Final Report

Project code: B.AHE.0303

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Date published: June 2017

ISBN: [Request through Publications Database]

PUBLISHED BY
Meat & Livestock Australia Limited
Locked Bag 991
NORTH SYDNEY NSW 2059

Protecting vulnerable land from high wallaby densities

Stage 2

Meat & Livestock Australia acknowledges the matching funds provided by the Australian Government to support the research and development detailed in this publication.

1 Abstract

Conflict between Top End livestock producers and high densities of Agile Wallabies (*Macropus agilis*) on pastoral land has been ongoing for decades. In recent years, wallaby numbers and densities on pastoral lands have increased dramatically. In some agricultural situations wallaby densities are 1,000 times greater than the natural density (<0.5 animals/ha). A conservative estimate based on 2004 figures of the cost of wallaby control and lost income due to wallabies competing with livestock for graze in the Top End was \$1.95 million. By 2013 this figure had more than doubled and was closer to \$5 million in the Top End. Here we present the final report on the outcomes from stage 2 of a project funded by Meat and Livestock Australia, aimed to develop a case for the establishment of a Northern Territory Agile Wallaby management plan. The evidence gathered here supports the perceived high abundance of Agile Wallabies on pastoral land. From 2013 to 2015, the density of wallabies varied from 56 ind/km^2 (95% CI 42 - 77) to 289 ind/km^2 (95% CI 126 - 670), depending on the region. During 2016, wallaby densities were 205 ind/km^2 (95% CI 170 - 247) in the Douglas Daly region. At high densities, agile wallabies can consume 226,366.4 kg/km^2/yr (95% CI 132,224.7 – 320,508.0) of pasture, equivalent to 55.5 Adult Equivalent (AE)/km^2/yr (95% CI 24.9 – 96.8) loss in carrying capacity. Through pasture biomass loss modelling, we estimated 1 AE to be 26.8 Wallabies (95% CI 0.03-27), supporting the previously reported 24.5 Wallabies per AE. Assuming the current minimum price per kilogram of live weight for medium cows (\$2.29 per kg) and heavy steers (\$3.66 per kg), this loss in carrying capacity can represent \$122,007.7 per km^2/yr (95% CI 28,830.7 – 320,185.8). Estimates of losses derived from questionnaires completed by landholders in 2014, suggested that losses were variable and complex, ranging from \$6.7 to \$857 per km^2/yr, resulting in a reduction of livestock carrying capacity between 6.5% and 13% per year. Of concern is that livestock producers considerably underestimate the losses to production caused by wallabies. In 2015 we found that high wallaby densities affected native grass community structure by increasing the species patchiness of native pastures (low Shannon's Evenness Index). Sampling done that same year also showed that the long-term (more than 1 year) effects of high agile wallaby density on native grass communities were increased grass species richness and diversity. These effects were not detectable in the short term (< 3 months). Sampling carried out in 2016 contrasted with 2015 preliminary results, with high wallabies' densities only having an effect on biomass but not on pasture composition or structure. During stage 1 of this project we identified the alternative management options for controlling wallaby numbers on pastures as culling (shooting), wallaby-proof fencing and baiting; the first two being the most common methods currently used by landholders. Radio-tracking of collared individuals showed significantly larger home ranges than previously reported for the species. Average home ranges during the dry season for females and males was 31.8 ha (±8.5 ha) and 30.2 ha (±9.6 ha), respectively. There was no difference in home range size between the sexes. Home range size differed depending on the habitat occupied by the wallabies. Animals inhabiting mostly the ecotone between bush and pasture had an average home range of 43.2 ha (± 8.7 ha) (Females: 44.0 ha ± 8.7 ha; Males 42.4 ha ± 8.7 ha), while animals inhabiting ecotones between bush and human settlements, incorporating irrigated lawns and gardens, had a smaller average home range of 18.8 ha (±9.4 ha) (Females: 19.6.0 ha ± 8.2 ha; Males 18.0 ha ± 10.6 ha). Using our initial estimates of wallaby densities, stratified by land use and vegetation, we tested different management scenarios using the Spatial Population Abundance Dynamics Engine (SPADE). However, due to the current development stage of SPADE we were unable to carry out this testing successfully. However, some of our data suggest that if nothing is done to manage the species, wallaby populations on pastoral land could increase to 30 times the current estimate (maximum carrying capacity in Pastoral land 3,855 ind/km^2). We estimated that rangeland production is currently experiencing an average loss of \$12,820.0 per km^2/yr (95% CI 6,699.1 – 19,429.7). While properties using improved pastures and/or irrigation can suffer losses from

$48,921.9 per km^2/yr (95% CI 25,190.0 – 75,216.1). These estimates could increase as the wallaby population grows, reaching levels of $148,514.3 per km^2/yr (95% CI 77,981.8 – 224,008.6) on rangeland production stations; and $232,780.0 per km^2/yr (95% CI 121,001.7 – 354,620.4) on stations with improved pastures and irrigation. Comparing our estimates of economic losses, the cost of the current alternatives for control, and the potential increase in revenue after management; it appears that wallaby management by culling only, is feasible for properties with wallaby populations higher than 1,854.0 Ind/km^2 (95% CI 846.7-3,755.6). However, properties with improved pastures –i.e. higher carrying capacities- a combination of wallaby proof fencing, followed by shooting can be economically feasible (with return of investment in as little as 5 years) with initial wallaby populations as low as 40.5 Ind/km^2 (95% CI 24.6-62.6). It follows that for properties that are or are planning to intensify their production, and currently do not experience high wallaby populations, wallaby proof fencing prior to intensification seems to be the best option. Currently, no clear regional strategy for removal of wallabies is cost effective at a Northern Territory scale, and logistics relating to personnel and the vast area requiring management are the most limiting factors a management plan will face. Therefore, we recommend that wallaby management be conducted at regional/station level. Unable to develop a Territory wide management plan for the agile wallaby, we present a decision three that can help inform property level management and target investment in control methods.

2 Executive Summary

Agile Wallabies (*Macropus agilis*) are considered a pest species by pastoralists in northern Australia, particularly in the Top End. In recent decades, wallaby numbers and densities on pastoral lands have increased dramatically. Properties with improved pastures are most severely affected by wallabies. By 2013, the impact of wallabies on farm production was perceived by farmers to have almost doubled since 2004. A conservative 2013 estimate, based on 2004 figures of the cost of wallaby control and lost income due to wallabies for the whole of the Top End, was $1.95 million.

In 2009, Katherine Pastoral Industry Advisory Committee (KPIAC) reported a dramatic increase in wallaby numbers since the late 1990's, and requested that the NT government survey populations and allow large culls around farmland. The NT government suggested that the pastoral industry should gather further evidence of numbers, trends and impacts, to justify the research and development of a wallaby management plan.

In May 2012 a first meeting between pastoralists and Charles Darwin University (CDU) researchers discussed the possibility of developing a research program to devise an Agile Wallaby management plan for the Top End. A partnership between Meat and Livestock Australia (MLA) and Charles Darwin University commenced in 2013, with a proposed three stages project (over 5 years), with the final objective of developing and applying a stakeholder supported Agile Wallaby management plan.

In 2015 the report for stage 1 of this partnership was delivered, covering the following general aims: (1) develop a case for where research and development investment should be targeted; and (2) establish potential partnerships among and with key stakeholders with a vested interest in supporting the development and implementation of a wallaby management plan.

This report covers the results of stage 2, with the following aims: (1) To develop a density–damage function to guide cost-effective management options on pastoral lands; (2) to determine the collateral effects of managing wallabies; (3) to explore if controlling wallaby densities in non-grazed areas would benefit livestock producers and land managers; (4) to identify general concepts and recommendations for implementation of a wallaby management plan that are demonstrated to improve the feed base for cattle on pastoral properties; and (5) to provide insights and recommendations on the feasibility of indigenous wallaby harvest, and the possibility of adding value by culling and marketing meat, skin and bone products. The specifics aims and objectives of stage 2 were:

- To develop a density–damage function, based on population modelling (Spatial Population Abundance Dynamics Engine- i.e. SPADE) to guide cost-effective management options on pastoral lands.
- To explore the potential shifts in grass species caused by grazing pressure, in native woodland and pastoral properties.
- To determine if management of wallabies on pastoral land has the potential to create artificial wallaby sinks, negating the effectiveness of wallaby management.
- Draft outlines of at least two journal manuscripts.
- Convene stakeholder meetings to describe focus, funders and service providers for implementation/validation of northern Australia Stage 3 wallaby management plan.
- Document in-principle support (cash and in-kind) from stakeholders to implement a Stage 3 project.
- Develop a draft wallaby management plan and have it evaluated by the Steering Committee.

The evidence gathered during stage 2 of this project confirms some of the results obtained during stage 1: During stage 1, the estimated density of wallabies was 57 ind/km^2 (95% CI 42, 77) to 289 ind/km^2 (95% CI 126 - 670), depending on the region, while during stage 2, wallaby densities were estimated at 153 ind/km^2 (95% CI 112, 210) in the Douglas Daly region. At high densities, agile wallabies were estimated to consume between 244,240 kg/km^2/yr (Stage 1 estimate) and 226,366.4 kg/km^2/yr (Stage 2 estimate) of pasture, equivalent to a 55.5 Adult Equivalent (AE) per km^2/yr (95% CI 24.9 – 96.8) loss in carrying capacity. Assuming the current minimum price per kilogram of live weight for medium cows ($2.47 per kg) and heavy steers ($3.43 per kg), this loss in carrying capacity represents $122,007.7 per km^2/yr (95% CI 28,830.7 – 320,185.8). Estimates of losses derived from questionnaires completed by landholders during stage 1 suggested that losses were variable and had complex causes, ranging from $6.7 to $857 per km^2/yr, resulting in a reduction of livestock carrying capacity between 6.5% and 13% per year. Livestock producers appear to considerably underestimate the financial cost to production caused by wallabies.

During stage 1, we found that high wallaby densities affected native grass community structure by increasing the species patchiness of native pastures. Moreover, long-term (> 1 year) effects of high agile wallaby density on native grass communities were increased pasture species richness and species diversity. These effects were not detectable in the short term (< 3 months). Sampling carried out in a wider context, with greater replication during stage 2 contrasted with these findings. High densities of wallabies only affected grass biomass, but had no effect on pasture composition or structure even after a year. By fitting a linear model or pasture biomass loss against wallaby density, 1 AE was estimated to be 26.8 Wallabies (95% CI 0.03-27), supporting the previously reported 24.5 Wallabies per AE.

Radio-tracking of collared individuals in the Douglas-Daly district found significantly larger home ranges, up to double the size, than the only previous records reported for the species. Our estimates of average home ranges during the dry season for females and males was 31.8 ha (±8.5 ha) and 30.2 ha (±9.6 ha) respectively. We did not find a difference in home range between the sexes, but differences were habitat-dependent. Animals inhabiting the ecotone between bush and pasture had an average home range of 43.2 ha (± 8.7 ha) (Females: 44.0 ha ± 8.7 ha; Males 42.4 ha ± 8.7 ha), while animals inhabiting ecotones between bush and human settlements, incorporating irrigated lawns and gardens, had a smaller average home range of 18.8 ha (±9.4 ha) (Females: 19.6.0 ha ± 8.2 ha; Males 18.0 ha ± 10.6 ha).

Using our estimates of wallaby densities, stratified by land use and vegetation, we attempted to test different management scenarios using the Spatial Population Abundance Dynamics Engine (SPADE). The current management alternatives are limited to culling (shooting), wallaby-proof fencing and baiting; the first two being the most common methods currently used by landholders. Therefore, we based our testing on culling by shooting as the management approach, and the different scenarios were constructed according to different levels of shooting intensity. Unfortunately, due to the current development stage of SPADE we were unable to carry out this testing successfully i.e. glitches in the software output showed inconsistencies with the data collected. However, some of our data suggest that if nothing is done to manage the species, wallaby populations on pastoral land could be 30 times the current estimate 10 years from now.

Our spatially explicit estimates of wallaby density, carrying capacity and loss to production allowed a more in depth assessment of the economic losses suffered by farmers due to wallabies. In rangeland production stations (i.e. not using improved pastures or irrigation) current losses were $12,820.0 per km^2/yr (95% CI 6,699.1 – 19,429.7). On the other hand, properties that are currently using improved pastures and/or irrigation, experienced average losses of $48,921.9 per km^2/yr (95% CI 25,190.0 – 75,216.1). If nothing is done, these figures could increase, as the wallaby population grows, reaching levels of \$148,514.3 per km^2/yr (95% CI 77,981.8 – 224,008.6) on rangeland production properties; and \$232,780.0 per km^2/yr (95% CI 121,001.7 – 354,620.4) on properties with improved pastures and irrigation.

On the other hand, the cost of management by shooting (\$137.50 to \$163.63 per hour with an efficiency varying between 18 and 37% and a maximum of 60 animals shot per hour) increases exponentially as wallaby abundance is reduced. Comparing our estimates of economic losses, the cost of the current alternatives for control, and the potential increase in revenue after management; it appears that wallaby management by culling only, is feasible for properties with wallaby populations higher than 1,854.0 Ind/km^2 (95% CI 846.7-3,755.6). However, properties with improved pastures and/or irrigation –i.e. average Top End property 497 km^2 with an average paddock size of 29 km^2 - the estimated cost of wallaby proof fencing is \$987.9 per km^2 in materials and \$81.9 per km^2/yr in labour and maintenance. In these cases, a combination of wallaby proof fencing, followed by intense shooting (removal of all wallabies within the first year) can be economically feasible, experiencing a return in investment in as little as 5 years. This is the case even with initial wallaby populations as low as 40.5 Ind/km^2 (95% CI 24.6-62.6).

This suggests that the best approach for producers is a combination of fencing followed by shooting. This is especially true for producers that are not currently using improved pastures but are planning to do so, who would benefit from creating smaller paddocks with wallaby-proof fencing, and controlling the local populations of wallabies by culling immediately after, all this to be done prior to improving the feed base. A scenario that seems likely for most farmers under the current Developing the North Initiative.

The implementation of an Agile Wallaby management plan in the Northern Territory will be complex and difficult. Currently, no clear strategy for removal of wallabies is cost-effective at a Northern Territory scale, and logistics relating to personnel and the vast area requiring management are the most limiting hurdles a management plan will face. Moreover, the feasibility of obtaining subsidies through revenue from wallaby harvesting seems promising, but is still to be determined by DPI&F (See Hunt and Mullen 2015). Therefore, we consider that wallaby management must be approached at regional/property level. Unable to develop a Territory wide management plan for the agile wallaby, we present a decision three that can help inform property level management and target investment in control methods.

3 Contents

4 Background

Conflict between Top End producers and high densities of Agile Wallabies (*Macropus agilis*) on pastoral land has been ongoing for decades. In the 1960s Agile Wallabies were declared agricultural pests and research into their biology and potential control actions began (Bill Bolton *pers. comm.*, CSIRO). A formal/official management plan for the Agile Wallaby was not developed, and wallabies were given protected status shortly afterward in 1971. However, the Agile Wallaby is still considered a pest species by pastoralists in northern Australia, particularly in the Top End.

In recent decades, the density and number of wallabies on pastoral lands have increased dramatically. In the tropical savanna of the Top End, wallaby densities are typically low (<0.5 animals per km^2) (Fisher et al. 2004). However, recent research shows that in some agricultural situations wallaby densities are 1000 times greater (>500 animals per km^2) than the natural density. Properties with improved pastures have the highest densities of wallabies, and are most severely affected by the increase in wallabies. Pastoralists claim that such high wallaby densities cause environmental degradation, significantly increase production costs (e.g. labour, fencing), and ultimately affect farm viability. Of further concern is that wallaby impacts can appear suddenly. In a 2010 Department of Primary Industries and Fisheries Pastoral survey, two pastoral stations reported a sudden increase in wallaby numbers over a 12 month period, although they previously thought numbers were low (Hausler 2004; Cowley et al. 2010). One of these properties has already invested in wallaby-proof fencing for a high value crop (Cowley et al. 2010).

The 2010 survey of pastoral stations in the Katherine and Top End regions, showed an increase in high impact effects of wallabies on productivity in those regions since 2004 (Tables 1 and 2 below)(Hausler 2004; Oxley 2004; Cowley et al. 2010). Across both regions, 42% of stations surveyed (n = 71) in 2010 considered wallaby impacts to be high, up from 23% in 2004. With 117 properties that meet the criteria for a cattle enterprise in the Katherine and Top End regions, this equates to potentially 49 businesses or nearly half of all properties adversely affected by wallabies. A conservative estimate based on 2004 figures of the cost of wallaby control and lost income due to wallabies for the Top End was $1.95 million (Cowley et al. 2010). By 2013, the impacts of wallabies on farm production were perceived by farmers to have doubled since 2004.

Table 1. The percent proportion of Katherine producers surveyed and the level of perceived impact of wallabies on their station (N/A = respondents either had no wallabies or did not regard the animals as a pest).

Year	*High Impact*	*Medium Impact*	*Low Impact*	*N/A*	*No. surveyed*
2004	16	19	53	11	62
2010	33	24	43	0	51

Table 2. The percent proportion of Top End producers surveyed and the level of perceived impact of wallabies on their station (N/A = respondents either had no wallabies or did not regard the animals as a pest).

Year	*High Impact*	*Medium Impact*	*Low Impact*	*N/A*	*No. surveyed*
2004	42	25	25	8	24
2010	65	10	25	0	20

In light of these perceived impacts and costs to productivity, the Territory Natural Resource Management identified the need for management options to control Agile Wallabies in their Integrated NRM Plan in 2010 (see Management Action 42, TNRM (2010-2015)).

Around the same time (2009), the Katherine Pastoral Industry Advisory Committee (KPIAC) reported a dramatic increase in wallaby numbers since the late 1990's, and requested that the Northern Territory government survey populations and allow large culls on and around farmland. Although the NT government recognized the need to manage the burgeoning populations, more permits were issued to cull wallabies than were apparently culled, suggesting either that culling was under-reported or that the wallaby problem was exaggerated. Thus, the NT government suggested that the pastoral industry gather further evidence of numbers, trends and impacts, to justify the research and development of a wallaby management plan.

In December 2011, the Northern Territory Cattleman's Association (NTCA) raised concerns about the increase in Agile Wallaby numbers, the cost to pastoralists, and the lack of management options. In response, Peter Clifton (then the NT Regional Landcare Facilitator for the NTCA) began developing a research project to gather the evidence of wallaby impacts required by the NT government. In May 2012, the first meeting between pastoralists and Charles Darwin University (CDU) researchers discussed the possibility of developing a research program to devise an Agile Wallaby management plan for the Top End. A partnership between Meat and Livestock Australia (MLA) and CDU commenced in 2013, with a proposed three-stage project (over 5 years), with the final objective of developing and applying a stakeholder supported Agile Wallaby management plan.

Stage 1 of the project was conceptualised as a scoping and feasibility study aimed to: (1) establish where research and development investment should be targeted; and (2) establish potential partnerships among and with key stakeholders interested in supporting the development and implementation of a wallaby management plan. The key aim of Stage 1 was to determine the impacts of high density Agile Wallaby populations on pastoral land in the Top End, Katherine, Sturt Plateau and Victoria River District regions, in collaboration with pastoralists, Landcare and other associations.

Surveys conducted during Stage 1 confirmed the high abundance of Agile Wallabies on pastoral land, with estimates ranging from 57 ind/km^2 (95% CI 42, 77) and 289 ind/km^2 (95% CI 126 - 670). This is substantially higher than estimates from "natural" areas (e.g. 17-62 ind/km^2 in Kakadu NP). During Stage 1, landholders were also surveyed to estimate the costs to production of Agile Wallabies. Analysis of landholder responses estimated the costs to production to be between \$6.7 and \$857 per km^2/yr. Additionally, direct grazing pressure experiments indicated that wallabies may consume up to 177,736 kgDM/km^2/yr.

The results from Stage 1 clearly indicated substantial effects of agile wallabies on pastoral lands and production, indicating the need for potential management options. To this end, in April 2015 the projects steering committee and the Katherine Pastoral Industry advisory committee endorsed the RD&E plan to be covered by Stage 2. Critical questions to be answered included: (1) does the density of wallabies on pastures reduce the cattle carrying capacity below economic viability thresholds?; (2) does collateral damage to the environment, caused by unnaturally high wallaby densities, affect the potential to optimise the use of native pastures in the future?; and (3) does the increase in wallaby abundance prevent intensification of land use by increasing costs of intensified production (e.g. the cost of wallaby-proofing fencing)?

The main aim of Stage 2 was to produce a more detailed evidence based RD&E (Research, Development & Engineering) report, supported by relevant stakeholders, to describe the focus, funding contributors and service providers in northern Australia for completion of Stage 3 of the project.

5 Project Objectives

After negotiations with Meat & Livestock Australia, and consideration of potential sources of funding to carry out the RD&E plan, Stage 2 was conceived with the following aims:

1. To develop a density–damage function to guide cost-effective management options of agile wallabies on pastoral lands; based on population modelling (Spatial Population Abundance Dynamics Engine- i.e. SPADE)
2. To determine the collateral effects of managing wallabies. This included potential shifts in grass species composition, as well as the effects on wallaby dispersal dynamics.
3. To explore potential benefits to livestock producers and land managers if wallabies are to be controlled in non-grazed areas;
4. To identify general concepts and recommendations for the implementation of a wallaby management plan that can be demonstrated to improve the feed base of pastoral landholders;
5. To provide insights and recommendations on the feasibility of indigenous wallaby harvest, and the possibility of adding value by culling and marketing meat, skin and bone products of over-abundant wallabies;
6. Draft outlines of at least two manuscripts for publication in peer-reviewed journals;
7. Convene stakeholder meetings to describe focus, funders and service providers for implementation/validation of northern Australia Stage 3 wallaby management plan;
8. Document in-principle support (cash and in-kind) from stakeholders to implement a Stage 3 project.
9. Develop a draft wallaby management plan and send it for evaluation by the Steering Committee.

6 Methods

The methodology followed for this project comprised a series of ecological surveys, sampling, experiments and mathematical modelling that support the different objectives of the project. Here, the methods are described in a logical order with reference to the objectives.

6.1 Wallaby population assessment at the Douglas Daly research farm

A total of 5 properties were visited monthly from February 2014 to April 2015 (Bedoya-Pérez et al. 2015). After April 2015, visits were restricted to the Douglas Daly Research Farm every 3 months. During all visits, Agile Wallaby density and abundance was estimated along at least six 1-km transects. The line transect method is the most common method of estimating macropod and other herbivore densities (Burnham et al. 1980; Southwell 1994; Anderson and Southwell 1995; Southwell et al. 1997; Lundie-Jenkins et al. 1999; le Mar et al. 2001; Hacker et al. 2002; Woolnough 2005). For kangaroos, this method is commonly carried out by aircraft, and at large scales (Clancy et al. 1997; Pople et al. 1998a; Pople et al. 1998b; Clancy 1999; Cairns et al. 2008). However, Agile Wallabies preferentially inhabit the grassland/woodland ecotone (Ride and Fry 1970), making aerial observations difficult, due to reduced detectability. Therefore, we used vehicle line transects. Our survey transects followed fence lines or unsealed roads, and thus were not always straight-line transects. This approach to line transects is common in rugged or inaccessible terrain (Defler and Pintor 1985; Whitesides et al. 1988).

During each survey, an observer in a vehicle drove slowly (5 km/h), along a previously marked transect. Once an individual wallaby was detected, the vehicle stopped and the following measurements were recorded:

- Transect direction (i.e. orientation): taken with a compass.
- Bearing to the individual/s: the bearing to the detected individual from the vehicle. Taken with a compass.
- Distance to individuals: the distance between the vehicle and the individual. Taken with Nikon ProStaff 3 6x21 Laser Rangefinder.
- Distance along transect: the distance along the transect of the sighting. Taken using a Garmin Colorado 400t GPS handheld, in-built odometer.
- Demographics of the individual: Age group (i.e. adult, juvenile, joey on foot), gender, presence of pouch young for females, and signs of mange - according to classification schemes of Stirrat (2008) and McLelland and Youl (2005).
- Habitat: Qualitative observation of the habitat type where the individual was detected.

Once the data were collected, the observer continued to drive slowly (5 km/h) until the next individual was detected. In cases where several individuals were detected in a group, direction, sighting distance and distance along the transect were recorded to the middle of the group. A group was defined as individuals that were within 5 metres of each other.

<u>Statistical analyses:</u> Data from the populations survey were processed using the program Distance 7.0 (Thomas et al. 2010), and ggplot2 package (Wickham 2009), in R 3.3.1 (R Core Team 2015). The direction and distance was used to calculate perpendicular distance of individuals to transect, following the methodology described in Burnham et al. (1980). The program Distance 7.0 was used to select the best fitted model to describe wallaby abundance, based on the small sample corrected Akaike Information Criterion (AICc) (Quinn and Keough 2009). Habitat, weather and month, were added to the initial model as covariates.

6.2 Wallaby population demographics

Wallaby demographics and ecology was based both on the literature review carried out in Stage 1 (Bedoya-Pérez et al. 2015), and direct sampling of wallaby carcases.

6.2.1 Literature review:

All literature relevant to Agile Wallaby ecology and management was collated using three methods:

a) A literature review of all research papers relevant to Agile Wallaby ecology and management recorded in the Charles Darwin University Library, Google Scholar and Web of Science published up to July 2016 (inclusive). Some of the keywords used in our search included, but were not limited to: Agile Wallaby; *Macropus agilis*; macropod; macropod management; herbivore management; macropod diseases; macropod predation; herbivore population modelling.
b) Through government and other institutional websites, we searched for relevant reports and legislation. Some of the websites visited included, but were not limited to: Atlas of Living Australia; Northern Territory Department of Primary Industries and Fisheries; Northern Territory Department of Land Resource Management; Parks and Wildlife Commission NT; City of Darwin; Territory Natural Resource Management; Department of Primary Industries, Parks, Water and Environment Tasmania; Queensland Department of Agriculture, Fisheries and Forestry; Department of Agriculture and Food Western Australia; New South Wales Department of Primary Industries; NSW National Parks and Wildlife Service; Cooperative Research Centres Association (CRCs); Australian Government, Department of the Environment.
c) Unpublished reports and manuscripts obtained through experts and stakeholders.

We collected a total of 191 relevant manuscripts, reports and books. From these, only 34 directly mentioned Agile Wallabies (5 books, 1 PhD Thesis, 2 Government Reports and 26 peer-review articles; see Appendix 1).

6.2.2 Carcases survey:

Wallaby carcases were collected opportunistically from shooters under the Douglas Daly Research Farm damage mitigation permit. A total of 89 animals were collected, 34 in October 2014 and 55 between September and October 2015 (Appendix 2 shows the measurements and characteristics taken from each individual).

For animals obtained in 2015, the heads were collected for aging through molar eruption (Sharman et al. 1964; Dudzinski et al. 1977) and molar progression (Kirkpatrick 1965; Dudzinski et al. 1977; Newsome et al. 1977; Knowlton 1984). Both methods of aging are commonly used in a wide range of macropod species (Jackson 2007) (For a complete description of the aging procedure see Appendix 3). By following the methodology described by Kirkpatrick and Johnson (1969), the age in days of the pouch young was estimated using the tail length and the pes length.

Additionally, we obtained morphometric data on 2043 individuals culled by ABS Scrofa Pty Ltd, from 2007 to 2013. Due to prior privacy arrangements, the location where these individuals were culled cannot be discussed in this report. However, they were all obtained under relevant regulation permits approval, and following humane procedures (Department of the Environment 2008).

<u>Statistical analyses:</u> Morphometric and age data were used to characterise the population. We

compared the effects of the independent variables: Location (Douglas Daly Research Farm or Disclosed location), Age group (Juvenile, Sub Adult or Adult), Season of collection (Wet season or Dry season) and Year of collection (2007 to 2015) on the response variable: Sex ratio. Due to the binomial nature of the response variable (Female or Male) the multinomial family was used for model fitting (Quinn and Keough 2009; Zuur et al. 2009). For animals collected only at the Douglas Daly Research Farm, Pouch young sex ratio was first tested using Chi-sq test. Then we compared the effects of the independent variables: Mothers age (by Molar Eruption and by Molar progression), mothers age group (by weight), mothers weight, mother's pes length, mother's health score (pes length / weight) and month of birth, on pouch young sex in separate models. Again we used the multinomial family for model fitting (Quinn and Keough 2009; Zuur et al. 2009). Analyses used packages MASS 7.3–16 (Venables and Ripley 2013), coda (Plummer et al. 2006), deSolve (Soetaert et al. 2010), devtools (Wickham and Chang 2015), entropy (Hausser and Strimmer 2014), numDeriv (Gilbert and Varadhan 2012), optimx (Nash and Varadhan 2011), phenology (Girondot and Girondot 2016), shiny (Chang et al. 2016), Hmisc (Harrell Jr 2013), embryogrowth (Girondot 2016), MultinomialCI (Villacorta 2012) and ggplot2 (Wickham 2009), in R 3.3.1 (R Core Team 2015).

6.3 Estimation of wallaby grazing effects on pasture

Pastures in the northern tropics of Australia show a narrow window of growth during the wet season, and limited growth during the dry season. During Stage 1 of this project we sampled 6 sets of 6 m x 6 m wallaby and cattle proof enclosures in late February 2015. Two of these sets were already present at the Douglas Daly Research Farm, though their original purpose and date of construction are unknown. Four new sets of enclosures were built in December 2014 in other grazing paddocks at the Douglas Daly Research Farm (Bedoya-Pérez et al. 2015). During Stage 2, we sampled all at the peak of the dry season –i.e. July 2016, under the advice of land manager who argued that the impact of wallabies on pasture was markedly higher at this time of year. Initially 14 additional enclosures were built; however, eleven of these were destroyed by wet season flooding during 2015. Moreover, 1 of the enclosures sampled during stage 1 was no longer available due to changes in the use of the paddock where it was located (Figure 1).

Each set of enclosures consisted of a wallaby-proof fenced plot (6 m x 6 m). The fence was built of commercial pig-proof mesh fencing, commonly used by pastoralists to wallaby-proof paddocks and other infrastructure; and a cattle-proof fence of the same size, built with barbed-wire and fence pickets, preventing grazing by cattle but allowing free passage of wallabies (Figure 2).

