transects either alone or in pairs, following the transect as shown on the map and GPS as closely as possible.

Staff were assigned transects in a way that maximised time on transects and minimised time spent travelling between transects. Four-wheel drives, quad bikes and a helicopter were used to ferry observers to/from the ends of transects. Transects were walked once at 1–2 km^{-1} (i.e. a slow walking speed) in good visibility throughout the day. No sampling was undertaken in fog or rain, or at night. Unsafe terrain was occasionally encountered: observers were instructed to walk *around* the terrain and to return to the transect line as soon as possible. The most practical method for walking transects in our study area (Fig. 3) was to use the map and compass to identify the line to be walked and select a feature (e.g. rock or tree) ahead along the line to walk towards. The observer then walked towards the landmark, scanning forward left and right from the transect line, but with most search effort focused on and around the transect line. When one or more wallabies was sighted, the distance from the observer to the 'cluster' (defined as a group of wallabies; the minimum cluster size is one) was measured with the range finder and the bearing was measured with the sighting compass. Any other biota or items of interest could also be recorded on the data sheet (e.g. chamois *Rupicapra rupicapra* were seen along one transect).

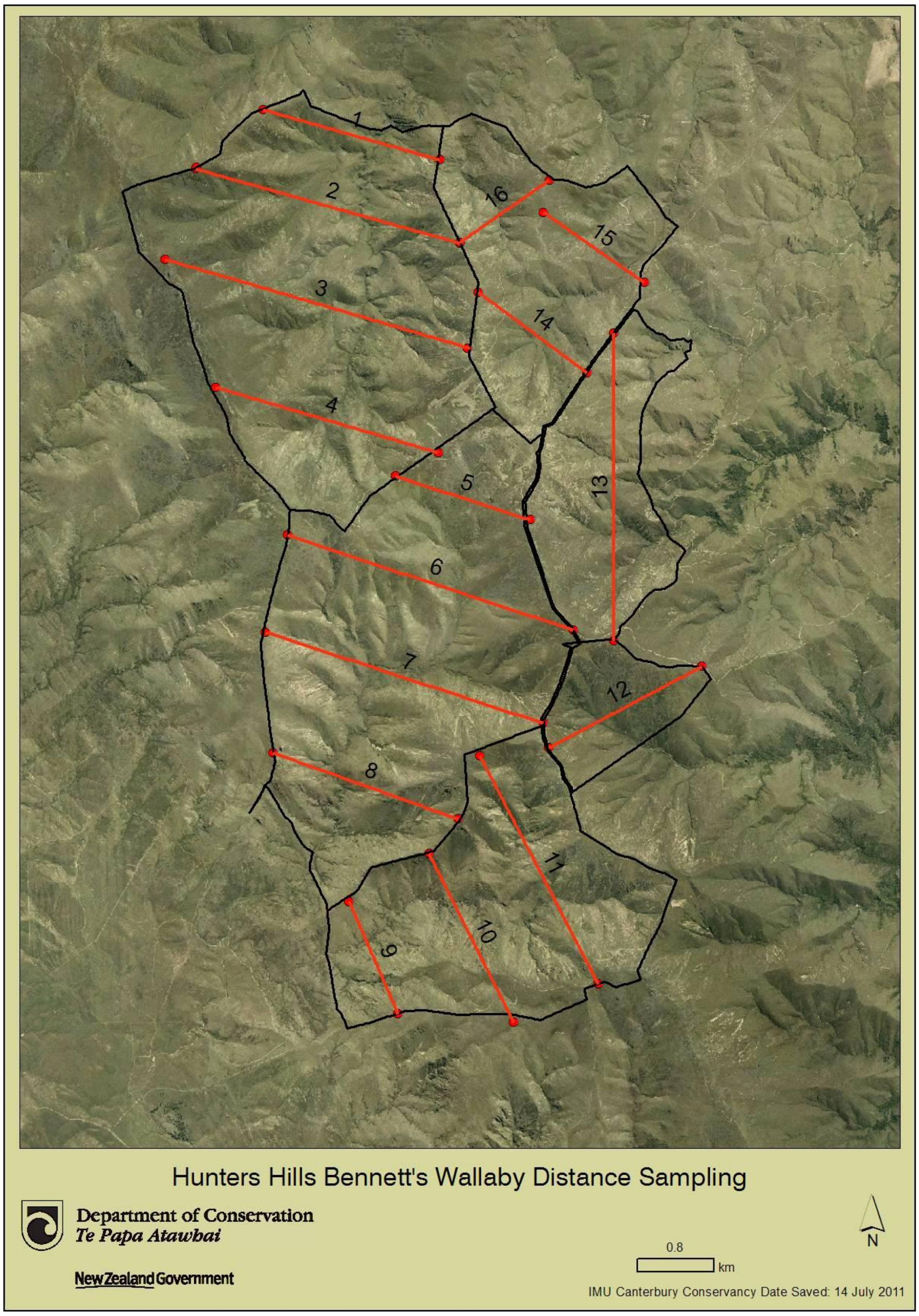


Figure 2. Boundaries of the study area showing the location of the 16 numbered line transects that were each walked once in February 2010.

Figure 3. Typical view along a transect in our study area (photo: D.M. Forsyth).

Data collection

The field sheet used to collect the data required for distance sampling (Fig. 4) was printed on waterproof paper. You may need to record additional data depending upon the objectives of your study.

The columns were as follows:

- 'Cluster size (# animals)' is the number of animals in the group (minimum is 1).
- 'Distance (m)' is the (radial) distance in metres from the observer (standing on the transect line) to the cluster.
- 'Angle (0–90°)' is the bearing from the observer to the cluster.
- 'Habitat (Tussock, Scrub or Bush)'—since wallabies would be expected to be more visible in tussock compared to scrub and bush, each cluster was assigned to one of these vegetation types.

The field work was conducted in 2 days (9 and 12 February 2010) by five people (i.e. a total of 10 staff field-days). Visibility was excellent and wind was classified as either calm or light on all 16 transects. A total of 85 clusters was sighted on the 16 transects, which is greater than the minimum 60–80 recommended for robust estimation of density using distance sampling by Buckland et al. (2001).

Data storage

Following completion of the survey, data sheets were photocopied and scanned (as a pdf) before data were entered into the worksheet 'All data' in the Excel spreadsheet 'Wallaby_data_DISTANCE_28Feb2010.xls' (Fig. 5).

Raukapuka Bennett's wallaby DISTANCE data

Date: Observer(s):
Cloud cover (%): Wind: Calm/Light/Moderate/Gale
Transect: Bearing: Length:
Start coordinates: Time started transect:
End coordinates: Time finished transect:

Cluster size (# animals)	Distance (m)	Angle (0–90°)	Habitat (Tussock, Scrub or Bush)	Notes

Figure 4. Field sheet used to collect distance sampling data.

