Metapopulation Model to Assess Control Options for Cape Barren Geese on Phillip Island

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Metapopulation Model to Assess Control Options for Cape Barren Geese on Phillip Island

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Contents

Summary **5**

1 Introduction **7**

Project objectives 7

2 Methods **9**

2.1 Population model for Cape Barren Geese 9

2.1.1 Brief life history of Cape Barren Geese 9

2.1.2 Overview of metapopulation model structure 9

2.1.3 Accounting for local population regulation with nest density 11

2.1.4 Incorporating fox predation and fox eradication 11

2.1.5 Emigration and immigration 12

2.2 Parameter estimation and specification 12

2.2.1 Specialist Cape Barren Geese workshop for model development 12

2.2.2 Emigration and immigration probabilities 13

2.2.3 Survey data and model calibration 14

2.2.4 Sensitivity analysis 15

2.3 Control scenarios 15

What is the goal of control? 16

2.4 Interpretation of model output 17

3 Results **18**

3.1 Model calibration 18

3.2 Population projections to 2065 21

3.3 Control scenarios 23

3.4 Sensitivity analysis 28

4 Discussion **30**

4.1 Insights from the metapopulation model 30

4.2 Recommendations for future data collection 31

4.3 Conclusions 32

References **33**

Appendix: Supplementary Figures 35

Implementing control strategies on Phillip Island only 35

Implementing winter flock removal strategies on Phillip Island and French Island 40

Implementing combined egg and winter flock removal strategies on Phillip Island and French Island 45

Implementing egg and winter flock removal strategies on Phillip Island and removing all winter flock on French Island 48

Implementing gosling and winter flock removal strategies on Phillip Island and French Island 51

Summary

Context:

Phillip Island is a c. 100 km^2 island off the coast of Victoria and is home to a variety of native birds and mammals. Following an island-wide program to eradicate foxes (commenced in 2006), several species including Cape Barren Geese have increased in numbers to the extent that they now have negative impacts on agriculture and other biodiversity. The Phillip Island (Millowl) Wildlife Plan (DELWP, 2021) includes an action to understand populations of Cape Barren Geese and their negative impacts, with a specific task focused on the development of modelling tools to examine the effects of various management interventions intended to reduce Cape Barren Geese population abundance. Given the highly visible nature of wildlife management and interventions on Phillip Island, wildlife managers require clear information and advice on the likely effectiveness of different management interventions and any sources of uncertainty or key knowledge gaps.

Aims:

This project aims to develop a metapopulation model for Cape Barren Geese to assist the Department of Energy, Environment and Climate Action and the Phillip Island Nature Parks to investigate the effects of various management interventions for reducing population abundance on the island and provide advice on future research directions and priorities to manage Cape Barren Geese on Phillip Island.

Methods:

Cape Barren Geese were modelled using an age-structured metapopulation model that comprised populations on Phillip Island, French Island and the Bass Coast. The model separated adult age classes into nesting and winter flocking geese, movement between the three populations, and included the impacts of foxes and density-based cues for emigration and nesting. Model parameters were based on current knowledge of the species and its life history, with input from managers and species experts via a workshop during early stages of model development and calibration against field observations. The species expert workshop also expressed a clear goal for control options to manage the greater metapopulation.

The metapopulation model was used to assess 19 different control strategies focused on various combinations of removing geese from the winter flock and egg or gosling (flightless young) removal, as well as a baseline, “no control” scenario. Scenarios differed in the location of interventions (Phillip Island, French Island, or both) and the rate of removal of geese (ranging from 250 geese per year to removing all of the winter flock). We defined 3 different targets (acute, moderate, and relaxed) for a successful strategy compared with the mean of the 2065 level of the measure examined for Phillip Island (Total Population, Winter Flock, Emigrants, Nesting Birds).

Results:

Models for an uncontrolled Cape Barren Geese metapopulation showed the metapopulation to continue to increase, including an increase in the winter flock on both Phillip and French Islands. A mix of control interventions were considered successful, which included different rates of winter flock removal and combinations of different rates of winter flock removal and different rates of egg or gosling removal. Interventions on both Phillip Island and French Island were critical to the modelled effectiveness of different control strategies. Interventions targeting only Phillip Island reduced the Cape Barren Geese population on Phillip Island but not elsewhere and, therefore, were not considered successful as they failed to meet the Nesting Population target for all goal levels (acute, moderate, and relaxed). Lower levels of winter flock removal were not successful, with a target of removing 500 winter flock geese annually being successful only in combination with egg or gosling removal. Removing more geese per year produced a faster control response in Total Population, Winter Flock, Emigrants, and Nesting Birds with some interventions achieving success by 2030 on three measures and by late 2030s based for Nesting Birds. All successful interventions achieved the measure of success by approximately 2045.

Conclusions and Implications:

Cape Barren Geese on Phillip Island will likely continue to increase, providing emigrants to other areas. Based on these findings, we provide the following recommendations and key findings:

1. Control should be implemented immediately if the Cape Barren Geese population on Phillip Island and the winter flock are to remain below current levels. Not implementing control options immediately is expected to lead to an increase in the number of Cape Barren Geese on Phillip Island, including the winter flock (approaching 3500 birds by 2025 under the current model assumptions).
2. If control is implemented immediately, the population on Phillip Island may be reduced to desirable levels by 2045. Reducing the Phillip Island population to desirable levels is contingent on removal of at least 500 winter flock per year (when combined with egg or gosling removals) or at least 750 winter flock per year (without egg or gosling removals). Importantly, reductions to desirable levels requires control measures on both Phillip Island and French Island.
3. Following successful control (e.g., reducing the Phillip Island population below 2005 levels), ongoing control measures will be required to maintain population numbers (particularly the winter flock) at these levels. Cape Barren Geese have a high capacity for population growth, which would suggest that numbers would increase rapidly if control were ceased. However, ongoing control measures may not need to remain at the levels used during the initial period of control (e.g., > 500 winter flock removed per year), with ongoing removals of 200–400 winter flock and 80–95 eggs or goslings per year predicted to maintain populations on Phillip Island and French Island.
4. A mix of control strategies was predicted to be successful, with egg and gosling removals reducing the culling rate of winter flock required to achieve successful control. We did not model the logistics of different strategies but note that culling can be implemented now (subject to an application and assessment process by the regulator), whereas egg or gosling management would require targeted research to demonstrate that the methods used are humane and effective (required before approvals can be sought to implement these methods).
5. Ongoing monitoring of the population of Cape Barren Geese on Phillip Island and increased monitoring of the French Island population are critical to refine current population estimates, establish baselines for any control measures, and assess the effectiveness of any implemented control actions. In particular, French Island may contribute significant numbers of Cape Barren Geese to the wider meta-population in coming years and requires immediate population assessment and management. Essential monitoring approaches are annual counts of the total population and winter flock, and potential additional targets for monitoring are nest counts (e.g., with drone flyovers and image analysis) and mark-resight/recapture studies to estimate survival rates, emigration rates and destinations (e.g., with a mark-recapture program), transition rates of juveniles to breeding territories, and density-dependent feedback.
6. Update the population model as new data and information are obtained through monitoring and further research.

1 Introduction

Phillip Island is a c. 100 km^2 island off the coast of Victoria and is home to a variety of native bird species including the iconic Little Penguin (*Eudyptula minor*), Short-tailed Shearwaters (*Ardenna tenuirostris*), Hooded Plovers (*Charadrius cucullatus*) and Cape Barren Geese (*Cereopsis novaehollandiae*) as well as populations of native mammals including Swamp Wallabies (*Wallabia bicolor*) and Common Brushtail Possums (*Trichosurus vulpecula*). In 2006, an island-wide program to eradicate foxes on the island commenced, which resulted in the island officially being declared fox free by 2017. However, since the removal of foxes, some species including Cape Barren Geese (CBG) have increased in numbers on the island resulting in negative impacts to agriculture and biodiversity. CBG impact agriculture predominantly through grazing pressure on crops and pasture but can also impact native vegetation, infrastructure and other public amenities (including a hazard to motor vehicles). Due to the island's environment and landscape, wildlife and its management are highly visible and interventions, such as lethal control of abundant native wildlife can be a point of contention in the community. Hence, there is a need to explore the effectiveness of different lethal and non-lethal management actions intended to reduce populations of CBG or mitigate their negative impacts on the island.

