Reprinted from

Pacific Conservation Biology

Volume 13 Number 3

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D. Lunney, S. Gresser, L. E. O'Neill, A. Matthews and J. Rhodes

Surrey Beatty & Sons

43 Rickard Road, Chipping Norton, New South Wales, 2170 Australia
Telephone: (02) 9602 3888 Facsimile: (02) 9821 1253
Email: surreybeatty@iform.com.au

The impact of fire and dogs on Koalas at Port Stephens, New South Wales, using population viability analysis

DANIEL LUNNEY[1,*], SHAAN GRESSER[1], LISA E. O'NEILL[1,2], ALISON MATTHEWS[1,2] and JONATHAN RHODES[3]

The Port Stephens Koala *Phascolarctos cinereus* population has been regarded as one of the strongholds for Koalas in New South Wales. This study applied population viability analysis to investigate the impact of fire and predation by dogs on the viability of the local population. The rapid decline of the modelled Koala population under basic assumptions throws the assumed security of such large populations into question. In all the modelled management scenarios, reducing mortality had more influence than any other factor. Reducing the severity and frequency of large catastrophic fires improved the probability of survival for the population, though the modelled population size still declined sharply. Any management action to improve Koala survival must be accompanied by a reduction in mortality from dog attacks. Fires and dogs will have an ever greater impact on Koala populations as coastal forests become more fragmented and isolated by urban development, and their combined control will be needed to complement land-use planning measures to address habitat loss and fragmentation.

Key words: Dog predation, Extinction, Fire, Koala, *Phascolarctos cinereus*, Population Viability Analysis.

INTRODUCTION

In the summer of 1993–1994, fires burnt extensive portions of the north coast of New South Wales (NSW), including half of a large forest fragment at Port Stephens. Many Koalas *Phascolarctos cinereus* were killed or injured by the fire, which prompted us to initiate a radio-tracking study of the population with the aim of examining the impact of the fire on the population. It extended the scope of our recently completed studies of defining and mapping Koala habitat in the Port Stephens Shire (Lunney *et al.* 1998); of using historical information to reconstruct Koala habitat at first European settlement in 1801 (Knott *et al.* 1998); of using community knowledge to determine the threats to the local Koala population (Lunney *et al.* 2001); and of preparing a plan of management for the shire (Callaghan *et al.* 1994; Port Stephens Council 2002). In this way we obtained extensive demographic information on which to conduct population analyses. The aim of the study presented here was to distinguish between the relative effects of altered fire regimes and predation by dogs on the dynamics of this population of Koalas in a coastal forest that has been fragmented by rural and urban development.

Koala populations across Australia vary markedly in their conservation status, from secure in some areas, to vulnerable or extinct in others, to overpopulation in a number of southern populations (e.g., ANZECC 1998). This has led to a range of contrasting management responses in different regions. In NSW, where the Koala is listed as a Vulnerable species under the *Threatened Species Conservation Act 1995*, a draft statewide recovery plan has been circulated (NPWS 2003) and local plans of management have been implemented to halt declining populations (e.g., Lunney *et al.* 1999; Port Stephens Council 2002). Melzer *et al.* (2000) recommended that studies on regional variation in the Koala be intensified and that information about Koala ecology in fragmented and naturally restricted habitats be developed. Habitat loss has been identified as the key cause of the decline of Koalas in NSW (Reed and Lunney 1990) and habitat availability is a fundamental factor affecting both declining and expanding Koala populations (ANZECC 1998), but a more detailed understanding of the factors affecting Koala population dynamics is essential for management.

Modelling of a local population can assist in achieving this objective. In this study, we use Population Viability Analysis (PVA) to examine factors influencing the survival of the Port Stephens Koala population and to compare the response of the population to alternative fire regimes and dog control strategies. While PVA is unable to accurately predict population dynamics and absolute extinction risks (Ludwig 1996; Fieberg and Ellner 2000; Coulson *et al.* 2001), it is useful for making relative inferences about alternative management scenarios (Lindenmayer and Possingham 1996; Beissinger and

[1]Department of Environment and Conservation (NSW), PO Box 1967, Hurstville, New South Wales, Australia 2220.
[2]School of Environmental and Information Sciences, Charles Sturt University, Albury, New South Wales, Australia 2640.
[3]School of Geography, Planning and Architecture, University of Queensland, Brisbane, Queensland, Australia 4072. Current address, CSIRO Marine and Atmospheric Research, GPO Box 1538, Hobart, Tasmania, Australia 7001.
*Corresponding author: Dan Lunney, Department of Environment and Conservation (NSW), PO Box 1967, Hurstville, New South Wales, Australia 2220. Email: dan.lunney@environment.nsw.gov.au
PACIFIC CONSERVATION BIOLOGY Vol. 13: 189–201. Surrey Beatty & Sons, Sydney. 2007.

Westphal 1998; Possingham *et al.* 2002; McCarthy *et al.* 2003), which were among the reasons for undertaking this study.

The impact of fire on wildlife becomes increasingly important as populations become fragmented. Predation pressures are considered to increase in a post-fire environment (Whelan *et al.* 2002), and predation is facilitated even more in a highly fragmented, anthropogenic landscape (Laurance and Cochrane 2001). Dogs emerged as the highest-ranked perceived threat to Koalas in Port Stephens in a major community survey in 1992, with 95 per cent of the households naming dogs as a cause of the decline of the local population (Lunney *et al.* 2001). The three-year radiotracking program of Koalas in Port Stephens (1994–97) revealed high mortality in the population from dog predation (Lunney *et al.* 2004). Consequently, we examined the impact of different fire management options on the Koala population in tandem with various management actions for reducing death by dogs.

METHODS

Study area

Port Stephens is located on the coast of NSW about 150 km north of Sydney. The north coast has been identified as the stronghold for Koalas in the state (Reed *et al.* 1990) and Port Stephens as a key local area (Lunney and Reed 1990). The study population of Koalas occurs within a 7 000 ha area of the Tomago Sandbeds in the Port Stephens local government area and is bounded by Grahamstown Lake to the north, Fullerton Cove to the south, Siddons Swamp to the west and Majors Flat to the east (32°35'S to 32°50'S and 151°30'E to 152°30'E). Koala habitat, identified by Lunney *et al.* (1998), covers about 4 000 ha of this area. A further 2 000 ha is mainly cleared land with scattered trees and the remaining land is covered by vegetation types not used by Koalas. This fragment had survived clearing because it forms the catchment of the town reservoir but it has, none the less, been modified by management roads, an airforce base and sand mining (Fox *et al.* 1996). The surrounding lands continue to be transformed from forest or farms to housing estates and the adjacent roads carry heavy traffic, which is a well-known threat to Koalas (ANZECC 1998; Dique *et al.* 2003a), and to the local population in particular (Callaghan *et al.* 1994; Lunney *et al.* 2001; Port Stephens Council 2002).

