


Ballina Koala Plan

Koala Population Viability Analysis of the proposed Pacific Highway Upgrade near Wardell, NSW

Prepared for NSW Roads and Maritime Services

January 2016

Document control

Project no.: 2266

Project client: NSW Roads and Maritime Services (RMS)

Project office: Sydney

Document description: Population Viability Analysis for the Ballina Koala population, considering the proposed section 10 W2B upgrade.

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Internal review:

Document status:

Document address:

Local Government Area: Ballina

Document revision status

Author	Revision number	Internal review	Date issued
R. Kavanagh, C. McLean	D0	F. Lemckert	21 September 2015
R. Kavanagh	D1	RMS	23 September 2015
R. Kavanagh	D2	RMS, KEAC	2 October 2015
R. Kavanagh	D3	RMS, KEAC	6 November 2015
R. Kavanagh	D4	RMS, KEAC	16 December 2015
R. Kavanagh	D5	KEAC	29 January 2016

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Cover photograph: Koala living in Broad-leafed Paperbark and Swamp Mahogany forest; and, the study area, showing the route of the proposed Pacific Highway Upgrade in Section 10, west of Wardell.

Executive summary

Context

The Australian Government Conditions of Approval for Section 10 of the Pacific Highway Upgrade near Wardell in northern NSW require the approval holder to demonstrate that the impacts to the Ballina Koala population as a result of the proposed highway upgrade are acceptable over a 50 year period. A population simulation and threat modelling process (Population Viability Analysis) was the method specified to undertake this assessment. A local Koala ecological and population demographic study, and two genetics studies, were commissioned by the Roads and Maritime Services to provide the parameter estimates needed to run the PVA. A range of mitigation options was also available for assessment.

Aims

To estimate the likely impact of the proposed highway upgrade in Section 10 on Koala population viability over a 50 year period, and over a range of plausible management scenarios.

Methods

The VORTEX (version 10) PVA software program was used to conduct the analyses. All population size, distribution, demographic and stochastic inputs to the model, as well as the frequency of likely catastrophic events, were provided by the authors of the local Koala field study, which included details for 50 captured animals. The genetics studies were used to estimate the minimum numbers of Koalas immigrating into and emigrating from the study area because the distribution of habitat in the region showed that the population was not "closed". These studies were also used to estimate the minimum numbers of animals dispersing, and the extent of inbreeding, within the study area. The impact of the proposed road was assessed by comparing population projections based on differences in the rate of dispersal between two sub-populations as influenced by the proposed connectivity structures. The provision of supplementary habitat for Koalas in the study area was modelled through an increase in the projected carrying capacity of the habitat. Management options were investigated by varying the levels of key population parameters.

Key results

Population projections showed a gradual decline over 50 years, with or without the proposed highway upgrade. The impact of the road was estimated to range between no effect and up to a 9.7% decline in the projected population size after 50 years, depending on the uncertainty associated with estimates of the demographic parameters and assumptions about the effectiveness of the connectivity structures that will be provided. In contrast, population projections could be improved substantially through management intervention, including through the provision of supplementary habitat (0.5%) and by a combination of approaches that result in reduced mortality and increased fecundity (potentially up to 496%).

Conclusions and Management implications

The projected population decline was due to births not being adequate to offset deaths, regardless of the presence of the highway upgrade. Any efforts to increase fecundity and/or reduce mortality in the region will improve population viability.

Significant opportunities exist to reduce Koala mortality by the provision of a range of mitigation structures, including Koala-proof fencing along the proposed highway upgrade and other roads in the area, and other management interventions. Community involvement is needed to control dog predation and to support trials of a new *Chlamydia* vaccine to increase fecundity.

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1. Introduction

1.1 Context

The NSW and Australian Governments are upgrading the Pacific Highway between Woolgoolga-Ballina (155 km) as part of State Significant Infrastructure. This Project is divided into 11 Sections, each of which has been subject to ecological surveys to determine the likely effects of the proposed upgrade on flora and fauna. The Koala in NSW is listed as 'vulnerable' under the Threatened Species Conservation Act 1995 (TSC Act), and also as 'vulnerable' under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). The present study incorporates the results of surveys and other assessments for the Koala in Section 10.

The Koala population located in Section 10, between Bagotville and Coolgardie west of Wardell, has been proposed by Phillips and Chang (2013) as suitable for listing as an "important population" under the EPBC Act. This population is referred to specifically in the draft Comprehensive Koala Plan of Management (2015) for the Ballina Shire Local Government Area and in the Conditions of Approval for the Project.

1.2 Conditions of Approval

On 14 August 2014, the Australian Minister for the Environment approved the Pacific Highway Upgrade from Woolgoolga to Ballina, NSW, subject to conditions, including Conditions 5, 6, 7, 8, 9 and 10 that refer specifically to the Koala.

Condition 5 states: "In order to ensure the long-term viability of the Ballina Koala population, the approval holder must engage a suitably qualified expert to undertake **population viability modelling** of the Ballina Koala population over a time period of no less than 50 years, taking into account the impacts resulting from the road upgrade in Section 10. This modelling should consider the current proposed route and any proposed avoidance or mitigation measures as appropriate".

Condition 7 states: "In addition to the Koala Management Plans(s) required by NSW approval conditions D8 and D9 (approved by the NSW Minister for Planning on 24 June 2014), to ensure that an unacceptable impact will not occur to the Ballina Koala population, the approval holder must submit for the Minister's approval a **Ballina Koala Plan** no less than 3 months prior to the commencement of Section 10. The Minister will only approve the plan and the commencement of Section 10 of the action if the impacts to the Ballina Koala population are demonstrated to be acceptable within the Ballina Koala Plan. The Ballina Koala Plan (this document) must include:

a. The modelling required by Condition 5 and the results of this modelling, and the peer review required by Condition 6;
b. Discussion of the future viability of the Ballina Koala population;
c. In the context of relevant environmental and economic considerations, any additional avoidance, mitigation or offsets, beyond those required by the NSW approval conditions, proposed to minimise the impacts to the Ballina Koala population; and
d. Evidence that any additional avoidance and mitigation measures proposed have been considered in the modelling required in Condition 5.

The approval holder must not commence Section 10 unless the Ballina Koala Plan has been approved by the Minister. The approved Plan must be implemented".

This Ballina Koala Plan is an essential component of the overall strategy to minimise and mitigate the impacts to the Ballina Koala population within Section 10 of the proposed Pacific Highway Upgrade.

1.3 Project objectives

The objectives of this project and report are to satisfy the Australian Government's Conditions of Approval in relation to preparation of the Ballina Koala Plan. This includes the requirement to:

- estimate the likely impact of the proposed highway upgrade in Section 10 on Koala population viability over a 50 year period; and to
- investigate the relative benefits of a range of plausible management scenarios that could be implemented by RMS to minimise any potential impacts of the proposed highway upgrade.

2. The Study Area

2.1 Study area

The Koala population located in Section 10, which extends 13.5 km north of the Richmond River and includes the localities of Bagotville and Coolgardie west of Wardell, is the subject of this study. This population has been proposed by Phillips and Chang (2013) as suitable for listing as an "important population" under the EPBC Act. The area nominated as enclosing this population is approximately 8,250 ha, the boundaries of which are displayed in Figure 1. This population is not considered as "closed" for the purposes of modelling because of the degree of habitat connectivity with surrounding areas (Figure 1).

The general landscape context within the study area is a predominantly-cleared, sometimes waterlogged, fertile valley surrounded to the west by mostly tall forested lands on slopes and ridges along the Blackwall Range, and to the east by low slopes covered mostly by drier forests and woodlands with large areas of tall heathland growing on less fertile soils (Figure 1). The valley and lower slopes have been used extensively for grazing and sugar cane production, although significant areas of remnant or regrowth native vegetation still remain, particularly along watercourses. The proposed route of the highway upgrade in Section 10 traverses through the eastern side of the valley and will result in the loss of a further 34 ha of native vegetation, half of which (17 ha) is recognised as good habitat for Koalas (Table 1).

2.2 Geology

Five main geological types are present in the study area (Figure 2). These geological types are ranked in approximate order of the fertility of the soils derived from them:

- Basalt (Tllb)
- Meta-basalt (Cnx)
- Undifferentiated alluvial deposits/floodplain and swamp deposits (Qa)
- Coarse-grained conglomerates (Rjbwx)
- Dune sand and sand sheets (Qb)

2.3 Vegetation types

A range of remnant or regrowth native vegetation types is present in the study area (Figure 3). The vegetation types likely to be of most importance to Koalas, due to the expected presence of Koala food tree species within them, include:

- Paperbark (depending on the proportion of Swamp Mahogany *Eucalyptus robusta*);
- Lowland Red Gum;
- Wet Flooded Gum – Tallowwood;
- Foothill Grey Gum – Ironbark – Spotted Gum;
- Northern Open Grassy Blackbutt

Other vegetation types present in the study area are less likely to make a significant contribution to Koala habitat but may contribute to Koala dispersal and habitat connectivity in the region.

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Study Area

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FIGURE 1

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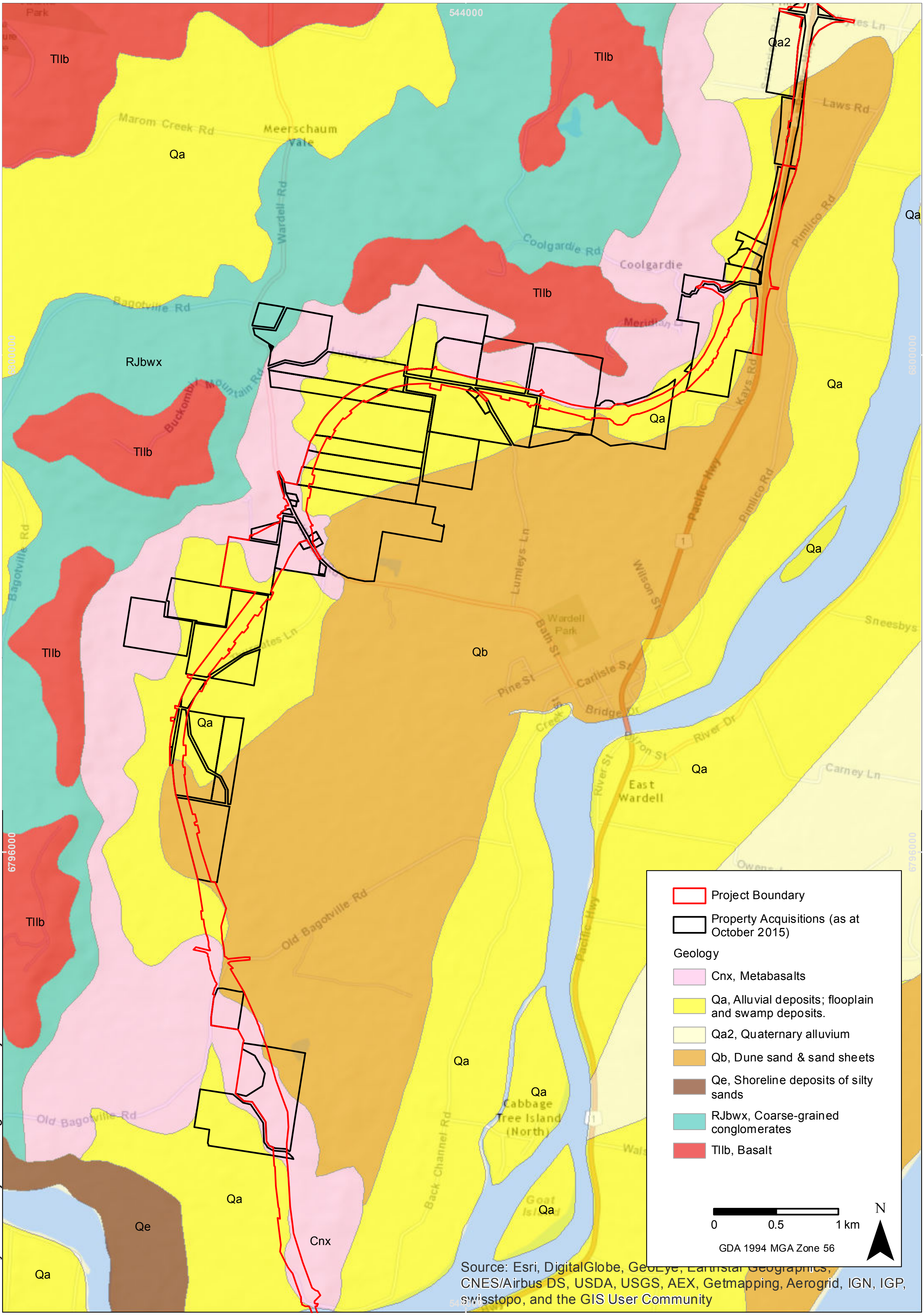

Section 10 - Geology

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FIGURE 2

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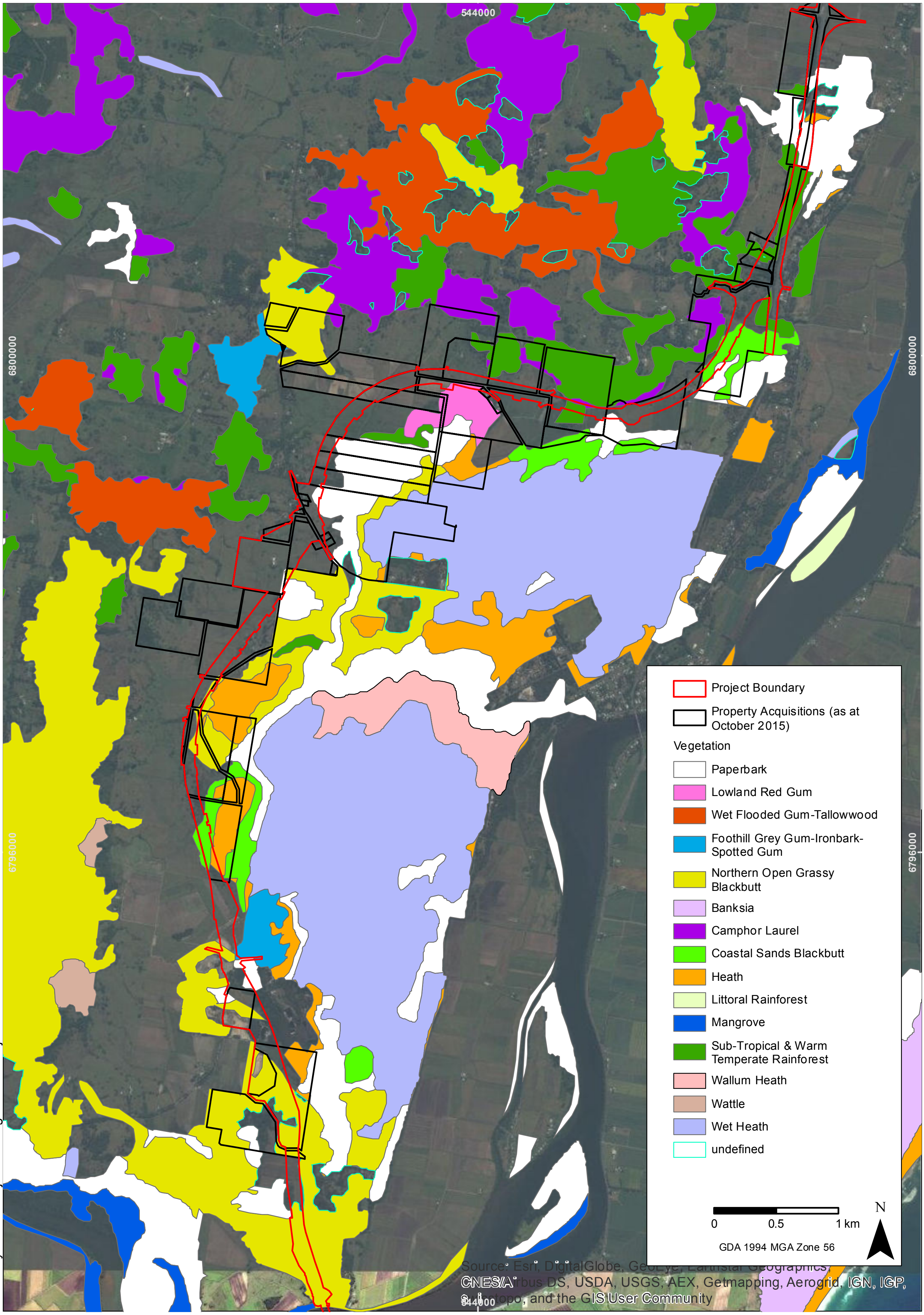

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Section 10 - Vegetation type

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FIGURE 3

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Table 1: Koala habitat quality scores (EPBC Act 1999 Environmental Offsets Policy Calculator) and the areas (ha) of each Biometric Vegetation Type occurring within the clearing "footprint" of Section 10 of the proposed Pacific Highway Upgrade between Bagotville and Coolgardie near Ballina. Source: Pellow and Semeniuk (2015).