Wildlife populations, such as the CBG population on Phillip Island, can be characterised as highly structured, stochastic, dynamic systems about which we usually have incomplete information. However, decision makers require knowledge of how these systems respond to management actions, especially where species of economic or conservation importance are involved (Thomas et al. 2005). When managers are required to make decisions about how to manipulate natural systems in the face of uncertainty, Adaptive Management (AM) is a natural framework to inform decisions while learning about how a system might respond (Walters and Holling 1990; Gerber and Kendall 2018). Adaptive Management aims to improve decision-making around natural resources by decreasing the uncertainty about how systems respond to management. Central to the implementation of AM is the development of models of the system and the use of these models to generate explicit predictions about how the population will respond to various management actions. These predictions can inform decisions in the short term and are then tested against observations of the population obtained through a structured monitoring program, often within an experimental framework (Schreiber et al. 2004).

Project objectives

The Phillip Island (Millowl) Wildlife Plan (DELWP, 2021), *Action 3 – Understand populations of Cape Barren Geese, Swamp Wallabies and Common Brushtail Possums and their negative impacts* includes the specific task:

Develop a metapopulation model for Cape Barren Geese to assist the Phillip Island (Millowl) Wildlife Plan Implementation Working Group to investigate the effects of various management interventions for reducing population abundance on the island, potentially within an Adaptive Management framework, and provide advice on future research directions and priorities to manage Cape Barren Geese on Phillip Island.

This project aims to address this task with the construction of a metapopulation model that uses knowledge of CBG life history to model the dynamics of the Phillip Island CBG population. The development of this model forms an initial step towards an AM framework to manage CBG populations. The model accounts for the key elements of the CBG life history such as nesting, flocking, and migration, and includes uncertainties in the dynamics of the system, specifically, uncertainty around population processes (e.g., variation in vital rates such as reproduction, survival and movement), uncertainty in observations (monitoring) and uncertainty in the effects or effectiveness of different management actions. Developed in this way, population models are a useful tool to: 1) identify key knowledge gaps, research opportunities and required data; 2) determine resource allocation among management actions by projecting and evaluating the likely outcomes of management plans; 3) rank management options based on their efficacy, cost or other criteria; and 4) resolve conflicts about the best management strategies by shifting the focus of stakeholders from specific interests to population/island-level outcomes. The model can be updated as new information comes to hand through a formal AM process or from targeted research to address key sources of uncertainty.

The study has the following specific objectives:

1. Develop a metapopulation model for Cape Barren Geese on Phillip Island, French Island and the mainland.
2. Develop and test hypotheses about how the CBG population may respond to various management actions.
3. Use long-term monitoring data available for CBG on Phillip Island to calibrate the metapopulation model.

4. Assist Phillip Island (Millowl) Wildlife Plan agencies to identity key management questions and options relating to CBG.
5. Assist Phillip Island (Millowl) Wildlife Plan agencies to identify priorities for future research relating to CBG.
6. Provide support to disseminate metapopulation model outputs and associated recommendations to stakeholders.

2 Methods

2.1 Population model for Cape Barren Geese

2.1.1 Brief life history of Cape Barren Geese

Cape Barren Geese (CBG), *Cereopsis novaehollandiae*, are large geese endemic to southern Australia (Robinson et al. 1982) and are relatively long lived with the oldest recorded goose living to 18.7 years (Australian Bird and Bat Banding Scheme database 2023). CBG are a highly specialised grazer of green pasture (Pellis and Pellis 1982), with four CBG consuming as much as one sheep (Dorward et al 1980). The geese breed in winter (Mariott 1970, Hoysted et al. 1981), are sexually mature by 3 years of age (Pearse 1975) and fall into three groups, breeders, non-breeders and juveniles, where non-breeders and juveniles may form large flocks (Guiler 1967, Robinson et al. 1982, Delroy et al. 1989). The geese have been observed to remain together as pairs throughout the year (Guiler 1967, Pearse 1975) are known to pair for life and are strongly territorial (Marriott 1970, Pearse 1975, Hoysted et al. 1981). Densities of nests can be high with Guiler (1967) recording high nesting densities of 1 pair per 0.4-0.6 per hectare on the breeding islands of the Furneaux Group in Bass Strait, depending on food and ground cover. Clutch size varies from 1 to 8 eggs (Robinson et al. 1982) likely depending on food availability/quality (Guiler 1967) and has been recorded to average up to 4.9 eggs per nest (Robinson et al. 1982, Wagner and Seymour 2001). Successfully breeding pairs produce an even sex ratio in offspring (Pearse, 1975). The incubation period is around 35 days (Hoysted et al 1981) with goslings feeding on young grass shoots (Robinson et al 1982). Independent feeders from hatching, goslings remain with their parents for up to 16 weeks (Weatherly 1971 in Pellis and Pellis 1982) after which they form flocks of juveniles (Robinson et al. 1982, Delroy et al. 1989).

2.1.2 Overview of metapopulation model structure

The full metapopulation model structure is illustrated in Figure 1. The single population model for the CBG (Phillip and French Islands and Bass Coast) is based on an age-structured population model with 19 age classes (ages 1, 2, …, 18, 19 years). The life history of CBG suggests that a significant component of the population is composed of non-breeding adults at high population abundances. Therefore, the adult stage requires subdivision of the population into 'breeding' and 'non-breeding' adults, as has been used, for example, in models of Canada Geese (Hauser et al. 2007). Subdividing the population into stages and age classes is useful as this means that the effects of management on particular stages can be evaluated (e.g., interventions targeting winter flocking geese). Sex-structure was also included, and an annual projection interval was adopted for the model to coincide with available management actions, life history and the frequency of the monitoring data. The dynamics of the local population can be described mathematically as:

$$\mathbf{n}^{t+1} = \mathbf{A}\mathbf{n}^{t} \qquad \text{Eq. } \mathbf{1}$$

where $\mathbf{n}^{t}$ is a vector of abundances of individuals in each stage and sex at time t and $\mathbf{A}$ is a projection matrix containing the transition rates between ages/stages (e.g., survival and recruitment) (Caswell 2001). Estimates of the transition and vital rates (e.g., survival rates) were derived from count data and model fitting to observed population patterns.

The population of CBG on Phillip Island can be considered to be part of a metapopulation and is linked to French Island and the mainland (Bass Coast) by the movement or dispersal of individuals. Hence, equation 1 can be generalised to multiple populations combining transition matrices for each population with movement or dispersal probabilities $\mathbf{M}$ for each stage to produce a spatial metapopulation model (Hunter and Caswell 2005). For example, if there are only 2 populations then the state of the metapopulation can be described by the following vector:

$$\boldsymbol{N}^{t} = \frac{\text{Pop 1}}{\text{Pop 2}} = \begin{pmatrix} n_{1,1}^{t} \\ \vdots \\ n_{19,1}^{t} \\ \hline n_{1,2}^{t} \\ \vdots \\ n_{19,2}^{t} \end{pmatrix}$$

where $n_{i,j}^{t}$ is the abundance of stage *i* in population *j* at time *t*. Hunter and Caswell (2005) describe a system where firstly demographic change occurs within each population and then dispersal redistributes individuals among patches as:

$$\begin{pmatrix} \mathbf{n}_1^{t+1} \\ \hline \vdots \\ \hline \vdots \\ \hline \mathbf{n}_k^{t+1} \end{pmatrix} = \mathbf{P}^{\mathrm{T}}\mathbf{MPB} \begin{pmatrix} \mathbf{n}_1^{t} \\ \hline \vdots \\ \hline \vdots \\ \hline \mathbf{n}_k^{t} \end{pmatrix} \qquad \text{Eq. } \mathbf{2}$$