Both wildfire and hazard reduction burns (i.e., low-intensity prescribed fires to reduce fuel load) have occurred throughout the study area. A network of roads and powerline easements form a boundary for many of the fires and have helped to create a habitat mosaic of different fire frequencies and intensities (Fox *et al.* 1996). Six fires occurred in the study area from 1994-2003 and show a wide range of area burnt (Table 1).

Table 1. Fires within the study area on the Tomago Sandbeds 1994–2003. The areas were calculated from maps drawn by team members immediately after the fire from ground and helicopter inspection. Additional sources: Rural Fire Service; Karen Ross (University of New South Wales/DEC NSW).

Date of Fire	Wildfire or Hazard Reduction	Approx. area burnt (ha)
January 1994	Wildfire	2 500
June 1994	Hazard Reduction	50
September 1994	Wildfire	600
February 1997	Wildfire	50
March 1998	Wildfire	800
October 2003	Wildfire	2 000

PVA package

VORTEX (version 8.21) was used to model Koala population survival, particularly the impact of two key mortality factors: fire and dog-related deaths. VORTEX is a PVA software package that models the impact of deterministic forces, such as habitat clearing, and stochastic events, such as demographic stochasticity, climatic variation and bushfire on wildlife population dynamics (Lacy 1993; Miller and Lacy 1999). The software is an individual-based model, which is particularly useful for modelling small populations (Lacy 1993, 2000). It is therefore well suited to modelling the restricted Port Stephens Koala population. This package has been successfully applied to the Iluka Koala population (Lunney *et al.* 2002) and in a number of other studies (e.g., Lindenmayer *et al.* 1993; Hoyle *et al.* 1998; Penn *et al.* 2000).

The VORTEX output used, as indicators of population viability, were mean and standard deviation of population growth rate (r), probability of population survival and standard error, and mean and standard deviation of population size for all replications.

Basic assumptions

The parameter assumptions applied to the basic scenario model (Table 2) were carefully considered in recognition of the need for quality data to produce relevant modelling (Brook *et al.* 2000; Coulson *et al.* 2001). Data on mortality and fertility of the population were obtained from our three-year radiotracking study following the 1994 fires (Lunney *et al.* 2004). It was difficult to determine appropriate assumptions specific to this population for some other factors, so the remaining demographic assumptions were based on those in an extensive analysis of a comparable, healthy Koala population at

Table 2. Assumptions used as initial input for variables in VORTEX for the basic scenario. Standard deviations due to environmental variation are shown in brackets.

Parameter	Value
Initial Population Size	800
Initial Age Structure	Stable
Maximum Age	12
Minimum Female Breeding Age	2
Minimum Male Breeding Age	3
Sex Ratio at birth (% male)	53%
Female Fertility Rate	77 (±7.0) %
% Males in Breeding Pool	100%
Female Mortality age 0	40 (± 4.0) %
Female Mortality age 1	40 (± 4.0) %
Female Mortality adult	23 (± 2.3) %
Male Mortality age 0	40 (± 4.0) %
Male Mortality age 1	40 (± 4.0) %
Male Mortality age 2	40 (± 4.0) %
Male Mortality adult	39.0 (± 3.9) %
Density Dependence	Nil
Number of Catastrophes	2
Probability of Catastrophe 1	10%
Severity on Reproduction	50%
Severity on Survival	50%
Probability of Catastrophe 2	33%
Severity on Reproduction	5%
Severity on Survival	5%
Carrying Capacity (K)	2 500
Inbreeding Depression	Nil
Environmental Variation between Survival and Reproduction	Concordant
Harvest	Nil
Supplement	Nil

Springsure, Queensland (Penn *et al.* 2000). Changes were made to reflect the conditions experienced by the Port Stephens Koala population, as outlined below.

Mortality rates were based on recorded mortality from radiotracked Koalas (*n* = 50) at Port Stephens. Annual mortality rates were derived from Kaplan-Meier survival estimates calculated over the three years, as detailed in Lunney *et al.* (2004). The mortality rates presented here were calculated using data from burnt and unburnt Koalas (Lunney *et al.* 2004), as well as a group of Koalas rehabilitated from injuries other than fire. Mean mortality rates were calculated for adults by sex (females n = 20, males n = 17) and for juveniles (n = 13) irrespective of sex. Greater detail was not possible for juveniles because of the limited sample size. Observed mortality at Port Stephens was higher than that recorded at Springsure (Penn *et al.* 2000).

The assumed female *fertility rate* was based on births observed in the radiotracking data (birth of 24 offspring over three years), which was similar to that at Springsure (Penn *et al.* 2000).

Catastrophes were modelled to represent the effect of fire on the Koala population. The severity of fire on survival was determined from post-fire rescue searches conducted after three fires in the 1994–1998 period (September 1994, February 1997 and March 1998). These rescue searches were co-ordinated by the local wildlife care organization, the Native Animal Trust Fund (NATF) (for photos, see Lunney and Matthews 2004). Each search involved a number of people walking through predetermined sections of the burnt bush for a number of hours. The wildlife carers observed a large (unquantified) number of dead animals and few unburnt animals during their extensive post-fire searches (approximately 600 person days of effort following the January 1994 fire).

Two catastrophes were modelled to represent the two different fire regimes observed in the study area. The risk of a moderate to severe fire was estimated as a 1 in 10 year probability, based on the fire history records of the study area over the last 30 years (Fox *et al.* 1996; Port Stephens Bush Fire Management Committee 2000; Hunter Water Corporation 2001; Ross *et al.* 2004; Table 1). A 50% reduction in reproduction and survival was assumed in the year following the catastrophe. This was based on the impact of the January 1994 fire, which burnt half of the Koala habitat in the study area and was considered to have killed all Koalas in the path of the fire. The risk of a minor fire was estimated as a 1 in 3 year probability (Hunter Water Corporation 2001; Brendon Harrod, Hunter Water Corporation, pers. comm. 2003; Table 1), with a 5% impact on survival and reproduction.

The *starting population* was assumed to be 800 individuals. This figure was the upper limit of the estimated number of Koalas in the study area (range 350 to 800). These estimates were based on extrapolations applied to the entire study area from the Koala density in each habitat, which was calculated from the counts in the intense searches carried out to rescue live Koalas, and record dead Koalas, affected by the three fires in the 1994–98 period. These three post-fire Koala counts provided an opportunity to determine a reasonable estimate of density across the study area because the fires affected most of the major vegetation types. Where estimates varied within the same vegetation types being sampled in different fires, an average was taken. Where a habitat, i.e., a vegetation association, was not affected by fire, an estimated density of 0.75 Koalas/ha was applied if preferred Koala habitat trees were dominant in the tree layer (specifically *Eucalyptus robusta* and *E. parramattensis*, Phillips *et al.* 2000).

