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Population estimation methods, home range and habitat use for wild red deer (*Cervus elaphus*) at Cressbrook Dam, south-eastern Queensland

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Abstract

Red deer (*Cervus elaphus*) have been in Australia for over 150 years. The first documented release in Queensland was on Cressbrook Station in 1873. Following further releases they have spread through the Brisbane, Mary, and Burnett River Valleys to have an estimated population of 15,000 animals. Red deer were a protected species for many years in Queensland, but in 2009 were declared a Class 3 pest animal. The Invasive Animals Cooperative Research Centre National Feral Deer Management Workshop in 2005 reported there was a lack of credible, scientific knowledge about deer in Australia.

This project addressed the following research questions relating to wild red deer in south-eastern Queensland:

- What is the optimal method for estimating abundance?
- What is their annual and seasonal home range?
- Do red deer exhibit habitat preferences and what factors affect those preferences?

Estimating Abundance: Walked line transect distance sampling, aerial line transect distance sampling, vehicle based spotlight counts and faecal pellet counts were used to estimate or obtain indices of abundance of wild red deer at Cressbrook Dam. For each method the labour input, costs and precision were estimated. Spotlighting performed best overall when comparing labour and costs with precision, but had a number of limitations. Walked line transects gave estimates of adequate and repeatable precision but the method was expensive for both labour and equipment. Aerial survey estimates were quick, relatively cost-effective and comparable to walked line transect estimates, but not as precise as other methods. Faecal pellet counts were expensive in terms of labour, but were very precise. Choosing a method for counting deer will be site and circumstance specific, and some recommendations are provided to assist land managers choose a method. The density of wild red deer at the study site was very high - estimated to be between 26 and 30 deer/km^2.

Home Range: Wild red deer were fitted with GPS collars to provide location information every 90 minutes. Data were obtained from 22 collared deer – 11 male (4 young adult, 7 mature adult) and 11 female (1 young adult, 10 mature adult). Annual home range was estimated using the 95% Local Convex Hull method to be approximately 359 ha for hinds and 1,323 ha for stags. The data indicate

that the size of seasonal home range may be linked to seasonal conditions. Stags at our study site showed no elevated activity in summer compared to European reports. The home ranges at our study site were very large considering the high deer densities encountered.

Habitat Use: Habitat preferences of GPS collared deer were explored by computing the resource selection ratios. The available and used resources for individual animals were compared at the home range level for various habitat components. The large data set (over 117,000 deer locations) allowed in-depth examination of possible factors that might affect habitat use. I examined foliage projective cover, aspect and slope to explore deer habitat preferences during the winter, summer and rut for day vs. night. Hinds showed a preference for using heavier cover in the day compared to night regardless of season, whereas stags only showed this preference in winter. Hinds showed a preference for southerly facing aspects in all seasons. Stags showed southerly and easterly preferences in winter and easterly preferences in summer. Hinds generally selected gentle to medium slopes, while stags chose moderate to steep slopes.

Given the spread of deer generally in Australia most land managers will likely work towards population maintenance or reduction. Estimating deer abundance will be critical in monitoring progress towards set targets. If population reduction of wild red deer is desirable the best strategy may be to reduce the number of hinds. The home range data suggest that hinds have smaller home ranges than stags. Habitat preferences observed indicate that night time is the best time to target deer in less heavily vegetated environments where they are more visible.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Publications during candidature

Conference Abstracts/Papers

Amos, M., Baxter, G., Finch, N. and Murray, P. Preliminary population estimates using three methods for wild red deer (*Cervus elaphus*) in South-east Queensland. **15th Australasian Vertebrate Pest Conference, Sydney June 2011.** (Abstract and Presentation)

Amos, M., Baxter, G., Finch, N. and Murray, P. Red deer (*Cervus elaphus*) home range responses to an extreme flooding event in South-east Queensland. **Queensland Pest Animal Symposium, Caloundra, July 2012**. (Paper and Presentation)

Amos, M., Baxter, G., Finch, N. and Murray, P. The influence on climate on home range of wild red deer in SE Qld. **16th Australasian Vertebrate Pest Conference, Brisbane, May 2014**. (Abstract and Presentation)

Peer reviewed papers:

Amos, M., Baxter, G., Finch, N., Lisle, A., and Murray, P. 2014. I just want to count them! Considerations when choosing a deer population monitoring method. *Wildlife Biology*, vol. 20, no. 6, pp. 362-70 (http://www.wildlifebiology.org/).

Amos, M., Baxter, G., Finch, N. and Murray, P. 2014. At home in a new range: wild red deer in south-eastern Queensland. *Wildlife Research*, vol. 41, no. 3, pp. 258-65.

Amos, M., Baxter, G., Finch, N. and Murray, P. Home amongst the gum trees: habitat preferences of wild red deer in south-eastern Queensland. Submitted to *Wildlife Research*

Publications included in this thesis

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Contributor	Statement of contribution
Matthew Amos (Candidate)	Designed experiments (58%) Wrote the paper (75%)
Dr Greg Baxter	Designed experiments (10%) Wrote and edited paper (10%)
Neal Finch	Designed experiments (10%) Wrote and edited paper (8%)
Associate Professor Peter Murray	Designed experiments (10%) Wrote and edited paper (5%)
Dr Allan Lisle	Designed experiments (12%) Wrote and edited paper (2%)

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Associate Professor Peter Murray	Designed experiments (10%) Wrote and edited paper (8%)

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Matthew Amos (Candidate)	Designed experiments (85%) Wrote the paper (75%)
Dr Greg Baxter	Designed experiments (5%) Wrote and edited paper (10%)
Neal Finch	Designed experiments (5%) Wrote and edited paper (8%)
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Contributions by others to the thesis

Significant input was contributed to this project in the area of non-routine technical work (such as co-ordinating field personnel, leading field personnel groups, darting and collaring of animals, etc.) by Glen Harry, Keith Staines, Mike Brennan and Les Kowitz.

Statement of parts of the thesis submitted to qualify for the award of another degree

None

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"The Lord God is my strength, and he will make my feet like hinds' feet, and he will make me to walk upon mine high places." The Holy Bible - Habakkuk 3:19 (KJV)

Keywords

Australia, *Cervus elaphus*, habitat, home range, Queensland, red deer, survey

Australian and New Zealand Standard Research Classifications (ANZSRC)

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Abbreviations

ADA – Australian Deer Association

GPS – Global Positioning System

LoCoH – Local Convex Hull

NSW – New South Wales

MCP – Minimum Convex Polygon

NT – Northern Territory

OH&S – Occupational Health and Safety

QLD - Queensland

SA – South Australia

SSAA – Sporting Shooters Association of Australia

VIC – Victoria

VHF – Very High Frequency

TAS – Tasmania

TRC – Toowoomba Regional Council

WA – Western Australia

Chapter 1 - Introduction

Plate 1 Official launch of the "*Management of wild deer in Australia* Research Project" at Cressbrook Dam in August 2009. (Photo P. Murray)

1.1 Setting the scene

Of the many animals that have been introduced to Australia since 1788, few species divide public perception as much as the deer species (Finch & Baxter 2007). To the avocado farmer they may be a real and present pest, but to the hunter they may be a resource to be protected. To the urban householder deer may be a beautiful addition to nature, but to the motorist they may be a threat to public safety. Regardless of the reader's perception, deer species are here to stay, and numbers and distribution in Australia appear to be increasing (Jesser 2005; Moriarty 2004). However, little peer-reviewed scientific research has been conducted on deer in Australia (Forsyth 2005a). This thesis increases the current scientific knowledge of the ecology of wild red deer (*Cervus elaphus*), one of the six species of deer to be found in wild populations in Australia (Bentley 1998; Jesser 2005), and one that has been little researched in the Australian setting.

1.2 Background

This PhD research project forms a part of the much broader *Management of wild deer in Australia* Research Project – a collaborative project between The University of Queensland, Biosecurity Queensland, Department of Environment and Heritage Protection (Queensland), Toowoomba Regional Council, Australian Deer Association (National and Queensland Branch), and the Sporting Shooters Association of Australia (National and Queensland Branch). The *Management of wild deer in Australia* Research Project was launched in August 2009 with aims to research some of the many unknown biological factors of wild red deer in Australia. This project ran for three years and involved a number of student and professional researchers as well as volunteers.

1.3 Problem Statement

Wild red deer have been in present in Queensland since 1873 (Bentley 1998; Roff 1960). They were a protected species in Queensland from 1952 until their protection was removed with the advent of the *Nature Conservation Act 1992* (Jesser 2005). In a reversal of their former status, red deer were declared a Class 3 pest species in Queensland on the 5th May 2009 under the *Land Protection (Pest and Stock Route Management) Act 2002* by the Queensland Government (Biosecurity Queensland 2013). Similarly red deer are declared pest species in South Australia and Western Australia, whilst in Victoria and New South Wales red deer have some protection as game species. Regardless of their legal status, little is known about some of the major aspects of the ecology of red deer in Australia (Finch n.d.). This includes information on the abundance, home range and habitat preferences of wild red deer in the wild in Australia. It is important to understand these and other ecological factors so that better decisions can be made on their management by both land managers and policy makers.

1.4 Project Aims & Objectives

Overall Aim: The overall aim of this PhD project was to try to raise awareness and increase knowledge of some of the important ecological factors of wild red deer in an Australian setting.

Objectives: The project had three main objectives:

1. Compare methods for estimating the abundance of wild red deer in an Australian sub-tropical environment.
2. Estimate the annual and seasonal home range of wild red deer in south-eastern Queensland.
3. Explore habitat preferences of wild red deer in south-eastern Queensland.

1.5 Research Questions

The following research questions were proposed from the three main objectives:

Objective 1 (Estimating Abundance)

Questions:

1. What is the best method to estimate the absolute abundance of wild red deer in an Australian sub-tropical environment?
2. What is the best method to provide an index of abundance for wild red deer in an Australian sub-tropical environment?
3. What is the most useful method for land managers to use to monitor wild red deer numbers in an Australian sub-tropical environment?
4. What is the estimated abundance of red deer at the study site?

Objective 2 (Home Range)

Questions:

1. What is the annual home range of both male and female wild red deer in south-eastern Queensland?

2. What are the seasonal home ranges of both male and female wild red deer in south-eastern Queensland?

3. Are the home range areas of introduced wild red deer in Australia comparable to those of red deer in their native range in Europe?

4. What are the implications for land managers from the home range areas of wild red deer in south-eastern Queensland?

Objective 3 (Habitat Preferences)

Questions:

1. Do wild red deer display seasonal habitat preferences in south-eastern Queensland?

2. Do wild red deer display 24 hour habitat preferences in south-eastern Queensland?

3. What are the implications for land managers from habitat preferences of wild red deer in south-eastern Queensland?

1.6 Overview of Thesis Document

This thesis is divided into sections based around the main objectives:

- Chapter 2 comprises a literature review of the issues surrounding this research, starting with red deer in Australia, and then moving on to population estimation methods, home range methods and concluding with habitat selection methods.

- Chapter 3 comprises a description of the study site.

- Chapter 4 comprises the paper “I just want to count them! Considerations when choosing a deer population monitoring method." by Amos, M., Baxter, G., Finch, N., Lisle, A., and Murray, P. 2014. *Wildlife Biology*, vol. 20, no. 6, pp. 362-70 which completes Objective 1.

It is a comparison of methods for estimating abundance or indices of abundance for wild red deer in an Australian sub-tropical environment. Methods used include Distance Sampling (Walked Line Transects), Aerial Survey (Mark Recapture Distance Sampling), Spotlight Survey, and Faecal Pellet Index.

- Chapter 5 comprises the paper "At home in a new range: wild red deer in south-eastern Queensland." by Amos, M., Baxter, G., Finch, N. and Murray, P. 2014. *Wildlife Research*, vol. 41, no. 3, pp. 258-65 which completes Objective 2. This paper describes the movement, annual and seasonal home ranges and core areas of wild red deer in south-eastern Queensland. Estimators for annual home range are the Minimum Convex Polygon (MCP), Kernel Utilization Distribution (Kernel) and Local Convex Hull (LoCoH). The LoCoH method is also used to describe seasonal home range areas and core areas.

- Chapter 6 comprises the paper "Home amongst the gum trees: habitat preferences of wild red deer in south-eastern Queensland." by Amos, M., Baxter, G., Finch, N. and Murray, P. (Submitted to *Wildlife Research)* which completes Objective 3. This paper describes the habitat use of wild red deer for the parameters of foliage projective cover, slope, and aspect. The habitat selection ratios (HSR) or ratios of used habitat units to available units for each animal were analysed using the Design III methods of Manly *et al.* (2002) for studies with resources defined by several categories.

- Chapter 7 concludes this research with a general discussion, conclusions, and recommendations from the research.

1.7 Overview

This research on the comparison of population estimation methods, home range and habitat use of wild red deer fills a very important gap in the scientific knowledge of the ecology of this species in the Australian setting. This increased knowledge will in turn help land owners, land managers and policy makers make better decisions when managing red deer in Australia.

Chapter 2 - Ecology of red deer and review of research methodology

Plate 2 Group of hinds in the Cressbrook Dam catchment reserve. (Photo G. Harry – October 2010)

This literature review initially focuses on red deer in the Australian setting. It starts with their introduction to Australia and then moves on to some biological and ecological information. The literature review then looks at various population estimation methods. A review of pertinent home range methods follows. The review concludes with a section on the methods for analysing habitat selection.

2.1 Red Deer in Australia

2.1.1 Origin and Arrival in Australia

Red deer originated in Europe and Asia (Bentley 1998; Jesser 2005). They are found in the wild from Great Britain in the west to Afghanistan and Tibet in the east and to a limited extent in North Africa (Bentley 1998; Jesser 2005). Deer are not native to Australia, and red deer are one of six deer species that have naturalised in the Australian bush (Bentley 1998; Jesser 2005). The other deer species in Australia are Chital deer (*Axis axis*), Hog deer (*Axis porcinus*), Rusa deer (*Cervus timorensis*), Sambar deer (*Cervus unicolor*) and Fallow deer (*Dama dama*) (Jesser 2005; Moriarty 2004). By number, red deer are estimated to be the third most abundant deer species in Australia (Moriarty 2004).

It is unclear exactly when the first red deer arrived in Australia as many old documents have been lost, but they were certainly in Victoria in 1860 (Bentley 1998). In April of that year Mr Thomas Chirnside of Werribee Park, Victoria received six red deer as a gift from Prince Albert (Bentley 1998). More documented introductions of red deer in Victoria occurred in 1862 and 1888 (Bentley 1998). Following the first Victorian introduction, various acclimatisation societies tried to establish red deer populations in Queensland, New South Wales, South Australia, and Western Australia (Bentley 1998).

In Queensland, Queen Victoria presented six red deer to the Queensland Acclimatisation Society in 1873 (Bentley 1998; Roff 1960). This group, consisting of two stags (adult males) and four hinds (adult females), was released at Cressbrook Station near Toogoolawah in the headwaters of the Brisbane River Valley. Another release of red deer was made at the same site in 1874 (Bentley 1998; Roff 1960). Subsequent releases of red deer followed in the Brisbane River Valley, the upper Mary Valley, and near Cunningham's Gap on the Great Dividing Range (Searle 1981).

2.1.2 Distribution

The current distribution of red deer in Australia is largely the result of early attempts at acclimatisation plus releases and escapes from deer farms along with translocations by hunters (Moriarty 2004). Red deer can be found in habitats varying from rainforest to grassland (Bentley 1998; Searle 1981). The red deer distribution in Australia mainly encompasses the south-east corners of Queensland and South Australia, and the central and eastern sections of New South Wales and Victoria (Moriarty 2004). This distribution is shown in Figure 2-1 adapted from Moriarty (2004). The major Australian wild red deer herds are located in the Brisbane and Mary River Valleys of south-eastern Queensland and the Grampian and Otway Ranges in Victoria and are largely the result of early acclimatization attempts (Bentley 1998; Moriarty 2004). The south-eastern Queensland herd is the largest in Australia and has been estimated at greater than 10,000 head by Moriarty (2004) and greater than 15,000 head by Dryden (2005). The south-eastern Queensland herd contains approximately half of all Australian wild red deer (Moriarty 2004).

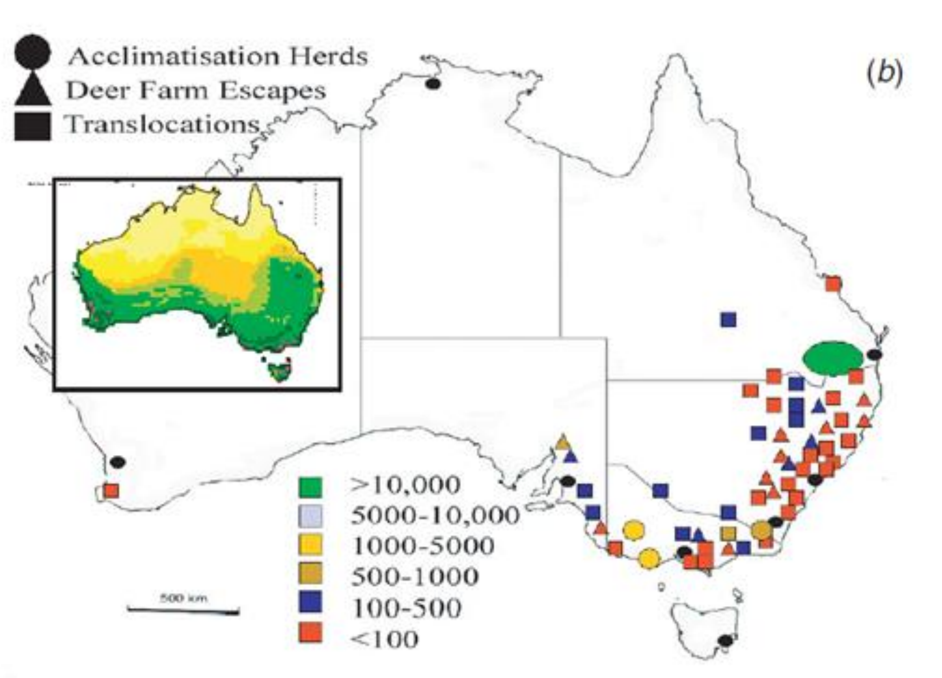

Figure 2-1 Distribution and Abundance Red Deer in Australia in 2000 from Moriarty (2004)

2.1.3 Physical Description

Red deer are usually reddish brown in colour, but coat colour may vary from sandy to a dark brown (Bentley 1998; Roff 1960; Searle 1981). Coat colour may also vary seasonally, with the thick long winter coat being greyer compared to the short red summer coat (Bentley 1998). Red deer have a distinctive creamy or straw coloured rump or caudal patch under their tail (Bentley 1998; Searle 1981). The combination of coat colour, rump colour, general body size and head shape make red deer easily distinguishable from other deer established in Australia.

Mature red deer stags stand approximately 120 cm at the shoulder, and may weigh as much as 180 kg according to Searle (1981), but usually weigh between 135 and 160 kg (Australian Deer Association n.d.). Mature red deer hinds are not as large as the stags and usually stand approximately 90 cm at the shoulder and weigh about 92 kg (Australian Deer Association n.d.). Red deer young, called calves, are born with white spots that fade by six weeks to three months of age (Australian Deer Association n.d.; Jesser 2005).

Whilst it is extremely rare for a red deer hind to grow antlers, red deer stags grow antlers that are cast every year (Searle 1981). Antlers are composed of bone opposed to other ruminants with horns that are keratin based (Finch 2003). The juvenile stag grows his first set of antlers at about eight months of age and is referred to as a "spiker" (Searle 1981). These first antlers or spikes are usually without any branching. The second set of antlers usually has two or three points on each antler, and subsequent sets have more points depending on nutrition and seasonal condition (Searle 1981). In Queensland it is usual for antlers to be cast in September-October and then regrown by January-February (Searle 1981).

Red deer are adaptive to changing their diet with the vegetation and seasonal conditions they encounter (Bentley 1998; Jesser 2005). Research in south-eastern Queensland suggests that red deer browse more in winter when the grass is dry and of lower nutritional value, and graze more in summer when the grass is rich and green (Finch 2000). The same research has confirmed that diet changes in response to geographic location.

In other countries, red deer display a diurnal movement pattern (Mitchell et al. 1977). In south-eastern Queensland red deer are crepuscular and nocturnal, being active in the early morning, late afternoon and night and relatively inactive in the middle of the day (Finch 2003).

Red deer often congregate in groups that vary greatly in size, usually hinds with their young led by a mature hind, and to a lesser extent stags and spikers roam in bachelor groups (Bentley 1998).

2.1.4 Reproduction

Red deer have a short breeding season called the rut or roar that occurs in Autumn for approximately six weeks (Bentley 1998; Roff 1960; Searle 1981). The breeding season in Australia is in March/April, approximately six months out of phase with European red deer (Bentley 1998). During the rut the stags compete to establish mating groups with mature hinds (Bentley 1998; Searle 1981). Stags challenge rival males with a loud roar and in most cases establish dominance at a distance, but at times a roaring match may escalate into a fight (Bentley 1998; Roff 1960). The stag spends considerable energy keeping the harems together, challenging rivals, and mating, leaving him little time to eat (Searle 1981). The result is that the stag loses a great deal of body condition by the end of the rut.

Red deer hinds have an 18 day oestrous cycle and are seasonally poly-oestrus (*Australian deer farming manual* 1993; Searle 1981). It is normal for the hinds to cycle 2 or 3 times during the rut (*Australian deer farming manual* 1993; Searle 1981). The gestation period is approximately 231 days with calves born late November through December (*Australian deer farming manual* 1993; Searle 1981). Weaning occurs by 8 months of age, although calves often stay with the hind until 12 to 15 months of age.

As with other ruminants, onset of sexual maturity is linked to body condition, mostly a result of nutrition (*Australian deer farming manual* 1993; Searle 1981). Hinds may conceive at approximately 16 months of age if conditions are favourable, but usually don't conceive until 28 months of age (*Australian deer farming manual* 1993; Searle 1981). Stags may reach puberty as early as 14 months of age (*Australian deer farming manual* 1993), but rarely have the ability and body condition to control a mating group until much older, usually at about 5 years of age (Searle 1981). The seasonal behaviour of red deer in Queensland is shown in Figure 2-2.

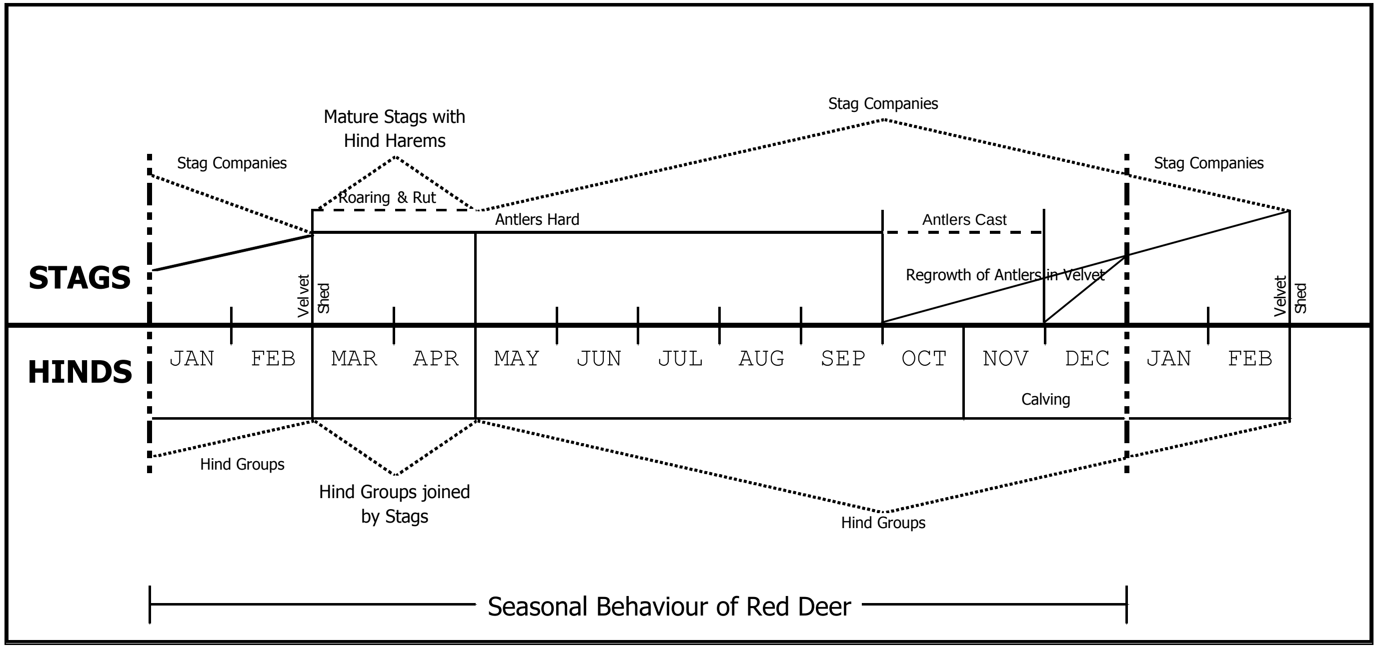

Figure 2-2 Seasonal Behaviour of Red Deer in South East Queensland (adapted from Roff 1960)

2.2 Population Estimation Methods for Wild Red Deer

There are numerous methods used by wildlife biologists to estimate the actual or relative abundance of wildlife populations. This review focusses on population estimation methods commonly used for deer or ungulate species worldwide.

2.2.1 Distance Sampling

Distance sampling is a population estimation method by which an estimate of actual abundance is obtained using either direct or indirect counts (Buckland et al. 2001). Distance sampling methodology falls into two categories: line samples (strips) or point samples (Buckland et al. 2001). Direct observation methods using line sampling include aerial surveys, vehicle surveys, and walked surveys (Buckland et al. 2001). Line transect distance sampling is very useful for ungulate population studies, particularly for deer species (Buckland et al. 2001). The walked line transect method of distance sampling has been used for population estimates of red deer in southern Spain (Acevedo et al. 2008), roe deer (*Capreolus capreolus*), muntjac (*Muntiacus muntjac*), red, fallow and sika deer (*Cervus nippon*) in the United Kingdom (Gill et al. 1997), fallow and roe deer in Italy (Focardi et al. 2013; Focardi et al. 2002a), chital, sambar deer and muntjac in southern India (Jathanna et al. 2003), rusa deer in Indonesia (Ariefiandy et al. 2013) and white-tailed deer (*Odocoileus virginianus*) in Mexico (Mandujano & Gallina 1995). Derivations have been used to estimate fallow deer populations in Georgia, USA (Morse & Miller 2009).

To use the line transect method of distance sampling the observer records sightings of the target animal or cluster of target animals as he or she traverses the transect (Buckland et al. 2001). Whilst recording a sighting, the observer records the distance to the animal (usually obtained from a laser rangefinder) and compass bearing to the animal (Buckland et al. 2001). This information is used to later calculate the perpendicular distance of the animal to the transect line.

The data are then analysed using the computer software package Distance© to yield an estimate of density with associated statistical factors including error and variance (Thomas et al. 2009).

The distance sampling model has three fundamental underlying assumptions that must be fulfilled to give a reliable density estimate (Buckland et al. 2001) as follows:

1. Objects directly on the line or point are always detected (i.e. they are detected with probability 1, or $g(0) = 1$).

2. Objects are detected at their initial location, prior to any movement in response to the observer.

3. Distances (and angles where relevant) are measured accurately (ungrouped data) or objects are correctly counted in the proper distance interval (grouped data).

One major advantage of using distance sampling methodology is that an estimate of absolute abundance is obtained (Buckland et al. 2001). Another strength is that a probability of detection is calculated, which is unique to this method (Thomas et al. 2009). Distance sampling is a statistically powerful technique and performed the best at detecting changes in deer population densities in one English study comparing a number of methods (Smart et al. 2004). This method is useful in woodland and forest situations, although may be better suited to open forests more than dense forests (Focardi et al. 2002a; Gill et al. 1997).

One disadvantage of this method is that a minimum number of target animals must be obtained before the animal density can be estimated with any precision or accuracy (Buckland et al. 2001; Jathanna et al. 2003). Therefore this method can be labour intensive particularly if the encounter rate of target animals is low (Acevedo et al. 2008; Ariefiandy et al. 2013; Focardi et al. 2002a; Jathanna et al. 2003). In low density populations, this method, although precise, may not yield the desired accuracy, especially to detect yearly population density changes (Smart et al. 2004).

2.2.2 Spotlight Counts

Spotlight Counts are very commonly used to estimate or index deer populations (Acevedo et al. 2008; Belant & Seamans 2000; Collier et al. 2007; Focardi et al. 2001; Garel et al. 2010). Spotlight counts can be conducted on foot or from a vehicle (Chiarello 1999; Fafarman & DeYoung 1986). Spotlight counts are commonly used to provide an index of animal abundance such as a kilometric abundance index (Acevedo et al. 2008). They have also been used to estimate actual abundance via distance sampling or by working out the visible area of the spotlight transect (Fafarman & DeYoung 1986; Morse & Miller 2009).

Spotlight counts are widely used because they are easy to conduct and inexpensive (Belant & Seamans 2000; Collier et al. 2007). Deer species are easy to count with a spotlight because of their bright eye reflection (Belant & Seamans 2000) as opposed to other ungulates such as wild boar whose eyes do not reflect well (Focardi et al. 2001). Indices from spotlight counts can perform well in certain environments when compared with other population estimation methods (Acevedo et al. 2008). Spotlighting with additional use of binoculars performed better in a comparison of animal age and sex classification than thermal imaging in one study (Collier et al. 2007). Spotlighting has been used effectively to monitor red deer abundance in a long term study in north-eastern France (Garel et al. 2010).

One main drawback of spotlight counts is that they do not account for changes in detection rate due to habitat permeability, such as counting fewer animals due to longer grass in a high rainfall year (Acevedo et al. 2008). Spotlight counts have been found in a number of studies to underestimate deer numbers when compared to thermal imaging (Collier et al. 2007; Focardi et al. 2001) a method by which a specialised camera collects the infrared radiation from the animal (Gregory 2005). Also, one study showed that observer bias whilst spotlighting varied detection rates by as much as 30% (Collier et al. 2007). This detection variability has led one author to question the usefulness of spotlighting as a method for providing abundance information to land managers (Collier et al. 2013).

2.2.3 Aerial Surveys

Aerial surveys have been used to estimate deer populations in various places (Daniels 2006; Fafarman & DeYoung 1986; Potvin & Breton 2005). Although current aerial surveys are often used in thermal imaging studies (Daniels 2006; Gregory 2005; Naugle et al. 1996; Potvin & Breton 2005), this section will concentrate on visual aerial surveys. Most current aerial surveys of deer have moved away from fixed wing aircraft and are using helicopters (Potvin & Breton 2005). These surveys mainly use double count (mark-recapture) methodology on strip transects or line transect distance sampling methodology (Potvin & Breton 2005). More recently double counting and distance sampling methodology has been combined for helicopter surveys to utilise the strengths of both methods (Fewster & Pople 2008).

Helicopter surveys have been shown to be useful and effective on deer (Daniels 2006; Potvin et al. 2004). Helicopter surveys can produce confidence intervals of ±20% and are cost and time efficient compared to some methods (Daniels 2006; Potvin et al. 2004). Unfortunately, helicopter survey counts appear to be biased downwards, which may or may not be acceptable depending on the study constraints (Fafarman & DeYoung 1986; Hone 2008; Potvin & Breton 2005). One main constraint of using this method is that when the probability of sighting the target species is low the resulting accuracy is also likely to be low, rendering this method not as useful for situations where vegetation canopy cover is dense, or the population density of target species is sparse (Potvin & Breton 2005).