The projection matrix from Eq 1 for this system is $\mathbf{A} = \mathbf{P}^{\mathrm{T}}\mathbf{MPB}$ with block demography matrix $\mathbf{B}$ and the block dispersal matrix $\mathbf{M}$ and the vec-permutation matrix $\mathbf{P}$. For a simplified system with maximum age 4, where birds mature at age 3 and only adults disperse (3 and 4yo) the projection matrix $\mathbf{A} = \mathbf{P}^{\mathrm{T}}\mathbf{MPB}$ becomes:

$$\mathbf{A} = \left(\begin{array}{c|c|c} \mathbf{A}_1 & \mathbf{M}_{2\to1} & \mathbf{M}_{3\to1} \\ \hline \mathbf{M}_{1\to2} & \mathbf{A}_2 & \mathbf{M}_{3\to2} \\ \hline \mathbf{M}_{1\to3} & \mathbf{M}_{2\to3} & \mathbf{A}_3 \end{array}\right) \qquad \text{Eq. } \mathbf{3}$$

where $\mathbf{A}_1$, $\mathbf{A}_2$, and $\mathbf{A}_3$ are the sub-matrices of transition rates (survival, recruitment, emigration) in population 1, 2 and 3, respectively, and $\mathbf{M}_{i\to j}$, $i \neq j$ $i,j =$ 1, 2, or 3, are the probabilities of adult immigration from population *i* to *j*, with:

$$\mathbf{A}_i = \begin{pmatrix} 0 & 0 & S_{0i}S_{ei}C_{3i} & S_{0i}S_{ei}C_{4i} \\ S_{1i} & 0 & 0 & 0 \\ 0 & (1 - M_{ij} - M_{ik})S_{2i} & 0 & 0 \\ 0 & 0 & (1 - M_{ij} - M_{ik})S_{3i} & 0 \end{pmatrix} \qquad \text{Eq. } \mathbf{4}$$

and M_{ij} and M_{ik}, $j \neq i, k \neq i, k \neq j$ $i, j, k =$ 1, 2, or 3.

$$\mathbf{M}_{i\to j} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & M_{ij}S_{2i} & 0 & 0 \\ 0 & 0 & M_{ij}S_{3i} & 0 \end{pmatrix} \qquad \text{Eq. } \mathbf{5}$$

where C_{3i} and C_{4i} are the female only clutch size for 3 and 4 year olds in population i, S_{ei} is the probability of eggs hatching, S_{0i} is the probability of goslings surviving to be 1 year old, S_{1i} is the probability of 1 year olds surviving to be 2 years old, S_{2i} is the probability of 2 year olds surviving to be 3 years old and S_{3i} is the probability of 3 year olds surviving to be 4 years old. Equation 3 is the general form of the CBG 3 population metapopulation model with equations 4 and 5 extended to 19 age classes.

Differentiating between breeders (nesting adults up to age 19) and non-breeders (winter flocking adults up to age 19), male and females, and including temporal stochasticity (environmental and demographic), spatial stochasticity (differences between populations) and density dependence produces a nonlinear metapopulation model. Figure 1 represents a simplified schematic of the metapopulation model without sex and adult age classes, where, as nest density increases, increasing numbers of juveniles transition ($N_d\!: 0 \leq N_d \leq 1$, Figure 1) to become winter flocking adults. It is possible for winter flocking adults to become nesting adults if the density of nests drops allowing winter flocking adults to establish nests ($N_d\!: 0 \leq N_d \leq 1$, Figure 1). Once a breeding pair has established a nest it is assumed that they remain nesting adults and do not become winter flocking adults. It is also assumed that a breeding pair does not emigrate, only winter flocking adults emigrate with emigration occurring between all populations. Nesting adults produce female eggs, *C*, of which a proportion hatch (survive) S_e, and survival of goslings to 1 year olds, S_0 (Figure 1). Demographic stochasticity was incorporated using a binomial distribution to model the number of individuals surviving between consecutive time steps for each population, and a binomial distribution was also used to model the numbers of eggs produced each year for each population with n equal to nest count multiplied by the maximum clutch sizes with probability of success given by the mean clutch size divided by the maximum clutch size. Environmental stochasticity was incorporated by randomly varying the survival rates each year. Survival rates, S_e, S_0, S_1, S_2, and S_a, were drawn from normal distributions transformed to the unit interval (Todd and Ng 2001), with specified means and a 10% coefficient of variation and specifying correlation between each population of 80%, assuming if conditions are good for survival they are likely to be generally good across subpopulations, though providing some spatial variation in survival rates. No exogenous drivers were used as correlates for variation through time.

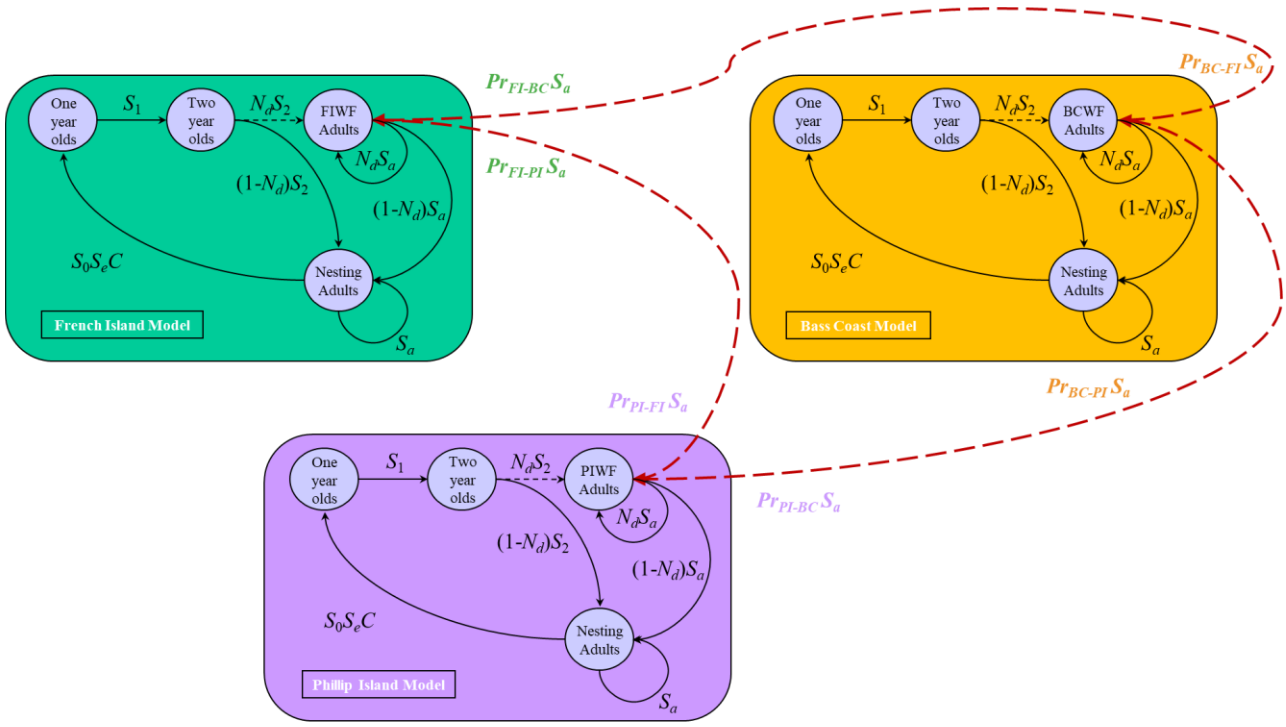

Figure 1. Simplified schematic of the metapopulation model for CBG, red lines indicate movement and survival of adults to a different location, black lines indicate transition from one age/stage to the next, with Phillip Island (PI), French Island (FI), Bass Coast (BC), and Winter Flock (WF)

2.1.3 Accounting for local population regulation with nest density

Plausible models of biological populations should recognise that populations cannot grow without limit (Brook and Whitehead 2005). Competition for key resources is likely to increase as the density of individuals increases and this is likely to be reflected, in turn, by changes in the population vital rates. This negative feedback between the density of the population and survival and recruitment rates or density-dependence needs to be included in the model to increase biological realism. As food availability appears not to be limited where improved pasture is broadly available for grazing, therefore key resources that are likely to affect survival and recruitment rates are not limiting. However, nesting sites close to available high-quality pasture for grazing may become limiting. CBG are highly territorial (Pearse 1975, Hoysted et al. 1981), and adults will defend a territory around the breeding site for most of the year (Guiler 1974), and moreover, Guiler (1967) observed that territories are retained where some nests are reused or new nests constructed beside the old nests. We incorporate density-dependence into the CBG metapopulation model using nest density, where for each population we define a nest threshold with a nest count related to the nest threshold affecting two population processes: 1) the transition of 2 year old juveniles to nesting adults if there are available nests, competing with winter flocking adults for the same nests, otherwise they become winter flocking adults with any remaining winter flocking adults; and 2) emigration of adults occurs when the nest count is greater than the nest threshold.