Microsoft Excel - Wallaby_data_DISTANCE_28Feb2010.xls

	Date	Transect	Start time	Finish time	Observer(s)	Transect bearing (°)	Cloud cover (%)	Wind	Transect start easting	Transect start northing
2	9/02/2010	11	10:30	14:46	David Anderson	311	50%	Light	1425789	507168
3	9/02/2010	11	10:30	14:46	David Anderson	311	50%	Light	1425789	507168
4	9/02/2010	11	10:30	14:46	David Anderson	311	50%	Light	1425789	507168
5	9/02/2010	11	10:30	14:46	David Anderson	311	50%	Light	1425789	507168
6	9/02/2010	11	10:30	14:46	David Anderson	311	50%	Light	1425789	507168
7	9/02/2010	11	10:30	14:46	David Anderson	311	50%	Light	1425789	507168
8	9/02/2010	11	10:30	14:46	David Anderson	311	50%	Light	1425789	507168
9	9/02/2010	11	10:30	14:46	David Anderson	311	50%	Light	1425789	507168
10	9/02/2010	11	10:30	14:46	David Anderson	311	50%	Light	1425789	507168
11	9/02/2010	11	10:30	14:46	David Anderson	311	50%	Light	1425789	507168
12	9/02/2010	11	10:30	14:46	David Anderson	311	50%	Light	1425789	507168
13	9/02/2010	11	10:30	14:46	David Anderson	311	50%	Light	1425789	507168
14	9/02/2010	11	10:30	14:46	David Anderson	311	50%	Light	1425789	507168
15	9/02/2010	11	10:30	14:46	David Anderson	311	50%	Light	1425789	507168
16	9/02/2010	11	10:30	14:46	David Anderson	311	50%	Light	1425789	507168
17	9/02/2010	12	15:38	17:31	David Anderson	40	20%	Light	1425275	507412
18	9/02/2010	12	15:38	17:31	David Anderson	40	20%	Light	1425275	507412
19	9/02/2010	12	15:38	17:31	David Anderson	40	20%	Light	1425275	507412
20	9/02/2010	12	15:38	17:31	David Anderson	40	20%	Light	1425275	507412
21	9/02/2010	9	10:23	11:52	Luke Woodford	158	60%	Light	1423204	507253
22	9/02/2010	9	10:23	11:52	Luke Woodford	158	60%	Light	1423204	507253
23	9/02/2010	9	10:23	11:52	Luke Woodford	158	60%	Light	1423204	507253
24	9/02/2010	9	10:23	11:52	Luke Woodford	158	60%	Light	1423204	507253
25	9/02/2010	9	10:23	11:52	Luke Woodford	158	60%	Light	1423204	507253
26	9/02/2010	9	10:23	11:52	Luke Woodford	158	60%	Light	1423204	507253
27	9/02/2010	9	10:23	11:52	Luke Woodford	158	60%	Light	1423204	507253
28	9/02/2010	9	10:23	11:52	Luke Woodford	158	60%	Light	1423204	507253
29	9/02/2010	9	10:23	11:52	Luke Woodford	158	60%	Light	1423204	507253
30	9/02/2010	9	10:23	11:52	Luke Woodford	158	60%	Light	1423204	507253
31	9/02/2010	9	10:23	11:52	Luke Woodford	158	60%	Light	1423204	507253
32	9/02/2010	9	10:23	11:52	Luke Woodford	158	60%	Light	1423204	507253

DISTANCE data | All data | Transect lengths

Figure 5. Excel worksheet in which all the information on the field data sheet (see Fig. 4) has been entered.

Microsoft Excel - Wallaby_data_DISTANCE_28Feb2010.xls

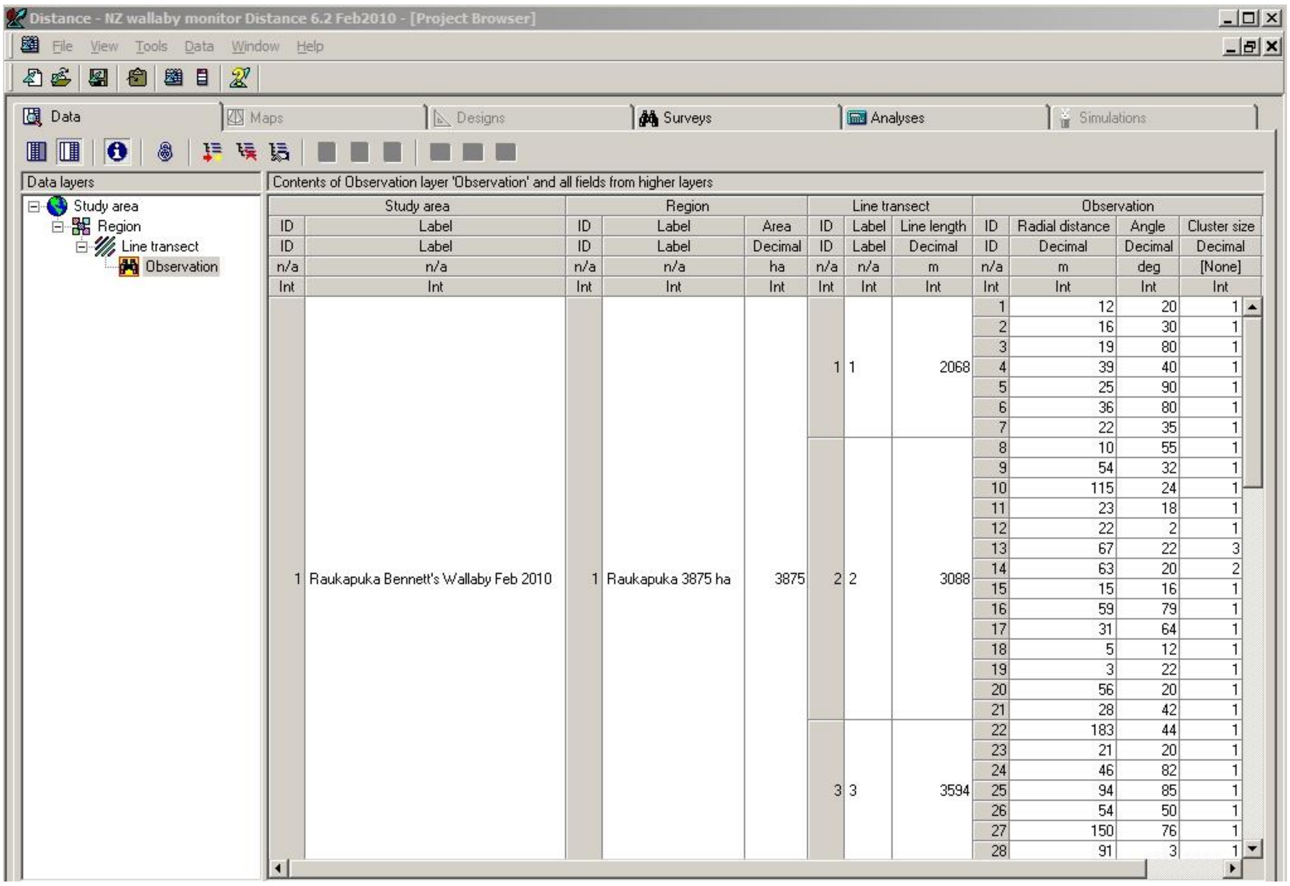
	Stratum	Area	Transect	Length	Radial Distance	Angle	Cluster size	Vegetation
2	1	3875	1	2068	12	20	1	T
3	1	3875	1	2068	16	30	1	T
4	1	3875	1	2068	19	80	1	T
5	1	3875	1	2068	39	40	1	T
6	1	3875	1	2068	25	90	1	T
7	1	3875	1	2068	36	80	1	T
8	1	3875	1	2068	22	35	1	T
9	1	3875	2	3088	10	55	1	T
10	1	3875	2	3088	54	32	1	T
11	1	3875	2	3088	115	24	1	T
12	1	3875	2	3088	23	18	1	T
13	1	3875	2	3088	22	2	1	T
14	1	3875	2	3088	67	22	3	T
15	1	3875	2	3088	63	20	2	T
16	1	3875	2	3088	15	16	1	T
17	1	3875	2	3088	59	79	1	T
18	1	3875	2	3088	31	64	1	T
19	1	3875	2	3088	5	12	1	T
20	1	3875	2	3088	3	22	1	T
21	1	3875	2	3088	56	20	1	T
22	1	3875	2	3088	28	42	1	T
23	1	3875	3	3594	183	44	1	T
24	1	3875	3	3594	21	20	1	T
25	1	3875	3	3594	46	82	1	T
26	1	3875	3	3594	94	85	1	T
27	1	3875	3	3594	54	50	1	T
28	1	3875	3	3594	150	76	1	T
29	1	3875	3	3594	91	3	1	T

DISTANCE data | All data | Transect lengths

Figure 6. Excel worksheet containing the data to be imported into DISTANCE. The worksheet is saved as a text file (i.e. *.txt) for import.