Koala Habitat Quality Score Vegetation Types in Section 10 clearing "footprint"	0	1	2	3	4	5	6	7	8	9	10	Total
Blackbutt- Pink Bloodwood Shrubby Open Forest					0.05	2.21	0.14	2.97				5.38
Blackbutt Grassy Open For.							0.23	0.93	0.91		1.53	3.60
Cinnamomum camphora				1.44								1.44
Cleared	115.02				0.14			0.93				116.09
Mangrove-Grey Mangrove Low Closed Forest	0.17											0.17
Narrow-leaved Red Gum Woodlands						1.06	2.01	0.70		1.26	3.92	8.94
Paperbark Swamp Forest	0.00			0.41	0.88	1.61	2.17			0.25	0.64	5.96
Scribbly Gum-Needlebark Heathy Open Forest						1.98	1.47					3.45
Swamp Mahogany Swamp Forest						0.63	0.27		1.23			2.12
Tuckeroo-Riberry-Yellow Tulipwood Low Rainforest	0.01				0.19	0.89						1.09
White Booyong-Fig Subtropical Rainforest				0.39	0.52	0.47		0.53				1.92

3. Population Viability Analysis

3.1 Definition and purpose

Conservation problems are almost always multi-faceted, involving not only complex dynamics of biological populations, but also interactions with human populations. Many people need to contribute knowledge, expertise, and ideas in order to achieve the recovery of threatened species. Population viability analysis (PVA) can provide a framework for incorporating the many needed kinds of knowledge into species conservation efforts because PVAs provide a means for assessing the relative contributions of factors that can threaten the persistence of populations (Lacy 1993, Lindenmayer *et al.* 1993). Compared to other alternatives for making conservation decisions, PVA provides a rigorous methodology that can use different types of data, a way to incorporate uncertainties and natural variabilities, and products or predictions that are relevant to conservation goals (Akçakaya and Sjögren-Gulve 2000).

Shaffer (1981) first defined a minimum viable population (MVP) as the size at which a population has a 99% probability of persistence for 1000 years, but it has become more meaningful biologically to consider it to be the size below which a population's fate becomes determined largely by the range of stochastic factors that threaten its existence (Soulé 1987). In simple terms, small populations are more vulnerable to extinction than large populations because unexpected catastrophic events can lead to the death of all individuals, however, even large populations are threatened over time if birth rates are insufficient to offset death rates (Caughley 1994). There is no true consensus on a definition of the term PVA, with previously used definitions ranging from qualitative, verbal processes without models, through to mathematically-sophisticated, spatially-explicit, stochastic simulation models (Reed *et al*. 2002), while numerous practitioners have suggested that the latter definition be used (Ralls *et al.* 2002) and, with the availability of population-modelling software, this has become the most common approach.

The general concept of 'island biogeography' (see Diamond and May 1976) applies to the management of wildlife populations. As wildlife populations become smaller, additional threats to stability and persistence arise, which from a certain point forward, may be difficult to reverse (Lacy 2000b). These problems of small populations usually arise from stochastic processes (Lacy 2000b). Many aspects of population biology are 'sampling processes', such as breeding success, transmission of genetic alleles, survival and dispersal (Lacy 2000b). Uncertainty arises from their outcomes, leading to instability in population dynamics (Lacy 2000b). Demographic stochasticity is the random variation in deterministic factors, such as the numbers of births, deaths and sex ratio in a population, that result from the fates of individuals being outcomes of probability-based events (i.e. reproduction, mortality and sex determination; Shaffer 1981). The function of a PVA model is to assess, over a defined time period, the relative contributions of all deterministic factors and variations in demographic stochasticity towards long-term population persistence. This process can identify those variables which are likely to have the greatest influence on population outcomes, and accordingly which variables should be targeted for management attention should the projected population increase, or decrease, beyond acceptable limits.

3.2 Brief review of PVAs

Simulation-based PVAs (compared to a qualitative PVA) use computer software to model (predict) population trends for a single species, over time. The PVA process relies upon the availability of accurate demographic data for the population being modelled. Common software used for simulation-based PVA includes ALEX (Analysis of the Likelihood of Extinction; Possingham and Davies 1995), RAMAS (Applied Mathematics, NY, USA) and VORTEX (Lacy 1993). These programs have been reviewed and found to be appropriate for a wide range of applications (Lindenmayer *et al*. 1995).

In recent times a number of code-based models have been developed, such as 'PVAClone' in the statistical package R, while others have completed PVA analyses using transition matrix models (Edwards *et al*. 2015) and simulation modelling software such as E-Surge (Choquet *et al.* 2009, Hernández-Matías *et al*. 2015). In general PVAs may consider the following types of scenarios (as examples):

- Assess the effectiveness of different control measures for pest animals (Rømer *et al*. 2015).
- Management and recovery of threatened species (Bode and Brennan 2011, Lindenmayer and Possingham 1995, Taylor and Goldingay 2013).
- Competition with introduced species (Glen and Dickman 2013).
- Assessment of the potential success of re-introductions (King *et al*. 2014).
- Future trends in populations, particularly in relation to disturbance regimes (Lunney *et al*. 2007, Lindenmayer and Possingham 1995).

3.3 Strengths and weaknesses of PVAs

Modern applications of PVA are not intended to provide a definitive statement about population size after a specified time period. Instead, the value of this technique is to provide an opportunity for interested parties to assemble relevant information about the status of a population and likely threats to its persistence. The technique is used primarily to evaluate the relative impacts of alternative management scenarios that can be used to inform management actions (Beissinger and Westphal 1998, Coulson *et al*. 2001).

There have been few empirical studies that have attempted to verify the accuracy of PVAs. Brook *et al*. (2000) retrospectively examined the long-term population trends for a range of species based on 21 long term studies in which the actual population sizes were known. They found that the PVA predictions were relatively accurate, with population size estimates not differing substantially between the predicted and observed numbers (Brook *et al*. 2000). However, this level of optimism was criticised by Coulson *et al*. (2001) who cautioned that, while PVAs could be useful for comparing the consequences of different management or conservation strategies, the lack of long-term demographic data and confidence in the future (e.g. impact of catastrophes, habitat availability) would preclude accurate projections of the status of most wild populations. Lindenmayer and McCarthy (2006) used data collected over a seven year period to examine changes in populations of arboreal marsupials in timber production forests. They found that, while many variables were difficult to estimate and contributed to some variation, the overall PVA model was generally consistent with field observations.

One of the biggest influences on the outcome of a PVA is the size of the study area in which populations are being modelled. This is because of the strong relationship between population size and its resilience to the factors which may lead to its extinction; it is well known that smaller populations are much more likely to become extinct than larger populations, all else being equal (Caughley 1994). Thus, when assessing the impact of a development, it is important to ensure that the study area is not so large that most individuals in the population will have no interaction with the proposed development, but not so small that the population is likely to become extinct anyway due to the "small population paradigm" (Caughley 1994).

The main weakness of the PVA process is determining the overall accuracy of the input data (Beissinger and Westphal 1998, Coulson *et al*. 2001). If the input data over or underestimates particular parameters, then the final output will report erroneous results. Any model is only as good as the data which are used, and it is important to be cautious in the interpretation of results (Lindenmayer *et al*. 1995, Beissinger and

Westphal 1998). Often it is recommended to obtain long-term data over many years, in an attempt to calibrate the PVA model (see Lindenmayer and McCarthy 2006).

The strength of the PVA process is it can be used to construct and inform management decisions, to determine if different actions are likely to result in a positive or negative effect on a particular population. The PVA process includes a prediction of population size, thus well designed monitoring programs can be used to test the original predictions from the PVA.

3.4 Examples of the use of PVA

Mammals in Australia

Population viability analysis has been completed for a range of mammal species in Australia, investigating a range of research and management questions. These include the minimum viable area for the Yellow-bellied Glider (*Petaurus australis*; Goldingay and Possingham 1995), the effect of urban fragmentation and the use of connectivity structures for the Squirrel Glider (*Petaurus norfolcensis*; Taylor and Goldingay 2013), and competition between Foxes (*Vulpes vulpes*) and the Spotted-tailed Quoll (*Dasyurus maculatus*; Glen and Dickman 2013). In the Central Highlands of Victoria, several PVAs have been completed for the Leadbeater's Possum (*Gymnobelideus leadbeateri*) in relation to different disturbance regimes (i.e. logging and burning; Lindenmayer *et al.* 1993, Lindenmayer and Possingham 1995, Lindenmayer and Possingham 1996).

The Koala

Three publications, covering PVAs for four Koala populations have been completed (Table 2). These studies have considered both large and small population sizes, ranging from 20 to 800 individuals. Populations considered include the Iluka population, located to the southeast of this study area (Lunney *et al.* 2002), the Port Stephens population (Lunney *et al*. 2007), one population in southeast Queensland and another in Central Queensland (Penn 2000). All of these studies used Vortex to model changes in the Koala populations of those areas.

Three of the four Koala populations examined showed evidence of a significant decline, due primarily to high mortality and sometimes low fecundity. In all modelled scenarios, attempts to reduce mortality had more influence on population viability than any other factor. None of these studies explicitly examined the role of vehicle collisions, although this factor was recognised as one of several that may be contributing to high rates of population mortality. In south-east Queensland, Rhodes *et al*. (2011) reported on the separate effects of an array of threatening processes leading to the decline of a large population of Koalas, and road mortality was a significant factor.

Table 2: Input values for key variables used in previously published PVAs for the Koala.

Variable	Iluka (Lunney *et al.* 2002)	Oakey (SE Queensland; Penn 2000)	Springsure (Central Queensland; Penn 2000)	Port Stephens (Lunney *et al*. 2007)
Initial population size	20	46	20	800
Stable age structure at start	Yes, calculated by Vortex			Yes
Initial population gender structure	13F, 7M			
Maximum age	12	12	12	12
Minimum female breeding age	2	2	2	2
Minimum male breeding age	3	3	3	3
Sex ratio (% male)	55%	57%	53%	53%
% litter size 1	20% (±10%)	57% (±17.85%)	31% (±15.61%)	77% (7%)
% litter size 0	80%	43% (±17.85%)	69% (±15.61%)	33%
% males in breeding pool	50%	50%	50%	100%
Female mortality age 0	32.5% (±3.25%)	32.5% (3.25%)	30% (3%)	40% (4%)
Female mortality age 1	17.3% (±1.73%)	17.27% (1.727%)	15.94% (1.594%)	40 (4%)
Female mortality adult	9.2% (±0.92%)	9.17% (0.917%)	8.47% (0.847%)	23 (2.3%)
Male mortality age 0	20% (±2%)	20% (2%)	20% (2%)	40% (4%)
Male mortality age 1	23% (±2.3%)	22.96% (2.296%)	22.96% (2.296%)	40% (4%)
Male mortality age 2	23% (±2.3%)	22.96% (2.296%)	22.96% (2.296%)	40% (4%)
Male mortality adult	26.4% (±2.64%)	26.36% (2.636%)	26.36% (2.636%)	39% (3.9%)
Density dependence	Nil	Nil	Nil	Nil
Probability of catastrophe	3%	5%	5%	10%
Severity on reproduction	50%	55%	55%	5%
Severity on survival	50%	63%	63%	5%
Inbreeding depression	Nil	Nil	Nil	Nil
Environmental variation, survival and reproduction	Concordant	Concordant	Concordant	Concordant
Carrying capacity (K)	50	70 (7)	60 (6)	2500
Harvest	Nil			Nil
Supplementation	1 male, age 2 per annum	Nil	Nil	Nil

4. Vortex software

4.1 Vortex

VORTEX is an individual-based simulation program that models the effects of mean demographic rates, demographic stochasticity, environmental variation in demographic rates, catastrophes, inbreeding depression, harvest and supplementation, and metapopulation structure on the viability of wildlife populations (Lacy 2000a).

Vortex has been reviewed on many occasions in relation to other computer software packages, but it is important to remember that any computer program necessarily contains a large number of assumptions and simplistically models the behaviour of animals. Thus, the results of viability analyses can only be estimations of the actual dynamics of wild populations. As a result, caution should be used when interpreting and applying the results of any such analyses (Lindenmayer *et al*. 1995).

4.2 Assumptions and limitations

In their simplest form, population viability analyses assume that the population being modelled is a “closed” population (e.g. Penn 2000, Lunney *et al*. 2007), with no immigration in, and no emigration out, however this is rarely the case and Vortex contains the flexibility to take this into account if the information is available. The landscape context in the study area, with its fragmented forests and woodlands set in, or surrounded by an agricultural matrix, is clearly “porous” to Koala movements (Neaves *et al*. 2015, Norman *et al*. 2015) and, therefore, it is important to account for immigration and emigration (this was done in the present study using the “supplementation” and “harvest” features, respectively, of the program).

Vortex requires an assessment of whether inbreeding depression (i.e. the reduction in fitness of offspring produced by inbred mating) is present in the population being modelled and, while this can have a significant effect on results, the information is rarely available for wild populations. Some authors caution not to disregard the influence of inbreeding depression on extinction risk (O’Grady *et al*. 2006) as it may lead to serious overestimates of the survival prospects of threatened taxa, so the presence of inbreeding depression has been assumed for this population.

However, inbreeding may or may not lead to inbreeding depression, as the latter depends on the numbers and types of lethal alleles that are present in the population and whether matings are random in populations of at least moderate size. The Ballina Koala population was reported to have high levels of genetic diversity with very low levels of inbreeding (Neaves *et al*. 2015, Norman *et al*. 2015). Unfortunately, nothing is known about the number of lethal alleles that are present in this population, or the extent to which free-ranging wild populations are likely to be impacted. Again, based on the recommendations of O’Grady *et al*. (2006), we assumed the likely presence of lethal alleles in the population and have accepted the Vortex default value of 6.29 lethal alleles, although a range of values was also considered in this study. Accordingly, in the current study, all scenarios were modelled with inbreeding depression and the presence of lethal alleles. This had the effect of reducing population size projections by approximately 20-40% of those estimated when inbreeding depression and the presence of lethal alleles was switched “off” in the analyses.

Population viability analyses require accurate demographic data and accurate measures of the variability in these data over months and years. Most studies, including this one, take snapshot samples of population demography within usually one year or season, and hope that this information is representative of the population of interest. Of course, the incidence of drought, disease, predation and many other factors can combine to ensure that once-only samples can be unrepresentative, leading to misleading results.

One of the most difficult aspects of PVA using Vortex is to estimate the year-to-year variability associated with the mean values that are calculated for most variables (Beissinger and Westphal 1998). Without large sample sizes and extended periods of data collection, variability is difficult to calculate yet inaccurate measures can have a large effect on results.

PVAs also require an accurate understanding of population size and its distribution. If population size is under or overestimated, an inaccurate model will be produced.

Population dispersal rates and the success of these movements (i.e. percent survival) between sub-populations are crucially important in modelling the effects of a major highway bisecting this population yet, while Koalas have been observed using them, the effectiveness of the proposed connectivity structures is not well known.

4.3 Structure and inputs

Vortex requires data inputs for numerous variables in multiple categories. These inputs are usually means, as well as the variation around these means that is caused by environmental and annual fluctuations. However, environmental and annual variation cannot usually be estimated from short term studies (see above). Instead, most studies, including this one, incorrectly substitute the standard deviation around the mean for one particular year as the best available input for the Environmental Variation (EV) that is associated with each parameter estimate, given that we have no idea of the inter-year variability of these estimates. The principal categories of information requiring inputs in Vortex are:

- Scenario settings
- Inbreeding depression and number of lethal alleles
- Dispersal
- Reproductive system
- Reproductive rates
- Mortality rates
- Catastrophes
- Mate monopolisation
- Initial population size
- Carrying capacity
- Harvest rates
- Supplementation rates
- Genetics

A summary of the key inputs required for Vortex are presented in Table 2 (based on other studies) and Table 3 (this study).

5. Sources of Information for Modelling

5.1 Ecosure/Biolink study

An area of approximately 8250 hectares has been nominated as one encompassing an "important population" of Koalas in the Ballina Local Government Area (Phillips and Chang 2013, Phillips *et al*. 2015), and this was selected as the focal area for this study. The study area is located in the Ballina Local Government Area and is known locally as the Blackwall Range to the west and north of the proposed alignment and as Wardell heath to the east. The eastern and southern boundary of the study area is the Richmond River, with Sugar Cane plantations predominating in the east (Figure 1). Some forest connectivity occurs to the west and north, with rainforest vegetation occurring to the north (Figure 3). The landscape context is porous to Koala movements, with Koalas living adjacent to the study area and elsewhere in the LGA.

Population distribution and habitat occupancy

Within the 8247 ha study area, 2152 hectares was estimated to contain Preferred Koala Habitat (PKH), including 96 hectares of Primary Koala Habitat (Phillips *et al.* 2015; Appendix 1). Mean Koala population densities typical of the vegetation types present in the study area were estimated from existing data collected in the region by Phillips *et al*. (2015). Koala population density was estimated from observations of live animals encountered on 1 ha sampling plots distributed throughout the study area.

Sampling procedure for demographic determinations

A 2.5 km x 2.5 km grid square was applied across the study area, where up to seven Koalas were sampled from any one grid square. When Koalas were encountered, they were captured using either flagging or the fence-trap method. Once on the ground, Koalas were anesthetised, with the animal's gender, weight and body condition score recorded. The reproductive status of captured females was assessed using a four tier system consisting of 1/ no pouch young present, nor evidence of recent lactation; 2/ pouch young present; 3/ back young present; 4/ neither pouch young or back young present, but evidence of recent lactation. Tooth wear classes (after Gordon 1991) were determined, ranging from TWC 2-6.

A total of 40 Koalas was captured using the flagging or fence-trap method, while a further two were captured by hand when they were observed in the open. Another nine Koalas were found deceased in the study area, with three being from dog/fox attack and six as a result of vehicle strike. Koalas sampled were broadly distributed throughout the study area, however, some aggregations did occur in the southern part of the study area. Ocular and urogenital swabs, fur samples and ear tissue were also taken from each captured animal, in order to undergo various pathological and genetic analyses. The results of these data were unavailable at the time of the present study.

Of the 30 female Koalas sampled, 13 showed evidence of reproduction, distributed between Tooth Wear Classes 3-5, resulting in a reproductive rate of 43.33% (SD= 9.2%) which was later updated to 44.83% (SD=9.27) (Phillips *et al.* 2015; Appendix 1). Overall annual mortality was estimated at 9.94% (SD= 8.91%), however this average estimate varied greatly among age classes (Table 3), due to an unusual age-class distribution in the population.