The population was assumed to form a stable age population, as determined by VORTEX.

Carrying capacity was modelled on an assumed maximum of 2 500 individuals, based on an estimate of the maximum number of Koalas each habitat association would be able to support in the study area. Densities of 2 Koalas/ha for forest habitats containing known preferred Koala habitat trees, and 1 Koala/ha for woodland associations containing known preferred Koala habitat trees, were applied. The maximum Koala density observed during the rescue of live Koalas, and found in the records of dead Koalas, were applied to the remaining habitats.

A nil net *migration* was assumed. Immigration into the study area was likely to have been small because patches of Koala habitat have been fragmented and reduced in size and quality in surrounding areas due to increasing urbanization (Tilligerry Peninsula to the east, Medowie and Karuah/Ferodale to the north, Raymond Terrace to the west and Fullerton Cove/Stockton Bight to the south) (Knott *et al.* 1998; Lunney *et al.* 1998; Port Stephens Council 2002). Similarly, emigration was likely to have been small because the resident population was well under carrying capacity. None of the adult, radio-tracked Koalas emigrated from the study site and the dispersal distance of juveniles was likely to be small enough to be contained within the study area (e.g., Dique *et al.* 2003b). The study population was probably a source for the regional population, but due to the uncertainty in the degree of migration, emigration and immigration were considered to be equal.

There was assumed to be no *density dependence* on reproduction. It was conservatively assumed there was no *inbreeding* depression in the Koala population. *Environmental variations* of survival and reproduction were assumed to be concordant.

Minimum and *maximum breeding ages* were based on general Koala biology (Lee *et al.* 1990; Martin and Handasyde 1999). The *sex ratio at birth* was based on the Springsure data because such data were unavailable for the Port Stephens population.

The population was modelled to a maximum 50 years, rather than a longer period, to limit the increasing uncertainty associated with long-term estimation (Beissinger and Westphal 1998; Ellner *et al.* 2002). Each simulation was repeated for 1 000 iterations, assuming that none of the factors would alter over the period of the simulation.

Model validation

Validation of the model is an important step in the PVA process (Beissinger and Westphal 1998). Although independent census data were not available to effectively validate this model, the general model and similar basic assumptions were previously validated for a PVA on a Koala population at Iluka, NSW (Lunney *et al.* 2002). Assumptions in this study vary from that model only in line with observed differences in mortality, fertility and catastrophes.

Sensitivity analysis

An important component of PVA, sensitivity analysis, is used to examine model sensitivity and the potential impact of uncertainty in parameter assumptions (Burgman *et al.* 1993; Reed *et al.* 2002). This model was examined for sensitivity to variation in mortality, fertility, migration, fire catastrophe, starting population and carrying capacity. To identify those assumptions to which the model is particularly sensitive, and those which are less influential (McCarthy *et al.* 1995, 1996), a small constant variation of 10% in each of mortality, fertility, carrying capacity and fire was modelled. Migration effects were examined by addition to, or loss from, the population of a single adult male Koala per annum. To further assess the impact of model parameter uncertainty, and the impact that errors in assumptions could cause, plausible extreme values of each parameter were modelled (Table 3). This was considered particularly important for migration, where the basic assumption was no net migration.

Management scenarios

Four sets of management scenarios were modelled and compared to the base assumptions:

Scenario 1: reduced dog-related mortality

Dog predation resulting in Koala deaths was a particular problem for the Port Stephens Koala population (Lunney *et al.* 2004). Of the 50 Koalas radiotracked, 17 were alive at the end of the study, 23 had died and 10 were missing or had slipped their radio-collars. Dog attacks were identified as the cause of 10 Koala deaths (43% of observed mortality). For this scenario, a 50% and 100% reduction in dog-related mortality was examined.

Scenario 2a: reduced large fire frequency and severity

The effect of reducing large fires was examined over a range of fire frequencies and severity of impacts on the population. As an extreme comparison, total exclusion of fire was also modelled.

Scenario 2b: reduced frequency of large and severe fires accompanied by an increase in small (prescribed) fires

More realistic fire regimes were examined in the form of frequent, small patch (prescribed) burns combined with an assumed reduced frequency of larger (unplanned) catastrophic fires.

Scenario 3: supplementation

The level of supplementation that would be required to maintain the current population, and to increase the population to carrying capacity, was investigated by the addition of female and male Koalas.

Scenario 4: combinations of these options

Mortality due to dog attack was identified as a key factor affecting the survival of the population. Further scenarios combined a reduced

Table 3. Results of the sensitivity analysis. Statistical significance of the difference between basic assumptions and the sensitivity scenario were tested using a Students two-tailed t-test. * P < 0.05, ** P < 0.01, *** P < 0.005.

3a. Constant change

	Population Growth Rate (r) [mean (sd)]	Probability of Survival to 50 years [mean (se)]	Size of all populations at 50 yrs [mean (sd)]
Basic Assumptions	-0.22 (0.29)	0%	0
10% Increase Mortality	-0.26 (0.29)***	0%	0
10% Decrease Mortality	-0.18 (0.29)***	1.3% (0.4%)	0.1 (1) ***
10% Increase Fertility	-0.20 (0.29)	0.2% (0.1%)	0
10% Decrease Fertility	-0.24 (0.29)	0%	0
Supplement 1 male pa	-0.18 (0.29)***	1.4% (0.4%)	2.4 (1) ***
Harvest 1 male pa	-0.25 (0.29)*	0%	0
10% Decrease Carrying Capacity	-0.22 (0.29)	0%	0
10% Increase Severity Large Fire	-0.23 (0.32)	0%	0
10% Decrease Severity Large Fire	-0.21 (0.27)	0%	0
10% Increase Severity Small Fire	-0.22 (0.29)	0%	0
10% Decrease Severity Small Fire	-0.22 (0.29)	0%	0
10% Increase Frequency Large Fire	-0.23 (0.30)	0%	0
10% Decrease Frequency Large Fire	-0.22 (0.29)	0%	0

3b. Plausible extreme assumptions

	Population Growth Rate (r) [mean (sd)]	Probability of Survival to 50 years [mean (se)]	Size of all populations at 50 yrs [mean (sd)]
Basic Assumptions	-0.22 (0.29)	0%	0
Minimum start population (350)	-0.22 (0.29)	0%	0
Maximum start population (2,500)	-0.22 (0.29)	0.1% (0.1%)	0
Minimum mortality (Springsure) [1]	-0.02 (0.25)***	96.6% (0.6%)	602 (690)***
Maximum mortality [2]	-0.55 (0.32)	0%	0
Minimum fertility (Iluka) [3]	-0.41 (0.28)	0%	0
Maximum fertility [4]	-0.18 (0.29)***	1.3% (3.6%)	0.1 (0.0)***
Net migration loss 5 male 5 female pa	-0.36 (0.37)	0%	0
Net migration gain 5 male 5 female pa	-0.05 (0.25)***	100% (0%)	59 (19)***
Worst case fire catastrophe [5]	-0.40 (0.51)	0%	0
Best case fire catastrophe [6]	-0.16 (0.19)***	1.6% (0.4%)	0.1 (0.0)***