Analysis

The data to be imported into DISTANCE were copied and pasted from the 'All data' spreadsheet into the 'DISTANCE data' worksheet (Fig. 6), and the latter worksheet was saved as a text file 'Wallaby_data_DISTANCE_28Feb2010.txt' and imported into the freeware DISTANCE 6.0 version 2 (Thomas et al. 2009).[2] The data following import into DISTANCE are shown in Fig. 7, and the column variables in Fig. 7 are defined in Table 1.



Study area		Region			Line transect			Observation			
ID	Label	ID	Label	Area	ID	Label	Line length	ID	Radial distance	Angle	Cluster size
ID	Label	ID	Label	Decimal	ID	Label	Decimal	ID	Decimal	Decimal	Decimal
n/a	n/a	n/a	n/a	ha	n/a	n/a	m	n/a	m	deg	[None]
Int	Int	Int	Int	Int	Int	Int	Int	Int	Int	Int	Int
1	Raukapuka Bennett's Wallaby Feb 2010	1	Raukapuka 3875 ha	3875	1	1	2068	1	12	20	1
								2	16	30	1
								3	19	80	1
								4	39	40	1
								5	25	90	1
								6	36	80	1
								7	22	35	1
					2	2	3088	8	10	55	1
								9	54	32	1
								10	115	24	1
								11	23	18	1
								12	22	2	1
								13	67	22	3
								14	63	20	2
								15	15	16	1
								16	59	79	1
								17	31	64	1
								18	5	12	1
								19	3	22	1
								20	56	20	1
								21	28	42	1
					3	3	3594	22	183	44	1
								23	21	20	1
								24	46	82	1
								25	94	85	1
								26	54	50	1
								27	150	76	1
								28	91	3	1

Figure 7. Data from Figure 6 after importing into DISTANCE 6.0 version 2.

[2] Available at http://www.ruwpa.st-and.ac.uk/distance/

Table 1. Definition of column variables in Figures 6 and 7.

Spreadsheet column	Corresponding column in DISTANCE	Explanation
-	Study area: Label	Contains information that applies to the whole study.
A	Region: Label	Name of study area or stratum.
B	Region: Area	Area of region (ha) used to calculate density and abundance.
C	Line transect: Label	Transect number: in this example there were 16 (Fig. 2), with only three visible on the Fig. 7 screenshot (i.e. transects 1, 2 and 3).
D	Line transect: Line length	The length of each of the 16 transects in metres (estimated with a Geographic Information System).
E	Observation: Radial distance	Radial distance in metres from the transect to the cluster of animals.
F	Observation: Angle	Angle in degrees from the transect to the cluster of animals. The angle can range from 0 to 90.
G	Observation: Cluster size	Number of wallabies in the cluster. The minimum cluster size is 1.

Exploratory analyses

We first conducted exploratory data analyses to examine the distribution of observations as a function of distance from the transect line. We did this by defining a set as 'Exploratory data visualisation' in the Analysis browser. All distances reported henceforth are perpendicular distances calculated in DISTANCE. The most distant observation was 174.3 m from the line.

We first plotted the distribution of sightings in 10 m intervals from 0–200 m (Fig. 8). That histogram revealed that there was strong evidence of 'spiking' in the first distance class (0–10 m) and a very long 'tail' (i.e. there were many observations beyond about 80 m that would distort the detection function model). The histogram is similar to that reported for eastern grey kangaroos (*Macropus giganteus*) on Rotamah Island (Coulson & Raines 1985), although spiking is more pronounced in Fig. 8 and is usually caused by observers rounding bearings close to the transect line to zero (Buckland et al. 2001).

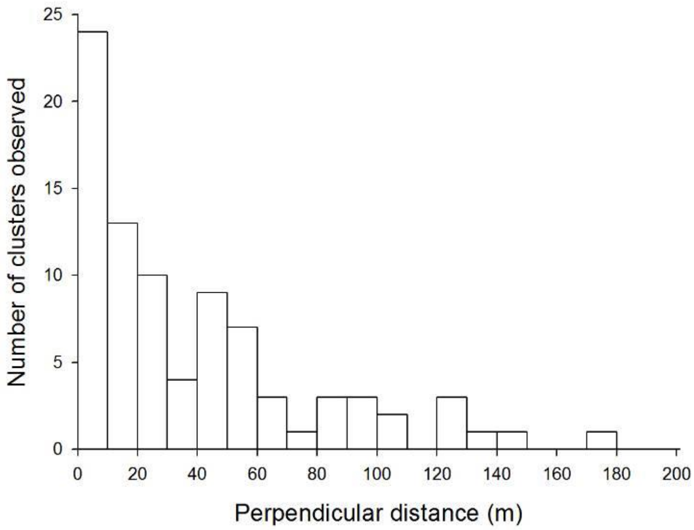


Figure 8. Histogram of the number of clusters of Bennett's wallaby observed in a 3875 ha area of the Hunters Hills as a function of perpendicular distance from the transect line. These data indicate spiking in the 0–10 m distance class, and a very long tail requiring truncation at about 80 m.

Model selection

The first step in model selection involves selecting a suitable truncation distance *w* for the data. The truncation of larger distances is recommended so as to reduce the impact of outliers and improve model fit (Buckland et al. 2001, p. 151). Inspection of Fig. 8 reveals that little additional information (in terms of estimating a detection function) is contained in the 14 sightings beyond 80 m, so we chose *w* = 80 m. Although a greater percentage of sightings were truncated (17%) compared to the standard recommendation (5%) of Buckland et al. (2001), up to 17% of data were truncated in ground surveys of multiple macropod species by Clancy et al. (1997), so this is not without precedent. Moreover, this highlights the need to carefully consider data on its own merits.

Because of the spiking evident around the transect line (Fig. 8), we next grouped our data so as to improve estimates of density and abundance. We chose a relatively wide first interval to ensure that as few as possible detections were erroneously allocated to the first interval through measurement error and, in particular, through rounding a small sighting angle to zero (Buckland et al. 2001, pp. 109–110). We explored the consequences of other truncation distances (e.g. 110 m), numbers of intervals and interval widths manually in the Data Filter option of the 'Analyses' tab in concert with the following model options (Thomas et al. 2010): uniform key with cosine adjustments, half-normal key with cosine adjustments, half-normal key with Hermite polynomial adjustments. We used the automated selection of adjustment terms function, with sequential one-step selection up to a maximum of five terms based on AIC_c. We also evaluated the effects of estimating cluster size as the mean of observed clusters or from size-biased regression on density estimates. We assessed the fit of the various models to our data with histograms and goodness-of-fit tests along with our biological understanding of wallabies in the study area. (Note that we could not use quantile–quantile plots and Cramér–von Mises tests as diagnostic tools for these analyses because our data were analysed as grouped rather than as exact distances because of the spiking on the transect line.)