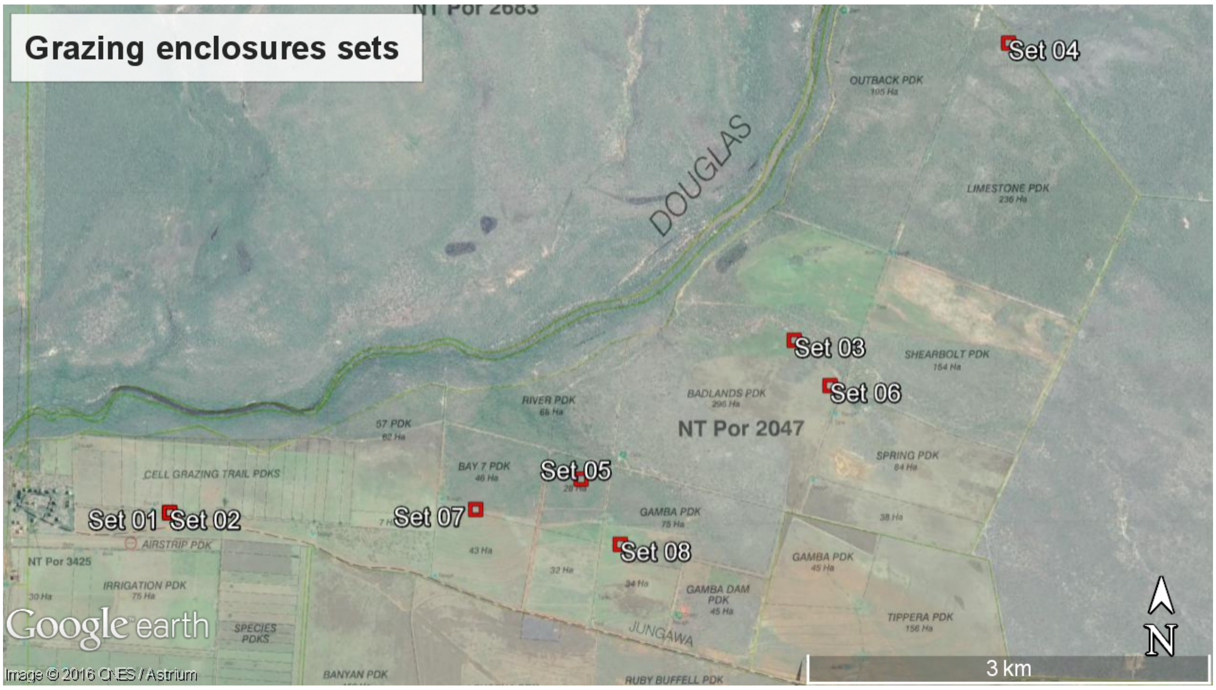

Figure 1. Grazing enclosures sets located at the Douglas Daly Research Farm. Sets 01 to 05 were use during Stage 1 and 2 of the project. Sets 06 to 08 were built in December 2015. All sets were sampled in 2016 as part of stage 2 only.

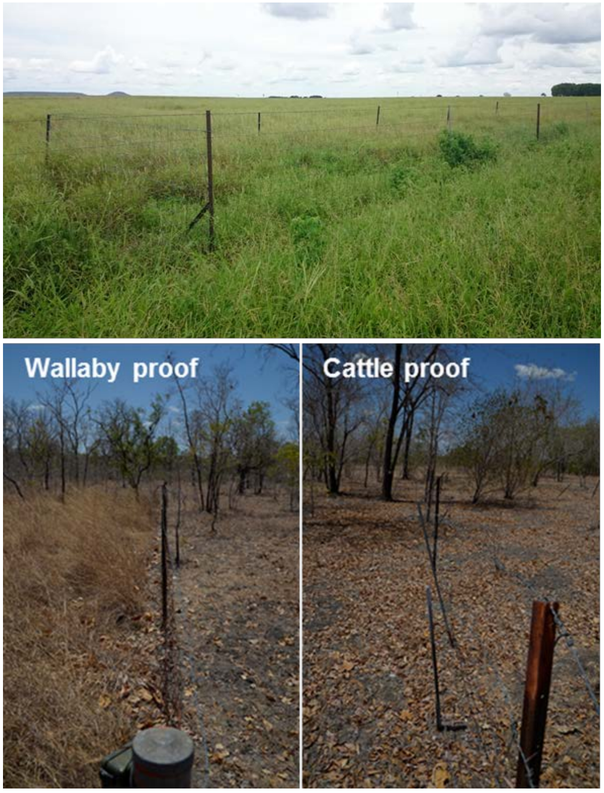

Figure 2. Examples of wallaby proof (pig proof mesh) and cattle proof (barbed wire) enclosures. Top panel shows a recently constructed enclosure. Lower panels show photos of pre-existing enclosures at the Douglas Daly Research Farm, during the dry season, showing pasture cover differences between

the inside (left) and the outside (right), of wallaby proof (pig-proof mesh) and cattle proof (barb wire) enclosures.

Each enclosure was sampled using five 50 cm x 50 cm quadrats placed inside each enclosure (i.e. Wallaby-proof and cattle-proof) with another 5 quadrats placed outside the enclosures. The vegetation present in each quadrat was identified to morpho-species (and to species whenever possible), and the biomass was sampled by removing all vegetative material in the quadrat to 1cm above the ground. The collected vegetation was separated by morpho-species and placed in labelled paper bags. Two pink flags were placed at the diagonal corners of each quadrat to identify each quadrat for future sampling. Samples were transported to Charles Darwin University and were placed in a drying oven at 80˚C for 72 hours. Once dry, samples were weighed to the nearest ±0.01g. Simpson (*D*) and Shannon (*H*) diversity indexes, and their measures of Evenness (*E* and *J*) were calculated for each quadrat (Begon et al. 2006).

<u>Statistical analyses</u>: We compared the effects of the independent variables: Set (1 to 8), Age (Pre-existing, 2014 enclosures or 2015 enclosures), sampling (2015 or 2016) and Enclosure (Wallaby Proof, Cattle Proof and outside the enclosures) on Biomass, Species Richness, Diversity (S and H) and Evenness (E and J) in separate models. Shapiro-Wilkinson Test of normality and residual plots were used to choose the distribution used in the model fitting (Quinn and Keough 2009; Zuur et al. 2009). Appropriate distributions for Biomass, Simpson's Diversity Index and Simpson's Evenness Index could not be determined, and the data were Log_{10}- transformed. The Richness model was tested under a quasi-poisson distribution, while the transformed data were tested under a normal distribution (Zuur et al. 2009). Calculated biomass loss versus wallaby densities by line transect (Section 6.1) were paired and fitted to a series of functions (linear, logarithmic, power and exponential). Analyses used packages MASS 7.3–16 (Venables and Ripley 2013), ggplot2 (Wickham 2009), and the *lm* and *nls* functions in R 3.3.1 (R Core Team 2015).

6.4 Wallaby capture, collaring and radio tracking

From March to May 2016, a total of 40 agile wallabies were caught and fitted with a VHF collar (V5C 163E 130-260mm VHF Std Collar Sirtrack Ltd), at the Douglas Daly research Farm. Across two areas of the farm we established 17 capture locations, each of which were separated by at least 2.5 km. This gave us 8 capture locations around the farm homestead and 9 in grazing paddocks (Figure 3). We used drop nets similar to those described by Lentle et al. (1997). However, the method used was significantly modified by wildlife management practitioners ABS Scrofa Pty Ltd. For a complete description of the capture and processing of the wallabies, see Appendix 4.

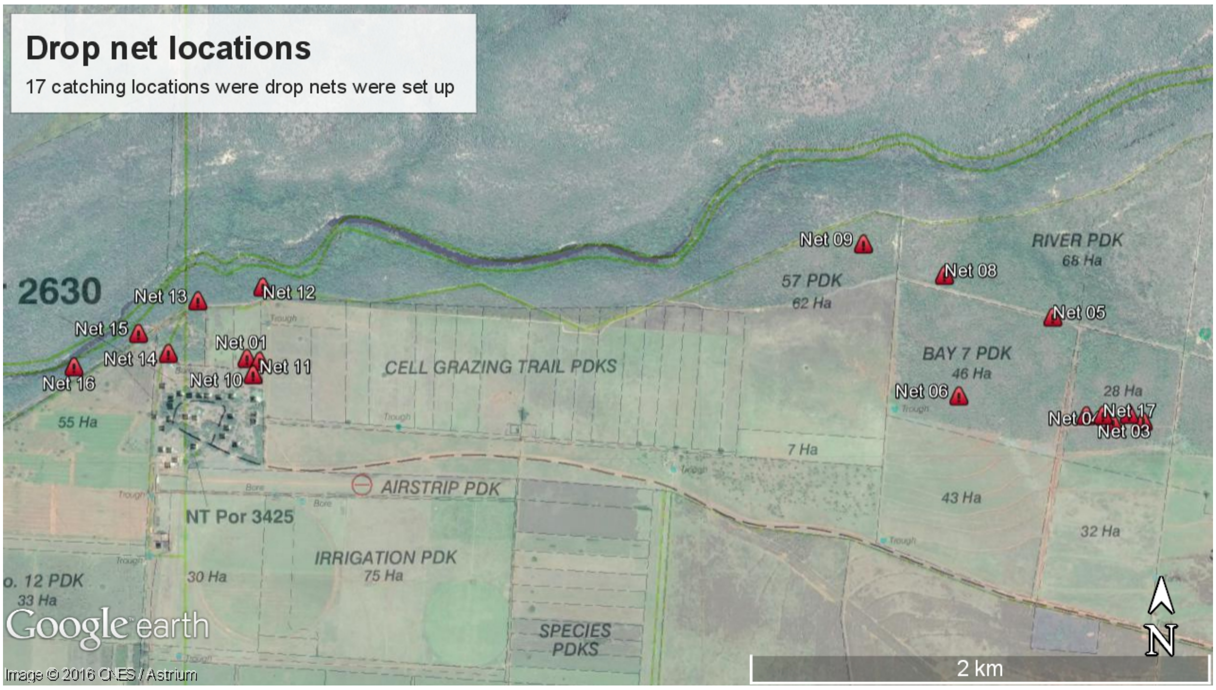

Figure 3. Seventeen drop net locations at the Douglas Daly Research Farm in two different areas. (1) Around the homestead on the west part of the farm, and (2) on grazing paddocks on the east side of the farm. Both areas within 2 km of the Douglas Daly River that fringes the north of the farm.

Tracking of the collared wallabies occurred from June to August 2016, distributed in four, 10-day long tracking trips, with each tracking session occurring at morning (6:00 – 8:00), midday (10:00 – 13:00), afternoon (17:00 – 19:00) and midnight (23:00 – 01:00). This allowed for up to 32 positional fixes per animal. Positional fixes where achieved by triangulation, based on a minimum of 3 receivers at previously located fixed triangulation towers (See appendix 5 for details on triangulation towers construction, location and use).

The bearings obtained at each tracking tower for each collared individual were then analysed using the 'sigloc' package (Berg 2015), in R 3.3.1 (R Core Team 2015). The location points obtained for each individual at each tracking session were then uploaded into ArcGIS 10.2.1 Desktop (ESRI 2013), and the home range for each animal was calculated as the minimum complex polygon (MCP). The number of fixes in each habitat and at different times of the day were also fitted in binomial models using the package MASS 7.3–16 (Venables and Ripley 2013) and ggplot2 (Wickham 2009), in R 3.3.1 (R Core Team 2015).

6.5 Estimation of the current extent, abundance and carrying capacity of the agile wallaby population in the Northern Territory

The current distribution of Agile Wallabies in the Northern Territory was estimated during Stage 1 of the project (Bedoya-Pérez et al. 2015), using occurrence records obtained from the Atlas of Living Australia (NCRIS 2016). We combined this information with reported habitat preferences (Bolton et al. 1982; Press 1988; Dressen 1993; Stirrat 1995; Stirrat 2000; Van Dyck and Strahan 2008); reported wallaby abundance in the native habitat (Dressen 1993; Stirrat 1995; Stirrat 2000); carrying capacity estimates by land system, derived from the Department of Primary Industries and Fisheries Livestock estimates; as well as our own estimates of wallaby abundance on farmland, to map a spatially and density specific distribution of the wallaby population. For this purpose we used the National Vegetation Identification System: Major Vegetation Groups (NVIS)(DEE 2012), hydrological information regarding distance to water sources (Williams 2011a; Williams 2011b); 2009-2008 Annual Rainfall (mm) (BRS 2009); the 2010-2011 Northern Territory Pastoral Leases (DLPE 2015); and Land use of Australia (ACLUMP 2014).

Potentially inaccurate records for agile wallabies, obtained from the Atlas of Living Australia (NCRIS 2016), were eliminated. These included, but were not limited to: records with unknown coordinates systems, occurrences in biologically irrelevant habitats (e.g. records in water bodies) and occurrences significantly out of the previously reported distribution for the species (e.g. records in Tasmania and Alice Springs). These records were then loaded into the Biodiversity and Climate Change Virtual Laboratory (BCCVL) (NeCTAR 2016). Six different species distribution models based on climatic data were run – i.e. Bioclim, Flexible Discriminant Analysis, Generalized Linear Model, Generalized Additive Model, Multivariate Adaptive Regression Splines and Surface Range Envelope. Relative Operating Characteristic (ROC) plots and values were used to choose the best distribution model fitting the data. Once the best species distribution model for agile wallabies was chosen, the spatially explicit output was used to construct distribution borders (minimum complex polygon) for the species within the Northern Territory (ESRI 2013) .

To estimate the carrying capacity of agile wallabies within the constructed distribution map, the pixels (1,000 m x 1,000 m) were categorized according to land use and cadastre maps (ACLUMP 2014; DLPE 2015) – i.e. Agricultural land, Urban and Native habitat. Pixels in each category were then treated as follows:

Agricultural land pixels: carrying capacity in these pixels was estimated separately for areas with improved pastures and areas with native pastures.

Wallaby carrying capacity in areas with improved pastures was estimated based on calculations of carrying capacity for cattle (Adult Equivalent) based on annual rainfall (BRS 2009; Cameron et al. 2014)(Table 3). One Adult Equivalent was equivalent to 24.5 individual agile wallabies based on the species average body mass and the previously reported calibrations for other macropods (Statham and Statham 2013).

Table 3. Carrying Capacity on Improved pastures according to Arthur Cameron, The Department of Primary Industry and Fisheries.

Region	*Rainfall (mm)*	*Max. agile wallaby Carrying Capacity (Ind/km^2)*
Top End	>1,300	3,062.5
Douglas Daly	1,200 - 1,300	2,450
Katherine	1,000 - 1,200	1,960
Lower rainfall	600 -1,000	1,617

Wallaby carrying capacity on native pastures was estimated from the carrying capacity for cattle (Adult Equivalent) according to land type, derived from the Department of Primary Industries and Fisheries Livestock estimates. As for improved pastures, one Adult Equivalent was equivalent to 24.5 individual agile wallabies based on the species average body mass and the previously reported estimates for other macropods (Statham and Statham 2013).

These calculations were then compiled and adjusted to produce two versions of carrying capacity mapping based on current and projected extent of improved pastures, estimated based on projections from the 2010 Pastoral Industry Survey (Cowley et al. 2010), and the projected increase in water allocations for agriculture, proposed in the White paper on Developing Northern Australia (Abbott et al. 2015) .

According to the 2010 Pastoral Industry Survey (Cowley et al. 2010), 43% of properties in the

Northern Territory currently use improved pastures (95% in the Top End and 51% in Katherine), although this comprises only 1.5% of the total area of the properties (4.8% in the Top End and 3% in Katherine). 80% of properties in the Top End and 29% of properties in Katherine are considering increasing their investment in improved pastures, and 9% of properties in Katherine are considering introducing improved pastures to their properties. Also, the white paper on Developing Northern Australia (Abbott et al. 2015), includes a proposed increase in irrigated agriculture of a maximum of 130,000 ha between the Darwin Region (from 3,000ha to 30,000 ha) and the Victoria River basin (to a max 100,000 ha). The area covered by pastoral lease in the Top End is 34,464 km^2 (40 properties), and Katherine, which includes the Victoria River District, is 234,227 km^2 (108 properties).

To make the appropriate adjustments to estimates of wallaby carrying capacity, the following assumptions were made: (i) the increases in irrigated agriculture, funded by the Developing Northern Australia initiative, will be reflected directly in an increase in the area under improved pastures; (ii) the increase in area under improved pasture will occur inside properties that already have improved pastures - the 2010 Pastoral survey states that only 9% of properties want to invest in improved pastures for the first time, and most properties that want to invest in improved pastures are the ones that already have improved pastures; and (iii) the increase in carrying capacity is directly proportional to the increase in area under improved pastures.

A multiplier for the increase in agile wallaby carrying capacity was based on the projected increase in improved pastures. The multiplier was used to calculate a new carrying capacity value on improved pastures based on Table 3. Unfortunately, during the 2010 Pastoral survey, the Douglas Daly region and the Top End region were merged, thus the same multiplier was used for both regions (Table 4).

Table 4. Estimation of potential increase in carrying capacity based on proposed investment in irrigated agriculture by the Developing the North Initiative

Region	*Pastoral Lease Area (km^2)*	*Properties*	*% Imp Past Properties*	*Imp Past % area per property*	*Area under imp past (km^2)*	*Exp. Increase (km^2)*	*Multiplier*	*New Carrying capacity (Ind/km^2)*
Top End	34,464	40	95	4.8	1,571.6	300	1.2	3,647.1
Douglas Daly	*	*	*	*	*	*	1.2	2,917.7
Katherine	234,227	108	51	3	3,583.7	1,000	1.3	2,506.9

*Stations in the Douglas Daly region were combined with the stations in the Top End, thus same multiplier was used.

Urban pixels: carrying capacity in urban pixels was assumed to be zero. These pixels included buildings, roads and housing developments.

Native habitat pixels: Wallaby carrying capacity in native habitat was estimated based on reported wallaby densities and habitat preferences (Bolton et al. 1982; Press 1988; Dressen 1993; Stirrat 1995; Stirrat 2000; Van Dyck and Strahan 2008). This information was used to classify vegetation data (DEE 2012) into four categories: (1) Ideal habitat – i.e. Mangroves, tropical eucalypt woodlands/grasslands and other forests and woodlands; (2) Preferred habitat – i.e. rainforest and vine thickets; (3) Good habitat – i.e. eucalypt low open forests, eucalypt open forests, eucalypt open woodlands, eucalypt woodlands, *Melaleuca* forests and woodlands and tussock grasslands; (4) Poor habitat – i.e. *Acacia* forests and woodlands, *Acacia* open woodlands, *Acacia* shrublands, *Casuarina* forests and woodlands, chenopod shrublands, samphire shrublands and forblands, cleared non-native vegetation, hummock grasslands, inland aquatic (freshwater, salt lakes, lagoons), mallee woodlands and shrublands, naturally bare (sand, rock, claypan, mudflat), other grasslands, herblands, sedgelands and rushlands, other shrublands and unclassified native vegetation.

Pixels in these four habitat categories were then classified according to their distance to either permanent or any water sources (Williams 2011a; Williams 2011b). A distance of 2 km from water sources was established as the threshold above which carrying capacity declined. To convert reported densities to carrying capacity, wallaby densities were adjusted using the reported mortality rates –10 to 20% per annum (Bolton et al. 1982; Stirrat 2008). We assumed that a population with a zero-mortality rate, should approach carrying capacity. Carrying capacity for each pixel was then defined as the mortality adjusted maximum reported density for the particular vegetation type, if the pixel was within 2 km of a water source; or the mortality adjusted minimum reported density for the particular vegetation type, if the pixel was further than 2 km from a water source (Table 5).

Table 5. Agile Wallaby Carrying Capacity estimated from habitat preferences and distance to water (km)

Habitat Classification	*Reported Densities (Ind/km²)*	*Distance to water (km)*	*Carrying Capacity (Ind/km²)*
Ideal habitat (Bolton et al. 1982; Stirrat 1995; Stirrat 2000; Van Dyck and Strahan 2008)	185	≤ 2	232.1
		> 2	167.5
Preferred habitat (Press 1988; Dressen 1993)	62	≤ 2	77.8
		> 2	56.1
Good habitat (Press 1988; Dressen 1993; Stirrat 1995; Stirrat 2000; Van Dyck and Strahan 2008)	17 to 27	≤ 2	33.9
		> 2	15.4
Poor habitat (Press 1988)	*	≤ 2	1.3
		> 2	0.9

*For these vegetation types there were no reported wallaby densities, thus a density of 1 Ind/km^2 was assumed.

By using two separate hydrology data sets – distance to permanent water sources and distance to any water sources (permanent and temporal) – two versions of agile wallaby carrying capacity in native habitat were estimated. These two versions were then combined with the two variants for carrying capacity in agricultural land – current and projected extent of improved pastures – obtaining four different spatial (maps) estimates of agile wallabies carrying capacity: (i) Current carrying capacity based on distance to any water sources; (ii) projected carrying capacity based on distance to any water sources; (iii); current carrying capacity based on distance to permanent water sources; and (iv) projected carrying capacity based on distance to permanent water sources.

To estimate the current densities of agile wallabies within the constructed distribution map, the carrying capacity estimates were used as base maps. Densities in native habitats were adjusted to reflect reported densities (Table 5), and in cases where only one estimate of density per habitat type was available, the higher mortality rate reported (Bolton et al. 1982; Stirrat 2008) was used to estimate lower densities.

Densities on agricultural land were estimated based on the reported mortality rates, and adjusted by fitting a Generalized Linear Model to the field survey estimates (See section 6.1) comparing the effects of the independent variables: land type, rainfall, distance to water, pasture (native vs improved) on wallaby density. The Shapiro-Wilkinson Test of normality and residual plots were used to choose the distribution used in the model fitting (Quinn and Keough 2009; Zuur et al. 2009), and a logarithmic ($\log_{10}$) transformation was applied to the data. Analyses used MASS 7.3–16 package (Venables and Ripley 2013), in R 3.3.1 (R Core Team 2015).

Similarly, to the carrying capacity mapping, the use of two different hydrological data sets allowed for the estimation of two versions of current agile wallaby density: (i) current density based on distance to any water sources; and (ii) current density based on distance to permanent water sources.

6.6 Logistics and costs associated with management actions

Considering the ultimate goal of reducing the impacts of agile wallabies on agricultural land, while ensuring the species' persistence in native habitat, a spatially explicit management mask was constructed based on cadastre and land use (ACLUMP 2014; DLPE 2015). The purpose of this mask was to limit the areas, within the agile wallaby distribution, where control can occur. It was assumed that control of agile wallabies by culling could only take placed on pastoral leases and other areas dedicated to agriculture, while culling in urban areas, nature reserves and national parks would not be feasible. This decision was based on the current management approach for large macropod species – red kangaroo, *Macropus rufus*; eastern grey kangaroo, *M. giganteus*; western grey kangaroo, *M. fuliginosus*; common wallaroo or euro, *M. robustus*; bennet's wallaby, *M. rufogriseus rufogriseus*; and Tasmanian pademelon, *Thylogale billardierii.(Morellet et al. 2007; OEHNSW 2011; DEWNR 2013; DPIPWE 2013a; QLD 2013; DPW 2014).* For these species, all culling occurs outside nature reserves and national parks, which are considered refugia for the species.

Estimates of shooting costs per hour were obtained from wildlife management practitioners (ABS Scrofa Pty Ltd). Cost per hour was based on two shooters, on a vehicle, with basic equipment (i.e. centre point 22 magnum rifle and spotlight). Shooting efficiency was derived from data collected previously by ABS Scrofa Pty Ltd, including wallaby density and success rate per hour. Calculated cost per animal removed versus wallaby density were fitted to a power function and an exponential function using the package ggplot2 (Wickham 2009) and the *nls* function in R 3.3.1 (R Core Team 2015).

The reported Adult Equivalent (AE) to 24.5 individual agile wallabies - based on the species average body mass and the previously reported equivalencies for other macropods (Statham and Statham 2013); estimates of AE to wallabies in sections 6.2 and 6.3; and the current minimum price per kilogram of live weight for medium cows ($2.29 per kg lwt) and heavy steers ($3.66 per kg lwt) of brahma (*Bos indicus*) and cross breeds (See Table 8 for AE scores), we estimated the wallaby costs to production.

These costs were then compared first to shooting efficiency alone, to estimate cut-off wallaby densities above which management by shooting is economically feasible. For this, it was assumed that management by shooting would occur in a short timeframe (within a year), thus not allowing for natural population growth of wallabies. Finally, the cost of fencing based on current prices of pig fencing materials and yearly maintenance. In the Top End, the average property is 497 km^2 with an average paddock size of 29 km^2, assuming each paddock shares at least two fence lines with a neighbouring paddock, the estimated cost of wallaby proof fencing is $987.9 per km^2 in materials and $81.9 per km^2/yr in labour and maintenance. This estimate was incorporated to the calculation of wallaby population cut-offs and new cut-offs calculated based on potential return in investment within 1, 5, 10, 15 and 25 years. Fencing was assumed to be 100% successful, thus shooting would only be required for removal of the initial population enclosed after fencing.

6.7 Spatial Population Abundance Dynamics Engine (SPADE): Model building

Based on the data gathered above (sections 6.1 to 6.6) we attempted to test nine different managements strategies with four variants each using the Spatial Population Abundance

Dynamics Engine (SPADE)(Beeton et al. 2015). The basic parameters used in model building are summarized in Table 6.

Table 6. Summary of model parameters and demographics used in SPADE

Model Parameters	
Duration	10 years
Model type	Continuous
Integration time steps per season	10
Maximum available budget	Unconstrained
Demographics	
r_{max}	0.34
Θ	1.3
Dispersal model	Korobenko et al. (2013)
Dispersal (*D*)	0.5
Management costs	
Removal method	Proportional
Removal equation	$y = a + be^{cx}$
Intercept for removal equation (*a*)	12.99
Coefficient for removal equation (*b*)	314.55
Exponential rate (*c*)	-0.01

y = cost per animal culled; x = animals per km²

The justification and reasoning for the use of these parameters is as follows:

- *Duration:* All management strategies were run for 10 years. However, SPADE allows for longer time periods. Due to the short generational time for the species, 10 years was considered sufficient to observe population changes and stabilization.
- *Model type:* Due to the non-seasonality of agile wallaby breeding, a continuous model was chosen.
- *Integration time steps per season:* This parameter relates to the number of culling events in a year. Because of the wet-dry seasonal climate in the Top End, access to all areas of the Northern Territory over a year is not realistic. Culling was modelled in the dry season only, when most areas are accessible. Thus, there are 10 time steps indicating 10 years, with one culling event per year.
- *Maximum available budget:* Due to the exploratory nature of our analyses, the maximum budget available was left unconstrained to obtain an estimate of the cost of the modelled management objectives.
- R_{max} is the maximum rate of population increase, and it is a species specific demographic parameter that is a function of survival probability and fertility. The value used here is a combination of the estimated R_{max} from allometric (body size) relationships explained in Caughley (1980), previously reported values by Stirrat (2008), and personal communications with wildlife management practitioners (ABS Scrofa Pty Ltd). R_{max} is a dimensionless parameter, but $100\times (1- e^{r_{max}})$ is equal to the seasonal percentage increase in the population (McMahon et al. 2010)
- *Theta (θ)* is the parameter that defines the relationship between r_{max} and the population size (*N)*, this value was assume to be higher than 1, to reflect a stronger effect of density closer to carrying capacity (Fowler 1981; Owen-Smith 2006). The specific value of 1.3 was chosen based on previously reported values for similar sized macropods (Wiggins et al. 2014).
- *Population dispersal model:* Since long distance dispersal of individual agile wallabies is unknown, and both our estimates and reported literature suggests little migration, we use a carrying capacity driven diffusion model (Korobenko et al. 2013)
- *Dispersal parameters (D):* Based on the small average home range reported and calculated for agile wallabies, in addition to previously reported dispersal parameters for similar sized macropods (Wiggins et al. 2014) we designated a dispersal parameter (*D*) of 0.5
- *Removal method:* SPADE allows for three types of removal methods: Proportional, Absolute and Capped Proportional (Beeton et al. 2015). For these scenarios,

Proportional removal was chosen, which removes a specified proportion of the population per cell. Thus, the removal equation is based on the predicted behaviour of this removal type.

- *Cost per hour:* As explained in section 6.6 estimates of shooting costs per hour were obtained from wildlife managers practitioners (ABS Scrofa Pty Ltd). Estimations were based on two shooters, on a vehicle, with basic equipment (i.e. centre point 22 magnum rifle and spotlight). Shooting efficiency was derived from data previously collected by ABS Scrofa Pty Ltd. including wallaby density and success rate per hour.
- *Intercept (m) and slope (b) for removal equation:* Calculated cost per animal removed versus wallaby density were fitted to a power function and an exponential function using the package ggplot2 (Wickham 2009) and the *nls* function in R 3.3.1 (R Core Team 2015).

For all management strategies, the target proportional population in the management region was set to 0.01, and the density (Ind/km^2) at which removal stops in a cell as 1. The nine management strategies were classified according to their intensity: (0) Do nothing; (1) Very low intensity; (2) Low Intensity; (3) Medium intensity; (4) Moderate Intensity; (5) High Intensity; (6) Very high intensity; (7) Extreme intensity; (8) Very extreme intensity. The parameters used for these managements scenarios are summarized in Table 7.

Table 7. Parameters for the eight management scenarios tested in SPADE

Scenario		*1st year removal*	*Removal rate after first year*
0	Do nothing	0	0
1	Very low intensity	20%	10%
2	Low intensity	30%	20%
3	Medium intensity	50%	30%
4	Moderate intensity	50%	50%
5	High intensity	60%	40%
6	Very high intensity	70%	50%
7	Extreme intensity	80%	60%
8	Very extreme intensity	90%	90%

Due to the different combinations of carrying capacity and initial conditions estimates, 4 different versions for each scenario were tested. In addition, to determine the potential benefits of managing agile wallabies on non-grazed areas, the models were also run without a management mask.

Unfortunately, due to programing issues, SPADE was not ready in time for this report – there were glitches in the software output and inconsistencies in the results. Notwithstanding these problems, the spatially explicit estimates of wallaby density, carrying capacity and loss to production (see sections 6.3, 6.5 and 6.6) were calculated, in combination with the average pasture requirements of brahma (*Bos indicus)* and cross breed cattle (McLean and Blakeley 2014; McLennan 2015) (Table 8), assuming the current minimum price per kilogram of live weight for medium cows ($2.29 per kg) and heavy steers ($3.66 per kg) (Thomas 2016). We estimated current and potential economic losses to cattle production due to wallaby grazing alone.

Table 8. Average Adult Equivalent (McLean and Blakeley 2014) and pasture biomass requirements per head per day (kg DM/head/day) based on average rangeland pasture quality in the Northern Territory of 6.5±1.5 MJ ME/kg DM (megajoules of metabolisable energy per kilogram of dry matter) (McLennan 2015).

	Brahma (*Bos indicus*)		Cross breeds	
	AE score	Pasture requirement (kg DM/head/day)	AE score	Pasture requirement (kg DM/head/day)
400kg Steer	1.38 (0.81-1.95)	15.4 (9.0-21.8)	1.42 (0.86-2.00)	15.9 (9.6-22.3)
200kg Steer	0.82 (0.46-1.20)	9.2 (5.1-13.4)	0.85 (0.49-1.23)	9.5 (5.5-13.7)
Dry Cow	0.91 (0.69-1.12)	10.2 (7.7-12.5)	0.96 (0.73-1.19)	10.7 (8.2-13.3)
Lactating Cow	1.52 (0.71-2.18)	17.0 (7.9-24.3)	1.59 (0.75-2.28)	17.8 (8.4-25.5)

As explained in section 6.5, one Adult Equivalent was equivalent to 24.5 individual agile wallabies based on the species average body mass and the previously reported calibrations for other macropods (Statham and Statham 2013).