[1]Springsure mortality: males 0–1 yrs 20%, 1–3 yrs 23%, adult 26%, females 0–1 yrs 30%, 1–2 yrs 16%, adult 8.5% (Penn *et al.* 2000). [2]50%. [3]Iluka fertility: 20 ± 10% (Lunney *et al.* 2001). [4]100%. [5]large fire frequency 5 yrs severity 67%, small fire frequency 2 yrs severity 10%. [6]large fire frequency 20 yrs severity 33%, small fire frequency 5 yrs severity 2.5%.

rate of dog-related deaths with other options, including a range of different fire regimes. To allow a ranking of management options, and provide an indication of possible outcomes of real management changes, combinations of plausible and extreme management options were modelled and compared. To investigate how fires affect a population that is experiencing natural variation via migration, the addition (immigration) and loss (emigration) of one female and one male animal per year were modelled. Options were also modelled using a low starting population (n = 350) to allow for this possibility in practice.

RESULTS

Sensitivity analysis

After a small change (10%) in assumed rates, mortality and migration were the only assumptions to have a significant effect on the output variables (Table 3a). This indicates that these are the variables to which the modelled population is most sensitive. The model was sensitive to plausible extremes, which lead to population gains — decreased mortality, increased fertility, immigration into the population and reduced fire catastrophe. However, mortality was the key factor impacting on the size of the population; other variables led only to small, if any, long-term population gains (Table 3b). The low probabilities of survival at most extremes identified that significant changes to the management of the area will be required to arrest the decline of the Koala population.

Management scenarios

The effects of altering the assumptions to reflect possible management options, as outlined in the following scenarios, are shown in Table 4.

Scenario 1: reduced dog-related mortality

The modelled effect of decreasing deaths due to dogs on the probability of population survival is large under both options (Fig. 1a). However, population size declines swiftly, even with a halving in the dog-related death rate (Fig. 1b). Management of dog-related deaths was therefore identified as the key issue for population survival.

Scenario 2a: reduced fire frequency and severity

Modelling showed that reducing the severity and, to a lesser extent, the frequency of large catastrophic fires, improves the probability of survival for the population (Table 4 and Fig. 2a), although population size still declines dramatically (Fig. 2b) even under unrealistically low fire conditions.

Scenario 2b: reduced fire frequency and severity and increased small fire frequency

Decreased frequency of large catastrophic fires, accompanied by increased frequency of small fires, had little remedial effect on the probability of survival or population size (Table 4, Figs 2c and 2d). Even halving the severity of large fires had no more than a delaying effect on the probability of the population not surviving. It identifies that the high frequency of small fires, a commonly used means of reducing large catastrophic fires, reduces any advantages for the Koala population that may have been gained by reducing the impact of large, infrequent fires.

Scenario 3: supplementation

Supplements to the population did remove the likelihood of extinction, because the regular addition of Koalas meant that the proportion of populations extant was a constant 100% at all levels of supplementation. However, there was no plausible supplementation level that would maintain current population levels (Table 4, Fig. 3). This warns that, while supplementation may delay the decline of the population, it is unlikely to prevent a population decline toward extinction over the long term.

Scenario 4: combined management options

The impact of basic, fire catastrophe assumptions on a population experiencing natural migration was found to differ little from that of an enclosed population (Tables 3a and 3b). Combining reduced, dog-related deaths with a supplemented population effectively doubled the rate of supplement to the population, yet that was still insufficient to maintain the population at existing levels (Table 4). A low starting

Table 4. Results of PVA modelled scenarios for Port Stephens Koala population.

	Population Growth Rate (r) [mean (sd)]	Probability of Survival to 50 years [mean (se)]	Size of all populations at 50 yrs [mean (sd)]	Ranking
Basic Assumptions	-0.22 (0.29)	0%	0	
Scenario 1 — Dog-related mortality				
Halve dogs (base mortality × 0.75)	-0.12 (0.28)	29.3% (1.4)%	6 (15)	
No dogs (base mortality × 0.5)	-0.03 (0.26)	96.5% (0.6)%	452 (588)	
Scenario 2a — Large fires				
Decrease large fire frequency — 1 in 20 yrs	-0.18 (0)	0.1% (0)%	0	
Decrease large fire severity — 33%	-0.20 (0)	0.1% (0)%	0	
Decrease large fire — 1 in 20 yrs at 33%	-0.17 (0.2)	0.2% (0.1)%	0	
Best case (above and small — 1 in 5 yrs at 2.5%)	-0.16 (0.19)	1.6% (0.4)%	0.1	
Increase large fire — 1 in 5 yrs at 67%	-0.36 (0.51)	0% (0)%	0	
Worst case (above and small — 1 in 2 years at 10%)	-0.40 (0.51)	0% (0)%	0	
No fire	-0.13 (0.16)	10.4% (1)%	0.1	
Scenario 2b — Hazard reduction burns				
Large 50 yr @ 50%, Small 1 yr @ 5%	-0.20 (0.20)	0%	0	
Large 50 yr @ 50%, Small 1 yr @ 1%	-0.16 (0.20)	1.6% (0.4)%	0	
Large 50 yr @ 25%, Small 1 yr @ 5%	-0.20 (0.18)	0%	0	
Large 50 yr @ 25%, Small 1 yr @ 1%	-0.15 (0.17)	2.3% (0.5)%	0	
Large 50 yr @ 25%, Small 2 yrs @ 1%	-0.14 (0.17)	3.7% (0.6)%	0	
Scenario 3 — Supplementation				
Supplement 1 male and 1 female pa	-0.09 (0.30)	100% (0)%	12 (5)	
Supplement 5 male and 5 female pa	-0.05 (0.25)	100% (0)%	59 (19)	
Supplement 10 male and 10 female pa	-0.04 (0.23)	100% (0)%	118 (37)	
Supplement 20 male and 20 female pa	-0.03 (0.23)	100% (0)%	234 (69)	
Scenario 4 — Combined management options				
Half dogs, supp 5 males and 5 females pa	-0.04 (0.25)	100% (0)%	130 (63)	3
Half dogs, fires best large	-0.07 (0.14)	93.2% (0.8)%	45 (41)	6
Half dogs, fires large 50 yr @ 50% small 1 yr @ 1%	-0.05 (0.14)	97.8% (0.5)%	99 (80)	4
Half dogs, fires best large and small	-0.05 (0.13)	98.6% (0.4)%	92 (79)	5
Half dogs, no fire	-0.02 (0.06)	100% (0)%	314 (127)	2
No dogs, no fire	0.07 (0.04)	100% (0)%	2 497 (22)	1
Low start population (350)	-0.22 (0.29)	0% (0)%	0 (0)	
Low start population (350), half dogs	-0.12 (0.28)	17% (1.2)	3 (7)	
Low start population (350), no dogs	-0.03 (0.26)	88.7% (1)%	263 (447)	

Fig. 1a.