Catastrophes

The likely distribution, frequency and severity of drought and fire on Koala survival and breeding success were reported in Phillips *et al*. (2015).

Table 3: Input values for key variables used in this study (primary source: Phillips *et al.* 2015).

Variable	Values used in this study
Initial population size	Total 236 individuals (includes estimated number of 0-1 year old males and females, based on fecundity of breeding females – otherwise 196 individuals, 125 females and 71 males) Individuals distributed as 180 west and 56 east of the proposed road upgrade.
Stable age structure at start	No. Local baseline "snapshot" field data used.
Initial population gender structure	0.64F: 0.36M, but 50:50 at birth
Maximum age	10
Minimum female breeding age	2
Maximum female breeding age	8
Minimum male breeding age	4
Sex ratio (% male)	36%
% litter size 1	44.83%
% litter size 0	56.66%
% males in breeding pool	76.47%
Female mortality age 0	19.7% (±11.63%)
Female mortality age 1	19.7% (±11.63%)
Female mortality adult	7% (±4.421%)
Male mortality age 0	19.45% (±11.49%)
Male mortality age 1	19.45% (±11.49%)
Male mortality age 2	30.56% (±18.05%)
Male mortality age 3	4.3% (±2.54%)
Male mortality adult	4 (±2.525%)
Density dependence	Nil (unknown)
Probability of catastrophe over 50 years	Drought 21% Fire 3%
Severity on reproduction	Drought effects restricted to upper slopes (32% of Koala habitat) in the study area. Severity: reduction of reproductive output by 15% in drought years. Fire effects restricted to 10% of the study area. Severity: reduction of reproductive output by 15%.
Severity on survival	Drought causes no additional mortalities. Fire results in 40% mortality of all individuals living within the fire boundary (i.e. 10% of the population).
Inbreeding depression	Modelled with inbreeding depression. Number of lethal alleles set to default 6.29.
Environmental variation, survival and reproduction	Concordant; i.e. good years for reproduction also typically good for adult survival.
Dispersal	Modelled for two sub-populations. Levels set to 3.95 individuals (1.98 each way) per year (see section 5.4), as well as other plausible values (0.792, 4, 8, 10, and 20 individuals each way per year).
Carrying capacity (K)	Population carrying capacity set at 291 (±15) individuals (approximately half of the available habitat remains unutilised). For sub-populations, 222 (±15) individuals distributed in the west and 69 (± 15) in the east. Replanting of 130 ha of new habitat for Koalas was modelled by gradually raising the carrying capacity by three animals per year beginning at year 7 (i.e. to a maximum of 25 and 16 animals for each sub-population) over a 15 year period, after accounting for the potential loss of 5 animals due to habitat clearing during road construction.
Harvest	The effects of mortality due to vehicle strike and dog attack in the study areas are already included in the mortality estimates. However, because of the porous boundaries of the study area, 2.85 individuals (60%M:40%F) (see section 5.5) were permitted to emigrate from the study area each year
Supplementation	Similar to above, 2.85 (60%M:40%F) (see section 5.5) individuals were permitted to immigrate into the study area each year.
Genetic inputs	Initial allele frequencies were entered using a spreadsheet provided by Dr C. Grueber (Sydney University) based on the results of the two genetics studies. 30 neutral loci modelled. Additional loci only included in summary statistics.

5.2 Interpretation and use of parameter estimates

All population size, distribution, demographic and stochastic inputs to the PVA model, as well as the frequency of likely catastrophic events (i.e. the “baseline” model), were provided by the authors of the local Koala field study, which included details for 50 captured animals (Phillips *et al*. 2015; Appendix 1). It is unknown whether the “baseline” demographic parameters, collected from this once-only snapshot sample, are truly representative of the population.

Population demography

The age-class and gender distribution of the Koala population sampled by Phillips *et al.* (2015) contained a number of unexpected results. Firstly, the sex ratio of the sample was highly biased towards females (64%). Secondly, the proportional representation within the population of young females and males in the 2-3 year old age-classes was unusually small, suggesting very high mortality of young Koalas. Thirdly, breeding success per year among adult females was relatively low (44.83%), and was restricted to females occurring within age-classes 3-7 years. For a species with an expected lifespan of approximately 10 years, the observed low breeding success suggests one of the following: that environmental conditions were not favourable to the population during the years prior to sampling; that habitat quality was not as good as expected; that disease may be a factor limiting reproductive output; and, that high mortality could be accounting for the relatively few older-aged, potentially-breeding, animals in the population. The causes of the observed demographic “imbalance” are unknown. However, mortality due to vehicle-strike in the study area appeared to be relatively high and clinical signs of disease appeared to be relatively low (Phillips *et al*. 2015).

Population size

Population estimates provided by Phillips *et al*. (2015) were based on an (unmapped) assessment of the distribution and amount of habitat (i.e. 2152 ha) considered as “preferred” by Koalas in the study area. The results of two surveys, conducted 2 years apart, were pooled to estimate Koala population size occurring within the area of preferred habitat. In the first survey, one Koala was observed in diurnal searches of 42 x 0.2 ha plots (8.4 ha sampled), providing a population density estimate of 0.12 ± 0.05 (SD) Koalas per ha or 259 ± 107 Koalas in the study area. In the second survey, three Koalas were observed in diurnal searches of 46 x 1 ha plots (45.34 ha sampled), providing a population density estimate of 0.066 ± 0.037 (SD) or 142 ± 80 Koalas in the study area. When the results of these two surveys were pooled, Phillips *et al*. (2015) estimated 196 ± 65 (SD) Koalas in the study area which, based on the skewed sex ratios observed in the demographic study (above), translated to a population comprised of 125 females and 71 males.

In the PVA model, we used an initial population size of 236 which included an additional 40 animals that we calculated to form the un-sampled 0-1 year age-class (TWC 1), based on the estimated numbers and breeding success of adult females aged 3-7 years.

Carrying capacity

As indicated above, the amount and distribution of habitat for Koalas in the study area was unmapped, but estimates from previous studies in the region, and elsewhere, were used by Phillips *et al*. (2015) to classify 2,152 ha into four Koala habitat classes (Primary - 96 ha, Secondary A - 578 ha, Secondary B – 808 ha, and Secondary C – 670 ha) with associated Koala population densities (0.63/ha, 0.42/ha, 0.23/ha, and <0.1 Koalas/ha, respectively). This habitat classification was based primarily on the distribution and abundance of three preferred food tree species: Tallowwood (*Eucalyptus microcorys*), Swamp Mahogany (*E. robusta*) and Forest Red Gum (*E. tereticornis*). The estimated population densities were derived from a range of earlier studies by the authors (Phillips *et al*. 2015).

The accuracy of this information, as it applies to the study area, could not be tested. However, the information was used to estimate the carrying capacity of the habitat in the study area as suitable for approximately 556 Koalas (Phillips *et al*. 2015). These authors then considered that such a population density to be unsustainable and reduced their estimate by nearly 50% to a long-term carrying capacity of 291 Koalas (Phillips *et al*. 2015). In the PVA model, carrying capacity was set at 291 Koalas in the study area, but we need to identify the limitations that were involved with this estimate.

A total of 17 ha of good habitat for the Koala is proposed for removal during road construction in Section 10 of the highway upgrade (Table 1). This amounts to the potential loss of habitat for approximately 5 Koalas (17*0.63/2) in the study area, assuming that these animals are unable to re-establish themselves within part of their previous home-ranges. This habit loss was scheduled to occur during clearing for road construction (year 2 of the model).

Roads and Maritime Services has also committed to planting at least 130 ha of new habitat for the Koala (see section 5.3). Using similar calculations to those above, this amounts to the provision of new habitat for approximately 41 Koalas (130*0.63/2). In the PVA model, these were distributed as habitat for 25 new animals on the western side of the road and 16 new animals on the eastern side of the road (i.e. in proportion to proposed areas of planted habitat on both sides of the road). Carrying capacity was scheduled to increase to 327 (222+69-5+41) in yearly increments of three animals, beginning in year 7 (tree plantings were established in year 1), and continuing until year 15 for the western plantings and year 12 for the eastern plantings. Eucalypt plantations comprised mainly of preferred Koala food tree species and aged 6-15 years are rapidly occupied by Koalas if the animals are present nearby (Kavanagh and Stanton 2012, Rhind *et al*. 2014).

In this study, the expected loss of habitat for up to five Koalas and the proposed area of new habitat (revegetation) that will be provided for approximately 41 Koalas were treated in the model as initially reducing (for five years post road construction) then increasing (from seven to 15 years post-plantation establishment) the carrying capacity of the habitat in the study area.

Catastrophic events

Three drought years were identified over the previous 14 years (i.e. frequency of ~ 0.21), but these drought effects were considered by Phillips *et al*. (2015) as likely to affect only ridgeline areas of Koala habitat (i.e. 700/2152 ha) or 32% of Koala habitat in the study area. Estimates of a reduction in breeding success and survival due to drought in 32% of Koala habitat available were 0.85 and 1.0, respectively, of the baseline inputs for these parameters (Phillips *et al*. 2015). Hence, to calculate the average effect of drought across the entire study area (as required for the PVA), there would be no change in breeding success across 68% of the study area (1 x 0.68) but a 0.85 (or 15%) reduction within 32% of the study area (0.85 x 0.32), which, when summed, provided an overall input value of 0.952 (or 4.8%) reduction. There was no predicted reduction in animal survival in areas affected by drought (i.e. no animals died), so the input value for an average reduction in survival due to drought remains as 1.0 (i.e. no change in the parameter estimates).

The probability of a catastrophic fire event was estimated to be once in every 35 years (i.e. at a frequency of ~ 0.03), but this event was considered likely to encompass only 10% of the study area (Phillips *et al*. 2015). Estimates of a reduction in breeding success and survival due to a fire event within 10% of the Koala habitat available were 0.85 and 0.60, respectively, of the baseline inputs for these parameters (Phillips *et* *al*. 2015). So, to calculate the effect of a fire event on average breeding success across the entire study area (as required for the PVA), there would be no change in breeding success across 90% of the study area (1 x 0.9) but a 0.85 (or 15%) reduction within 10% of the study area (0.85 x 0.1), providing an overall input value of 0.985 (or 1.5%) reduction. Similarly, the input value for an average reduction in survival due to a fire event was no change across 90% of the study area (1 x 0.9) but a 0.6 (or 40%) reduction within 10% of the study area (0.60 x 0.1), providing an overall input value of 0.96 (or 4%) reduction.

5.3 Genetics studies

Two studies were conducted to profile the genetic structure and composition of the Ballina Koala population (Neaves *et al*. 2015, Norman *et al*. 2015; Appendices 3 and 2, respectively). These studies measured the levels of genetic diversity in the study area compared to surrounding areas. The Australian Museum study (Neaves *et al*. 2015) obtained tissue samples for 38 Koalas in the study area and compared these using microsatellites with 231 Koala samples from an existing database (Australian Centre for Wildlife Genomics) for four surrounding locations in NSW and south-east Queensland (Port Macquarie, Coffs Harbour, Tyagarah and Coomera). Mitochondrial DNA analyses were also performed for a total of 454 Koalas across the species' distribution to place the population in the study area within a broader context. The Southern Cross University study (Norman *et al*. 2015) analysed tissue samples for 47 Koalas collected within the study area and compared these to samples from 88 Koalas collected from nearby but outside of the study area (42 from west of the study area and south of Lismore, 30 to the north-east of Lismore and 16 from between Lismore and Casino).

Both studies reported that the levels of genetic diversity present within the Ballina Koala population (i.e. within the study area) were comparable to that found at other locations in the region. The levels of genetic variation are within the range reported for populations in northern NSW, central NSW and south-east Queensland but exceed those reported for populations in Victoria. The Australian Museum (AM) study reported no evidence of genetic structuring within the study area, but the Southern Cross University (SCU) study reported that there was genetic differentiation between the northern and southern sub-populations within the study area. This difference was explained by the northern sub-population receiving more immigrants from surrounding areas compared to the southern sub-population which is surrounded on two sides by natural barriers to Koala movement (i.e. the Richmond River and the Tuckean Broadwater). For the purposes of PVA modelling, no genetic sub-structuring was assumed for the population in the study area.

In a regional context, there was evidence for gene flow across the populations sampled in the region, but with some genetic differentiation associated with geographic distance. Both studies found evidence of long-range (up to 20 km) dispersal, although distances of up to 3.5 km were more typical, and animals that were geographically closer to each other were more likely to be closely related. Both studies provided estimates of dispersal (i.e. number of Koalas per generation), both between the study area and surrounding areas and within the study area between areas east and west of the proposed highway. These estimates assumed that dispersal was symmetrical because in most cases it was not possible to determine the direction of dispersal.

Both studies reported that the average level of inbreeding is negligible in the study area. The SCU study provided estimates of the effective number of alleles in the population in the study area, and the AM study provided frequencies for each allele in the population. This information was compiled into a spreadsheet by Dr Catherine Grueber (Sydney University) and used in the PVA modelling to obtain an estimate of the genetic diversity (number of alleles remaining) resulting from each set of scenarios.

5.4 Estimating dispersal

Dispersal occurs at multiple levels, and rates, throughout the study area and it is difficult to estimate these values. Within the study area, one aspect of dispersal (a) is an estimate of the number of animals, per generation, that have successfully contributed to the breeding pool in an adjacent sub-population. This information has been provided by the two studies of genetic diversity in the Ballina Koala population (Neaves *et al*. 2015, Norman *et al*. 2015; Appendices 3 and 2, respectively). These studies estimated that 2.9, or 5 (± 2.2), individuals (mean 3.95), respectively, move from their natal home ranges to their new breeding home ranges across a nominal line coinciding with the location of the proposed road in the study area. These data are based on a Koala generation length of 6.02 years, which was estimated for a free-ranging, *Chlamydia*-positive population in north-eastern New South Wales (Phillips 2000).

Another aspect of dispersal (b) is that which includes all movements that may occur within the Koala population, but which do not necessarily contribute to the breeding pool in an adjacent sub-population (e.g. transient animals, and animals which breed only in one sub-population but whose home-ranges are large enough to overlap parts of two sub-populations). In most years, this form of dispersal is likely to be inconsequential, as the effective rates of dispersal have already been encompassed within estimates for dispersal type (a). However, dispersal type (b) is likely to be density-dependent and so could become very important in certain years through the provision of "population rescue" when a sub-population has been severely depleted by some catastrophe, or if there is a steady decline in the size of an adjacent sub-population. Dispersal type (b) is difficult to parameterise in the model because these population density-dependent relationships are unknown. The relevance of considering this form of dispersal is that, in some years, the rate could be much greater than that normally occurring and the capacity to accommodate this may be affected by the number of connectivity structures provided.

A range of plausible estimates for dispersal were used in the PVA models, beginning with the estimates provided by the two genetic studies (i.e. mean 1.98 animals each way per year). However, because less than half (44.83%) of the females of breeding age actually bred during the year of the local field study (2014-2015), it could be argued that the number of Koala movements through the connectivity structures (if they were present) might be at least twice the numbers for dispersal estimated by the two genetics studies (i.e. more than 4 animals each way per year). Further guidance may be provided by long-term Koala radio-tracking studies elsewhere. For example, 40 (23 males and 17 females) of 195 (20.5%) radio-collared Koalas dispersed in south-east Queensland (Dique *et al*. 2003). Ninety-three percent of these dispersing animals were 20-36 months of age, with the mean straight-line distance between natal and subsequent breeding home ranges measured at 3.5 km for males (range 1.1-9.7 km) and 3.4 km for females (range 0.3-10.6 km). In the Pilliga forests of northern NSW, 6 of 32 (18.8%) radio-collared Koalas were initially captured at one location but moved to establish a new home-range during the 12 month study (Kavanagh *et al.* 2007). These 6 animals were all 2-3 years old (four males and two females). The mean daily (straight-line) movements for all animals in the study was 89 m, but this included the large daily movements (up to 897 m) when young animals were dispersing.

In the PVA modelling, only animals aged 1-4 years (both genders) were permitted to disperse. Dispersal inputs ranged from 1.98 individuals (based on the mean estimate provided by the genetics studies), through to 4, 8, 10 and 20 individuals moving each way per year to encompass a range of potential dispersal scenarios. Dispersal rates were treated as "symmetric" between the two sub-populations, as per the assumptions of the genetics analyses. Dispersal was also modelled as the number of animals dispersing rather than as a percentage of each sub-population because the smaller, eastern sub-population acted as a sink when equal percentages of each sub-population were permitted to disperse. Mortality was assumed to be zero for all dispersing animals.

5.5 Estimating immigration and emigration

The study area boundary (Figure 1) and the surrounding vegetation types were shown by the genetics studies not to constitute a barrier to Koala movements. Accordingly, the “harvest” and “supplementation” features of Vortex were used to account for emigration out of, and immigration into, the study area each year, respectively. As in the previous section (5.4), rates of immigration and emigration can be viewed as dispersal type (a) and dispersal type (b), although it is more difficult to estimate values for these parameters (especially for dispersal type b) because of the large area and perimeter involved. Fortunately, the two recent studies of genetic diversity in the Ballina Koala population (Neaves *et al*. 2015, Norman *et al*. 2015) also compared their results with other Koala populations nearby (Tyagarah and Lismore, respectively).

These studies estimated that 5.7 (± 2.8) Koalas move per year between the study area and the broader Lismore area (Norman *et al*. 2015; Appendix 2), and that 0.8 individuals move per year between the study area and the more distant Tyagarah Koala population (Neaves *et al*. 2015; Appendix 3). Given that the Lismore samples were in closer proximity to the study area (approximately 15 km vs 40 km away), we decided to model immigration and emigration in Vortex using the values of 2.85 and 2.85, respectively (sum=5.7). No estimates of dispersal type (b) could be determined for immigration and emigration, and so only the above values (2.85) were used in modelling immigration and emigration.