2.2.4 Infra-Red Surveys (Thermal Imaging)

Thermal imaging has been used to estimate populations of deer species (Belant & Seamans 2000; Collier et al. 2007; Collier et al. 2013; Daniels 2006; Focardi et al. 2001; Focardi et al. 2013; Franke et al. 2012; Gill et al. 1997; Gregory 2005; Smart et al. 2004). Thermal infrared cameras detect infrared radiation from an object and convert it into an image (Gregory 2005). The target species is displayed as a different colour due to the temperature contrast with the background and an animal may be observed that would otherwise be missed by the human eye (Sinclair et al. 2006). Thermal infrared detectors may be used day or night as they do not rely on the visible spectrum of light (Gregory 2005; Sinclair et al. 2006). This method works best when the infrared camera has a clear view of the target species, such as in deciduous forest in winter when vegetation does not shield the animal, and when the weather conditions allow a good temperature contrast with the target species, such as in winter in cooler climates (Daniels 2006; Gregory 2005; Sinclair et al. 2006) or when overcast (Franke et al. 2012). Thermal imaging is mainly vehicle or aircraft based (Franke et al. 2012; Gill et al. 1997; Gregory 2005) but with units getting smaller and cheaper is also used in surveys whilst walking (Focardi et al. 2013).

Thermal imaging has been used to provide an index of abundance, and also to provide estimates of absolute abundance via distance sampling or mark recapture methods (Focardi et al. 2001; Focardi et al. 2013; Gill et al. 1997; Gregory 2005). Thermal imaging has been shown to yield more detections of deer in comparison with spotlighting (Collier et al. 2013; Focardi et al. 2001) and the walked line transect method of distance sampling (Gill et al. 1997). Thermal imaging may offer good levels of precision when used with distance sampling protocols (Focardi et al. 2013; Gill et al. 1997; Smart et al. 2004).

Thermal imaging has proven to be time effective when compared to other methods (Daniels 2006; Gill et al. 1997). However, thermal imaging is an expensive method due to high equipment cost (Belant & Seamans 2000; Collier et al. 2007; Focardi et al. 2001; Gill et al. 1997; Smart et al. 2004). This cost may be acceptable, however, when averaged over the life of the study (Focardi et al. 2013).

2.2.5 Faecal Pellet Counts

Faecal pellet counts have been used extensively to provide population estimates of deer species (Acevedo et al. 2008; Alves et al. 2013; Ariefiandy et al. 2013; Batcheler 1975; Brodie 2006; Campbell et al. 2004; Forsyth et al. 2007; Smart et al. 2004). Faecal pellet counts are especially useful in forested areas where direct counts are much harder (Acevedo et al. 2008; Forsyth 2005b;

Jenkins & Manly 2008). Like other population estimation methods, faecal pellet counts can be impacted by observer bias or error (Daniels 2006; Jenkins & Manly 2008). Because they are an indirect method of counting, faecal pellet counts do not provide information on population structure such as age and sex ratios (Daniels 2006). Faecal pellet counts appear to fall into three main categories according to methodology: (1) Faecal Standing Crop, (2) Faecal Accumulation Rate, and (3) Faecal Pellet Index.

2.2.5.1 Faecal Standing Crop

The Faecal Standing Crop (FSC) method requires estimates of three parameters: (1) the density of faecal pellets in the study area, (2) the decomposition rate of the faecal pellets, and (3) the defecation rate of the animal studied (Campbell et al. 2004; Smart et al. 2004). If these criteria can be met, the method can be used to estimate the actual abundance of the animal in the study area (Campbell et al. 2004; McClean et al. 1998; Smart et al. 2004; Sullivan et al. 2004).

Observers generally sample narrow strips, counting all the faecal pellets in that strip to derive a density of faecal pellets in the area (Marques et al. 2001). When counting pellets in narrow strip transects, bias can occur if large pellet groups occur spread over the edge of the strip, as some observers may count that group and others not (Marques et al. 2001). Distance sampling techniques have been utilised in the FSC method to overcome this problem with the additional benefits that the counting of all pellets away from the centre line is not as critical, and a wider strip can be utilised (Marques et al. 2001).

Generally, the FSC method appears to require less labour than the Faecal Accumulation Rate (FAR) method and hence may be more efficient (Campbell et al. 2004; Marques et al. 2001; Smart et al. 2004). Also, it has been suggested that the FSC method is more precise than the FAR method (Campbell et al. 2004; Marques et al. 2001).

The main drawbacks associated with the FSC method revolve around meeting the assumptions of the defecation rate of the animal and decomposition rate of the faecal material (Forsyth 2005b; Forsyth et al. 2007; Marques et al. 2001). Ideally defecation rates of wild animals in their natural environment should be used, but as this is problematic, data from captive animals are used (Forsyth 2005b; Marques et al. 2001). Also, daily defecation rates may vary seasonally with forage availability and quality and among animals (Marques et al. 2001). Results may be further biased as often defecation rates from animals in other locations are used (Forsyth 2005b).

Estimating the decomposition rate of the faecal pellets is also a potential source for bias (Forsyth 2005b; Marques et al. 2001). Faecal pellet decomposition varies with habitat and season (Brodie 2006; Jenkins & Manly 2008). Ideally, fresh faecal pellets should be identified and monitored at the study site in the months preceding the faecal pellet count to make the decomposition rate as accurate as possible (Marques et al. 2001). Unfortunately, local monitoring of faecal pellet decomposition has potential to add greatly to the expense of this method (Campbell et al. 2004).

2.2.5.2 Faecal Accumulation Rate

The Faecal Accumulation Rate (FAR) method of faecal pellet counting measures the rate of pellet group accumulation between two points in time (Campbell et al. 2004; Smart et al. 2004). The strips or plots to be counted are either first cleared of all faecal material, or accurate measures are made from reference markers to all faecal pellet groups. The plots are then counted for any new faecal pellet groups a subsequent time. To derive an estimate of absolute abundance from this method, an assumption as to the defecation rate of the animal must be made similar to in the FSC method.

The FAR method has been shown in one study to be less prone to bias than the FSC method (Campbell et al. 2004) and more efficient at high densities (Alves et al. 2013). However, other studies concluded that this method requires more labour input (Campbell et al. 2004; Marques et al. 2001; Smart et al. 2004) although researchers often don’t include labour input to determine faecal decomposition rate for the FSC method (Campbell et al. 2004). This method may also be affected more by seasonal conditions such as heavy or wet season rain between counts (Mandujano & Gallina 1995). In a recent study, the FAR method performed precisely and reliably and was cost effective compared to remote cameras and infrared survey (deCalesta 2013).

Like the FSC method, assumptions regarding the defecation rate of the animal are crucial to the successful utilization of the FAR method (Mandujano & Gallina 1995). If the defecation rate cannot be obtained locally, then a potential source of bias exists (Forsyth 2005b; Mandujano & Gallina 1995). Like the FSC method, the FAR method is also subject to variability due to observer bias (Jenkins & Manly 2008).

2.2.5.3 Faecal Pellet Index

The Faecal Pellet Index (FPI) method of faecal pellet counting produces an index of relative abundance rather than an estimate of absolute abundance (Acevedo et al. 2008; Forsyth 2005b; Forsyth et al. 2007). The methodology varies, but basically a representative number of strips or plots are surveyed to count all the individual faecal pellets and/or pellet groups (Acevedo et al. 2008; Forsyth 2005b; Forsyth et al. 2007). A number of researchers have shown that there is a positive and linear relationship between faecal pellet abundance and red deer abundance, justifying the use of this method as a population monitoring technique (Acevedo et al. 2008; Forsyth et al. 2007).

The main advantage of using the FPI method is that it does not rely on assumptions for deer defecation rates (Forsyth 2005b). Another advantage is that the researcher does not have to spend time working out faecal pellet decay rates (Acevedo et al. 2008; Forsyth 2005b). For these reasons this method should theoretically be more cost effective than the other faecal pellet counting methods.

Unfortunately the FPI method only provides an index of abundance, so it cannot be used where management requires estimates of absolute abundance (Acevedo et al. 2008; Forsyth 2005b; Forsyth et al. 2007). However, indices of abundance may be useful for local management of animals, as Acevedo (2008 p. 38) maintains that "…most abundance indices in red deer are used for (1) management at a local scale (i.e. a few thousand hectares); (2) middle to low-density populations (<30 ind/100 ha); (3) forested areas."

Like the other faecal pellet count methods, the FPI method may suffer from observer bias (Forsyth 2005b; Jenkins & Manly 2008). It also may still be more labour intensive than other methods (Daniels 2006), although it was shown to use half the labour of distance sampling in one recent study (Ariefiandy et al. 2013).

2.2.6 Passive Activity Index (Soil Plots)

The soil plot or track plot method is an indirect method of collecting population data that provides an estimate of relative abundance (Allen et al. 1996; Engeman et al. 2000; Kuijper et al. 2009, Lyra-Jorge et al. 2008, Mandujano & Gallina 1995, Weckerly and Ricca 2000). In this method a defined area (plot) of soil is prepared by working the soil with a rake-hoe, steel garden rake or similar so that it is fine enough to show animal tracks which are observed after a given time, usually the next day (Allen et al. 1996; Engeman et al. 2000; Kuijper et al. 2009, Mandujano & Gallina 1995). These soil plots are often located on vehicle tracks for ease of use by the observer, and also because wild canids and other animals often use vehicle tracks (Allen et al. 1996; Engeman et al. 2000; Engeman et al. 2002; Mandujano & Gallina 1995).

Various derivations of the soil plot method have been used worldwide and studies including deer species have been conducted in North America, South America, Europe and India (Allen et al. 1996; Bali et al. 2007, Engeman et al. 2000; Kuijper et al. 2009, Lyra-Jorge et al. 2008, Mandujano & Gallina 1995, Weckerly and Ricca 2000). In Australia, one derivation of this method, the Passive Activity Index (PAI), was adapted to obtain data on dingo (*Canis lupus dingo*) populations (Allen et al. 1996). Since then animals that have been successfully monitored in Australia using the same methodology include dingoes, Macropods (Macropodidae), feral cats (*Felis catus*), and feral pigs (*Sus scrofa*) (Engeman & Allen 2000). The same methodology has also been used in Texas, U.S.A. to monitor populations of coyote (*Canis latrans*), bobcat (*Felis rufus*), white-tailed deer, javelina (*Tayassu tajacu*), and feral pigs (Engeman & Allen 2000).

One positive aspect of the PAI method is the ability to detect multiple species simultaneously (Engeman & Allen 2000; Engeman et al. 2002). The method is easy to use and is sensitive to changes in population numbers (Allen et al. 1996; Engeman et al. 2002). Individual PAI studies on average only need to run for 4 consecutive days to get a population sample in time, and sometimes adequate data can be obtained in as little as 2 days (Engeman & Allen 2000).

As with many other methods, the PAI method is subject to observer bias (Engeman et al. 2000, Weckerly and Ricca 2000). Also, the method is susceptible to poor weather such as high wind or heavy rain making the animal tracks unreadable (Allen et al. 1996; Engeman et al. 2000, Kuijper et al. 2009). At times the detection of the exact number of multiple animal entries onto a plot can be problematic if the tracks cross over each other or follow the same line (Allen et al. 1996; Engeman et al. 2000). Also, soil plots are best suited to lightly used vehicle tracks, as excessive vehicle movements or even movements of livestock can make them unreadable (Allen et al. 1996; Engeman et al. 2000; Engeman et al. 2002).

2.2.7 Remote Camera Surveys

The use of remote infrared triggered cameras is a recent development for monitoring wildlife populations (Jacobson et al. 1997; Koerth et al. 1997). Remote cameras have been utilised successfully in a number of wildlife studies around the world on a variety of species (Dougherty & Bowman 2012; Jacobson et al. 1997; Koerth et al. 1997; Larrucea et al. 2007; Marker et al. 2008; Roberts et al. 2006; Rowcliffe et al. 2008; Vine et al. 2009; Winarni et al. 2004). White-tailed deer appear to be the main deer species studied using this method (Jacobson et al. 1997; Koerth et al. 1997; McCoy et al. 2011; Roberts et al. 2006).

Remote cameras may be used to provide a relative index of abundance or an absolute estimate of abundance depending on method used (Jacobson et al. 1997; Koerth et al. 1997; Rowcliffe et al. 2008). Most camera studies use a variation of a Lincoln-Petersen Mark/Recapture estimate or a variation of the camera estimate developed by Jacobson et al. (1997) to estimate the absolute abundance of an animal (Dougherty & Bowman 2012; Jacobson et al. 1997; Koerth et al. 1997; Larrucea et al. 2007; Marker et al. 2008; Roberts et al. 2006). These studies rely on the recognition of some individual animals by characteristics such as antler growth, coat colour, body size, etc. or by an individual identifying item applied during actual animal capture such as a radio collar or ear tag (Dougherty & Bowman 2012; Jacobson et al. 1997; Koerth et al. 1997; Larrucea et al. 2007; Marker et al. 2008; Roberts et al. 2006). In contrast, one camera study has proposed a model of estimating absolute abundance for animals without any uniquely identifying characteristics which is based on trapping rates alone (Rowcliffe et al. 2008). The Jacobson et al. (1997) method does not provide methodologies for generating measures of uncertainty for parameter estimates, but these have since been developed by Weckel et al. (2011).

The minimum time that cameras should be left in place may need to be determined at the study site (Jacobson et al. 1997). There is also a minimum density of cameras required to gain reasonable accuracy that may vary with study site and species (Jacobson et al. 1997). Most of the camera studies of deer involve the use of bait stations (Dougherty & Bowman 2012; Jacobson et al. 1997; Koerth et al. 1997), however, this may introduce biased population estimates (Jacobson et al. 1997; McCoy et al. 2011).

Using remote cameras may be more informative than other methods. Cameras may produce information regarding population structure or habitat preference that is not forthcoming with a faecal pellet count or a passive soil plot survey (Jacobson et al. 1997; McCoy et al. 2011). The use of cameras may be time and cost-effective (Jacobson et al. 1997; McCoy et al. 2011; Roberts et al. 2006) although the time spent analysing multitudes of photographs is not often included in studies. Cameras are especially useful in forested areas where other survey methods are hampered by poor animal visibility (Jacobson et al. 1997; Koerth et al. 1997; McCoy et al. 2011; Roberts et al. 2006). Cameras may also provide more information than other methods where the animal is shy or cryptic in behaviour (Larrucea et al. 2007; Vine et al. 2009; Winarni et al. 2004).

A disadvantage of using cameras to estimate absolute abundance is that a number of animals must be marked or uniquely identifiable (Dougherty & Bowman 2012). The assumptions of equal detectability and closed populations are not likely met if mark/recapture techniques are used

(Jacobson et al. 1997; Sinclair et al. 2006). Another disadvantage of camera studies is the potential for extremely large numbers of photographs that need to analysed (Jacobson et al. 1997).

2.2.8 Population Manipulation Indices

There are a number of population estimation methods that are useful if the target population is to be exploited or manipulated in some way including population reconstruction methods, the change in ratio method and the index-manipulation index method (Baxter et al. 2008; Millspaugh et al. 2009, Sinclair et al. 2006).

2.2.8.1 Population reconstruction methods

There are a number of variations of population reconstruction methods for harvested populations that include the sex-age-kill (SAK) method (Millspaugh et al. 2009, Skalski & Millspaugh 2002), the Lang and Wood (1976) Pennsylvania method and the Downing (1980) reconstruction method. These methods are widely used by state agencies in North America to monitor deer, especially white-tailed deer, as well as other species (Millspaugh et al. 2009). The reconstruction methods use harvest data such as sex and age (or age class) to estimate the population size before the harvest (Downing 1980, Lang & Wood 1976, Skalski & Millspaugh 2002). Depending on the method additional estimates of parameters such as the adult sex ratio, fawn/doe ratio, annual survival, and the harvest mortality rate may be required (Skalski & Millspaugh 2002).

Population reconstruction methods are popular because the data utilised are routinely collected by the relevant agencies as part of their licensing/harvest system (Skalski & Millspaugh 2002). Potential sources of bias that could affect performance of these methods are changes in hunting effort/success, inaccurate reporting of age, and inaccurate estimates of sex and adult/juvenile ratios (Downing 1980, Lang & Wood 1976, Skalski & Millspaugh 2002). Millspaugh et al. (2009) have also reported that the SAK method is sensitive to violation of the assumptions of a stable age distribution and a stationary population.

2.2.8.2 Change in Ratio Method

The change in ratio method is useful if there are two classes of animals that can be reliably identified in the target population such as male and female (Sinclair et al. 2006). First a population index survey is conducted yielding numbers for both classes of the animal. Then a population manipulation is applied, either an increase or decrease of one of the animal classes. Finally, another population index survey is conducted for both classes of the animal. The overall size of the population before the manipulation occurred can then be estimated. There is an assumption with this method that the population is closed apart from the population manipulation, so it is normally conducted over a short time period.

This method has been trialled on white-tailed deer with positive results (Conner et al. 1986). It was estimated that this method works best where the ratio of the animal class to be manipulated forms a much smaller percentage of the overall population than the other class (Conner et al. 1986). Conner et al. (1986) predicted that the sample size and hence sampling effort to obtain a reasonable population estimate using this method would vary with the openness of the habitat and the deer density, being much easier in an open habitat with high deer density.

2.2.8.3 Index Manipulation Index

The index-manipulation index method is another method for calculating the size of a population when the population is to be manipulated (Sinclair et al. 2006). This method is particularly useful if the population is being exploited in the form of some sort of harvest or removal. The index-manipulation method also requires a pre- and post-manipulation population indices survey similar to the change in ratio method, but it is not segregated into classes such as male and female. The size of the change in the ratio between the indices from before and after the manipulation can then be combined with actual numbers from the population manipulation to gain an estimate of overall abundance. This method also has an assumption that the target animal population is closed, so is conducted over a short time. No peer-reviewed journal articles could be obtained which use this method to estimate deer numbers although it has been used on goats in Australia (Pople et al. 1998). However, this method has previously been utilised to estimate wild red deer numbers in the Cressbrook Cam catchment reserve (Finch 2003).

2.2.9 Selection of Methods

The four methods chosen for estimating the abundance or indices of abundance of red deer at Cressbrook Dam were: Distance Sampling (Walked Line Transects), Aerial Survey (Mark Recapture Distance Sampling), Spotlight Survey, and Faecal Pellet Index. Distance sampling was chosen due to worldwide use on a number of animal species including ungulates, the forested environment on much of the research site, the expected high density of deer at the research site, and the available labour on the research project. Aerial survey was chosen for similar reasons to distance sampling, although it wasn't expected to need much labour input. In addition, aerial survey is already the accepted method in Queensland for estimating broadscale Macropod abundance. Spotlighting was chosen because of its widespread use on deer species, its simplicity and ease of use and due to the fact that Toowoomba Regional Council had records of a spotlight survey from previous years for comparison. The faecal pellet index was chosen due to its positive and linear relationship with red deer abundance in New Zealand (Forsyth et al. 2007), its application for use in a forested environment, and due to the available labour.

Remote cameras were not chosen due to lack of time and because they were already being trialled on site by an Honours student (S. Chinook). Infrared thermal surveys were not chosen due to initial cost of purchase. Soil plots were not chosen because they are not reportedly widely used on deer. Population manipulation indices were not chosen as there was no deer cull included in the scope of the research.

2.3 Home Range of Wild Red Deer

Home range is an area which an animal often moves within during its daily activities (Burt 1943). Home range has been defined by Burt (1943, p. 351) as "…that area traversed by the individual in its normal activities of food gathering, mating, and caring for young. Occasional sallies outside the area, perhaps exploratory in nature, should not be considered as in part of the home range." Home ranges for animals have been described by various mathematical formulas and geometric shapes, and Mohr (1947) cemented the concept of a minimum home range.

According to Rodgers and Kie (2011, p. 1) models for estimating home range from point location data fall into four categories: "…minimum convex polygons, bivariate normal models (Jennrich-Turner estimator, weighted bivariate normal estimator, multiple ellipses, Dunn estimator), nonparametric models (grid cell counts, Fourier series smoothing, harmonic mean), and contouring models (peeled polygons, kernel methods, hierarchical incremental cluster analysis)." Each model gives a different view of what the home range might look like (Girard et al. 2002).

Formerly, the most commonly used of these home range estimators was the Minimum Convex Polygon (MCP) (Girard et al. 2002; Seaman et al. 1999). A disadvantage of this method is that it is impacted by sample size, and may underestimate or overestimate home range (Girard et al. 2002; Jerina 2009; Morse et al. 2009; Seaman et al. 1999). However the minimum convex polygon can provide important information to researchers (Girard et al. 2002). Nearly all the foundational home range studies of red deer used the MCP method (Catt & Staines 1987; Clutton-Brock et al. 1982; Georgii 1980; Jeppesen 1987a), so it remains important – especially for comparison purposes.

Variations of the kernel method are also widely used to estimate home range (Girard et al. 2002; Rodgers & Kie 2011; Seaman et al. 1999). Some authors advocate the use of kernel methods as having the closest correspondence between the animals home range and the location data (Girard et al. 2002; Seaman et al. 1999). However, kernel methods may also have bias relating to sample size and location data distribution (Girard et al. 2002; Seaman et al. 1999). To use the kernel method the researcher must choose a smoothing parameter or reference bandwidth (Kie et al. 2010). Kernel methods have been used on deer species including recent home range studies of red deer (Bocci et al. 2010; Jerina 2012)

More recent methods for estimating home range include the Brownian bridge movement model (BBMM) (Horne et al. 2007), the potential path area (PPA) (Long & Nelson 2012), alpha hulls (Burgman & Fox 2003) and the local convex hull method (LoCoH) (Getz & Wilmers 2004). All of these methods are well suited to home range estimation of GPS data (Burgman & Fox 2003; Getz & Wilmers 2004; Horne et al. 2007; Long & Nelson 2012). The BBMM and PPA methods rely on the time between data points as part of their calculation (Horne et al. 2007; Long & Nelson 2012) whereas the alpha hull and LoCoH methods are both based on derivations of the use of convex hulls (Burgman & Fox 2003; Getz & Wilmers 2004). Of particular interest for use at Cressbrook Dam, the LoCoH method has been reported to be very good at calculating home range areas where there are distinct boundaries that limit animal access (Getz & Wilmers 2004).

For some estimation methods, the frequency of data collection is important in minimising bias in home range estimation (Girard et al. 2002), especially using VHF tracking techniques. A minimum of 30 locations and preferably ≥50 locations are needed to construct a home range (Seaman et al. 1999). Girard et al. (2002) found that a minimum of 1 location every 3 days and preferably 1 location/day were needed to minimise bias in estimating seasonal and yearly home ranges for Moose (*Alces alces*). However, low sampling rates and sparse data are not a problem with GPS tracking collars. In fact, the higher rates of collection of GPS tracking collars can lead to autocorrelation problems (Fieberg et al. 2010), especially for methods such as the kernel method. Collecting data from representative time periods throughout the day should be factored into sampling as one researcher found that there was a significant difference in the size and composition of the home range of red deer when comparing diurnal only data with data collected over the full 24 hours (Jerina 2009).

GPS collars purchased for the project recorded a location every 90 minutes. This gave sufficient data to compare different times of the day but still have a reasonable battery life (~2 years). The LoCoH estimator was chosen as the best method to gain annual and seasonal home range estimates due to the sharp geographic boundaries of the water bodies at the study site. Also, autocorrelation is not an issue with this method (Getz & Wilmers 2004). The MCP and a kernel method were also chosen to provide estimates of annual home range to compare with results from prior research on red deer.

2.4 Habitat Selection of Wild Red Deer

Habitat selection according to Girard et al. (2006, p. 1249) "…is one of the most studied aspects of behavioural ecology". The habitat selection of a species is important to land managers trying to manage the land resources available to the species (Girard et al. 2006). Habitat selection studies usually compare resource use and resource availability in a given time period (Thomas & Taylor 1990), but could also compare resource non-use with either use or availability (Manly et al. 2002). This resource use may be affected by resource quality, resource quantity, social behaviour, predator activity and human disturbance (Jerina 2009; Morse et al. 2009; Sinclair et al. 2006). Habitat selection may vary for the time of the day and/or the season or year (Girard et al. 2006; Jerina 2009; Morse et al. 2009).

Habitat selection studies usually take the form of a resource selection function (RSF) (Manly et al. 2002). The RSF is a statistical model where resource units are first measured for use or non-use and availability. The measurements are incorporated in the model to predict a value for each resource unit that is proportional to the probability of use.

For habitat selection there is a minimum number of animals that must be studied to conduct proper statistical analysis (Aebischer et al. 1993; Girard et al. 2006). Aebischer et al. (1993) recommended a minimum of 10 animals be used, and Girard et al. (2006) recommended a minimum of 12 animals. The number of locations for each animal determines the accuracy of the analysis, and for radio-collared animals this is determined by the tracking schedule (Aebischer et al. 1993; Girard et al. 2006). On a home range scale, a tracking schedule of 1 per week for moose yielded beneficial data (Girard et al. 2006). However, tracking schedules should be constructed to give an unbiased representation of the animals movements in regards to habitat selection (Aebischer et al. 1993), and many studies up to date have collected daytime data only, at the expense of understanding night time habitat selection (Jerina 2009).

Habitat studies estimating both the available and utilized resources have been classified into the following three designs by Thomas and Taylor (1990): design-1 studies estimate available and used resources for all animals in the defined study area, design-2 studies estimate the available resources in the whole study area, but the utilized resources according to the individual animals, while design-3 studies estimate both the utilized and available resources according to each individual animal. Erickson et al. (2001) have since added design-4 studies where use and availability measures are paired for each use (location point). With the advent of GPS tracking collars, most recent habitat selection studies have used the individual animal as the sampling unit in design 3 studies, and conducted spatial analysis using a Geographic Information Systems (GIS) program with the resources available defined by the individual animal's home range (Girard et al. 2006; Jerina 2009; Morse et al. 2009; Rodgers & Kie 2011).

Common assumptions of habitat use studies based on resource selection functions include: 1. Marked animals are a random sample of the population, 2. Locations are independent in time (depending on the type of analyses conducted), 3. Marked animals select resources independently of each other, 4. Availability of resources does not vary during the study, and 5. Resources are classified correctly (Erickson et al. 2001; Manly et al. 2002).

Numerous statistical tests for analysing the availability and use (or non-use) of resources have been utilised including chi-squared tests for goodness-of-fit, compositional analysis, logistic regression, discrete-choice models, generalized linear mixed-models, movement-based models and other methods (Fieberg et al. 2010; Manly et al. 2002; Thomas & Taylor 2006). McClean et al. (1998) noted the difficulty faced by ecologists when choosing a method for analysis when there are so many to choose from. Manly et al. (2002 p. 14) described this choice as "complex and sometimes controversial".

Logistic regression and compositional analysis appear to be popular methods of habitat analysis (Thomas & Taylor 2006). Goodness of fit tests are still being used although they appear to be less popular now with so many other methods available (McClean et al. 1998; Thomas & Taylor 2006). Although logistic regression is a popular method, dealing with correlation in location points can be problematic (Fieberg et al. 2010). Also, compositional analysis was not recommended by Thomas and Taylor (2006) because of high type I error rates reported for this method. The chi-squared goodness of fit test as described by Manly et al. (2002) is easily understood, and well suited to data in categories, so was chosen for analysis of the data for this research.

2.5 Summary

Red deer have been in Australia for over 150 years and have established wild populations. There is little peer-reviewed research on wild red deer in Australia. The Cressbrook Dam catchment reserve is contained within the area containing the south-eastern Queensland wild red deer herd – the largest population of red deer in Australia. Four population estimation methods were identified for use in this research: distance sampling, aerial survey, spotlighting and faecal pellet counts. The LocoH method was identified as being useful for estimating home range in areas with sharp geographic boundaries so would be suitable for estimating home range around the Cressbrook Dam foreshore. The chi-squared goodness of fit test was identified as a method suited to analyse the habitat preferences of red deer when habitat data are in categories. These methods were all implemented in this research project to improve the general knowledge and understanding of wild red deer in the Australian context.

Chapter 3 - Cressbrook Dam Catchment Reserve - The Study Site

Plate 3 Don Baxter leaning on a rub tree in the Cressbrook Dam catchment reserve. (Photo M. Amos – September 2011)

This research was conducted in the catchment reserve surrounding Cressbrook Dam. This chapter contains a description of the study site including location, elevation, climate, vegetation and large animal species.

3.1 Location, Area, and Use

Cressbrook Dam is located approximately 55 km north-east of Toowoomba in south-eastern Queensland at latitude 27.258° S longitude 152.195° E (see Figure 4-1 on page 35). Cressbrook Dam and surrounding catchment reserve is managed by the Toowoomba Regional Council (TRC) and comprises approximately 4,893 ha (M McDermid 2011 pers. comm., 14 June). Apart from being major water supplies for Toowoomba, Cressbrook Dam and adjoining Perseverance Dam form very important recreation areas for the general public with facilities to picnic, camp, fish, boat, sail and bushwalk.

3.2 Elevation

Cressbrook Dam is located in part of the mountain chain that forms the Great Dividing Range of eastern Australia and varies greatly in elevation. Adjoining Cressbrook Dam is Mount Jockey at 607 metres above sea level, over 300 metres higher than the water in the dam. The dam spillway height is at 280 metres above sea level, and the water in the dam when full is a maximum of 34 metres deep (Toowoomba Regional Council 2009).

3.3 Climate

Cressbrook Dam is located in the warm/humid zone of subtropical Australia (Australian Bureau of Meteorology 2012). There are no official temperature records for Cressbrook Dam, but the mean minimum overnight temperatures for nearby Toowoomba range from 5.3°C in July to 16.7°C in January, while the mean daily maximum temperatures range from to 16.3°C in July 27.6°C in January (Australian Bureau of Meteorology 2007). The mean annual rainfall at Cressbrook Dam from 1990 to present is 740.6 mm, but the longer term average could possibly be higher as at nearby Lake Perseverance rainfall records from 1971 show a mean annual rainfall of 836.3mm (Australian Bureau of Meteorology 2014). On average 60% of the rain falls between November and March (Australian Bureau of Meteorology 2014).

3.4 Vegetation

The Cressbrook Dam catchment has two main vegetation types: open grassland with gullies and rolling hills and dry sclerophyll forest with much steeper gullies, hills and mountains. Of the 4,893 ha of land managed by TRC, approximately 82% (4,016 ha) is dry sclerophyll forest (M McDermid 2011 pers. comm., 14 June). In 2009 approximately 15% (730 ha) was open grassland (M McDermid 2011 pers. comm.). This reduced to approximately 7% (352 ha) in early 2011 when the dam filled from heavy rains (M McDermid 2011 pers. comm.). Conversely, the dam water level covered approximately 3% of the total area in 2009, but this increased to nearly 11% (526 ha) in early 2011 (M McDermid 2011 pers. comm.) (see Figure 4-1 on page 35). Wild red deer densities were estimated to be high in the open grasslands and low in the dry sclerophyll forest, varying with the vegetation type present (Amos 2010).

3.4.1 Open Grassland

Dominant ground cover in the open grassland consists of Rhodes grass (*Chloris gayana*.), Blady grass (*Imperata cylindrica*), Speargrass (*Stipa* sp.), Pili grass (*Heteropogon contortus*), Bracken Fern (*Pteridium* sp.), Lantana (*Lantana camara*), Guinea Grass (*Megathyrsus maximus*), Broomsedge (*Andropogon virginicus*), New Holland Daisy (*Vittadinia dissecta*), Stinking Pennywort (*Hydrocotyle laxiflora*), Weeping grass (*Microlaena stipoides*), Native Geranium (*Geranium solanderi*), Blue Heliotrope (*Heliotropum amplexicaule*), Spiked Sida (*Sida hackettiana*), Mint Vine (*Mentha diemenica*), Many-flowered Mat-rush (*Lomandra multiflora*), Milkweed (*Asclepias* sp.), and Purple Verbena (*Verbena* sp.). Some common weeds in this area include Scotch Thistle (*Onopordum acanthium*), Balloon Cottonbush (*Gomphocarpus* sp.), and Fleabane (*Conyza bonariensis*). The dominant mature tree species in the open grassland is Narrow-leaved Ironbark (*Eucalyptus crebra*), which also occurs in a juvenile regrowth form along with Moreton Bay Ash (*Corymbia tessellaris*), Crab Apple (*Angophora* sp.) and Pink Bloodwood (*Corymbia intermedia*) as dominant regrowth species. In the creek lines of the open grassland there are many She-Oaks (*Allocasuarina* sp.), Fig trees (*Ficus* sp.), Bottlebrush (*Callistemon* sp). and Crab Apples (*Angophora* sp.). A photograph typical of the open grassland is shown in Plate 4 on page 31.