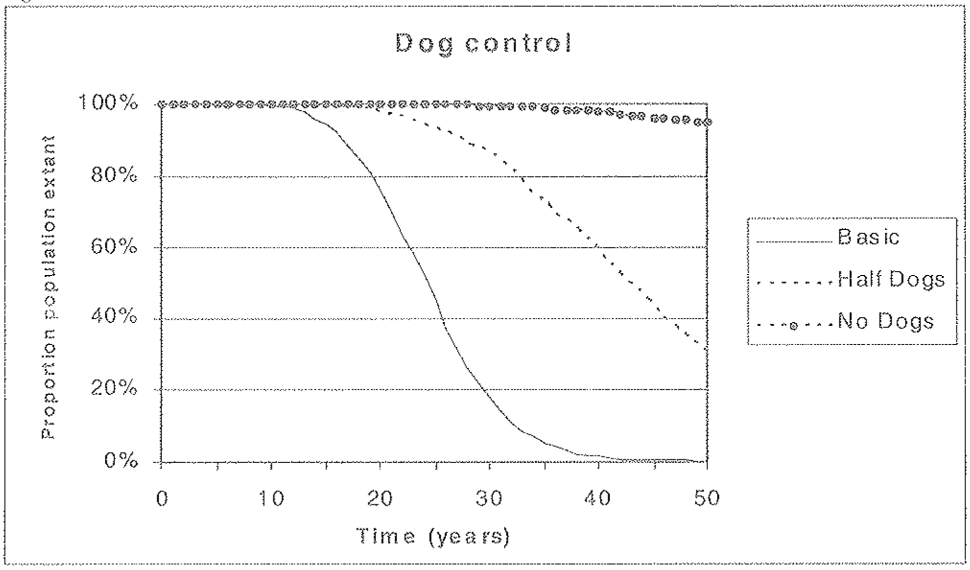

Fig. 1b.

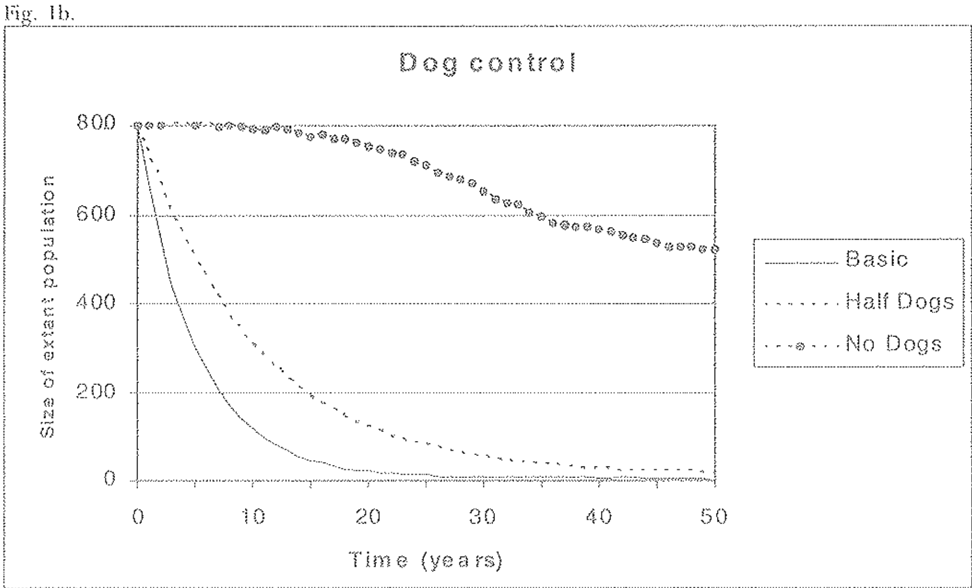

Fig. 1. Simulated survival curves for the Port Stephens Koala population over 50 years. a) effects of changes in dog-related mortality on the probability of survival; b) effects of changes in dog-related mortality on population size.

population did not alter final outcomes (it slightly reduced the proportion of extant populations and mean final population sizes), but it shortened the time to extinction (Table 4). Removing all dog-related mortality, and all fire, resulted in an increase in population size, such that the population rapidly reached carrying capacity. This was the only scenario to show both a positive population growth and a zero chance of extinction (Figs 4a and 4b). Further, halving dog-related mortality led to a dramatic improvement in survival in combination with reduced risk of fire (Figs 4c and 4d). Management options ranked according to improvements in outcomes are shown in Table 4.

DISCUSSION

The most striking outcome of these analyses was the rapid decline of the Koala population modelled under the basic assumptions. The Port Stephens Koala population had been regarded as one of the strongholds for Koalas in NSW (Lunney and Reed 1990; Reed *et al.* 1990), so its potential decline is a warning for managers. While small local population extinctions have occurred (e.g., Reed *et al.* 1990; Smith and Smith 1990; Lunney *et al.* 2002), and have contributed to the species becoming listed as threatened in the state (Lunney *et al.* 1996), the status of larger populations has not been apparent. Pulliam (1988) has shown how large