7 Results

7.1 Wallaby population assessment at the Douglas Daly research farm

By the end of Stage 1 of this project, thirteen months of population monitoring had been completed. At that stage, the data gathered confirmed that wallaby numbers and densities on pastoral land were several times greater than the densities reported from native tropical savanna. Reported Agile Wallaby densities in native savanna in the NT vary from 8 ind/km^2 around Adelaide River (Croft 1987), to 17-62 ind/km^2 in Kakadu NP (Dressen 1993) and 27-185 ind/km^2 at Berry Springs (Stirrat 1995). Densities of semi-captive populations in highly modified environments (e.g. East Point Reserve) are between 300 and 2100 ind/km^2 (Stirrat 2000; Stirrat 2008). Stage 1 on-pasture estimates were 289 ind/km^2 (95% CI 126 - 670) for properties in the Douglas Daly with 72% of land under improved pastures and 13% under native pastures; 103.80 ind/km^2 (95% CI 69 - 156) for properties in the Victoria River District where all pastures were native; 56 ind/km^2 (95% CI 42 - 77) for properties at Mataranka with 95% native pastures and 5% improved pastures; and 8 ind/km^2 (95% CI 3 - 23) for unstocked and undeveloped areas on properties in the Victoria River District. The magnitude of the 95% confidence intervals for all density estimates indicates the considerable variation in Agile Wallaby densities across regions and properties (Figure 4).

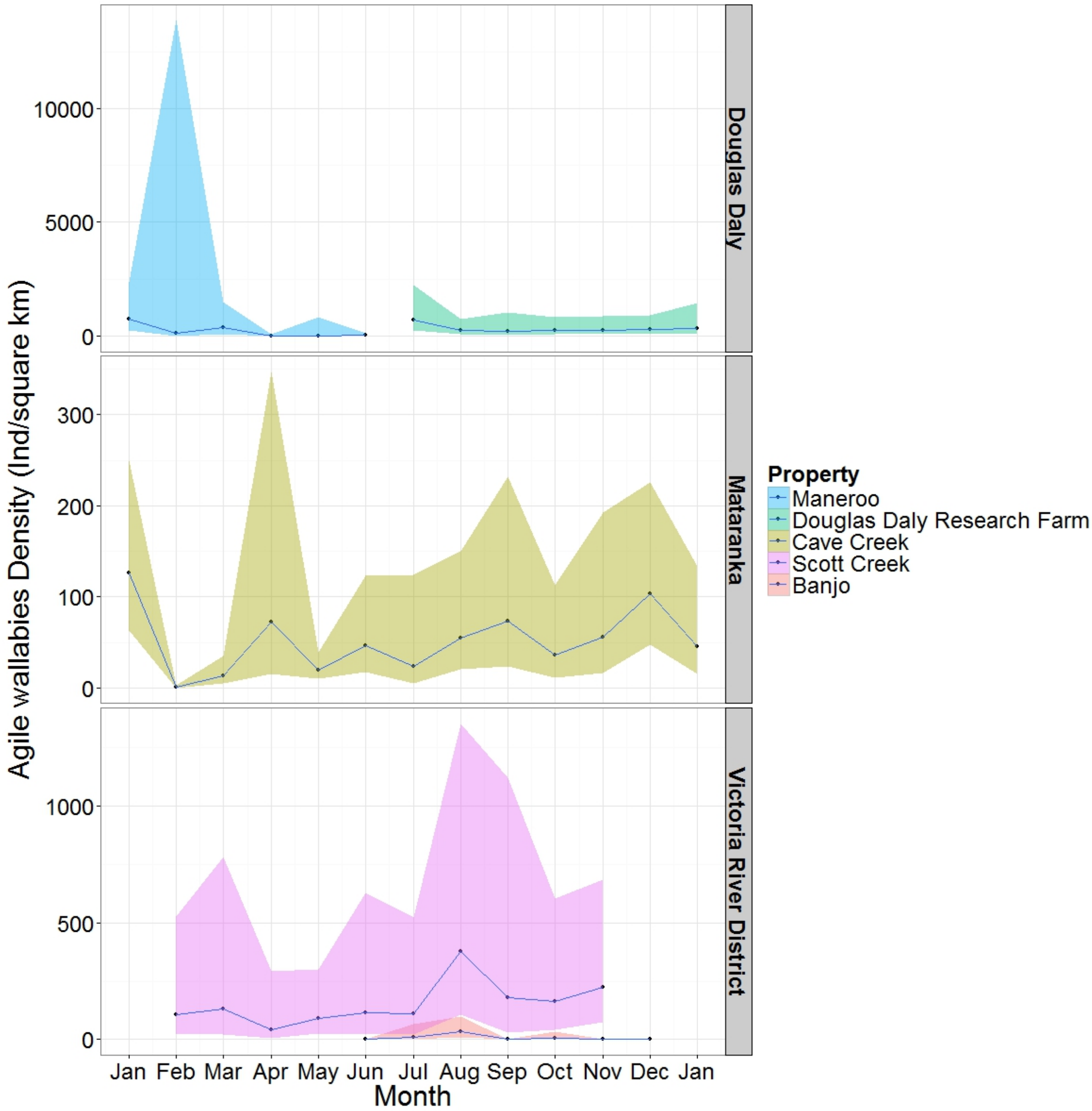

Figure 4. Agile Wallaby density in 2014, from 3 different regions (Douglas Daly, Mataranka and Victoria River District) and pastoral leases within each region (Maneroo, Douglas Daly Research Farm, Cave Creek, Scoot Creek and Banjo) of the Northern Territory. Colour shaded areas represent 95% confident intervals for each pastoral lease.

During Stage 2, we continued population monitoring focusing on the Douglas Daly Research farm. Our current estimate of the agile wallaby population at the farm is 205 ind/km^2 (95% CI 170 - 247) with habitat type being the only factor marginally affecting detectability in only one of the transects surveyed (p = 0.049, Transect 3). Similar, to the data from 2014, we found no evidence of change in wallaby abundance across seasons with the exception of a slight decline from the densities estimated for 2014 (Figure 5)

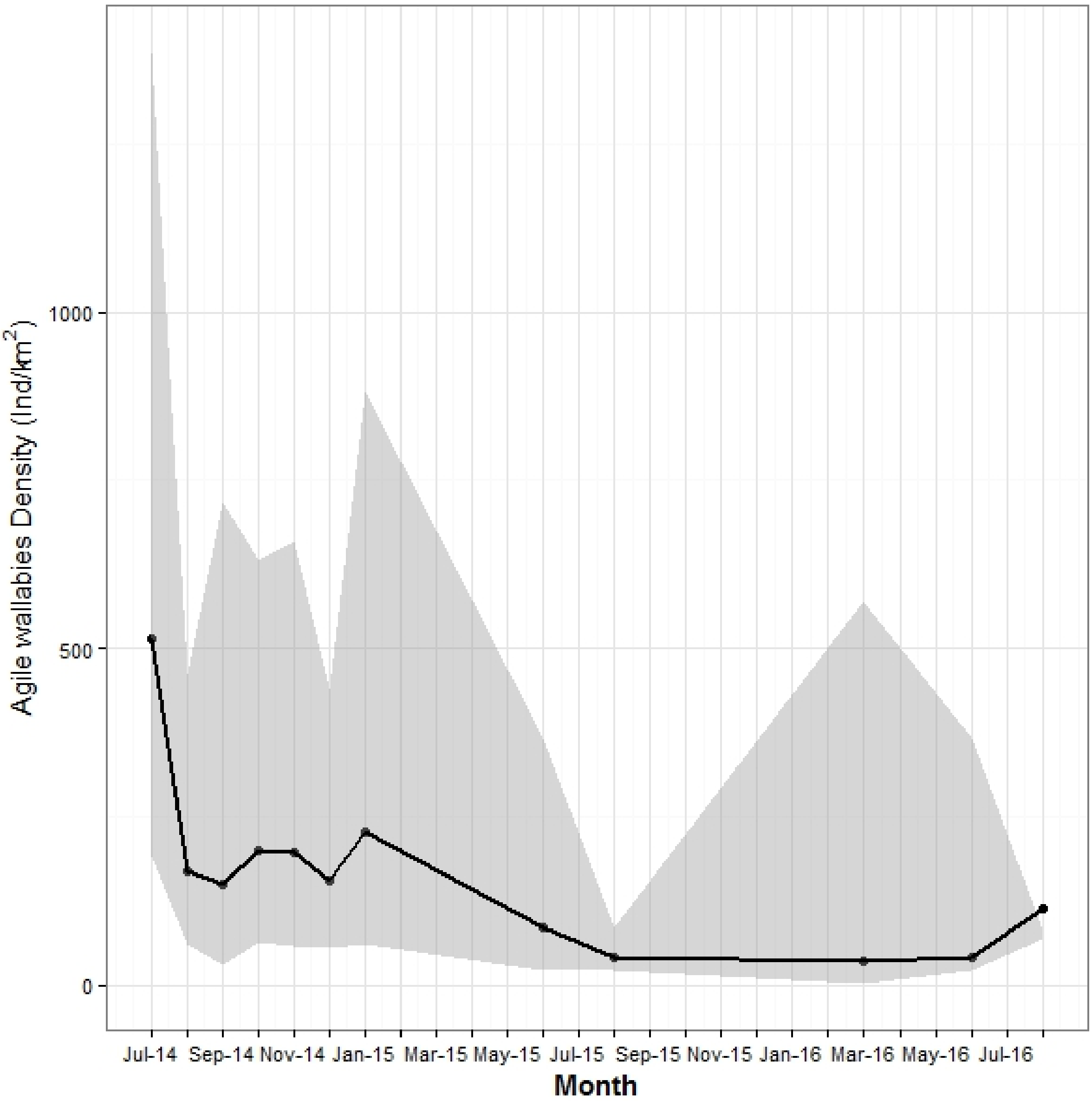

Figure 5. Agile Wallaby density from 2014 to 2016, at the Douglas Daly Research Farm. Shaded areas represent 95% confidence intervals.

7.2 Wallaby population demographics

The Agile Wallaby is the most common macropod in the wet-dry tropics of coastal Australia and the southern and eastern lowlands of Papua New Guinea (Van Dyck and Strahan 2008). It is widely distributed in the northern regions of Western Australia, the Northern Territory and Queensland as well as the Papuan subregions of the Australian zoogeographic region (Maynes 1989). There are isolated populations on Stradbroke and Peel Islands in Moreton Bay, Queensland, and a recently introduced population in eastern Tasmania (Maynes 1989; Van Dyck and Strahan 2008; DPIPWE 2013b). There is evidence of a range contraction in the distribution of this species, probably in the last 5,000 years, with populations occurring as far south as Rockhampton on the east coast of Australia (Maynes 1989).

Within its distribution, the Agile Wallaby occurs in lowland areas, including savanna woodland, open forest, mangrove forest, gallery forest along rivers and streams and dense monsoon rain forest (Ride and Fry 1970; Thomson et al. 1985; Press 1988; Maynes 1989; Flannery 1995; Stirrat 2000; Van Dyck and Strahan 2008). The preferred habitat of this species is grassland/woodland ecotones, particularly grass thickets in riverine areas or gallery forests with associated grasslands and savanna, sedgelands and herbaceous swamps, allowing them to shelter in forest areas and feed on adjacent savanna or grassy plains (Ride and Fry 1970; Bolton et al. 1982; Press 1988; Stirrat 2000). Woodland and riverine areas on the margins of properties may act as refugia for wallaby populations that feed on pastures and crops. Recently burnt open plains also attract high densities of Agile Wallabies, and it has been suggested that wallabies may be attracted to regenerating grasses (Bell 1973; Thomson et al. 1985).

To our knowledge, only one study has measured the home range of the Agile Wallaby. Stirrat (2003) found that male home range is larger than female home range and, in both sexes, home ranges increased during the dry season, when food quality was lower and sparser (mean home range: 16.6 ha for males and 11.3 ha for females during the wet season; and 24.6 ha for males and 15.3 ha for females during the dry season). However, they are considered one of the least social macropods, with no stable group formation or monopolization of territories (Johnson 1980; Dressen 1993). Therefore, if resources are plentiful, direct competition between individuals is unlikely until resources are seriously depleted. Their loose sociality means that resource availability does not regulate populations, or has little or no effect on limiting local densities until threshold limits of natural pasture recovery have been surpassed. Consequently, high density populations of wallabies on pastures may occur and their potential to destroy pastures is enormous.

Agile Wallaby populations have high juvenile mortality and male-biased adult mortality, resulting in a slightly skewed sex-ratio towards females in the adult population (Stirrat 2000; Stirrat 2008). In captivity Agile Wallabies can live for 10 to 12 years but this rarely occurs in the wild, and females are reproductively mature at 12 months (Kirkpatrick and Johnson 1969; Merchant 1976; Bolton et al. 1982; Stirrat 2000; Stirrat 2008; Sadler 2010). It is suggested, however, that the age of sexual maturity depends on body weight (Ottley *pers com*). This species is reproductively active throughout the year, as long as food is available (Merchant 1976; Bolton et al. 1982; Stirrat 2000; Stirrat 2008). Consequently, it is expected that pastures will support higher rates of reproduction than unmodified habitat. The reproduction biology of Agile Wallabies closely parallels that of red kangaroos (Bolton et al. 1982). Short oestrous and gestation (30 days each) and a pouch life of 207 to 242 days can result in a maximum reproductive output of 3 young per year per adult female (Kirkpatrick and Johnson 1969; Merchant 1976; Bolton et al. 1982; Sadler 2010). The loss of pouch young triggers oestrus (Merchant 1976). The estimated maximum rate of increase of populations, based on bodyweight (modified from Caughley and Krebs 1983) ranges from 0.47 to 0.57 per individual (a doubling of the population every 2-3 years). However, in the Northern Territory, Stirrat (2008) estimated the rate of population increase at 0.23, and other estimates by experts are closer to red kangaroo estimates at 0.35 (Ottley *pers. com.*).

The main predators of Agile Wallabies, other than humans actively culling animals, are dingoes and wild dogs (Blumstein et al. 2003; Stirrat 2008). It is plausible that dingo and wild dog control in the Northern Territory has allowed an increase in Agile Wallaby abundance. There is extensive evidence of dingos and wild dogs preferentially feeding on macropods of similar and larger size than the Agile Wallaby (Whitehouse 1977; Caughley et al. 1980; Shepherd 1981; Robertshaw and Harden 1986; Croft 1987; Pople et al. 2000; Eldridge et al. 2002; Stirrat 2008; Colman et al. 2014). Moreover, in habitats where other macropod species co-exist with the Agile Wallaby, experts suggest that dingos and wild dogs target Agile Wallabies over other more abundant macropods (Ottley *pers. com.*). However, pastoralists' perceptions of dingoes and wild dogs as pests make the possibility of combined management of dingoes and Agile Wallabies challenging and unlikely. Other reported minor predators include crocodiles (Doody et al. 2007), birds of prey (Blumstein et al. 2003) and pythons, however, they mostly prey on young and weak animals and thus hardly affect the reproductive potential of the adult population.

Agile Wallabies suffer from sarcoptic mange, a skin disease caused by the mite *Sarcoptes scabiei* (McLelland and Youl 2005). Mange affects body condition and can result in a moribund state and death. This condition is common in dogs, but has been reported in wombats and possums. Sarcoptic mange is transmitted by direct contact, and it is hypothesised that in high density host populations, rates of transmission between individuals is increased, thus potentially leading to density-dependent population regulation and a natural population control mechanism, however, this requires further investigation. Anecdotal information suggests that mange-affected Agile Wallabies are more common in high density populations during the transition between the dry and wet seasons.

The maximum rate of population increase (r_{max}) for agile wallabies was estimated at 0.34. R_{max} is a species specific demographic parameter and a function of survival probability and fertility. We estimated r_{max} from allometric (body size) relationships (Caughley 1980), previously reported values by Stirrat (2008), and personal communications with wildlife management practitioners (ABS Scrofa Pty Ltd). R_{max} is a dimensionless parameter, but $100\times(1-e^{r_{max}})$ is equal to the seasonal percentage increase in the population (McMahon et al. 2010).

A total of 132 animals were measured at the Douglas Daly Research Farm. 89 obtained between 2014 and 2015 through opportunistic collection of carcases of individuals culled under damage mitigation permits, and 43 through drop net capture (see section 6.4). For the 89 culled individuals the average age in years by molar eruption and progression is presented in Table 9. Figure 6 shows examples of molar progression index estimation for 4 individuals (2 females and 2 males).

Table 9. Average age estimated by molar eruption (ME) and molar progression (MP) for 89 agile wallabies sampled in October 2014 and September-October 2015

	Mean (years)	*SD*	*Min (years)*	*Max (years)*	*SE*
Molar eruption	4.5 (5.3♀;3.7♂)	1.5 (1.3♀;1.3♂)	1.8 (4.3♀;1.8♂)	8.2 (8.2♀;5.8♂)	0.2 (0.3♀;0.3♂)
Molar progression	4.8 (5.6♀;4.2♂)	1.9 (2.1♀;1.4♂)	2.2 (3.7♀;2.2♂)	10.7 (10.7♀;7.8♂)	0.3 (0.5♀;0.3♂)

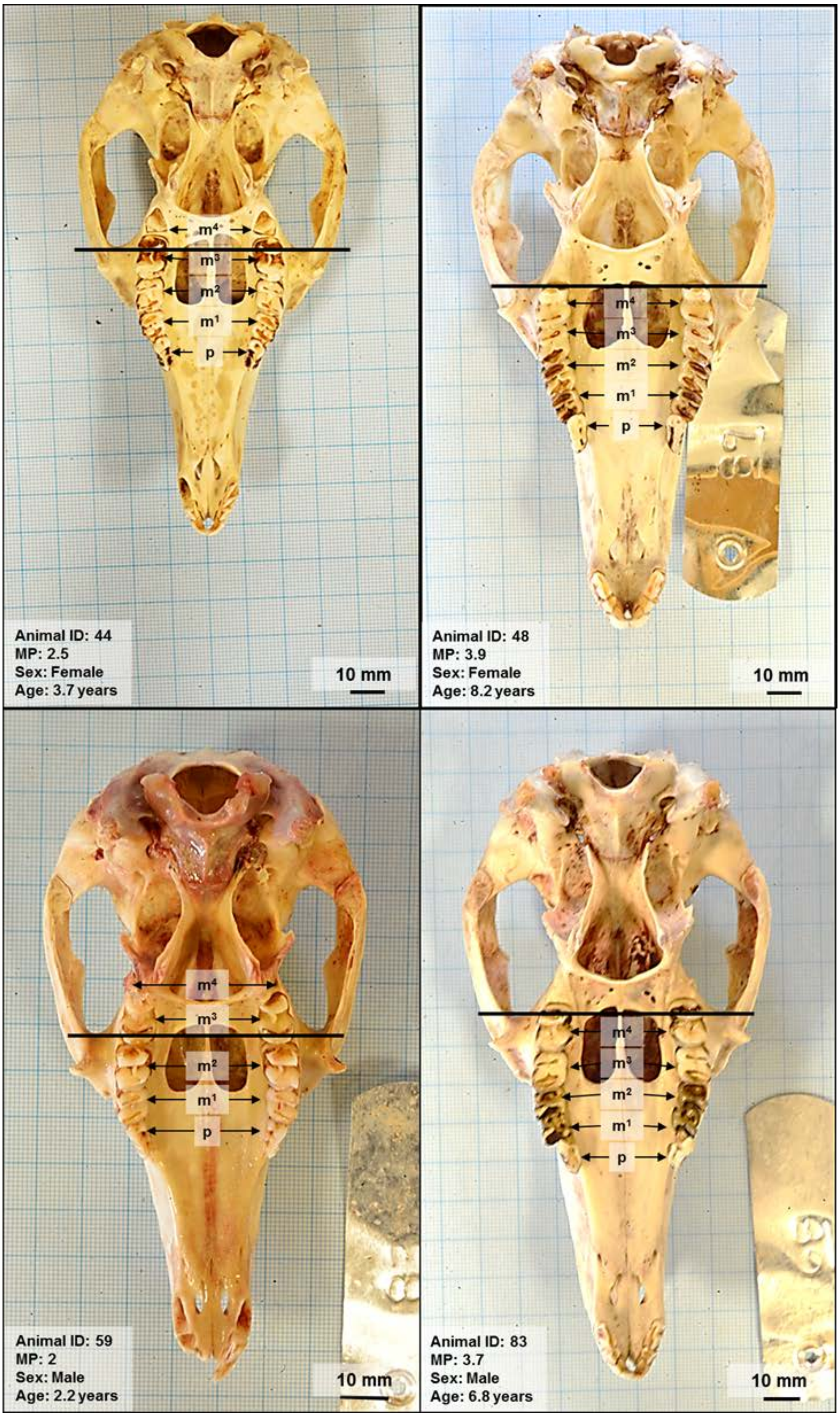

Figure 6. Agile wallaby skulls showing the estimation of the Molar Progression (*MP*) index. Top panels show female individuals (left 3.7 years old, and right 8.2 years old) and bottom panels show male individuals (left 2.2 years old, and right 6.8 years old)

Data from another 2043 individuals was obtained from ABS Scrofa Pty Ltd, from 2007 to 2013. Due to prior privacy arrangements, the location where these individuals were culled cannot be discussed in this report. However, they were all obtained under relevant regulation permits approval, and following humane procedures (Department of the Environment 2008).

Combining the data collected at the Douglas Daly Research Farm and the one supplied by ABS Scrofa Pty Ltd, we estimated the average body weight per animal, by sex, age group, and population (Table 10)

Table 10. Average weight for individuals sampled at the Douglas Daly Research Farm from 2014 to 2016, and data obtained from ABS Scrofa Pty Ltd.

	Mean (kg)	*SD*	*Min (kg)*	*Max (kg)*	*SE*
Douglas Daly	11.3(9.5♀;13.6♂)	4.3(2.1♀;5.1♂)	2.4(2.4♀;4.2♂)	24.1(14.0♀;24.1♂)	0.4(0.2♀;0.7♂)
Juveniles	3.6(2.7♀4.4;♂)	1.0(0.4♀;0.3♂)	2.4(2.4♀;4.2♂)	4.6(3.0♀;4.6♂)	0.5(0.3♀;0.2♂)
Sub Adults	9.8(7.7♀;11.0♂)	2.9(1.0♀;3.0♂)	5.2(5.5♀;5.2♂)	15.6(8.9♀;15.6♂)	0.4(0.2♀;0.5♂)
Adults	13.0(10.5♀;19.2♂)	4.4(1.3♀;2.8♂)	9.2(9.2♀;16.0♂)	24.1(14.0♀;24.1♂)	0.5(0.2♀;0.6♂)
ABS Scrofa	9.33(7.8♀;10.9♂)	5.1(2.6♀;6.4♂)	1.5(1.5♀;1.5♂)	30.1(14.5♀;30.1♂)	0.1(0.1♀;0.2♂)
Juveniles	3.47(3.3♀;3.6♂)	0.8(0.7♀;0.8♂)	1.5(1.5♀;1.5♂)	4.9(4.3♀;4.9♂)	0.1(0.1♀;0.1♂)
Sub Adults	7.74(6.5♀;8.7♂)	2.5(1.3♀;2.8♂)	4.5(4.5♀;5.0♂)	15.8(8.9♀;15.8♂)	0.1(0.1♀;0.1♂)
Adults	14.11(10.4♀;21.2♂)	5.7(1.1♀;3.7♂)	9.0(9.0♀;16.0♂)	30.1(14.5♀;30.1♂)	0.3(0.1♀;0.3♂)
Overall	9.49(8.0♀;11.1♂)	5.1(2.6♀;6.4♂)	1.5(1.5♀;1.5♂)	30.1(14.5♀;30.1♂)	0.1(0.1♀;0.2♂)

The agile wallaby population sex ratio was estimated as no different from a 1♂:1♀ ratio (*chi-sq* = 0.71; *df* = 1; *p-value* = 0.400). And the sex ratio was not affected by population (ABS Scrofa or Douglas Daly Research Farm), year of collection, season of collection (wet or dry), or age group. However, model fitting showed that the simple model that included age group, was the best fit to the data (AIC: 86.47; Null deviance: 29.68 on 52 degrees of freedom) (Figure 7).

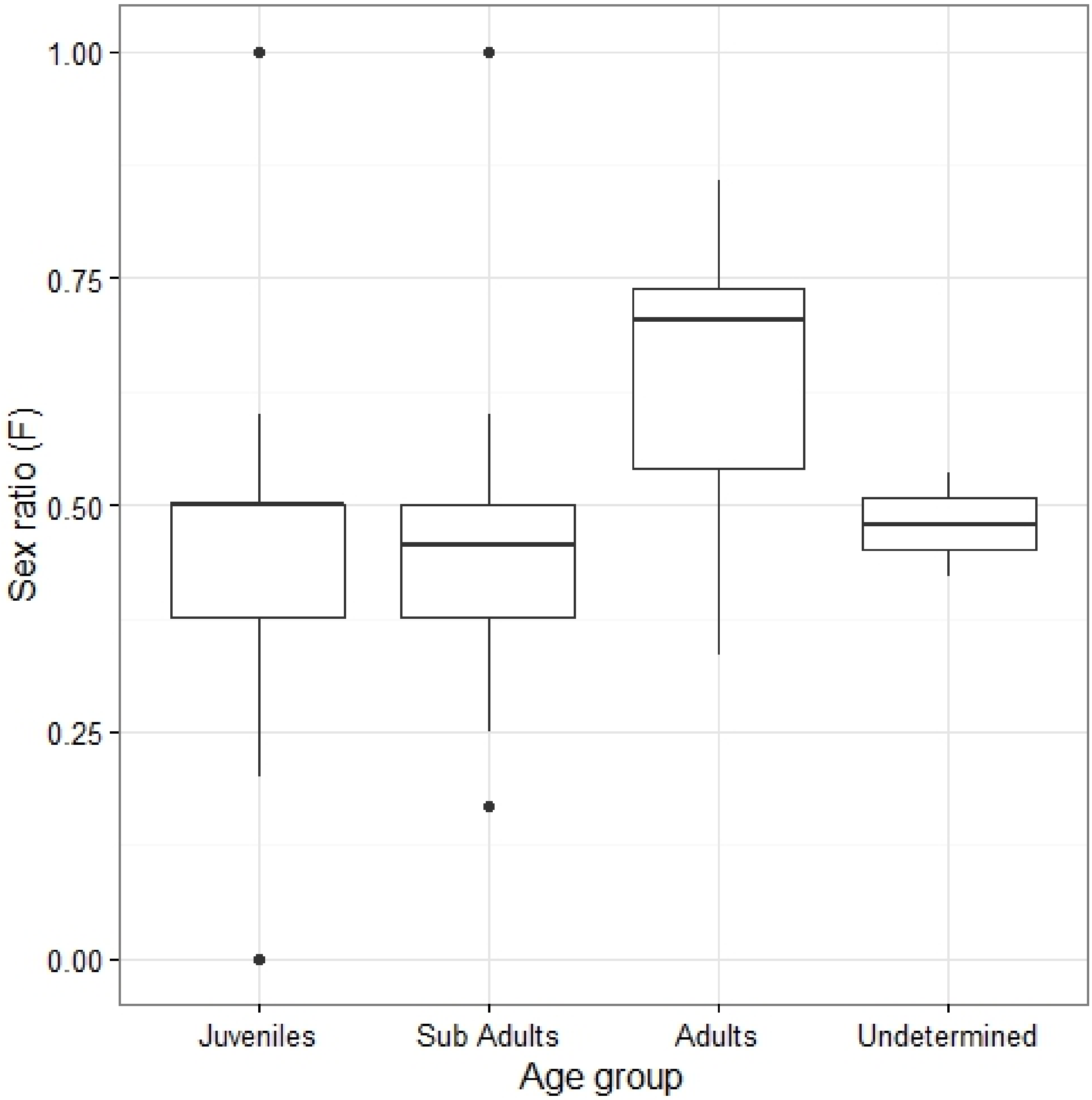

Figure 7. Agile wallaby population sex ratio (Number of females/Number of males) by age group.

By contrast, the pouch young sex ratio showed a strong bias towards females, with 7 out 10 pouch young being females (*chi-sq* = 6.08; *df* = 1; *p-value* = 0.014). However, we found no effect of: mothers age by molar eruption (*chi-sq* = 2.76; *df* = 5; *p-value* = 0.736) or molar progression (*chi-sq* = 13.993; *df* = 8; *p-value* = 0.082); mothers age group (*chi-sq* = 1.64; *df* = 1; *p-value* = 0.252); mothers weight (*chi-sq* = 0.35; *df* = 1; *p-value* = 0.559); mothers health score (Pes length/Weight) (*chi-sq* = 0.04; *df* = 1; *p-value* = 0.843); mothers body size (Pes length) (*chi-sq* = 0.74; *df* = 1; *p-value* = 0.389); or birth month (estimated from pouch young pes and tail length) (*chi-sq* = 0.03; *df* = 1; *p-value* = 0.863).

7.3 Estimation of wallaby grazing effects on pasture

We combined the data collected from pastures enclosures during Stage 1 in 2015, and the data collected from pastures enclosures in 2016. From these data, both enclosure type and exclosure set showed an effect on the biomass consumed (Table 11).

Table 11. Contingency table from best model fitted to biomass data collected from 9 sets of grazing exclusion trials at the Douglas Daly Research Farm, between 2015 and 2016. Each set comprised a wallaby proof fenced enclosure, a cattle proof fenced enclosure and an open enclosure.

	Df	*Deviance*	*Resid. Df*	*Resid. Dev*	*F*	*Pr(>F)*
NULL			119	224.31		
Set	7	58.77	112	165.55	9.33	<0.0001
Enclosure	2	35.17	110	130.38	19.53	<0.0001
Set:Enclosure	14	43.96	96	86.41	3.49	<0.001

Based on the model described above, we estimated that in areas with high densities of agile wallabies 226,366.4 DMkg/km^2/yr (95% CI 132,224.7 – 320,508.0) of pasture is consumed (Figure 8).