2.1.4 Incorporating fox predation and fox eradication

Foxes (*Vulpes vulpes*) have had a significant impact on the CBG population on Phillip Island, with CBG numbers increasing substantially since 2006 in response to the successful eradication of foxes from the island (DELWP, 2021). Young CBG goslings are naive, small, and exhibit poor vigilance behaviour, and with expanding activity are increasingly conspicuous, making them vulnerable to predation (Pellis and Pellis 1982). The survival rate of goslings was reduced by the fox predation rate (FPR) for the Phillip Island population, e.g. $S_0 PI * (1 - FPR)$. To model fox eradication a simple nonlinear decline in fox predation was used, $FPR_{t+1} = FPR_t(1 - (t - FoxControlStart)/FoxControlDuration)$ for $t \geq FoxControlStart$ and $FPR_{t+1} = FPR_t$ otherwise. The Phillip Island fox eradication program began in 2006 (Kirkwood et al. 2014) and the last fox was detected in August 2015 and foxes were declared eradicated from Phillip Island in 2017 (University of Melbourne, 2022) see Figure 2, the decline in predation being similar to the decline in fox numbers (Rout et al. 2014).

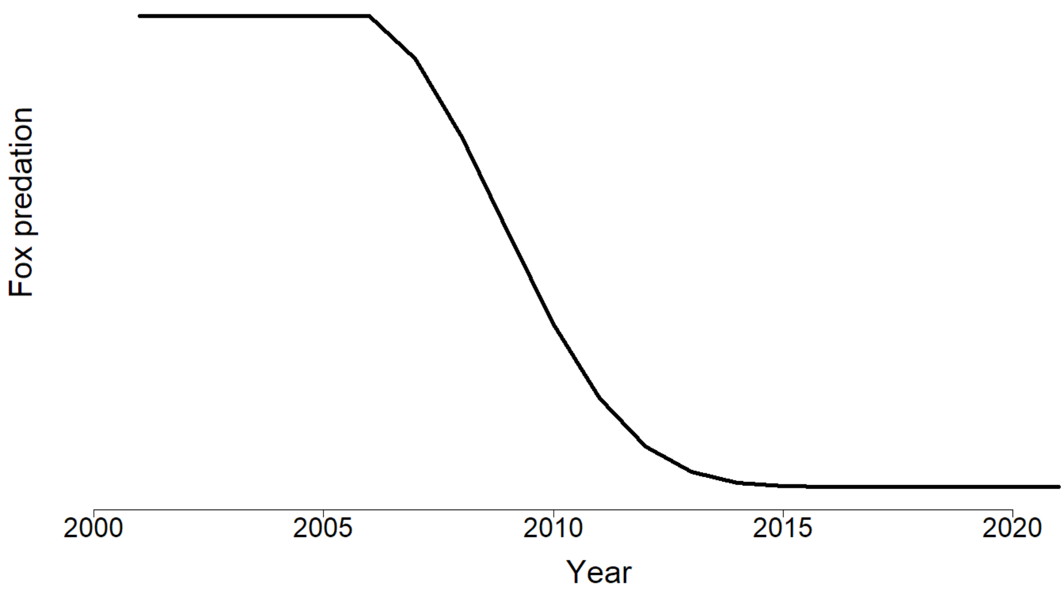

Figure 2. Modelled fox predation with control implemented in 2006.

2.1.5 Emigration and immigration

Winter flocking adults emigrate once the nest count rises above the specified nest threshold. To capture subpopulation-specific movements, the movement matrix was constructed with two probabilities: the probability of geese moving from Phillip Island (PI), French Island (FI), or Bass Coast (BC) (denoted as $Pr(PI)$, $Pr(FI)$, and $Pr(BC)$); and the probability of arriving at a specific destination, e.g., French Island from Phillip Island (denoted as $Pr(PI \rightarrow FI)$). Movement only occurs when the nest count is greater than 80% of the specified nest threshold for each population. From equations 3 and 5 we must specify 6 movement elements M_{ij}, $i \neq j$ $i, j =$ 1, 2, or 3. If we denote PI as 1, FI as 2, and BC as 3 the corresponding movement elements and generalised probabilities can be found in Table 3.

2.2 Parameter estimation and specification

2.2.1 Specialist Cape Barren Geese workshop for model development

A workshop was held in July 2023 attended by specialists in the ecology and management of CBG on Phillip Island (Table 1). The purpose of the workshop was to assess available information on CBG that would contribute to the development of a population model to test management options for CBG on Phillip Island. It was also expressed at this workshop that managing the greater metapopulation was a desired outcome for control options. There were concerns that growing numbers of CBG were being seen on the mainland and French Island and that the numbers on Phillip Island were contributing to these observations and that if populations establish at these other locations that these will in turn interfere with control options on Phillip Island.

Table 1. Workshop attendees.

Specialist CBG workshop attendees		
Simon Ruff	Charles Todd	Duncan Sutherland
Lachlan Clarke	Raoul Mulder	Stuart Murphy
Maria Schreider	Vincent Knowles	Peter Dann

The topics covered were:

- Life history of CBG
- Linking environment and management to ecology (for each life stage - eggs, goslings, juveniles, adults)
- Responses to management interventions
- Recent changes to populations/key populations
- Movements and dispersal (what are known/gaps)

- Nest densities/population densities
- Habitats
- Survival rates and fecundity
- Scale: management/model scales (spatial scales, number of sites), timeframes
- Other threats and issues

Cape Barren and Magpie geese were released on Phillip Island in late 1970s. Numbers of both geese were released into an enclosure with their wing feathers clipped, but after their first moult, CBG started to commute in and out of the enclosure during the day and eventually spread out across Phillip Island. CBG have since spread to fox-free French Island (breeding), Corinella (20+) and Bass (70+) on eastern side of Western Port and parts of the Mornington Peninsula. There is no breeding recorded at sites other than French Island.

Table 2. Life history parameters from the specialist CBG workshop

Survival rates and fecundity		Survival rates and fecundity	
Clutch size	1 – 8	Juvenile survival	unknown
Clutch average	5	Adult survival	unknown
Hatching success (S_0)	90% (0.9)	Movement	
Gosling success (S_0)	54% likely higher on PI	Gosling	0
Survival egg to 1yr old	22 – 47% likely higher on PI	Juveniles	Unknown but suspected to be zero
		Adult	Unknown but expected to be non-zero

Numerous knowledge gaps were identified relating to model development which included survival rates of juvenile and adult CBG, movement and dispersal rates (Table 2). CBG count data from surveys showed a large increase in CBG numbers on Phillip Island following a fox control program that led to fox eradication on Phillip Island (Figure 3). CBG reduce productivity of pasture and forage crops, reduce the viability of some crops for human consumption, expose stock to potential disease, expose humans to potential disease, can be a hazard to motor vehicles, and are known to be impacting on nesting sites of the Little Penguin. Greatest impact comes from geese that are in large flocks of non-breeding birds (either immature/non-territorial occupiers). Relatively little impact from geese that are dispersed on breeding territories. Reductions in the size of flocks of non-breeding birds during autumn/winter could improve pasture production from autumn/ winter renovation and cropping. Egg removal was trialled on Flinders Island (Tasmania) but was not considered a success as CBG moved and relayed (Robbie Gaffney pers. comm.).