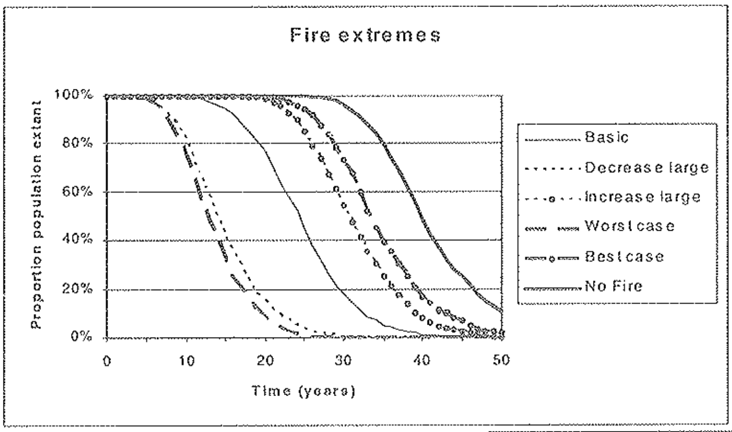

Fig. 2a

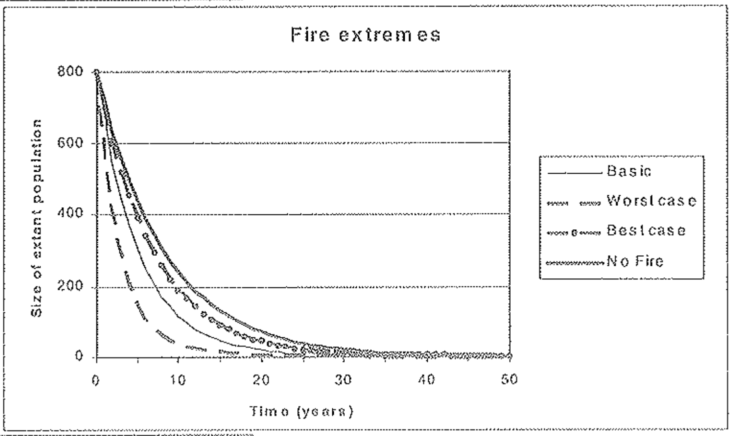

Fig. 2b

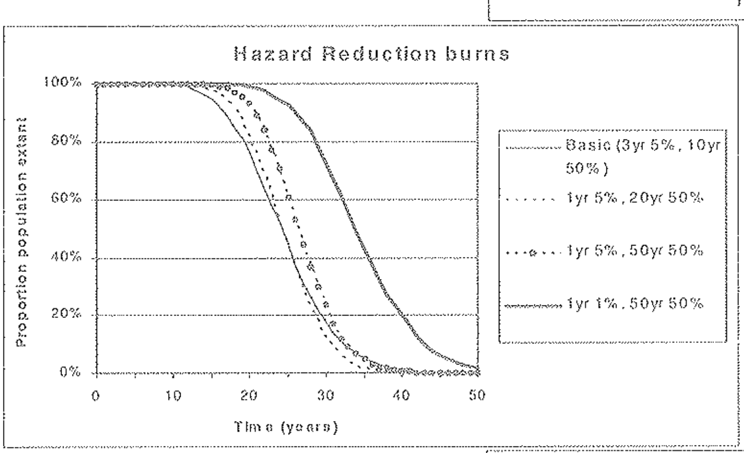

Fig. 2c

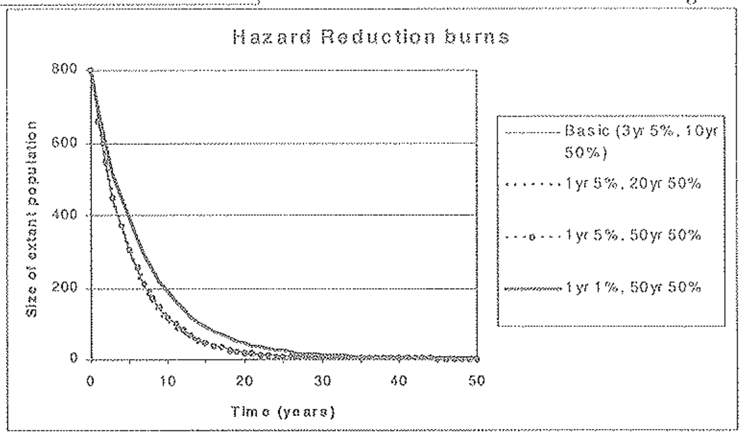

Fig. 2d

Fig. 2. Simulated survival curves for the Port Stephens Koala population over 50 years. a) effects of reduced fire frequency and severity on the probability of survival; b) effects of reduced fire frequency and severity on population size; c) effects of reduced fire frequency and severity and increased small fires on the probability of survival; d) effects of reduced fire frequency and severity and increased small fires on population size.

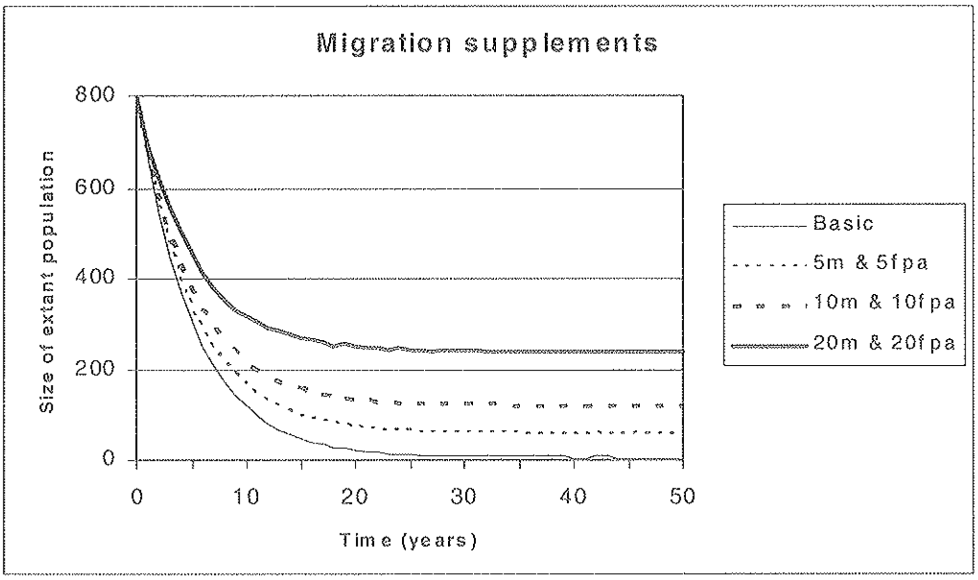

Fig. 3. Simulated survival curves for the Port Stephens Koala population over 50 years showing the effect of supplementation on the probability of survival. Note: the proportion of populations extant is 100% for each supplementation scenario because individuals are added to the population each year.

populations can be affected by impacts over a relatively small area if that area is a source for the population. The results from this study now throw the assumed security of large Koala populations into question. If the worst-case scenarios identified in this study have general applicability, then it can be predicted that there will be widespread collapse of all Koala populations throughout coastal NSW. The conclusions from population studies at a landscape scale both across the shire at Port Stephens, and in other coastal strongholds in NSW and south-east Queensland, give added weight to this conclusion (McAlpine *et al.* 2006; Rhodes *et al.* 2005, 2006).

In all the modelled scenarios, reducing mortality had more impact than any other factor. Furthermore, because mortality was so high, even 100% fertility (maximum potential births per female) would not be able to arrest the decline. The sensitivity of population dynamics to adult mortality has also been shown for other long-lived species (e.g., Brooks *et al.* 1991; Goldingay and Possingham 1995; Wiegand *et al.* 1998). This shows that reducing the mortality of Koalas will be fundamental for any management plan to improve the long-term viability of this population.