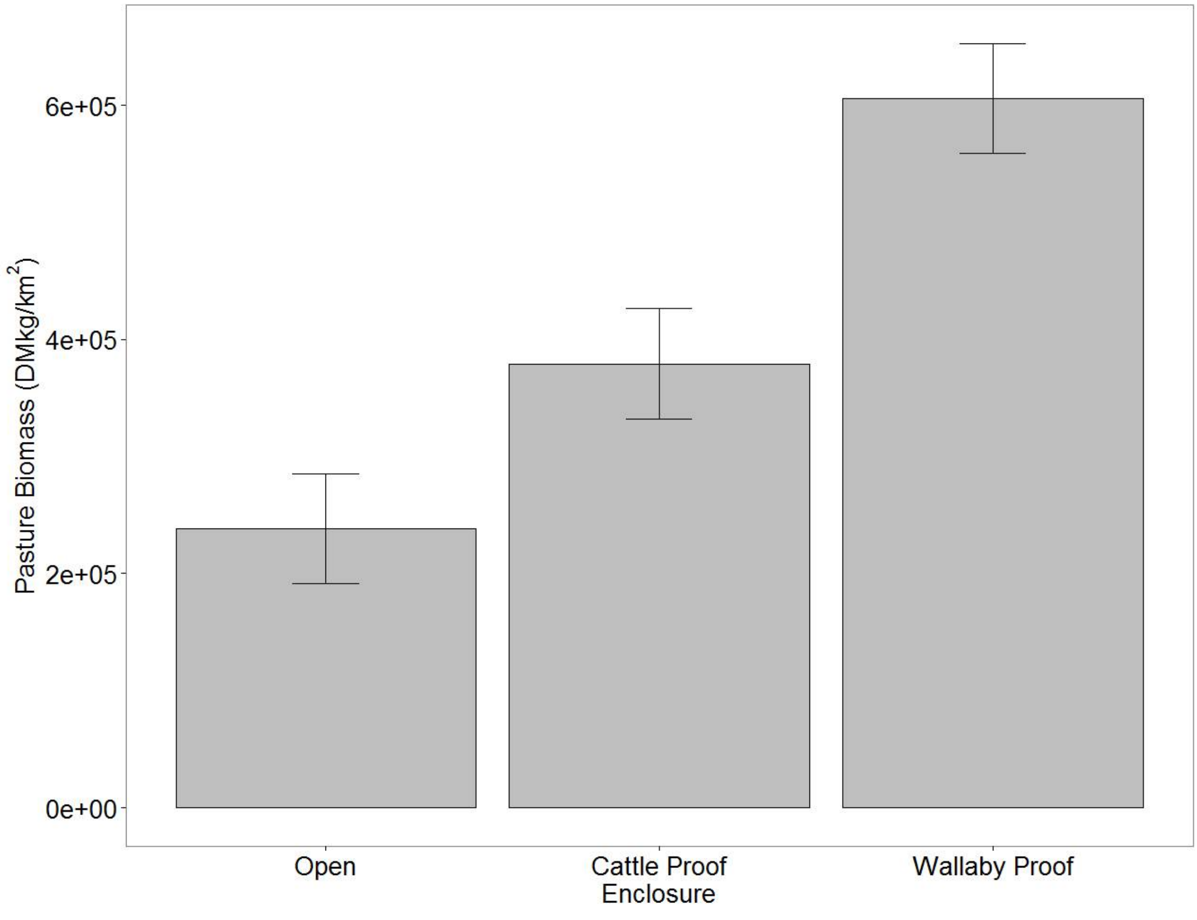

Figure 8. Pasture biomass dry matter (DM kg/km^2) measured at nine sets of pasture enclosures. Each set of enclosures consisting of a 'wallaby proof' fenced plot built of commercial pig-proof mesh fencing, a 'cattle proof' fence, built with barbed-wire and fence pickets, and the 'outside' of both enclosures where grazing was allowed (control plot). Error bars are standard errors.

Wallaby density had no effect on pasture composition (no difference in species Richness, Simpson's and Shannon's Diversity Indexes, and Simpson's and Shannon's Evenness Indexes) (Figures 9 to 13).

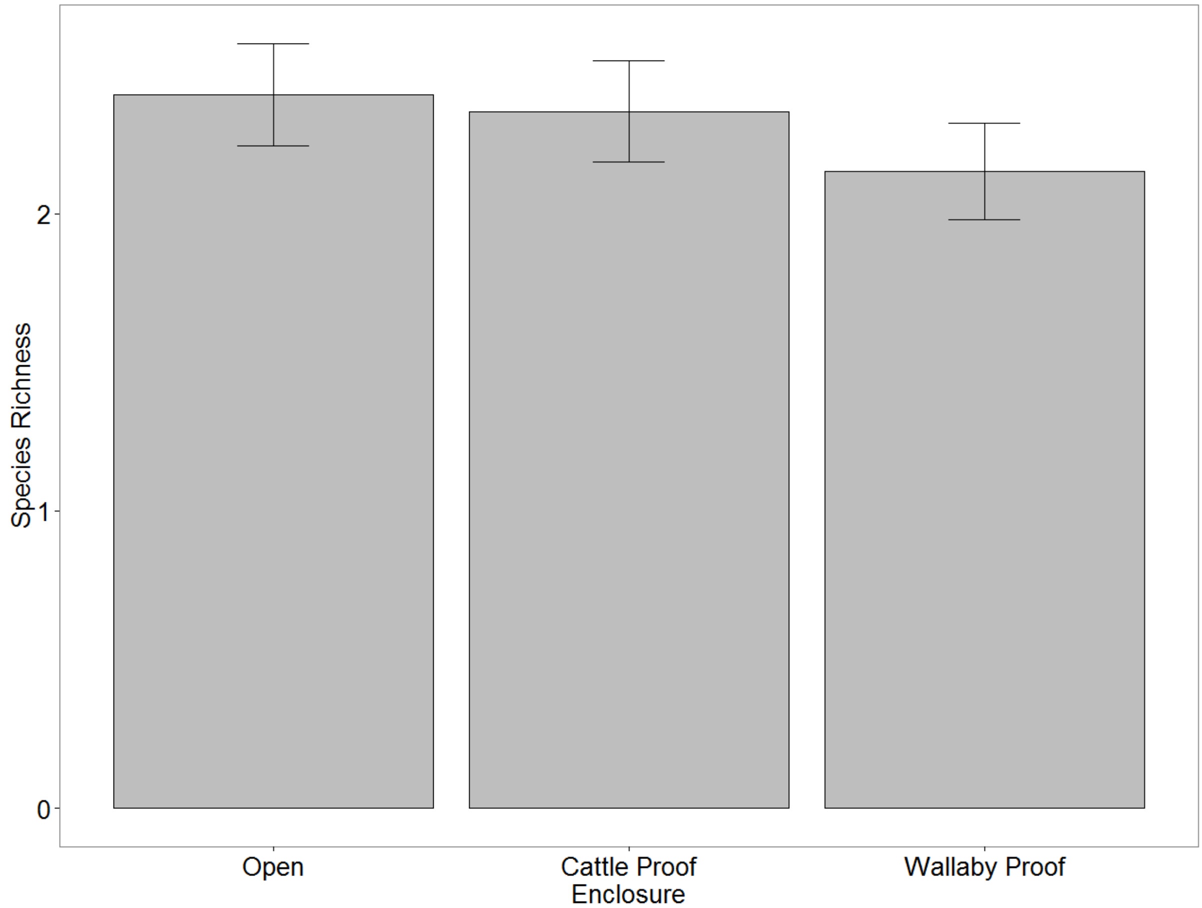

Figure 9. Number of species (Richness) measured at nine sets of pasture enclosures. Each set of enclosures consisting of a ‘wallaby proof’ fenced plot built of commercial pig-proof mesh fencing, a ‘cattle proof’ fence, built with barbed-wire and fence pickets, and the ‘outside’ of both enclosures where grazing was allowed (control plot). Error bars are standard errors.

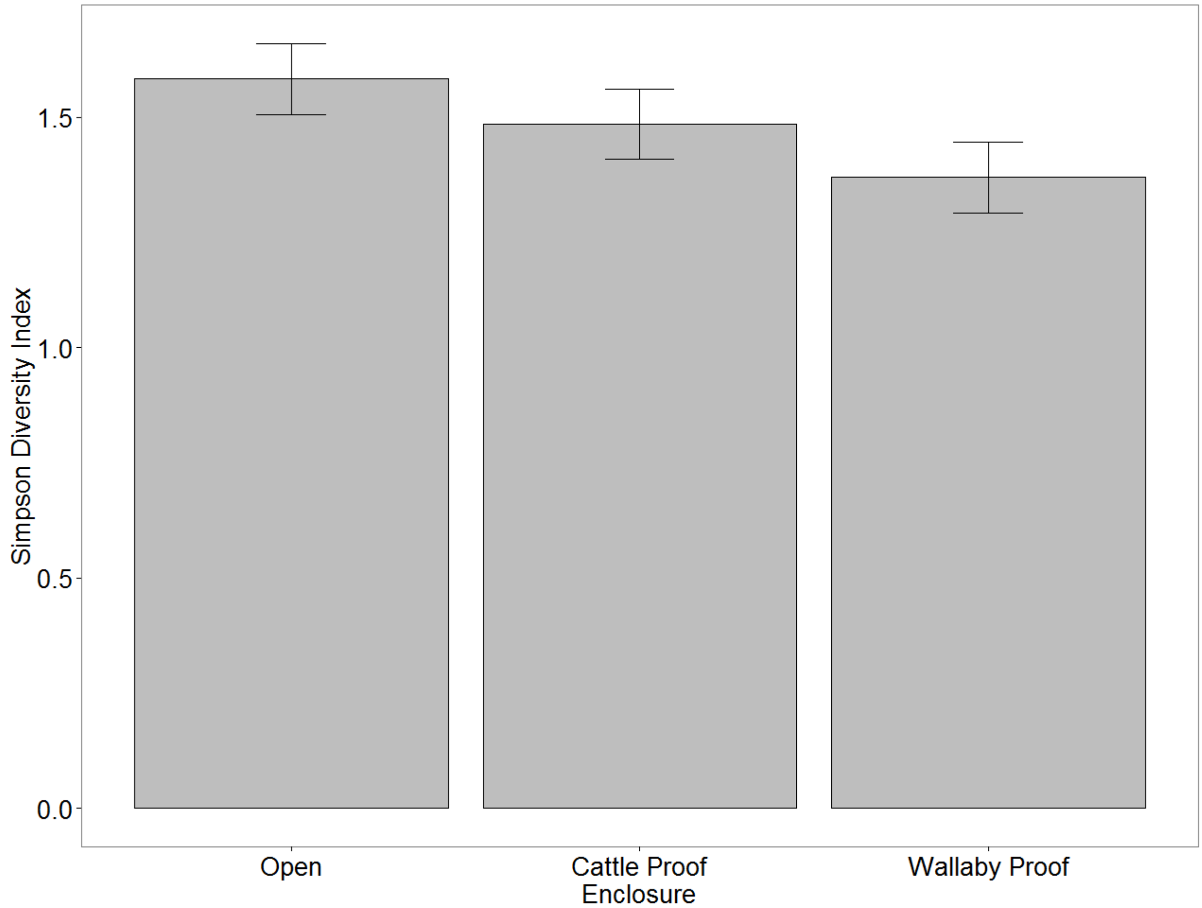

Figure 10, Simpson's Diversity Index measured at nine sets of pasture enclosures. Each set of enclosures consisting of a 'wallaby proof' fenced plot built of commercial pig-proof mesh fencing, a 'cattle proof' fence, built with barbed-wire and fence pickets and the 'outside' of both enclosures where grazing was allowed (control plot). Error bars are standard errors.

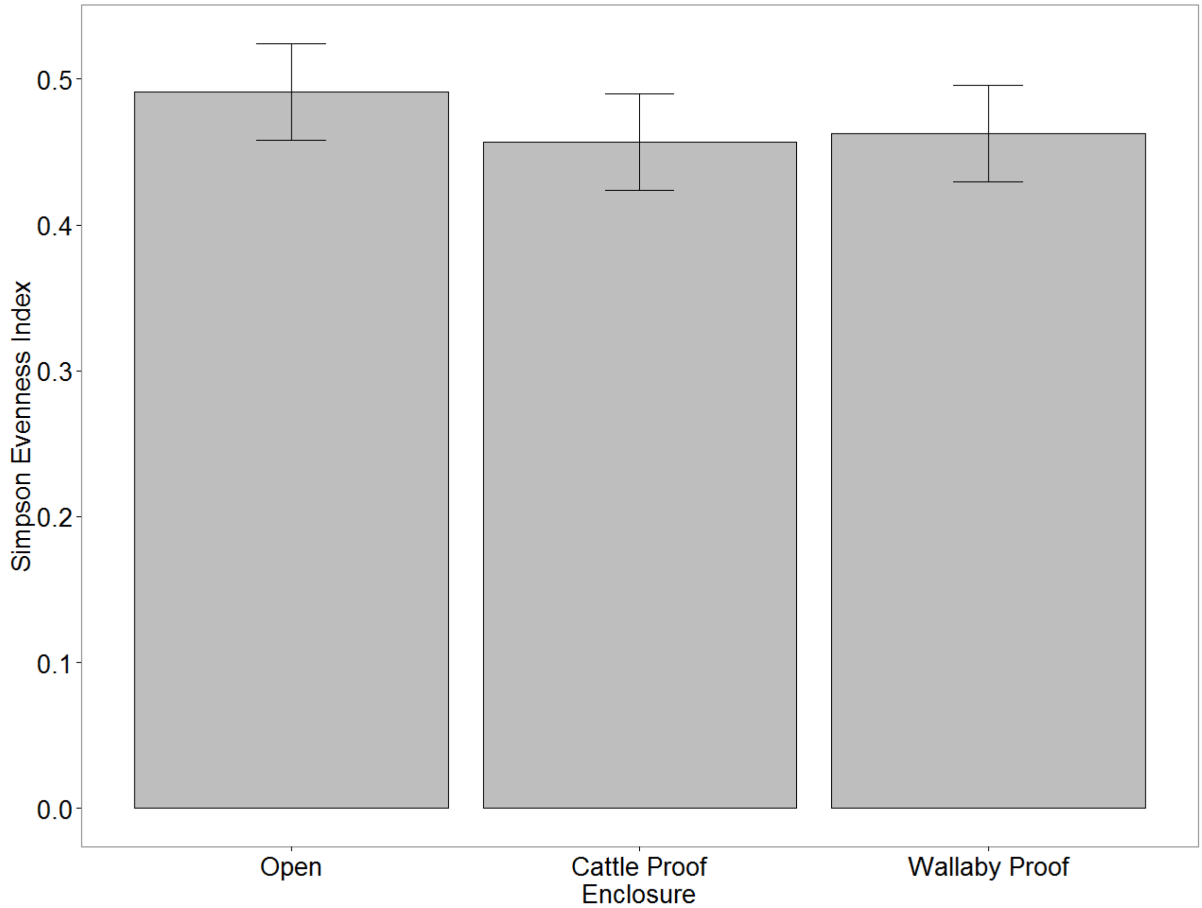

Figure 11. Simpson's Evenness Index measured at nine sets of pasture enclosures. Each set of enclosures consisting of a 'wallaby proof' fenced plot built of commercial pig-proof mesh fencing, a 'cattle proof' fence, built with barbed-wire and fence pickets, and the 'outside' of both enclosures where grazing was allowed (control plot). Error bars are standard errors.

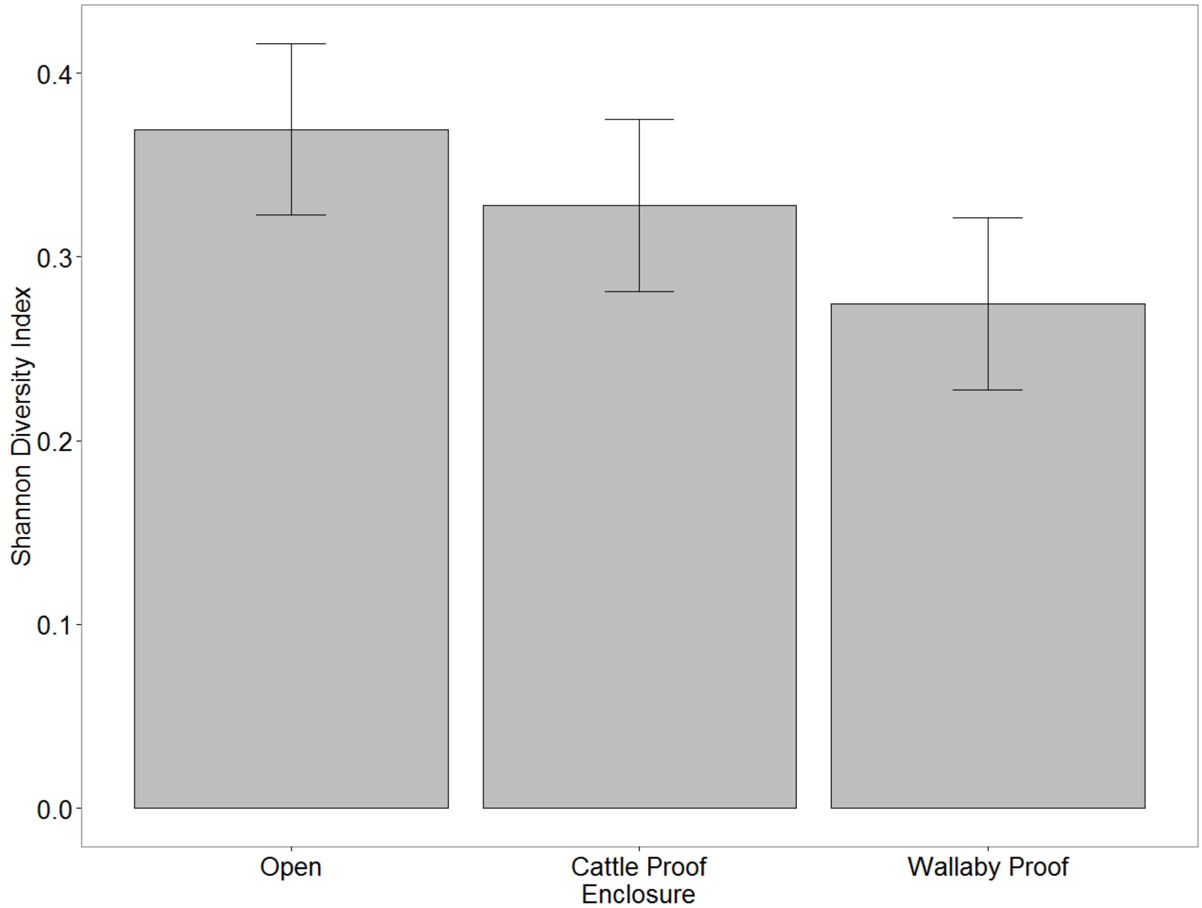

Figure 12. Shannon's Diversity Index measured at nine sets of pasture enclosures. Each set of enclosures consisting of a 'wallaby proof' fenced plot built of commercial pig-proof mesh fencing, a 'cattle proof' fence, built with barbed-wire and fence pickets, and the 'outside' of both enclosures where grazing was allowed (control plot). Error bars are standard errors.

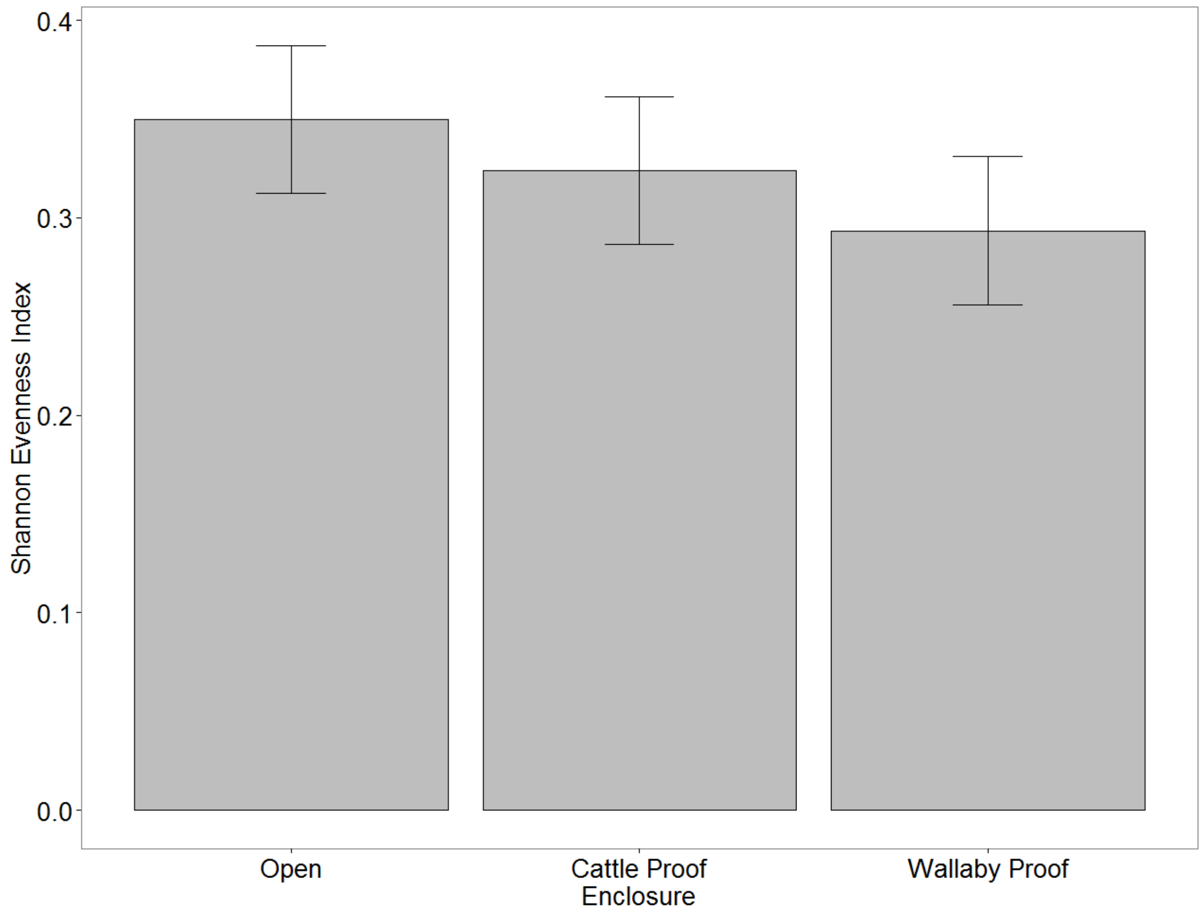

Figure 13. Shannon's Evenness Index measured at nine sets of pasture enclosures. Each set of enclosures consisting of a 'wallaby proof' fenced plot built of commercial pig-proof mesh fencing, a 'cattle proof' fence, built with barbed-wire and fence pickets, and the 'outside' of both enclosures where grazing was allowed (control plot). Error bars are standard errors.

The best fitting function of biomass loss and wallaby density was a linear function with an adjusted R^2 of 0.549 ($F_{1,15} = 20.44$, $p = 0.0004$) (Figure 14; equation 1).

$$y = -131734 + 5075x \qquad (1)$$

Equation 1: Were y is the biomass loss in kilograms per square kilometre per year and x is the number of wallabies per square kilometre

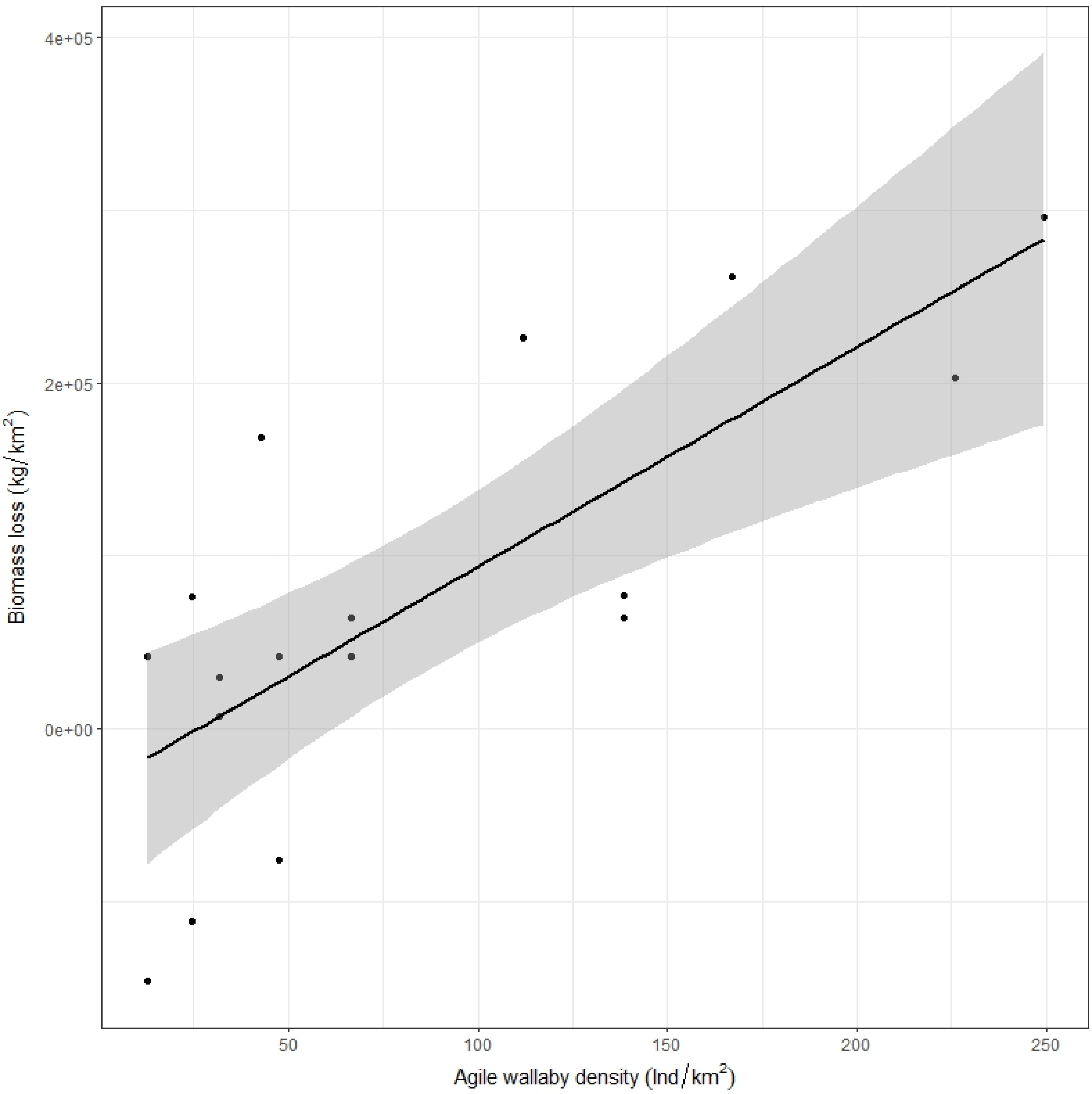

Figure 14. Agile wallaby density-damage (biomass loss) linear function fitted (R^2 = 0.549)

We equated 1 AE to 26.8 wallabies (95% CI 0.03 – 27) by combining this fitted linear model (Equation 1), the reported Average Adult Equivalent (McLean and Blakeley 2014) and pasture biomass requirements per head per day (kg DM/head/day) based on average rangeland pasture quality in the Northern Territory of 6.5±1.5 MJ ME/kg DM (megajoules of metabolisable energy per kilogram of dry matter) (McLennan 2015) (see Table 8).

7.4 Wallaby capture, collaring and radio tracking

Radio tracking of collared individuals at the Douglas Daly research farm found significantly larger home ranges than the previously reported estimate by Stirrat (2003) at East Point Reserve. Stirrat (2003) reported average dry season home range sizes for females and males of 15.3 ha and 24.6 ha, respectively. Our estimates of average home range size during the dry season for females and males was 31.8 ha (±8.5 ha) and 30.2 ha (±9.6 ha), respectively. Figure 15 shows examples of the smallest and largest estimated home ranges by sex.

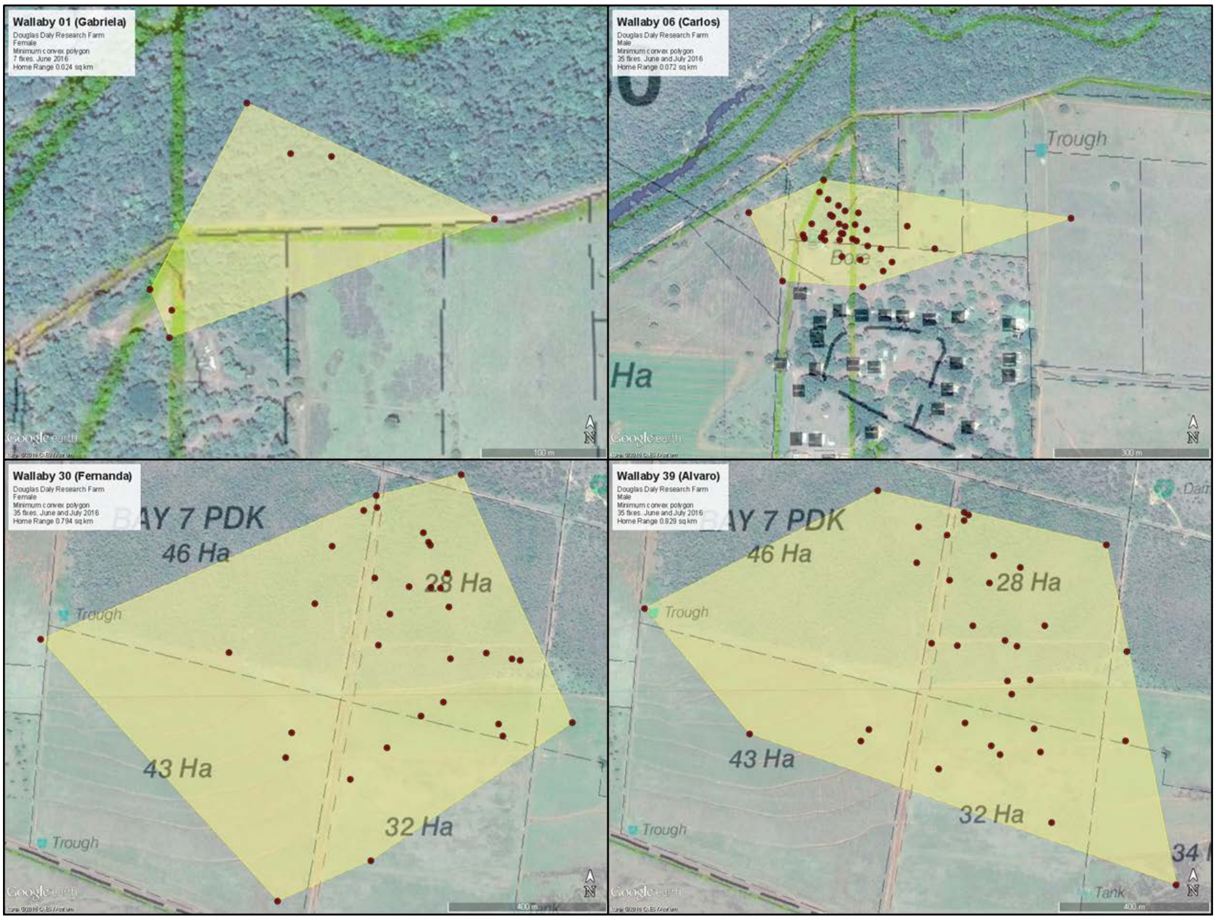

Figure 15. Examples of calculated home ranges from female and male wallabies at the Douglas Daly Research Farm. On the left the home ranges of two females are shown, at the top the smallest at 2.4 ha (0.024 km^2), and at the bottom the largest at 0.794 km^2. On the right the home ranges of two males are shown, at the top the smallest at 7.2 ha (0.072 km^2) and at the bottom the largest at 89.9 ha (0.829 km^2). Note that the wallabies use native habitat as well as pastures.

We did not find a difference in home range size between the sexes, and the only difference we detected was in the habitat the individuals occupied (Table 12, Figure 16). We also found no habitat preferences during a day (Table 13, Figure 17).