2.2.2 Emigration and immigration probabilities

We assumed that CBG are less likely to move from high quality habitat, we assumed Phillip Island and French Island to be higher quality habitat than Bass Coast, therefore we set $Pr(PI) = Pr(FI) = 0.1$ and $Pr(BC) = 0.3$ (Table 3). We have no information on preferred destinations, we assumed birds would be more likely to emigrate to French Island from Phillip Island and that birds emigrating from either French Island or Bass Coast had no destination preference. We set the destination probabilities as $Pr(PI \to FI) = 0.8$, $Pr(PI \to BC) = 0.2$, $Pr(FI \to PI) = Pr(FI \to BC) = Pr(BC \to PI) = Pr(BC \to FI) = 0.5$ (Table 3).

Table 3. Movement elements and probabilities.

Movement element	Population movement	Population movement probability
M_{12}	$M_{PIFI} = Pr(PI)Pr(PI \to FI)$	$M_{PIFI} = 0.1{\times}0.8 = 0.08$
M_{13}	$M_{PIBC} = Pr(PI)Pr(PI \to BC)$	$M_{PIBC} = 0.1{\times}0.2 = 0.02$
M_{21}	$M_{FIPI} = Pr(FI)Pr(FI \to PI)$	$M_{FIPI} = 0.1{\times}0.5 = 0.05$
M_{23}	$M_{FIBC} = Pr(FI)Pr(FI \to BC)$	$M_{FIBC} = 0.1{\times}0.5 = 0.05$
M_{31}	$M_{BCPI} = Pr(BC)Pr(BC \to PI)$	$M_{BCPI} = 0.3{\times}0.5 = 0.15$
M_{32}	$M_{BCFI} = Pr(BC)Pr(BC \to FI)$	$M_{BCFI} = 0.3{\times}05 = 0.15$

2.2.3 Survey data and model calibration

The population of CBG on Phillip Island has been surveyed annually since 1993 (Figure 3) with significant increases evident following the successful eradication of foxes from the island and improved agricultural practices (DELWP, 2021). Survey data on CBG provide information on past counts of CBG, which we used to calibrate the model based on the principle that modelled outcomes should reflect the survey data if the underlying model is plausible. Model calibration was focused on two key model mechanisms: the strength of fox predation (FPR) and the nest threshold above which nesting sites are limited (see Section 2.1.3), causing increasing numbers of juveniles to enter the winter flocking adult stage. Fox predation provides a mechanism to suppress the CBG population prior to fox control, while the nest threshold determines population regulation with greater numbers of birds entering the winter flock and increasing emigration following the removal of foxes.

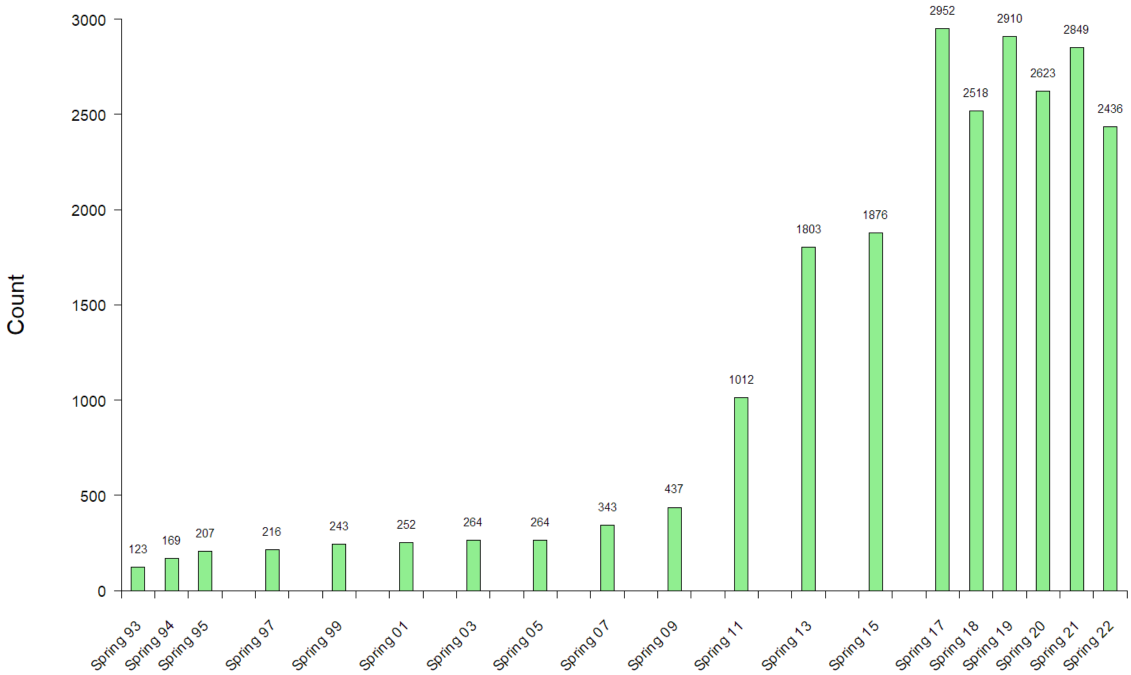

Figure 3. Cape Barren Geese spring count data on Phillip Island 1993-2022.

Table 4. Sets of model parameterisation tested

Model Parameterisation			
Parameter	**Set 1**	**Set 2**	**Set 3**
Hatching success (S_e)	0.9	0.9	0.9
Gosling success (S_0)	0.54	**0.9**	0.9
1yr old survival (S_1)	0.5	0.5	**0.6**
2yr old survival (S_2)	0.7	0.7	**0.8**
Adult survival (S_a)	0.85	0.85	**0.9**
Average clutch size (C)	0.5x5	0.5x5	0.5x5
Population growth rate (λ)	1.15	1.28	1.39
Fox predation rate (FPR)	0.48	0.7	0.828
Nest Threshold (NT)	3000	320	210

Note: clutch size has a factor of 0.5 to ensure a female only model when calculating the population growth rate, assuming an even sex ratio, see Section 2.1.1.

Unquantified parameters for the metapopulation model construct were gosling, juvenile and adult survival, as well as the nest threshold and fox predation rate. We calibrated the model by testing three different population growth constructs: Set 1 $\lambda = 1.15$; Set 2 $\lambda = 1.28$; and Set 3 $\lambda = 1.39$ (Table 4). Coluccy et al. (2003) constructed a model of giant Canada geese with a population growth $\lambda = 1.15$ with high survival rates for goslings, juveniles and adults and the Canada geese model developed by Hauser et al. (2007) used generally high survival rates $S_{1+} = 0.86$. From Table 2 gosling survival was estimated at 0.54 and in the absence of fox predation likely to be higher. We adopted the principle that juveniles would likely have a lower survival rate than adults, and as CBG are relatively long-lived, adult survival needs to be high for birds to live up to 19 years. With lower gosling survival and choosing juvenile and adult survival rates producing a growth rate $\lambda = 1.15$, gives Set 1. Modifying gosling survival to reflect the expected higher survival on Phillip Island and selected to be high to capture no predatory effects generating a growth rate $\lambda = 1.28$, gives Set 2. Increasing juvenile and adult survival with a higher population growth rate $\lambda = 1.39$, gives Set 3. A lower population growth rate requires a higher nest threshold (NT) and a lower fox predation rate (FPR) to generate population dynamics that increases substantially with fox control, with increasing population growth rate the nest threshold (NT) declines and the fox predation rate (FPR) increases to obtain the appropriate dynamics of population suppression and then strong increase following fox control (Figure 3) in 2006. The French Island and Bass Coast population models used the same parameterisation as the Phillip Island model except NT was fixed at 250 and FPR fixed at zero on French Island and for Bass Coast NT was fixed at 500 and FPR fixed at 0.95 (no recorded recruitment but allow for low level recruitment on Bass Coast).