5.6 Mitigation options

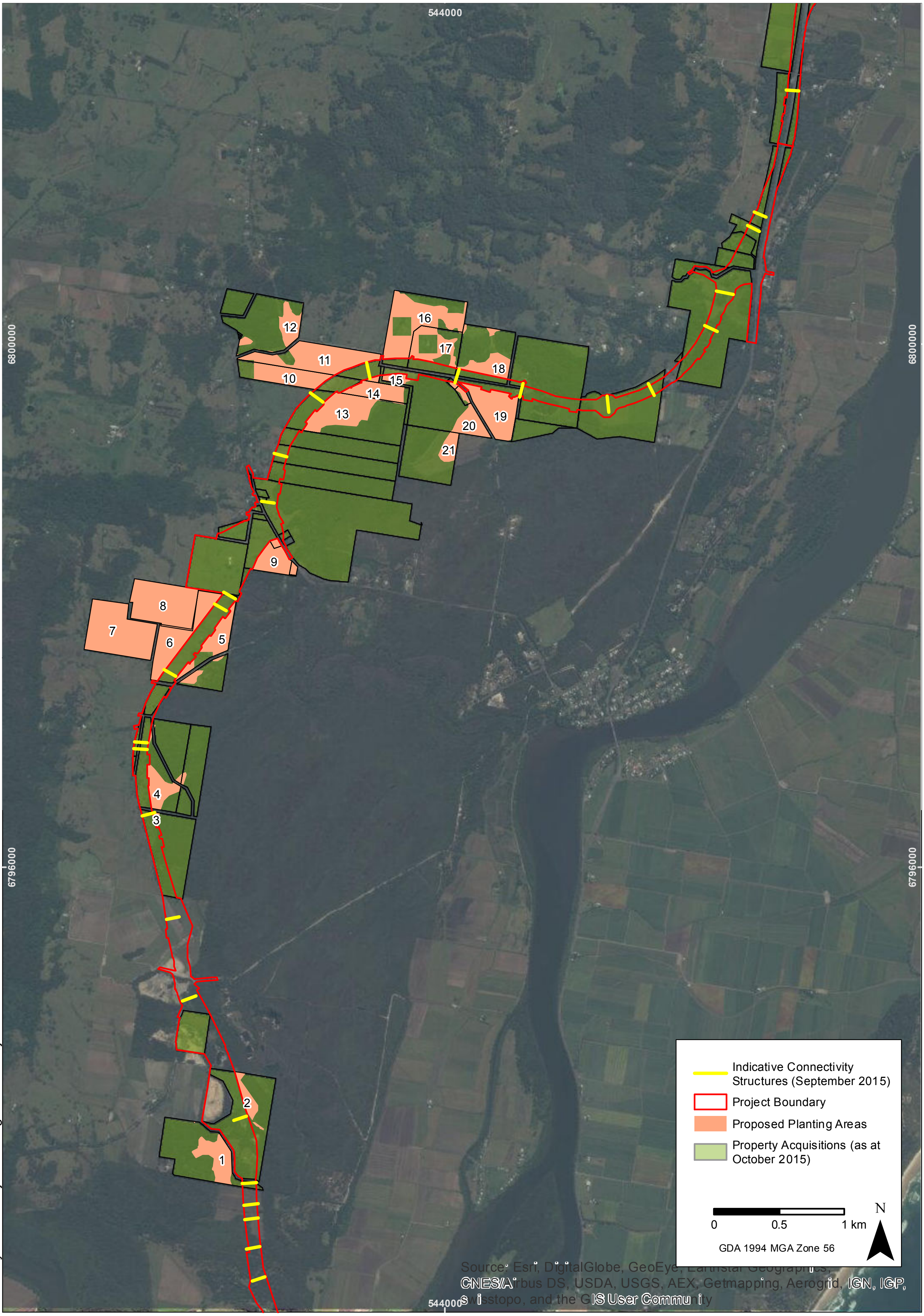
Roads and Maritime Services, in consultation with other agencies and Koala experts, have agreed to build 26 connectivity structures along the 13.5 km of Section 10 of the proposed highway upgrade, all of which are likely to have value in enhancing the dispersal and movements of Koalas in the study area (Figure 4; Appendix 4). This is a significant increase in the numbers and type (i.e. Koala-friendly designs) of these structures compared to those proposed in the EIS/SPIR (2012/2013) (Figure 5; Appendix 4).

On average, it is proposed that there will be approximately 1.9 connectivity structures per km of new road, or about one connectivity structure per 520 m of the road. With Koala home-ranges averaging about 15 ha (i.e. 437 m diameter; Kavanagh *et al.* 2007), this represents nearly one connectivity structure per Koala home-range either side of the proposed highway upgrade in Section 10, providing opportunities for most animals living near the proposed road to cross safely or to disperse.

The highway upgrade along Section 10 will also be fully-fenced, using Koala-proof floppy-top fencing, with the provision of grids near the intersections with other roads, to create a fully closed system to prevent vehicle-strike to Koalas (Appendix 4).

Roads and Maritime Services has acquired at least 621 ha (as at October 2015) of forested and cleared land near the proposed highway upgrade in Section 10, of which 151 ha is available for revegetation. Eucalypt plantations comprised mainly of preferred Koala food tree species are rapidly occupied by Koalas if the animals are present nearby (Kavanagh and Stanton 2012, Rhind *et al*. 2014). The NSW Minister for Roads and Freight has made a commitment to plant at least 130 ha of Koala food trees in the study area, if the proposed upgrade is approved, and a Koala revegetation strategy has been developed (Kavanagh and McLean 2015; Figure 4). This is equivalent to the provision of new habitat for approximately 41 Koalas (see section 5.2). As described in the previous section, this new habitat was incorporated in the model through incremental changes (from years 7-15) in the carrying capacity of the study area.

The proposed new Koala food tree plantations will also enhance dispersal between the western and the eastern sub-populations by focussing Koala movements towards the connectivity structures that will be provided, and will facilitate Koala movements through adjacent areas that are currently cleared farmland.



Drawn by: GT Project Manager: RK Project Number: 2266 Date: 02/10/2015

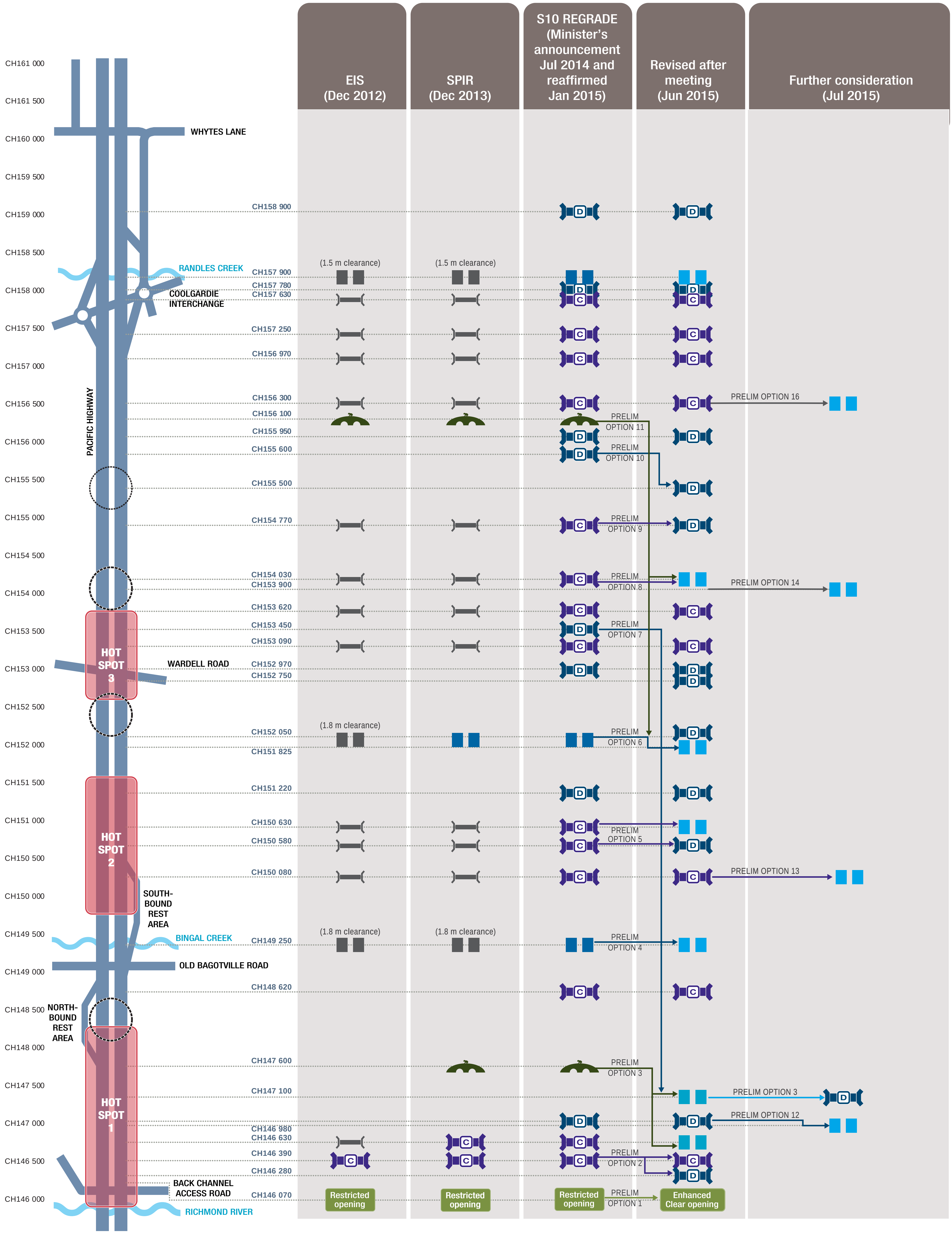
Section 10 - RMS Proposed Planting Areas

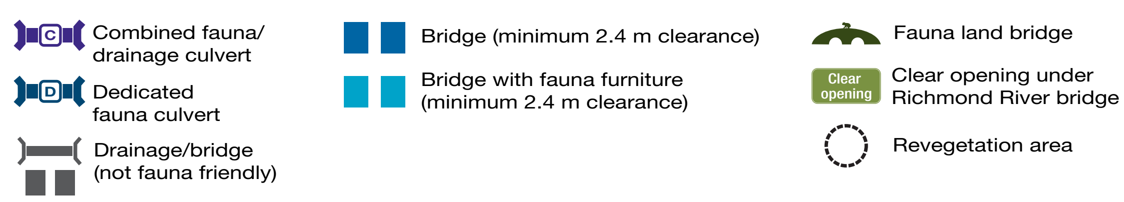
niche
Environment and Heritage

FIGURE 4

Path: T:\spatial\projects\a2200\a2266_W2B_KPoM\Maps\report\2266_Figure_4_planting.mxd

KOALA CONNECTIVITY DEVELOPMENT





Note:
(1) Koala friendly crossing shown have a minimum 2.4 m clearance

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5.7 Road impacts

Road impacts may adversely affect Koala populations through habitat fragmentation and barrier effects, as well as through direct mortality from vehicle strikes. Independent studies have shown that roadkills can be a major source of mortality for Australian wildlife, including Koalas (Taylor and Goldingay 2003, 2004, 2010; Hobday and Minstrell 2008; AMBS 2011). Over a four-year period from 2005-2008, a total of 530 Koalas was presented to veterinary clinics near Port Stephens in NSW, 205 (38.7%) of which had been struck by motor vehicles (D. Hudson, personal communication).

In the Ballina study area, of 109 "call-outs" reported by Lismore Friends of the Koala (data from 1989-2014), 35 (32.2%) Koala deaths were due to vehicle strikes, compared to 22 (20.2%) due to dog attacks, 40 (36.7%) due to disease, and 12 (11.0%) due to natural causes (Phillips *et al*. 2015). These authors reported four locations in the study area as known "hot spots" for Koala mortalities (Pacific Highway, Bruxner Highway, Wardell Road and Bagotville Road; Appendix 5), and observed six road-killed Koalas during their six-month field study (Phillips *et al*. 2015). A recent update reported that at least 10 Koalas were hit by vehicles in the study area during 2015, eight of them within the four hot spots identified (S. Phillips, *pers. comm.* 14/12/2015) (see also section 6.4).

5.8 Koala use of connectivity structures

Crossing structures (underpasses and overpasses) have been shown to be effective for Koalas provided they are large enough in cross-section, not too long (<50 m), and are combined with Koala-proof fencing and revegetation (Taylor and Goldingay 2003, AMBS 2011, RMS unpublished data). However, research is lacking on the extent to which mitigation measures reduce the risk of local extinction, given the overall context of the major linear infrastructure (Taylor and Goldingay 2010, Van der Ree *et al.* 2011). No relationship has yet been established between the numbers of connectivity structures available and the probability that an animal will cross, or the numbers of individual Koalas using them. As indicated above (section 5.4), the number of connectivity structures normally required to satisfy Koala dispersal type (a), may be less than the numbers required to facilitate Koala dispersal type (b) during the period following a catastrophe when sub-population rescue is needed. Accordingly, we modelled dispersal across a continuum of values (0.792, 1.98, 4, 8, 10, 20 animals each way per year) to investigate this possibility. In this PVA, we assumed that all 26 connectivity structures proposed for Section 10 were required to meet the needs of dispersal at each level (1.98, 10 or 20 animals), and that the worst-case scenario for road impact was that connectivity may be reduced to 40% of these levels (0.792, 4 or 8 animals). This worst-case estimate of 40% dispersal was based on each connectivity structure having a "catchment area" of 200 m (i.e. 100 m fencing either side of each connectivity structure), amounting to approximately 40% of the total length of the road.

5.9 Output measures

All PVA scenarios were modelled across a timeframe of 50 years (see section 1.2).

Each model-run in Vortex produced comprehensive output for each sub-population (east and west of the proposed highway upgrade) and for the overall population. These outputs included tables showing the projected number of Koalas remaining after 50 years, the probability of extinction after 50 years, the population growth rate, the number of alleles remaining in the population, and the variability around each of these estimates based on 1000 simulations of each modelled scenario. A wide range of graphical outputs can also be displayed.

6. Modelled Scenarios

6.1 Impact assessment

The impact of the proposed road was assessed by comparing population projections based on differences in the rate of dispersal between two sub-populations as influenced by the proposed connectivity structures. The provision of supplementary habitat for Koalas in the study area was modelled through an increase in the projected carrying capacity of the habitat. Management options were investigated by varying the levels of key population parameters (e.g. fecundity, mortality) in a series of sensitivity tests.

Before any impacts due to the road could be assessed, it was important to untangle any confounding effects that may be caused by splitting the population into two sub-populations. That is, smaller populations are inherently more prone to extinction than larger populations, regardless of any road effects. Accordingly, all modelled scenarios were conducted on the basis of comparisons between two sub-populations in which the level of dispersal was either unconstrained (i.e. the no-road scenario) or constrained (i.e. the presence of the road). For the purposes of assessing the impact of the proposed road, it was assumed (expert workshop discussions, 14 October 2015 organised by NSW Koala Expert Advisory Committee) that the 26 connectivity structures to be provided (section 5.6) would either cater fully for the dispersal needs of the population (i.e. 100% connectivity) – and therefore result in no impact of the road – or, as a worst case scenario, would limit the rate of dispersal to 40% of the numbers of animals attempting to disperse. The worst-case estimate of 40% dispersal was based on each connectivity structure having a "catchment area" of 200 m (i.e. 100 m fencing either side of each connectivity structure), amounting to approximately 40% of the total length of the road. It was also assumed that the proposed road would be fully fenced to prevent any additional Koala mortalities. The "worst-case" impact of the road could therefore be estimated as a percentage by dividing the projected number of animals remaining in the population after 50 years in the 40% connectivity scenario by the numbers remaining after 50 years in the 100% connectivity scenario, and subtracting the result from 100.

The scenarios modelled included the following:

- No habitat supplementation or management interventions, but comparing dispersal rates either unconstrained (100% connectivity) or constrained (40% connectivity) – including sensitivity tests to determine the effects of uncertainty in the estimates of demographic parameters. Note, this scenario is simply provided as a reference point because road construction will require the removal of habitat for some animals.

- No habitat supplementation or management interventions, but comparing dispersal rates either unconstrained (100% connectivity) or constrained (40% connectivity), including the loss of habitat for 5 Koalas during road construction. These scenarios also included sensitivity tests to determine the effects of uncertainty in the estimates of demographic parameters.

- Effect of habitat supplementation for up to 41 Koalas after accounting for the loss of habitat for 5 Koalas. These scenarios also include sensitivity tests for an overall reduction in mortality by 20% across all age-gender classes, increasing population fecundity by 20%, and both reducing mortality by 20% and increasing fecundity by 20%. Note, these variations in fecundity and mortality rate are also provided to indicate the potential for management (unspecified) to affect population outcomes.

- Effect of reducing mortality by either 4 or 8 young animals per year, combined with habitat supplementation.

In each of these scenarios, the PVA models incorporated dispersal estimates ranging from 1.98-20 animals per year moving each way across the proposed road.

6.2 Sensitivity analysis

Sensitivity testing was undertaken to achieve an understanding of the most influential variables in the analysis, and to determine the effects on model results of uncertainty in the estimates of key demographic parameters. The sensitivity test (ST) function in Vortex was used to simultaneously compare a range of inputs for certain parameters, while holding all the rest of the parameters constant. Variables tested in this way were breeding success, female and male mortality rates by age-class, initial population size, carrying capacity and the number of lethal alleles in the population. Subsequently, the effects of uncertainty in the estimates of fecundity, mortality and dispersal on model results were tested by varying these parameters up or down by 20% of their base values (Phillips *et al.* 2015). Inbreeding depression was also assumed to be present for these sensitivity tests.