Table 12. Contingency table from best model fitted to home range data collected from 22 individual wallabies (13 females and 9 males) tracked during the dry season (July and August) 2016 at the Douglas Daly Research Farm.

	Df	*Deviance*	*Resid. Df*	*Resid. Dev*	*F*	*Pr(>F)*
NULL			21	12.47		
Location	1	3.34	20	9.13	7.31	0.0137

Table 13. Contingency table from best model fitted to occurrences by time of day and habitat, from data collected from 22 individual wallabies (13 females and 9 males) tracked during the dry season (July and August) 2016 at the Douglas Daly Research Farm.

	Df	*Deviance*	*Resid. Df*	*Resid. Dev*	*F*	*Pr(>F)*
NULL			174	243.51		
Time of day	3	0.002	171	243.51	0.001	0.999
Habitat	1	33.05	170	210.47	33.046	<0.0001
*Time of day*Habitat*	3	7.24	167	203.23	2.413	0.065

Animals inhabiting the ecotone between bush and pasture had an average home range size of 43.2 ha (± 8.7 ha) (Females: 44.0 ha ± 8.7 ha; Males 42.4 ha ± 8.7 ha), while animals inhabiting ecotones between bush and human settlements, incorporating irrigated lawns and gardens, had a smaller average home range size of 18.8 ha (±9.4 ha) (Females: 19.6.0 ha ± 8.2 ha; Males 18.0 ha ± 10.6 ha) (Figure 16).

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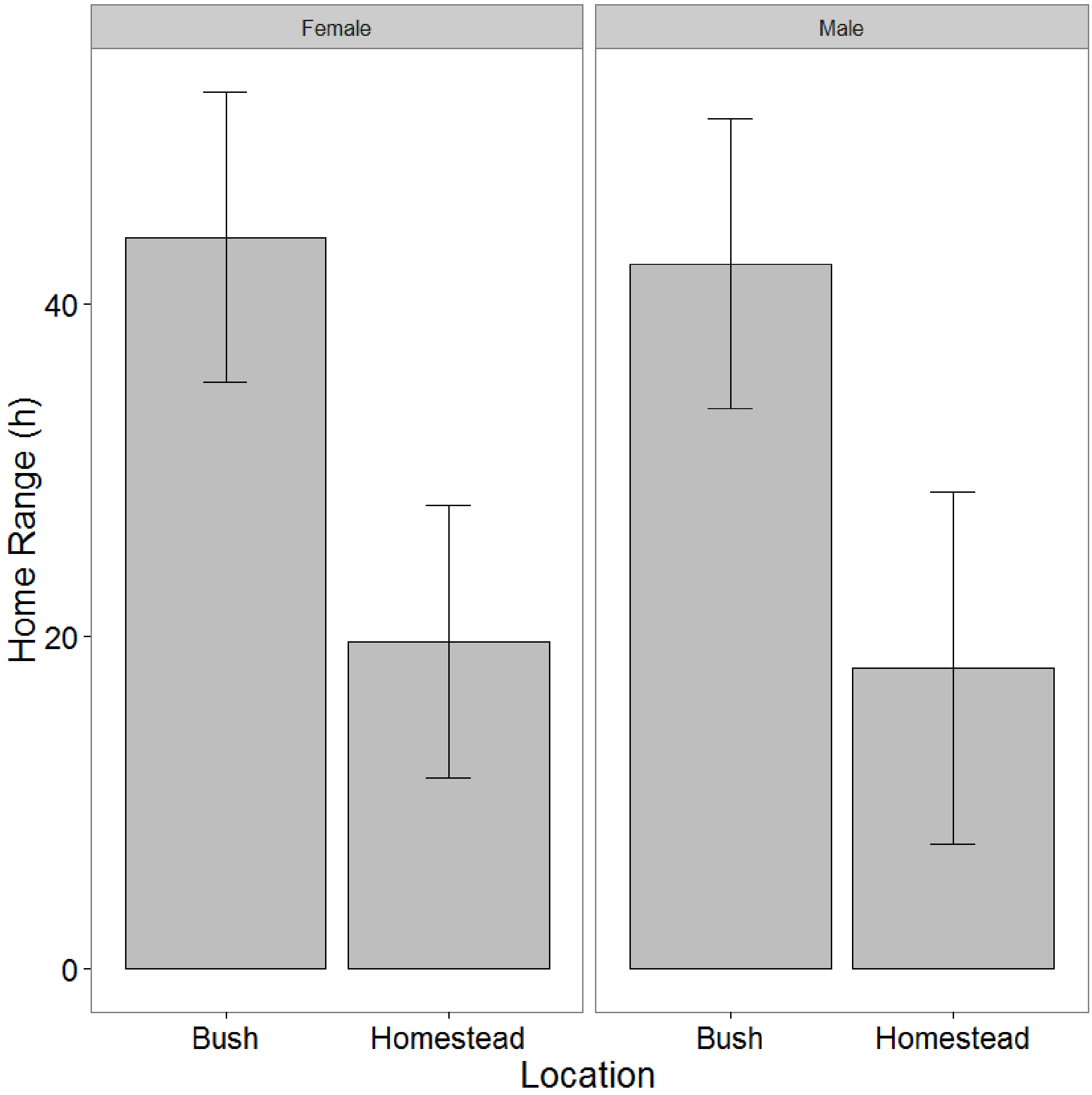

Figure 16. Average agile wallaby home range sizes calculated by minimum convex polygon based on 22 individual wallabies (13 females and 9 males) tracked during the dry season (July and August) 2016. 10 individuals inhabiting ecotones between bush and human settlements, incorporating irrigated lawns and gardens (Homestead), and 12 individuals inhabiting the ecotone between bush and pasture (Bush). Error bars represent standard errors. Home ranges were smaller where the animals frequented areas near to human settlements.

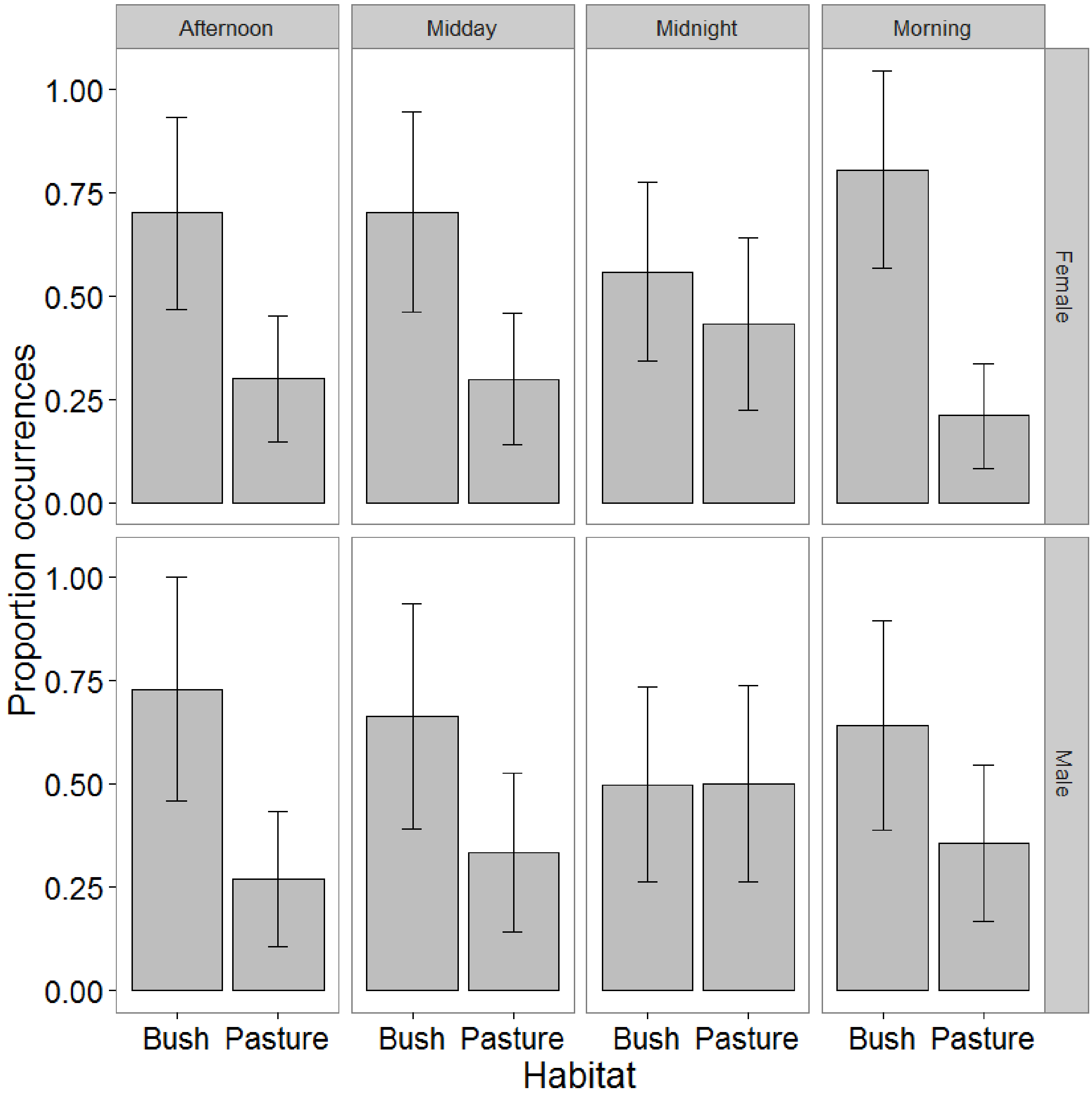

Figure 17. Proportion of occurrences when individual wallabies were recorded in different habitat types, across 4 different times. Based on 22 individual wallabies (13 females and 9 males) tracked during the dry season (July and August) 2016. Error bars represent standard errors.

7.5 Estimation of the current extent, abundance and carrying-capacity of the agile wallaby population in the Northern Territory

Comparing Relative Operating Characteristic (ROC) plots, we selected the Generalized Additive Model (AUC = 0.98) to characterise wallaby distribution (Figures 18 and 19)

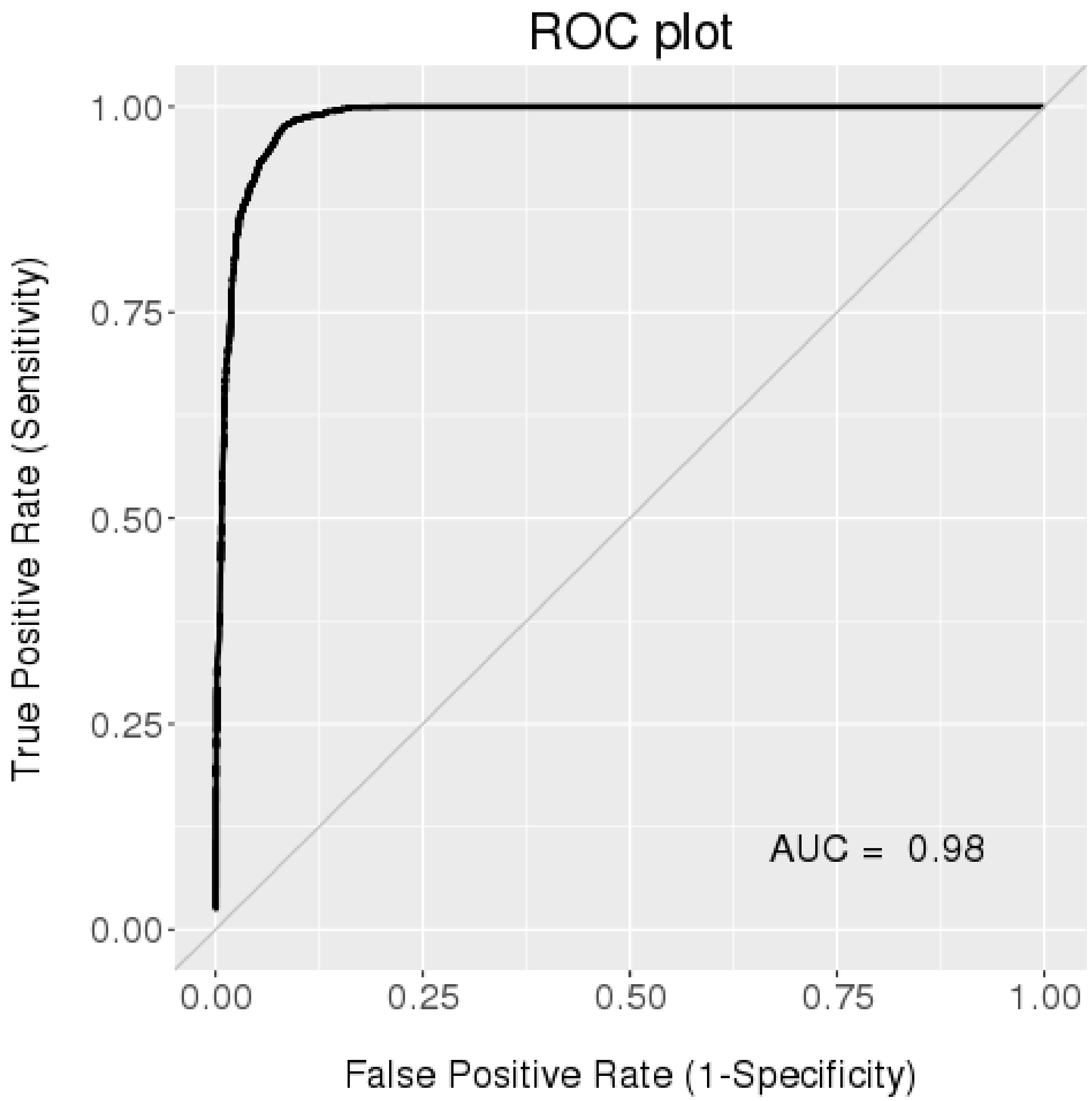

Figure 18. Relative Operating Characteristic (ROC) plot from Generalized Additive Model applied to Agile Wallaby occurrence data and climatic variables.

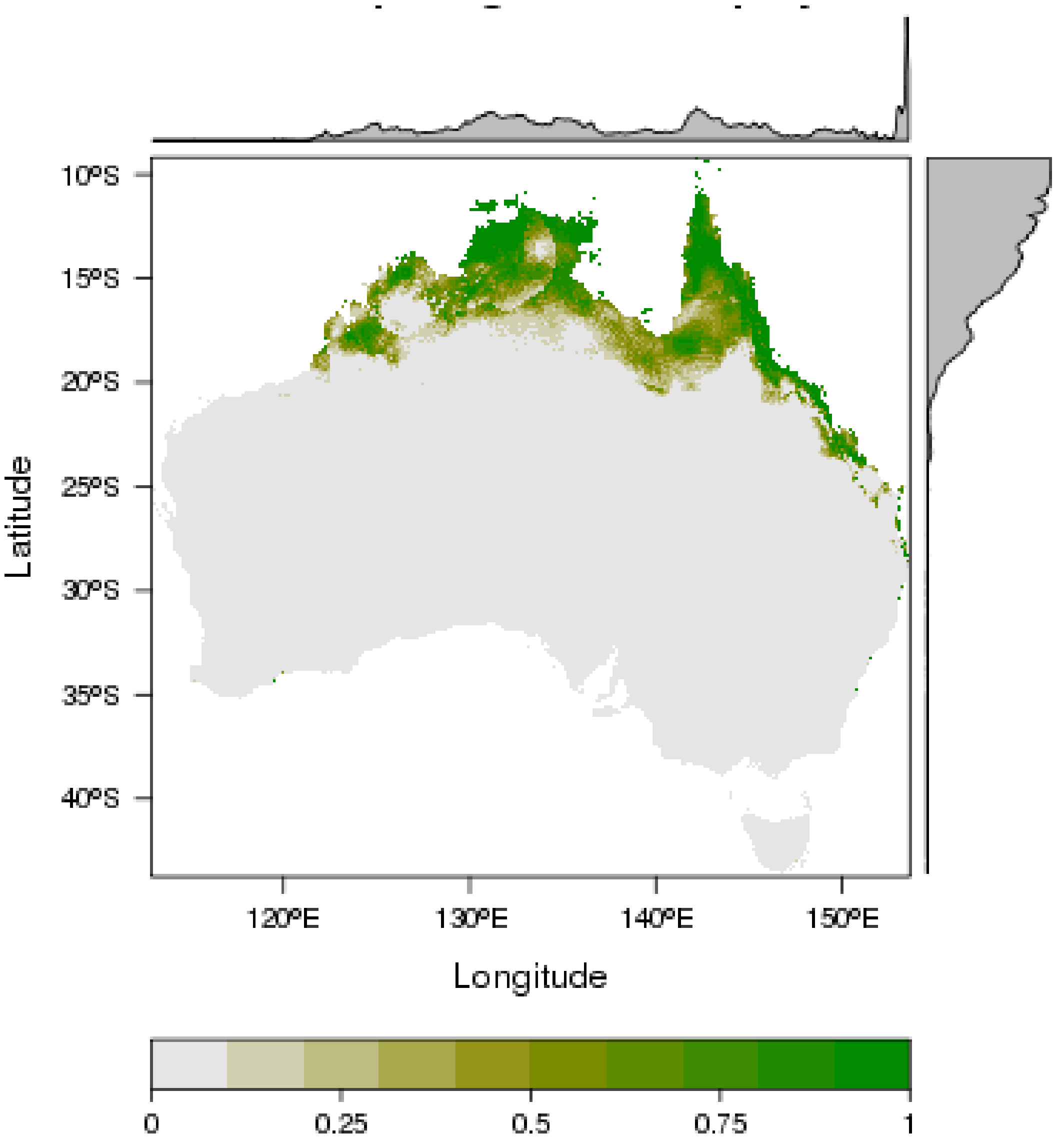

Figure 19. Agile wallaby distribution projection based on GAM species modelling.

Our current estimate of abundance for agile wallabies within their distribution in the Northern Territory based on the National Vegetation Identification System: Major Vegetation Groups (NVIS)(DEE 2012), hydrological information regarding distance to water sources (Williams 2011a; Williams 2011b); 2009-2008 Annual Rainfall (mm) (BRS 2009); 2010-2011 Northern Territory Pastoral Leases (DLPE 2015), Land use of Australia (ACLUMP 2014), Department of Primary Industries and Fisheries cattle carrying capacity by land type, and 2014 – 2015 line transect surveys of wallaby abundance is 47,082,811 individuals (average 97 ind/km^2), regardless of whether we based our estimates on distance to any water source (Figure 20), or distance to only permanent water sources (Figure 21) (see stratified values by land use in Table 13).

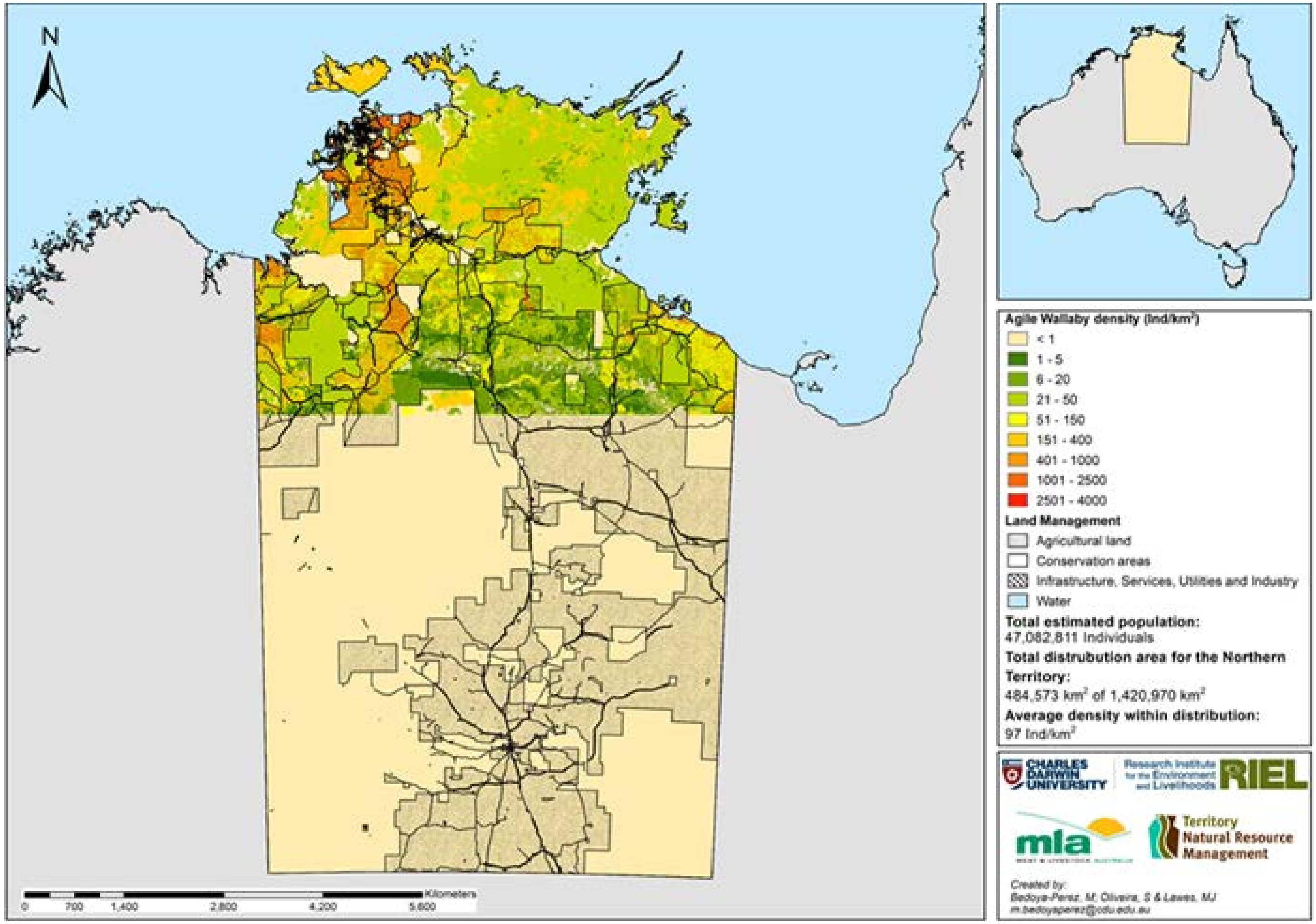

Figure 20. Estimates of current densities (ind/km^2) of the agile wallaby (*Macropus agilis*) population within its Northern Territory distribution, stratified by land use. The estimates are based on National Vegetation Identification System: Major Vegetation Groups (NVIS)(DEE 2012), hydrological information regarding distance to any water source (Williams 2011a; Williams 2011b); 2009-2008 Annual Rainfall (mm) (BRS 2009); 2010-2011 Northern Territory Pastoral Leases (DLPE 2015); Land use of Australia (ACLUMP 2014); Department of Primary Industries and Fisheries cattle carrying capacity by land type, and 2014 – 2015 line transect surveys of wallaby abundance.

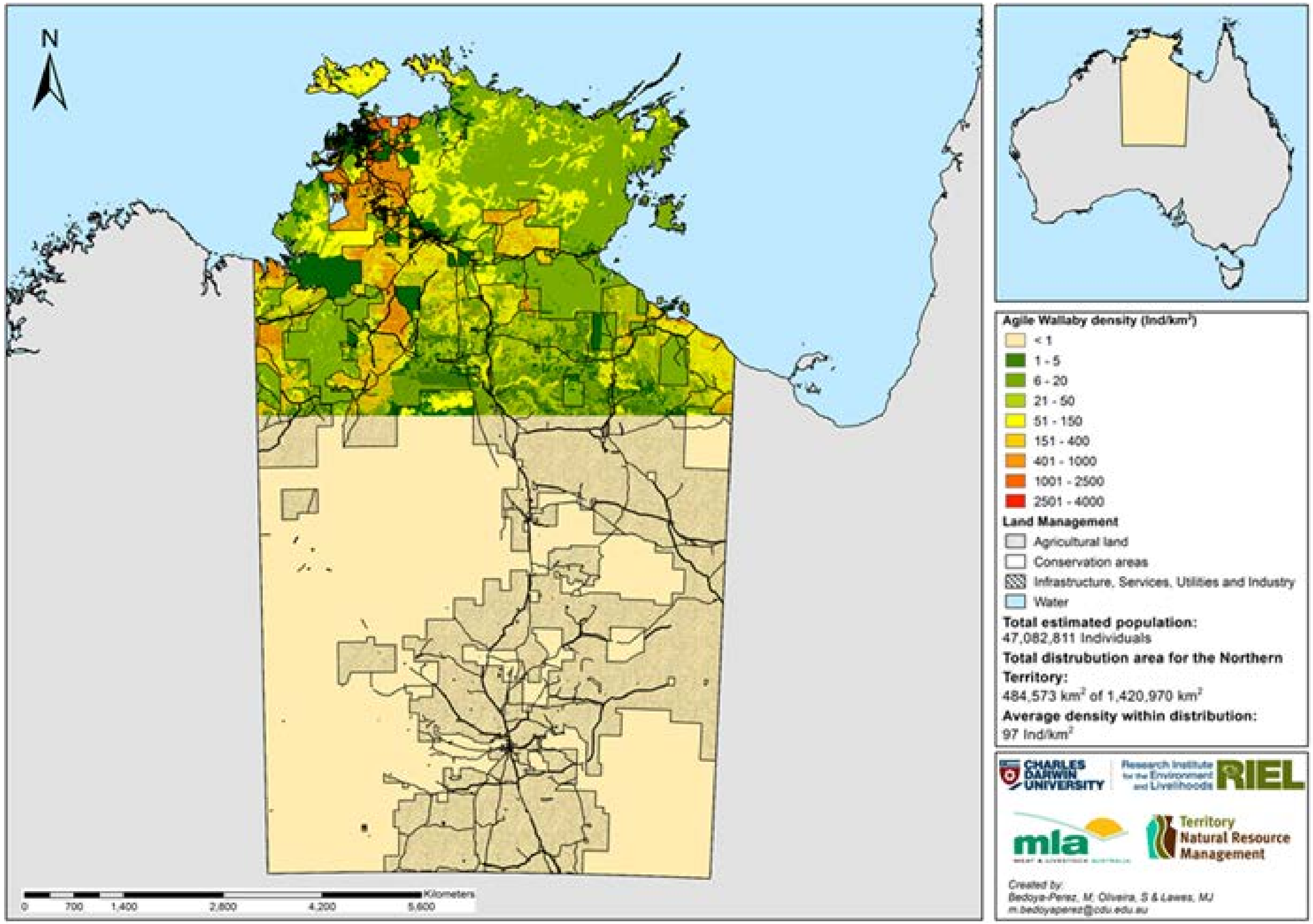

Figure 21. Estimates of current densities (ind/km^2) of the agile wallaby (*Macropus agilis*) population within its Northern Territory distribution, stratified by land use. The estimates are based on National Vegetation Identification System: Major Vegetation Groups (NVIS)(DEE 2012), hydrological information regarding distance to permanent water sources (Williams 2011a; Williams 2011b); 2009-2008 Annual Rainfall (mm) (BRS 2009); 2010-2011 Northern Territory Pastoral Leases (DLPE 2015); Land use of Australia (ACLUMP 2014); Department of Primary Industries and Fisheries cattle carrying capacity by land type, and 2014 – 2015 line transect surveys of wallaby abundance.

Our estimates of carrying capacity showed that the Agile Wallaby population has the potential to increase to 394,844,067 individuals (average 815 ind/km^2), based on distance to any water and current improved pasture usage (Figure 22); 396,684,171 individuals (average 819 ind/km^2), based on distance to any water and improved pastures usage projections (Figure 23); 390,083,081 individuals (average 805 ind/km^2), based on distance to permanent water sources and current improved pasture usage (Figure 24); and 391,923,186 individuals (average 809 ind/km^2), based on distance to permanent water and projected improved pasture usage (Figure 25) (see stratified values by land use in Table 14).

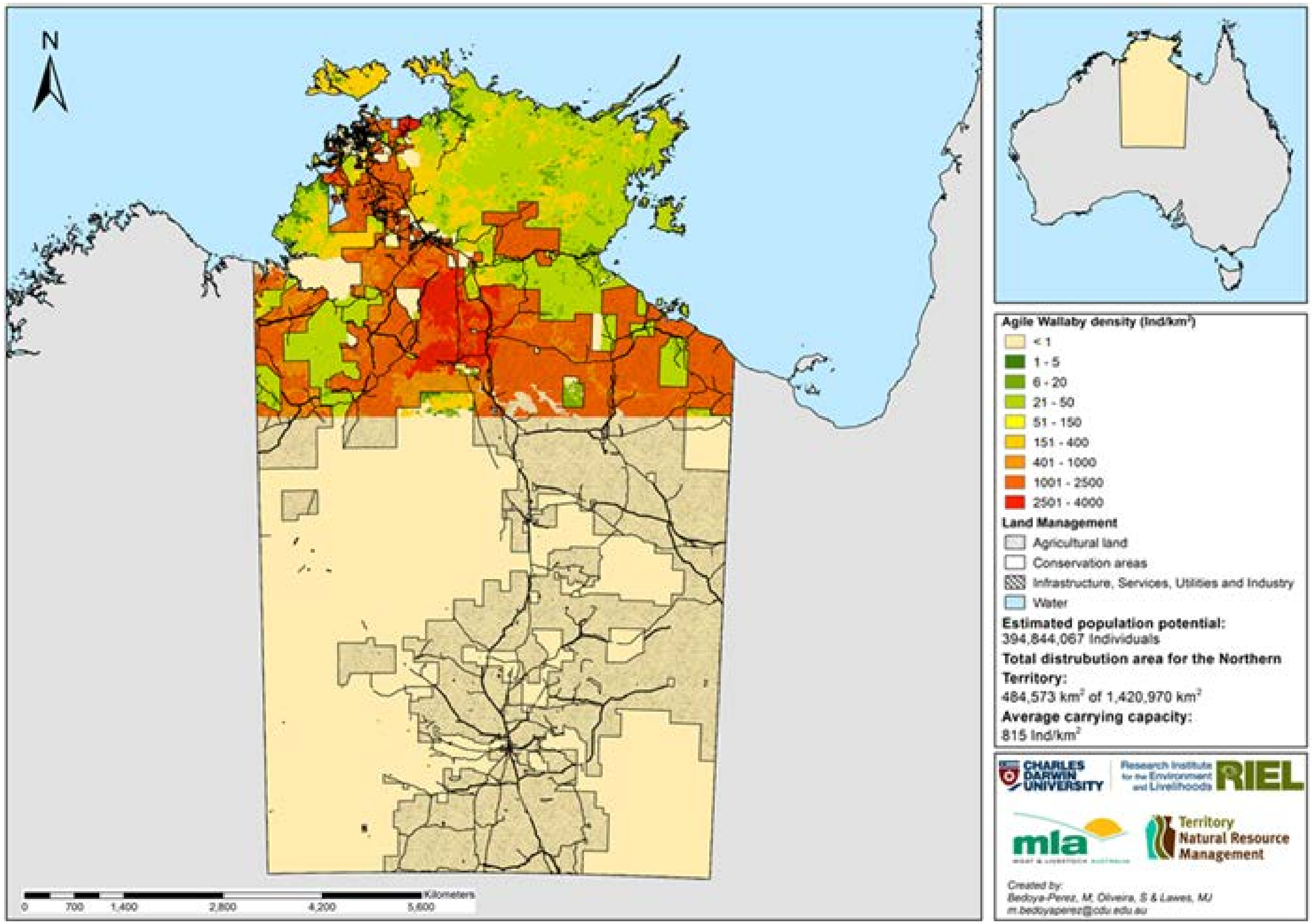

Figure 22. Estimates of carrying capacity (ind/km^2) of the agile wallaby (*Macropus agilis*) population within its Northern Territory distribution, stratified by land use. The estimates are based on National Vegetation Identification System: Major Vegetation Groups (NVIS)(DEE 2012), hydrological information regarding distance to any water sources (Williams 2011a; Williams 2011b); 2009-2008 Annual Rainfall (mm) (BRS 2009); 2010-2011 Northern Territory Pastoral Leases (DLPE 2015); Land use of Australia (ACLUMP 2014); Department of Primary Industries and Fisheries cattle carrying capacity by land type, and current extend of improved pasture usage.