Plate 4 Typical Open Grassland in the Cressbrook Dam catchment reserve. (Photo M. Amos – May 2010)

Plate 5 Typical Dry Sclerophyll Forest Vegetation in the Cressbrook Dam catchment reserve. (Photo P. Murray – March 2009)

3.4.2 Dry Sclerophyll Forest

Typical dominant groundcover vegetation in the dry sclerophyll forest area is made up of Lantana, Kangaroo grass (*Themeda triandra*), Speargrass, Blady grass, Wiregrass (*Aristida* sp.), Yellow Buttons (*Chrysocephalum apiculatum*), Common prostrate vine (*Rostellularia adscendens*) and prickly pear (*Opuntia* sp.). Typical tree species include Blue Gum (*Eucalyptus tereticornis*), Brush Box (*Lophostemon confertus*), Pink Bloodwood, Grey Gum (*Eucalyptus punctata*), Narrow-leaved Ironbark and Moreton Bay Ash. A photograph typical of the dry sclerophyll forest is shown in Plate 5 on page 31.

3.5 Red Deer at Cressbrook Dam

A relatively recent study has shown the red deer in the Cressbrook Dam catchment reserve to be in "excellent physical condition" (Finch 2003). Deer in that study showed little or no evidence of internal or external parasites (Finch 2003). The only potential predators of wild red deer present at this site other than humans are dingoes or wild dogs, and to a lesser degree Wedge-tailed eagles (*Aquila audax*) (Finch 2003) although Bentley (1998) maintained there are no predators of deer in Australia.

Cressbrook Dam is approximately 35 km from Cressbrook Station, the original release site of red deer in Queensland, and is certainly within the historic range of wild red deer described by Roff (1960). The densities of wild red deer in this area are suggested at 1 deer to 35 – 45 hectares (Dryden 2005). In contrast, Finch (2003) estimated that there were likely more than 1,000 deer in the Cressbrook Dam catchment reserve, a density of perhaps 1 deer to 5 hectares. However this research was based on a study of 8% of the catchment reserve with the results extrapolated to the whole site and Finch ((2003, p. 22) warned that "Extreme caution should be exercised when using this figure, however, as extrapolations of this kind without further sampling are inaccurate."

3.6 Other Species

Apart from red deer, there are other large terrestrial vertebrates in the Cressbrook Dam catchment including Eastern Grey Kangaroos (*Macropus giganteus*), Whip-tailed Wallabies (*M. parryi*), Red-necked Wallabies (*M. rufogresius*), Swamp Wallabies (*Wallabia bicolor*), Feral Pigs (*Sus scrofa*), Dingoes (*Canis lupus dingo*), and Cattle (*Bos taurus*).

Chapter 4 - Population Estimation Methods

Chapter 4 comprises the paper "I just want to count them! Considerations when choosing a deer population monitoring method." by Amos, M., Baxter, G., Finch, N., Lisle, A., and Murray, P. 2014. *Wildlife Biology*, vol. 20, no. 6, pp. 362-70 (http://www.wildlifebiology.org/)

Plate 6 Mike Brennan and Glen Harry (standing) counting faecal pellets in the Cressbrook Dam catchment reserve. (Photo M. Amos – September 2010)

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"I just want to count them! Considerations when choosing a deer population monitoring method"

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Effective management of any population involves decisions based on the levels of abundance at particular points in time. Hence the choice of an appropriate method to estimate abundance is critical. Deer are not native to Australia and are a declared pest in some states where their numbers must be controlled in environmentally sensitive areas. The aim of this research was to help Australian land managers choose between widely used methods to count deer. We compared population estimates or indices from: distance sampling, aerial surveys, spotlight counts, and faecal pellet counts. For each we estimated the labour input, cost, and precision. The coefficient of variation varied with method and time of year from 8.7 to 36.6%. Total labour input per sampling event varied from 11 to 136 h. Total costs of vehicles and equipment per sampling event varied from AU$913 to $2966. Overall, the spotlight method performed the best at our study site when comparing labour input, total cost and precision. However, choice of the most precise, cost effective method will be site specific and rely on information collected from a pilot study. We provide recommendations to help land managers choose between possible methods in various circumstances.

Of the 18 species of deer introduced into Australia only six survive in free roaming wild populations (Bentley 1998, Jesser 2005). Most deer populations have been restricted in distribution for almost a century but many are now increasing in number and distribution (Moriarty 2004, Jesser 2005). Few introduced species (or group of species) in Australia divide community attitudes as much as deer. In Tasmania, Victoria and NSW they are classified as Game and protected through legislation whilst in other states they are either declared pests or have no legal status. In Queensland, wild deer were protected in legislation from 1863 until 1994. They then had no legal status until 2009 when they were declared pests. The importance of deer to many people as either a valued resource or a declared pest implies a management imperative, yet there is a dearth of information in the peer reviewed literature relating to these species in Australia (McLeod 2009).

Effective management of any species usually involves making decisions from knowledge of their population abundance or trends in abundance (Sinclair et al. 2006) and managers often perform counts of the population to estimate these parameters. Obtaining estimates of abundance that are useful to management requires the best choice of method (Sinclair et al. 2006).

Often researchers will start with a decision to either estimate absolute or relative abundance (Sinclair et al. 2006). For deer species worldwide popular methods for estimating absolute abundance include line transect distance sampling (Focardi et al. 2002, Jathanna et al. 2003, Acevedo et al. 2008, Ariefiandy et al. 2013), aerial surveys (Fafarman and DeYoung 1986, Potvin and Breton 2005, Daniels 2006, Kantar and Cumberland 2013), thermal imaging (Belant and Seamans 2000, Focardi et al. 2001, 2013, Smart et al. 2004, Daniels 2006, Collier et al. 2013), camera surveys (Roberts et al. 2006, Curtis et al. 2009, McCoy et al. 2011, Dougherty and Bowman 2012), population manipulation indices (Conner et al. 1986, Sinclair et al. 2006), and faecal pellet counts (Marques et al. 2001, Campbell et al. 2004, Smart et al. 2004, Mandujano et al. 2013, Alves et al. 2013). Popular methods of estimating relative abundance for deer include spotlight counts (Belant and Seamans 2000, Focardi et al. 2001, Collier et al. 2007, Acevedo et al. 2008, Garel et al. 2010) and faecal pellet counts (Forsyth et al. 2007, Acevedo et al. 2008, 2010, Ariefiandy et al. 2013).

Data on the performance of various methods is, however, for most managers in Australia based on research conducted in other countries with different climates and habitats. Also, as little research has been conducted on the ecology of deer species in Australia, it is unknown if their behaviour in this environment will impact on the success of methods used elsewhere. We tested four of the most widely used survey methods for deer using the same population of deer within the same time period and in the context of the resources available to Australian land managers.

Taking into consideration the steep terrain of our study area, the target species wild red deer *Cervus elaphus*, the relatively high density of the deer, and available resources (labour, finance and equipment) we chose distance sampling, aerial survey (mixed distance sampling/mark–recapture), spotlight counts and faecal pellet indices to estimate relative abundance. To help land managers choose appropriate methods to suit their needs we provide a comparison of these four methods for the estimates or indices obtained, labour input, cost, and precision at our study site.

Material and methods

Study area

This research was conducted in the Cressbrook Dam catchment (27°25′8″S, 152°19′5″E) between October 2010 and October 2012. Cressbrook Dam is located approximately 55 km northeast of the major provincial city of Toowoomba in southeast Queensland in the warm/humid zone of subtropical Australia (Australian Bureau of Meteorology 2012). Cressbrook Dam catchment reserve (Fig. 1) is managed by the Toowoomba Regional Council (TRC) and comprises approximately 4893 ha (M. McDermid, TRC, pers. comm.). The reserve area is fenced to exclude domestic livestock (i.e. cattle and horses), but not to exclude or contain wild animals (i.e. deer, kangaroos, wallabies, feral pigs and wild dogs).

Cressbrook Dam is located in part of the mountain chain that forms the Great Dividing Range of eastern Australia. Elevation in the study area varies from 280 m to 607 m a.s.l. (Toowoomba Regional Council 2009). Topography in the Cressbrook Dam catchment varies from relatively gentle slopes in the lower elevations around the dam foreshore to steep gullies, ridgelines and hills at higher elevations.

Approximately 82% of the 4,893 ha, (4016 ha) is dry sclerophyll forest. In 2009 approximately 15% (730 ha) was open grassland but this reduced to about 7% (352 ha) in early 2011 when the water reservoir filled rapidly after heavy rains (M. McDermid, pers. comm.). Conversely, the reservoir water level covered approximately 3% (147 ha) in 2009, but this increased to nearly 11% (526 ha) in early 2011 and was maintained at this area for the balance of the study (M. McDermid, pers. comm.). Approximately 1400 ha of dry sclerophyll forest in the northeast part of the catchment reserve had access restrictions during the course of the study.

Red deer were originally released in southeast Queensland in 1873 close to the Cressbrook Dam catchment (Bentley 1998, Jesser 2005). Deer flourished in the region and have built up to a herd estimated at between 10 000 and 15 000 (Moriarty 2004, Jesser 2005). Deer numbers locally in the Cressbrook Dam catchment reserve currently comprise a high density population (Finch 2003, Amos et al. 2011). Red deer at the study site display a similar life cycle to where they originated in the Northern Hemisphere, but timing of events is six months advanced. Thus the rut (mating season) is still in Autumn, but this occurs at the study site in late March through April rather than late September through October as in Scotland (Clutton-Brock et al. 1982). Toowoomba Regional Council staff conducted a management cull of deer in the Cressbrook Dam catchment reserve between July and September 2011 removing 85 animals.

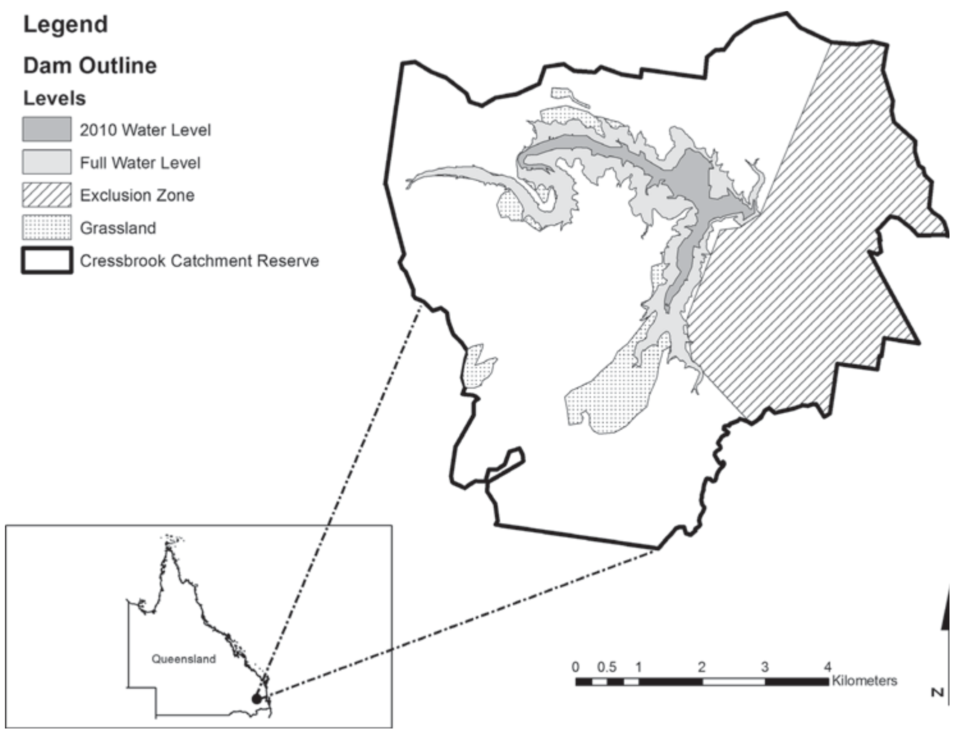

Figure 1. Location of Cressbrook Dam and surrounding catchment reserve. Dam water levels for 2010 and post January 2011 are shown, as well as the grassland area and exclusion zone.

Ethics approval

This research had The University of Queensland animal ethics approval (SAS/239/09 UQ) and Queensland government Eco-access permit (WITK05993409).

Distance sampling

Distance sampling from walked line transects has been used extensively in a variety of circumstances to count deer and has generally been regarded as providing reliable estimates (Mandujano and Gallina 1995, Focardi et al. 2002, Jathanna et al. 2003, Acevedo et al. 2008, Ariefiandy et al. 2013). Distance sampling was conducted following standard methodology (Buckland et al. 2001). A single observer traversed a transect on foot recording the distance and compass bearing to the centre of target animal groups. Distance was measured with a laser rangefinder and compass bearing with a magnetic compass. Observers carried binoculars with a magnification of 8 or 10 times to aid counting at longer distances. Observers noted the species and group number of the target animals whilst traversing the transects at a speed of approximately 2.4 km h^{-1}. A pilot study (Amos 2010) suggested sampling should be conducted in spring (September to November) when deer groups were the largest and easiest to detect. Transects were undertaken within 2 hours of sunset to avoid possible complications with morning fog but when deer were active after resting in the middle of the day.

There were between 15 and 21 transects sampled each year that varied from 0.5 to 4.5 km in length and covered the accessible area of the catchment reserve (Supplementary material Appendix 1 Fig. A1). Transects were located far enough apart to avoid the possibility of double counting or flushing animals on another transect, whilst providing a good coverage of the survey region. Multiple transects were sampled on the same afternoon using multiple trained observers. A sampling event consisted of sampling 10 to 21 of the 21 transects each afternoon for four consecutive afternoons. Transects were located on low use vehicle tracks not open to the public.

Data were analysed using Distance 6.0 release 2 (Thomas et al. 2010). As detection probability for individual vegetation types (forest or grassland) was similar between years, data were pooled by vegetation type for all years. The grassland data were truncated at 500 m and the forest data at 160 m to eliminate outliers (Buckland et al. 2001). For each vegetation type the detection function and cluster size were calculated from the pooled data but density and encounter rate were calculated for each year. Cluster size was estimated as the mean of observed clusters. When transects were resampled within a sampling event, individual transect data were pooled and the line length multiplied by the number of visits. We used the uniform key with cosine adjustments, half normal key with cosine adjustment, half-normal key with Hermite polynomial adjustments, and hazard rate key with simple polynomial adjustment models as recommended in Thomas et al. (2010). The selection of the best model and adjustment term were based on Akaike's information criterion (AIC), goodness of fit, and visual inspection of the histogram (Buckland et al. 2001). Results for different vegetation type by year were combined together to get an overall estimate. Standard error overall for each year was calculated by summing the square of the standard error for estimates of deer for each vegetation type, then taking the square root as the overall result.

Aerial survey

An aerial survey using mark–recapture distance sampling methods was conducted as a single sampling event in October 2011 following the methodology of Fewster and Pople (2008). Eight east/west transects 1 km apart were flown with a helicopter over the study area (Supplementary material Appendix 1 Fig. A2). The helicopter was flown at 61 m (200 ft) above the ground at 93 km h^{-1} (50 knots). Two independent observers sat on the left of the aircraft simultaneously recording sightings whilst one observer searched from the right of the aircraft. Independence between observers was maintained by turning off electronic communication between observers and by the noise of the helicopter with doors removed. Observers searched for deer clusters in five distance classes defined by aluminium poles extending perpendicularly on either side of the helicopter with intervals 0–20, 20–40, 40–70, 70–100 and 100–150 m perpendicular to the transect line.

Data was analysed using Distance 6.0 release 2. First a mark–recapture distance sampling (MRDS) model was built to analyse the double sightings from independent observers on the left hand side of the aircraft. The best model using different covariates for cluster size, observer, and distance, was determined by the use of AIC (Laake et al. 2008). Detection probability on the transect line ($g(0)$) was calculated from this model. A conventional distance sampling (CDS) analysis was then run in Distance 6.0 release 2 using results from 1 observer on each side of the aircraft with the detection probability on the transect line included as a multiplier in the analysis. The same models as for distance sampling above were utilised.

Spotlight counts

Spotlight counts were recorded from a motor vehicle driven at 8 km h^{-1} (5 mi h^{-1}). A single sampling event consisted of three consecutive nights sampling and the deer/night result for that sampling event was taken as the mean of the three nights sampling (Sinclair et al. 2006). Spotlighting occurred approximately 1–2 h after dark using 100 watt spotlights. The survey team consisted of four people inside a vehicle – a driver, a scribe, and two observers using spotlights – one on each side of the vehicle. Spotlight counts were carried out yearly between October 2010 and October 2012. The spotlight transect was 5.9 km long before January 2011. After flooding rains in January 2011 it was re-designed to 4.4 km due to track closures. The spotlight transects covered grassland areas in the southern portion of the catchment reserve (Supplementary material Appendix 1 Fig. A3).

The spotlight transect area was calculated by taking distance measurements of the approximated visible spotlight range with a laser rangefinder every 100 m along the spotlight transect. Distance measurements were taken either side of the track at right angles to the direction of travel and GPS locations were also recorded at the same location. This data was combined to construct an average spotlight area polygon in ArcMap 10.1 (ESRI). This polygon had an area of 130.3 ha for the 2010 transect and 83.2 ha for the 2011 and 2012 transects. Both estimates of abundance (no. deer km^{-2}) and indices of abundance (no. deer km^{-1}) were calculated for the spotlighting method.

Faecal pellet index

We conducted the faecal pellet index as described by Forsyth (2005). Sixty random sites were computer generated – thirty sites each for both the grassland and dry sclerophyll forest vegetation types (Supplementary material Appendix 1 Fig. A4). Each site represented the start of a 150 m transect with a random direction of travel. Plots one m in radius were checked every five m along the transect line to count faecal pellets. All intact deer faecal pellets inside the plot were counted. This method does not rely on assumptions for deer defecation rate or faecal pellet decay rate, so these parameters were not calculated. Sampling was conducted in August/September in 2010 and 2011. Data were entered into spreadsheet and the index was then calculated as the mean number of pellets per transect overall and for each vegetation type. 95% confidence limits were obtained by using the free POPTOOLS (<www.cse.csiro.au/poptools/download.htm>) add in and calculating the mean of 10 000 bootstrap samples from the total number of pellets for each transect and then analysing the bootstrap samples with a Monte Carlo analysis. Overall results for the two years were compared with a student's *t*-test and a general linear model was used to examine the fixed effects of year, vegetation type and their interaction.

Inter-method comparisons

As the accuracy of the estimate by any given method compared to the actual abundance is unknown, one way to compare the various methods is to compare the precision or sampling error of the methods. To do this we compared the relative precision of each method via the coefficient of variation as defined in Buckland et al. (2001) – the ratio of the standard error to the estimator expressed as a percentage of the estimate. We derived a pooled relative precision estimate as above for all years for each method by first pooling the standard deviation (root mean square) for each method and combining with the mean estimator and mean number of observations. An average labour input was calculated for a single sampling event for each method. We also projected the relative precision for all methods for varying levels of labour input by first estimating the projected sample size for the labour input. The projected sample size was estimated by multiplying the actual mean sample size of the method by the projected labour time and then dividing by the actual mean labour input for that method. The projected sample size was then combined with the mean estimator and pooled standard deviation to derive the projected relative precision. The varying levels of labour input for the projected relative precision for comparing methods were set as 24, 36, 48, 72 and 96 h which corresponded to 0.5×, 0.75×, 1×, 1.5× and 2× the mean sampling effort from distance sampling. Some extra levels of labour input were added at 6 and 12 h for aerial survey since this method had such a low field labour input.

To calculate the cost of labour a rate of AU\$30 h^{-1} was used. Assumptions for comparison of vehicle and equipment costs are listed in Supplementary material Appendix 1 Table A1. Equipment costs for the faecal pellet index were negligible so these were not included.

Results

Distance sampling

We observed 2870 deer in 479 groups whilst distance sampling. (Table 1). The grassland model (uniform model with cosine adjustment) fitted the grassland observations well (Kolmogorov–Smirnov test: $D = 0.076$, $p = 0.33$) although there was some evidence of evasive movement of the deer prior to detection was noted in the perpendicular distance histograms at approximately 190 to 250 m (Fig. 2a – Grassland). The forest model (half normal with cosine adjustment) however did not fit the observations well (Kolmogorov–Smirnov test: $D = 0.155$, $p < 0.01$) and there was a spike at zero (Fig. 2b – Forest). Grouping the data into distance classes did not improve the model. Detection probability varied between the vegetation types (grassland ~ 0.5, forest ~ 0.4). Encounter rate had the greatest effect on variance in the grassland (60 – 82% of variance). Cluster size had the greatest effect on variance for the forest in 2010 (50% cluster size vs. 35% encounter rate) whereas in 2011 and 2012 encounter rate had the greatest effect on variance (82 and 75% respectively). Deer densities were estimated to be lower in the forest (23.7–29.3 deer km^{-2}) than grass-

Table 1. Statistics relative to October distance sampling and aerial surveys at Cressbrook Dam. Distance sampling and aerial survey estimates showing strata, year, sample size (n), encounter rate (n/L, cluster km^{-1}), effective strip width (ESW, m), detection probability (*P*), expected cluster size (*E*(s)), estimated population abundance ($\hat{N}$), and 95% confidence intervals (95%CI). %CV denotes the coefficient of variation for the column on its left.

												95% CI	
Strata	Year	n	n/L	%CV	ESW	*P*	%CV	*E*(s)	%CV	$\hat{N}$	%CV	Lower	Upper
Forest	2010	75	0.8	13.1	70.9	0.44	8.4	4.6	15.7	1025	22.1	664	1583
	2011	104	1.1	23.8	70.9	0.44	8.4	3.7	7.1	1176	26.2	675	2049
	2012	92	0.8	22.1	70.9	0.44	8.4	4.3	9.3	951	25.4	566	1597
Grassland	2010	38	1.5	25.4	265.6	0.53	3.4	15.4	20.3	325	32.7	165	640
	2011	49	3.2	30.0	265.6	0.53	3.4	6.6	13.5	140	33.1	64	310
	2012	72	3.2	33.6	265.6	0.53	3.4	8.6	22.8	182	40.8	78	425
Overall	2010									1350	18.5	942	1935
	2011									1316	23.7	833	2079
	2012									1133	22.3	735	1746
Aerial survey	2011	28	0.4	24.6	70.8	0.40	14.4	5.6	22.1	1284	36.6	632	2608

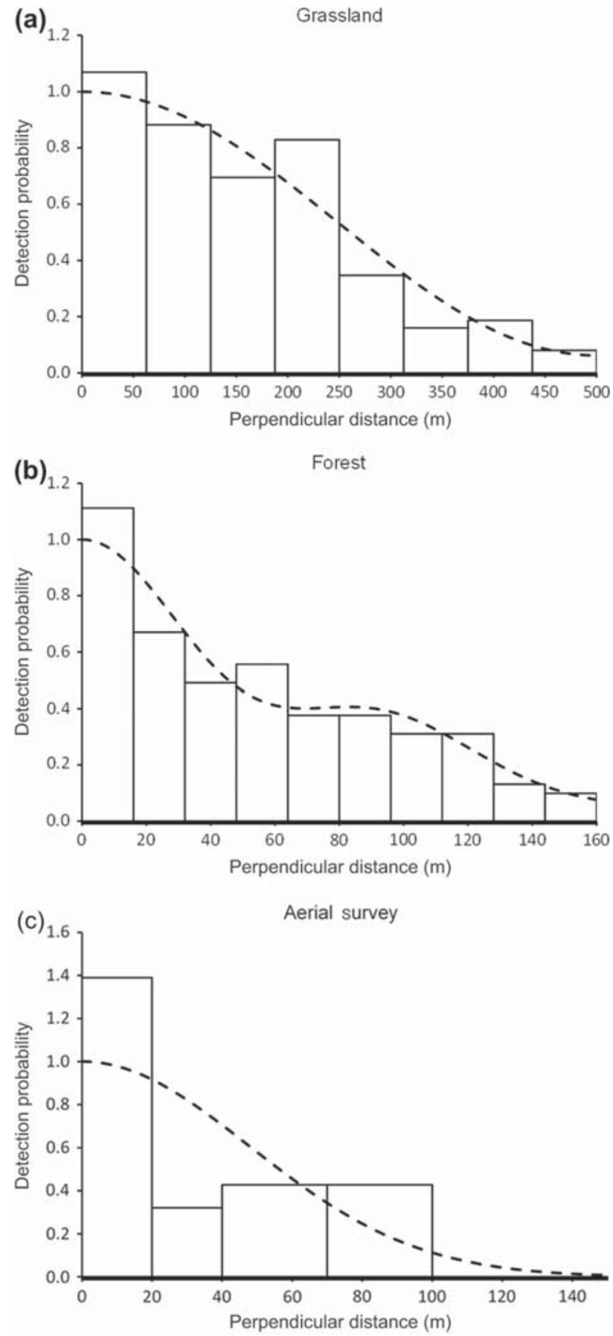

Figure 2. Histograms of perpendicular distances and detection probability (broken lines) for distance sampling in grassland and forest vegetation types (pooled for October 2010, 2011 and 2012) and for aerial survey (October 2011).

land areas (39.8–51.7 deer km^{-2}). Population estimates more than halved for the grassland from 2010 ($\hat{N} = 325$) to 2011 ($\hat{N} = 140$) but this did not change the estimated density (Table 2) as the area of grassland in the Cressbrook Dam catchment reserve also halved due to rises in the dam water levels. Given the effective strip width of the grassland model of 265.6 m we calculated the coverage of the grassland transects in 2010 to be approximately 300 ha and in 2011 and 2012 to be approximately 230 ha due to rises in the dam water level. We calculated the coverage of the forest transects with an effective strip width of 70.9 m to be approximately 234 ha for all years.

Aerial survey

The MRDS analysis estimated a detection probability on the transect line of $g(0) = 0.76 \pm 0.05$. The CDS analysis gave an overall deer population estimate of 1285 deer in the Cressbrook Dam catchment reserve (Table 1). The model fit could not be evaluated as with data from exact distances, but visual estimation of the model fit suggests it is a poor fit due to a spike at zero distance (Fig. 2c – Aerial survey). Encounter rate (45.0%) and cluster size (36.3%) were the greatest contributors to variance. Given the effective strip width of 70.8 m, we calculated the aerial survey coverage to be approximately 202 ha.

Spotlight counts

The spotlight estimates for 2010 and 2012 were more than double the 2011 estimate (Table 2). The spotlight indices with standard error (in parentheses) were 31.3 (3.2), 10.7 (1.9), and 25.6 (2.3) deer/km for 2010, 2011 and 2012 respectively. The trends for the spotlight indices closely followed the trends of spotlight abundance.

Faecal pellet index

Faecal pellet indices for 2010 and 2011 did significantly differ between years at the $P = 10\%$ level ($t = 1.89$, DF = 116, p = 0.061) and grassland sites had higher indices than forest sites for both years (F = 6.76, DF = 1, p = 0.011) (Fig. 3). There was no significant effect of vegetation type on the year that faecal counts took place (F = 0.00, DF = 1, p = 0.956).

Inter-method comparisons

Estimates of abundance from the distance sampling, aerial survey and spotlighting are summarised in Table 2 for comparison.

The aerial survey method estimate of 1285 deer was comparable to the distance sampling estimate for 2011 of 1316 deer (Table 1). The distance sampling covered a much wider strip in the grassland than the aerial survey, but results were similar in the forest. The detection probability for aerial surveys was again similar to the distance sampling for the forest. The variance was greater for the aerial survey compared to overall results for distance sampling.

Spotlighting estimates for 2010 were more than triple and 2012 more than double distance sampling estimates for the grassland. Only the 2011 spotlight estimate was comparable to distance sampling estimates for the grassland.

The faecal pellet index indicated a decline in relative deer abundance from 2010 to 2011(Fig. 3) but this trend was not shared with overall distance sampling (Table 2). However, the faecal pellet index indicated a lower relative abundance in the forest in both years, which was similar to distance sampling.

Spotlighting had the highest relative precision for any single sampling event (Table 3), but high precision was not

Table 2. Estimates of wild red deer abundance. Spring estimates of population density (deer km^{-2}) in the grassland and overall at Cressbrook Dam between October 2010 and October 2012. Figures in brackets denote the 95% confidence intervals.

	Grassland			Overall		
Method	2010	2011	2012	2010	2011	2012
Distance sampling	44.6 (22.6–87.7)	39.9 (18.0–88.1)	51.6 (22.1–120.7)	28.4 (19.8–40.8)	30.1 (19.1–47.6)	25.9 (16.8–40.0)
Aerial survey					29.4 (14.5–59.7)	
Spotlighting	141.7 (114.7–168.7)	56.6 (36.5–76.7)	135.7 (112.7–158.8)			

as consistent for this method as for the distance sampling and faecal pellet index methods. The faecal pellet index method was the most labour intensive method, while the aerial survey was the least labour intensive (Fig. 4). When comparing estimates of pooled relative precision and mean field labour input, spotlighting performed well against other methods for the level of precision versus the labour input (Table 4). Spotlighting was predicted to be the most efficient method from projected precision estimates (Fig. 5).

Total estimated costs for the faecal pellet index and distance sampling methods were more than double the costs of the other methods (Fig. 6). Distance sampling had the highest relative equipment costs (Fig. 6).

Discussion

As expected, there were tradeoffs associated with cost, labour input, and precision for the methods used in this research. Both distance sampling and faecal pellet indices indicated a lower density of deer in the forest compared to the grassland. Distance sampling, spotlighting and faecal pellet indices showed similar trends for the grassland from 2010 to 2011 (Table 2, Fig. 3). However, this trend agreement between years was not shared for distance sampling and faecal pellet index for the forest and overall and cannot be adequately explained. Possibly the rate of decay of faecal pellets was different in the two years due to the high rainfall in January 2011 compared to 2010 when conditions were very dry and stable. Also the increased vegetation cover in 2011 made the counting harder, and more pellets may have been overlooked. Distance sampling for the grassland showed a slight increase from 2011 to 2012 which was in agreement with spotlighting. Spotlighting results in 2011 were likely to be negatively affected by spotlight culls of deer in the preceding months. As distance sampling (Table 1) indicated a relatively stable population over the whole study area for the study duration, it is hard to predict which of the methods were most useful for estimating trends in deer abundance.

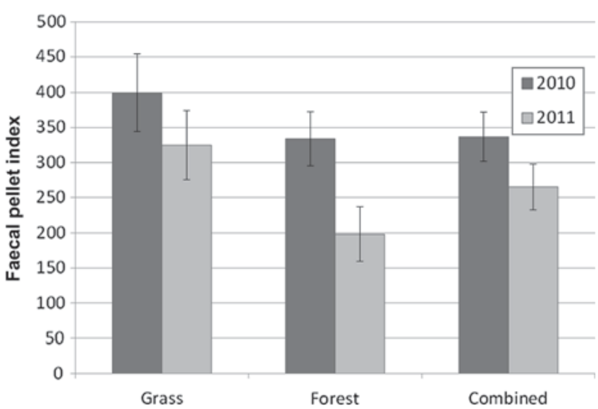

Figure 3. Faecal pellet indices of wild red deer abundance within the Cressbrook Dam catchment reserve for spring 2010 and spring 2011 showing standard error.

We found that distance sampling gave repeatedly precise estimates, and the aerial survey gave reasonable precision for the small labour input. We would recommend the distance sampling method to gain an estimate of absolute deer abundance if sufficient labour was available. If labour was limiting, the terrain and vegetation cover suitable and funds available, we would recommend aerial survey. The population estimates from these two methods were comparable to each other, and also comparable to an earlier estimate by Finch (2003) in the same study area using the Index–manipulation index method.

Of the methods we trialled, the spotlight method performed the best when comparing total expense, total labour cost and precision. However, the small spotlight sample size and sampling on sequential nights may have tended to underestimate the 'true' variability in population size. This method is mostly used to provide an index of abundance (Focardi et al. 2001, Collier et al. 2007, Acevedo et al. 2008, Garel et al 2010) and we found that absolute abundance estimates from this method were generally not comparable to those from distance sampling. This is somewhat expected as the two methods were conducted at different times of the day, and deer generally move out from the forest into the grassland in the evening leading to higher spotlight estimates.