2.2.4 Sensitivity analysis

Solving the characteristic equation of the projection matrix produces the finite rate of increase or deterministic growth rate for the projection matrix in equation 1:

$$1 = S_e S_f S_1 \sum_{j=3}^{j=19} \lambda^{-j} F_j \prod_{i=3}^{i=j} S_{i-1}$$

The growth rate was calculated for each set of parameters in Table 4 using the characteristic equation. As part of model development, it is important to examine the sensitivity of the model to parameter estimation (Beissinger and Westphal 1998; Todd et al. 2017). Three types of mathematical analysis were considered: (i) elasticity analysis, measuring the proportional rate of change in the growth rate given a small change in a vital rate; (ii) sensitivity analysis, measuring the absolute rate of change in growth rate given a small change in a vital rate; and (iii) reproductive value analysis, measuring the contribution of an age class to future generations, and summarising reproduction, survival, and timing (Caswell 2001). Typically, with age structured models, it is common to report on the age specific perturbation analysis results, however as the vital rates of adult survival and fecundity do not vary with age, we report on the specific stage. We use only Set 3 for the sensitivity analysis as following model calibration, set 3 was determined to be the most realistic parameterisation and so was used for modelling control scenarios.

2.3 Control scenarios

Three control methods were used in the population model, removing winter flocking birds, removing eggs and removing goslings (Table 5). Control measures were not applied to the Bass Coast population. The control scenarios chosen were to determine if either egg removal or culling on Phillip Island would be an effective control strategy. Then combinations of control strategies (culling and egg removal) were examined for both Phillip Island and French Island. Lastly, combinations of control strategies substituting gosling removal instead of egg removal were tested. Scenarios S12-S14 used the maximum culling strategy only for French Island as a larger culling programme might be more tenable on French Island.

Table 5. Control scenarios for the CBG metapopulation model.

Control scenario	Winter flock removal[1]		Average no. of eggs removed per detected nest		Average no. of goslings removed per detected nest	
	PI	FI	PI	FI	PI	FI
S0	0	0	0	0	0	0
S1	0	0	4	0	0	0
S2	500	0	0	0	0	0
S3	All	0	0	0	0	0
S4	500	0	4	0	0	0
S5	All	0	4	0	0	0
S6	250	250	0	0	0	0
S7	500	500	0	0	0	0
S8	750	750	0	0	0	0
S9	1000	1000	0	0	0	0
S10	All	All	0	0	0	0
S11	250	250	4	4	0	0
S12	500	500	4	4	0	0
S13	750	750	4	4	0	0
S14	250	All	4	0	0	0
S15	500	All	4	0	0	0
S16	750	All	4	0	0	0
S17	250	250	0	0	4	4
S18	500	500	0	0	4	4
S19	750	750	0	0	4	4

[1]: Target setting for the removal of winter flock geese, if there are not enough geese to meet the target removal then all winter flock geese are removed.

Winter flocking birds were removed by setting an annual removal goal (see Table 5), if the winter flock estimate is less than the minimum winter flock size target, no culling occurs (set at 20 for PI and 0 for FI). For egg removal, nests must be located and not all nests can be located, given limited resources. A nest detection rate of 40% was used as a plausible level of nest location, with the number of nests located binomially distributed with the nest count (calculated within the model) and the nest detection rate. We set the average number of eggs removed from the located nests at 4 (see Table 3) and eggs were removed from the located nests if the located nests were less than the minimum number of locatable nests target (set at 20 for both PI and FI), no eggs were removed. Using the same nest detection rate as for eggs, we set the average number of goslings removed from the located nests at 4 (see Table 3) and goslings were removed from the located nests if the located nests were less than the minimum number of locatable nests target (set at 20 for both PI and FI). Control options implemented on the Phillip Island population begin in 2025 and acknowledging that resources are finite the control options implemented on the French Island population begin in 2030.

What is the goal of control?

From the workshop it was identified that reducing the size of flocks of non-breeding birds during autumn/winter could improve pasture production from autumn/ winter renovation and cropping. We set the first goal of control to reduce the winter flock on Phillip Island. Furthermore, it was acknowledged at the workshop that CBG were establishing populations elsewhere, as emigrants from Phillip Island, and that there may be immigration to

Phillip Island from these surrounding populations even if the Phillip Island were controlled. Moreover, there was an interest from the workshop in ensuring that CBG did not become an undesirable species in these other locations as well. Therefore, the second goal was to reduce overall emigration. The third goal of control is to minimise the ongoing cost of meeting the first two goals. While we have not built the cost of control into the scenarios we test, options that minimise ongoing control effort would likely minimise any ongoing costs of control. At the specialist workshop it was stated that farmers would tolerate the impacts of around 500 CBG, though it was not clear if this was a total population of 500 or a winter flock of 500. The measures of scenario success were the mean of the 2065 level of Total Population, Winter Flock, Emigrants, Nesting Population for Phillip Island and low emigration from the other populations, relative to the following quantitative goals.

We define 3 goals to determine whether a strategy was successful by: 1) an acute goal comparing predicted 2065 measures to their mean values in 2005 (aligned with the pre-fox eradication programme); 2) a moderate goal with a total population size of 492 geese (mean value modelled in 2008 and aligned with the tolerance thresholds of farmers); and 3) a relaxed goal higher than what famers will tolerate with a winter flock target of 619 (mean value modelled in 2010 and approximately aligned with the tolerance thresholds of farmers if focusing on the winter flock). These thresholds are somewhat subjective but provide a range of outcomes from all scenarios for clear decision making.

We define 3 goals to determine whether a strategy was successful: 1) a severe goal comparing predicted 2065 measures to their mean values in 2005 (aligned with the pre-fox eradication programme); 2) a moderate goal comparing predicted 2065 measures to their mean values corresponding with a total population size of 492 geese (as observed in 2008 and aligned with the tolerance thresholds of farmers); and 3) a relaxed goal comparing predicted 2065 measures to their mean values corresponding with a winter flock target of 619 (as observed in 2010 and approximately aligned with the tolerance thresholds of farmers if focusing on winter flock). These thresholds are somewhat subjective but provide a range of outcomes from all scenarios for clear decision making.

2.4 Interpretation of model output

The population model generated 1000 replicate trajectories for each scenario. As example output of the thousand trajectories, we present total population figures with all 1000 trajectories in the section for model calibration, to provide a sense of the variety of trajectories provided within a single scenario over the 29 years in which population count data was collected (1993 to 2022, Figure 3). We then summarise these scenarios using mean trajectories (the average of the 1000 replicates) of the total population with shaded areas representing ±1 standard deviation around the mean trajectory for the three sets of model parameterisation.

For control scenario examination we generate the best fit trajectory by finding the trajectory that minimises sum of squared differences between the 1000 trajectories modelled and the observed population count data. We include this trajectory in subsequent Phillip Island figures as a reference when the projected period is increased to 1993 to 2065 (40 years following first control measures). For the control scenarios, we use a mix of figure types of mean trajectories only and of mean trajectories with shaded areas for a variety of different population measures.

3 Results

3.1 Model calibration

The model parameterisation using sets 1,2 and 3 produce plausible population outcomes (Figures 4 – 6). Comparing the dynamics of each parameterisation set to the survey count data indicates that count data sits within the array of dynamics that each model parameterisation produces. The associated growth rate with Set 1 meant that the nest threshold had to be set high (relative to the other parameter sets) and the fox predation rate to be set low (relative to the other parameter sets) to achieve a range of outcomes similar to the count data. Nest threshold influences the size of the winter flock, with parameters Set 1, the winter flock increases slowly compared with the other 2 parameter sets (Figure 7). French Island relies upon immigration to establish a population, Set 1 produces first immigrants in 2021, Set 2 produces first immigrants in 2005 and Set 3 produces first immigrants in 1997 (Figure 8) and first breeding in 1998 which fits with the observation that CBG first arrived on French Island in 1997 with first breeding in 1998 (pers comm. Dave Stevenson, Parks Victoria). From these results the model was calibrated on parameter Set 3 which produced plausible immigration to French Island, where the other 2 sets did not. Parameter Set 3 has the highest population growth rate, consequently if control options tested under this parametrisation are considered a success, then the same control options will perform for models with a lower population growth rate.