6.3 Road effects models: role of habitat supplementation

Habitat supplementation for up to 41 Koalas after accounting for the loss of habitat for 5 Koalas was achieved by initially reducing the carrying capacity of the habitat in the study area by five animals for 6 years after clearing for road construction, followed by small increases in carrying capacity each year from 7-15 years after plantation establishment (see section 5.2). These scenarios also included sensitivity tests for an overall reduction in mortality by 20% across all age-gender classes, increasing population fecundity by 20%, and both reducing mortality by 20% and increasing fecundity by 20%. The primary reason for including these scenarios was to assess the effects of uncertainty in these parameter values, but they also provide an indication of the potential for management (unspecified) to affect population outcomes (e.g. by reducing Koala mortality through fencing on other local roads, controlling dog predation, and by increasing Koala fecundity by limiting the frequency and severity of disease in the population through the application of a *Chlamydia* vaccine, or both).

6.4 Road effects models: applying management to control mortality

Long-term data collected by the Lismore Friends of the Koala group for the numbers and locations of Koalas killed by vehicles on roads in the study area averaged 1.23 animals per year, although annual mortalities of 4-6 animals were considered more likely (Phillips *et al*. 2015). These authors observed six Koala mortalities caused by vehicle-strike during the six months of their field study, and at least 10 mortalities in 2015 (S. Phillips, *pers. comm*. 14/12/2015). Four main road-kill "hot-spots" were identified (Appendix 5). The same long-term data set also showed that at least 1.64 Koalas were killed annually by predation by domestic dogs. This information suggests that there may be opportunities for management to reduce the numbers of "avoidable" Koala mortalities by up to four or possibly eight animals per year in the study area. These two scenarios are included because they represent achievable objectives for management because reducing mortality by 4 or 8 animals could occur by fencing known road-kill hotspots, and by controlling local dog predation.

Reducing Koala mortality by either 4 or 8 animals in the study area due to management control was modelled by eliminating "harvest" (emigration) from the study area (i.e. 2.85 animals per year) and adding the balance (either 1.15 or 5.15 animals per year, respectively) to the existing level of 2.85 for "supplementation" (immigration). This reduction in mortality was applied at the rate of 40% for young females (1-3 years old) and 60% for young males (1-4 years old) because of the greater propensity for males to be killed by cars (Phillips *et al*. 2015).

7. Results

7.1 Deterministic population growth rate

All scenarios modelled, with or without the proposed highway upgrade, showed a gradual decline in this population of Koalas. Deterministic projections of population growth (i.e. in the absence of catastrophes and other unplanned stochastic events) were negative. This is, in 2014-2015, the birth rate was insufficient to offset the death rate in this population. The exponential rate of increase for the population was $r=-0.0049$, the annual rate of change was $\lambda=0.9951$, and the per-generation rate of change or "net replacement rate" was $R_0=0.8092$. The population was found likely to persist for at least 50 years under most scenarios, but at much reduced numbers (Figure 6; Tables 4-5).

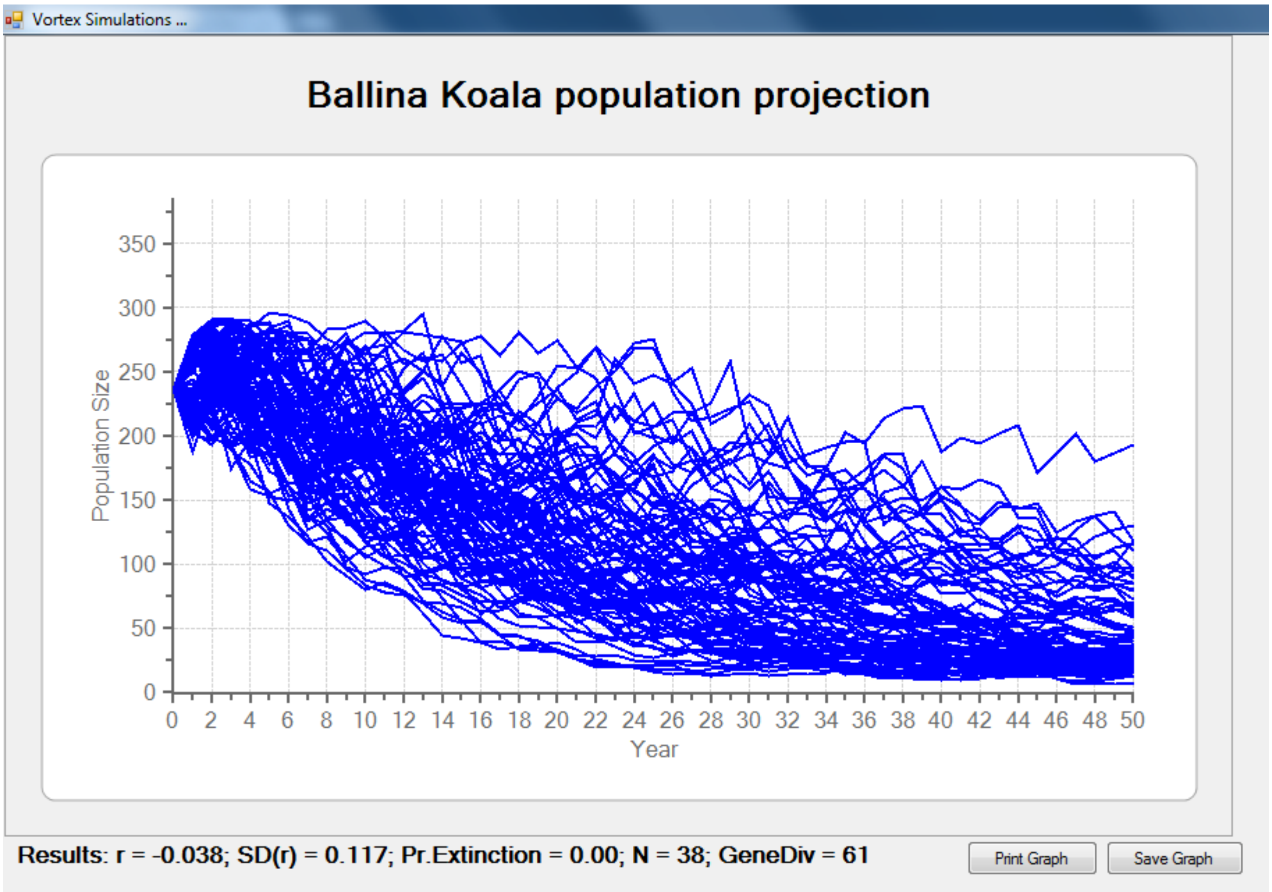


Figure 6: Projected Koala population decline in the study area over 50 years, in the absence of the proposed highway (results of 1000 simulations). The projection incorporates the likelihood of drought and fire in the study area, together with a small allowance (2.85 individuals per year) for both immigration and emigration. The projection also assumes the presence of inbreeding in the population.

Assumptions about the presence of inbreeding depression in the population had a significant effect on the results. Including inbreeding depression and the presence of lethal alleles in all models had the effect of reducing population size projections by approximately 20-40% of those estimated when inbreeding depression and the presence of lethal alleles was switched "off" in the analyses. The genetics studies by Neaves *et al*. (2015) and Norman *et al*. (2015) both reported very low levels of inbreeding in the Ballina Koala population but, to be conservative, we presented our final PVA results with the assumption that inbreeding depression was present in the population.

7.2 Sensitivity tests – identifying the most influential variables

Sensitivity tests were applied within Vortex to investigate the influence of parameter estimates for key population variables. There will always be uncertainty surrounding the results of “snapshot” estimates derived from short-term field studies because these estimates vary from one year to another but, in the absence of long-term population data, the real question is - for which variables are these errors likely to have a significant impact on the results? Conversely, which variables are most likely to influence population viability outcomes if they can be controlled or manipulated by management?

Sensitivity tests showed that breeding success (population fecundity; Figure 7) and female mortality rates for both juveniles and adults (Figure 8) were highly influential in the results of the PVA (i.e. in projected population sizes). This means that any errors in the estimation of these two variables are likely to have a significant effect on the results, and also that efforts to manipulate these variables through management are likely to have a beneficial effect on population viability. In contrast, sensitivity tests for other variables, including male mortality rates for juveniles, sub-adults and adults (Figure 9), initial population size (Figure 10), habitat carrying capacity (Figure 11), and the number of lethal alleles in the population (Figure 12), showed that management attempts to vary these parameters would be unlikely to have a large effect on the results, and, of course, that errors in the initial estimates for these parameters are unlikely to be of major concern for the analysis.

The importance of birth rates (breeding success) being adequate to cover death rates (mortality) in this population is clearly shown in Figure 10 where population size is projected to decline rapidly. However, it should be noted that the declines observed in year 1 for initial population sizes of 500 and 400 animals were due to carrying capacity remaining capped at 291 individuals in the model. Management efforts to improve breeding success and/or to reduce mortality would be highly beneficial for this population. It is likely that by reducing mortality of females in particular (Figures 8 and 9), that breeding success in the population would also increase.

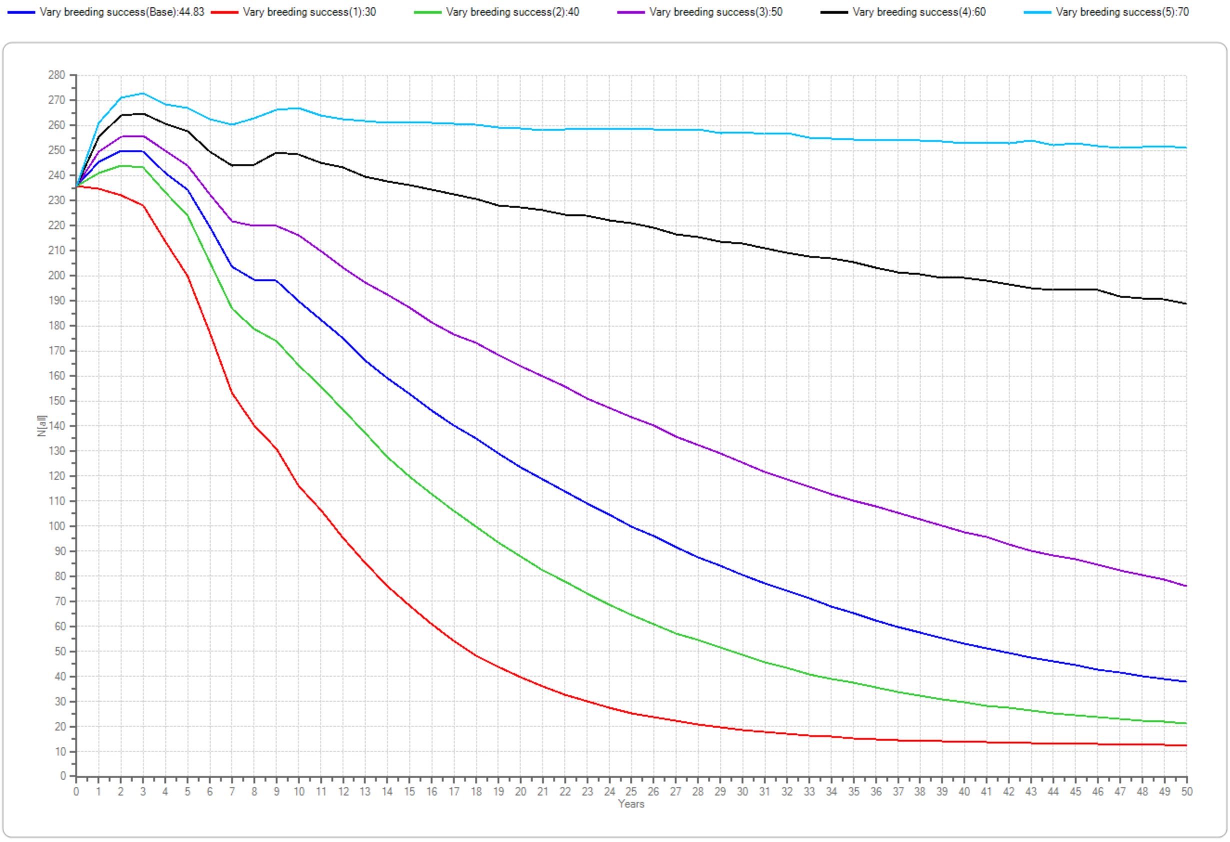
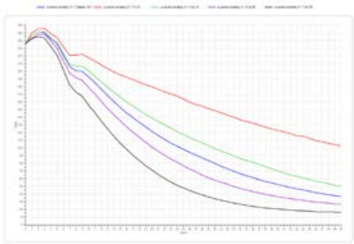
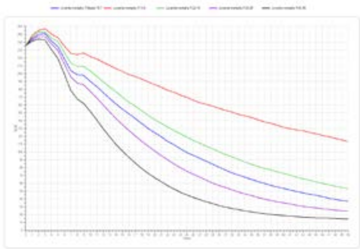


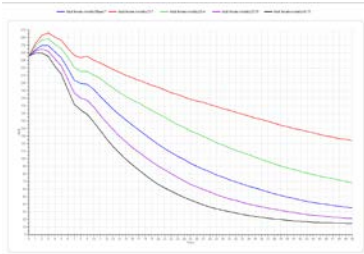
Figure 7: Sensitivity tests showing the effect of varying breeding success from 30% (red line) to 70% (turquoise line) on Koala population size after 50 years. The blue line (44.83%) shows the baseline estimate used in this study.



(a) Juvenile females (0-1 years)

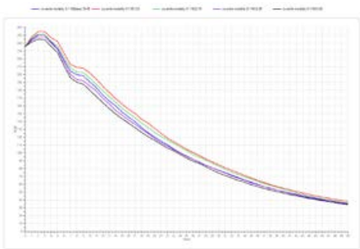


(b) Sub-adult females (1-2 years)

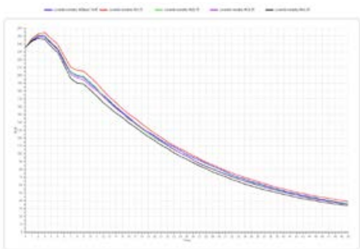


(c) Adult females (3+ years)

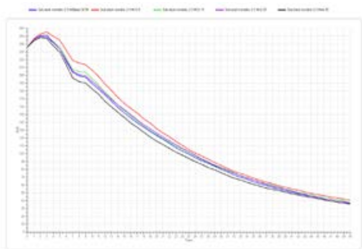
Figure 8: Sensitivity tests showing the effect of varying female mortality in age-classes 0-1 and 1-2 years from 5% (red line) to 35% (black line) on Koala population size after 50 years. For adult females, the range was from 1% (red line) to 13% (black line). In each case (a-c), the blue line shows the baseline estimates used in this study.



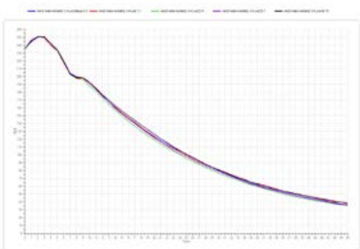
(a) Juvenile males (0-1 years)



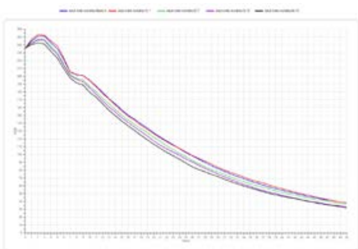
(b) Juvenile males (1-2 years)



(c) Sub-adult males (2-3 years



(d) Adult males (3-4 years)



(e) Adult males (4+ years)

Figure 9: Sensitivity tests showing the effect of varying male mortality in age-classes 0-1, 1-2, and 2-3 years from 5% (red line) to 35% (black line) on Koala population size after 50 years. For adult males, the range was from 1% (red line) to 10% (black line). In each case (a-e), the blue line shows the baseline estimates used in this study.

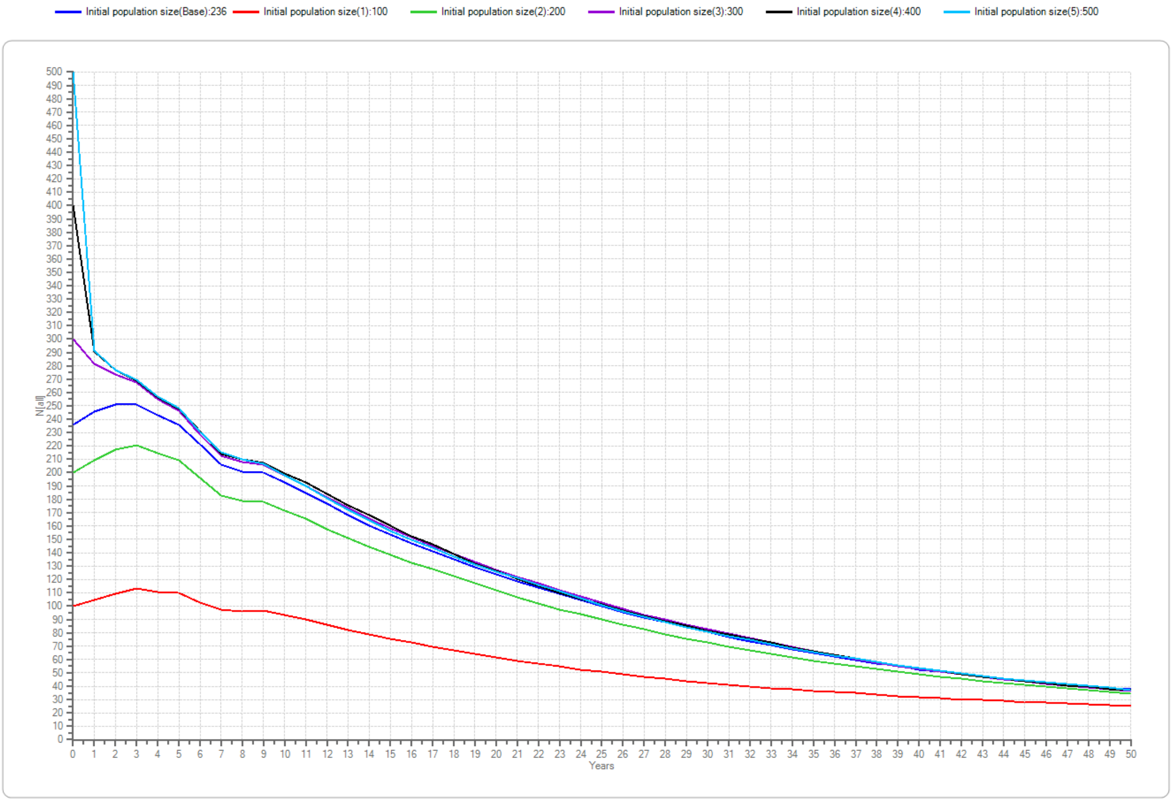


Figure 10: Sensitivity tests showing the effect of varying initial population size from 100 (red line) to 500 (turquoise line) on Koala population size after 50 years. The blue line shows the baseline estimate (236) used in this study. Note the effect of the cap on carrying capacity (291) in these simulations.