The usefulness of spotlighting to monitor deer populations is very controversial. Garel et al. (2010) recently described spotlighting as 'reliable' from a long term study of red deer in a forested environment in northeastern France. The findings of Garel et al. (2010) indicate that spotlighting is useful for monitoring abundance annually. In contrast Collier et al. (2013) questioned the usefulness of spotlighting in any circumstances following study of white-tailed deer *Odocoileus virginianus* in South Carolina, USA. Those authors found

Table 3. Relative precision (CV%) results from spring estimates. Relative precision (CV%) for all methods used to estimate deer abundance within the Cressbrook Dam catchment reserve from 2010 to 2012 showing estimates from spring sampling.

Year	2010	2011	2012
Distance sampling	18.5	23.7	22.3
Aerial survey		36.6	
Spotlight count	9.7	18.1[a]	8.7
Faecal pellet index	10.4	12.3	

[a]sampling occurred after spotlight cull of deer.

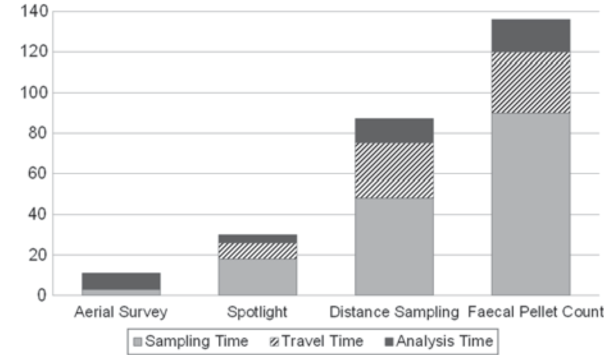

Figure 4. Total labour estimate per sampling event comparing all methods used to monitor wild red deer abundance in the Cressbrook Dam catchment reserve between 2010 and 2012.

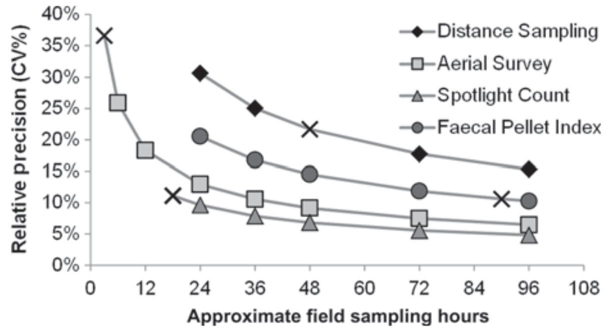

Figure 5. Projected relative precision for varying levels of field labour input from pooled spring estimates and indices of wild red deer abundance in the Cressbrook Dam catchment reserve. X denotes the actual pooled relative precision realised from the actual mean field sampling labour input for each method.

that spotlighting had such a highly variable detection probability that it was unlikely to provide abundance data useful for management decisions. Although we also experienced variable detection probability using this method, trends between years generally agreed with distance sampling estimates for the grassland. Given the level of precision at our study site and low overall costs, we would recommend this method to gain an index of relative abundance for red deer in open woodland and grassland habitats in Australia. However, low detection rates in dense vegetation would likely make this method more unsuitable in forest areas.

We obtained consistently high precision from the faecal pellet index which is used elsewhere in Australia to monitor changes in Sambar deer *Cervus unicolor* relative abundance (D. Forsyth pers. comm.). We found this method extremely labour intensive in subtropical grassland with dense vegetation cover and the deer densities we encountered. However, this method was most likely designed with lower deer densities in mind, as bootstrapping in the analysis made no difference to 95% confidence intervals as compared to those derived without bootstrapping.

When comparing all methods, regardless of whether an estimate of absolute or relative abundance, we found the spotlight method to be the most efficient in terms of labour and equipment costs compared with precision. However, because consistently high precision was only obtained by methods utilising a relatively high labour input, we conclude that there are no short cuts to monitoring populations of wild red deer in a context such as we encountered in the Cressbrook Dam catchment reserve. Each method has desirable and undesirable traits, and choosing a method for any given study site will involve a thorough evaluation of the methods available (Acevedo et al. 2008).

We advocate the use of a pilot study to obtain an estimate of the variability of deer sighting over time and space before conducting counts using any particular method. A pilot study is particularly useful in determining if the sampling method is suitable for the study site, and may indicate the sampling effort required to achieve the survey goals. We used a pilot study effectively for the distance sampling method (Amos 2010) to determine the transect line length as described in Buckland et al. (2001) to achieve reasonable precision.

Not all methods could be trialled at exactly the same time due to high labour requirements for some methods. Some methods may have also negatively affected results for other methods if conducted at the same time by inducing deer avoidance due to high personnel presence. This timing of events introduces some extra variation into the comparison of the experiments, but all estimation methods were undertaken as temporally and spatially close to one another as logistically possible, hence this variation was minimised.

Finally, researchers and land managers must be aware that our comparison of these methods was conducted in a region where deer densities are high by world standards. For example some European red deer densities have been reported in the range of 1.7–7 deer km^{-2} (Georgii 1980, Kamler et al. 2008, Jerina 2009), 14 deer km^{-2} (Clutton-Brock et al. 1982) and 25–26 deer km^{-2} (Lovari et al. 2007). A recent

Table 4. Mean sampling time and associated statistics for spring estimates of absolute and relative abundance. Mean field sampling hours (*t*) per sampling event, mean sample size (n), mean estimator (E), pooled standard deviation (SD) and pooled relative precision (CV%) for all methods used to estimate deer abundance within the Cressbrook Dam catchment reserve from 2010 to 2012 showing estimates from spring sampling.

Method	*t*	n	E	SD	CV%
Distance sampling	48	143	1266	3287	21.5
Aerial survey	3	28	1284	,487	36.6
Spotlight count	18	3	115	22	11.1
Faecal pellet index	90	60	301	247	10.6

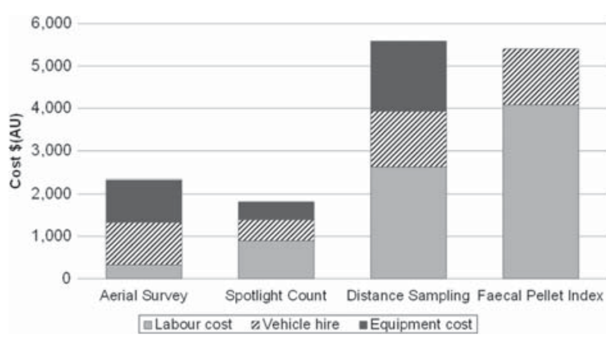

Figure 6. Total cost of methods used to monitor wild red deer abundance in the Cressbrook Dam catchment reserve 2010 and 2012 with labour input valued at $30 h^{-1} (Australian dollars).

study in a Mediterranean climate classified red deer density as low between 0.04–20.0 deer km^{-2} and high between 20.01–66.77 deer km^{-2} (Acevedo et al. 2008). Our density estimates from distance sampling methods in the Cressbrook Dam catchment reserve estimated wild red deer density to be approximately 25–30 deer km^{-2}.Hence all our analyses must be evaluated in that context and may not be applicable in other locations with a lower deer density, or in different terrain types.

Conclusions

This research highlights the importance of assessing the available methods for estimating deer abundance prior to choosing a monitoring method. Our study will help Australian land managers and researchers make informed decisions regarding method choice for monitoring deer populations in the future.

Acknowledgements – This research was conducted by a University of Queensland student as part of his postgraduate studies, hence the limited time series. The research was part of the 'Wild Deer Management in Australia' Research Project and acknowledges the collaboration and contribution of the following organisations: The University of Queensland (UQ); Toowoomba Regional Council; Biosecurity Queensland; Environmental Protection Agency (Queensland); Sporting Shooters Association of Australia (National and Queensland Branch); Australian Deer Association (National and Queensland Branch); NSW Game Council; Safari Club International (Downunder Chapter). We also thank S. Focardi who provided useful comments to improve manuscript drafts.

References

Acevedo, P. et al. 2008. Estimating red deer abundance in a wide range of management situations in Mediterranean habitats. – J. Zool. 276: 37–47.

Acevedo, P. et al. 2010. Estimating roe deer abundance from pellet group counts in Spain: an assessment of methods suitable for Mediterranean woodlands. – Ecol. Indicators 10: 1226–1230.

Alves, J. et al. 2013. Pellet group count methods to estimate red deer densities: precision, potential accuracy and efficiency. – Mammal. Biol. 78: 134–141.

Amos M. 2010. A comparison of population estimation methods for wild red deer (*Cervus elaphus*) at Cressbrook Dam, southeast Queensland. – Honours thesis, Univ. of Queensland, Gatton, Australia.

Amos, M. et al. 2011. Preliminary population estimates using three methods for wild red deer (*Cervus elaphus*) in south east Queensland. – In: Saunders, G. and Lane, C. (eds), 15th Australasian Vertebrate Pest Conf. Vertebrate Pest Committee, Sydney, New South Wales, Australia,pp. 81.

Ariefiandy, A. et al. 2013. Monitoring the ungulate prey of the Komodo dragon *Varanus komodoensis*: distance sampling or faecal counts? – Wildl. Biol. 19: 126–137.

Australian Bureau of Meteorology 2012. Climate data. – In: Climate Statistics for Australian Locations'. Commonwealth of Australia, Bureau of Meteorology. <www.bom.gov.au/climate/data/> accessed on 1 November 2012.

Belant, J. L. and Seamans, T. W. 2000. Comparison of 3 devices to observe white-tailed deer at night. – Wildl. Soc. Bull. 28: 154–158.

Bentley, A. 1998. An introduction to the deer of Australia, with special reference to Victoria. Bunyip Edn. – The Australian Deer Research Foundation, Melbourne, Australia.

Buckland, S. T. et al. 2001. Introduction to distance sampling: estimating abundance of biological populations. – Oxford Univ. Press.

Campbell, D. et al. 2004. Comparing the precision and cost-effectiveness of faecal pellet group count methods. – J. Appl. Ecol. 41: 1185–1196.

Clutton-Brock, T. H. et al. 1982. Red deer: behavior and ecology of two sexes. – Univ. of Chicago Press.

Collier, B. A. et al. 2007. Detection probability and sources of variation in white-tailed deer spotlight surveys. – J. Wildl. Manage. 71: 277–281.

Collier, B. A. et al. 2013. Spotlight surveys for white-tailed deer: monitoring panacea or exercise in futility? – J. Wildl. Manage. 77: 165–171.

Conner, M. C. et al. 1986. Precision of the change-in-ratio technique for deer population management. – J. Wildl. Manage. 50: 125–129.

Curtis, P. D. et al. 2009. Estimating deer abundance in suburban areas with infrared-triggered cameras. – Human–Wildlife Conflicts 3: 116–128.

Daniels, M. J. 2006. Estimating red deer *Cervus elaphus* populations: an analysis of variation and cost-effectiveness of counting methods. – Mamm. Rev. 36: 235–247.

Dougherty, S. Q. and Bowman, J. L. 2012. Estimating sika deer abundance using camera surveys. – Popul. Ecol. 54: 357–365.

Fafarman, K. R. and DeYoung, C. A. 1986. Evaluation of spotlight counts of deer in south Texas. – Wildl. Soc. Bull. 14: 180–185.

Fewster, R. M. and Pople, A. R. 2008. A comparison of mark-recapture distance-sampling methods appled to aerial surveys of eastern grey kangaroos. – Wildl. Res. 35: 320–330.

Finch, N. 2003. Final report on Cressbrook Deer. – The Univ. of Queensland. <www.deerresearch.com.au/wp-content/uploads/Final-report-on-Cressbrook-deer-2003.pdf> accessed on 30 April 2013.

Focardi, S. et al. 2001. Comparative evaluation of thermal infrared imaging and spotlighting to survey wildlife. – Wildl. Soc. Bull. 29: 133–139.

Focardi, S. et al. 2002. The use of distance sampling and mark–resight to estimate the local density of wildlife populations. – Environmetrics 13: 177–186.

Focardi, S. et al. 2013. Nocturnal distance sampling of a Mediterranean population of fallow deer is consistent with population projections. – Wildl. Res. 40: 437–446.

Forsyth, D. M. 2005. Protocol for estimating changes in the relative abundance of deer in New Zealand forests using the faecal pellet index (FPI). – <www.doc.govt.nz/documents/conservation/threats-and-impacts/animal-pests/fpi-protocol.pdf> accessed on 13 December 2013.

Forsyth, D. M. et al. 2007. Modelling the relationship between fecal pellet indices and deer density. – J. Wildl. Manage. 71: 964–970.

Garel, M. et al. 2010. Are abundance indices derived from spotlight counts reliable to monitor red deer *Cervus elaphus* populations? – Wildl. Biol. 16: 77–84.

Georgii, B. 1980. Home range patterns of female red deer (*Cervus elaphus L.*) in the Alps. – Oecologia 47: 278–285.

Jathanna, D. et al. 2003. Estimation of large herbivore densities in the tropical forests of southern India using distance sampling. – J. Zool. 261: 285–290.

Jerina, K. 2009. How the estimates of home range size and composition are affected by diurnal, nocturnal and 24-hour sampling methods: example of the red deer (*Cervus elaphus*) in Slovenia. – Zbornik Gozdarstva in Lesarstva 89: 3–15.

Jesser, P. 2005. Deer in Queensland: pest status review series – land protection. – Dept of Natural Resources and Mines, Brisbane, Queensland.
Kamler, J. F. et al. 2008. Home ranges of red deer in a European old-growth forest. – Am. Midl. Nat. 159: 75–82.
Kantar, L. E. and Cumberland, R. E. 2013. Using a double-count aerial survey to estimate moose abundance in Maine. – Alces 49: 29–37.
Laake, J. L. et al. 2008. Visibility bias in aerial survey: mark–recapture, line-transect or both? – Wildl. Res. 35: 299–309.
Lovari, S. et al. 2007. Space use, habitat selection and browsing effects of red deer in Sardinia. – Ital. J. Zool. 74: 179–189.
Mandujano, S. and Gallina, S. 1995. Comparison of deer censusing methods in tropical dry forest. – Wildl. Soc. Bull. 23: 180–186.
Mandujano, S. et al. 2013. Habitat-population density relationship for the white-tailed deer *Odocoileus virginianus* during the dry season in a Pacific Mexican tropical dry forest. – Mammalia 77: 381–389.
Marques, F. F. C. et al. 2001. Estimating deer abundance from line transect survyes of dung: sika deer in southern Scotland. – J. Appl. Ecol. 38: 349–363.
McCoy, J. C. et al. 2011. Bias associated with baited camera site for assessing population characteristics of deer. – J. Wildl. Manage. 75: 472–477.
McLeod, S. R. 2009. Proceedings of the National Feral Deer Management Workshop. – In: McLeod, S. R. (ed.), National Feral Deer Management Workshop, November 2005, Canberra, Australia, Invasive Animals Cooperative Research Centre.
Moriarty, A. 2004. The liberation, distribution, abundance and management of wild deer in Australia. – Wildl. Res. 31: 291–299.
Potvin, F. and Breton, L. 2005. Testing two aerial survey techniques on deer in fenced enclosures: visual double-counts and thermal infrared sensing. – Wildl. Soc. Bull. 33: 317–325.
Roberts, C. W. et al. 2006. Comparison of camera and road survey estimates for white-tailed deer. – J. Wildl. Manage. 70: 263–267.
Sinclair, A. R. E. et al. 2006. Wildlife ecology, conservation and management, 2nd edn. – Blackwell.
Smart, J. C. R. et al. 2004. Monitoring woodland deer populations in the UK: an imprecise science. – Mamm. Rev. 34: 99–114.
Thomas, L. et al. 2010. Distance software: design and analysis of distance sampling surveys for estimating population size. – J. Appl. Ecol. 47: 5–14.
Toowoomba Regional Council 2009. Toowoomba's Dams – Cressbrook Dam. <www.toowoombarc.qld.gov.au/environment-and-waste/water-supply-and-dams/dams-a-bores/toowoomba-bulk-water/5311-cressbrook-dam.html> accessed on 26 March 2010).

Supplementary material (available online as Appendix wlb.00080 at <www.wildlifebiology.org/readers/appendix>). Appendix 1

Wildlife Biology

WLB-00080

Amos, M., Baxter, G., Finch, N., Lisle, A. and Murray, P. 2014. I just want to count them! Considerations when choosing a deer population monitoring method. – Wildlife Biology doi: 10.2981/wlb.00080

Appendix 1

Table A1. Assumptions of vehicle and equipment costs for methods used to estimate wild red deer abundance. All cost estimates in Australian dollars.

Method	Vehicle hire	Equipment	Equipment cost
Distance sampling	8 days at \$164.57 day^{-1} [a]	rangefinder, binoculars and compass	3 sets min. at \$550 each
Aerial survey	\$1000 h^{-1}	sighting boom	\$1000
Spotlight count	3 days at \$164.57 day^{-1} [a]	spotlights	2 at \$210[c]
Fecal pellet index	8 days at \$164.57 day^{-1} [a]	rope, tape etc	negligible

[a] vehicle hire cost ex. Brisbane

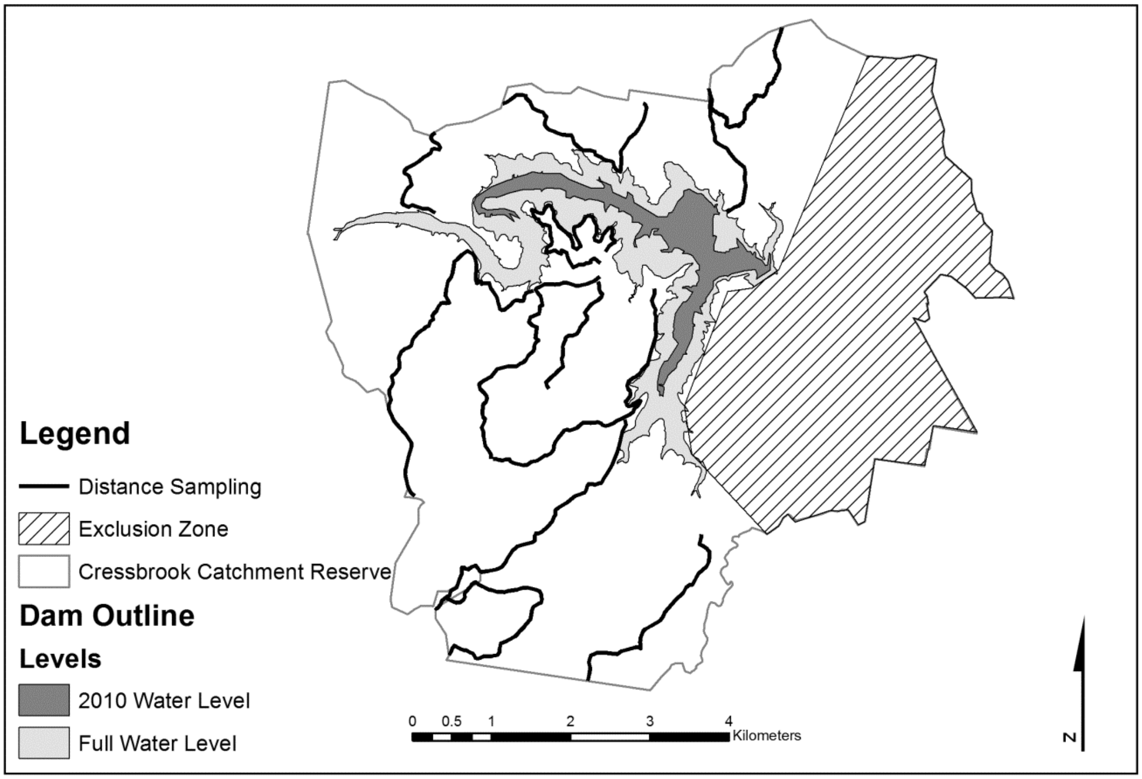

Figure A1. Distance sampling in the Cressbrook Dam catchment reserve in October 2010, 2011 and 2012. Transects denoted by solid black lines.

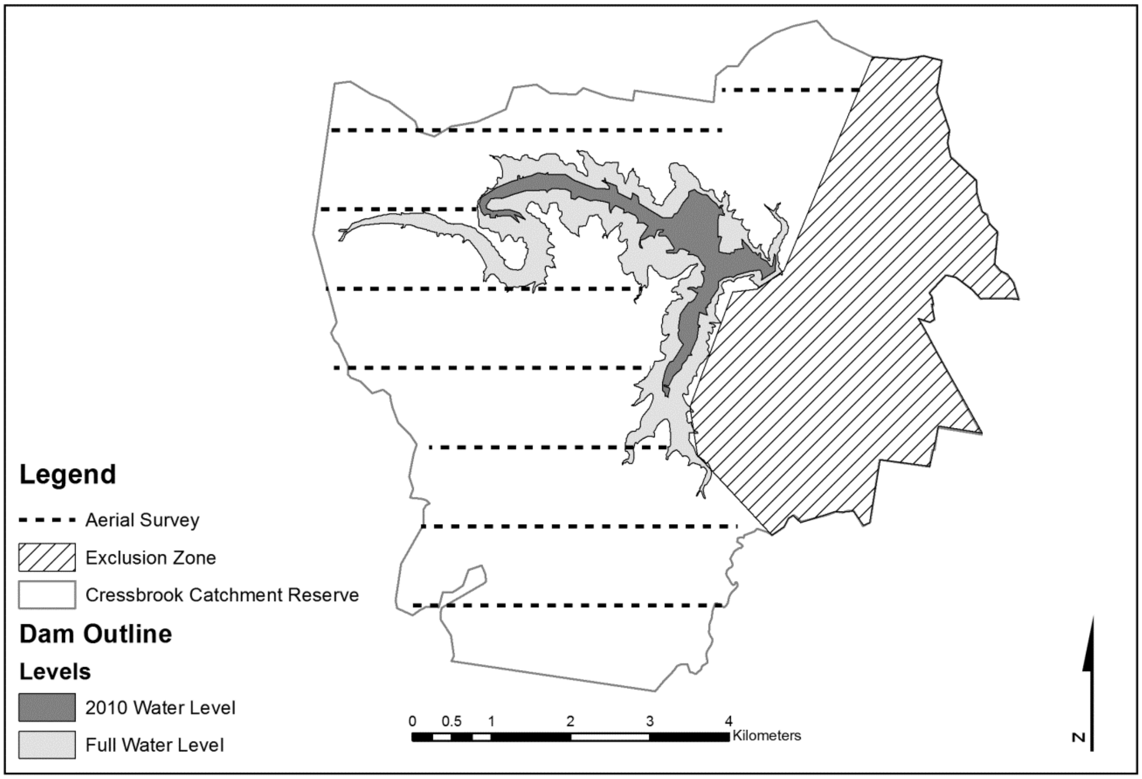

Figure A2. Aerial survey in the Cressbrook Dam catchment reserve in October 2011. Transects denoted by dashed black lines.

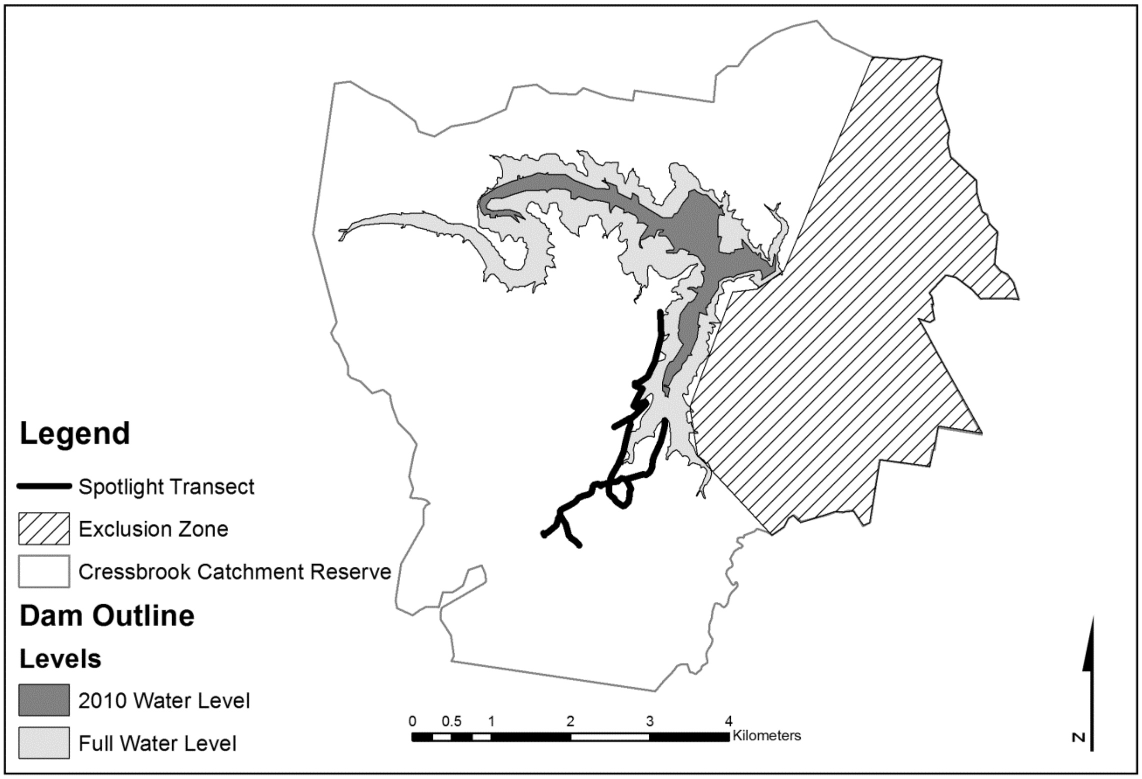

Figure A3. Spotlight counts in the Cressbrook Dam catchment reserve between October 2009 and October 2012. Transect denoted by solid black line.

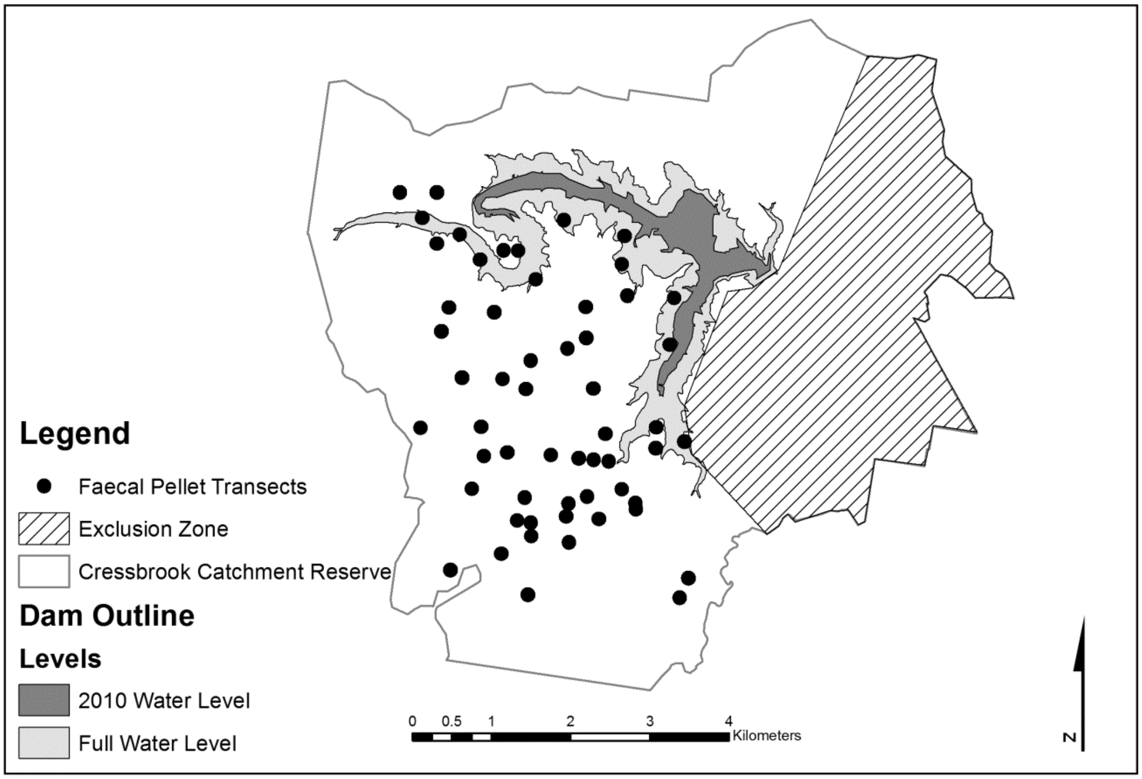

Figure A4. Faecal pellet counts in the Cressbrook Dam catchment reserve in August/September 2010 and August/September 2011. Transect placement denoted by circle markers.

Chapter 5 - Home Range

Chapter 5 comprises the paper "At home in a new range: wild red deer in south-eastern Queensland." by Amos, M., Baxter, G., Finch, N. and Murray, P. Published in *Wildlife Research* vol. 41 no.3, 2014 (pp. 258-65)

Plate 7 Keith Staines with "Big Red" just prior to release after darting and fitting with a GPS collar. (Photo N. Finch – April 2011)

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At home in a new range: wild red deer in south-eastern Queensland

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Abstract

Context. Wild deer are increasing worldwide and, in Australia, prompting land managers to review management strategies. Management activities may be ineffective without a sound understanding of the ecology of the species. No peer-reviewed research has been published for wild red deer in Australia, where they have been introduced.

Aims. To help land managers gain an understanding of some movement parameters of introduced wild red deer out of their natural range.

Methods. GPS collars were used to obtain movement rates ($m\,h^{-1}$), annual home range using three estimators and seasonal home range using the Local Convex Hull estimator.

Key findings. Deer at our study site displayed typical crepuscular movements. However, the lack of elevated activity for stags in summer varies greatly to reports from overseas. The annual home range of hinds was much smaller than that of stags. Large differences for seasonal home ranges from the same deer for two winters suggest that seasonal conditions may exert a large influence on the size of home ranges. The home ranges of deer at our study site were comparable with the largest reported in European studies, but the relationship between deer density and home-range area was markedly different.

Conclusions. It appears that Australian wild red deer behave differently from their European conspecifics for several important movement parameters. Wild stags did not display the high levels of movement activity in summer, like those in Europe, and the home-range areas of our deer were very large for the high densities we encountered compared with overseas reports.

Implications. Targeted management of hinds may prove beneficial as hinds had a much smaller and continuous home range than stags. If managers want to target stags, there is only a short rut period when they continually associate with hinds and that may be the most efficacious time for control. Additionally, future research may need to explore the link between home range and deer density, and the effect of variation in rainfall on home range and movement of wild red deer which may influence management activities more than do the regular seasonal patterns found in Europe.

Additional keywords: *Cervus elaphus*, home range, movement.

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Introduction

Deer of various species (cervids) are widespread throughout the world and are native to most continents, with Australia being one of the notable exceptions (Jesser 2005). Deer were first introduced to Australia by early settlers and acclimatisation societies in the early 1800s (Bentley 1998; Moriarty 2004). Only 6 of the 18 deer species introduced to Australia have survived and become established in the Australian environment (Bentley 1998; Jesser 2005). Because of several factors, including more recent releases from deer farms and private (often illegal) translocations, distribution and abundance of wild deer in Australia appears to be increasing (Moriarty 2004; Jesser 2005). Yet, there has been little peer-reviewed scientific research conducted on deer species in Australia (Forsyth 2005).

Red deer (*Cervus elaphus*) make up ~30% of the wild deer herds reported in Australia in 2004 (Moriarty 2004). They are predicted to be suited to the bioclimatic zone that encompasses the southern third of Australia, north into south–central Queensland (Moriarty 2004). The wild red deer herd in south-eastern Queensland has been estimated to contain 10 000 to 15 000 animals (Moriarty 2004; Jesser 2005).