Of the four key-adjustment models considered, the hazard-rate model fitted an implausible shape to the detection function (i.e. no shoulder) and is not considered further here, and neither the cosine nor Hermite polynomial adjustment was required for the half-normal model. Hence, only the half-normal model (with no adjustments) and the uniform key with cosine adjustments are considered further. Diagnostic output from DISTANCE (histograms with χ^2 goodness-of-fit tests) is shown below for the two models (Figs 9 and 10), and suggest that both models provided reasonable fits to the data. The AIC_c values for each model were also very similar (half-normal = 217.42; uniform+cosine = 217.92), indicating that both models should be considered in the third and final stage of analysis.

Note that the model selection phase involved considering other cutpoints, numbers of intervals, values of *w*, and estimation of group size using size-bias regression. The results of each of those models is not reported here for brevity (but are stored in the DISTANCE project), but in summary the estimates of density and abundance did not change greatly as these variables were changed. The models reported here are the most sensible of those evaluated. There were too few observations to estimate detection functions for each of the three habitat types (tussock, scrub and bush) separately.

Final analysis and inference

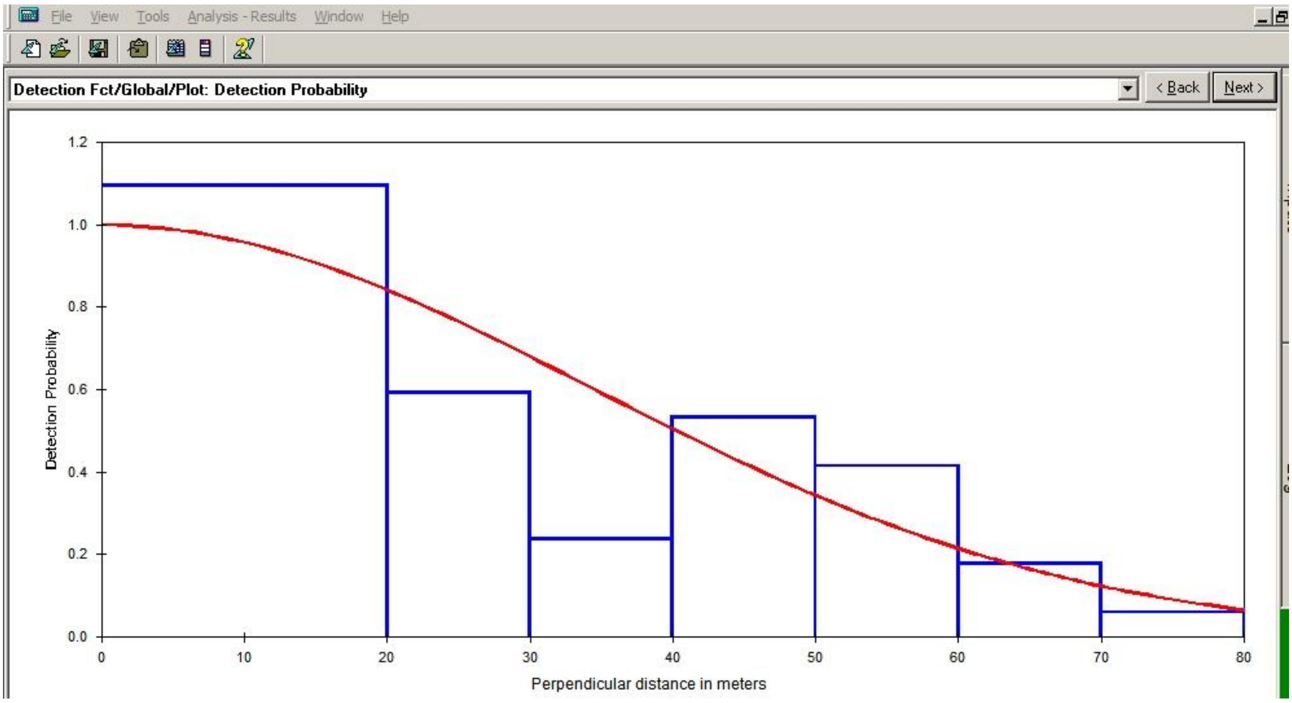
The third and final phase of analysis is selection of the best models and reporting estimates of density and abundance and their associated uncertainties. The two models in Figs 9 and 10 are virtually indistinguishable in terms of model diagnostics, and their density and abundance estimates are similar (Fig. 11).

Because the estimates of density were so similar for the two models, we selected the half-normal model (upper row in Fig. 11) as the model to make our inferences from. Note that this is a conservative approach, as model-averaging would in this example decrease the confidence interval widths. The density estimates from DISTANCE are shown in Fig. 12. The output shows effort (the total length of transect walked) as 37 380 m, that there were 16 transects, that the maximum width (*w*) was 80 m, that there was no left-truncation (0 m) and that 71 observations were used in the analyses (recall that 14 were removed following truncation at *w* = 80 m). The mean estimated density was 0.2544 wallabies ha^{-1}, with a 95% confidence interval (CI) of 0.15 to 0.43 wallabies ha^{-1}, which translated to 986 wallabies (95% CI; 582–1669) in the survey area. The lower table in Fig. 12 indicates that the primary cause of uncertainty in the estimates of density and abundance was the estimated encounter rate (i.e. transect-to-transect variation in the number of wallabies observed per unit length of transect) rather than the estimated detection function or estimated cluster size.

The next page of DISTANCE output summarises encounter rates (Fig. 13). The variable '*n*/L' is the number of wallaby clusters encountered per m of transect (i.e. 0.0019; 95% CI, 0.0012–0.00311): these are more usefully reported per km of transect (1.9; 95% CI, 1.2–3.1), and would be helpful for planning further distance sampling monitoring programmes for this species in this type of habitat.

The next page of DISTANCE output summarises detection probabilities (Fig. 14). Perhaps the most useful information here is the estimated Effective Strip Width (ESW), in this case 42.1 m (95% CI, 34.7–51.0 m). If all objects were detected out to that distance on either side of the transect (and none beyond), then the expected number of objects detected would be the same as for the actual survey (Buckland et al. 2001, p. 53).

The next page of DISTANCE output is the estimated cluster size (Fig. 15). We set this option to 'Mean observed cluster size', and this was 1.12 wallabies (95% CI, 1.03–1.24). Note that we also investigated the effect of estimating cluster size from a size-bias regression, but that had little effect on the estimated densities.



File View Tools Analysis - Results Window Help

Detection Fct/Global/Chi-sq GOF Test

Cell i	Cut Points		Observed Values	Expected Values	Chi-square Values
1	0.000	20.0	37	31.93	0.804
2	20.0	30.0	10	12.91	0.654
3	30.0	40.0	4	10.01	3.607
4	40.0	50.0	9	7.13	0.490
5	50.0	60.0	7	4.67	1.166
6	60.0	70.0	3	2.81	0.013
7	70.0	80.0	1	1.55	0.195

Total Chi-square value = 6.9304 Degrees of Freedom = 5.00

Probability of a greater chi-square value, P = 0.22587

The program has limited capability for pooling. The user should judge the necessity for pooling and if necessary, do pooling by hand.