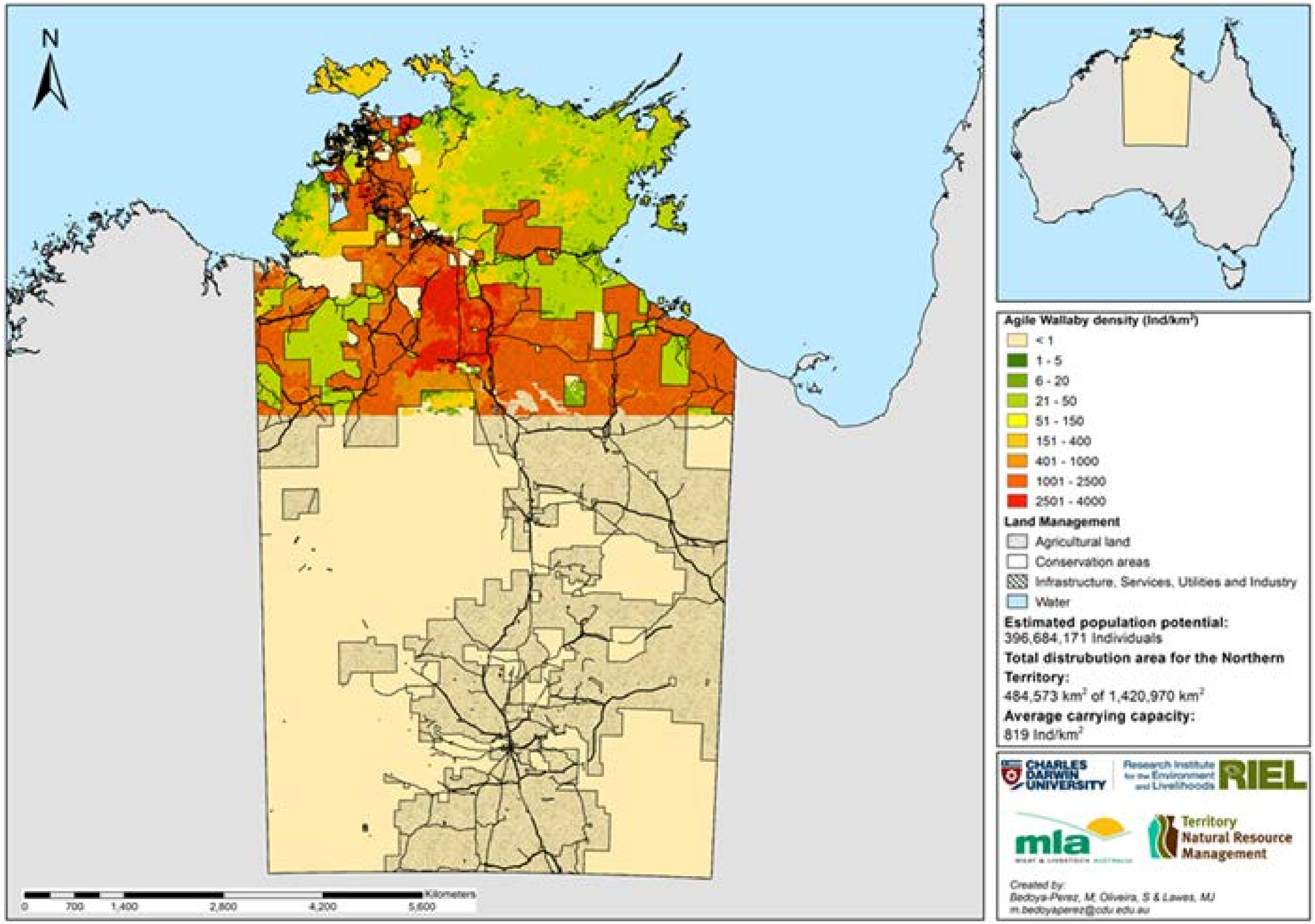

Figure 23. Estimates of carrying capacity (ind/km^2) of the agile wallaby (*Macropus agilis*) population within its Northern Territory distribution, stratified by land use. The estimates are based on National Vegetation Identification System: Major Vegetation Groups (NVIS)(DEE 2012), hydrological information regarding distance to any water sources (Williams 2011a; Williams 2011b); 2009-2008 Annual Rainfall (mm) (BRS 2009); 2010-2011 Northern Territory Pastoral Leases (DLPE 2015); Land use of Australia (ACLUMP 2014); Department of Primary Industries and Fisheries cattle carrying capacity by land type, and projected improved pasture usage.

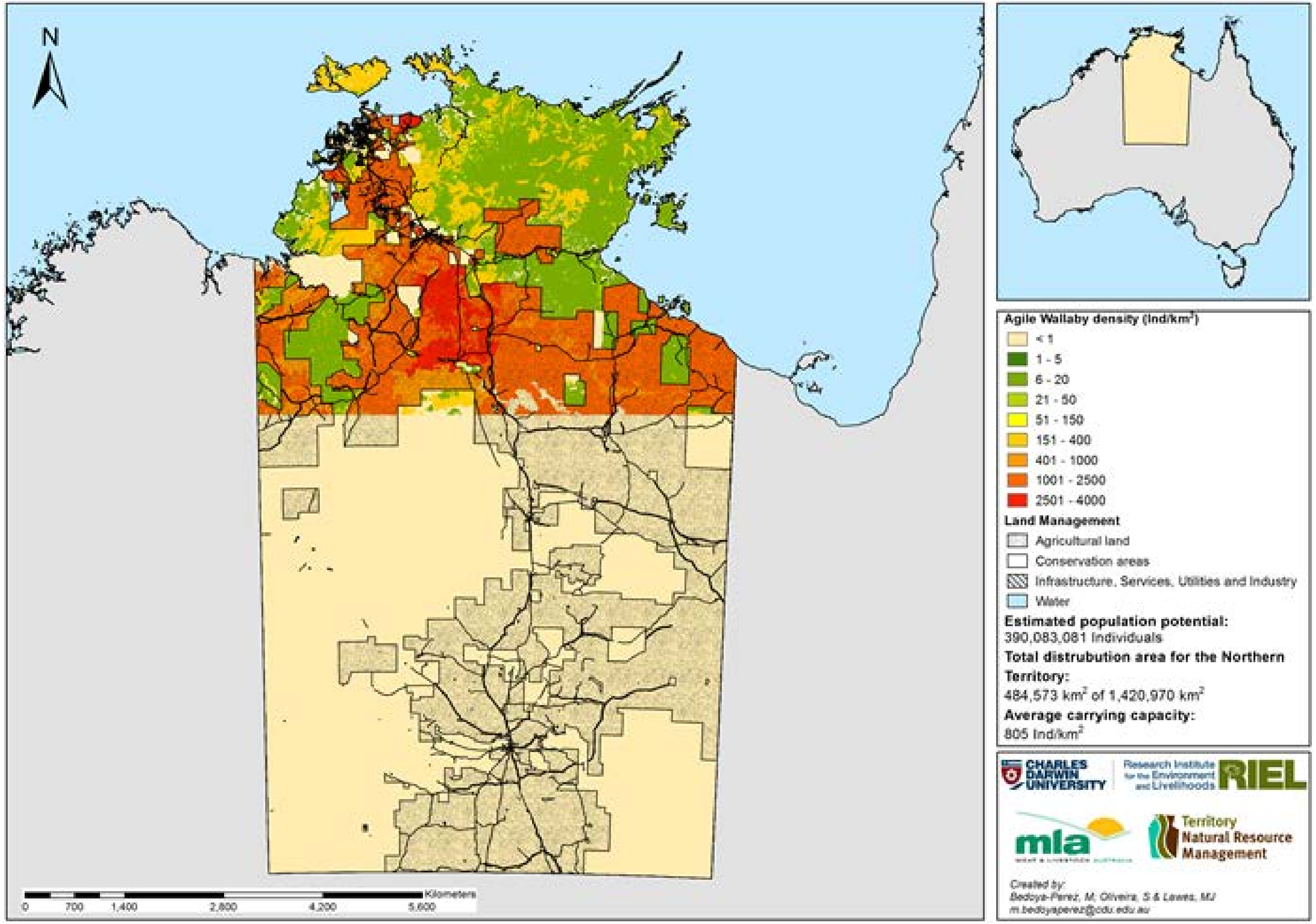

Figure 24. Estimates of carrying capacity (ind/km^2) of the agile wallaby (*Macropus agilis*) population within its Northern Territory distribution, stratified by land use. The estimates are based on National Vegetation Identification System: Major Vegetation Groups (NVIS)(DEE 2012), hydrological information regarding distance to permanent water sources (Williams 2011a; Williams 2011b); 2009-2008 Annual Rainfall (mm) (BRS 2009); 2010-2011 Northern Territory Pastoral Leases (DLPE 2015); Land use of Australia (ACLUMP 2014); Department of Primary Industries and Fisheries cattle carrying capacity by land type, and current improved pasture usage.

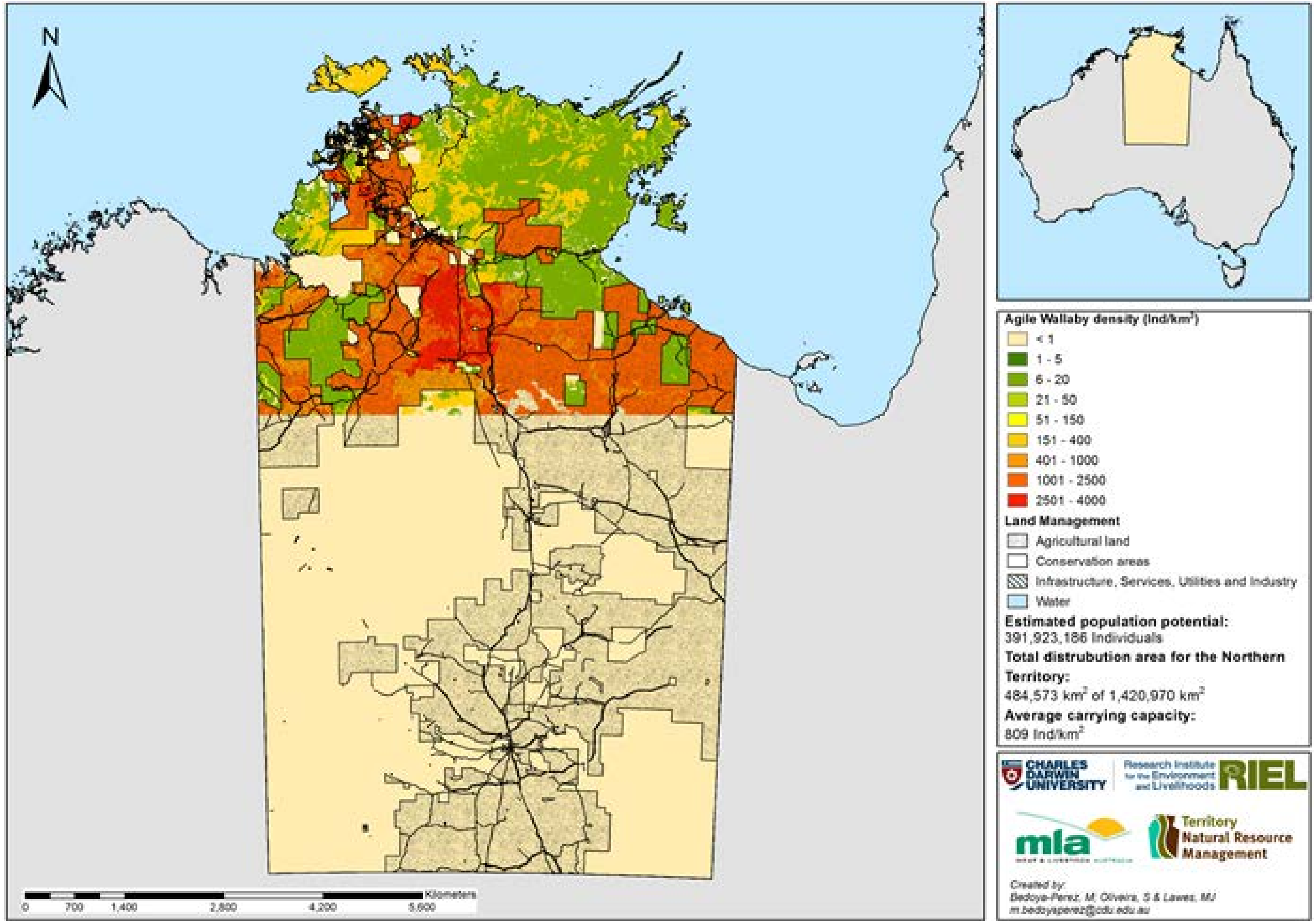

Figure 25. Estimates of carrying capacity (ind/km²) of the agile wallaby (*Macropus agilis*) population within its Northern Territory distribution, stratified by land use. The estimates are based on National Vegetation Identification System: Major Vegetation Groups (NVIS)(DEE 2012), hydrological information regarding distance to permanent water sources (Williams 2011a; Williams 2011b); 2009-2008 Annual Rainfall (mm) (BRS 2009); 2010-2011 Northern Territory Pastoral Leases (DLPE 2015); Land use of Australia (ACLUMP 2014); Department of Primary Industries and Fisheries cattle carrying capacity by land type, and projected improved pasture usage.

Table 14. Current estimates and carrying capacity of agile wallabies (Ind.km^{-2}) within the species Northern Territory distribution, based on distance to water (permanent and perennial/permanent) and use of improved pastures (current and projected), stratified by land use: Conservation areas, agricultural land, grazing in native pastures and grazing/cropping on improved pastures.

Stratification	*Max (ind.km^{-2})*	*Mean $_{(95\% CI)}$ (ind.km^{-2})*
Current density based on distance to perennial water		
Conservation areas	1,584.5	52.6$_{(52.4-52.9)}$
Agricultural Land	2,276.4	149.1$_{(148.1-150.0)}$
Grazing in native pastures	1,658.8	143.2$_{(142.3-144.1)}$
Improved pastures and hay cropping	2,276.4	545.5$_{(534.1-556.9)}$
Current density based on distance to permanent water		
Conservation areas	1,584.5	32.4$_{(32.2-32.7)}$
Agricultural Land	2,276.4	149.0$_{(148.1-150.0)}$
Grazing in native pastures	1,658.8	142.7$_{(141.7-143.6)}$
Improved pastures and hay cropping	2,276.4	545.4$_{(534.0-556.9)}$
Carrying capacity based on distance to any water and current improved pasture use		
Conservation areas	3,062.5	74.6$_{(74.0-75.3)}$
Agricultural Land	3,855.0	1,663.8$_{(1,661.1-1,666.4)}$
Grazing in native pastures	3,855.0	1,655.6$_{(1,653.0-1,658.2)}$
Improved pastures and hay cropping	3,855.0	2,386.4$_{(2,359.6-2,413.2)}$
Carrying capacity based on distance to any water and projected improved pastures use		
Conservation areas	3,647.1	75.1$_{(74.5-75.8)}$
Agricultural Land	3,855.0	1,671.7$_{(1,669.0-1,674.4)}$
Grazing in native pastures	3,855.0	1,656.3$_{(1,653.6-1,658.9)}$
Improved pastures and hay cropping	3,855.0	2,804.7$_{(2,771.2-2,838.1)}$
Carrying capacity based on distance to permanent water and current improved pasture use		
Conservation areas	3,062.5	55.7$_{(55.0-56.3)}$
Agricultural Land	3,855.0	1,663.7$_{(1,661.1-1,666.4)}$
Grazing in native pastures	3,855.0	1,655.6$_{(1,653.0-1,658.2)}$
Improved pastures and hay cropping	3,855.0	2,386.3$_{(2,359.6-2,413.1)}$
Carrying capacity based on distance to permanent water and projected improved pasture use		
Conservation areas	3,647.1	56.2$_{(55.5-56.8)}$
Agricultural Land	3,855.0	1,671.6$_{(1,668.9-1,674.3)}$
Grazing in native pastures	3,855.0	1,656.2$_{(1,653.6-1,658.9)}$
Improved pastures and hay cropping	3,855.0	2,804.6$_{(2,771.2-2,838.0)}$

7.6 Logistics and costs associated with management

Estimates of shooting costs per hour were obtained from wildlife managers practitioners (ABS Scrofa Pty Ltd). Cost of shooting varied according to the strategy used by the shooters. Hiring professional shooters under contract, the costs can vary between $440.96 per hour and $823.63 per hour. If the shooters are allowed to sell carcases as part-payment, and no contract is made, the cost of shooting with basic equipment (i.e. centre point 22 magnum rifle and spotlight) can vary between $137.50 to $163.63 per hour. We decided to based our cost estimates on two shooters, on a vehicle, with basic equipment (i.e. centre point 22 magnum rifle and spotlight), and use $137.50 per hour.

Shooting efficiency – number of animals shot per animals seen - varied between 18% and 37% depending on wallaby abundance, with a maximum of 60 animals shot per hour, if collection of the carcases is not required, and 30 animals shot per hour, if carcases are collected. The relationship between cost per animal removed and wallaby density, was best modelled using an exponential equation (equation 2) (R^2 = 0.991), and to a lesser extent a power equation (equation 3) (R^2 = 0.892) (Figure 38).

$$\beta = 12.960 + 314.549e^{-0.007\alpha} \qquad (2)$$

$$\beta = 497.193\alpha^{-0.294} \qquad (3)$$

Equations 2 and 3: Were β is the cost per animal removed in AU$ and α is the number of wallabies per square kilometre.

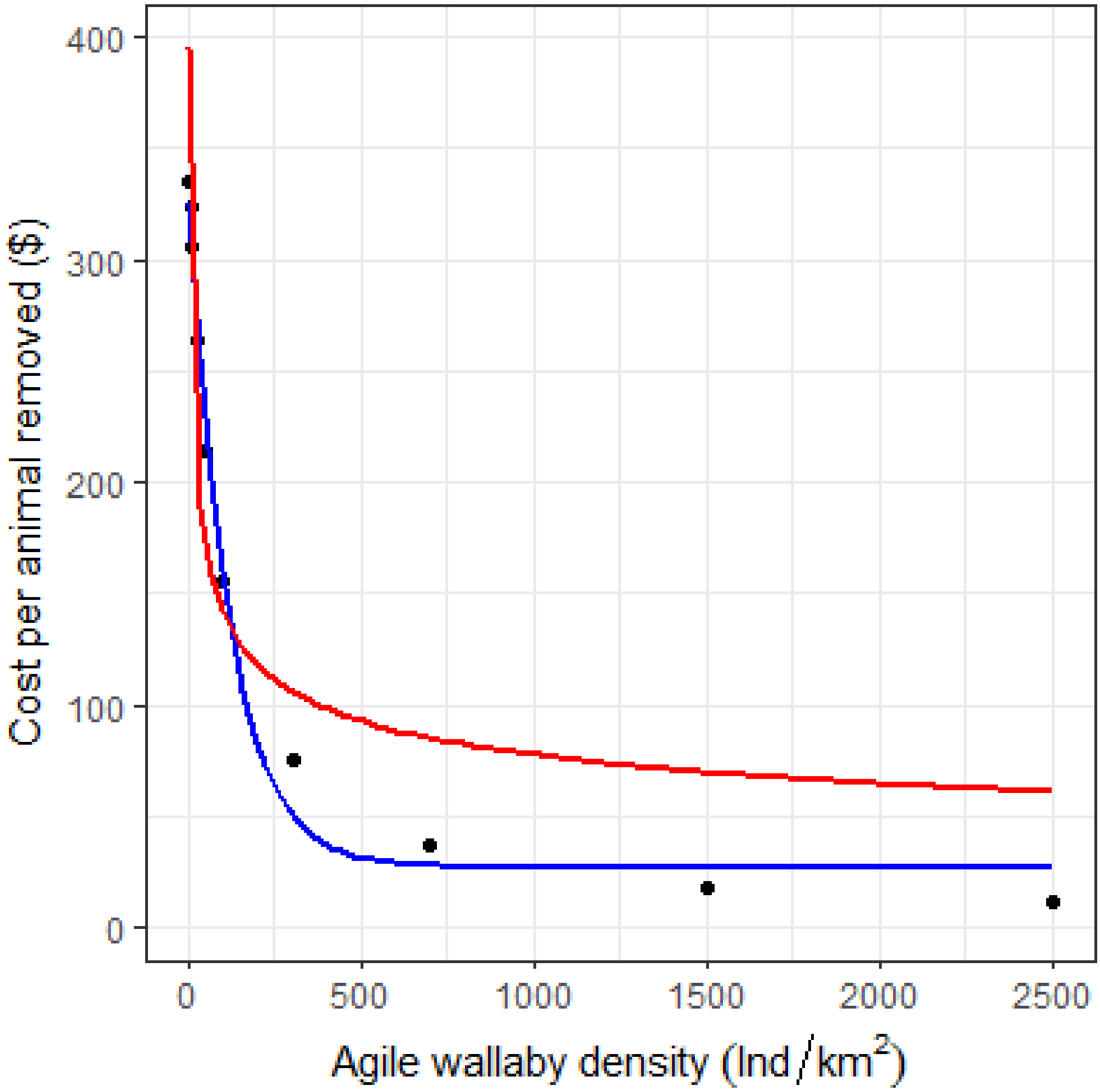

Figure 26. Power (red) and exponential (blue) functions fitted to data obtained from ABS Scrofa Pty Ltd, showing the relationship between wallaby density (Ind/km^2) and cost per animal removed, calculated from reported shooting efficiency.

The area designated for active management of Agile Wallabies, constructed from cadastre and land use information (ACLUMP 2014; DLPE 2015), includes 227,020 km^2, representing 46.8% of the entire distribution of the species in the Northern Territory (Figure 27). The designation of this management area is based on the current management approach for large macropod species, where all culling occurs outside nature reserves and national parks, which are consider refugia for the species.

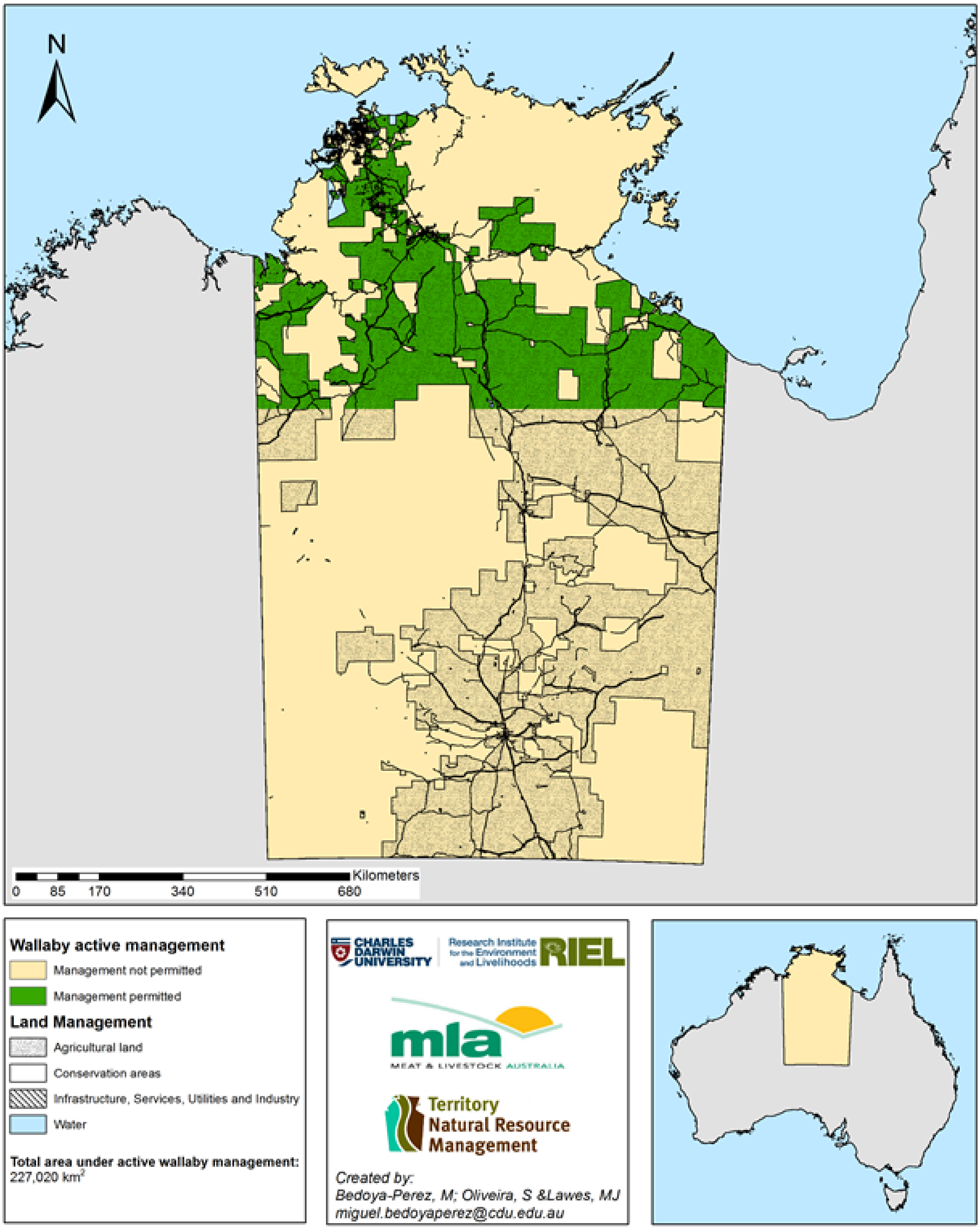

Figure 27. Map of the areas where management of agile wallabies would be permitted, constructed from cadastre and land use information (ACLUMP 2014; DLPE 2015) and based on the current management approach for large macropod species where all culling occurs outside nature reserves and national parks, which are consider refugia for the species.

Comparing the costs of control by shooting only (based on equations 2 and 3), with the costs experienced by producers based on the reported Adult Equivalent (AE) to 24.5 individual agile wallabies, the calculated 26.8 wallabies (95% CI 0.03- 27) per AE (see section 7.3); and the current minimum price per kilogram of live weight for medium cows (See Table 8 for AE scores); wallaby management by culling only, is feasible for properties with wallaby populations higher than 1,854.0 Ind/km^2 (95% CI 846.7-3,755.6)(Figure 28).

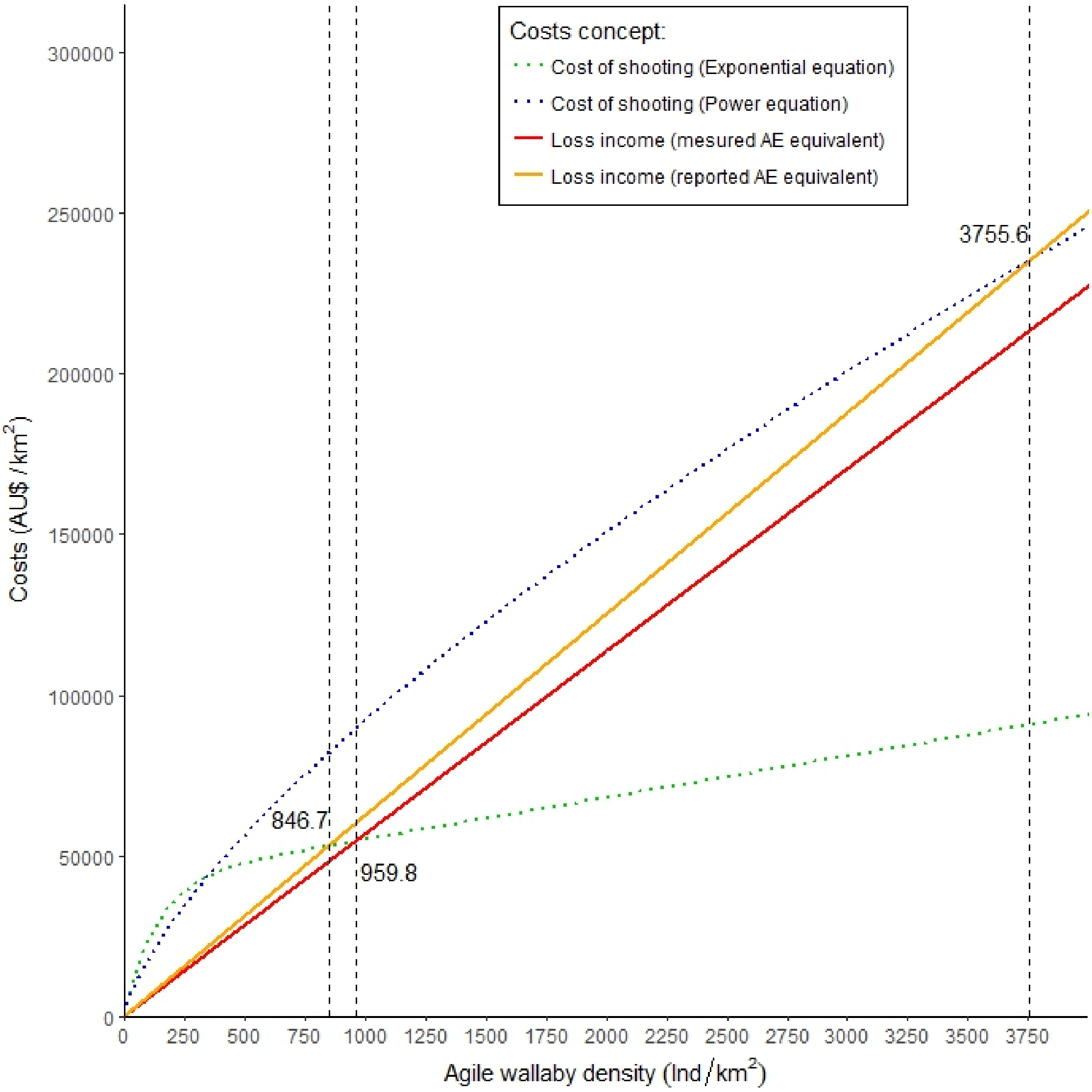

Figure 28. Estimation of minimum agile wallaby population (Ind/km^2) required to make investment in control by shooting economically feasible. The yellow and red lines represent the costs to production, derived either by AE=24.5 wallabies (yellow line) or AE=27 wallabies (red line) in relation to wallaby population per year. The green and blue dashed curves represent the fitted models for cost of culling by shooting either exponential (green line) or power (blue line) in relation to wallaby population per year. The vertical black dashed lines denote the cut-off minimum wallaby populations for investment in control to be feasible (shooting function crosses the costs to production function), and the actual wallaby population size cut-off values are shown next to each cut-off line.