Management of deer in Australia is an important and emerging topic (Moriarty 2004; Forsyth 2005; Jesser 2005; Hall and Gill 2007). However, Burt's (1943, p. 351) question of 70 years ago is still pertinent today, 'How can we manage any species until we know its fundamental behaviour pattern?' Much research has been conducted on red deer overseas (Clutton-Brock *et al*. 1982; Georgii and Schroder 1983; Catt and Staines 1987; Carranza *et al*. 1991; Bocci *et al*. 2012), but how do we know that we can manage an introduced species on the basis of observations made in their native range? Our objectives were to estimate annual and seasonal home-range use and movement rates of wild red deer in Australia, and to provide management recommendations based on our findings.

Materials and methods

Study area

Cressbrook Dam (27.258°S, 152.195°E) is located in south-eastern Queensland, Australia, and is one of three major water supplies for the nearby city of Toowoomba. We conducted research in this 4893 ha catchment reserve. The dam storage levels fluctuated markedly during the course of the study, from ~8% (147 ha surface area) in late 2009 to over 100% (526 ha surface area) in January 2011 (M. McDermid, pers. comm.), which meant that the area of gently sloping grassland around the dam varied greatly during the study. The climate is subtropical (Australian Bureau of Meteorology 2012) and warm and humid in summer, with a short mild winter. The average annual precipitation at Cressbrook Dam is 740.6 mm and rain falls predominantly in the summer (Australian Bureau of Meteorology 2013).

Elevation at the study site varies from ~300 to 600 m (Toowoomba Regional Council 2009). The vegetation in the Cressbrook Dam catchment reserve is predominantly dry sclerophyll forest, with some open grassland in the lower-elevation areas around the dam. The landform varies from gentle slopes and gullies in the lower elevations to steep hills in the higher elevations.

The Cressbrook Dam catchment reserve is within the area containing the herd of wild red deer originally released by the Queensland Acclimatisation Society (Moriarty 2004; Jesser 2005). Although it is unknown exactly how long red deer have been at the study site, they were released ~35 km to the east at Cressbrook Station in 1873 (Roff 1960; Bentley 1998) and observed in the general vicinity of the study site in a wild red deer survey in 1956 (Roff 1960). The deer density at the study site is high at ~28 deer km^2 (M. Amos, G. Baxter, N. Finch and P. Murray, unpubl. data).

Radio-collaring deer

We chemically immobilised 25 wild red deer for collaring by using anaesthetic darts. Darts were delivered from a Pneu-Dart X-Caliber™ (Williamsport, PA, USA) dart projector by personnel stalking deer on foot. Darts contained a mixture of Xylazil 100® (Ilium Veterinary Products, Troy Laboratories (Australia) Pty Ltd, Glendenning, NSW, Australia) (4.2 mg kg^{-1} xylazine hydrochloride) and Zoletil 100® (Virbac Australia Pty Ltd, Milperra, NSW, Australia) (1.4 mg kg^{-1} tiletamine hypochloride and 1.4 mg kg^{-1} zolazepam hypochloride) used under veterinary supervision. Because the drug mixture took ~5–10 min to anaesthetise the deer, we used Pnue-Dart transmitter darts so that the darted animal could be found using a radio receiver and Yagi antenna. Anaesthetised deer were placed in a sternal position and their breathing and pulse were monitored. We fitted sedated deer with Sirtrack® G2C wildlife global positioning system (GPS) tracking collars with timed release units. We recorded the capture location with a handheld GPS unit. Following collaring, the effects of the xylazine hydrochloride were reversed with Reverzine™ (Bayer AG, 875 Pymble, NSW, Australia) (0.25 mg kg^{-1} yohimbine hydrocholoride). The chemical restraint and handling of these animals took ~18 min and was approved by The University of Queensland's Animal Ethics Committee Approval SAS/239/09. Captured deer ranged from young adult (≥18 months) to ~10 years of age, as estimated from inspection of teeth eruption and wear patterns and physical characteristics. Stags were classified as 'young' (18 months to 3.5 years) and 'mature' (3.5 years and over) because home-range patterns appeared to differ with age for stags as per Georgii and Schroder (1983).

The GPS collars were programmed to obtain a GPS coordinate every 90 min, 24 h a day, between March 2010 and March 2013. We tracked deer fortnightly using an Australis 26k™ 150-MHz receiver (Titley Scientific, Lawnton, Qld, Australia) to monitor deer location and survival. During these surveys, we also recorded the date, collar frequency and GPS location of all collared deer sighted.

The average position error for the GPS collars was calculated at two random locations where collars automatically released from deer. Both test collars were located in typical woodland vegetation community sites in the study area. Estimated position error was obtained by first calculating the 'true' location position as the average of all test locations, then calculating the Euclidean distance between each individual location and the 'true' location and taking the average of these results as per Lewis *et al*. (2007). The two collars recorded 3120 and 1653 locations after dropping from the animal over 199 days and 115 days, respectively, to return an estimated position error of ± 12.31 m and ± 15.20 m for all locations without any GPS error screening. Raw GPS location data from retrieved collars were screened as described by Bjørneraas *et al*. (2010).

Movement

We calculated 'movement' – the distance and movement rate (m h^{-1}) between consecutive location points as the distance between these points divided by the time taken to cover that distance in Microsoft® Excel (Redmond, WA, USA) for all deer. Because the timing and duration of deployment for individual collars varied greatly, we constructed a linear mixed-effects model in the 'nlme' package in R (version 2.15.0, http://www.r-project.org/, verified 30 March 2010) to analyse movement data. Gender, time of day and the interactions between gender and time of day were included as fixed effects. Individual animals were included as random effects. The number of GPS locations for each animal for each time period was included as a weighting. Analysis was conducted separately for three seasons per year as per the seasonal home-range analysis.

Home range

GPS data from collars were analysed for overall, annual and seasonal home range for individual deer. Overall, home range was simply the home range generated from all the GPS data collected by an individual deer. Analysis of annual home range was conducted for deer that had ~12 months or more GPS data. Where possible, the annual home range was taken from the middle of the non-breeding season (August) one year to the next. Annual home-range analysis included visual inspection of the asymptote graph (graph of home-range size as sequential location points are added) using the minimum convex polygon (MCP) method in OpenJUMP HoRAE (Steiniger and Hunter 2012).

For seasonal analysis of home range, three seasons per year were identified that reflected different biologically important time periods for deer at our study site similar to Carranza *et al*. (1991). The seasons were set as winter (3 May to 31 October), summer (1 November to 21 March) and rut (red deer breeding season in this locality; 22 March to 2 May). The winter season corresponds to the pregnancy in hinds, and the non-breeding season for stags until they have cast their antlers (Roff 1960). The summer season corresponds to calving and calf rearing in the hinds, and antler regrowth and recovery of body condition in the stags (Roff 1960). The summer season is also when two-thirds of the annual precipitation falls in the Cressbrook Dam catchment (Australian Bureau of Meteorology 2013).

We calculated annual home-range area using MCP, kernel utilisation distribution (Kernel) and the local convex hull (LoCoH) non-parametric kernel estimators. The MCP method (Mohr 1947) is one of the most widely used home range-estimation methods (Laver and Kelly 2008). Many older red deer home-range studies used this method (Georgii 1980; Clutton-Brock *et al*. 1982; Catt and Staines 1987; Jeppesen 1987*a*), so we included this method for comparison purposes. This method did not perform particularly well on our data, given the sharp water boundaries at Cressbrook Dam, and included many areas under water that we knew deer did not regularly utilise as part of their home range. We analysed data at the 95% level to eliminate some of the outliers that greatly increased the home-range area.

Kernel methods have also been used extensively on many home-range studies (Laver and Kelly 2008), including recent studies of red deer (Bocci *et al*. 2010; Jerina 2012). We, therefore, decided to use this method for comparison because it more accurately portrayed our data than did the MCP method, although it included areas under water that we knew deer did not regularly utilise. We used an 80% fixed kernel estimator with the h_{ref} smoothing parameter (Worton 1995). We first attempted to use the least-squared cross-validation smoothing parameter but the cross-validation criterion could not be minimised.

The LoCoH method (Getz and Wilmers 2004) is one of the newer methods of home-range estimation. It has been described as particularly useful for calculating home-range areas with distinct boundaries (Getz and Wilmers 2004) as at our study site. This method appeared to fit our data well, especially in areas we knew that deer did not utilise at Cressbrook Dam. We used the adaptive (α-LoCoH) method described by Getz *et al*. (2007), with the heuristic rule that 'a_1 is the maximum distance between any two points in the dataset'. Home-range analysis was set at the 95% level with the LoCoH method and core-area analysis at the 50% level. Intensity was measured as the core area (50% LoCoH) divided by home range (95% LoCoH) expressed as a percentage. Intensity represents the proportion of the home-range area that deer spent 50% of their time in.

We calculated annual home-range areas using MCP and Kernel estimators in Oztrack (Hunter *et al*. 2013). We calculated overall, annual and seasonal home-range areas and core areas by using the LoCoH (Getz and Wilmers 2004) estimator. Analysis for the LoCoH method was conducted in the adehabitat package (Calenge 2006) in R.

Annual and overall home-range (LoCoH) results and seasonal home-range results for three hinds and one stag in winter 2010 and winter 2011 were compared with a paired *t*-test in Microsoft® Excel. Stag and hind estimates for annual home range, seasonal home range, core area and intensity of use were compared in Microsoft® Excel by first conducting a two-sample *F*-test to test for equality of variance. Subsequently, all stag and hind estimates for annual home range and seasonal home range except summer 2011/12 were compared with two-sample *t*-tests for unequal variance, whereas seasonal home range for summer 2011/12, core area and intensity of use estimates were compared with two-sample *t*-tests for equal variance.

Results

Movement

GPS collars from 22 deer were retrieved, including 11 male (4 young adult, 7 mature adult) and 11 female (1 young adult, 10 mature adult), with a resulting dataset of over 117 000 GPS relocation fixes. The maximum movement rate reached by individual stags between any two consecutive locations ranged between 97 and 277 m h^{-1} (Mean = 168 m h^{-1}), whereas the maximum movement rate reached by individual hinds ranged from 81 to 223 m h^{-1} (Mean = 164 m h^{-1}). Mean movement for stags was similar to hinds for summer and winter and varied significantly ($P < 0.001$) only in the rut season (Table 1). Both stags and hinds showed very similar bimodal crepuscular movement patterns with peaks in the early morning (0730 hours) and evening (1800 hours), and periods with low movement rates in the middle of the day and through the night (Fig. 1). This crepuscular movement varied significantly by time of day in all seasons (winter $F_{15,270} = 73.52$, $P < 0.001$, summer $F_{15,255} = 44.31$, $P < 0.001$ and rut $F_{15,240} = 36.72$, $P < 0.001$). There was no significant interaction between time of day and sex in the winter ($F_{15,270} = 1.23$, $P = 0.25$) and rut ($F_{15,240} = 1.23$, $P = 0.25$) seasons, but there was a slight interaction in summer ($F_{15,255} = 2.03$, $P = 0.014$) where hinds showed greater movement at 1800 hours ($t_{255} = -2.61$, $P = 0.010$) and 1930 hours ($t_{255} = -2.26$, $P = 0.025$) in the evenings than did stags.

Annual home range

Of the 22 collars retrieved, seven mature adult hind and four stag collars (two young stags and two mature stags) contained

Table 1. Comparison of mean movement of wild red hinds and stags at Cressbrook Dam Reserve, south-eastern Queensland by season between March 2010 and March 2013, using a linear mixed-effects model

Mean movement (m h^{-1}), showing 95% confidence intervals in parentheses; d.f., *F* and *P* are also given

Season	Hind	Stag	d.f.	*F*	*P*
Winter	94 (76–112)	107 (86–128)	1,18	3.15	0.093
Summer	101 (78–123)	91 (66–115)	1,17	0.71	0.410
Rut	70 (54–86)	127 (107–147)	1,16	130.76	<0.001

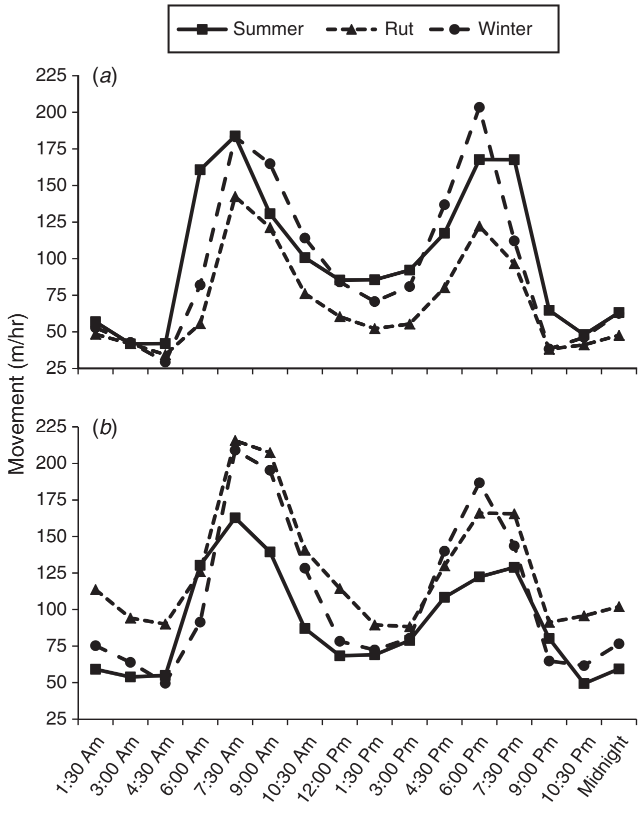

Fig. 1. Mean daily movement of (*a*) wild red hinds and (*b*) stags for the summer, winter and rut seasons at Cressbrook Dam Reserve, south-eastern Queensland between March 2010 and March 2013.

~12 months or more GPS data. All seven hinds and four stags displayed an asymptote in home-range size for the annual home-range data. The mean stag annual home-range estimate using the 95% LoCoH method was ~3.5 times larger than for hinds ($t_3 = -2.64$, $P = 0.039$) (Table 2). There was no statistically significant difference between the results for overall home range and annual home range ($t_{10} = -1.24$, $P = 0.122$).

Seasonal home range

Seasonal home-range areas varied in relation to annual home-range areas (Fig. 2). The area of male seasonal home ranges was significantly larger than that for females in the rut season of both 2011 ($t_3 = -2.75$, $P = 0.035$) and 2012 ($t_4 = -4.62$, $P = 0.005$), as well as in winter 2011 ($t_2 = -4.01$, $P = 0.028$). However, the size of male and female home ranges did not vary significantly in winter 2010 ($t_2 = -1.51$, $P = 0.134$), summer 2010/11 ($t_2 = -1.56$, $P = 0.130$) and summer 2011/12 ($t_6 = -0.74$, $P = 0.244$). Three hinds that contributed to both the winter 2010 and winter 2011 data had significantly larger home-range areas ($t_2 = 2.97$, $P = 0.049$) in winter 2010. Only one stag contributed to both winter 2010 and winter 2011, and when data from all four collars (3 female, 1 male) were combined, the mean home range of all four deer in winter 2010 was approximately double that of winter 2011 ($t_3 = 2.35$, $P = 0.050$).

Table 2. Home-range data from wild red deer collared at Cressbrook Dam Reserve, south-eastern Queensland for ~1 year or more between March 2010 and March 2013

Mean area, ± s.e. and/or a range for three annual home-range estimators and one overall estimator are given. Kernel, kernel utilisation distribution; LoCoH, local convex hull; MCP, minimum convex polygon

Group	Hind	Stag	Subgroup Young stag	Subgroup Mature stag
Number	7	4	2	2
Months collared	17.2 (11.9–21.4)	15.7 (11.5–22.7)	15.2–22.7	11.5–13.3
Overall home range (ha) (95% LoCoH)	410 ± 88 (198–838)	1506 ± 568 (610–3112)	804–3112	610–1499
Annual home range (ha) (95% LoCoH)	359 ± 78 (179–774)	1323 ± 357 (610–2237)	805–2237	610–1499
Annual home range (ha) (95% MCP)	682 ± 136 (274–1372)	6018 ± 3304 (1192–15799)	1192–15799	3233–3747
Annual home range (ha) (80% Kernel)	314 ± 80 (147–769)	2898 ± 1848 (620–8422)	620–8422	1191–1358

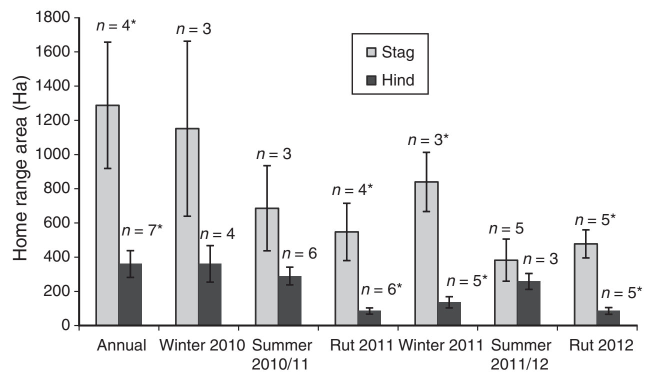

Fig. 2. Mean wild red stag and hind annual and seasonal home-range areas (95% local convex hull, LoCoH), showing number of individuals and standard error at Cressbrook Dam Reserve, south-eastern Queensland between March 2010 and March 2013. Asterisk indicates a pair where males and females were significantly different from each other using a two-sample *t*-test for unequal variance.

Seasonal location

Geographically, hinds displayed a continuous home-range area for all seasons, whereas two of the four stags displayed a discontinuous home range. The oldest stag displayed a discontinuous home range with a separate rut area and continuous winter and summer area, whereas the other showed a separate rut to summer area, with a winter area that overlapped both. The two other stags showed excursion behaviour in the rut.

Seasonal core areas and intensity of use

The mean annual core area of stags (= 143.5 ha) was larger than that of hinds (= 73.4 ha) ($t_9 = -1.85$, $P = 0.049$) (Fig. 3). The mean annual intensity of use of core areas for hinds (= 19.3%) was larger than that for stags (= 12.0%) ($t_9 = 2.61$, $P = 0.014$) (Fig. 4).

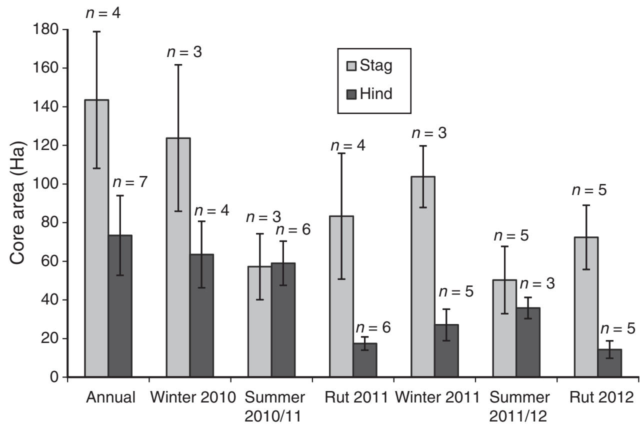

Fig. 3. Mean annual and seasonal core areas (50% local convex hull, LoCoH) for wild red stags and hinds at Cressbrook Dam Reserve, south-eastern Queensland between March 2010 and May 2013, showing number of individuals and standard error.

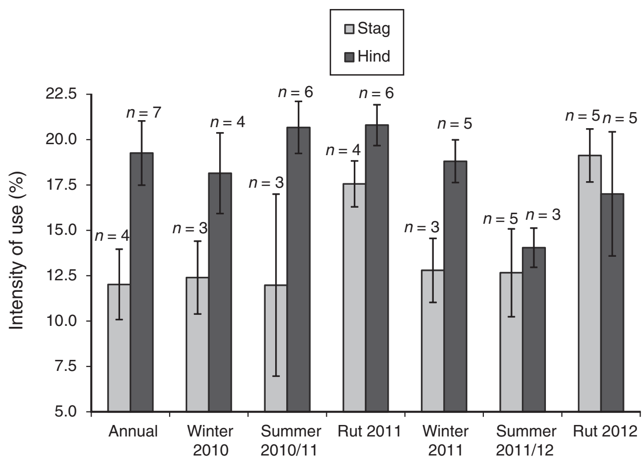

Fig. 4. Mean annual and seasonal intensity of use of home-range areas for wild red stags and hinds at Cressbrook Dam Reserve, south-eastern Queensland between March 2010 and March 2013, showing number of individuals and standard error. Intensity is the core area (50% local convex hull, LoCoH) divided by home range (95% LoCoH) expressed as a percentage. Intensity represents the proportion of the home-range area that deer spent 50% of their time in.

Discussion

Although managed as an important recreational resource in several jurisdictions, deer are not native to Australia and have the potential for detrimental impacts (Jesser 2005; Bilney 2013). Deer management activities are therefore likely to be linked to population maintenance or reduction rather than species conservation. Our results, although limited by a small sample size, suggest that managers should consider each sex separately and target effort accordingly. When targeting hinds, the continuous and, on average, smaller home range of hinds than of stags is an important consideration. For stag management, the summer and rut seasons appear to be the most appropriate time to conduct such activity. This is because of trends indicating smaller home ranges and core areas in summer and rut, with the additional benefits of the very vocal presence of stags during the rut and close spatial association with hinds.

Variable rainfall has been observed to have an impact on the home-range size of Australian macropods (Fisher and Owens 2000). The results reported here from two very different winter seasons (winter 2010 followed months of extremely low rainfall and winter 2011 followed months of extremely high rainfall) indicated that wild red deer may respond similarly in Australia, although caution should be exercised because of the limited sample size. Both home range and movement patterns could potentially be location and time specific. Whether targeting hunter effort over a broad area or localised reduction programs, managers may require species-specific information linked to the seasonal conditions.

The red deer at our study site displayed a typical crepuscular activity pattern (Clutton-Brock *et al.* 1982; Georgii and Schroder 1983; Catt and Staines 1987; Carranza *et al.* 1991). Georgii and Schroder (1983) concluded that peaks in activity are closely associated with dawn and dusk throughout the year, and our findings support that conclusion. From observation at our study site, it appears that the high movement rates at dusk and dawn correspond with deer moving into more open areas at dusk, alternating between grazing and resting through the night, and then moving back toward vegetative cover in the early morning.

Our primary focus for the movement and seasonal home-range analyses was to compare the effect of sex in different seasons, given the temporal variability of the data we had from individual animals and the small sample sizes. Our analysis suggested that apart from the rut season, stags and hinds appear to have very similar movement rates and daily movement patterns. This similarity between sexes was also observed in some of the results for seasonal core areas and intensity of use. However, similarities between stags and hinds were not apparent for annual and seasonal home-range areas.

We found no evidence to suggest that movement patterns and seasonal home range for stags were greatest in summer, which disagrees with the findings of Georgii and Schroder (1983) and Clutton-Brock *et al.* (1982). This is most likely attributed to the mild climatic conditions in winter at our study site. It is expected that stags maintain a higher bodyweight over winter in this climate than they do in more extreme northern hemisphere climates and do not need to invest as much energy into increasing bodyweight in summer before the autumn rut (Bocci *et al.* 2010).

Results of two (Catt and Staines 1987; Kamler *et al.* 2008) of six European studies of red deer reporting an annual home range (MCP) for hinds (Table 3) were comparable with our results, whereas four studies reported home ranges at least two and a half times smaller. These differences may have been an artefact of the different estimators and/or the small sample size. Mature stags at our study site had an annual home-range area (MCP) similar to that in one other study (Kamler *et al.* 2008), while being about five times larger than those in three other studies (Clutton-Brock *et al.* 1982; Carranza *et al.* 1991; Lovari *et al.* 2007). Our results for the Kernel method of home-range estimation were again similar to or larger than those in equivalent European studies (Table 3). One of our young stags had a home-range area (1192 ha MCP) similar to that of stags in two of the European studies (Catt and Staines 1987; Kamler *et al.* 2008),

Table 3. Reported red deer annual home range and density from various studies and locations
non-migrating red deer mean (or range as appropriate) annual home range and density from European studies, compared with our results. Studies ordered by decreasing home-range size for minimum convex polygon (MCP) and then kernel utilisation distribution (Kernel) methods. Stag-age classes are given as years old (Y.O.)

Author	Country	Habitat	Hind annual home range (ha)	Stag annual home range (ha)	Method	Estimated deer density (n km^{-2})
Kamler *et al*. (2008)	Poland	Temperate old growth forest	840	3600 (≥2 Y.O.)	100% MCP	5–7
This study	Australia	Subtropical dry sclerophyll forest	682	3490 (≥3.5 Y.O.)	95% MCP	~28
Catt and Staines (1987)	Scotland	Sitka-spruce plantation	406–1008	1062–1182 (1–3 Y.O.)	MCP	Not reported
Carranza *et al*. (1991)	Spain	Mediterranean shrub	258	655 (~3–4 Y.O.)	Minimum polygon	50–100
Jeppesen (1987*a*)	Denmark	Pine-spruce plantation	257	Not reported	MCP	6–9 (Jeppesen 1987*b*)
Clutton-Brock *et al*. (1982)	Scotland (Isle of Rhum)	Heath, bog and grassland	180	110	Minimum polygon	14
Lovari *et al*. (2007)	Sardinia	Mediterranean shrub	114	190 (>5 Y.O.)	100% MCP	25–26
This study	Australia	Subtropical dry sclerophyll forest	314	1275 (≥3.5 Y.O.)	80% Fixed kernel	Approx. 28
Jerina (2012)	Slovenia	Fir-beech forest (Dinaric Mountains)	399	576 (≥4 Y.O.)	95% Kernel	0.7–6.6
Bocci *et al*. (2010)	Italy	Spruce and larch forest (Dolomites)	137–212	Not reported	90% Kernel	6

whereas the home-range area (15 799 ha) of the other young stag was extremely large in comparison to anything else reported. The movement of this second young stag was consistent with him making exploratory movements out of his home range. However, he consistently returned to the area where he was collared.

Stags at our study site had larger home-range areas than did hinds for overall, annual and some seasonal home ranges, which were similar to those in most European red deer studies (Georgii 1980; Georgii and Schroder 1983; Lovari *et al*. 2007; Kamler *et al*. 2008; Jerina 2012). Hinds behaved like those in a temperate climate in southern France (Pépin *et al*. 2008), displaying a continuous home-range area regardless of season. Mature stags at our study site had two discontinuous seasonal areas, similar to stags in other studies showing two or three distinct seasonal areas (Georgii and Schroder 1983; Pépin *et al*. 2008; Bocci *et al*. 2012). The oldest stag in our study (~7.5 years old) showed a pattern very similar to that of mature stags in the study of Georgii and Schroder's (1983), having a very small and defined rutting range that was some way away from their main home-range area.

Given the agreement of the home-range analysis from our study with the European studies mentioned above, it would be easy to conclude that red deer in Australia are behaving similarly to European red deer, as in most cases they are. However, when the density of red deer in the Cressbrook Dam catchment is taken into consideration compared with the home-range areas, some noteworthy divergence appears. Jerina (2012) has linked a decrease in the home-range size with increasing deer density, which is supported by Carranza *et al*. (1991) who reported the highest deer density (50–100 deer km^{-2}). Our study site had a density of ~28 deer km^{-2} (M. Amos, G. Baxter, N. Finch and P. Murray, unpubl. data), which is high compared with most European examples, yet the annual home-range areas for mature males and females at our study site were among the largest of those reported (Table 3). There could be many reasons for these large home ranges at a relatively high deer density, but they are likely to include poor Australian soils, mild winters and highly variable rainfall in Australia compared with Europe. All these factors would necessitate larger home ranges allowing greater movement than in Europe.

Conclusions

As the first study on wild red deer in Australia, we have recorded some spatial and temporal information that provides base-line data about this animal as an introduced species. This may assist land managers make informed decisions when implementing population maintenance or control activities. Hinds showed a continuous home range that is smaller than that of stags. Stags have small summer and rut seasonal home ranges, and are vocal and present with hinds during the rut.

Although our study has shown many similarities between Australian red deer home range and movement behaviour and those reported from the red deer's native area, some divergence has also appeared. To gain a better understanding of this animal in the Australian setting, we believe there is scope for further research to explore the potential difference in stag summer movement behaviour in Australia compared with overseas, the effect of varying Australian seasonal conditions on seasonal home ranges, and the link between home-range size and wild red deer density at various Australian locations.

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References

Australian Bureau of Meteorology (2012). Climate data. In 'Climate classification maps'. (Commonwealth of Australia, Bureau of Meteorology.) Available at http://www.bom.gov.au/jsp/ncc/climate_averages/climate-classifications/index.jsp?maptype=tmp_zones [verified 5 September 2014].

Australian Bureau of Meteorology (2013). 'Monthly Rainfall – Cressbrook Dam. Vol. 2013.' Climate Data. (Australian Government, Bureau of Meteorology.) Available at http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=139&p_display_type=dataFile&p_startYear=&p_c=&p_stn_num=040808 [verified 5 September 2014].

Bentley, A. (1998). 'An Introduction to the Deer of Australia, with Special Reference to Victoria.' Bunyip edn. (The Australian Deer Research Foundation Ltd: Melbourne.)

Bilney, R. J. (2013). Antler rubbing of yellow-wood by Sambar in East Gippsland, Victoria. *The Victorian Naturalist* **230**, 68–74.

Bjørneraas, K., Van Moorter, B., Rolandsen, C. M., and Herfindal, I. (2010). Screening global positioning system location data for errors using animal movement characteristics. *The Journal of Wildlife Management* **74**, 1361–1366. doi:10.1111/j.1937-2817.2010.tb01258.x

Bocci, A., Monaco, A., Brambilla, P., Angelini, I., and Lovari, S. (2010). Alternative strategies of space use of female red deer in a mountainous habitat. *Annales Zoologici Fennici* **47**, 57–66. doi:10.5735/086.047.0106

Bocci, A., Angelini, I., Brambilla, P., Monaco, A., and Lovari, S. (2012). Shifter and resident red deer: intrapopulation and intersexual behavioural diversities in a predator-free area. *Wildlife Research* **39**, 573–582.

Burt, W. H. (1943). Territoriality and home range concepts as applied to mammals. *Journal of Mammalogy* **24**, 346–352. doi:10.2307/1374834

Calenge, C. (2006). The package adehabitat for the R software: a tool for the analysis of space and habitat use by animals. *Ecological Modelling* **197**, 516–519. doi:10.1016/j.ecolmodel.2006.03.017

Carranza, J., Detrucios, S. J. H., Medina, R., Valencia, J., and Delgado, J. (1991). Space use by red deer in a Mediterranean ecosystem as determined by radio-tracking. *Applied Animal Behaviour Science* **30**, 363–371. doi:10.1016/0168-1591(91)90141-J

Catt, D. C., and Staines, B. W. (1987). Home range use and habitat selection by red deer (*Cervus elaphus*) in a sitka spruce plantation as determined by radio-tracking. *Journal of Zoology* **211**, 681–693. doi:10.1111/j.1469-7998.1987.tb04479.x

Clutton-Brock, T. H., Guinness, F. E., and Albon, S. D. (1982). 'Red Deer: Behavior and Ecology of Two Sexes.' (The University of Chicago Press: Chicago, IL.)

Fisher, D. O., and Owens, I. P. F. (2000). Female home range size and the evolution of social organization in macropod marsupials. *Journal of Animal Ecology* **69**, 1083–1098. doi:10.1046/j.1365-2656.2000.00450.x

Forsyth, D. M. (2005). How can research contribute to the management of wild deer in Australia? In 'National Feral Deer Management Workshop', November 2005, Canberra, Australia. (Ed. SR McLeod.) pp. 7–21.

Georgii, B. (1980). Home range patterns of female red deer (*Cervus elaphus L.*) in the Alps. *Oecologia* **47**, 278–285. doi:10.1007/BF00346833

Georgii, B., and Schroder, W. (1983). Home range and activity patterns of male red deer (*Cervus elaphus L.*) in the alps. *Oecologia* **58**, 238–248. doi:10.1007/BF00399224

Getz, W. M., and Wilmers, C. C. (2004). A local nearest-neighbor convex-hull construction of home ranges and utilization distributions. *Ecography* **27**, 489–505. doi:10.1111/j.0906-7590.2004.03835.x

Getz, W. M., Fortmann-Roe, S., Cross, P. C., Lyons, A. J., Ryan, S. J., and Wilmers, C. C. (2007). LoCoH: nonparameteric kernel methods for constructing home ranges and utilization distributions. *PLoS ONE* **2**, e207. doi:10.1371/journal.pone.0000207

Hall, G. P., and Gill, K. P. (2007). 'Management of Wild Deer in Australia with Particular Reference to Fallow Deer and Red Deer.' (Tasmanian Department of Primary Industries and Water: Longford, Tas.)