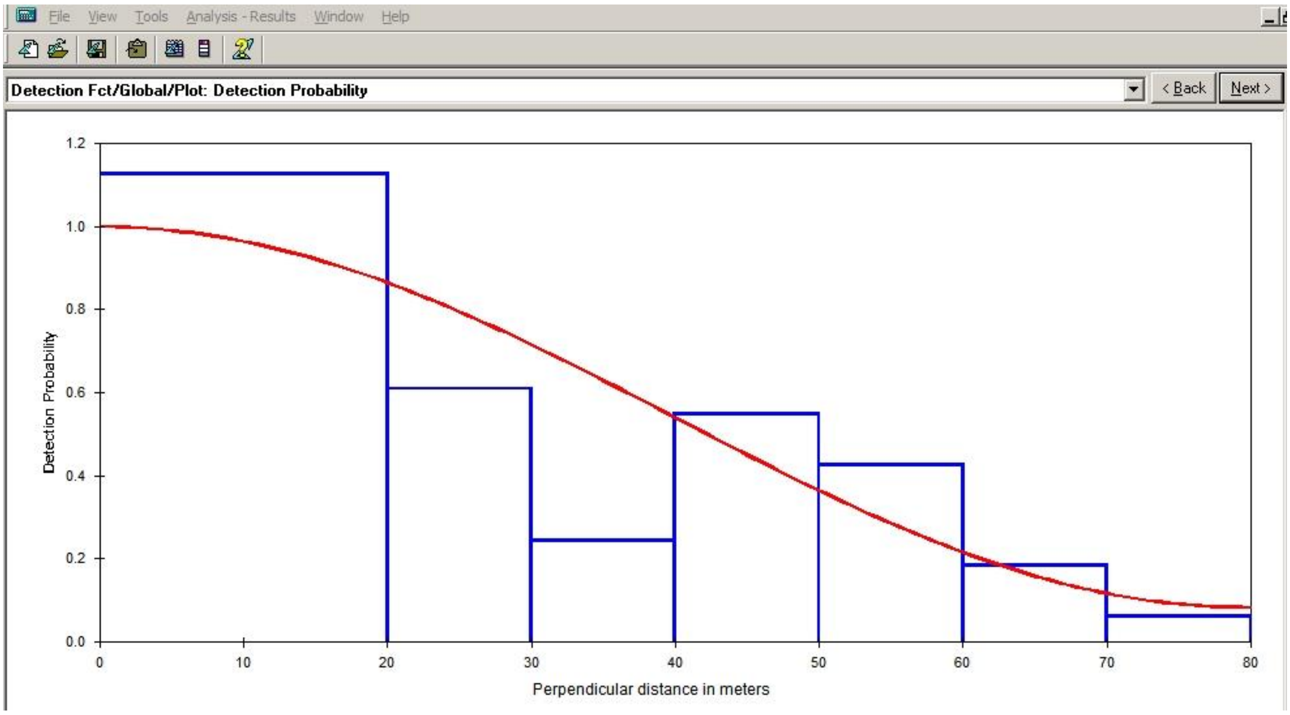
Goodness of Fit Testing with some Pooling

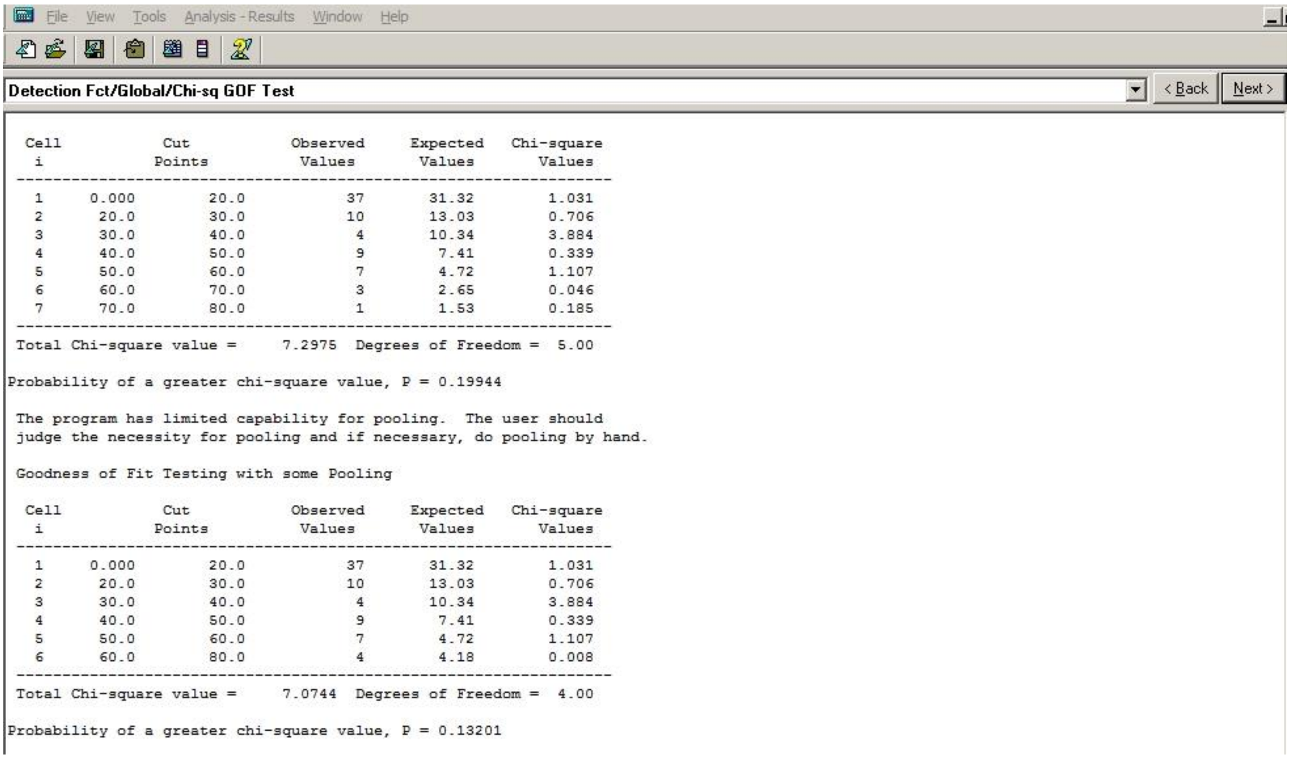
Cell i	Cut Points		Observed Values	Expected Values	Chi-square Values
1	0.000	20.0	37	31.93	0.804
2	20.0	30.0	10	12.91	0.654
3	30.0	40.0	4	10.01	3.607
4	40.0	50.0	9	7.13	0.490
5	50.0	60.0	7	4.67	1.166
6	60.0	80.0	4	4.36	0.029

Total Chi-square value = 6.7508 Degrees of Freedom = 4.00

Probability of a greater chi-square value, P = 0.14966

Figure 9. Diagnostic output for the half-normal model from DISTANCE. The upper panel is the histogram of detection probability for the specified intervals, and the lower panel shows the χ^2 goodness-of-fit tests. Note that as these data were analysed as grouped (cf. exact) distances, other model diagnostic options were unavailable.