Finally, incorporating the estimated cost of fencing initial wallaby populations as low as 40.5 Ind/km^2 (95% CI 24.6-62.6), could warrant management by fencing and shooting with returns within 5 years (Figure 29).

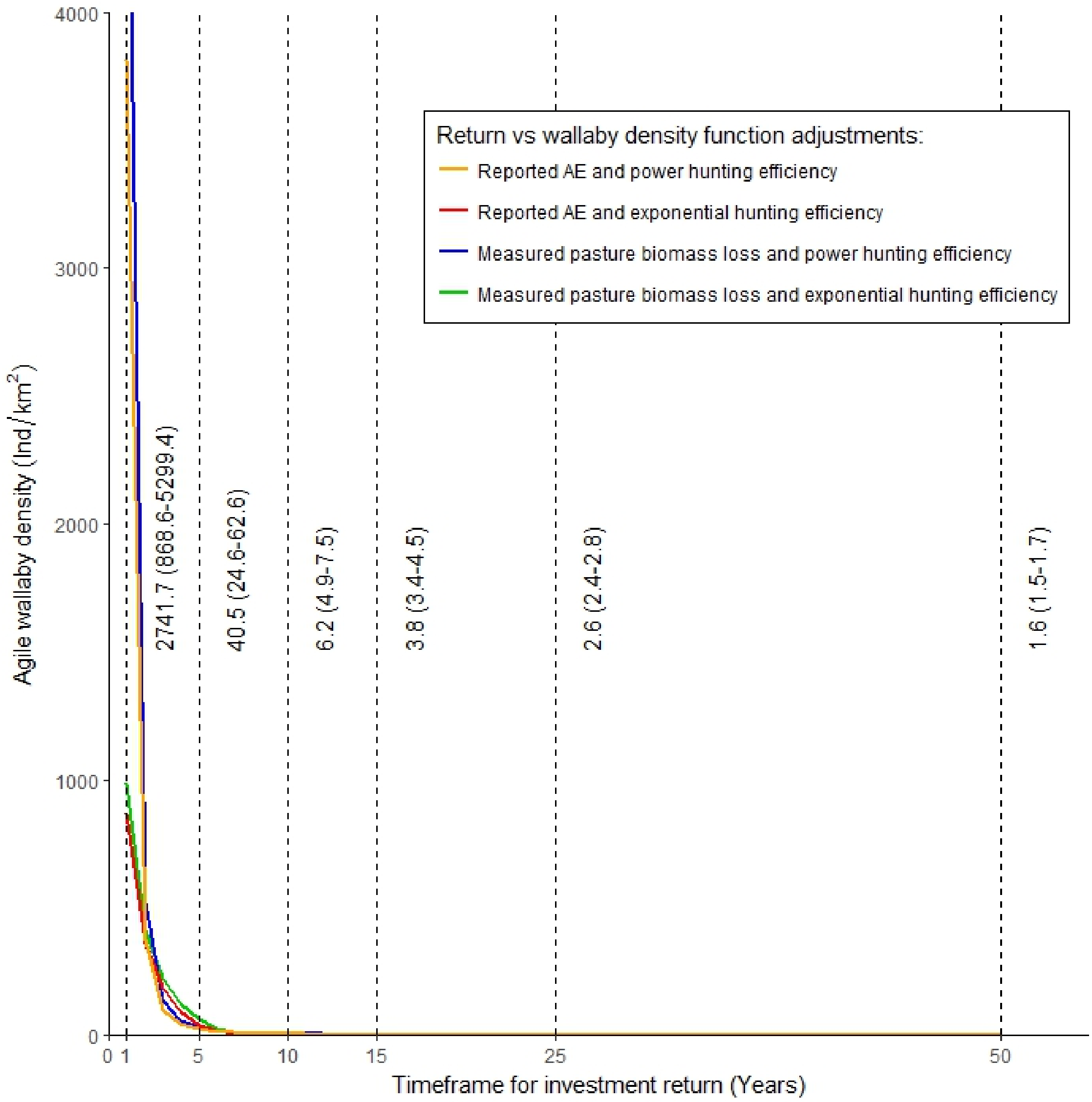

Figure 29. Estimation of minimum agile wallaby population (Ind/km^2) required to make investment in control by wallaby proof fencing and culling economically feasible within 1 to 50 years. The yellow, red, green and blue curves represents the fitted models incorporating cost of fencing and cost of culling by shooting (either exponential or power functions) in relation to costs to production (either by AE=24.5 wallabies or AE=27 wallabies) and wallaby population per year. The lines were drawn by fixing the net costs as 0 (cost of control methods – costs to production = 0). The vertical black dashed lines denote the cut-off timeframes for investment return (1, 5, 10, 15, 25 and 50 years) The average (minimum – maximum) initial wallaby density required to warrant investment in fencing and culling are shown next to each timeframe cut-offs lines.

7.7 Spatial Population Abundance Dynamics Engine (SPADE)

As explain above (see section 6.7), due to programing issues, SPADE did not produce consistent results. We are committed to continue to work alongside SPADE programmers to solve these issues and test the management scenarios already conceptualized.

Notwithstanding these issues, the spatially explicit estimates of wallaby density, carrying capacity and loss to production (see sections 7.3, 7.5 and 7.6) allowed a more in depth assessment of the economic losses currently experienced by farmers, the expected losses if the wallaby population is not control, and the projected losses based on the extent of improved pastures - see section 6.5 regarding 2010 Pastoral Industry Survey (Cowley et al. 2010), and White paper on Developing Northern Australia (Abbott et al. 2015).

In Table 15, we show estimated costs to cattle production based on AE to 24.5 wallabies equivalent and the projected potential for agile wallabies population increase within agricultural land.

Table 15. Estimates of current, expected and projected costs to cattle production based on wallaby density, carrying capacity, pasture biomass consumption (1 AE = 24.5 wallabies) by wallabies and current minimum price per kilogram of live weight for medium cows ($2.29 per kg lwt) and heavy steers ($3.66 per kg lwt) of brahma (*Bos indicus)* and cross breeds (See Table 8 for AE scores), stratified by improved pastures use.

	Brahma, Bos indicus				*Cross breeds*			
	Medium cows		*Heavy steers*		*Medium cows*		*Heavy steers*	
	Mean$_{(95\% CI)}$ ($/km^2/yr)	Max ($/km^2/yr)	Mean$_{(95\% CI)}$ ($/km^2/yr)	Max ($/km^2/yr)	Mean$_{(95\% CI)}$ ($/km^2/yr)	Max ($/km^2/yr)	Mean$_{(95\% CI)}$ ($/km^2/yr)	Max ($/km^2/yr)
Current								
Agricultural Land	5,511.8$_{(4,264.2-6,926.2)}$	76,593.2	20,575.6$_{(7,744.6-32,940.6)}$	364,272.5	5,832.2$_{(4,541.1-7,290.7)}$	80,624.5	21,555.4$_{(11,395.6-33,881.8)}$	374,680.3
Native pastures	5,285.5$_{(4,088.8-6,642.4)}$	76,593.2	19,731.1$_{(7,426.2-31,590.9)}$	364,272.5	5,592.8$_{(4,354.4-6,992.0)}$	80,624.5	20,670.7$_{(10,927.32,493.5)}$	374,680.3
Improved pastures	20,169.9$_{(15,374.9-25,714.1)}$	105,107.9	75,294.8$_{(27,923.8-122,294.4)}$	499,886.5	21,342.6$_{(16,373.2-27,067.4)}$	110,639.9	78,880,3$_{(41,087.9-125,788.5)}$	514,169.0
Expected								
Agricultural Land	61,520.2$_{(47,821.4-76,944.5)}$	141,407.1	229,656.7$_{(86,853.0-365,943.2)}$	672,925.0	65,097.0$_{(50,926.6-80,994.2)}$	148,850.0	240,592.7$_{(127,798.0-376,398.7)}$	691,740.0
Native pastures	61,219.0$_{(47,587.8-76,567.0)}$	141,407.5	228,532.4$_{(86,428.8-364,147.7)}$	672,525.0	64,778.3$_{(50,677.9-80,596.8)}$	148,850.0	239,414.9$_{(127,173.8-374,551.9)}$	691,740.0
Improved pastures	88,239.5$_{(67,929.2-111,424.2)}$	178,000.0	329,400.4$_{(123,372.8-529,926.4)}$	846,558.0	93,369.7$_{(72,340.2-117,288.6)}$	187,368.7	345,086.1$_{(181,534.3-545,067.1)}$	870,745.4
Projected								
Agricultural Land	61,811.9$_{(48,046.5-77,312.0)}$	168,400.8	230,745.6$_{(87,261.9-367,690.8)}$	800,903.2	65,405.6$_{(51,166.4-81,381.0)}$	177,264.0	241,733.5$_{(128,399.6-378,196.2)}$	823,786.1
Native pastures	61,242.3$_{(47,605.776,596.2)}$	168,400.8	228,619.1$_{(86,461.4-364,286.7)}$	800,903.2	64,802.9$_{(50,697.0-80,627.6)}$	177,264.0	239,505.7$_{(127,221.7-374,694.8)}$	823,786.1
Improved pastures	103,705.3$_{(79,779.3-131,043.3)}$	173,200.5	387,134.7$_{(144,895.0-623,233.4)}$	823,730.6	109,734.7$_{(84,959.8-137,940.3)}$	182,316.3	405,569.7$_{(213,202.6-641,040.0)}$	847,265.8

8 Discussion

8.1 To develop a density–damage function to guide cost-effective management options on pastoral lands

With a maximum adjusted R^2 of 0.549, we successfully fitted a linear function to the data for wallaby density and loss of biomass, showing a linear increase in biomass consume as the wallaby density increases. (Yokomizo et al. 2009). Comparing the estimated dry matter of pasture consumed by wallabies (section 7.3) and the estimated wallaby densities in the area sampled, the previously estimated 24.5 wallabies to 1 Adult Equivalent (AE), seems to match our findings, with an actual estimated ratio of 26.8 wallabies (95% CI 0.03 – 27) to 1 Adult Equivalent (AE).

At the Douglas Daly Research farm, where agile wallaby densities were estimated at 205 ind/km^2 (95% CI 170 - 247), the loss in biomass due to wallabies was 226,366.4 kg/km^2/year (95% CI 132,224.7 – 320,508.0), equivalent to 55.5 Adult Equivalent (AE)/km^2/year (95% CI 24.9 – 96.8) loss in carrying capacity (Figure 8). These new estimates are consistent with our previous estimates derived from direct measurements of pasture biomass (~244,240 kg/km^2/year) (Bedoya-Pérez et al. 2015). However, the data contrast noticeably with the estimated losses in carrying capacity, based on Livestock producers' questionnaires - i.e. $6.7 to $214 km^2/year on Native Pastures, $238 to $500 km^{-2} $year^{-1}$ on improved pastures, and a maximum of $857 km^2/year for properties that produce hay for cattle feed (Bedoya-Pérez et al. 2015). Assuming the current minimum price per kilogram of live weight for medium cows ($2.29) and heavy steers ($3.66) (Thomas 2016), this loss in carrying capacity can represent up to $122,007.7 per km^2/year (95% CI 28,830.7 – 320,185.8).

8.1.1 <u>Based on population modelling (Spatial Population Abundance Dynamics Engine-. SPADE)</u>

Using SPADE, we were able to carry out a more in depth assessment of the economic losses currently suffered by farmers, the expected losses if the wallaby population is not controlled, and the projected losses based on the extent of improved pastures - see section 6.5 regarding 2010 Pastoral Industry Survey (Cowley et al. 2010), and White paper on Developing Northern Australia (Abbott et al. 2015).

Comparing our estimates of economic losses, the cost of the current alternatives for control, and the potential increase in revenue after management, it appears that wallaby management needs to be assessed at the property level. On properties with improved pastures and irrigation (average Top End property 497 km^2 with an average paddock size of 29 km^2) the estimated cost of wallaby proof fencing is $987.9 per km^2 in materials and $81.9 per km^2/year in labour and maintenance (Caley 1999; DPIF 2008). Additionally, the cost of management by shooting ($137.50 to $163.63 per hour, with an efficiency varying between 18% and 37%, and a maximum of 60 animals shot per hour) increased exponentially as wallaby abundance declined. For this level of investment to be economically viable, each property first needs to estimate how much it is actually losing due to wallabies (Statham and Statham 2013).

According to our estimates some properties may experience as little as $5,511.8 per km^2/year (95% CI 4,264.2-6,926.2), but these are mostly properties with rangeland production in large paddocks (>100 km^2). In these cases, fencing is not feasible, since there are no effective ways of excluding the wallaby population from the paddock before or after fencing. Considering the cost of culling as an alternative, these properties may not have an effective wallaby control method and may have to accept these losses to wallabies.

On the other hand, properties experiencing greater economic losses due to wallabies, mainly those with improved pastures in smaller paddocks - our current estimate $78,880.30 per km^2/year (95% CI 41,087.9-125,788.5) – can definitely benefit from both fencing and culling. In these cases, the best approach for producers is a combination of fencing followed by shooting. This is especially true for producers that are not currently using improved pastures but are planning to do so, who would benefit from creating smaller paddocks with wallaby proof fencing and controlling the local populations of wallabies by culling. This scenario is set to become more common for farmers in Northern Australia under the current Developing the North Initiative (Abbott et al. 2015).

8.2 To determine the collateral effects of managing wallabies;

8.2.1 Potential shifts in grass species caused by grazing pressure in native woodland and pastoral properties

In contrast with our previous assessment (Bedoya-Pérez et al. 2015), wallaby densities did not affect pasture composition significantly (no difference in species Richness, Simpson's and Shannon's Diversity Indexes, and Simpson's and Shannon's Evenness Indexes), although all indices were lower for wallaby impacts than those by cattle (Figures 21 to 25). Based on this, we have no clear evidence to suggest that wallaby densities are causing changes to the grass layer. It is possible that these results may be an artefact of the current vegetation community in the area sampled, since it was evident during sampling, that most species were introduced either deliberately or by accident.

8.2.2 To determine if management of wallabies on pastoral land has the potential to create artificial wallaby sinks, negating the effectiveness of wallaby management

Based on our wallaby tracking survey, as well as the published data on Agile Wallaby home range (Stirrat 2003), we have no direct evidence to suggest managing wallaby populations would create an artificial wallaby sink in agricultural land (which would allow the population in native habitat to increase in abundance). However, due to difficulties obtaining the appropriate permits and licenses, we weren't able to measure directly the behavioural response of wallabies to lethal control. Ideally, the spatial response of the species to lethal control should be measured, as it has been done in the past with other species of macropods (Wiggins et al. 2010a; Wiggins et al. 2010b; Wiggins and Bowman 2011).

Wiggins et al. (2010a) and Wiggins and Bowman (2011) found in similar sized macropods, that lethal intervention (culling) caused slight shifts in their home range, an increase in the use of agricultural habitat but no change in the home range size. Assuming Agile Wallabies react in a similar way, it is unlikely that removal of individuals will create an artificial wallaby sink in agricultural land. However, monitoring during management would be crucial to detect any management effect.

8.3 To explore if there is a benefit to livestock producers and land managers of wallaby control in native habitat

With the data collected, is difficult to determine if there is any benefit from managing Agile Wallabies on non-grazed lands. As described in section 8.2, we detected no shift in grass species due to wallaby grazing. Furthermore, individuals did not preferentially move from unmanaged to a managed area. Therefore, management of wallabies on non-grazed areas is more likely to increase the costs of management for very little perceived benefit.

However, although not tested in this project, when similar size macropods have been managed by using fencing barriers, there has been a notable reduction in their use of agricultural land (Wiggins et al. 2010a). Although the cost of fencing is seen by producers as prohibitive, our results suggest that in comparison and in conjunction with culling, fencing may be a more cost-effective alternative. However, fencing can be logistically unfeasible and economically in properties with rangeland production, since paddocks in these properties are considerable larger than paddocks in properties with improved pastures, making management by shooting after fencing extremely difficult to achieve.

8.4 To identify general concepts and recommendations for implementation of a wallaby management plan that can be demonstrated to improve the feed base of pastoral landholders

From the evidence we have gathered so far, an Agile Wallaby management plan for the Northern Territory should comprise:

- A property specific evaluation of the costs and benefits of wallaby control. Every property is different, and management methods that are successful on one property may not be applicable on another.
- Multi-targeted approach. No one method of control is infallible, and combining several methodologies to accomplish specific goals will be more successful.
- Subsidiary off-takes. Management is expensive, and a way of reducing this cost is to obtain an economic benefit from the management method. For example, if the Agile Wallaby management plan includes culling of individuals, the carcases could be processed to obtain products for commercialization (e.g. meat for human and/or pet consumption, skins for the leather and pelt industry, bones and organs for fertilizer). Any economic benefit obtained from this process could reduce the net cost of management.

Some of the potential constraints we have identified are:

- The extent of the geographical area that requires management.
- The potential scarcity of trained wildlife managers (e.g. shooters).
- Animal Welfare issues.

The main economic opportunity we have identified is the potential development of an enterprise producing meat and fertilizer supplements from a wallaby harvesting program. This approach may increase economic productivity from pastoral properties in northern Australia. Harvesting of wallabies will also offer landholders a means of diversification that may assist with the challenges of the future economic landscape. See DPI&F report on economic feasibility of harvesting agile wallabies (Hunt and Mullen 2015)

8.5 To provide insights and recommendations on the feasibility of indigenous wallaby harvest, and the possibility of adding value by culling and marketing meat, skin and bone products

The mayor difficulty with developing a feasible and economically advantageous harvesting program for agile wallabies is the cost related to the maximum shooting efficiency (See figures 26 and 28).

As part of a separate initiative born out of the collaboration between researches involved in this project and the Department of Primary Industries and Fisheries NT, research funded by the Rural Industries Research and Development Corporation between 2015-18 addressed the economic feasibility of developing a harvesting initiative. This research included analyses into the biophysical aspects of harvesting wallabies, such as: carcass yields, meat qualities, meat safety, and the protein composition characteristics of Agile Wallaby skins. This project reaches a similar conclusion as the one reported here, recognizing that the harvesting of agile wallabies relies heavily in economic margins that at present appear to be very tight or non-existent. See DPI&F report on economic feasibility of harvesting agile wallabies (Hunt and Mullen 2015)

8.6 Draft outlines of at least two journal manuscripts.

Although based on preliminary data, we expect to publish the following journal manuscripts:

- "*Developing a cost-benefit analysis for native pest herbivore management by combining spatio-temporal modelling and socio-economic data*". Based on population and management scenario modelling.
- *"Land use and environmental factors affecting Agile Wallaby abundance: Yet another macropod favoured by agricultural practices?"* Based on wallaby surveys and grazing pressure measurements on improved vs native pastures.
- *"Female bias sex ratio in joeys born to agile wallaby females in agricultural landscapes".* Based on demographic data
- *"Drop nets: A new technique for capturing medium sized macropods".* Based on agile wallaby capturing records.
- *"Agile wallaby density-dependent fecundity: Are females more fertile when there are no other competitors".* Based on demographic data.

8.7 Convene stakeholder meetings to describe focus, funders and service providers for implementation/validation of northern Australia Stage 3 wallaby management plan.

8.8 Document in-principle support (cash and in-kind) from stakeholders to implement a Stage 3 project.

Due to the complexities related to the agile wallaby populations, their dynamics and effects on cattle production, a management needs to be concerted at property by property scale and it would greatly depend on the specific objectives and plans that each cattle producer has. Therefore, is extremely difficult to develop and implement an all-encompassing agile wallaby management plan, let alone, organize single sources of economic or in-kind support for its implementation.

8.9 Develop a draft wallaby management plan and send it for evaluation by the Steering Committee.

As stated previously the complexities related to the agile wallaby populations, their dynamics and effects on cattle production, as well as the specific goals of each cattle producer, greatly affect the management approach. Therefore, here we have opted to present a series of recommendations and decision making tools that can be used by producer in order to understand and talked their individual needs according to their specific situations.

9 Conclusions and Recommendations

The implementation of an Agile Wallaby management plan in the Northern Territory will be complex and difficult. Currently, no clear strategy for removal of wallabies is cost-effective at a Northern Territory scale, and logistics relating to personnel and the vast area requiring management are the most limiting hurdles a management plan will face. Moreover, the feasibility of obtaining subsidies through revenue from wallaby harvesting seems promising, but is still to be determined by DPI&F (See Hunt and Mullen 2015). Therefore, we consider that wallaby management must be approached at regional/property level. Below we offer a decision tree to help the decision making process according to the specific conditions of each producer/property or even region (Figure 30). This decision tree could also be applied a smaller scale, in cases where the wallaby populations are localized. It's important to note that the key aspects that need to be evaluated at a property by property basis are the current wallaby population, and the loss in pasture due to wallabies. We believe that this report, and previously publish tools (Statham and Statham 2013) can also offer guidance to farmers to estimate these.

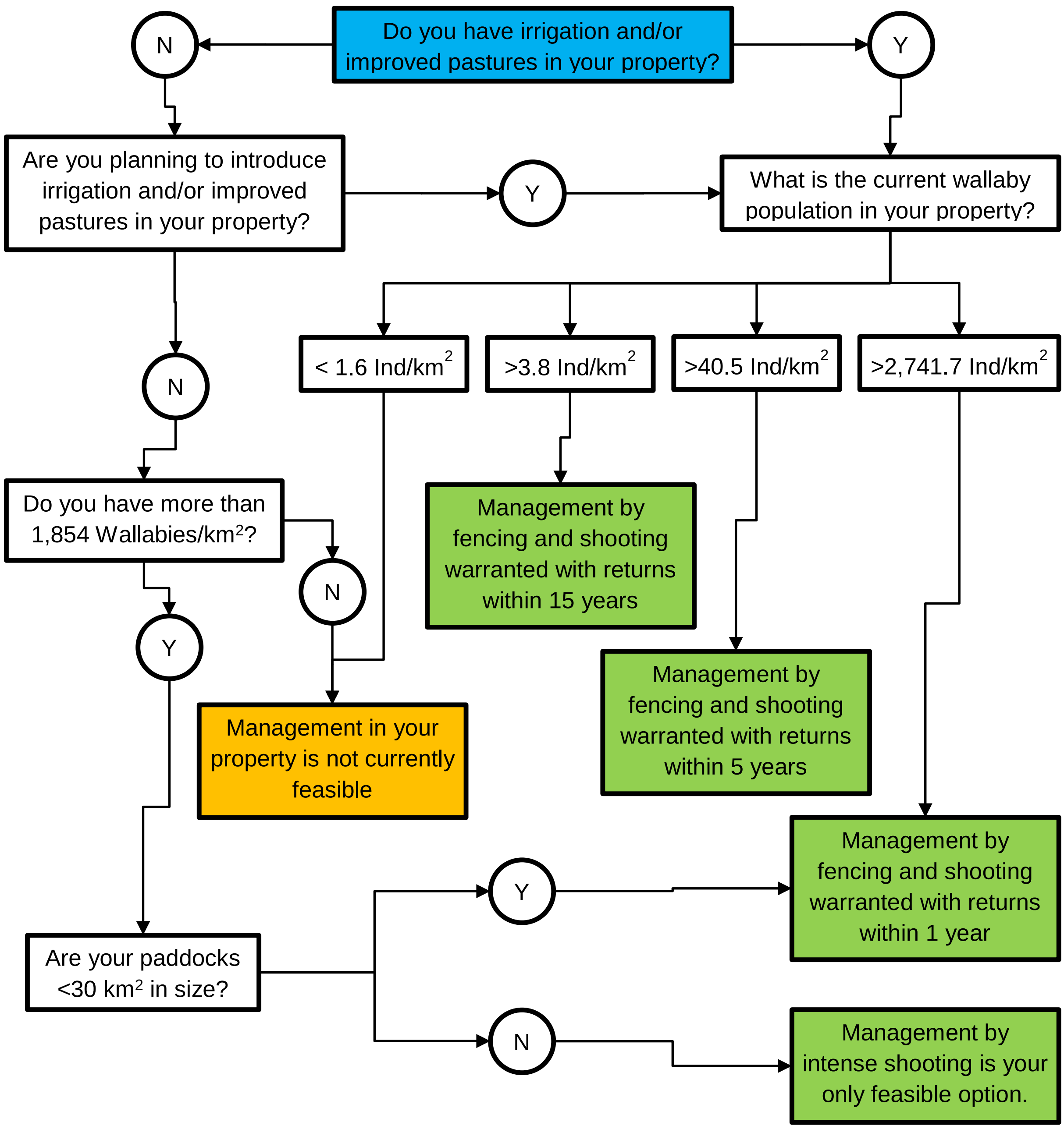

Figure 30. Decision map tool to be used by cattle producers in order to determine the best, economically feasible, option for management of agile wallabies in their property. Blue box represents the starting point, green boxes depict the scenarios where management is feaseable, and the yellow box depict the scenario where management is not warranted.

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11 Appendices

11.1 Appendix 1. Macropod management and ecology relevant literature collated up to March, 2015.

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11.2 Appendix 2. Measurements and characteristics taken from each individual obtained for carcases surveys.

- Sex;
- Tail length: measured from the cloaca to the end of the last vertebra at the tip of the tail (Figure 1);
- Pes length: measured from the back of the foot (i.e. heel) to the end of the longest toe, at the base of the claw (Figure 1);
- Tibia length: measured from the top of the knee joint to the bottom of the pes (Figure 1).
- Reproductive state:
    - For females, pouch content an appearance was recorded as:
        - Non-parous (females that have never bred): Pouch small with no skin folds, clean and dry, teats very small (Jackson 2007).
        - Parous (females that have bred previously but not presently): Pouch is small but distinct, dry and dirty, the teats are slightly elongated (Jackson 2007).
        - Pregnant: Pouch pink in colour and glandular in appearance, skin folds may be observed on the lateral margins of the pouch (Jackson 2007).
        - Pouch young present: attached to the teat (Jackson 2007).
            - Pouch young sex
            - Pouch young weight
            - Pouch young head length: from occiput to snout tip (Figure 1)
            - Pouch young head with: maximum width across the zygomatic arches
            - Pouch young crown rum length: Only for very small neonates (Figure 1)
            - Pouch young body length: from snout tip to cloaca (Figure 1)
            - Pouch young tail length: from cloaca to the end of the last vertebra of the tail tip (Figure 1)
            - Pouch young total length: from snout tip to tail tip (Figure 1)
            - Pouch young tibia length: from the knee to the bottom of the pes (Figure 1)
            - Pouch young pes length: from hell to the base of the longest toe, not including the claw (Figure 1).
        - Lactating (young absent from the pouch but still suckling): pouch area large, skin folds flaccid, hair sparse and stained, skin smooth and dark pink, teats elongated and producing milk when pressed (Jackson 2007).
        - Post lactation: with teats expressing only clear liquid and/or regressing (Jackson 2007).
    - For males, testis length and width was recorded.

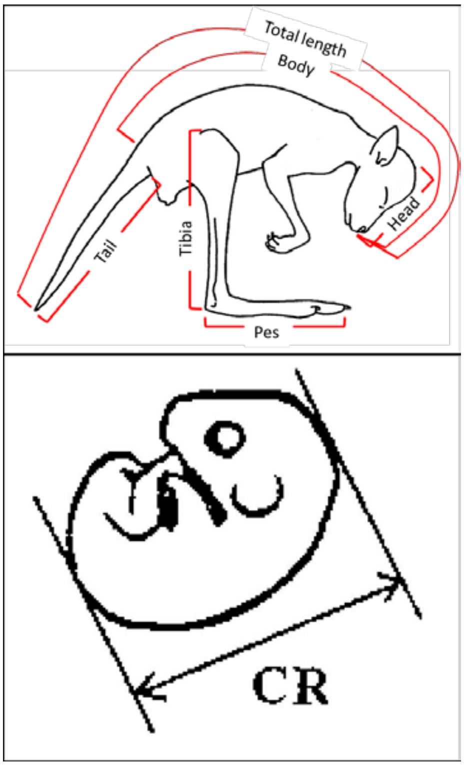

Figure 31. Morphometric measurements recorded for adults and pouch young of agile wallaby. Top panel shows a diagram of different measurements taken for both large pouch young and adult individuals (modified from Sharman et al. (1964)), while the bottom panel shows the Crown Rump (CR) measurement for small neonates.

11.3 Appendix 3. Aging of Agile wallabies using molar eruption (ME) and molar progression (MP).

Molar eruption occurs in all macropod species. It refers to the natural process of the molars erupting from the gum line as the animal ages. Molar progression refers to the forward movement of the teeth as the animals ages, and occurs only in heavy grazer or mixed feeder species of macropods (Sanson 1978; Sanson 1980; Sanson 1989; Jackson 2007). It is worth noting that Agile wallabies *(Macropus agilis)*, as a member of the genus *Macropus*, lacks canine teeth (Sanson 1989), its premolar is significantly reduced (Bensley 1903; Sanson 1978; Sanson 1989), and although with aberrant exceptions, the species has 4 molars in total (Jackson 2007).

Molar index by molar eruption (*ME*) was estimated by observing the proportion of the molar teeth that have erupted from the gum line (Figure 2). Five stages are recognized for each molar, each of which is given decimal notations accumulating in fifths (Table III, Figure 46). Each molar is designated a roman numeral – i.e. m^1 = I to m^4 = IV.