Hunter, J., Brooking, C., Brimblecombe, W., Dwyer, R., Campbell, H., Watts, M., and Franklin, C. (2013). OzTrack – e-Infrastructure to support the management, analysis and sharing of animal tracking data. In '9th IEEE International Conference on eScience'. (Ed. L. O'Conner) pp. 140–147. (Conference Publishing Services: Beijing.)

Jeppesen, J. L. (1987*a*). Impact of human disturbance on home range, movements and activity of red deer (*Cervus elaphus*) in a Danish environment. *Danish Review of Game Biology* **13**, 1–38.

Jeppesen, J. L. (1987*b*). Seasonal variation in group size, and sex and age compostion in a Danish red deer (*Cervus elaphus*) population under heavy hunting pressure. *Danish Review of Game Biology* **13**, 4–19.

Jerina, K. (2012). Roads and supplemental feeding affect home-range size of Slovenian red deer more than natural factors. *Journal of Mammalogy* **93**, 1139–1148. doi:10.1644/11-MAMM-A-136.1

Jesser, P. (2005). 'Deer in Queensland: Pest Status Review Series – Land Protection.' (Department of Natural Resources and Mines, Queensland: Brisbane.)

Kamler, J. F., Jedrzejewski, W., and Jedrzejewska, B. (2008). Home ranges of red deer in a European old-growth forest. *American Midland Naturalist* **159**, 75–82. doi:10.1674/0003-0031(2008)159[75:HRORDI]2.0.CO;2

Laver, P. N., and Kelly, M. J. (2008). A critical review of home range studies. *The Journal of Wildlife Management* **72**, 290–298. doi:10.2193/2005-589

Lewis, J. S., Rachlow, J. L., Garton, E. O., and Vierling, L. A. (2007). Effects of habitat on GPS collar performance: using data screening to reduce location error. *Journal of Applied Ecology* **44**, 663–671. doi:10.1111/j.1365-2664.2007.01286.x

Lovari, S., Cuccus, P., Murgia, A., Murgia, C., Soi, F., and Plantamura, G. (2007). Space use, habitat selection and browsing effects of red deer in Sardinia. *The Italian Journal of Zoology* **74**, 179–189. doi:10.1080/11250000701249777

Mohr, C. O. (1947). Table of equivalent populations of North American small mammals. *American Midland Naturalist* **37**, 223–249. doi:10.2307/2421652

Moriarty, A. (2004). The liberation, distribution, abundance and management of wild deer in Australia. *Wildlife Research* **31**, 291–299. doi:10.1071/WR02100

Pépin, D., Adrados, C., Janeau, G., Joachim, J., and Mann, C. (2008). Individual variation in migratory and exploratory movements and habitat use by adult red deer (*Cervus elaphus* L.) in a mountainous temperate forest. *Ecological Research* **23**, 1005–1013. doi:10.1007/s11284-008-0468-2

Roff, C. (1960). Deer in Queensland. *Queensland Journal of Agricultural Science* **17**, 43–58.

Steiniger, S., and Hunter, A. J. S. (2012). OpenJUMP HoRAE – a free GIS and toolbox for home-range analysis. *Wildlife Society Bulletin* **36**, 600–608. doi:10.1002/wsb.168

Toowoomba Regional Council (2009). Toowoomba's Dams – Cressbrook Dam. In 'Cressbrook Dam Data', Available at http://www.toowoombarc.qld.gov.au/environment-and-waste/water-supply-and-dams/dams-a-bores/toowoomba-bulk-water/5311-cressbrook-dam.html [verified 5 September 2014].

Worton, B. J. (1995). Using Monte Carlo simulation to evaluate kernel-based home range estimators. *The Journal of Wildlife Management* **59**, 794–800. doi:10.2307/3801959

Chapter 6 - Habitat Preferences

Chapter 6 comprises the paper "Home amongst the gum trees: preferences of wild red deer in south-eastern Queensland for vegetative cover, slope and aspect." by Amos, M., Baxter, G., Finch, N. and Murray, P. (Submitted to *Wildlife Research)*

Plate 8 GPS collared hind with calf in the Cressbrook Dam catchment reserve. (Photo K. Staines - January 2012)

Home amongst the gum trees: preferences of wild red deer in south-eastern Queensland for vegetative cover, slope and aspect.

RH: Amos *et al.* Habitat use red deer SE QLD.

19th September 2014

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6.1 Abstract

Context. Wild deer require management in all Australian states. They are classified as game in Victoria, New South Wales and Tasmania and declared pests in all others. Red deer are the third most abundant deer species established in Australia, but there is little published research on them here.

Aims. To gain a greater understanding of the preferences of wild red deer for certain habitat and landscape variables. This knowledge will assist in management decisions and predictions of range expansion.

Methods. We conducted analyses on location data from GPS collars using resource selection ratios. Preferences were calculated for individual deer at the home range level and combined to give overall preferences for use of foliage projective cover, slope, and aspect.

Key findings. At the study site wild red deer utilised heavier foliage projective cover in the day compared to the night. Hinds selected grassland areas at night regardless of season, but stags strongly selected open grassland areas only during winter nights. Hinds often chose a southerly aspect which is likely linked to nutritional requirements and available high quality pasture, and is probably an indicator that the mild climate at our study site was not limiting behaviour.

Conclusions. Time of year and time of day are very important considerations for management activities aimed at wild red deer. We found that deer in general, and stags in particular, will be much harder to find in the landscape in the day time due to preferential use of heavier cover during the day. In addition to the rut, there may be a window of opportunity to locate stags during winter nights due to their preference for gentle slopes and grassland areas at this time, which may also be an ideal time to trial feed attractants.

Implications. The spread of expanding populations of red deer will likely be influenced by habitat variables – with vegetative cover an important consideration. Climate does not appear to be severe enough to exert a strong influence on behaviour. Grazing pressure by wild red deer on pastures, crops and native vegetation will most likely be increased during winter nights.

Additional keywords: *Cervus elaphus*, habitat use, Queensland, red deer.

6.2 **Introduction**

During the late 19th and early 20th centuries many attempts were made by acclimatisation societies to establish wild herds of deer in Australia (Bentley 1998; Moriarty 2004). At least 18 species were released at various locations and times (Bentley 1998; Jesser 2005). Of these, only six species established wild populations that survive today (Bentley 1998; Jesser 2005). For most of the 20th century wild deer in Australia remained in small, discrete herds. Legislation throughout the country aimed to protect wild deer and conserve what was considered a valuable resource. However, by the end of the 20th century both the number of wild deer populations and the size of those populations increased significantly prompting a change in attitudes towards wild deer. At present wild deer are classified as Game in Tasmania, Victoria and New South Wales and declared pests in all other jurisdictions. Regardless of legal status wild deer populations are challenging land managers due to increasing numbers. Despite the importance of wild deer management there is a general lack of peer reviewed scientific research on deer in Australia (Forsyth 2005a).

The wild red deer (*Cervus elaphus*) herd in south-eastern Queensland, estimated to number 10,000 to 15,000 animals, is the largest single population of red deer in Australia (Jesser 2005; Moriarty 2004). Red deer are also present in wild populations in Victoria, New South Wales, Western Australia and South Australia (McLeod 2009). Community opinion about deer and deer management varies greatly (Finch & Baxter 2007; Jesser 2005) as do management goals on individual properties. Depending on the attitude of the landowner (and notwithstanding legislation), deer management goals in Australia vary from conservation, herd improvement, population maintenance and population control through to eradication. Regardless of the individual management goals, population monitoring should be a key component of deer management.

Here we attempted to broaden our understanding of wild red deer by analysing their preferences for certain habitat and landscape variables at different times of the day and for different seasons. This information will help land managers devise management programs that are appropriate for red deer in the habitat and landscape variables they prefer and at the time they are likely to be using them.

6.3 **Materials and methods**

6.3.1 Study area

This study was located in the Cressbrook Dam (latitude 27.258° S longitude 152.195° E) catchment reserve near Toowoomba in south-eastern Queensland. The reserve surrounding Cressbrook Dam is managed by the Toowoomba Regional Council (TRC) and is approximately 4,893 ha comprised predominantly of dry sclerophyll forest (82%) with some open grassland around the dam foreshore. The open grassland varied greatly in area during the course of the study with fluctuations in the water levels in the dam.

The climate at Cressbrook Dam is subtropical (Australian Bureau of Meteorology 2012). Summers are warm, humid and often wet with a predominantly summer rainfall pattern. Winters are short, mild and relatively dry. Average annual precipitation is approximately 740.6 mm (Australian Bureau of Meteorology 2014).

The study site is located in the mountain chain that forms part of the Great Dividing Range of eastern Australia. Study site elevation varies from approximately 300 to 600 m while topography varies from gentle slopes to steep hills.

Cressbrook Dam is only approximately 35 km from the original release site of red deer in south-eastern Queensland in 1873 (Bentley 1998; Roff 1960). It is within the area that contains the south-eastern Queensland wild red deer herd, estimated to number between 10,000 to 15,000 animals ten years ago (Moriarty 2004), and likely to be greater in number now. Although it is unknown exactly how long red deer have been at the study site, they were observed in the general vicinity of the study site in 1956 (Roff 1960). Deer density at the study site is high at approximately 28 deer/km^2 (Amos, M, unpublished data).

6.3.2 Collar Data

We obtained GPS location data from 22 radio-collared wild red deer between March 2010 and March 2013. Male deer comprised 11 of the 22 collared deer, of which 4 were estimated by tooth wear and eruption and physical characteristics to be aged between 1.5 and 3.5 years, with the remaining 7 estimated to be older than 3.5 years. Of the 11 female deer, 1 was estimated to be between 1.5 and 3.5 years, and the remainder were estimated to be older than 3.5 years. The deer were fitted with Sirtrack G2C Wildlife Global Positioning System collars as described in Amos *et al.* (2014). The restraint, handling, and collaring of these animals was approved by The University of Queensland’s Animal Ethics Committee Approval SAS/239/09.

The collars recorded a GPS location every 90 minutes with an estimated position error of between ±12.3 m and ±15.2 m (Amos et al. 2014). We screened errors in the GPS location data as described by Bjorneraas *et al.* (2010) deleting <0.1% of the location points. The resultant data set contained over 117,000 GPS location points.

6.3.3 Analysis

We conducted analysis at the individual animal home range level – the Design III level of Thomas and Taylor (1990). We examined three habitat and landscape variables within home ranges - foliage projective cover, slope and aspect. Our analysis followed the methodology of Manly *et al.* (2002) for studies with resources defined by several categories. This consists of statistically comparing the habitat selection ratios or ratios of used habitat units to available units for each individual animal at the home range level. Assumptions of this method are: (a) proportions of different categories do not change during the sampling period, (b) available resource units are correctly identified, (c) used resource units are correctly identified, (d) the variables which actually influence the probability of selections are correctly identified, (e) animals have unrestricted access to all available resource units, and (f) resource units are sampled randomly and independently. These probably held true during our study but not all could be confirmed.

Used habitat units were defined as the number of GPS fixes that intersected with each habitat attribute for each animal. The available habitat units for each animal were delineated by the 100% MCP home range of that animal for the analysis period (Rolley & Warde 1985). The analysis was performed in the adehabitatHS package (Calenge 2006) in R (version 2.15.0, http://www.r-project.org/, accessed 30/3/2010) and hinds and stags were treated as separate groups. The analysis first tests for individual habitat selection with a chi-squared goodness of fit test with the log-likilihood statistic as recommended by Manly *et al.* (2002) and then conducts another chi-squared test for overall selection. A Bonferroni post hoc test was used to group statistically significant results at the 5% level.

We analysed the data for proportional usage of habitat attributes for three seasons and two times of the day. The three seasons used were those identified as being biologically important to wild red deer at the study site in a parallel study (Amos et al. 2014): winter (3 May to 31 October), summer (1 November to 21 March) and rut (22 March to 2 May). Analyses of individual seasons were trialled (i.e. winter 2010, winter 2011, and winter 2012), but low numbers of deer for each data set resulted in no significant trends, hence data from different years were pooled by season. The two time periods per day were set as day (10:30 – 16:30) and night (19:30 to 7:30) for the winter and rut seasons, with a corresponding longer day (9:00 – 16:30) and shorter night (19:30 – 6:00) in summer. These periods were set according to the crepuscular nature of red deer we observed at the study site and corresponded to periods of lower movement (Amos et al. 2014). We did not include the morning and evening higher movement time periods in our final analysis, as initial analysis of the data showed that morning and evening results were predominantly either the same as corresponding day and night respectively, or they showed no significant habitat selection. Deer use the morning and evening time periods to move from one habitat type into another so it is reasonable to expect that they would not have significant habitat preferences at these times.

6.3.4 Foliage Projective Cover

We analysed the use of structural forms of vegetation cover by collared deer in vegetation categories based on foliage projective cover (FPC) defined by Specht (1970). The categories at the study site were: "open woodland/grassland" (<10% FPC), "woodland" (10 – 30%), "open forest" (30 – 70%) and "closed forest" (70 – 100%). The raster map "Foliage Projective Cover 2010 – Kingaroy" (Department of Science 2012) with resolution (pixel size) of 25 m was used to determine structural vegetative cover. This map was originally derived from Landsat 5 TM imagery (Department of Science 2012). The composition of vegetation cover categories in the Cressbrook Dam catchment was: grassland ~ 9%, woodland ~ 17%, open forest ~ 72% and closed forest ~ 2%. Due to extremely small quantities of available and utilised closed forest habitat, this category was combined with open forest to form a single "forest" category. Three subsets of the winter night data for stags were analysed for May/June, July/August, and September/October respectively to determine if there was a peak time within the winter season when grassland vegetation was targeted at night.

6.3.5 Slope

A raster maps for slope and aspect was derived from the "Digital elevation model - 25 metre - South East Queensland" (Department of Natural Resources and Mines 2011) by using the "Surface" tool in the Spatial Analyst toolbox in ESRI®'s ArcMap 10 (380 New York Street, Redlands, CA). This map had a 25 m pixel size. Slope values were categorized with reference to Speight (2009) but were merged to the following categories—"gentle" (0 - 5°45'), "moderate" (5°45' - 18°) and "steep" (18° - 47° - upper limit in study area) as Speight's categorisation would have resulted in six categories, with the 3 categories merged into "gentle" and two categories merged into "steep" containing little information in them separately. The composition of slope categories in the Cressbrook Dam catchment was: gentle ~ 21%, moderate ~ 56% and steep ~ 23%.

6.3.6 Aspect

A raster map for aspect was derived in a similar fashion as described above for slope using the same digital elevation model. Aspect was classified according to cardinal directions – "north" (315° - 45°), "east" (45° - 135°), "south" (135° - 225°) and "west" (225° - 315°). The composition of aspect categories in the Cressbrook Dam catchment was: north ~ 24%, east ~ 30%, south ~ 25% and west ~ 21%.

6.4 **Results**

The number of individual deer that showed strong habitat and landscape attribute selection (*P*<0.05) varied for sex, habitat type, time of year and time of day (Table 6-1). A high degree of individuality in selection was observed, even within a group for the same season, time period and habitat variable. For example, even though all stags in the summer night displayed strong preferential selection (*P*<0.05) for different vegetation cover categories, the habitat attribute selected often varied between individuals (Figure 6-1), resulting in an overall preference that was not significantly different for the three vegetation cover types available (Figure 6-2b).

Table 6-1 The number of individual wild red hinds and stags displaying significant (*P*<0.05) preferences for categories of cover, slope and aspect at Cressbrook Dam Reserve, south-eastern Queensland by season and time of day between March 2010 and March 2013.

Season	Winter		Summer		Rut	
	Day	Night	Day	Night	Day	Night
Hinds	(n=11)		(n=10)		(n=10)	
Cover	7	11	10	9	6	5
Slope	7	10	7	9	5	9
Aspect	10	11	10	9	7	9
Stags	(n=9)		(n=9)		(n=8)	
Cover	4	8	7	9	6	5
Slope	7	7	7	7	3	5
Aspect	7	8	8	9	3	5

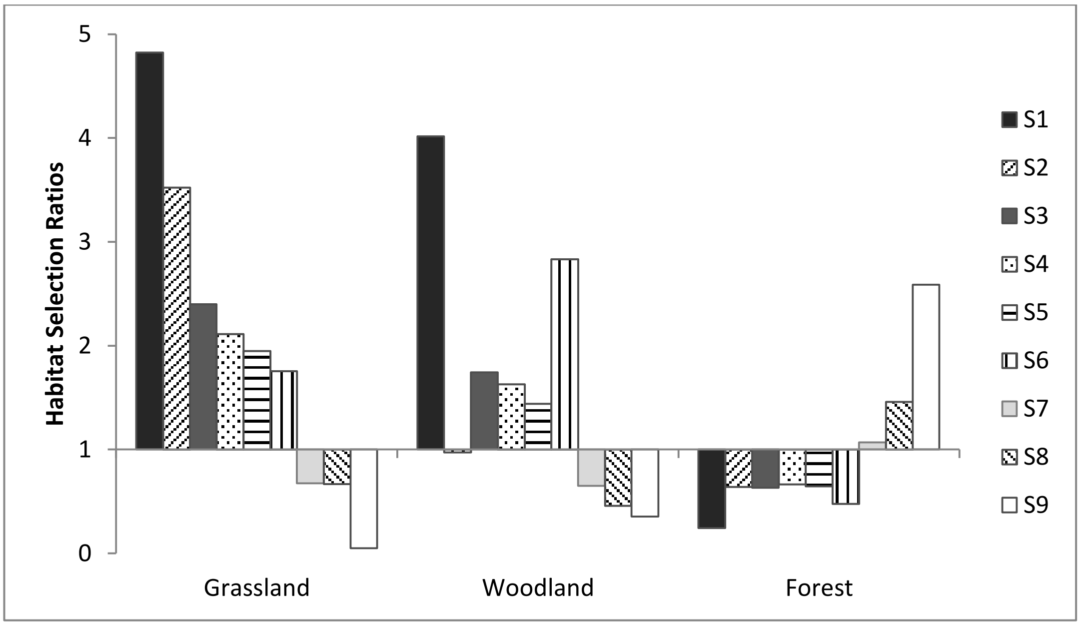

Figure 6-1 Individual habitat selection ratios (used vs. available habitat units) of nine wild red stags (S1, etc.) for three categories of foliage projective cover (see Materials and Methods – Foliage Projective Cover) at night in summer at Cressbrook Dam Reserve, south-eastern Queensland between March 2010 and March 2013.

Values >1 indicate preference for that habitat attribute, whilst values<1 indicate avoidance. All stags displayed a significant habitat preference (*P*<0.05).

6.4.1 Foliage Projective Cover

As a group, hinds displayed a preference for grassland over other vegetation cover classes at night, regardless of season (Figure 6-2a). During the day, hinds showed a preference for either woodland or forest cover classes. Grouped stag data showed that stags displayed a strong preference for grassland in winter nights, but this preference was not repeated in summer or the rut (Figure 6-2b). The analyses conducted on subsets of the winter night data for stags did not show any different trends to the seasonal results for winter nights. Stags did display a preference for the heavier cover of the forest in the day time regardless of season.

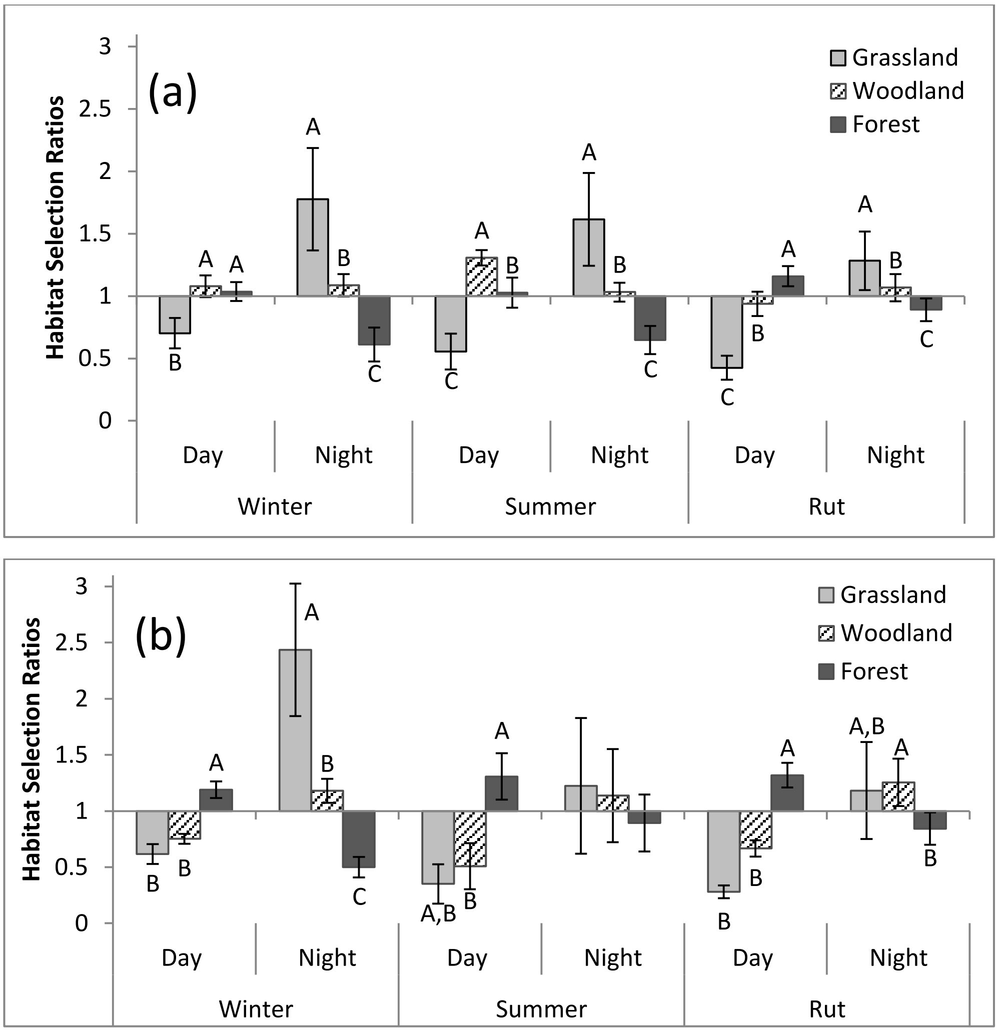

Figure 6-2 Overall habitat selection ratios (used vs. available habitat units) for wild red hinds (a) and wild red stags (b) for three categories of foliage projective cover (see Materials and Methods – Foliage Projective Cover) at Cressbrook Dam Reserve, south-eastern Queensland between March 2010 and March 2013 showing standard error and 95% Bonferroni post hoc groupings.

Values >1 indicate preference for that habitat attribute, whilst values<1 indicate avoidance. Results without letter groupings were not significantly different.

6.4.2 Slope

Hinds as a group selected for gentle slopes at night in the winter and summer (Figure 6-3a). During the day, hinds selected moderate slopes, regardless of season. The only time that stags selected gentle slopes was at night in winter (Figure 6-3b). Stags chose steep slopes for the time of day, regardless of season.

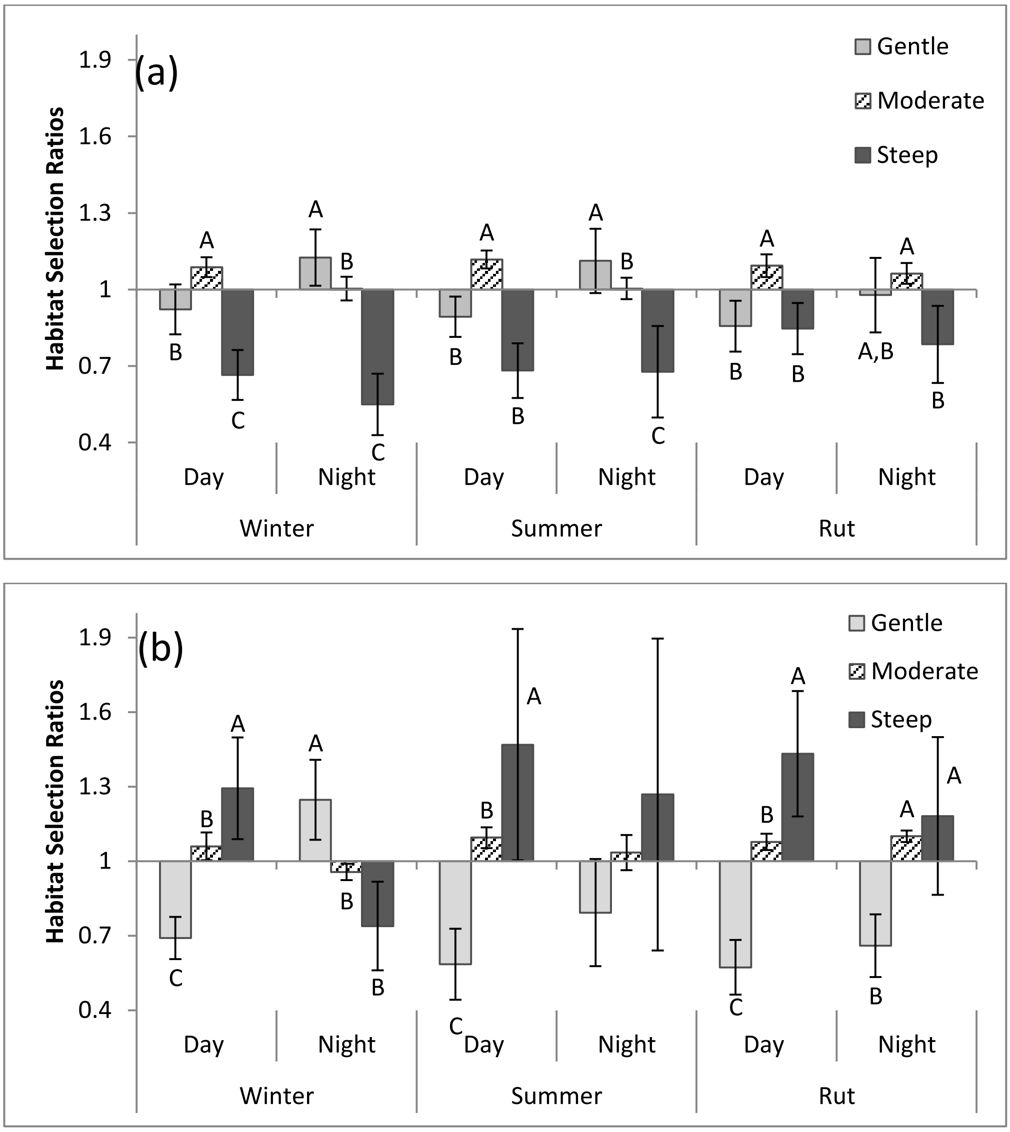

Figure 6-3 Overall habitat selection ratios (used vs. available habitat units) for wild red hinds (a) and wild red stags (b) for three categories of slope (see Materials and Methods – Slope) at Cressbrook Dam Reserve, south-eastern Queensland between March 2010 and March 2013 showing standard error and 95% Bonferroni post hoc groupings.

Values >1 indicate preference for that habitat attribute, whilst values<1 indicate avoidance. Results without letter groupings were not significantly different.

6.4.3 Aspect

Hinds selected for a southerly aspect during both day and night in the winter, and in the night during the rut (Figure 6-4a). Similarly, they selected for both southerly and westerly aspects during the day in both summer and the rut. The only time that stags showed a strong selection for a southerly aspect was during the night in winter (Figure 6-4b). Stags showed an affinity for an easterly aspect selection at all times of the year, which was significantly greater than selection of other aspects in the winter day and summer night.

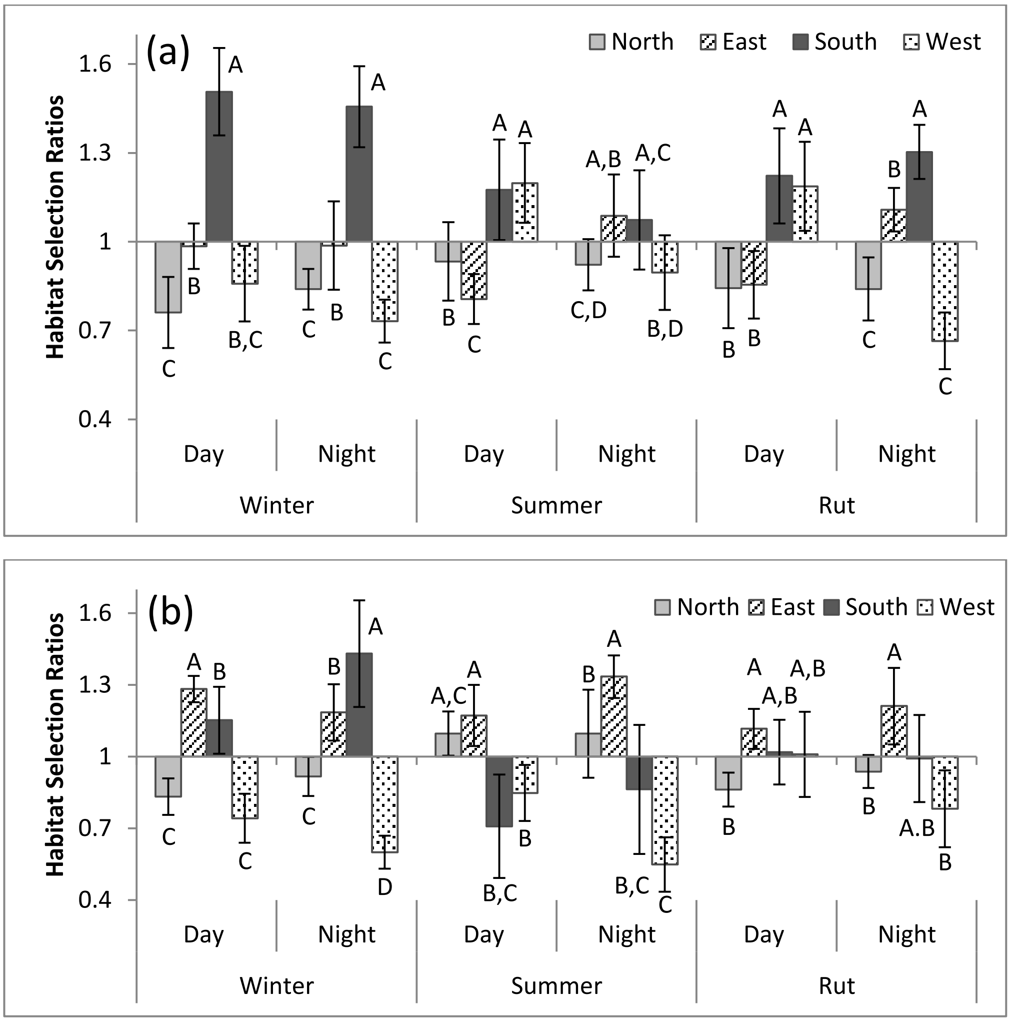

Figure 6-4 Overall habitat selection ratios (used vs. available habitat units) for wild red hinds (a) and wild red stags (b) for four categories of aspect (see Materials and Methods – Aspect) at Cressbrook Dam Reserve, south-eastern Queensland between March 2010 and March 2013 showing standard error and 95% Bonferroni post hoc groupings.

Values >1 indicate preference for that habitat attribute, whilst values<1 indicate avoidance.

6.5 Discussion

Both stags and hinds displayed a strong avoidance of open grassland in the day regardless of season with stags showing a corresponding preference for forest areas and hinds a preference for either woodland or forest areas in the day. We agree with Jerina (2009) that this behaviour is most likely using the Woodland and Forest as cover or refuge during the day to avoid human (or predator) interaction. An implication of this use of cover in the daytime that has been observed both in red deer overseas (Carranza et al. 1991; Jerina 2009; Zweifel-Schielly et al. 2012) and at our study site is that expanding wild red deer herds are not expected to preferentially establish new home ranges in purely open country with little cover present unless forced by other factors. There is scope for further habitat modelling for this introduced species, using vegetative cover as a predictor of suitable habitat for expanding populations.