Cell i	Cut Points		Observed Values	Expected Values	Chi-square Values
1	0.000	20.0	37	31.32	1.031
2	20.0	30.0	10	13.03	0.706
3	30.0	40.0	4	10.34	3.884
4	40.0	50.0	9	7.41	0.339
5	50.0	60.0	7	4.72	1.107
6	60.0	70.0	3	2.65	0.046
7	70.0	80.0	1	1.53	0.185

Total Chi-square value = 7.2975 Degrees of Freedom = 5.00

Probability of a greater chi-square value, P = 0.19944

The program has limited capability for pooling. The user should judge the necessity for pooling and if necessary, do pooling by hand.

Goodness of Fit Testing with some Pooling

Cell i	Cut Points		Observed Values	Expected Values	Chi-square Values
1	0.000	20.0	37	31.32	1.031
2	20.0	30.0	10	13.03	0.706
3	30.0	40.0	4	10.34	3.884
4	40.0	50.0	9	7.41	0.339
5	50.0	60.0	7	4.72	1.107
6	60.0	80.0	4	4.18	0.008

Total Chi-square value = 7.0744 Degrees of Freedom = 4.00

Probability of a greater chi-square value, P = 0.13201

Figure 10. Diagnostic output for the uniform key with cosine adjustment model from DISTANCE. The upper panel is the histogram of detection probability for the specified intervals, and the lower panel shows the χ^2 goodness-of-fit tests. Note that as these data were analysed as grouped (cf. exact) distances, other model diagnostic options were unavailable.

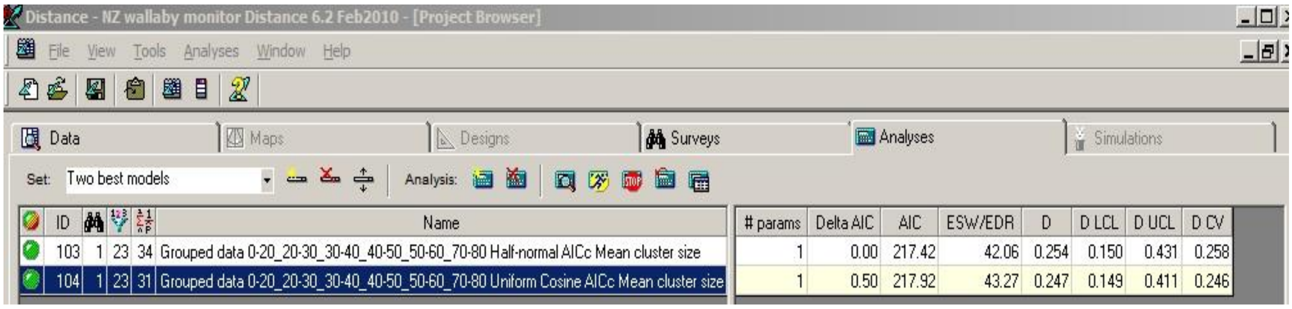


Figure 11. Model selection summary output from DISTANCE for the two best models estimating density and abundance of Bennett's wallaby in a 3875 ha area of the Hunters Hills.

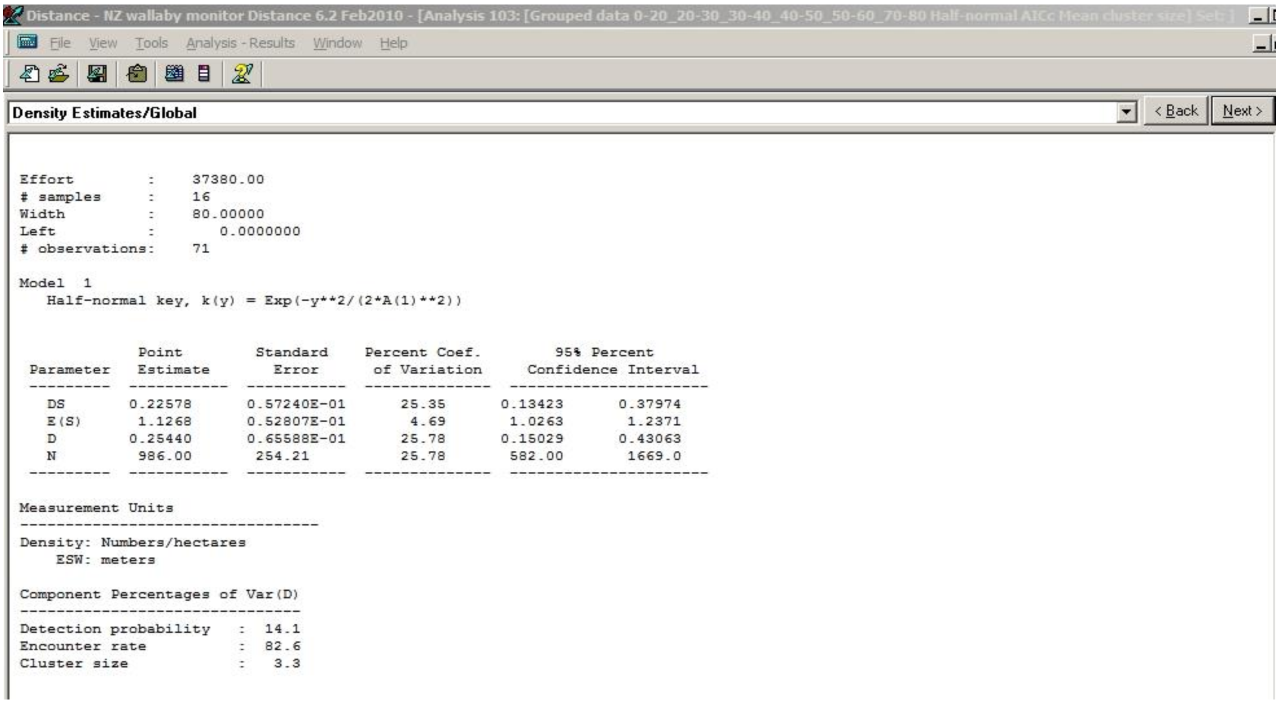


Figure 12. Density and abundance estimates for the half-normal key model from DISTANCE.

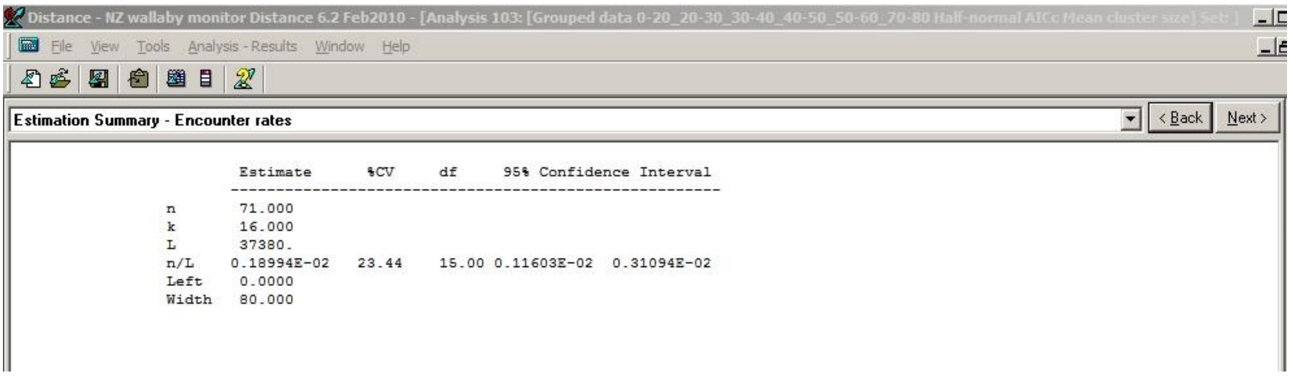


Figure 13. Encounter rate estimates for the half-normal key model from DISTANCE.