The model yielded an unexpected result regarding the effect of reduced fire. The surprise was that even a large reduction in major fires, when accompanied by increased small fire frequency, as one would expect in the application of hazard reduction burns, did not greatly diminish the probability of extinction or reduction in population size. The model used in this analysis does not incorporate spatial considerations, such as patterns of fire effects. Nor does it allow for complex temporal interactions, such as build-up of fuel load since previous fire events. This may be important. For example, Bradstock *et al.* (2005) showed that the rate and pattern of ignition of small irregular fires influenced the persistence of Malleefowl *Leipoa ocellata* populations. Also, McCarthy and Lindenmayer (1999) showed that as patch area is increased for Greater Gliders *Petauroides volans*, the expected risk of extinction falls more rapidly when fires are spatially correlated than when they are uncorrelated. Despite such limitations, the model does identify that considerable changes in the fire regime would be required to have a substantial effect on population survival. This identifies that factors other than fire are a more urgent management priority.

Immigration was shown to be essential for maintaining the Koala population on the Iluka Peninsula (Lunney *et al.* 2002). Consequently, it was assumed that immigration could be important to the Port Stephens Koala population. A range of plausible immigration levels was modelled to determine how much immigration would be required to stabilize the population. We found that there was no plausible supplementation level to maintain current population levels. This gives us confidence in our basic assumption of no net migration and the outcome of a declining population. Furthermore,

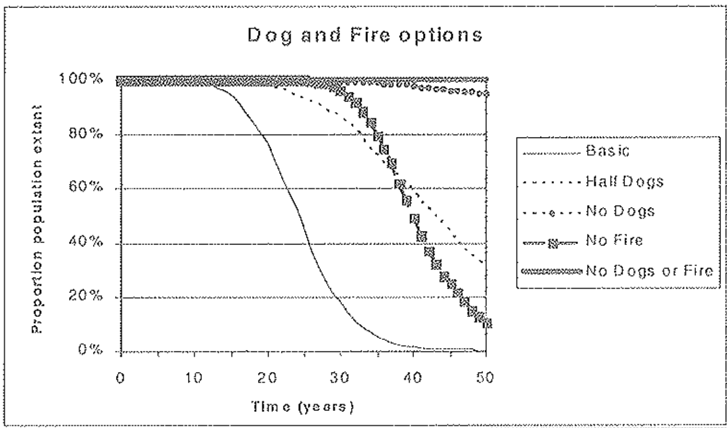

Fig. 4a

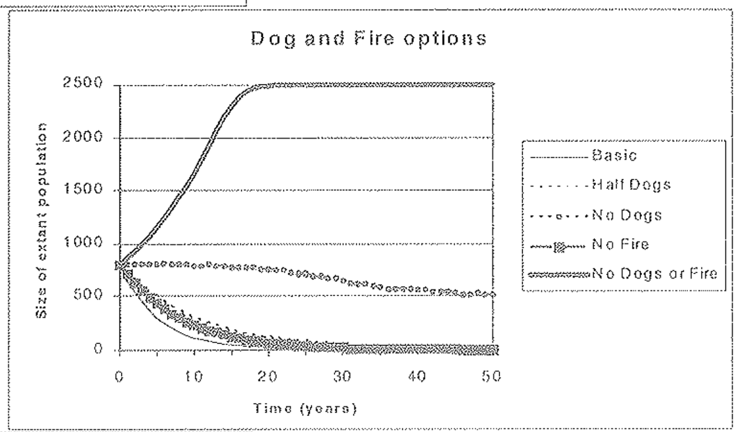

Fig. 4b

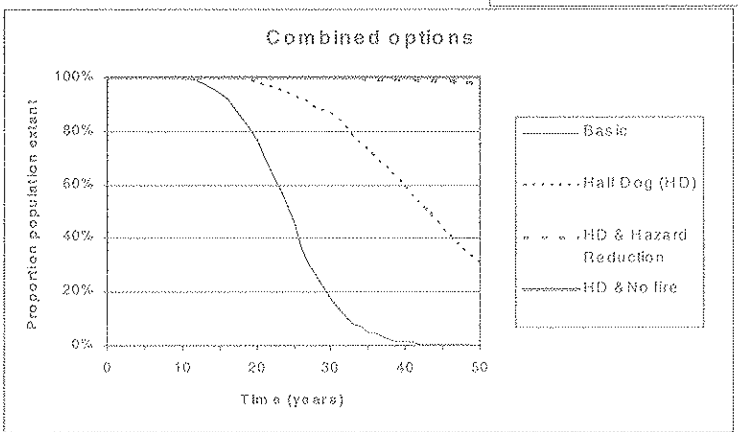

Fig. 4c

Fig. 4d

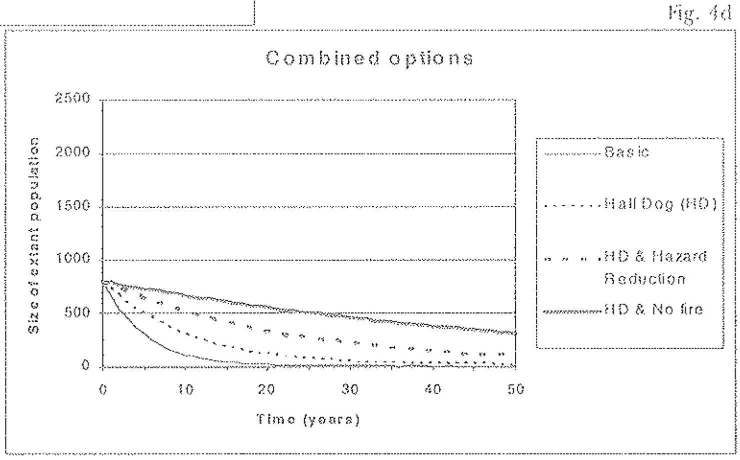

Fig. 4. Simulated survival curves for the Port Stephens Koala population over 50 years. a) effects of dog and fire management options on the probability of survival; b) effects of dog and fire management options on population size; c) effects of halving dog-related mortality in combination with fire management options on the probability of survival; d) effects of halving dog-related mortality in combination with fire management options on population size.

there are few remaining habitats in close proximity to the study population that could provide immigrants. This differs markedly from the population on the Iluka Peninsula, which could be regarded as a typical sink habitat (Pulliam 1988) from the neighbouring part of Bundjalung National Park beyond the Peninsula.

Ranking the management options needs to be measured against the practicality, or even the possibility, of achieving them. The "no fire" options were shown here to illustrate the impact of fire, but the notion of removing fire altogether is impractical. Fires and dogs will have an ever greater impact on Koala populations as the coastal forested landscape becomes more fragmented and isolated by continuing urban expansion and tourist development in Port Stephens. Control of dogs and the management of fire become increasingly important as Koala habitat continues to be lost and fragmented.