We found preferential habitat use of the grassland by both stags and hinds at night in the winter and by hinds at night in the others seasons. Grazing in more open areas at night is a trait of red deer also observed overseas (Carranza et al. 1991; Jerina 2009; Jerina 2012; Zweifel-Schielly et al. 2012). This indicates that timing of any management activities within the day may be crucial. Should land managers wish to just reduce deer numbers then the use of a vehicle and spotlight at night during winter would be appropriate where legal. Should a selective harvest of specific deer be desirable then management activities could be focussed on the late afternoon or early morning as deer utilise more open areas at these times. For monitoring purposes, the night, late afternoon and early morning are the best times of day to count deer due to the above mentioned factors.

From analysis of home range information (Amos et al. 2014) from the same collared deer as used in this study, we concluded that the summer and rut seasons appear to be the best seasons to locate deer when considering home range size, with the rut having the additional benefit of being the only time that both hinds and stags congregate together. Combining the information from that study with the above results we hypothesise that the rut is a good time for targeted monitoring or management of hinds, especially at night. During the rut, hind home range and core areas appear to be small, night time cover preferences are for grassland and slope preferences are for moderate to gentle slopes. The rut is the ideal time to monitor or manage stags from their very vocal presence and close association with hinds. However, the habitat preference data suggest that winter nights may also be a good time to monitor or manage stags. Winter nights were the only time when stags actively chose grassland areas with gentle slopes and a southerly orientation – which is a similar preference to hinds for this time period.

The winter habitat preference showed by both stags and hinds for the grassland at night is consistent with European studies (Carranza et al. 1991; Zweifel-Schielly et al. 2012). Zweifel-Schielly *et al.* (2012) concluded that for Alpine red deer this use of grassland in winter nights was to meet nutritional requirements. Even though winters at our study site are mild they are also dry and we speculate that animal nutritional requirements drive this behaviour as vegetation is greenest in the open grassland areas immediately adjacent to Cressbrook Dam. This winter use of open grassland by hinds and stags is likely to bring them into conflict with government land managers of high value native vegetation, farmers with nutritious winter crops, golf course caretakers and other land managers, as grazing pressure by red deer at this time of year will likely be higher. However, land managers could use this nutritional drive to trial feed attractants such as lick blocks, supplementary feed or small sacrificial crops to concentrate deer in localised areas to conduct management processes.

There was some correlation among habitat and landscape variables analysed at the study site, and this was also displayed in the results of analysis. For example, when stags showed a very strong preference for grassland vegetation cover on winter nights, it explains their preference also displayed for gentle slopes in the same time period, as grassland is generally found on the more gentle slopes at the study site. Another example of links between habitat and landscape variables is stags generally choosing steeper slopes and heavier vegetation categories - and these habitat categories also co-incide at the study site.

During winter and summer days, stags chose the heavier cover of the forest, while hinds either chose woodland or a mix of woodland and forest. This observation is in agreement with the findings of Carranza *et al.* (1991) where stags used wooded areas more than females in a Mediterranean ecosystem. The preference for heavier cover and steeper slopes by stags at our study site is likely to be linked to predator avoidance, differing nutritional requirements of stags compared to hinds and an avoidance of competition for resources with hinds (Carranza et al. 1991; Clutton-Brock et al. 1982).

We expected hinds to show a preference for an easterly or northerly aspect in winter to maximise early morning sunlight, but they showed a preference for a southerly aspect. The stags also showed a strong southerly preference for winter nights. This may be linked to pasture species that thrive more in the shaded southerly aspect in this dry time of the year, especially in the grassland. Unpublished data suggest that some dicots growing on the study area are highly palatable to deer (e.g. *Verbena bonariensis*) and that these are sought after in winter. We also expected hinds to avoid the westerly aspect in summer due to hot afternoon sunshine, but they preferentially chose the westerly and southerly aspects which may suggest that the climate at our study site is mild, and well within the ranges encountered in other parts of this deer's world-wide range.

Two of the general assumptions of using the methods of Manly *et al.* (2002) that may be problematic in our study are the independent sampling of resource units, and animals having unrestricted access to the entire distribution of available resource units. We could not guarantee the independent sampling of resource units as we could not determine independence between animals. We did not know the family lines of individual animals and the hinds at least were spatially close together, and may not have independently used resource units. Also, we do not know if individuals may have restricted access of others to some of the available resource units due to territoriality or herd hierarchy. However we attempted to address these concerns by a random selection of target animals and a relatively large sample size, taken from different parts of the study area.

6.6 **Conclusion**

Although the vegetation composition of our study site is mainly dry sclerophyll forest that varies from the habitat of the wild red deer's native range in Europe, we observed wild red deer choosing habitat variables in a similar way to their European conspecifics. In particular we found deer use higher levels of vegetative cover in the day compared to the night. The use of vegetative cover has implications for the type of landscape that expanding herds of wild red deer are likely to establish in, and there is scope for further research to model this association.

For land managers, we recommend choosing a suitable time of the year (i.e. rut or winter), and a suitable time of the day (i.e. night, early morning or late afternoon) to conduct management activities, or those activities may likely be unproductive. Stags at our study site selected for gentle slopes and grassland during winter nights, and this period may provide an opportune time additional to the rut for managers to locate these animals in locations similar to the Cressbrook Dam reserve. Winter nights are likely to be times when deer exert a higher grazing pressure on nutritious pasture, crops or native vegetation and this may in turn provide opportunities for land managers to concentrate deer in localised areas with feed attractants for management purposes.

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6.7 References

Amos, M., Baxter, G.S., Finch, N. and Murray, P. (2014), 'At home in a new range: wild red deer in south-eastern Queensland', *Wildlife Research*, vol. 41, no. 3, pp. 258-65.

Australian Bureau of Meteorology (2012). Climate Data. In 'Climate classification maps'. (Australian Government, Bureau of Meteorology.) Available at http://www.bom.gov.au/jsp/ncc/climate_averages/climate-classifications/index.jsp?maptype=tmp_zones [Verified 05 September 2014].

Australian Bureau of Meteorology (2013). Monthly Rainfall - Cressbrook Dam. In 'Climate Data Online'. (Australian Government - Bureau of Meteorology.) Available at http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=139&p_display_type=dataFile&p_startYear=&p_c=&p_stn_num=040808 [Verified 05 September 2014].

Bentley A. (1998). 'An introduction to the deer of Australia, with special reference to Victoria.' Bunyip edn. (The Australian Deer Research Foundation Ltd: Melbourne.)

Bjorneraas K., Van Moorter B., Rolandsen C. M. and Herfindal I. (2010). Screening global positioning system location data for errors using animal movement characteristics. *Journal of Wildlife Management* **74**(6), 1361-1366.

Calenge C. (2006). The package adehabitat for the R software: a tool for the analysis of space and habitat use by animals. *Ecological Modelling* **197**, 516-519.

Carranza J., Detrucios S. J. H., Medina R., Valencia J. and Delgado J. (1991). Space use by red deer in a Mediterranean ecosystem as determined by radio-tracking. *Applied Animal Behaviour Science* **30**(3-4), 363-371.

Clutton-Brock T. H., Guinness F. E. and Albon S. D. (1982). 'Red deer: behavior and ecology of two sexes.' (The University of Chicago Press: Chicago.)

Department of Natural Resources and Mines (2011). Digital elevation model - 25 metre - South East Queensland. (Queensland Government Information Service.) Available at http://dds.information.qld.gov.au/dds?title="Digital elevation model - 25metre - South East Queensland - data package" [Verified 18 September 2014].

Department of Science Information Technology Innovation and the Arts (2012). Foliage Projective Cover 2010 - Kingaroy. (Queensland Government Information Service.) Available at http://dds.information.qld.gov.au/dds?title="FoliageProjectiveCover2010-Kingaroy" [Verified 18 September 2014].

Finch N. and Baxter G. S. (2007). Oh deer, what can the matter be? Landholder attitudes to deer management in Queensland. *Wildlife Research* **34**, 211-217.

Forsyth D. M. (2005). How can research contribute to the management of wild deer in Australia? In 'National Feral Deer Management Workshop', November 2005, Canberra, Australia. (Ed. S. R. McLeod.), pp. 7-21.

Jerina K. (2009). How the estimates of home range size and composition are affected by diurnal, nocturnal and 24-hour sampling methods: example of the red deer (*Cervus elaphus*) in Slovenia. *Zbornik Gozdarstva in Lesarstva* **89**, 3-15.

Jerina K. (2012). Roads and supplemental feeding affect home-range size of Slovenian red deer more than natural factors. *Journal of Mammalogy* **93**(4), 1139-1148.

Jesser P. (2005). 'Deer in Queensland: Pest Status Review Series - Land Protection.' (Department of Natural Resources and Mines, Queensland: Brisbane.)

Manly B. F. J., McDonald L. L., Thomas D. L., McDonald T. L. and Erickson W. P. (2002). 'Resource selection by animals: statistical design and analysis for field studies.' Second edn. (Kluwer Academic Publishers: Dordrecht.)

McLeod S. R. (2009). 'Proceedings of the National Feral Deer Management Workshop.' November 2005, Canberra. (Invasive Animals Cooperative Research Centre: Canberra.)

Moriarty A. (2004). The liberation, distribution, abundance and management of wild deer in Australia. *Wildlife Research* **31**, 291-299.

Roff C. (1960). Deer in Queensland. *Queensland Journal of Agricultural Science* **17**, 43-58.

Rolley R. E. and Warde W. D. (1985). Bobcat habitat use in southeastern Oklahoma. *Journal of Wildlife Management* **49**(4), 913-920.

Specht R. (1970). Vegetation. In 'The Australian Environment.' 4th edn. (Ed. G. Leeper) pp. 44 - 67. (CSIRO - Melbourne University Press: Melbourne.)

Speight J. (2009). Landform. In 'Australian soil and land survey field handbook.' 3rd edn. (Ed. National Comittee on Soil and Terrain). (CSIRO Publshing: Melbourne.)

Thomas D. L. and Taylor E. J. (1990). Study designs and tests for comparing resource use and availability. *Journal of Wildlife Management* **54**(2), 322-330.

Zweifel-Schielly B., Leuenberger Y., Kreuzer M. and Suter W. (2012). A herbivore's food landscape: seasonal dynamics and nutritional implications of diet selection by a red deer population in contrasting Alpine habitats. *Journal of Zoology* **286**(1), 68-80.

Chapter 7 - General discussion and conclusions

Plate 9 End of a winter's night boat spotlighting. (L-R) Les Kowitz, Matt Amos, Cameron Wilson, Mike Brennan (shovel) and Gary Young. (Photo G. Harry – July 2011)

7.1 Introduction

The number of deer and deer population groups appear to be increasing generally in Australia (Jesser 2005; Moriarty 2004). Deer in certain circumstances may have detrimental environmental effects (Bilney 2013), can be an agricultural pest (Jesser 2005) and a potential danger to road users (Putman et al. 2011), yet they are also highly valued as a game species and for aesthetic reasons (Finch & Baxter 2007; Jesser 2005). Legislation in Australia reflects this conundrum and the legislative status of deer as either a pest or game animal varies between states. Red deer have been well researched in their native European environments for many important biological factors such as reproduction, population dynamics, home range, habitat use and population estimation techniques. However, there has been a lack of peer reviewed research on introduced deer species in Australia, particularly wild red deer. This research fills part of the knowledge gap about this species in the Australian context and provides land managers and policy makers information that is not inferred from other continents or climates.

This research focused on three main areas of wild red deer ecology: (I) a comparison of methods for estimating wild red deer abundance, (II) annual and seasonal home range of stags and hinds and (III) habitat preferences of wild red deer in various seasons and times of day. To manage a species effectively, management decisions must be based on sound population abundance estimates (Sinclair et al. 2006). In Chapter 4 a comparison of deer population estimation techniques was undertaken. Four popular methods of estimating deer numbers were compared for cost, labour input and precision: spotlighting, distance sampling, aerial surveys and faecal pellet counts. The annual and seasonal home range and movement of wild red stags and hinds was estimated at the study site in Chapter 5 using the LoCoH home range estimator. The MCP and Kernel home range estimators were also used to calculate annual home range for comparison with other studies. The seasonal habitat preference of stags and hinds were explored in Chapter 6. This research compared the used versus available habitat preferences for three habitat variables: foliage projective cover, slope and aspect. This research was conducted for individual deer at the home range level, with grouped results for three seasons and two times of the day.

7.2 Discussion

When comparing cost, labour input and precision, spotlighting performed the best overall. Distance sampling gave repeated measures of fair precision, but was expensive. Aerial surveys were quick but not as precise as other methods. Faecal pellet counts were precise but costly in terms of labour.

The absolute abundance of deer was estimated by distance sampling to be approximately 28 deer/km^2 at the study site, which is high by world standards.

It was expected that spotlighting would perform well as this method has been recommended for use with red deer (Acevedo et al. 2008; Garel et al. 2010). However, spotlighting has been heavily criticised for use with white-tailed deer due to detection variability (Collier et al. 2013). A high variability in detection was encountered in this research in 2011 when the number of deer detected by spotlighting varied greatly from night to night, as evidenced by an increased coefficient of variation of 18.1% compared to 9.7% and 8.7% for 2010 and 2012 respectively. This is most likely linked to a cull of deer by TRC staff at night using spotlights at the study site in preceding months resulting in the deer becoming wary of the spotlight. It may have also been associated with more vegetative cover following the exceptionally high rainfall events that occurred earlier in 2011 resulting in the deer being harder to detect. However, this research provides support for the use of the spotlighting method to provide an index of abundance for red deer in environments similar to the study site on the grounds of precision, cost effectiveness and general ease of use.

Overseas researchers have successfully used distance sampling for estimating abundance of deer populations (Acevedo et al. 2008; Focardi et al. 2002b; Gill et al. 1997; Jathanna et al. 2003) so this method was expected to work well at the study site given the expectations of a reasonably high deer density. Although it did give repeatable estimates of fair precision, this method was very labour intensive and used more than double the labour input of spotlighting in time spent sampling alone, without including time spent in travel or analysis. Part of the theory of this method is that if the animal to be counted occurs in clusters or groups, then each cluster or group is counted as one observation, and there needs to be approximately 60 to 80 observations to get a reasonable population estimate (Buckland et al. 2001). One potential way to utilise this method in a more cost effective manner, would be to conduct surveys at night using less intrusive methods such as red filtered spotlights or thermal imagery as per Focardi et al. (2013). Deer at the study site showed a much higher affinity for less heavily vegetated areas at night (see Chapter 5), so conducting the surveys at night is expected to maximise the catch per unit effort – thus somewhat reducing the labour requirement. From this research it is expected that unless (I) a large volunteer labour force was available, (II) the distance sampling method was adapted to maximise cost per unit effort, or (III) deer density was extremely high, the use of distance sampling to estimate abundance of red deer in Australian conditions is likely to be unviable on the grounds of high labour input.

Aerial surveys have been used effectively overseas for estimating deer abundance (Daniels 2006; Kantar & Cumberland 2013; Potvin et al. 2004). However, it was unknown if the terrain was too undulating and the vegetation cover too thick for aerial surveys to work well at the study site. This method did compare well with other methods in terms of labour input and overall cost, but was the least precise method. To increase precision, more time surveying would be needed, at extra cost in terms of labour and vehicle hire. It is likely that this method would prove quite expensive at low deer densities, but could be quite well utilised in a situation similar to this research site, especially if funds were available for helicopter hire and labour was limited.

The faecal pellet count derivation used (Faecal Pellet Index) in this this research has been utilised on red deer in New Zealand, and has been shown to have a positive and linear relationship with absolute abundance (Forsyth et al. 2007). It was expected to work well at the study site, and has been used elsewhere in Australia for counting other deer species (Forsyth et al. 2011). This research has shown that in sub-tropical grasslands this method was quite labour intensive – even though a repeatedly precise estimate was obtained. Relative precision projections suggest that the field effort could have been halved whilst still attaining a satisfactory level of precision (CV~15%) which would have dramatically reduced the cost of this method. It is expected that this method was designed with lower deer densities in mind as it has bootstrapping in the analysis. In this research the analysis was trialled with and without bootstrapping and it made no difference to the 95% confidence intervals. The results of this research indicate that the faecal pellet index would be better utilised in areas with lower numbers of deer and shorter or sparser pasture than was encountered in the catchment around Cressbrook Dam, or in similar high density deer localities the sampling effort could be reduced.

These methods of estimating abundance could not be compared against the actual abundance of deer for accuracy, as the actual abundance of deer at the study site was not known. Different methods for estimating abundance have been compared before using cost, labour input, and precision (coefficient of variation) (Acevedo et al. 2008; Daniels 2006). However the use of pooled standard deviation and pooled relative precision were unique in this study, as was the projection of relative precision for different labour inputs. All of the above comparisons would be of particular interest to land managers setting out to implement a red deer abundance monitoring program in similar conditions to that of the Cressbrook Dam catchment reserve.

The LoCoH method was used to estimate annual and seasonal home range of wild deer at the study site. The LoCoH estimator is reported as being particularly useful for estimating home range areas where there are sharp geographic boundaries (Getz & Wilmers 2004). This method did perform well and excluded areas that deer had not been observed using as part of their home range.

Annual home range (LoCoH) was estimated to be a mean of 359 ha for hinds and 1,323 ha for stags. Overseas studies have also reported a larger home range for stags than hinds (Georgii 1980; Georgii & Schroder 1983; Jerina 2012; Kamler et al. 2008; Lovari et al. 2007) so these results were expected. However, comparison of the annual home ranges estimated with the MCP and Kernel methods from this research with overseas research showed that wild red deer from south-eastern Queensland had annual home range areas that were among the largest of those reported. This was unexpected due to the high estimated deer density (Chapter 3) at the study site, as some researchers (Carranza et al. 1991; Jerina 2012) have proposed an inverse relationship between deer density and deer home range area. Although this variation in the relationship between density and home range area cannot be adequately explained from this research, it is expected that a contributing factor to Australian wild red deer having large home range areas at high densities is erratic rainfall patterns and possibly other factors such as a mild climate and poor soils.

Whilst exploring the above mentioned link between home range area and seasonal conditions in the seasonal home range analysis, four deer (1 stag, 3 hinds) that contributed data to both winter 2010 and winter 2011 had significantly larger seasonal home range areas in winter 2010. Although hampered by small sample size, this result would indicate that deer were behaving differently in those two seasons. When viewed against rainfall and pasture growth in those two years, the rainfall and thus pasture growth leading up to winter 2010 was extremely low, with quite the reverse in 2011 following flood rains in January of that year. As seasonal conditions affect the home range of other animals such as macropods (Fisher & Owens 2000) it is expected that the home range area of wild red deer in Australia may also vary inversely with seasonal conditions.

Other analysis of the seasonal home range areas showed no statistically significant trends, apart from males having greater home range areas than hinds in some seasons. However, there did appear to be a trend toward stags having larger winter home range areas than for other seasons. The large winter home range for stags is likely driven by nutritional requirements during this season for two reasons: (I) stags lose a lot of body weight during the rut and have high nutritional demands at this time (Mitchell et al. 1976) and (II) the winter season at Cressbrook Dam is the dry season, so generally the nutritional value of pasture (i.e. crude protein) is much lower at this time of year (Foster & Blight 1984). Due to these factors it is expected that stags roam more to try to source patches of food with higher nutrient content.

Wild red deer at Cressbrook Dam displayed typical crepuscular movement behaviour (Clutton-Brock et al. 1982). However, this research did not show that stags have elevated movement activity in summer. This coupled with the trend towards larger home range areas in winter mentioned above is different from overseas reports. In Europe, stags have larger home range areas and elevated activity in summer (Clutton-Brock et al. 1982; Georgii & Schroder 1983). This variation in behaviour for stags is most likely linked to mild climatic conditions in south-eastern Queensland compared to the reports from the red deer's native range with more extreme climatic conditions.

Wild red deer around Cressbrook Dam generally preferred areas with vegetative cover rather than open areas during the day regardless of season, with stags always choosing the heavier cover of forested areas during the day. These results were as expected, and agree with reported deer behaviour from overseas (Carranza et al. 1991; Jerina 2009; Zweifel-Schielly et al. 2012). There are no large predators such as wolves at the study site and the deer are reasonably protected from human hunting with only occasional culls or illegal hunting which suggests that deer have an innate preference for cover during the day, and/or even low levels of hunting are enough to reinforce or induce this behaviour.

Hinds showed a preference for open grassland during the night regardless of season. As most of the hinds had home range areas that bordered the lush open grassland of the lake foreshore, it seems reasonable that they would utilise this important resource, as pasture cover was much greater and thus nutritional value expected to be higher in the grassland than woodland or forested areas. Stags showed a strong preference for open grassland during winter nights, but not during the rest of the year. It is expected that nutritional demands drove this selection as unpublished data from the Cressbrook Dam research site suggest deer heavily graze dicots such as *Verbena bonariensis* in the grassland in winter (unpublished data).

Hinds showed a strong preference for a southerly aspect in both winter days and nights, and stags showed a strong preference for a southerly aspect on winter nights. Considering most of the cold winter winds come from the south or west, this result suggests that the mild climate at Cressbook Dam is not limiting deer winter behaviour. The reason for deer selecting a southerly aspect on winter nights is not understood, but one possibility, that is yet to be investigated, is that highly palatable or nutritious plants grows in a southerly aspect in the winter grassland pasture at the study site.

A strength of this research was the number of methods trialled and the volunteer labour available for the comparison of population estimation methods. In most research situations, there are few funds available to trial more than a couple of methods and not the available labour that was utilised in this study. It is estimated that the labour input to conduct the faecal pellet count twice was in the order of 240 person hours without analysis of the data. The large amount of volunteer labour available also meant that methods could be trialled over a short time period in a particular season to keep variance due to changes in weather or seasonal changes to a minimum. For example, all distance sampling events were conducted within a four day period utilising 8 or more people, whereas if only one or two people were utilised it would have required at least two weeks.

A limiting factor of this research was that the absolute density of deer at the research site was not known. Knowing the actual abundance would have helped evaluate methods. For example, there was not a consistent trend in abundance between years for the distance sampling and faecal pellet count methods, the two methods with a high labour input. As the absolute abundance was unknown for the study site, it could not be determined which method was more accurate, although relative precision was compared.

Another limiting factor of this research was the lack of both spatial and temporal replication. The study site had a high density of deer, and it would have been beneficial to replicate the population estimation methods in an area of low deer density. Also, the research was only conducted for 3 years, and it would have been valuable to trial these methods over a longer time frame. There was a lack of temporal replication for the aerial survey that could not be avoided due to financial constraints.

This home range study is a first for red deer in Australia, and important for understanding how these animals behave as an introduced species. The number of deer successfully collared in an Australian environment during the course of this research was a strength of the research, particularly since the methodology for capturing animals was limited by ethical reasons to darting on foot. A limitation of the home range research was that there could have been more spatial variation in where deer were captured, as many of the home range areas overlapped and individuals could well have been competing for the same resources. There was also no sure way of determining the independence of the individuals, as no genetic studies were conducted, although field observations and the resultant collar data indicate that collared deer were independent. Another limitation of the research was that deer capture and collaring occurred over a two year period. It would have been preferable to have deer radio-collared in a very short time period so that all location results could be compared for the same duration of time in the same seasons. It was not possible to radio-collar all deer at the same time due to the difficulty of locating deer without being seen, and then approaching the deer to within darting range (<50 m) without being observed.

A strength of the habitat research was the sampling rate of GPS location points (every 90 minutes) on the deer collars allowed a number of time periods to be sampled throughout the day. A limitation was that there was not a complementary vegetation analysis at the same time. Vegetation analysis would have allowed correlation of nutrient status with observed habitat preferences, however, such analysis was beyond the scope of this study.

7.3 Further Research

This research has some unanswered questions that could profitably be explored by further research. In my population estimation methods research, camera traps and thermal imaging were not trialled due to lack of time and finances. Camera traps have advantages such as being non-intrusive, requiring only low labour input in the field and sampling any time of the day and night. Camera traps were trialled at the study site as part of a separate honours project (Chinnock 2011) using the Jacobson camera method (Jacobson et al. 1997). Although the May 2010 camera estimate of 68.3 deer/km^2 was within the 95% confidence intervals of the October 2010 distance sampling results (22.6 – 87.7 deer/km^2)(see Chapter 4), the June 2010 camera estimate of 241.8 deer/km^2 was not (Chinnock 2011). An assumption of this method is that stags and hinds must be captured on photographs in the same proportions as they occur in the population (Jacobson et al. 1997). In the home range part of this thesis some stags were observed as having a different home range location for the mating season compared to the rest of the year, which accounts for the huge discrepancy between the camera estimates obtained in May and June. The mating season at the study site is in March/April and some stags were still present in May, but had largely moved out of the study site in June, affecting the stag/hind ratio and hence the population estimate. This method needs more refinement to be used on species of deer where the sexes do not reliably congregate together, and for red deer in Australia should be trialled in the mating season.

Thermal imagery could be very useful for nocturnal sampling when deer are in more open areas. It is less intrusive than spotlighting, and may be able to penetrate light cover more effectively than spotlighting. It is suggested that thermal imagery could be trialled as per Focardi et al. (2013) in conjunction with distance sampling. Another variation of thermal imaging that is expected to produce good results would be in aerial survey. With advances in technology, thermal imaging equipment prices are decreasing, and access to unmanned aerial vehicles (UAV) (drones) is increasing, so both of these technologies may be successfully integrated in future studies. Both or either of these methods could provide an important alternative to spotlighting to provide abundance information.

Further research could also include trials of population manipulation indices especially in areas where culls are scheduled to occur. Previously, Finch (2003) used the index-manipulation-index method at the study site and obtained a population density estimate of 35.2 deer/km^2 in an area that had a large proportion of open grassland. Although conducted much earlier than the current study this estimate corresponds to the distance sampling estimates in Chapter 4 of between 39.9 and 51.6 deer/km^2 in the grassland and between 25.9 and 30.1 deer/km^2 overall. The agreement of these studies indicate that the population manipulation indices may have some merit in similar circumstances, especially as they appear less labour intensive than distance sampling.

The home range research uncovered some areas of wild red deer ecology in Australia that should be further explored. Stags in Europe show elevated activity and larger home ranges in summer, and neither of these results were observed during this research. It appears that there is a link between seasonal conditions and seasonal home range at the study site that has not been previously documented, but was from a very limited sample size. Also, European researchers have proposed an inverse relationship between red deer density and home range area, yet wild red deer at the research site displayed comparatively large home range areas and relatively high densities which cannot adequately be explained.

Areas of further research related to the habitat preference should include further mapping or modelling of the relationships between the diurnal use of vegetation cover and both the percent and composition of vegetation cover available. Further research could also be conducted at the study site to develop fine-scale vegetation maps. The mapping of plant associations may verify causes of selection such as what plants were attracting deer to the southerly aspect of the grassland vegetation in the winter nights.

7.4 Conclusion

This research has achieved its aim of increasing the collective knowledge of wild red deer ecology in the Australian setting. The wild red deer sampled in this research were part of the south-eastern Queensland herd – the largest single population group of red deer in Australia. This population although not representative in terms of climate for all Australian wild red deer nonetheless could contain nearly half the population of red deer in Australia (Moriarty 2004).

This research shows that wild red deer were behaving in many aspects of home range and habitat preferences as expected from overseas research. Commonality between this research and overseas research included the crepuscular behaviour of wild red deer, males having a greater home range area than females, the winter night usage of open grassland areas and the general preference for vegetative cover in the day. This general predictability is important to land managers and policy makers as they can make general assumptions about Australian wild red deer based on overseas research for management purposes. However, this research highlights in particular some variations in Australian wild red deer behaviour that may have not have been previously documented. Australian stags do not display the large home range areas and elevated movement patterns in summer like stags overseas. There may be an important link between seasonal home range area and seasonal conditions and also between home range area and deer density that has not been shown in overseas research.

This research also compared four important methods used to estimate abundance or provide an index of abundance of wild red deer. Abundance monitoring is likely to become more important to land managers if deer herds continue to expand and the number of deer continues to increase. This research has not previously been conducted in an Australian setting and may prove invaluable for land managers who can’t afford such trials.

Land managers will in most cases choose spotlighting of the four methods trialled to monitor wild red deer abundance due to efficiency. Aerial surveys are also likely to be useful if deer densities are high, but may become quite expensive if numbers are low. It is unlikely that distance sampling as conducted in this research would be utilised by land managers and researchers due to the high labour input, but a derivation of this method may be useful. Faecal pellet counts are not likely to be used by land managers in sub-tropical settings unless deer density and pasture density is lower than experienced during this research, or the labour cost will be prohibitive.

Both the home range and habitat preference results suggest that monitoring and management of wild red deer may be ineffective if not undertaken at the optimum time of day and year. This research suggests that night is the best time of day to see deer in more open areas, with early morning and late afternoon the next best times. The rut season (March/April) is an opportune time for management activities as both stags and hinds are congregated, with stags showing a strong vocal presence, and hinds having very small home range areas. Winter nights are also a good time of year to find both stags and hinds in more open vegetation, and may be opportune for trialling feed attractants to congregate local deer populations.

This habitat preference research suggests that wild red deer preferentially use areas with vegetative cover during the day, so the availability of vegetative cover will most likely be an important factor in the spread of any expanding red deer populations. Observations at the study site did not suggest that there were any climatic constraints at the study site and so similar climates are not expected to hamper spread of any expanding populations.

Now that wild deer are established in Australia, and their spread is being assisted by anthropogenic factors (Moriarty 2004), it is likely that deer management will be an imperative for land managers and policy makers in new and established deer areas for the foreseeable future. The findings of this research will assist land managers and policy makers when making decisions based on the ecology of wild red deer. This research will also assist land managers evaluate and implement methods for estimating deer abundance in sub-tropical areas.

Chapter 8 - Overall Reference List

Acevedo, P, Ferreres, J, Jaroso, R, Duran, M, Escudero, MA, Marco, J & Gortazar, C 2010, 'Estimating roe deer abundance from pellet group counts in Spain: an assessment of methods suitable for Mediterranean woodlands', *Ecological Indicators*, vol. 10, no. 6, pp. 1226-30.

Acevedo, P, Ruiz-Fons, F, Vicente, J, Reyes-Garcia, AR, Alzaga, V & Gortazar, C 2008, 'Estimating red deer abundance in a wide range of management situations in Mediterranean habitats', *Journal of Zoology*, vol. 276, no. 1, pp. 37-47.

Aebischer, NJ, Robertson, PA & Kenward, RE 1993, 'Compositional analysis of habitat use from animal radio-tracking data', *Ecology*, vol. 74, no. 5, pp. 1313-25.

Allen, L, Engeman, R & Krupa, H 1996, 'Evaluation of three relative abundance indices for assessing dingo populations', *Wildlife Research*, vol. 23, no. 2, pp. 197-206.

Alves, J, da Silva, AA, Soares, AMVM & Fonseca, C 2013, 'Pellet group count methods to estimate red deer densities: precision, potential accuracy and efficiency', *Mammalian Biology*, vol. 78, no. 2, pp. 134-41.

Amos, M 2010, 'A comparison of population estimation methods for wild red deer (*Cervus elaphus*) at Cressbrook Dam, South-East Queensland', Honours thesis, The University of Queensland, Gatton.

Amos, M, Baxter, GS, Finch, N & Murray, P 2011, 'Preliminary population estimates using three methods for wild red deer (*Cervus elaphus*) in south east Queensland', *Proceedings of the 15th Australasian Vertebrate Pest Conference, Sydney, 20-23 June*, p. 81, viewed 20 June 2011, <http://www.feral.org.au/wp-content/uploads/2011/06/15thAVPC_Proceedings_June2011.pdf>.

Amos, M, Baxter, GS, Finch, N & Murray, P 2014, 'At home in a new range: wild red deer in south-eastern Queensland', *Wildlife Research*, vol. 41, no. 3, pp. 258-65.