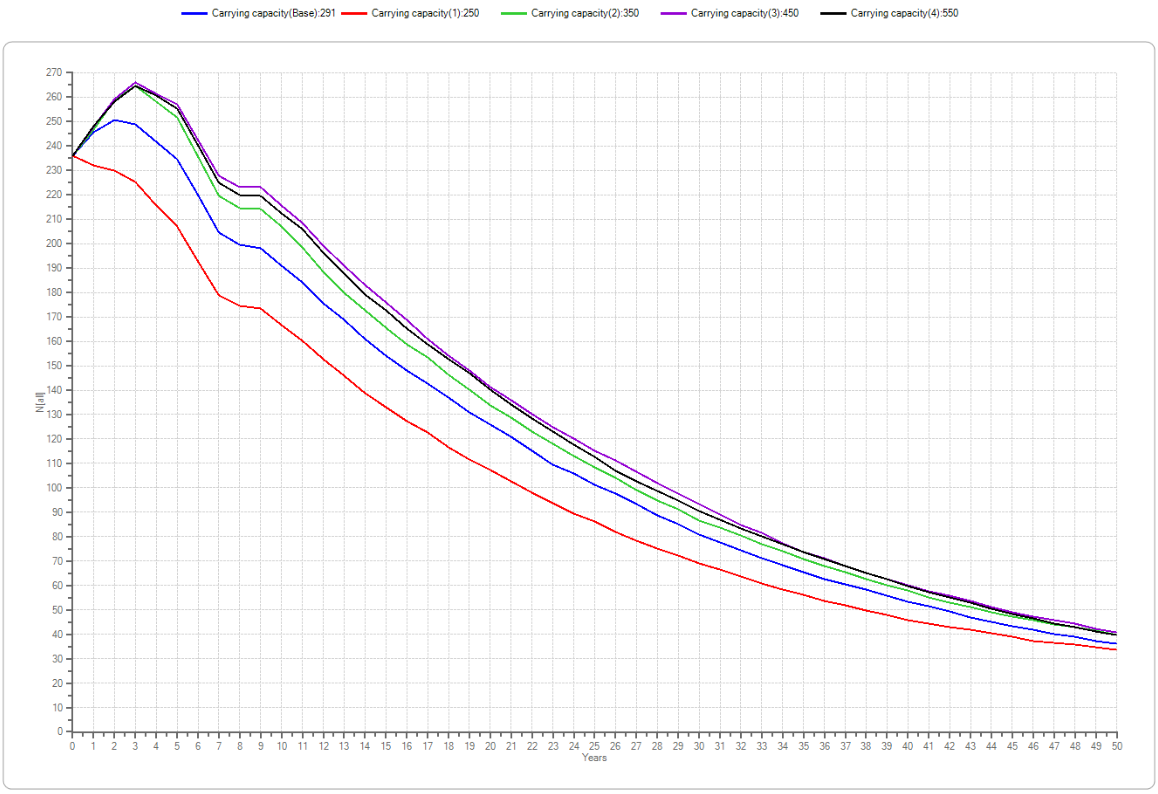


Figure 11: Sensitivity tests showing the effect of varying carrying capacity of the habitat from 250 (red line) to 550 animals (black line) on Koala population size after 50 years. The blue line shows the baseline estimate (291) used in this study.

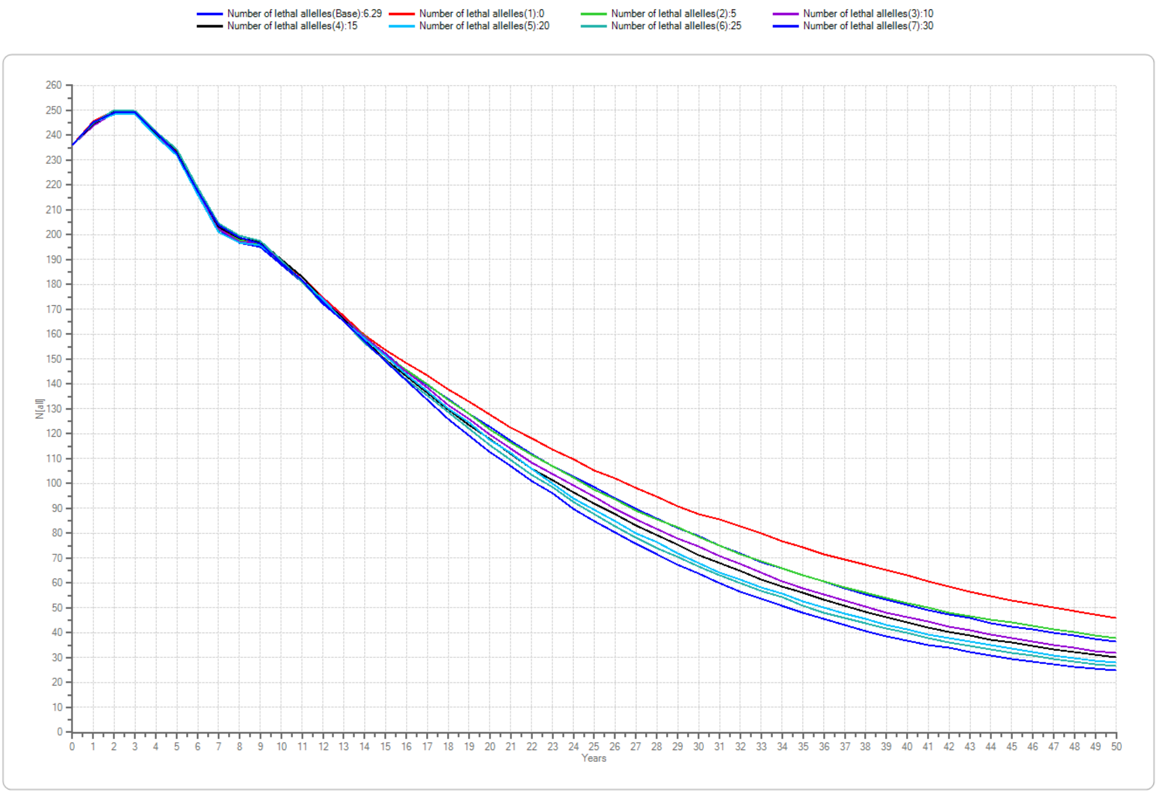


Figure 12: Sensitivity tests showing the effect of varying the number of lethal alleles in the population from 0 (red line) to 30 (lower blue line) on Koala population size after 50 years. The blue line near upper-middle shows the baseline "default" estimate (6.29) used in this study.

7.3 Effects of the proposed road – varying dispersal and connectivity

Three primary considerations need to be dealt with before the effects of the proposed road can be estimated. Firstly, it is important to untangle any confounding effects that may be caused by splitting the population into two sub-populations. This is because Vortex could calculate the probability of extinction for two sub-populations as greater than that for a single population of the same size, although this was not observed. Secondly, dispersal rates and the directions of animal movement between each sub-population are difficult to estimate, and these factors are likely to vary from one year to another depending on population density and population size. The minimum rate of dispersal in the study area was identified by the two genetics studies as approximately 3.95 animals (i.e. 1.98 each way) per year (section 5.4), although dispersal rates of up to 40 animals (i.e. 20 each way) were also modelled. Without further information, it was assumed (as did the genetics studies) that dispersal was symmetric (equal numbers of animals dispersing from west to east, and from east to west). Thirdly, relationships between dispersal rates and the numbers (or type) of connectivity structures provided are not well established. For the purposes of assessing the impact of the proposed road, it was assumed that the 26 connectivity structures to be provided (section 5.6) would either cater fully for the dispersal needs of the population (i.e. 100% connectivity) – and therefore result in no impact of the road – or, as a worst case scenario, would limit the rate of dispersal to 40% of the numbers of animals attempting to disperse. This result could also be interpreted as the likely outcome if only 40% of the planned connectivity structures were provided. The impact of the road would therefore be estimated as a percentage by dividing the projected number of animals remaining in the population after 50 years in the 40% connectivity scenario by the numbers remaining after 50 years in the 100% connectivity scenario, and subtracting the result from 100.

For analysis, the population was treated as two sub-populations divided by the location of the proposed road, but with full dispersal and connectivity between them to the extent indicated by the genetics results. A similar projected population decline was observed (Figure 13) to that shown in Figure 6.

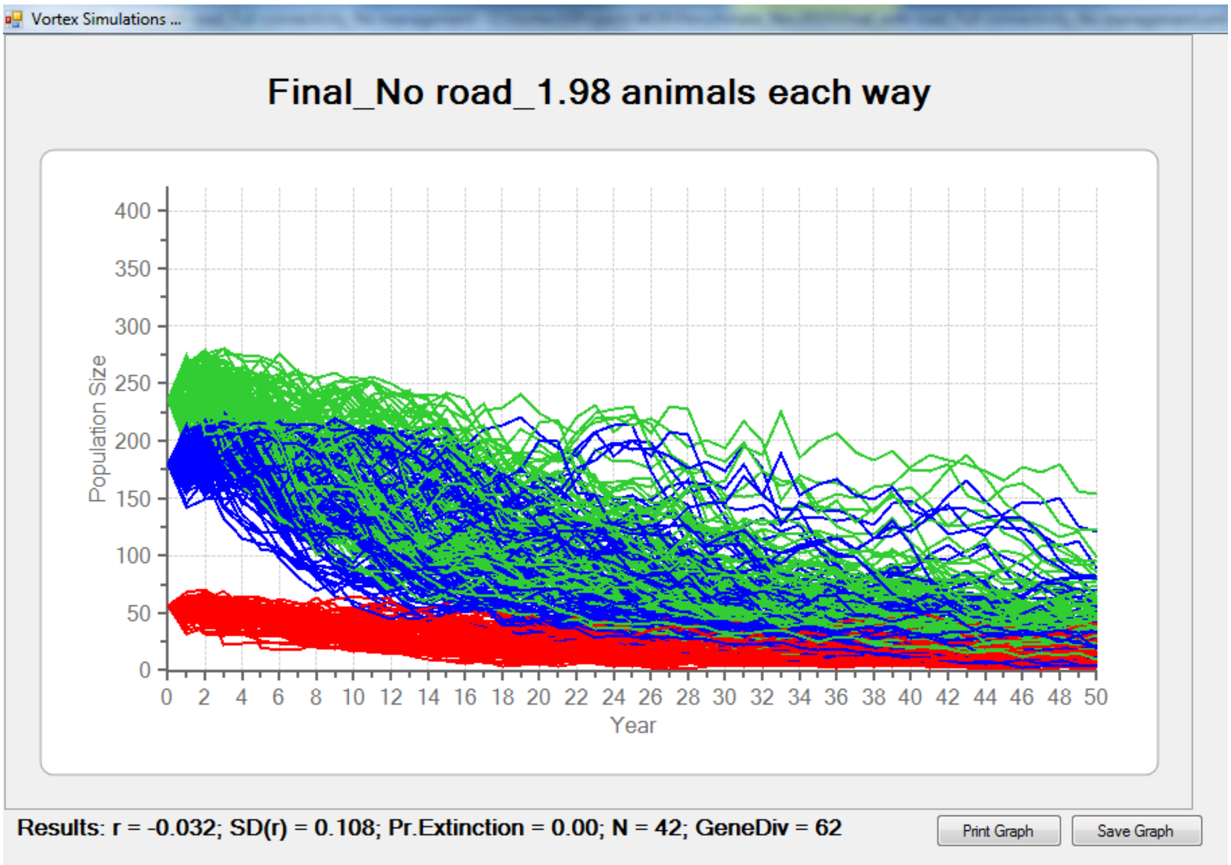


Figure 13: Projected Koala population decline over 50 years, without the proposed highway. Parameter estimates and model settings as for Figure 6, except that two sub-populations are modelled with 1.98 animals dispersing each way, per year, between them. The smaller, eastern sub-population is indicated in red, the larger western sub-population in blue, and the total population in green.

The results showed that, at the minimum levels of dispersal estimated to occur in the study area (1.98 animals moving each way per year), there was virtually no impact of the road on projected Koala population size after 50 years when reduced dispersal and connectivity was assumed (i.e. 100–[42.1/42.3*100] = -0.5%) (Table 4). If 10 animals were dispersing each way per year, there could be a 4% impact on the population if the connectivity structures limited dispersal to only 40% of this number (i.e. 100-[41.7/43.4*100] = -3.9%) (Table 4). Similarly, the impact of the road could increase to 8% if 20 animals were dispersing each way per year (i.e. 100-[43.0/46.8*100] = -8.1%) (Table 4).

Under all scenarios, with and without the road, the projected Koala population size in the study area declined substantially over the 50 year time frame (Table 4). However, varying levels of dispersal, and varying levels of connectivity, had relatively minor impacts on projected Koala population size. The final number of alleles estimated within the Koala population under each of the above scenarios ranged from 4.81-4.96.

Note, that these scenarios do not include the initial loss of habitat for 5 Koalas, or the provision of 130 ha of new Koala habitat; these are included in the following section (Section 7.4).

It should be understood that the data reported in the following series of tables are the results of simulations (i.e. probability based on 1000 runs analysed for each scenario using different values for each parameter depending on its range of variability) and so can vary slightly each time that a scenario is run using the same data inputs.

Table 4: Impacts of the proposed road on the Ballina Koala population near Wardell under a range of dispersal scenarios, not including initial habitat loss due to clearing for road construction.

All scenarios include the same demographic inputs, the same likelihood of two types of catastrophes, and 2.85 animals emigrating out of, and 2.85 animals immigrating into, the study area. Data inputs from Neaves *et al*. (2015), Norman *et al*. (2015) and Phillips *et al*. (2015). Assumes the presence of inbreeding depression and lethal alleles.

P(E), probability of extinction; N, estimated number of individuals present after 50 years.

Scenarios	Population P(E)	Population N	Western sub-Pop P(E)	Western sub-Pop N	Eastern sub-Pop P(E)	Eastern sub-Pop N
Single population	0.00	37.7	na	na	na	na
Two sub-populations, with dispersal 0 animals each way per year (zero connectivity)	0.00	38.2	0.00	23.6	0.01	14.8
Two sub-populations, with dispersal 1.98 animals each way per year (100% connectivity) **i.e. BASIC NO-ROAD SCENARIO**	0.00	42.3	0.00	27.4	0.02	15.3
Two sub-populations, with dispersal 0.792 animals each way per year (i.e. 40% connectivity)	0.00	42.1	0.00	27.0	0.01	15.4
Two sub-populations, with dispersal 10 animals each way per year (100% connectivity)	0.00	43.4	0.00	33.5	0.14	11.2
Two sub-populations, with dispersal 4 animals each way per year (i.e. 40% connectivity)	0.00	41.7	0.00	27.9	0.03	14.2
Two sub-populations, with dispersal 20 animals each way per year (100% connectivity)	0.00	46.8	0.00	41.6	0.34	7.3
Two sub-populations, with dispersal 8 animals each way per year (i.e. 40% connectivity)	0.00	43.0	0.00	31.7	0.09	12.2

7.4 Effects of the proposed road – initial habitat loss and revegetation

The provision of new habitat for up to 41 Koalas, following the loss of habitat for five animals during road construction, made little difference to the projected outcomes for the population; only fractional improvements were indicated by the modelling (Table 5). The same relativities between dispersal rates and connectivity in terms of projected population outcomes (Table 4) were observed when carrying capacity was raised to account for the planting of supplementary habitat (Table 5). This was because the deterministic decline in this Koala population ensured that there were not enough animals present to utilise the new habitat provided. The final number of alleles estimated within the Koala population under each of the above scenarios ranged from 4.86-4.94.

Table 5: Impacts of the proposed road on the Ballina Koala population near Wardell with revegetation and after accounting for initial habitat loss.

All scenarios include the same demographic inputs, the same likelihood of two types of catastrophes, 2.85 animals emigrating out of, and 2.85 animals immigrating into, the study area, and changes to habitat carrying capacity to model the effects of losing habitat for five Koalas during road construction followed by the provision of new habitat for up to 41 Koalas. Data inputs from Neaves *et al*. (2015), Norman *et al*. (2015) and Phillips *et al*. (2015). Assumes the presence of inbreeding depression and lethal alleles.

P(E), probability of extinction; N, estimated number of individuals present after 50 years.