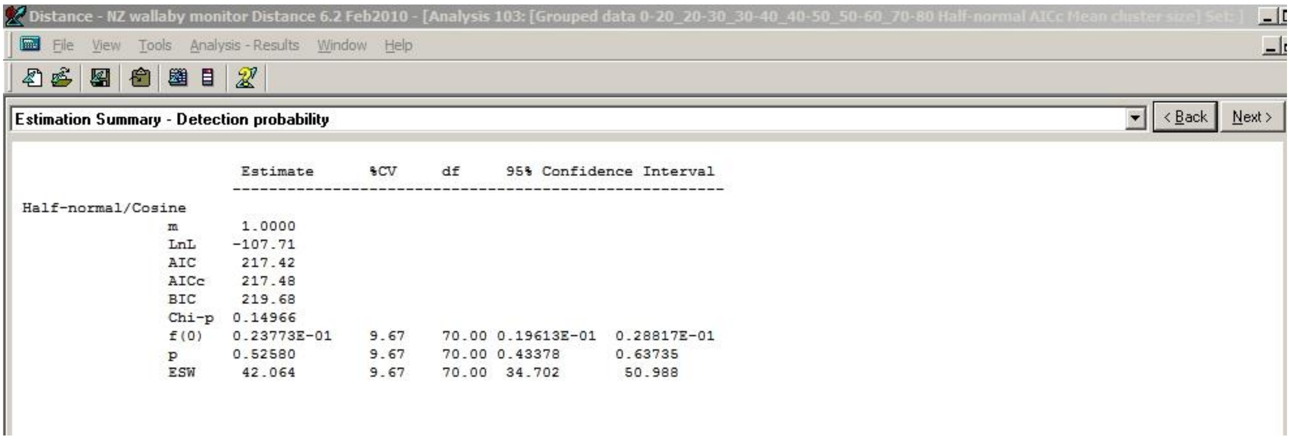


Figure 14. Detection probability estimates for the half-normal key model from DISTANCE.

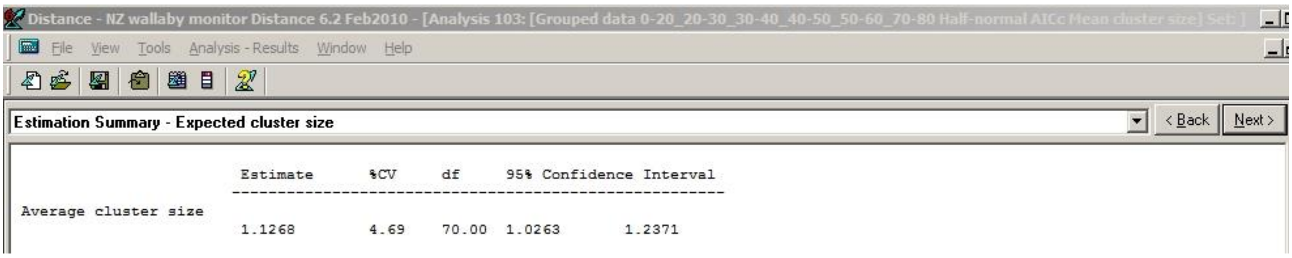


Figure 15. Cluster size estimates from DISTANCE.

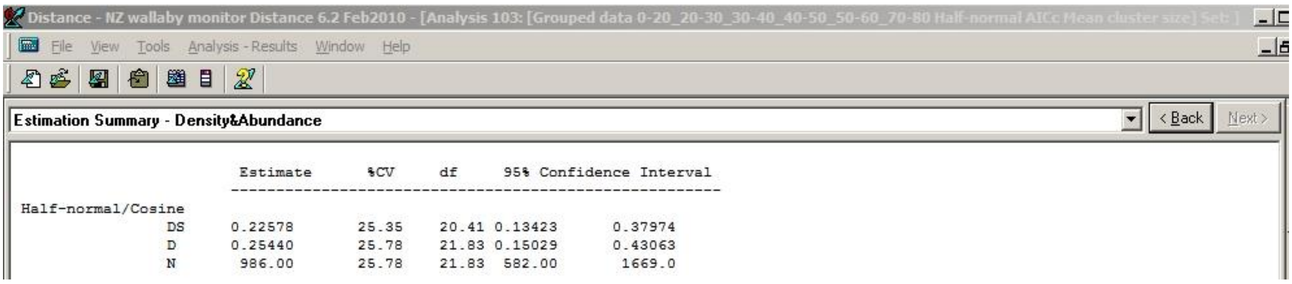


Figure 16. Estimated densities of wallaby clusters (*DS*) and wallabies (*D*), and estimated number of wallabies (*N*), in the 3875 ha study area from DISTANCE.

The final page of output from DISTANCE summarises the estimated densities and abundances of wallabies (Fig. 16). The information of most interest is the estimated density (*D*) and abundance (*N*), and their 95% CIs. The '%CV' is the coefficient of variation (%CV = [standard error/estimate]*100%), which is a measure of uncertainty in the density and abundance estimates (in this case 25.8%).

Limitations and points to consider

The two main limitations of our study were: (a) the relatively small number of observations for the effort expended (85 observations for 37 km of transect walked in 10 staff-days, excluding planning and training time), and (b) the evidence of spiking near the transect line. The first limitation is a consequence of the low density of wallabies in the study area and hence nothing can be done except to walk transects more than once and/or to add additional transects (i.e. greater survey effort). Hence, it is likely that the resources required to conduct distance sampling will often exceed those available (or required) for other methods (Warburton & Frampton 1993).

The second limitation, spiking of observations near the transect line (Fig. 8), was most likely caused by rounding bearings close to the transect line to zero. We believe that permanent marking of transects (e.g. with marker poles) would likely reduce this problem. It was not feasible to mark transects before we walked them in our study: doing so would have doubled the field work. However, given that the study described here has shown promise, we believe that future surveys should mark the transects prior to sampling. The transects should be marked such that the observer can always see one marker ahead and one marker behind: the observer need only walk in a straight line from marker to marker. We overcame the problem of spiking in our analyses by assigning a wider first interval (0–20 m) relative to the other intervals (all 10 m) (Figs 9 and 10) and by analysing the data as 'grouped distances' rather than 'exact distances': neither solution is 'ideal', but data collected in the real world are seldom ideal! It is hoped that data collected from permanently marked transects would not be subject to spiking and that the data could be analysed as exact distances.

This is the first study to attempt to estimate the absolute density of Bennett's wallaby in South Canterbury using distance sampling. Warburton & Frampton (1993) reported a density of 3 wallabies ha^{-1} in the Tasman Smith Scenic Reserve based on a carcass search following a poisoning operation, and this is likely to be the higher end of the density continuum (Warburton 2005). Our study area was at a higher elevation than the Tasman Smith Scenic Reserve and consisted primarily of sub-alpine grasslands (Figs 2 and 3) with only occasional patches of scrub along lower-elevation watercourses. Hence, we would expect wallaby densities to be lower in our study area relative to many other parts of their range on public conservation estate.