Ariefiandy, A, Purwandana, D, Coulson, G, Forsyth, DM & Jessop, TS 2013, 'Monitoring the ungulate prey of the Komodo dragon *Varanus komodoensis*: distance sampling or faecal counts?', *Wildlife Biology*, vol. 19, no. 2, pp. 126-37.

Australian Bureau of Meteorology 2007, *Summary statistics Toowoomba*, viewed 26 March 2010, <http://www.bom.gov.au/climate/averages/tables/cw_041103.shtml>.

Australian Bureau of Meteorology 2012, *Climate classification maps: temperature/humidity zones*, viewed 1 November 2012, <http://www.bom.gov.au/jsp/ncc/climate_averages/climate-classifications/index.jsp?maptype=tmp_zones>.

Australian Bureau of Meteorology 2014, *Monthly rainfall - Cressbrook Dam*, viewed 17 October 2014, <http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=139&p_display_type=dataFile&p_startYear=&p_c=&p_stn_num=040808>.

Australian Deer Association n.d., *Deer in Australia*, viewed 19 August 2011, <http://austdeer.com.au/deer-in-australia>.

Australian deer farming manual, 1993, Agricultural Business Research Institute (ABRI), University of New England, Armidale.

Bali, A, Kumar, A, & Krishnaswamy, J 2007, 'The mammalian communities in coffee plantations around a protected area in the Western Ghats, India', *Biological Conservation*, vol. 139, no. 1-2, pp. 93-102.

Batcheler, CL 1975, 'Development of a distance method for deer census from pellet groups', *The Journal of Wildlife Management*, vol. 39, no. 4, pp. 641-52.

Baxter, GS, Finch, N, Hall, GP & Murray, P 2008, *LPWM3005 Game management: the science of sustainable use - learning guide*, The University of Queensland, Gatton.

Belant, JL & Seamans, TW 2000, 'Comparison of 3 devices to observe white-tailed deer at night', *Wildlife Society Bulletin*, vol. 28, no. 1, pp. 154-8.

Bentley, A 1998, *An introduction to the deer of Australia, with special reference to Victoria*, Bunyip 3rd edn, Australian Deer Research Foundation, Melbourne.

Bilney, RJ 2013, 'Antler rubbing of yellow-wood by Sambar in East Gippsland, Victoria', *The Victorian Naturalist*, vol. 230, no. 2, pp. 68-74.

Biosecurity Queensland, Department of Agriculture, Fisheries and Forestry 2013, *Feral red deer Cervus elaphus*, The State of Queensland, viewed 17 October 2014, <http://www.daff.qld.gov.au/__data/assets/pdf_file/0016/73510/IPA-Red-Deer-Factsheet.pdf>.

Bjorneraas, K, Van Moorter, B, Rolandsen, CM & Herfindal, I 2010, 'Screening global positioning system location data for errors using animal movement characteristics', *The Journal of Wildlife Management*, vol. 74, no. 6, pp. 1361-6.

Bocci, A, Angelini, I, Brambilla, P, Monaco, A & Lovari, S 2012, 'Shifter and resident red deer: intrapopulation and intersexual behavioural diversities in a predator-free area', *Wildlife Research*, vol. 39, no. 7, pp. 573-82.

Bocci, A, Monaco, A, Brambilla, P, Angelini, I & Lovari, S 2010, 'Alternative strategies of space use of female red deer in a mountainous habitat', *Annales Zoologici Fennici*, vol. 47, no. 1, pp. 57-66.

Brodie, JF 2006, 'An experimentally determined persistence-rate correction factor for scat-based abundance indices', *Wildlife Society Bulletin*, vol. 34, no. 4, pp. 1216-9.

Buckland, ST, Anderson, DR, Burnham, KP, Laake, JL, Borchers, DL & Thomas, L 2001, *Introduction to distance sampling: estimating abundance of biological populations*, Oxford University Press, Oxford.

Burgman, MA & Fox, JC 2003, 'Bias in species range estimates from minimum convex polygons: implications for conservation and options for improved planning', *Animal Conservation*, vol. 6, no. 1, pp. 19-28.

Burt, WH 1943, 'Territoriality and home range concepts as applied to mammals', *Journal of Mammalogy*, vol. 24, no. 3, pp. 346-52.

Calenge, C 2006, 'The package "adehabitat" for the R software: a tool for the analysis of space and habitat use by animals', *Ecological Modelling*, vol. 197, no. 3-4, pp. 516-9.

Campbell, D, Swanson, GM & Sales, J 2004, 'Comparing the precision and cost-effectiveness of faecal pellet group count methods', *Journal of Applied Ecology*, vol. 41, no. 6, pp. 1185-96.

Carranza, J, Detrucios, SJH, Medina, R, Valencia, J & Delgado, J 1991, 'Space use by red deer in a Mediterranean ecosystem as determined by radio-tracking', *Applied Animal Behaviour Science*, vol. 30, no. 3-4, pp. 363-71.

Catt, DC & Staines, BW 1987, 'Home range use and habitat selection by Red deer (*Cervus elaphus*) in a Sitka spruce plantation as determined by radio-tracking', *Journal of Zoology*, vol. 211, no. 4, pp. 681-93.

Chiarello, AG 1999, 'Effects of fragmentation of the Atlantic forest on mammal communities in south-eastern Brazil', *Biological Conservation*, vol. 89, no. 1, pp. 71-82.

Chinnock, S 2011, 'Using the camera estimate method for population estimates of wild red deer (*Cervus elaphus*) in South East Queensland', Honours thesis, School of Agriculture and Food Sciences, The University of Queensland, Gatton.

Clutton-Brock, TH, Guinness, FE & Albon, SD 1982, *Red deer: behavior and ecology of two sexes*, University of Chicago Press, Chicago.

Collier, BA, Ditchkoff, SS, Raglin, JB & Smith, JM 2007, 'Detection probability and sources of variation in white-tailed deer spotlight surveys', *The Journal of Wildlife Management*, vol. 71, no. 1, pp. 277-81.

Collier, BA, Ditchkoff, SS, Ruth, CR, Jr & Raglin, JB 2013, 'Spotlight surveys for white-tailed deer: monitoring panacea or exercise in futility?', *The Journal of Wildlife Management*, vol. 77, no. 1, pp. 165-71.

Conner, MC, Lancia, RA & Pollock, KH 1986, 'Precision of the change-in-ratio technique for deer population management', *The Journal of Wildlife Management*, vol. 50, no. 1, pp. 125-9.

Curtis, PD, Boldgiv, B, Mattison, PM & Boulanger, JR 2009, 'Estimating deer abundance in suburban areas with infrared-triggered cameras', *Human-Wildlife Conflicts*, vol. 3, no. 1, pp. 116-28.

Daniels, MJ 2006, 'Estimating red deer *Cervus elaphus* populations: an analysis of variation and cost-effectiveness of counting methods', *Mammal Review*, vol. 36, no. 3, pp. 235-47.

deCalesta, DS 2013, ‘Reliability and precision of pellet-group counts for estimating landscape-level deer density’, *Human-Wildlife Interactions*, vol. 7, no. 1, pp. 60-8.

Department of Natural Resources and Mines 2011, *Digital elevation model - 25 metre - South East Queensland - data package*, Queensland Government Information Service, viewed 20 June 2011,

<http://dds.information.qld.gov.au/dds?title="DigitalElevationModel-25metre-SouthEastQueensland">.

Department of Science, Information Technology, Innovation and the Arts, 2012, *Foliage projective cover 2010 - Kingaroy*, Queensland Government Information Service, <http://dds.information.qld.gov.au/dds?title="FoliageProjectiveCover2010-Kingaroy">.

Dougherty, SQ & Bowman, JL 2012, 'Estimating sika deer abundance using camera surveys', *Population Ecology*, vol. 54, no. 2, pp. 357-65.

Downing, RL 1980, 'Vital statistics of animal populations', in SD Schemnitz (ed), *Wildlife management techniques manual*, The Wildlife Society, Washington, D.C., pp. 247-67.

Dryden, G 2005, 'Wild deer in SE Queensland - graziers' pest or charismatic megafauna?', in SR McLeod (ed.), *Proceedings of the National Feral Deer Management Workshop, Canberra, 9-10 November,* Invasive Animals Cooperative Research Centre, Canberra, pp. 97-105.

Engeman, RM & Allen, L 2000, 'Overview of a passive tracking index for monitoring wild canids and associated species', *Integrated Pest Management Reviews*, vol. 5, no. 3, pp. 197-203.

Engeman, RM, Pipas, MJ, Gruver, KS & Allen, L 2000, 'Monitoring coyote population changes with a passive activity index', *Wildlife Research*, vol. 27, no. 5, pp. 553-7.

Engeman, RM, Pipas, MJ, Gruver, KS, Bourassa, J & Allen, L 2002, 'Plot placement when using a passive tracking index to simultaneously monitor multiple species of animals', *Wildlife Research*, vol. 29, no. 1, pp. 85-90.

Erickson, WP, McDonald, TL, Gerow, KG, Howlin, S & Kern, JW 2001, 'Statistical issues in resource selection studies with radio-marked animals', in JJ Millspaugh & JM Marzluff (eds), *Radio tracking and animal populations*, Academic Press, San Diego, pp. 209-42.

Fafarman, KR & DeYoung, CA 1986, 'Evaluation of spotlight counts of deer in South Texas', *Wildlife Society Bulletin*, vol. 14, no. 2, pp. 180-5.

Fewster, RM & Pople, AR 2008, 'A comparison of mark-recapture distance-sampling methods appled to aerial surveys of eastern grey kangaroos', *Wildlife Research*, vol. 35, no. 4, pp. 320-30.

Fieberg, J, Matthiopoulos, J, Hebblewhite, M, Boyce, MS & Frair, JL 2010, 'Correlation and studies of habitat selection: problem, red herring or opportunity?', *Philosophical Transactions of the Royal Society B-Biological Sciences*, vol. 365, no. 1550, pp. 2233-44.

Finch, N 2000, 'The performance and condition of wild red deer in Queensland', Honours thesis, The University of Queensland, Gatton.

Finch, N 2003, *Final report on Cressbrook deer*, The University of Queensland, viewed 30 April 2013, <http://www.deerresearch.com.au/wp-content/uploads/Final-report-on-Cressbrook-deer-2003.pdf>.

Finch, N n.d., *Deer research: about the project*, The University of Queensland, Gatton, viewed 14 October 2013, <http://www.deerresearch.com.au/about-the-project>.

Finch, N & Baxter, GS 2007, 'Oh deer, what can the matter be? Landholder attitudes to deer management in Queensland', *Wildlife Research*, vol. 34, no. 3, pp. 211-7.

Fisher, DO & Owens, IPF 2000, 'Female home range size and the evolution of social organization in macropod marsupials', *Journal of Animal Ecology*, vol. 69, no. 6, pp. 1083-98.

Focardi, S, De Marinas, AM, Rizzoto, M & Pucci, A 2001, 'Comparative evaluation of thermal infrared imaging and spotlighting to survey wildlife', *Wildlife Society Bulletin*, vol. 29, no. 1, pp. 133-9.

Focardi, S, Franzetti, B & Ronchi, F 2013, 'Nocturnal distance sampling of a Mediterranean population of fallow deer is consistent with population projections', *Wildlife Research*, vol. 40, no. 6, pp. 437-46.

Focardi, S, Isotti, R, Pelliccioni, ER & Iannuzzo, D 2002a, 'The use of distance sampling and mark-resight to estimate the local density of wildlife populations', *Environmetrics*, vol. 13, no. 2, pp. 177-86.

Focardi, S, Isotti, R & Tinelli, A 2002b, 'Line transect estimates of ungulate populations in a Mediterranean forest', *The Journal of Wildlife Management*, vol. 66, no. 1, pp. 48-58.

Forsyth, DM 2005a, 'How can research contribute to the management of wild deer in Australia?', in SR McLeod (ed.), *Proceedings of the National Feral Deer Management Workshop, Canberra, 9-10 November,* Invasive Animals Cooperative Research Centre, Canberra, pp. 7-21.

Forsyth, DM 2005b, *Protocol for estimating changes in the relative abundance of deer in New Zealand forests using the Faecal Pellet Index (FPI)*, New Zealand Department of Conservation, Wellington, viewed 13 December 2013, <http://www.doc.govt.nz/documents/conservation/threats-and-impacts/animal-pests/fpi-protocol.pdf>.

Forsyth, DM, Barker, RJ, Morriss, G & Scroggie, MP 2007, 'Modelling the relationship between fecal pellet indices and deer density', *The Journal of Wildlife Management*, vol. 71, no. 3, pp. 964-70.

Forsyth, DM, Gormley, AM, Woodford, L & Fitzgerald, T 2011, *Effects of the Black Saturday fires on Sambar Deer occupancy and abundance: Black Saturday Victoria 2009 – Natural values fire recovery program*, Department of Sustainability and Environment, Heidelberg, Victoria, viewed 25th October 2014, <http://www.depi.vic.gov.au/environment-and-wildlife/arthur-rylah-institute/research-themes/fire-ecology-and-recovery/natural-values-2009-fire-recovery-program-ari-reports>.

Foster, AH & Blight, GW 1984, 'Liveweight response of cattle grazing native pasture in south east Queensland when supplemented with urea/molasses in winter and spring', *Tropical Grasslands*, vol. 18, no. 3, pp. 131-7.

Frank, U, Goll, B, Hohmann, U, & Heurich, M 2012, 'Aerial ungulate surveys with a combination of infrared and high-resolution natural colour images', *Animal Biodiversity and Conservation*, vol. 35, no. 2, pp.285-93.

Garel, M, Bonenfant, C, Hamann, J-L, Klein, F & Gaillard, J-M 2010, 'Are abundance indices derived from spotlight counts reliable to monitor red deer *Cervus elaphus* populations?', *Wildlife Biology*, vol. 16, no. 1, pp. 77-84.

Georgii, B 1980, 'Home range patterns of female red deer (*Cervus elaphus L.*) in the Alps', *Oecologia*, vol. 47, no. 2, pp. 278-85.

Georgii, B & Schroder, W 1983, 'Home range and activity patterns of male red deer (*Cervus elaphus L.*) in the alps', *Oecologia*, vol. 58, no. 2, pp. 238-48.

Getz, WM, Fortmann-Roe, S, Cross, PC, Lyons, AJ, Ryan, SJ & Wilmers, CC 2007, 'LoCoH: nonparameteric kernel methods for constructing home ranges and utilization distributions', *PLoS ONE*, vol. 2, no. 2, viewed 2 July 2013, <http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0000207#pone-0000207>.

Getz, WM & Wilmers, CC 2004, 'A local nearest-neighbor convex-hull construction of home ranges and utilization distributions', *Ecography*, vol. 27, no. 4, pp. 489-505.

Gill, RMA, Thomas, ML & Stocker, D 1997, 'The use of portable thermal imaging for estimating deer population density in forest habitats', *Journal of Applied Ecology*, vol. 34, no. 5, pp. 1273-86.

Girard, I, Dussault, C, Ouellet, J-P, Courtois, R & Caron, A 2006, 'Balancing number of locations with number of individuals in telemetry studies', *The Journal of Wildlife Management*, vol. 70, no. 5, pp. 1249-56.

Girard, I, Ouellet, J-P, Courtois, R, Dussault, C & Breton, L 2002, 'Effects of sampling effort based on GPS telemetry on home-range size estimations', *The Journal of Wildlife Management*, vol. 66, no. 4, pp. 1290-300.

Gregory, SK 2005, 'Comparison of density estimators for white-tailed deer using aerial thermal infrared videography', Masters thesis, University of Arkansas, Monticello.

Hall, GP & Gill, KP 2007, *Management of wild deer in Australia with particular reference to fallow deer and red deer*, Tasmanian Department of Primary Industries and Water, Longford, Tasmania.

Hone, J 2008, 'On bias, precision and accuracy in wildlife aerial surveys', *Wildlife Research*, vol. 35, no. 4, pp. 253-7.

Horne, JS, Garton, EO, Krone, SM & Lewis, JS 2007, 'Analyzing animal movements using Brownian bridges', *Ecology*, vol. 88, no. 9, pp. 2354-63.

Hunter, J, Brooking, C, Brimblecombe, W, Dwyer, R, Campbell, H, Watts, M & Franklin, C 2013, 'OzTrack: e-Infrastructure to support the management, analysis and sharing of animal tracking data', *9th IEEE International Conference on eScience, Beijing, China, 22-25 October*, pp. 140-7, viewed 11 August 2014, <http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6683901&tag=1>.

Jacobson, HA, Kroll, JC, Browning, RW, Koerth, BH & Conway, MH 1997, 'Infrared-triggered cameras for censusing white-tailed deer', *Wildlife Society Bulletin*, vol. 25, no. 2, pp. 547-56.

Jathanna, D, Karanth, KU & Johnsingh, AJT 2003, 'Estimation of large herbivore densities in the tropical forests of southern India using distance sampling', *Journal of Zoology*, vol. 261, no. 3, pp. 285-90.

Jenkins, KJ & Manly, BFJ 2008, 'A double-observer method for reducing bias in faecal pellet surveys of forest ungulates', *Journal of Applied Ecology*, vol. 45, no. 5, pp. 1339-48.

Jeppesen, JL 1987a, 'Impact of human disturbance on home range, movements and activity of red deer (*Cervus elaphus*) in a Danish environment', *Danish Review of Game Biology*, vol. 13, no. 2, pp. 1-38.

Jeppesen, JL 1987b, 'Seasonal variation in group size, and sex and age compostion in a Danish red deer (*Cervus elaphus*) population under heavy hunting pressure', *Danish Review of Game Biology*, vol. 13, no. 1, pp. 4-19.

Jerina, K 2009, 'How the estimates of home range size and composition are affected by diurnal, nocturnal and 24-hour sampling methods: example of the red deer (*Cervus elaphus*) in Slovenia', *Zbornik Gozdarstva in Lesarstva*, vol. 89, pp. 3-15.

Jerina, K 2012, 'Roads and supplemental feeding affect home-range size of Slovenian red deer more than natural factors', *Journal of Mammalogy*, vol. 93, no. 4, pp. 1139-48.

Jesser, P 2005, *Deer in Queensland: pest status review series - land protection*, Queensland Department of Natural Resources and Mines, Brisbane.

Kamler, JF, Jedrzejewski, W & Jedrzejewska, B 2008, 'Home ranges of red deer in a European old-growth forest', *American Midland Naturalist*, vol. 159, no. 1, pp. 75-82.

Kantar, LE & Cumberland, RE 2013, 'Using a double-count aerial survey to estimate moose abundance in Maine', *Alces*, vol. 49, pp. 29-37.

Kie, JG, Matthiopoulos, J, Fieberg, J, Powell, RA, Cagnacci, F, Mitchell, MS, Gaillard, J-M & Moorcroft, PR 2010, 'The home-range concept: are traditional estimators still relevant with modern telemetry technology?', *Philosophical Transactions of the Royal Society B-Biological Sciences*, vol. 365, no. 1550, pp. 2221-31.

Koerth, BH, McKown, CD & Kroll, JC 1997, 'Infrared-triggered camera versus helicopter counts of white-tailed deer', *Wildlife Society Bulletin*, vol. 25, no. 2, pp. 557-62.

Kuijper, DPJ, Cromsigt, JPGM, Churski, M, Adam, B, Jedrzejewska, B, & Jedrzejewski, W 2009, 'Do ungulates preferentially feed in forest gaps in European temperate forest?', *Forest Ecology and Management*, vol. 258, no. 7, pp. 1528-35.

Laake, JL, Dawson, MJ & Hone, J 2008, 'Visibility bias in aerial survey: mark-recapture, line-transect or both?', *Wildlife Research*, vol. 35, no. 4, pp. 299-309.

Lang, LM, & Wood, GW 1976, 'Manipulation of the Pennsylvania Deer Herd', *Wildlife Society Bulletin*, vol. 4, no. 4, pp159-66.

Larrucea, ES, Brussard, PF, Jaeger, MM & Barrett, RH 2007, 'Cameras, coyotes, and the assumption of equal detectability', *The Journal of Wildlife Management*, vol. 71, no. 5, pp. 1682-9.

Laver, PN & Kelly, MJ 2008, 'A critical review of home range studies', *The Journal of Wildlife Management*, vol. 72, no. 1, pp. 290-8.

Lewis, JS, Rachlow, JL, Garton, EO & Vierling, LA 2007, 'Effects of habitat on GPS collar performance: using data screening to reduce location error', *Journal of Applied Ecology*, vol. 44, no. 3, pp. 663-71.

Long, JA & Nelson, TA 2012, 'Time geography and wildlife home range delineation', *The Journal of Wildlife Management*, vol. 76, no. 2, pp. 407-13.

Lovari, S, Cuccus, P, Murgia, A, Murgia, C, Soi, F & Plantamura, G 2007, 'Space use, habitat selection and browsing effects of red deer in Sardinia', *Italian Journal of Zoology*, vol. 74, no. 2, pp. 179-89.

Lyra-Jorge, MC, Ciocheti, G, Pivello, VR, & Meirelles, ST 2008, 'Comparing methods for sampling large- and medium-sized mammals: camera traps and track plots', *European Journal of Wildlife Research*, vol. 54, no. 4, pp. 739-44.

Mandujano, S & Gallina, S 1995, 'Comparison of deer censusing methods in tropical dry forest', *Wildlife Society Bulletin*, vol. 23, no. 2, pp. 180-6.

Mandujano, S, Yanez-Arenas, CA, Gonzalez-Zamora, A & Perez-Arteaga, A 2013, 'Habitat-population density relationship for the white-tailed deer *Odocoileus virginianus* during the dry season in a Pacific Mexican tropical dry forest', *Mammalia*, vol. 77, no. 4, pp. 381-9.

Manly, BFJ, McDonald, LL, Thomas, DL, McDonald, TL & Erickson, WP 2002, *Resource selection by animals: statistical design and analysis for field studies*, 2nd edn, Kluwer Academic, Dordrecht.

Marker, LL, Fabiano, E & Nghikembua, M 2008, 'The use of remote camera traps to estimate density of free-ranging cheetahs in North-Central Namibia', *Cat News*, vol. 49, pp. 22-4.

Marques, FFC, Buckland, ST, Goffin, D, Dixon, CE, Borchers, DL, Mayle, BA & Peace, AJ 2001, 'Estimating deer abundance from line transect survyes of dung: sika deer in southern Scotland', *Journal of Applied Ecology*, vol. 38, no. 2, pp. 349-63.

McClean, SA, Rumble, MA, King, RM & Baker, WL 1998, 'Evaluation of resource selection methods with different definitions of availability', *The Journal of Wildlife Management*, vol. 62, no. 2, pp. 793-801.

McCoy, JC, Ditchkoff, SS & Steury, TD 2011, 'Bias associated with baited camera site for assessing population characteristics of deer', *The Journal of Wildlife Management*, vol. 75, no. 2, pp. 472-7.

McLeod, SR (ed.) 2009, *Proceedings of the National Feral Deer Management Workshop, Canberra, 9-10 November 2005*, Invasive Animals Cooperative Research Centre, Canberra.

Millspaugh, JJ, Skalski, JR, Townsend, RL, Diefenbach, DR, Boyce, MS, Hansen, LP, & Kammermeyer, K 2009, 'An evaluation of sex-age-kill (SAK) model performance', *Journal of Wildlife Management*, vol. 73, no. 3, pp. 442-51.

Mitchell, B, McCowan, D & Nicholson, IA 1976, 'Annual cycles of body weight and condition in Scottish Red deer, *Cervus elaphus*', *Journal of Zoology*, vol. 180, no. 1, pp. 107-27.

Mitchell, B, Staines, BW & Welch, D 1977, *Ecology of red deer: a research review relevant to their management in Scotland*, Institute of Terrestrial Ecology, Cambridge.

Mohr, CO 1947, 'Table of equivalent populations of North American small mammals', *American Midland Naturalist*, vol. 37, no. 1, pp. 223-49.

Moriarty, A 2004, 'The liberation, distribution, abundance and management of wild deer in Australia', *Wildlife Research*, vol. 31, no. 3, pp. 291-9.

Morse, BW & Miller, KV 2009, 'Population characteristics of an insular fallow deer (*Dama dama L.*) population on Little St. Simons Island, Georgia, USA', *Wildlife Biology in Practice*, vol. 5, no. 1, pp. 1-10.

Morse, BW, Nibbelink, NP, Osborn, DA & Miller, KV 2009, 'Home range and habitat selection of an insular fallow deer (*Dama dama L.*) population on Little St. Simons Island, Georgia, USA', *European Journal of Wildlife Research*, vol. 55, no. 4, pp. 325-32.

Naugle, DE, Jenks, JA & Kernohan, BJ 1996, 'Use of thermal infrared sensing to estimate density of white-tailed deer', *Wildlife Society Bulletin*, vol. 24, no. 1, pp. 37-43.

Pepin, D, Adrados, C, Janeau, G, Joachim, J & Mann, C 2008, 'Individual variation in migratory and exploratory movements and habitat use by adult red deer (*Cervus elaphus L.*) in a mountainous temperate forest', *Ecological Research*, vol. 23, no. 6, pp. 1005-13.

Pople, AR, Clancy, TF, Thompson, JA & Boyd-Law, S 1998, 'Aerial survey methodology and the cost of control for feral goats in Western Queensland', *Wildlife Research*, vol. 25, no. 4, pp. 393-407.

Potvin, F & Breton, L 2005, 'Testing 2 aerial survey techniques on deer in fenced enclosures: visual double-counts and thermal infrared sensing', *Wildlife Society Bulletin*, vol. 33, no. 1, pp. 317-25.

Potvin, F, Breton, L & Rivest, L-P 2004, 'Aerial surveys for white-tailed deer with the double-count technique in quebec: two 5-year plans completed', *Wildlife Society Bulletin*, vol. 32, no. 4, pp. 1099-107.

Putman, R, Langbein, J, Green, P & Watson, P 2011, 'Identifying threshold densities for wild deer in the UK above which negative impacts may occur', *Mammal Review*, vol. 41, no. 3, pp. 175-96.

Roberts, CW, Pierce, BL, Braden, AW, Lopez, RR, Silvy, NJ, Frank, PA & Ransom, D 2006, 'Comparison of camera and road survey estimates for white-tailed deer', *The Journal of Wildlife Management*, vol. 70, no. 1, pp. 263-7.

Rodgers, AR & Kie, JG 2011, *HRT: Home Range Tools for ArcGIS - user's manual*, Centre for Northern Forest Ecosystem Research, Ontario Ministry of Natural Resources, <http://flash.lakeheadu.ca/~arodgers/hre/HRT%20Users%20Manual%20Draft%20August%2010%202011.pdf>.

Roff, C 1960, 'Deer in Queensland', *Queensland Journal of Agricultural Science*, vol. 17, no. 1, pp. 43-58.

Rolley, RE & Warde, WD 1985, 'Bobcat habitat use in southeastern Oklahoma', *The Journal of Wildlife Management*, vol. 49, no. 4, pp. 913-20.

Rowcliffe, JM, Field, J, Turvey, ST & Carbone, C 2008, 'Estimating animal density using camera traps without the need for individual recognition', *Journal of Applied Ecology*, vol. 45, no. 4, pp. 1228-36.

Seaman, DE, Millspaugh, JJ, Kernohan, BJ, Brundige, GC, Raedeke, KJ & Gitzen, RA 1999, 'Effects of sample size on kernel home range estimates', *The Journal of Wildlife Management*, vol. 63, no. 2, pp. 739-47.

Searle, AK 1981, 'Red deer in Queensland', *Queensland Agricultural Journal*, vol. 107, no. 1, pp. 17-20.

Sinclair, ARE, Fryxell, JM & Caughley, G 2006, *Wildlife ecology, conservation, and management*, 2nd edn, Blackwell Science, Oxford.

Skalski, JR, & Millspaugh, JJ 2002, 'Generic variance expressions, precision, and sampling optimization for the sex-age-kill model of population reconstruction', *The Journal of Wildlife Management*, vol. 66, no. 4, pp. 1308-16.

Smart, JCR, Ward, AI & White, PCL 2004, 'Monitoring woodland deer populations in the UK: an imprecise science', *Mammal Review*, vol. 34, no. 1, pp. 99-114.

Specht, RL 1970, 'Vegetation', in GW Leeper (ed.), *The Australian environment*, 4th edn, CSIRO/Melbourne University Press, Melbourne, pp. 44-67.

Speight, JG 2009, 'Landform', in National Comittee on Soil and Terrain (ed.), *Australian soil and land survey: field handbook*, 3rd edn, CSIRO, Collingwood, Vic.

Steiniger, S & Hunter, AJS 2012, 'OpenJUMP HoRAE - A free GIS and toolbox for home-range analysis', *Wildlife Society Bulletin*, vol. 36, no. 3, pp. 600-8.

Sullivan, BJ, Baxter, GS, Lisle, AT, Pahl, L & Norris, WM 2004, 'Low-density koala (*Phascolarctos cinereus*) populations in the mulgalands of south-west Queensland. IV. Abundance and conservation status', *Wildlife Research*, vol. 31, no. 1, pp. 19-29.

Thomas, DL & Taylor, EJ 1990, 'Study designs and tests for comparing resource use and availability', *The Journal of Wildlife Management*, vol. 54, no. 2, pp. 322-30.

Thomas, DL & Taylor, EJ 2006, 'Study designs and tests for comparing resource use and availability II', *The Journal of Wildlife Management*, vol. 70, no. 2, pp. 324-36.

Thomas, L, Buckland, ST, Rexstad, EA, Laake, JL, Strindberg, S, Hedley, SL, Bishop, JRB, Marques, TA & Burnham, KP 2010, 'Distance software: design and analysis of distance sampling surveys for estimating population size', *Journal of Applied Ecology*, vol. 47, no. 1, pp. 5-14.

Thomas, L, Laake, JL, Rexstad, E, Strindberg, S, Marques, FFC, Buckland, ST, Borchers, DL, Anderson, DR, Burnham, KP, Burt, ML, Hedley, SL, Pollard, JH, Bishop, JRB & Marques, TA 2009, *Distance 6.0. Release 2*, Research Unit for Wildlife Population Assessment, University of St Andrews, UK, <http://distancesampling.org/>.

Toowoomba Regional Council 2009, *Toowoomba's dams - Cressbrook Dam*, viewed 26 March 2010, <http://www.toowoombarc.qld.gov.au/environment-and-waste/water-supply-and-dams/dams-a-bores/toowoomba-bulk-water/5311-cressbrook-dam.html>.

Vine, SJ, Crowther, MS, Lapidge, SJ, Dickman, CR, Mooney, N, Piggott, MP & English, AW 2009, 'Comparison of methods to detect rare and cryptic species: a case study using the red fox (*Vulpes vulpes*)', *Wildlife Research*, vol. 36, no. 5, pp. 436-46.

Weckel, M, Rockwell, RF, & Secret, F 2011, 'A modification of Jacobson et al.'s (1997) individual branch-antlered male method for censusing white-tailed deer', *Wildlife Society Bulletin*, vol. 35, no. 4, pp. 445-51.

Weckerly, FW, & Ricca, MA 2000, 'Using presence of sign to measure habitats used by Roosevelt elk', *Wildlife Society Bulletin*, vol. 28, no. 1, pp. 146-53.

Winarni, NL, Carroll, JP & O'Brien, TG 2004, 'The application of camera traps to the study of Galliformes in southern Sumatra, Indonesia', in RA Fuller & SJ Browne (eds), *Proceedings of the 3rd International Galliformes Symposium, Dehra Dun and Corbett National Park, India, 5-10 April*, World Pheasant Association, Fordingbridge, Hampshire, pp. 109-21.

Worton, BJ 1995, 'Using Monte Carlo simulation to evaluate kernel-based home range estimators', *The Journal of Wildlife Management*, vol. 59, no. 4, pp. 794-800.

Zweifel-Schielly, B, Leuenberger, Y, Kreuzer, M & Suter, W 2012, 'A herbivore's food landscape: seasonal dynamics and nutritional implications of diet selection by a red deer population in contrasting Alpine habitats', *Journal of Zoology*, vol. 286, no. 1, pp. 68-80.