Scenarios	Population P(E)	Population N	Western sub-Pop P(E)	Western sub-Pop N	Eastern sub-Pop P(E)	Eastern sub-Pop N
Two sub-populations, with revegetation: dispersal 0 animals each way per year (zero connectivity)	0.00	39.4	0.00	24.8	0.02	14.8
Two sub-populations, with revegetation: dispersal 1.98 animals each way per year (100% connectivity) **<u>i.e. WITH-ROAD SCENARIO, assuming no loss of connectivity</u>**	0.00	42.5	0.01	27.3	0.02	15.5
Two sub-populations, with revegetation: dispersal 0.792 animals each way per year (i.e. 40% connectivity) **<u>i.e. WITH-ROAD SCENARIO, assuming reduced connectivity</u>**	0.00	42.0	0.01	26.8	0.01	15.5
Two sub-populations, with revegetation: dispersal 10 animals each way per year (100% connectivity)	0.00	43.8	0.00	33.7	0.14	11.4

Two sub-populations, with revegetation: dispersal 4 animals each way per year (i.e. 40% connectivity)	0.00	42.5	0.00	27.4	0.02	15.4
Two sub-populations, with revegetation: dispersal 20 animals each way per year (100% connectivity)	0.00	47.8	0.00	42.5	0.34	7.4
Two sub-populations, with revegetation: dispersal 8 animals each way per year (i.e. 40% connectivity)	0.00	43.5	0.00	31.9	0.08	12.4

7.5 Effects of the proposed road - mortality reduced by 20 percent

A reduction in mortality by 20% across all age-gender classes each year would have a marked effect in improving Koala population viability (Table 6). If this reduced level of mortality could be achieved through local management efforts (e.g. comprehensive fencing arrangements on other roads in the study area), the Ballina Koala population is likely to remain viable in the long term, whether the highway upgrade is present or not. The range of estimates modelled for dispersal showed this variable to have only modest effects (<10%) on projected population size (Table 6). The final number of alleles estimated within the Koala population ranged from 5.14-5.18 for the models presented in Table 6.

The exponential rate of increase for the population when mortality is reduced each year by 20% was r=0.0220, the annual rate of change was λ=1.0223, and the per-generation rate of change or "net replacement rate" was R_0=0.9277.

Table 6: Impacts of the proposed road on the Ballina Koala population near Wardell when mortality is reduced by 20% across all age-gender classes.

All scenarios include the same demographic inputs, the same likelihood of two types of catastrophes, 2.85 animals emigrating out of, and 2.85 animals immigrating into, the study area, and changes to habitat carrying capacity to model the effects of losing habitat for five Koalas during road construction followed by the provision of new habitat for up to 41 Koalas. Data inputs from Neaves *et al*. (2015), Norman *et al*. (2015) and Phillips *et al*. (2015). Assumes the presence of inbreeding depression and lethal alleles.

P(E), probability of extinction; N, estimated number of individuals present after 50 years.

Scenarios	Population P(E)	Population N	Western sub-Pop P(E)	Western sub-Pop N	Eastern sub-Pop P(E)	Eastern sub-Pop N
Two sub-populations, with revegetation: dispersal 1.98 animals each way per year, and mortality reduced by 20%	0.00	90.8	0.00	66.2	0.00	24.7
Two sub-populations, with revegetation: dispersal 4 animals each way per year, and mortality reduced by 20%	0.00	97.4	0.00	72.5	0.01	25.0
Two sub-populations, with revegetation: dispersal 10 animals each way per year, and mortality reduced by 20%	0.00	98.5	0.00	75.2	0.02	23.8
Two sub-populations, with revegetation: dispersal 20 animals each way per year, and mortality reduced by 20%	0.00	100.2	0.00	81.2	0.07	20.4

7.6 Effects of the proposed road – fecundity increased by 20 percent

A 20% increase in fecundity of breeding-age females would significantly improve the long-term prospects for this population (Table 7). Increasing population fecundity by 20% would have a greater effect (almost 20%) on population viability than reducing population mortality by 20%. If this increase in fecundity could be achieved through local management efforts (e.g. in part by reducing mortality and thereby increasing the numbers of breeding females, or by vaccinating a proportion of the population for *Chlamydia*), the Koala population is likely to remain viable under all scenarios, whether the highway upgrade is present or not. The range of estimates modelled for dispersal showed this variable to have only modest effects (~<1%) on projected population size (Table 7). The final number of alleles estimated within the Koala population ranged from 5.15-5.18 for the models presented in Table 7.

The exponential rate of increase for the population when fecundity is increased each year by 20% was r=0.0287, the annual rate of change was λ=1.0291, and the per-generation rate of change or "net replacement rate" was R_0=0.9711.

Table 7: Impacts of the proposed road on the Ballina Koala population near Wardell when fecundity is increased by 20%.

All scenarios include the same demographic inputs, the same likelihood of two types of catastrophes, 2.85 animals emigrating out of, and 2.85 animals immigrating into, the study area, and changes to habitat carrying capacity to model the effects of losing habitat for five Koalas during road construction followed by the provision of new habitat for up to 41 Koalas. Data inputs from Neaves *et al*. (2015), Norman *et al*. (2015) and Phillips *et al*. (2015). Assumes the presence of inbreeding depression and lethal alleles.

P(E), probability of extinction; N, estimated number of individuals present after 50 years.

Scenarios	Population P(E)	Population N	Western sub-Pop P(E)	Western sub-Pop N	Eastern sub-Pop P(E)	Eastern sub-Pop N
Two sub-populations, with revegetation: dispersal 1.98 animals each way per year, and fecundity increased by 20%	0.00	112.8	0.00	87.0	0.01	25.9
Two sub-populations, with revegetation: dispersal 4 animals each way per year, and fecundity increased by 20%	0.00	112.8	0.00	85.3	0.01	27.6
Two sub-populations, with revegetation: dispersal 10 animals each way per year, and fecundity increased by 20%	0.00	113.0	0.00	87.8	0.01	25.5
Two sub-populations, with revegetation: dispersal 20 animals each way per year, and fecundity increased by 20%	0.00	114.5	0.00	91.9	0.06	23.8

7.7 Effects of the proposed road – increasing fecundity by 20% and reducing mortality by 20%

A 20% increase in annual fecundity of breeding-age females, combined with an overall 20% reduction in mortality across all age-gender classes each year, was projected to have a major beneficial effect on long-term viability of this Koala population (Table 8). Indeed, population projections showed that, if these two actions could be achieved, the combined effects of these two actions would result in population increases of approximately 186% and 231%, respectively, above those projected to result from either increasing fecundity or reducing mortality alone (Table 8). The projected population gains were also nearly five times greater (494%) than scenarios where neither fecundity nor mortality was manipulated (Tables 4, 5 and 8).

The deterministic rate of growth for the Ballina Koala population would be firmly in the positive if both management objectives (increasing fecundity and reducing mortality) could be achieved. In this scenario, the exponential rate of increase for the population was r=0.0561, the annual rate of change was λ=1.0577, and the per-generation rate of change or “net replacement rate” was R_0=1.1133.

The range of estimates modelled for dispersal again showed this variable to have little influence in the outcomes of the population projections (Table 8). The final number of alleles estimated within the Koala population ranged from 5.34-5.35 for the models presented in Table 8.

Table 8: Impacts of the proposed road on the Ballina Koala population near Wardell when fecundity is increased by 20% and mortality is reduced by 20%.

All scenarios include the same demographic inputs, the same likelihood of two types of catastrophes, 2.85 animals emigrating out of, and 2.85 animals immigrating into, the study area, and changes to habitat carrying capacity to model the effects of losing habitat for five Koalas during road construction followed by the provision of new habitat for up to 41 Koalas. Data inputs from Neaves *et al*. (2015), Norman *et al*. (2015) and Phillips *et al*. (2015). Assumes the presence of inbreeding depression and lethal alleles.

P(E), probability of extinction; N, estimated number of individuals present after 50 years.

Scenarios	Population P(E)	Population N	Western sub-Pop P(E)	Western sub-Pop N	Eastern sub-Pop P(E)	Eastern sub-Pop N
Two sub-populations, with revegetation: dispersal 1.98 animals each way per year, with fecundity increased by 20% and mortality reduced by 20%	0.00	209.9	0.00	167.6	0.00	42.3
Two sub-populations, with revegetation: dispersal 4 animals each way per year, with fecundity increased by 20% and mortality reduced by 20%	0.00	212.6	0.00	169.3	0.00	43.3
Two sub-populations, with revegetation: dispersal 10 animals each way per year, with fecundity increased by 20% and mortality reduced by 20%	0.00	212.9	0.00	169.5	0.00	43.4
Two sub-populations, with revegetation: dispersal 20 animals each way per year, with fecundity increased by 20% and mortality reduced by 20%	0.00	212.8	0.00	170.7	0.00	42.2

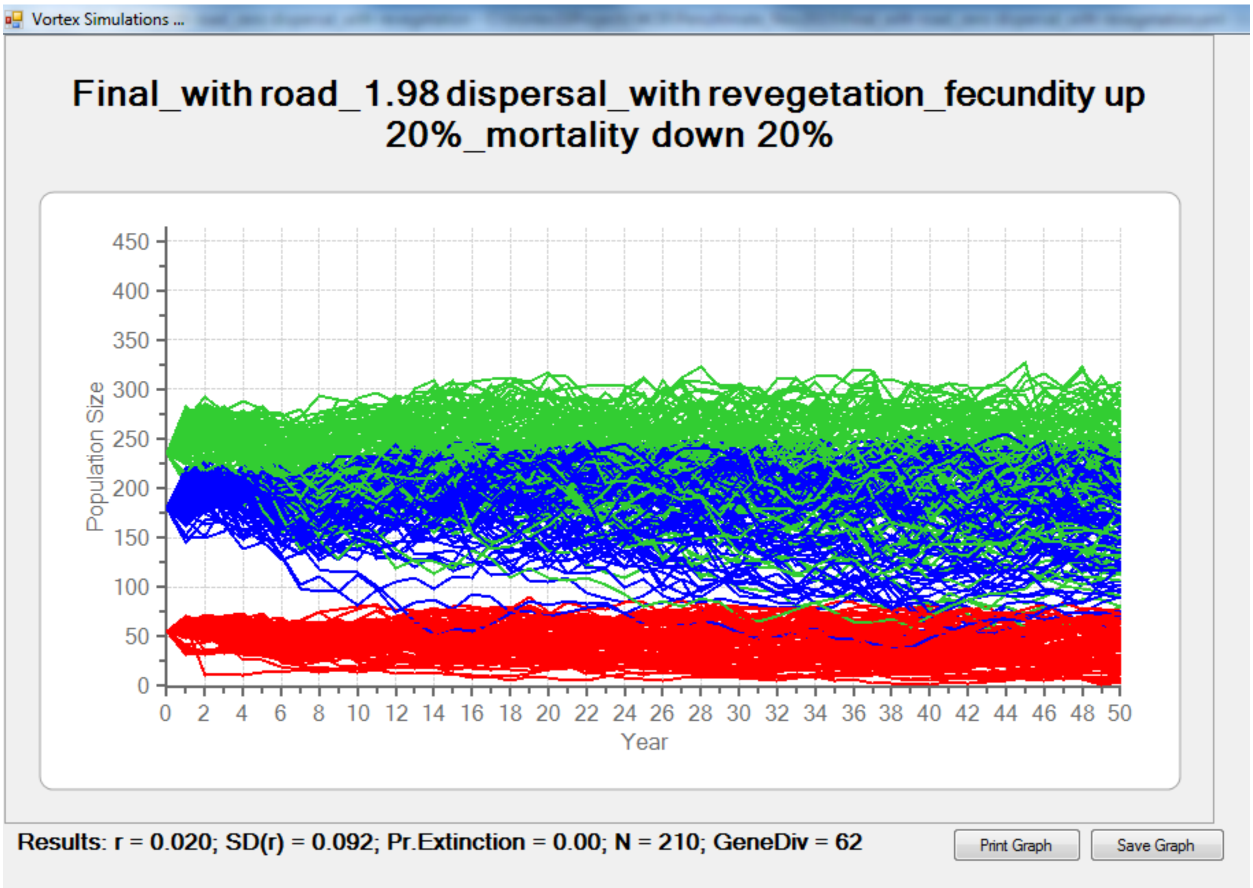


Figure 14: Stable Koala population projections over 50 years, with the proposed highway, when fecundity is increased by 20% each year and mortality is reduced by 20% each year across all age-gender classes. Other parameter estimates and model settings as for Figure 13, except that carrying capacity has been adjusted to reflect the steady increase in habitat availability that should result from new Koala food tree plantings in the study area. The smaller, eastern sub-population is indicated in red, the larger western sub-population in blue, and the total population in green.

7.8 Effects of the proposed road - using management to control mortality

Koala population viability in the study area was greatly enhanced by reducing mortality by eight young (<4 years) animals (5 males and 3 females) per year (Table 9; Figure 15). Under this scenario, the population was projected to decline very slowly, but still comprising approximately 170 animals after 50 years.

The easier target of reducing mortality by four young (<4 years) animals (2.5 males and 1.5 females) per year also had significant benefits to long-term Koala population viability with approximately 109 animals remaining after 50 years (Table 9; Figure 16).

These results suggest that management intervention to reduce Koala mortality due to vehicle strikes (e.g. fencing along the proposed road and other local roads within recognised hot spots), and local dog predation, have the potential to improve the prospects for this Koala population, compared to the current situation. It is unknown whether funding would be available without the road to undertake these important management actions (e.g. fencing).

Table 9: Impacts of the proposed road on the Ballina Koala population near Wardell when mortality is reduced by either 4 or 8 young animals per year.

All scenarios include the same demographic inputs, the same likelihood of two types of catastrophes, 2.85 animals emigrating out of, and 2.85 animals immigrating into, the study area, and changes to habitat carrying capacity to model the effects of losing habitat for five Koalas during road construction followed by the provision of new habitat for up to 41 Koalas. Data inputs from Neaves *et al*. (2015), Norman *et al*. (2015) and Phillips *et al*. (2015). Assumes the presence of inbreeding depression and lethal alleles.

P(E), probability of extinction; N, estimated number of individuals present after 50 years.

Scenarios	Population P(E)	Population N	Western sub-Pop P(E)	Western sub-Pop N	Eastern sub-Pop P(E)	Eastern sub-Pop N
Two sub-populations, with revegetation: dispersal 1.98 animals each way per year, with mortality reduced by 4 animals per year.	0.00	108.9	0.00	66.3	0.00	42.6
Two sub-populations, with revegetation: dispersal 1.98 animals each way per year, with mortality reduced by 8 animals per year.	0.00	170.7	0.00	112.0	0.00	58.6

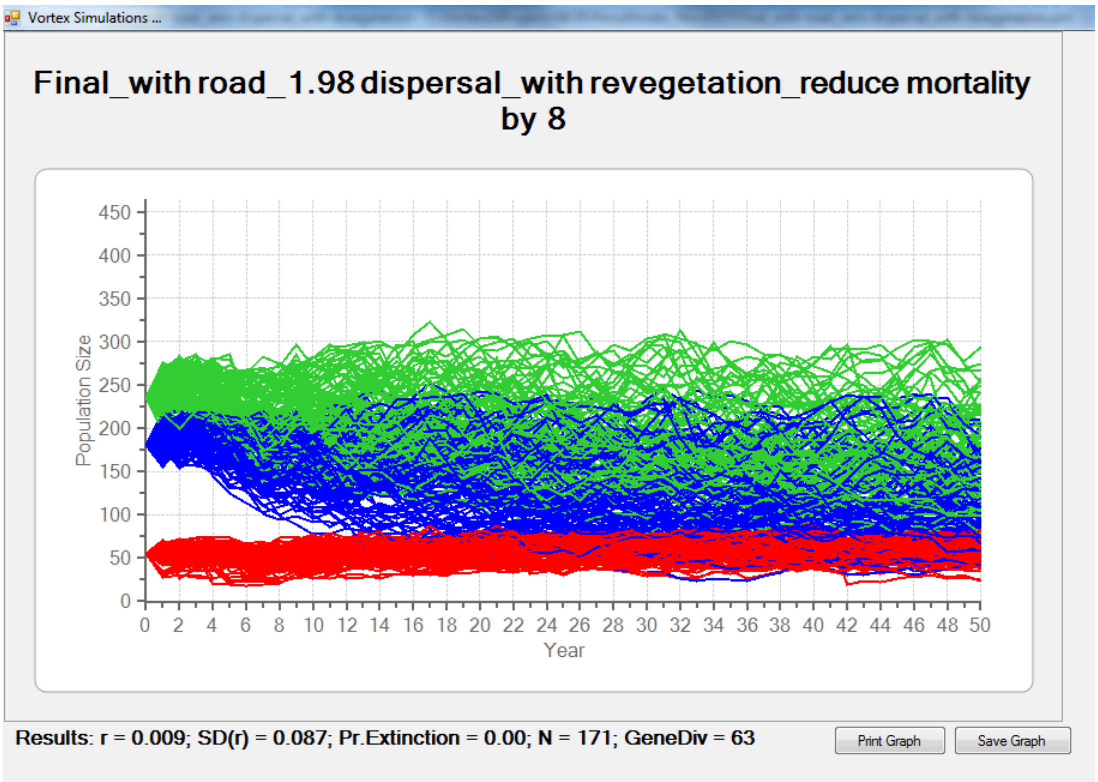


Figure 15: Koala population projections over 50 years, with the proposed highway, when mortality is reduced by 8 young animals per year through management intervention. Other parameter estimates and model settings as for Figure 14.