We chose to systematically sample the study area using parallel, equally spaced transects that sampled across the grain of each catchment (Fig. 2). However, this design means that data are not collected while moving between transects. A potential modification to our design that would maximise time spent walking transects would be to use a zigzag design (Buckland et al. 2001; Thomas et al. 2010).

With more observations it may have been possible to fit different detection functions to each of the three habitats (or to pooled subsets of habitat). It is highly likely that the detection function for wallabies in tussock would differ from that in scrub or bush, but a minimum of 60–80 observations would be required in each habitat before detection functions could be robustly modelled separately for each habitat. Future studies should at least consider this possibility in the design and analysis phases. A related issue is that of stratifying study areas on the basis of expected wallaby density and/or habitat. For example, if one wanted to estimate population size then it is *usually* most efficient to conduct more effort in higher density strata (Buckland et al. 2001). However, in some situations it may be desirable to allocate effort to ensure that the minimum 60 observations are obtained in all strata. During our study we saw more wallabies, and more wallaby sign, in the lower-elevation scrub and tall grassland habitats in gullies. Depending on the study objective(s), it might be efficient to stratify the study area into vegetation types and allocate effort (i.e. transect length per unit area) according to vegetation type.

We hope that our description of analyses highlighted the multiple options available when analysing data from line transects when using the DISTANCE analysis software. Indeed, the detailed options and recommendations for analyses provided by Buckland et al. (2001) and Thomas et al. (2009) can sometimes seem overwhelming. We believe that the primary objective should be to obtain *defensible* density and abundance estimates that are fit for your purpose, and at all times the analyst should be thinking about the likely behaviour and ecology of the study animal in the study area in relation to the way the line transect sampling was conducted. For example, we truncated our data at 80 m rather than using the recommendation by Buckland et al. (2001) to truncate at the distance that removes 5% of observations because the rolling terrain in parts of our study area meant that in some situations wallabies were seen very far away (e.g. when traversing a ridge). The recommendations provided by Buckland et al. (2001) and Thomas et al. (2009) are based on analyses of many taxa and study areas, but that does not mean they will always be appropriate to your situation.

More generally, our study highlights the need for observer training. Our study included the bare minimum training of observers (all but two had not conducted distance sampling previously) and the concept of searching most intensively on and near the transect line rather than simply counting the most wallabies on the transect is not something that can be grasped by all field staff. Similarly, not all staff can use range finders and sighting compasses in the manner required for distance sampling. We therefore recommend that more intensive training be given and that staff can only be observers once a required level of competency has been achieved (e.g. by a practical assessment or periodic checks).

The approach described here shows promise for estimating the density and abundance of Bennett's wallaby. The way that distance sampling will be employed to estimate the density and abundance of Bennett's wallaby will depend on circumstance (e.g. habitat, history of harvesting/control, population density), but the following three key references should be consulted: Buckland et al. (2001), Thomas et al. (2009) and Thomas et al. (2010). Based on our experiences, we recommend the following key steps:

1. **Survey objective(s) and area**
   The objectives of the survey need to be carefully considered and explicitly defined, and this includes delimiting the boundaries of the survey area in space and time. Is distance sampling the best of the available methods to address the survey objective(s), particularly in light of the required resources? If yes, proceed to the survey design and planning stage.

2. **Survey design and planning**
   Detailed information on survey design is available in Buckland et al. (2001) and Thomas et al. (2009, 2010). In general, the best approach is to systematically sample the study area with transects that sample across the grain of the habitat (i.e. across gullies rather than down or up). The study area may be stratified on the basis of habitat (e.g. grassland and forest) or expected densities (e.g. as a consequence of control history). A minimum of 15–20 transects is recommended, and consideration should be given to zigzag transects to

minimise time spent walking between transects. A minimum of 60–80 observations are required to robustly estimate density and abundance using distance sampling, so consideration needs to be given to how much survey effort (i.e. number of transects and number of times each transect is walked) is required to achieve this. It may be prudent to walk a sub-sample of transects once to estimate what resources will be required for the survey in terms of people, equipment and transport, etc.

3. **Observer training**
   Careful training of observers is required, and resources need to be allocated to this task. Observers must understand how to walk and search transects, and how to use equipment (e.g. a laser range finder and sighting compass) correctly. Not all field staff may have the skills to undertake distance sampling: minimum standards (i.e. performance criteria) for observers may need to be instituted.

4. **Data collection**
   Every attempt must be made to collect and record data as accurately as possible: failure to do so will reduce the accuracy and precision of the density estimate, and hence the value of the work. Checking of data should be conducted by the field team leader after the first transects have been sampled (to ensure that data is recorded correctly) and again at the end of the field trip: any apparent errors/anomalies in the data collection can then be resolved with the person who collected the data.

5. **Data entry and storage**
   When entering and archiving data, it is useful to think of what information someone else would need to recreate your analyses in the future if you were not available. Hence, the field sheets should be scanned and saved as *.pdf documents, and electronic and hard copies stored and archived. The data should be entered into a spreadsheet or database and archived, and imported into the latest version of DISTANCE (Thomas et al. 2009) for analyses. The person entering the data may detect errors/anomalies in the data collection, and these should be resolved with the field team leader and/or the person who collected the data.

6. **Analysis**
   The analysis of distance data is a large and growing literature, and general recommendations are provided in Buckland et al. (2001) and Thomas et al. (2009, 2010). The analyst(s) should also familiarise themselves with how other macropod distance sampling studies have been analysed (Coulson & Raines 1985; Southwell 1994; Clancy et al. 1997). Analyses usually follow three stages (Thomas et al. 2010). First, exploratory data analysis is conducted to understand the data and identify problems. Particular problems in wallaby surveys would be too few detections close to the transect line (most usually caused by animals moving away before the observer detects them) or, as occurred in our study, a 'spike' of observations near the line (usually caused by observers rounding small angles down to zero). It may be useful to assess the data collected by each observer: if an observer's data are very different from those of competent observers then it may be appropriate to exclude data from that observer from analysis.

The second stage of analysis is model selection. Truncation (left and/or right) of data and definition of intervals/cutpoints (for histograms, goodness-of-fit and other diagnostic tests) are conducted at this stage. The detection function is modelled, with four combinations usually tried (Thomas et al. 2010): uniform key with cosine adjustments, half-normal key with cosine adjustments, half-normal key with Hermite polynomial adjustments, and hazard-rate key with simple polynomial adjustments. Histograms, diagnostic tests and AIC are used to help assess the usefulness of each model, but the primary objective here should be to obtain *defensible* density estimates that are fit for your purpose, and at all times the analyst should be thinking about the likely behaviour and ecology of wallabies in the study area in relation to the way the line transect sampling was conducted.

The third and final stage of analysis is inference from the best model(s). Model-averaging and bootstrapping may be appropriate if several models have similar support. Details of encounter rates and detection probabilities (with associated sampling variances), and plots of calculated detection functions should be reported along with estimated densities and abundances for the study area (or strata).

7. **Reporting**
   The final report should include sufficient information so that your study could be duplicated by others without your assistance. It would therefore be useful to report the electronic locations of the scanned field sheets, stored data and DISTANCE project. The report should also include the study objectives and design, the observers used and any training given, and a detailed summary of the three stages of analysis (i.e. exploratory data analysis, model selection and inference from the best model(s)).

References and further reading

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Appendix A

The following Department of Conservation documents are referred to in this method:

docdm-146272 Standard inventory and monitoring project plan