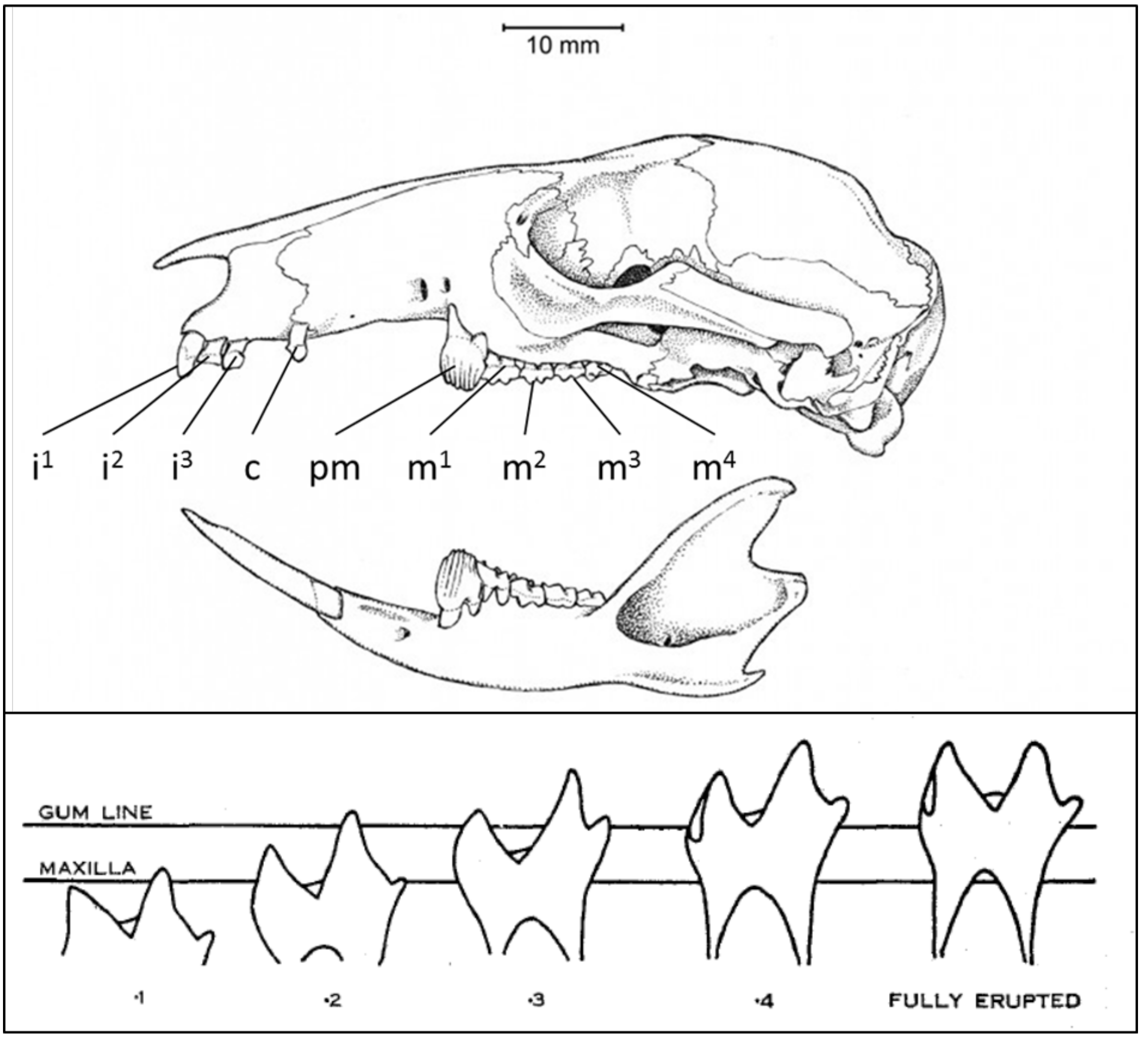

Figure 32. Basic structure of macropod skull and stages of molar eruption used for aging. Top panel shows teeth nomenclature: i^1 = first incisive, i^2 = second incisive, i^3 = third incisive, c = canine, pm = pre-molar, m^1 = first molar, m^2 = second molar, m^3 = third molar, m^4 = forth molar. Modified from Patricia Wynne: Skull of the musky rat kangaroo (*Hypsiprymnodon moschatus*). Bottom panel shows stages of eruption of molar teeth and decimal notation used in Red Kangaroos from Sharman et al. (1964).

Table 16. Eruption stages of partly erupted molars of kangaroos (Sharman et al. (1964))

Notation	*Position of Anterior Loph (cusp)*	*Position of Posterior Loph (cusp)*
.0	Below maxilla	Below maxilla
.1	Through maxilla, below gum	Below maxilla
.2	Just through gum	Through maxilla below gum
.3	Part way between gum and full eruption	Just through gum
.4	Fully erupted	Part way between gum and full eruption

Once the eruption stage was determined, equations for agile wallaby molar eruption (*ME*) (equations 3 and 4) were used to determine the animals age in days (as per Dudzinski et al. (1977)):

For females: $\ln(age) = 5.06 + 0.70ME$ (equation 3)

For Males: $\ln(age) = 5.20 + 0.60ME$ (equation 4)

The wallaby heads were then de-fleshed by boiling them in water for a minimum of 3 hours. Once clean, molar index by molar progression (*MP*) was estimated by observing the position of the nearest molar relative to an imaginary line drawn across the anterior limits of the orbits (Figure 3) (Kirkpatrick 1965; Knowlton 1984; Jackson 2007). A molar index is assign to the skull, in which 10 stages of progression in the molars are recognized and given decimal notations that accumulate in tenths – i.e. 0.1 to 1.0 for m^1, 1.1 to 2.0 for m^2, 2.1 to 3.0 for m^3, and 3.1 to 4.0 for m^4 (Figure 3) (Kirkpatrick 1965; Knowlton 1984; Jackson 2007).

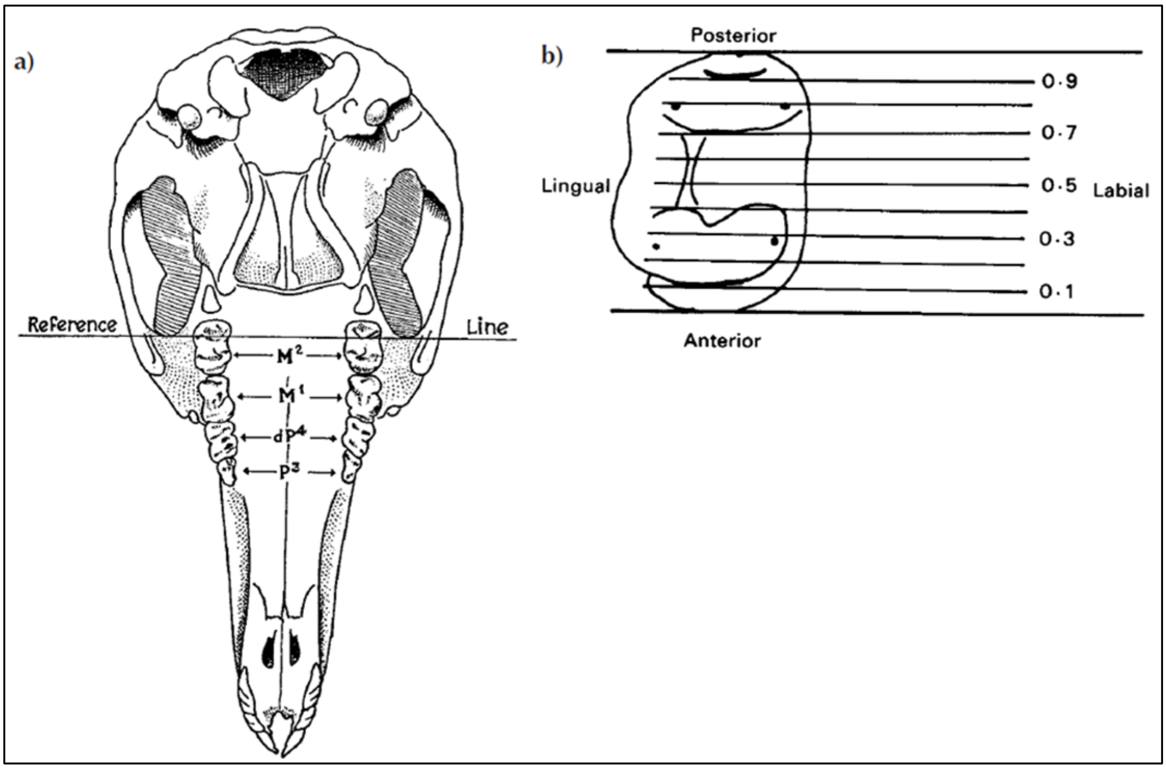

Figure 33. Diagram of macropod skull showing (a) the reference line used for age determination, via molar index, using molar progression, and (b) the one-tenth division of length that constitute the decimal point in the molar index value. Note this animal has a molar index of 1.7. Taken from Kirkpatrick (1965) and Knowlton (1984).

Similarly with molar eruption, Dudzinski et al. (1977) equations for agile wallaby molar progression (*MP*) (equations 5 and 6) were used to determine the animals age in days:

For females: $\ln(age) = 5.27 + 0.77MP$ (equation 5)

For males: $\ln(age) = 5.38 + 0.66MP$ (equation 6)

11.4 Appendix 4. Catching and handling of agile wallabies for radio collar fitting

Drop nets consisted of a monofilament nylon net approximately 20 m long, with 117 mm mesh size and 2 meters deep, suspended over 2 m fence pickets driven into the ground on a slight angle following the same directing the wallabies were expected to follow during the capture process (Figure 7, top left panel). The fence pickets were placed every 3 to 4 meters, following a perpendicular line crossing potential wallaby escapes routes identified prior to the catching session – e.g. fence lines, highly used pads (Figure 7, top right panel). Hessian fabric wings (2 meters high) were sometimes added to the sides of some of the nets to funnel animals towards the drop net (Figure 7, bottom left panel). The top side of the net was attached to the fence picket by light wire hooks. Before the start of a catching session, the bottom of the drop net was aligned to the bottom of the fence pickets folding the mesh to form a "pocket" that opened towards the direction where wallabies were expected to enter the net.

Figure 34. Drop net set up prior to catching session. Net is completely suspended to prevent animals getting caught outside a catching session. The two top images show net suspended on fence pickets across well used wallaby pad; bottom left shows hessian fabric wing funnelling towards net; bottom right shows net suspended on pickets on a wooded area.

Catching sessions occurred in the early morning and late afternoon, only when ambient temperatures were lower than 28ºC. During the catching session a minimum of two people (i.e. handlers) were hidden behind the net. Wet hessian bags were also hidden close by. Once the handlers were ready, a minimum of four other people (i.e. walkers), walked toward the net side to side forming a line parallel to the net. Walkers started approaching the net from up to approximately 1 km away from the net, depending on where the wallabies were expected to be. During the approach, walkers created disturbances (i.e. noise) to “flush” the wallabies towards the net.

Once an animal hit the net, the force of impact bent the light wire hooks, releasing the net from the fence picket and falling on top of the animal. As a consequence, the net was only able to be triggered once by one animal before falling. This allowed any other animal that may have been running away from the walker to jump over the fallen net. As soon as an animal was caught, the handlers approached it quickly, placing a hessian bag on top of it in order to calm it down, as well as holding it in place while the rest of the crew arrived on site. Diazepam (Ilium Diazepam injection 5mg/mL) was then administered as a muscle relaxant for the prevention of capture myopathy. 2 ml of diazepam were pre-drawn into 3 ml syringes prior to the capturing session. A first dose of Diazepam was administered at the point of capture based on visual estimation of body weight in a 5kg body weight range (Table IV), at a final dosage of 1mg/kg (Jackson 2007; Sadler 2010).

Table 17. Diazepam volume and dose according to agile wallaby weight.

Animal's weight	*Diazepam dose*	*Diazepam volume*
0 to 5 kg	5 mg	1 ml
5 to 10 kg	10 mg	2 ml
10 to 15 kg	15 mg	3 ml
15 to 20 kg	20 mg	4 ml
20 to 25 kg	25 mg	5 ml

Administration of diazepam occurred by intramuscular injection into the epaxial muscle (single use sterile 22-23 gauge, ¾ inch needles, 3mL syringe), applied while the animal was either restrained in the net or contained in the hessian bag (Figure 8).

Figure 35. Administration of Diazepan (5mg/mL) and Richtasol AD_3EC into the epaxial muscle of an immobilized agile wallaby. Injections were administered by single use of a sterile 22-23 gauge, ¾ inch needles, with 1-3mL syringes.

Following the administration of the first dose of Diazepan, the animal was untangled from the net, and put into a light proof hessian bag (Figure 9). The animal was then weighed inside the bag by means of a hanging weighing scale. The previously measured weight of the bag was then subtracted from the total weight. If the actual weight was higher than the visual estimate, a second dose of Diazepam was administered. At this point, the wallaby also received a dose of Richtasol (1mL/25kg) (Richtasol AD_3EC injection Richter – Vitamin A, D_3, E and C) by intramuscular injection (single use of a sterile 22-23 gauge, ¾ inch needles, with 1 mL syringe) into the epaxial muscle as per Diazepam (Figure 8). Richtasol was administered as a multivitamin for the prevention and treatment of capture myopathy (David McLelland per. com. 2015).

Figure 36. Agile wallaby being place into a light proof hessian bag.

The animal, still inside the hessian bag, was then placed on the ground. One of the handlers would then hold the head through the bag, while another handler reached through the bag, grasping the base of the tail and hind legs. The lower half of the wallaby's body was exposed in order to record the following measurements and characteristics (Figure 10):

- Tail length: measured from the cloaca to the end of the last vertebra at the tip of the tail (Figure 10a)
- Tail circumference: measured around the base of the tail.
- Pes length: measured from the back of the foot (i.e. heel) to the end of the longest toe, at the base of the claw (Figure 10b)
- Tibia length: measured from the top of the knee joint to the bottom of the pes (Figure 10c).
- Reproductive state:
    - For females, pouch content and appearance (Figure 10d) was recorded as:
        - Non-parous (females that have never bred): Pouch small with no skin folds, clean and dry, teats very small (Jackson 2007)

- Parous (females that have bred previously but not presently): Pouch is small but distinct, dry and dirty, the teats are slightly elongated (Jackson 2007).
- Pregnant: Pouch pink in colour and glandular in appearance, skin folds may be observed on the lateral margins of the pouch (Jackson 2007).
- Pouch young present: attached to the teat (Jackson 2007)
- Lactating (young absent from the pouch but still suckling): pouch area large, skin folds flaccid, hair sparse and stained, skin smooth and dark pink, teats elongated and producing milk when pressed (Jackson 2007).
- Post lactation: with teats expressing only clear liquid and/or regressing (Jackson 2007).

- For males, testis length and width was recorded (Figure 10e).

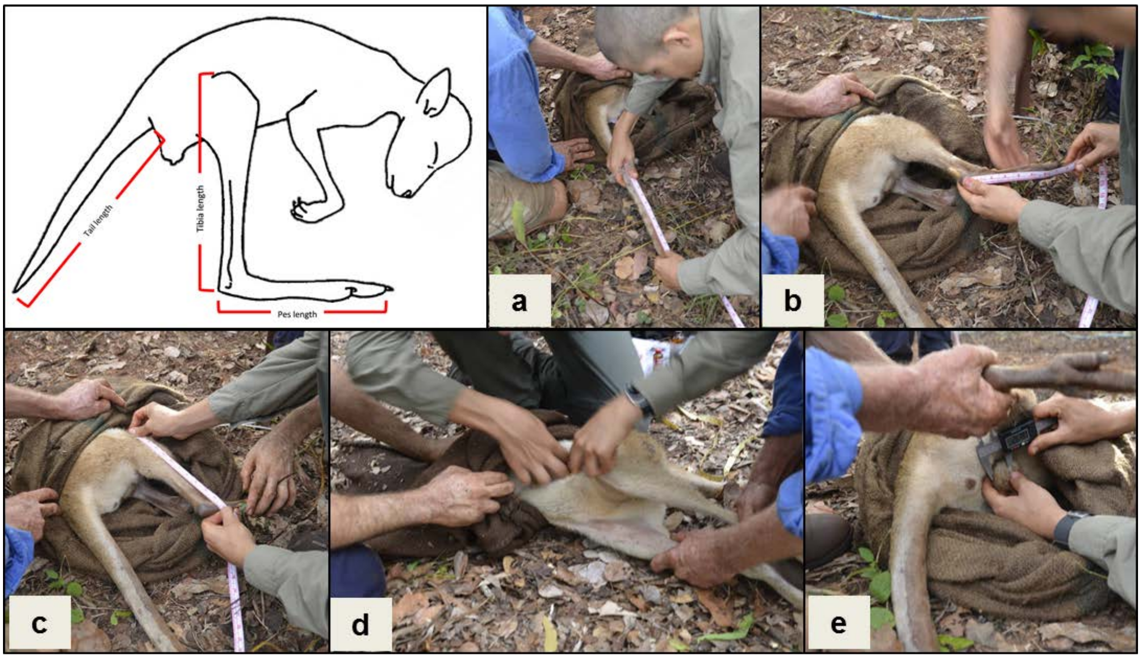

Figure 37. Morphometric and characteristics recorded from capture wallabies. Top left panel is a diagram of the main measurements recorded modified from Sharman et al. (1964); (a) tail length; (b) Pes length; (c) tibia length; (d) Pouch inspection for females; and (e) testis width and length.

After all measurements were recorded, each individual was fitted with a VHF collar (V5C 163E 130-260mm VHF Std Collar Sirtrack Ltd) with an expandable insert as self-release mechanism (Figure 11).

Figure 38. Fitting of VHF collar to captured Agile Wallaby. Top left shows the collar model used; Bottom left shows the elastic insert added to the collar for self-release; Top right shows the fitting of the collar; and bottom right shows a wallaby with the collar fitted.

Wallabies were also fitted with a custom made color-coded ear tag. Each ear tag was constructed from a single plastic transparent UV resistant identification cable tie (Figure 12a). A 3 cm section of clear heat shrink tubbing (6mm diameter) was pass through the identification cable tie and fixed by heat gun to the base (i.e. at the side closest to the locking head) (Figure 12b and 12c). This acted as a cushioned surface to prevent irritation of the pierced ear. One piece (1.5cm) of coloured heat shrink tubbing (1.6mm diameter) was then placed, and fixed by heat gun, over each side of the cable tie's identification tab (Figure 12d and 12e). The colours of shrink heat tubbing were selected to make 15 unique combinations (Figure 12f). Two tags of each colour combination were constructed in order to double the combinations to 30 by means of placing the tags in the right (female) or left (male) ear.

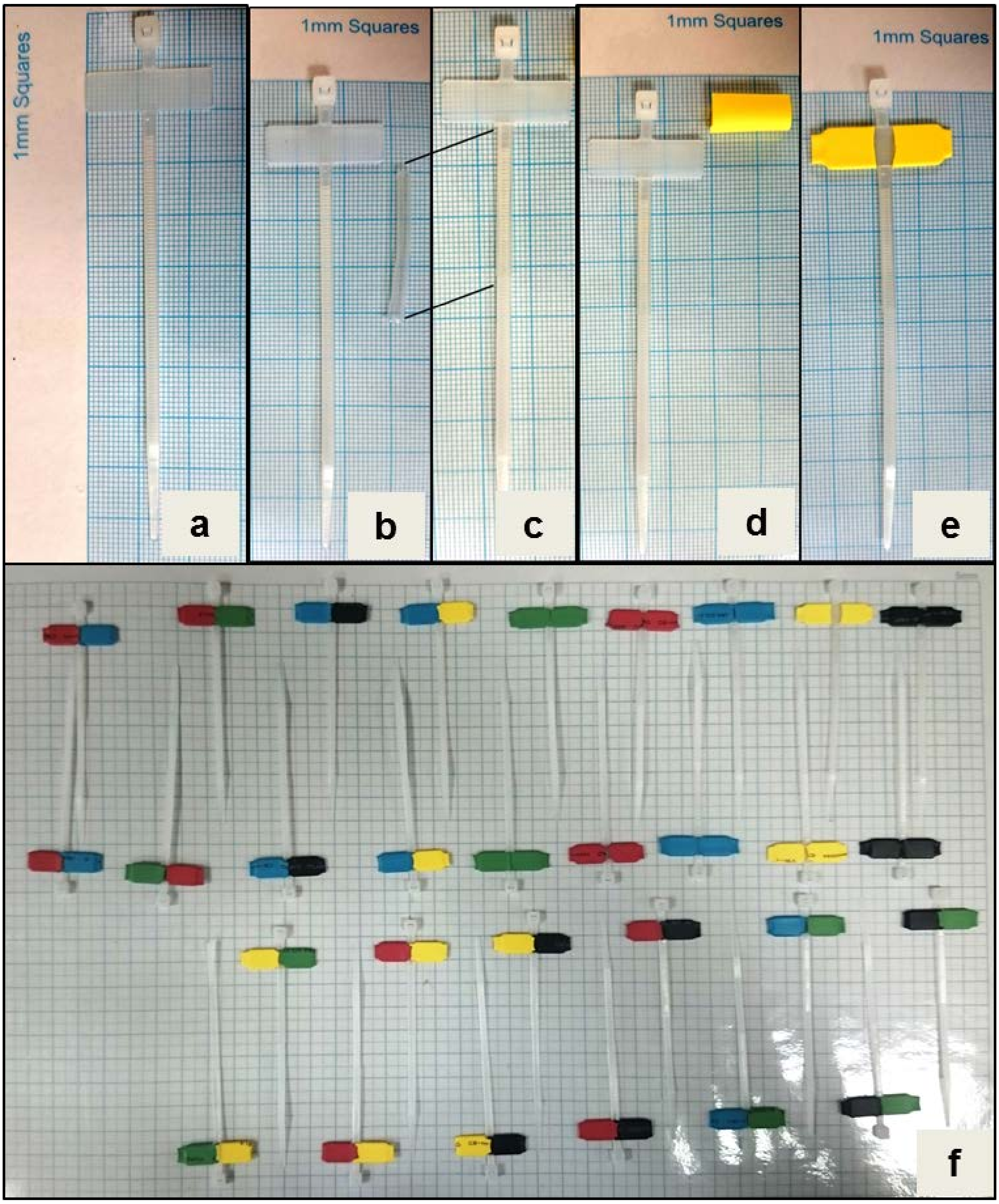

Figure 39. Construction of ear tags for agile wallabies: (a) plastic transparent UV resistant identification cable tie; (b) 3 cm section of clear heat shrink tubbing (6mm diameter) next to cable tie; (c) cable tie with clear heat shrink section fixed by heat gun to the base; (d) piece (1.5cm) of coloured heat shrink tubbing (1.6mm diameter) next to cable tie; (e) coloured heat shrink tubbing fixed by heat gun, over each side of the cable tie's identification tab; and (f) each colour combination constructed by pairs.

In order to fit the wallabies with the custom made coloured ear tag, the ear chosen for the purpose of ear tagging (right for females and left for males) was first clean with antiseptic wound cleansing wipes. Then a small scalpel (handle 7 with blade 15) (Figure 13a and 13b) was used to make a small (0.4cm) incision at the lower inner region of the ear characterized by heavy cartilage. The previously assembled identification cable tie was then passed through the incision, from the inside of the ear and locked in place by the cable ties mechanisms, and any excess cable tie cut (Figure 13c and 13d). After the tag was locked, the pierced area was sprayed with Iodine/chlorhexidine. Particular care was taken to ensure tags are loose enough to allow normal blood circulation, but sufficiently secured to minimize loss of tags (Figure 13e). Finally, individuals were released in the same area where capture.

Figure 40. Custom coloured ear tag fitting procedure for agile wallabies: (a) scalpel blade used to make the incision at the base of the ear; (b) scalpel handle used; (c) closed ear tag with excess cable tie cut off; (d) process of passing the ear tag through ear incision from the inside of the ear; and (e) ear tag in place, locked and with excess removed.

11.5 Appendix 5. Triangulation towers construction and use

Triangulation towers (Figure 14a) consisted of an 18 mm diameter x 50 cm length metal rod driven on the ground with a hammer. The rod had a wooden disc (10 cm diameter x 20 mm thick) fixed at a high of 25 cm from the bottom. On top of the wooden disc a plastic protractor was fixed (Figure 14c). The protractor was calibrated true north by a Suunto high accuracy compass (Suunto kb-14/360R G). On top of the protractor, the excess metal rod was used as a pivot point for an aluminium pipe (20 mm internal diameter x 3 m length) (Figure 14). At the base of the aluminium pipe, a bracket was used to fix a perpendicular needle, consisting of a section (1.5x10cm) of galvanized sheet (Figure 14c). At the top of the pipe a 3 element folding Yagi antenna (Sirtrack Ltd) was aligned to the needle and fixed to the pipe by an aluminium handle that slide into the aluminium pipe forming the tower (Figure 14b).

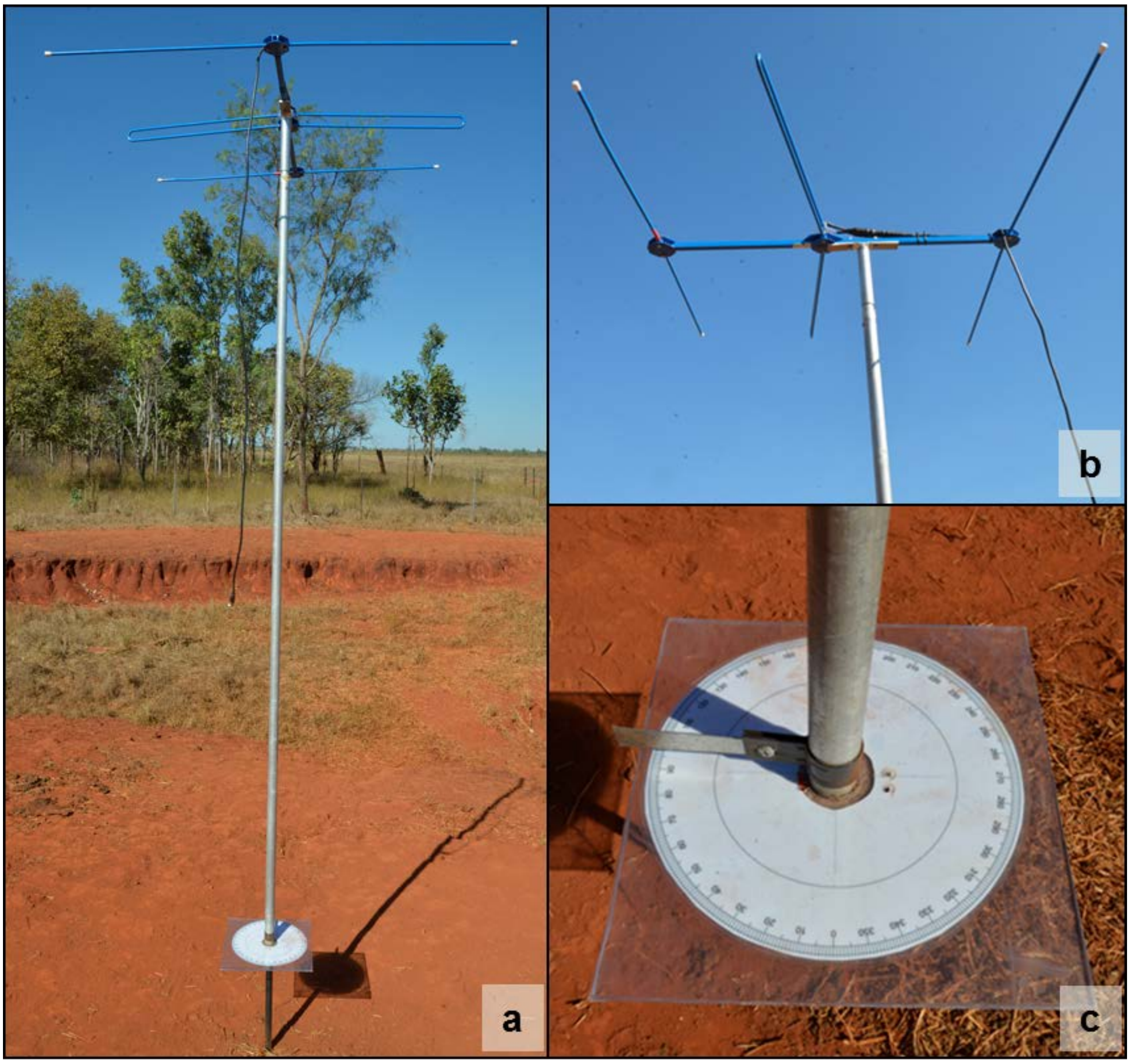

Figure 41. Triangulation towers consisting of an 18 mm diameter x 50 cm length metal rod driven on the ground with a hammer. (a) Shows the complete tower; (b) 3 element folding Yagi antenna (Sirtrack Ltd) aligned to the needle and fixed to the pipe by an aluminium handle that slide into the aluminium pipe forming the tower; and (c) Plastic protractor calibrated true north and showing the needle and bracket.

Eleven towers were built within 2 km of the 17 catching locations (Figure 15). During a triangulation session, a VHF receiver (either a Sirtrack Ultra receiver VSR 041A, or a Titley Scientific Australis 26K^{TM} Scanning receiver) was connected to the Yagi antenna fixed to the tower. At least three people, distributed across three different towers, track each one of the collared wallabies at the same time by using UHF handheld radios to coordinate timing. For each individual wallaby, the direction of the strongest signal was determined by rotating the aluminium pipe and thus the Yagi antenna. The direction of the signal and the time of the fix were recorded for each tower.

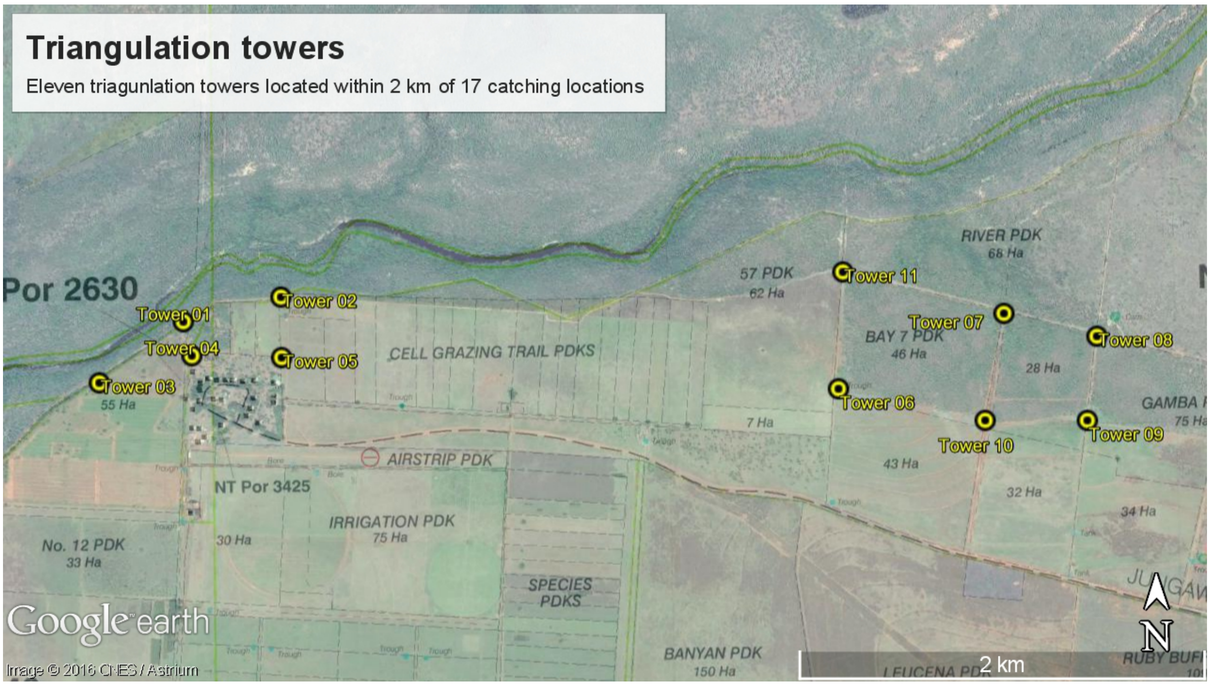

Figure 42. Triangulation towers across the Douglas Daly Research Farm