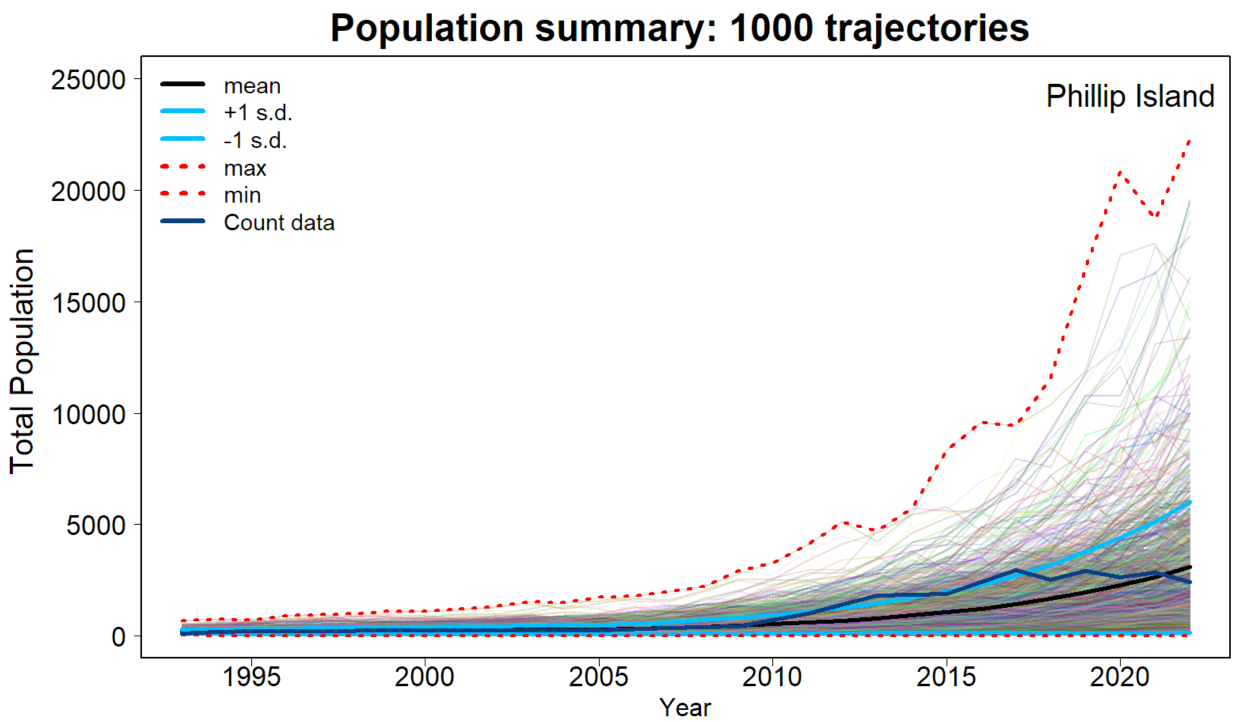

Figure 4. Model outcomes for Phillip Island using Set 1 model parameterisation together with Count Data from Figure 3.

Thin coloured lines are individual model trajectories, the thick black line is the mean modelled population trajectory, light blue lines present bounds (±1 standard deviation from the mean), and dotted red lines bound the lower and upper values in each year. The thick dark blue line displays observed population count data.

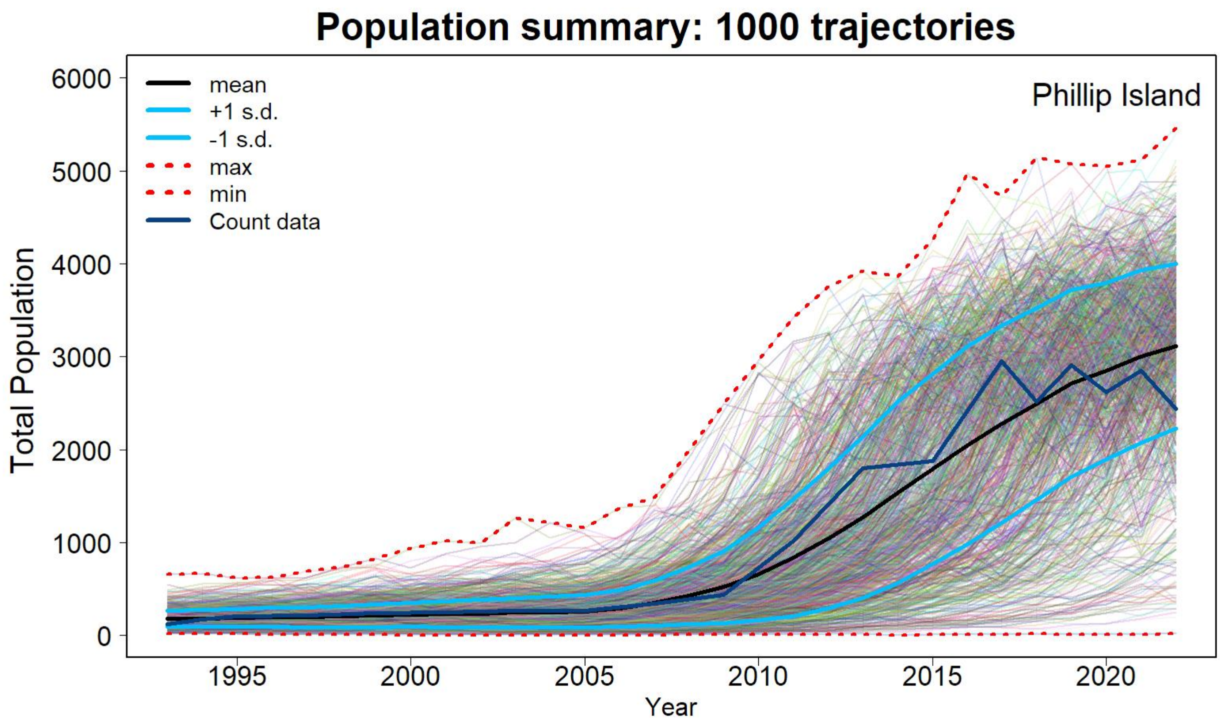

Figure 5. Model outcomes for Phillip Island using Set 2 model parameterisation together with Count Data from Figure 3.

Thin coloured lines are individual model trajectories, the thick black line is the mean modelled population trajectory, light blue lines present bounds (±1 standard deviation from the mean), and dotted red lines bound the lower and upper values in each year. The thick dark blue line displays observed population count data.

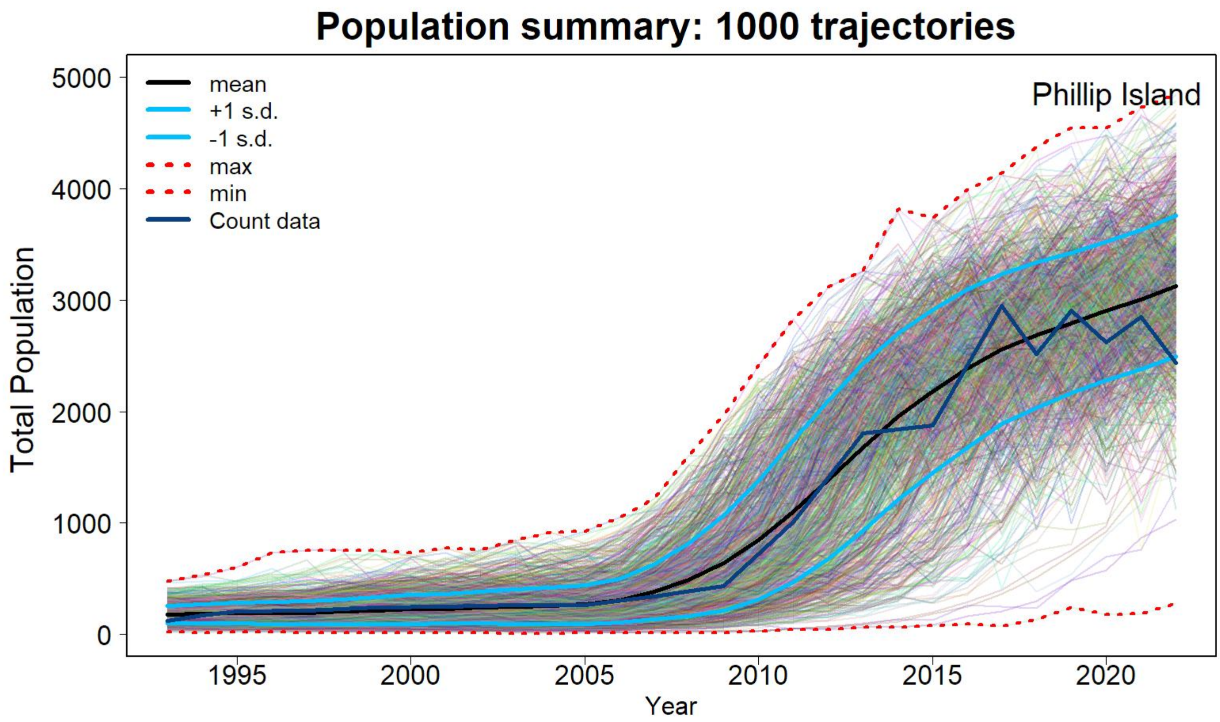

Figure 6. Model outcomes for Phillip Island using Set 3 model parameterisation together with Count Data from Figure 3.