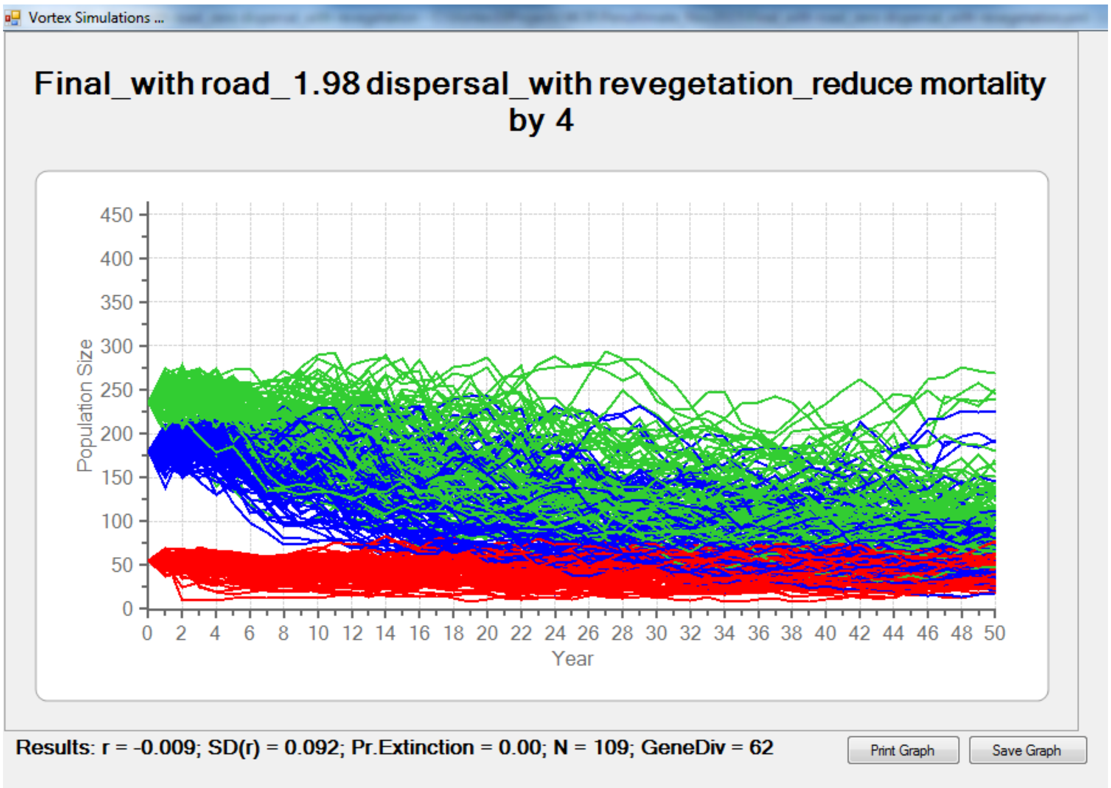


Figure 16: Koala population projections over 50 years, with the proposed highway, when mortality is reduced by 4 young animals per year through management intervention. Other parameter estimates and model settings as for Figure 14. The smaller, eastern sub-population is indicated in red, the larger western sub-population in blue, and the total population in green.

7.9 Effects of the proposed road – summary of impacts

The proposed road has the potential to cause a small adverse impact, reducing the projected population size over 50 years by 0-9.7%, depending on the rate of dispersal and assumptions about the effectiveness of the connectivity structures that will be provided (Table 10). Overall, dispersal rates did not have a major influence on the results (Tables 4-9).

The robustness of these findings was investigated using sensitivity tests of the impact of the proposed highway upgrade in relation to uncertainty in the estimates of demographic parameters (Table 10). These tests also included the impact of losing habitat for five Koalas following road construction. The sensitivity tests were performed by modelling an “optimistic” scenario (in which both mortality was reduced and fecundity was increased) and a “pessimistic” scenario (in which both mortality was increased and fecundity was reduced) for three different rates of dispersal.

These results (Table 10) showed that:

- Dispersal rate made little difference to the results (i.e. whether 100% is set at 1.98, or 10 or 20 animals dispersing each way per year).
- The impact of the road (i.e. the worst case scenario which modelled 40% of each of the above rates of dispersal) ranged between -0.5 to -9.4%, averaging -4.1%, across all scenarios.
- When the potential loss of habitat for 5 Koalas was taken into account, the impact ranged between -0.7—9.7%, averaging -4.8% across all scenarios.

Table 10: Sensitivity tests of the impact of the proposed highway upgrade in relation to uncertainty in the estimates of demographic parameters.

Scenarios represent variations on the standard parameter estimates for population fecundity and mortality (Phillips *et al*. 2015) and dispersal (Neaves *et al*. 2015, Norman *et al*. 2015), and they also incorporate the potential loss of habitat for five Koalas following road construction.

The road impact (%) is calculated from the modelled population projections resulting from each scenario, where "no road" represents 100% dispersal (i.e. 100% connectivity) and "with road" represents a "worst-case" reduction to 40% dispersal (i.e. 40% connectivity). Assumes the road is fully fenced to prevent additional mortality.

Scenarios / Impact assessments	Population projection (N) No road (100% dispersal)	Population projection (N) With road (40% dispersal "worst case")	Impact (%)
Dispersal = 1.98 animals each way/year			
No change in base rates (Table 4)	42.3	42.1	-0.5
- Including loss of habitat for 5 Koalas	42.3	42.0	-0.7
Optimistic: mortality reduced by 20% and fecundity increased by 20%	186.9	181.5	-2.9
- Including loss of habitat for 5 Koalas	186.9	180.1	-3.6
Pessimistic: mortality increased by 20% and fecundity decreased by 20%	19.5	19.2	-1.5
- Including loss of habitat for 5 Koalas	19.5	19.4	-0.3
Dispersal = 10 animals each way/year			
No change in base rates (Table 4)	43.4	41.7	-3.9
- Including loss of habitat for 5 Koalas	43.4	40.7	-6.2
Optimistic: mortality reduced by 20% and fecundity increased by 20%	187.3	186.3	-0.5
- Including loss of habitat for 5 Koalas	187.3	181.4	-3.1
Pessimistic: mortality increased by 20% and fecundity decreased by 20%	21.5	19.6	-8.7
- Including loss of habitat for 5 Koalas	21.5	19.4	-9.7
Dispersal = 20 animals each way/year			
No change in base rates (Table 4)	46.8	43.0	-8.1
- Including loss of habitat for 5 Koalas	46.8	42.3	-9.7
Optimistic: mortality reduced by 20% and fecundity increased by 20%	186.6	184.4	-1.1

- Including loss of habitat for 5 Koalas	186.6	185.0	-0.8
Pessimistic: mortality increased by 20% and fecundity decreased by 20%	22.3	20.2	-9.4
- Including loss of habitat for 5 Koalas	22.3	20.2	-9.2

7.10 Effects of the proposed road – summary of potential management responses

Management to reduce the incidence of vehicle strikes, dog predation, and potentially disease are required to improve the long-term viability of this population. The potential small adverse effects of the proposed road (section 7.9) could be reversed by the enormous potential to improve population projections through management intervention (Table 11). The form that these management interventions could take include:

- the provision of supplementary habitat after accounting for the loss of habitat for up to five Koalas resulting in a slight increase in projected population size (+0.5%)
- the provision of additional Koala-proof fencing along known road-kill hotspots in the study area, together with local dog control, so that Koala mortality is reduced by up to 4 or 8 animals per year resulting, with habitat supplementation, in large increases in projected population size (257%-404%), and
- improvements in the health of the population, potentially through the application of a new vaccine to counteract the effects of *Chlamydia* and so raise population fecundity resulting, with habitat supplementation, in a large increase in projected population size (267%) if breeding success could be raised by 20%.

Other combinations of these approaches could result in significant increases to the projected size of the population if mortality can be reduced and fecundity can be increased simultaneously (Table 11).

Table 11: Summary of the impacts of the proposed highway upgrade in relation to potential management interventions.

Scenarios represent variations on the standard parameter estimates for population fecundity and mortality (Phillips *et al*. 2015). They also incorporate the potential loss of habitat for five Koalas following road construction, and the provision of supplementary habitat for up to 41 Koalas by year 15. Management interventions also include full fencing along the proposed new road, with the potential to fence other roads (road-kill hotspots) in the study area.

The road impact (%) is calculated from the modelled population projections resulting from each scenario, where "no road" represents 100% dispersal (i.e. 100% connectivity) and "with road" represents a "worst-case" reduction to 40% dispersal (i.e. 40% connectivity).

Scenarios / Impact assessments	Population projection (N) No road (100% dispersal)	Population projection (N) With road (40% dispersal "worst case") plus management intervention	Impact (%)
Dispersal = 1.98 animals each way/year			
Effect of habitat supplementation, including the loss of habitat for 5 Koalas (Table 4 and Table 5)	42.3	42.5	+0.5
As above, but reducing mortality by 20% (Table 4 and Table 6)	42.3	90.8	+215
As above, but increasing fecundity by 20% (Table 4 and Table 7)	42.3	112.8	+267
As above, but reducing mortality by 20% and increasing fecundity by 20% (Table 4 and Table 8)	42.3	209.9	+496
Dispersal = 1.98 animals each way/year			
Effect of habitat supplementation, including the loss of habitat for 5 Koalas, with reducing mortality by either 4 or 8 young animals per year (Table 4 and Table 9)	42.3 42.3	108.9 (4) 170.7 (8)	+257 +404

7.11 Changes in genetic diversity

This section presents a summary of the number of alleles remaining within the Koala population under the range of modelling scenarios reported in sections 7.3-7.7. The scenarios reported in each section were conducted under a range of dispersal rates, and this accounts for the range in results. Projected population size was strongly correlated with the levels of genetic diversity in the population. Higher rates of dispersal in each scenario resulted in higher estimates of the number of alleles remaining in the population.

The effect of doubling the rate of dispersal from 1.98 to 4 individuals each way per year, to incorporate the effects of breeding rate being only 44.83%, resulted in a small increase in the number of final alleles in the population (4.89 to 4.90) even though the projected population size remained the same (i.e. 42.5 animals) (Table 5).

Table 12: Summary of the changes in genetic diversity resulting from the scenarios reported in sections 7.3-7.7.

Scenarios	Number of alleles remaining
1. Impact of the road under a range of dispersal scenarios, but not including the initial loss of habitat for five Koalas due to clearing for road construction and the provision of 130 ha of new Koala habitat.	4.81-4.96
2. Impact of the road under a range of dispersal scenarios, including the initial loss of habitat for five Koalas due to clearing for road construction as well as the provision of 130 ha of new Koala habitat	4.86-4.94
As for 2. above, but with mortality reduced overall by 20%	5.14-5.18
As for 2. above, but with fecundity increased by 20%	5.15-5.18
As for 2. above, but with both mortality reduced overall by 20% and fecundity increased by 20%.	5.34-5.35

Discussion

The projected population decline observed in all modelled scenarios is due to births not being adequate to offset deaths, regardless of any effects of inbreeding, the presence of the highway upgrade, or any of a range of mitigation efforts (i.e. Koala-proof fencing, connectivity structures, provision of new habitat) that might be implemented by RMS. This view was confirmed in email communications (18th and 30th September 2015) between Dr Rod Kavanagh and Dr Bob Lacy (the author of the Vortex software). Dr Lacy stated “If these birth and death rates are correct, and if they continue to pertain to the local population, then it could only be sustained if there is a continual inflow of Koalas from other, healthier populations”.

The primary issue is with the estimates of population demography, not with the presence of the road or the proposed mitigation efforts. It is unknown whether the demographic parameters, collected from a once-only snapshot sample, are truly representative of the population. Under the scenarios modelled, there are simply not enough Koalas to effectively utilise the new habitat that would be provided if the highway upgrade was constructed. The demographic estimates used in the models may well be correct but, if so, management attention needs to be focused strongly on measures that will either increase population fecundity, and/or reduce population mortality. As the models incorporating reductions in mortality by 4 or 8 young animals per year have shown, any efforts to reduce Koala mortality in the region will improve Koala population viability. This response is likely to occur primarily by increasing the numbers of breeding females in the population. Indeed, management interventions that result in an increase in fecundity by 20% are likely to be more effective in reversing the downward trend in this population than reducing mortality by the same amount, but if these measures can be combined, the population was projected to increase five-fold over current trends.

Dispersal was difficult to model initially for several reasons, although these problems were subsequently overcome. Firstly, dispersal is largely dependent on population density, although we have no clear understanding of these relationships. This issue was overcome using a range of plausible estimates derived from the genetics reports (Neaves *et al*. 2015, Norman *et al*. 2015) and from other field studies (Dique *et al.* 2003, Kavanagh *et al.* 2007). Secondly, initial attempts to model dispersal were expressed as percentage of the population, rather than as the number of animals dispersing. The application of dispersal as an equal percentage of each sub-population was problematic because the western sub-population was more than three times larger than the eastern sub-population. This effectively propped up the smaller sub-population (which was operating as a population sink by receiving three times as many individuals) at the expense of the larger sub-population. However, sensible comparisons were achieved when dispersal was treated symmetrically between the two sub-populations and expressed as the numbers of individuals dispersing per year. Thirdly, the impact of the road effectively rested upon comparisons between the rate of dispersal through the connectivity structures that are proposed, yet little published information is available about of these relationships. Assumptions about the effectiveness of the 26 connectivity structures (approximately one every 500 m along the proposed road) ranged from enabling 100% dispersal to a ‘worst case’ of only 40% dispersal. However, overall, dispersal rates did not have a major influence on the results.

Inbreeding was found to occur at very low levels in the population (Neaves *et al*. 2015, Norman *et al*. 2015), yet we took the conservative approach in our PVA modelling of assuming that inbreeding depression could present (O’Grady *et al*. 2006). This had the effect of reducing population projections by approximately 20-40% (unpublished preliminary results). The levels of genetic diversity in the population were strongly correlated with projected population size and the rate of dispersal. Therefore, any management interventions that serve to increase these two parameters are likely to result in improved genetic diversity within the population.

The proposed Pacific Highway Upgrade, by itself, is unlikely to contribute adversely to the viability of the Koala population near Wardell; the population is already in steady decline due to other factors (low breeding success, high mortality) and connectivity between the two sub-populations is not a big driver of population size. In the context of this steadily declining population, the proposed supply of 130 ha of new habitat for the Koala was unable to be fully exploited, but this could be reversed through management interventions to increase population size. Significant opportunities and benefits exist to reduce Koala mortality and thereby to assist an increase in fecundity as part of this Project. This could occur through the provision of a range of mitigation actions, including Koala-proof fencing along the proposed highway upgrade and at known Koala road-kill hotspots on other roads in the area. Similarly, efforts to limit the presumed incidence of disease in this population, if this had the effect of raising fecundity, would be highly beneficial to overall viability of the population.

Conclusions

The Conditions of Consent for this Project require that “the impacts to the Ballina Koala population are demonstrated to be acceptable within the Ballina Koala Plan”. No definition of “acceptable impact” has been provided, but in this study we have interpreted this to mean “no impact”. If by “no impact” we assume “no worse” than the status quo (i.e. no new road), then this study has shown that the proposed highway upgrade near Wardell (Section 10) could cause a reduction of between 0-9.7% in projected population size over the next 50 years. However, this small impact on the Ballina Koala population could be compensated for by the provision of Koala-proof fencing in the study area and by the establishment of 130 ha of supplementary new habitat. Indeed, the management responsibilities, actions and resources associated with this infrastructure have the potential to arrest the current steep decline in this population.

This study has shown that the Ballina Koala population is in desperate need of assistance because of its high mortality and low breeding success which will inevitably lead to its extinction if not addressed. Modest and achievable reductions in Koala mortality will improve the current unbalanced population structure and ensure that more females are available to increase population fecundity. Further work to investigate and reduce the incidence of disease in this population may be warranted if this has the effect of increasing fecundity.

All of the proposed connectivity structures and mitigation activities will benefit this population of Koalas, although some of them may not be fully utilised until the population decline is reversed.

Management Implications

Recovery of the Ballina Koala population is a responsibility for the whole community. The RMS has clear obligations to ensure that no Koala road-kills occur as a result of this Project, and indeed this organisation has committed to a fully-closed highway fencing system along the corridor, additional and enhanced connectivity structures, and the establishment of a minimum of 130 ha of new habitat for the Koala. In addition, the RMS is willing to undertake further work, such as fencing, at two known Koala hot-spots that occur on other roads in association with this Project (i.e. part of Wardell Road in the vicinity of the new highway, and part of the existing Pacific Highway north of Wardell to Coolgardie). The value of these additional measures, even if mortality could be reduced by just four animals per year, was clearly shown in the PVA modelling.

However, there are other road-kill hot spots, and other threats to this Koala population, that need to be addressed. The Bruxner Highway (a State road) and Bagotville Road (a Council road), each have significant Koala road-kill hotspots that require attention by the relevant authorities. Predation by domestic dogs is also likely to be a significant threat to Koalas in the study area and should be controlled. The local community and other government agencies have an important role to play in devising and implementing appropriate strategies to control dog predation on Koalas. This work could be done in conjunction with the management of a number of the offset properties adjacent to Section 10 that have been purchased by RMS on which predator control programs will be implemented. Koala mortality needs to be reduced by at least four to eight young animals per year to slow the rate of decline in this population.

The role of disease in potentially limiting population fecundity needs to be explored and understood. We know that disease is present in this population, but we do not know its true incidence and whether it is adversely affecting breeding success. Recent trials have shown that a newly-developed vaccine has the potential to protect wild Koalas from *Chlamydia* infections and to improve reproductive success in females (Waugh *et al*. 2015). Research funding is required to make the necessary assessments, and to consider whether medical intervention is required or indeed appropriate. Local community support may be the best way to obtain the research funds required.

Finally, regular and systematic long-term monitoring of the Koala population in the study area is required to determine whether recovery efforts and mitigation activities have been successful, and also to assess the accuracy of the PVA projections. RMS is responsible for initiating and funding such a monitoring program after road construction, as per the conditions of approval, but broader community involvement is required to maintain this program and to extend it in both space and time.

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