Overpopulation is a significant issue for Koalas in parts of Victoria and South Australia, such as Framlingham and Kangaroo Island respectively, resulting in overbrowsing and defoliation of food trees (e.g., ANZECC 1998; Masters *et al.* 2004). In our modelling, a rapid positive population growth was predicted with the total elimination of dogs and fire. Given that this problem has proved to be intractable in parts of Victoria and South Australia, we need to be alert to the problem developing in NSW. Any management actions, such as a dog-proof fence, that encloses the population to eliminate threats are not recommended. In the short term, the most urgent action needed is to reduce the number of koalas killed by dogs. Over the long term, other impacts, such as habitat loss, habitat fragmentation and road deaths also need to be addressed. Bushfires and roads were obvious causes of mortality in the shire (Callaghan *et al.* 1994), but they have been shown by this study to mask a more important cause of mortality, namely dogs. We do note that dogs were identified by the community questionnaire (Lunney *et al.* 2001) as a major threat. Now, with the findings from the current study, the case could begin to be made that feral and roving dogs constitute a "key threatening process" under the *NSW Threatened Species Conservation Act 1995*.

The current priority of Koala management in NSW is on habitat protection through state land-use planning policy, *State Environmental Planning Policy No. 44 — Koala Habitat Protection* (Lunney and Matthews 1997; Lunney *et al.* 2000; NPWS 2003). However, actions already listed to address mortality in this Port Stephens population, such as from dogs and roads (Callaghan *et al.* 1994; Port Stephens Council 2002), are now identified as essential. This study has demonstrated that dogs, in combination with the conspicuous threatening process of altered fire regimes, is causing a relentless decline in the Koala population in one of its remaining strongholds in coastal NSW. Further habitat loss and fragmentation will exacerbate Koala mortality caused by fire and roving dogs. The case for increased planning and management intervention, community support and innovative research is, in our view, powerful indeed.

ACKNOWLEDGEMENTS

The data for this study partly arose from a long-term effort by many people involved in several Koala programmes in Port Stephens, particularly the three-year radio-tracking programme. We acknowledge the contribution of the late John Barker, Anne Carey, Dionne Coburn, Tiffany Knott, Wendy Maitz, Audrey Koosmen and the Native Animal Trust Fund, NSW National Parks and Wildlife Service local staff, Port Stephens Shire Council, John Simpson RZM and Glen Stevenson. We also wish to thank the Rural Fire Service, the Hunter Water Corporation, and Karen Ross for fire history information, and Irina Dunn and Harry Recher for critical comments on the manuscript. The Foundation for National Parks and Wildlife assisted with funding.

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Changes in bird abundance following Common Myna control on a New Zealand island

S. DAVID TINDALL[1,3], C. JOHN RALPH[2,4] and M. N. CLOUT[1]

We censused landbird populations on a small island during a year of intense trapping of the Common Myna *Acridotheres tristis*. We successfully removed mynas on Moturoa Island, Bay of Islands, with populations on the island decreasing in most areas, while holding steady on other, nearby islands where no trapping was conducted. The populations of many other bird species increased coincidently with the removal of mynas. This was most notable in the Tui *Prosthemadera novaeseelandiae*, Grey Warbler *Gerygone igata*, and Blackbird *Turdus merula*. Of 60 species-route comparisons, we found that 23 (38%) increased, 33 (55%) had no change, and only four (7%) decreased. The relative role of rats *Rattus* spp. and succession is also discussed. The historical decline of many species in the North Island of New Zealand may have been related to the concomitant increase of the myna, and control of this species may be warranted in some cases, especially where restoration of the native fauna is the objective.

Key words: Invasive species, Common Myna, New Zealand, Island, Population census.

INTRODUCTION

HUMAN introduction of birds to New Zealand and throughout the Pacific is one of many factors which have likely exacerbated the decline and eventual extinction of much of the native avifauna. There is, however, little evidence of the actual role that introduced birds have had in native bird declines. In this study, we examine the possible effects on an island's bird assemblage of removing an introduced bird.

The Common (or Indian) Myna was introduced into New Zealand in the 1870s (Bull *et al.* 1985). While initially found in both the North and South Islands, since 1890 it has been found only on the North Island. Now it is only common in the northern half of that island. The myna appears to have spread only slowly up the North Island (Long 1981). It reached the Bay of Islands about 1960 (Heather and Robertson 1996). Although most abundant in modified environments, the myna is sympatric with native and other introduced birds throughout most habitats in northern New Zealand, including native forests (Pierce *et al.* 1993).

Although the effects of mynas on other species have not been supported by quantitative studies, negative interactions have been often cited in the literature from many areas from throughout the Pacific, as well as in its native range (e.g., Mason and Maxwell-Lefroy 1912; Manson 1921; Cunningham 1950; MacDonald 1951; Stoddart 1956; Wright 1962; Wilson 1973; Moeed 1975; Watling 1975; Wilson 1975; Moon and Lockley 1982; Hay and McCormack 1984; Bull *et al.* 1985; Seitre and Seitre 1992; Simberloff 1992; Dhanda and Dhindsa 1993). There is some evidence from these sources that mynas interact as predators or competitors with other birds. This includes observations of destruction of eggs, chicks, and nests, and the chasing of adult birds attempting to rear young within myna territories. It is their alleged direct interference competition at food and nesting sites, however, which has earned the mynas almost universal dislike (e.g., Wilson 1975).

Observations of isolated acts of competition or predation do not validate any general conclusions about the impact of the myna on a variety of species. However, if predation and interference competition by mynas were important factors in limiting resident bird populations, the abundance of affected birds should increase following myna removal. We tested this hypothesis over one year by censusing the entire bird community on the island where mynas were being removed. We also demonstrated the possible importance of the removal by monitoring mynas on other islands where they were not controlled.

METHODS

Study design

Bird communities were censused at five sites in the Bay of Islands in northern New Zealand (Fig. 1), with similar habitats but varying histories of myna control. Primary work was on Moturoa Island, where mynas were controlled for the year of the study (1995). On this island, bird censuses had been conducted by Ralph (unpubl. data) for 15 years prior to the myna control, as summarized in Tindall (1996). At some additional sites censuses were also conducted in 1995: a mainland site (Crater or Wharengarere Bay), and at two island sites (Motu-rua and Urupukapuka) where mynas were uncontrolled. On Roberton Island they had been controlled to an extent for the five years previous to censusing (1987–1994).

[1]School of Biological Sciences, University of Auckland, PB 92019, Auckland, New Zealand.
[2]USDA Forest Service, Redwood Sciences Laboratory, 1700 Bayview Drive, Arcata, California 95521 USA.
[3]Present address: 747 Ave E Port Allen, Louisiana 70767 USA.
[4]To whom correspondence should be addressed: Email: cjr2@humboldt.edu or cralph@fs.fed.us
PACIFIC CONSERVATION BIOLOGY Vol. 13: 202–12. Surrey Beatty & Sons, Sydney. 2007.