Thin coloured lines are individual model trajectories, the thick black line is the mean modelled population trajectory, light blue lines present bounds (±1 standard deviation from the mean), and dotted red lines bound the lower and upper values in each year. The thick dark blue line displays observed population count data. This model parameterisation was determined to fit observed data best and so used for modelling control scenarios.

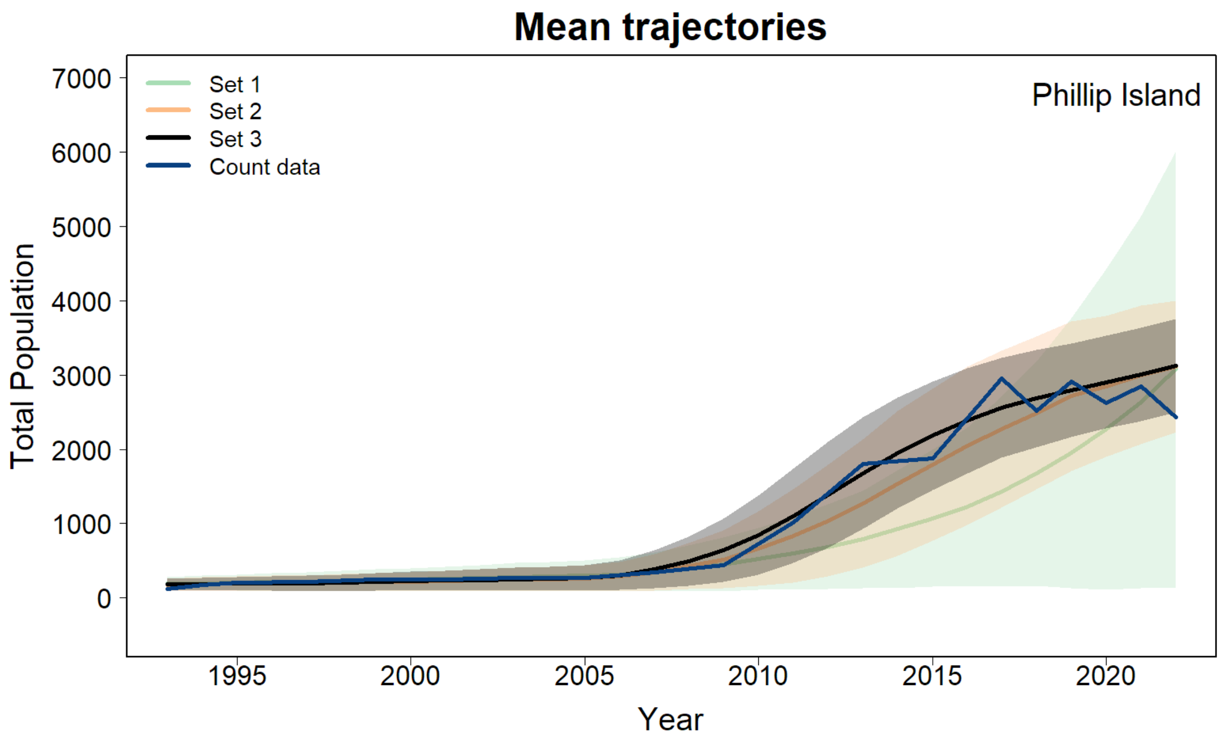

Figure 7. Comparisons between model outcomes for Phillip Island using the 3 sets of model parameterisation together with Count Data from Figure 3.

The solid lines are the mean total population size (males and females) from each parameterisation set through time; the shaded areas indicate ±1 standard deviation from the mean through time and the thick dark blue line displays observed count data.

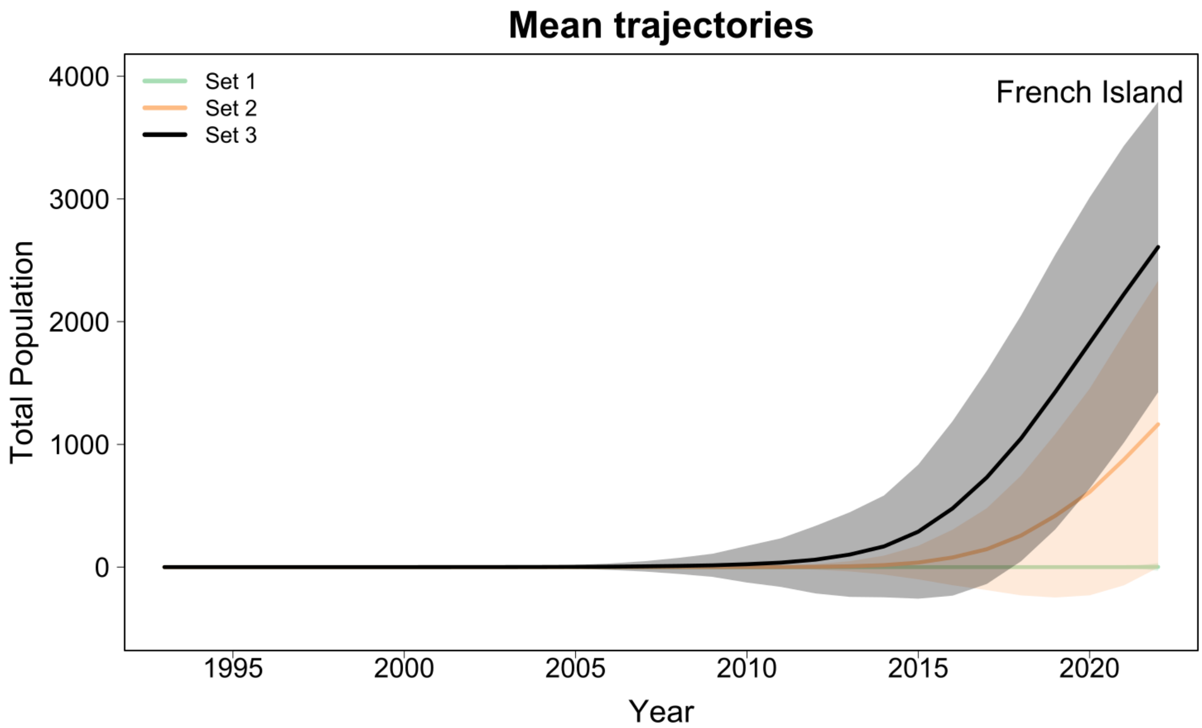

Figure 8. Comparisons between model outcomes for French Island using the 3 sets of model parameterisation.

The solid lines are the mean total population size (males and females) from each parameterisation set through time; the shaded areas indicate ±1 standard deviation from the mean through time.

3.2 Population projections to 2065

A “best fit” trajectory was identified by selecting the individual modelled trajectory most closely aligned with the count data (Figure 9). This trajectory illustrates that the model outputs not only bound the observed count data, but also include individual realisations very closely aligned with the inter-annual variation in count data (Figure 9). Projecting trajectories to 2065 indicates that the CBG population on Phillip Island may increase in abundance from current levels despite an observed downturn in count data in recent years (Figure 9). Comparing output from the three modelled populations shows the Phillip Island population increasing as observed then the French Island population increases and then the Bass Coast population increases, when all populations are uncontrolled (Figure 10). The Winter Flock initially increases on Phillip Island and then increases on French Island to be a large pool of potential immigrants (Figure 11).

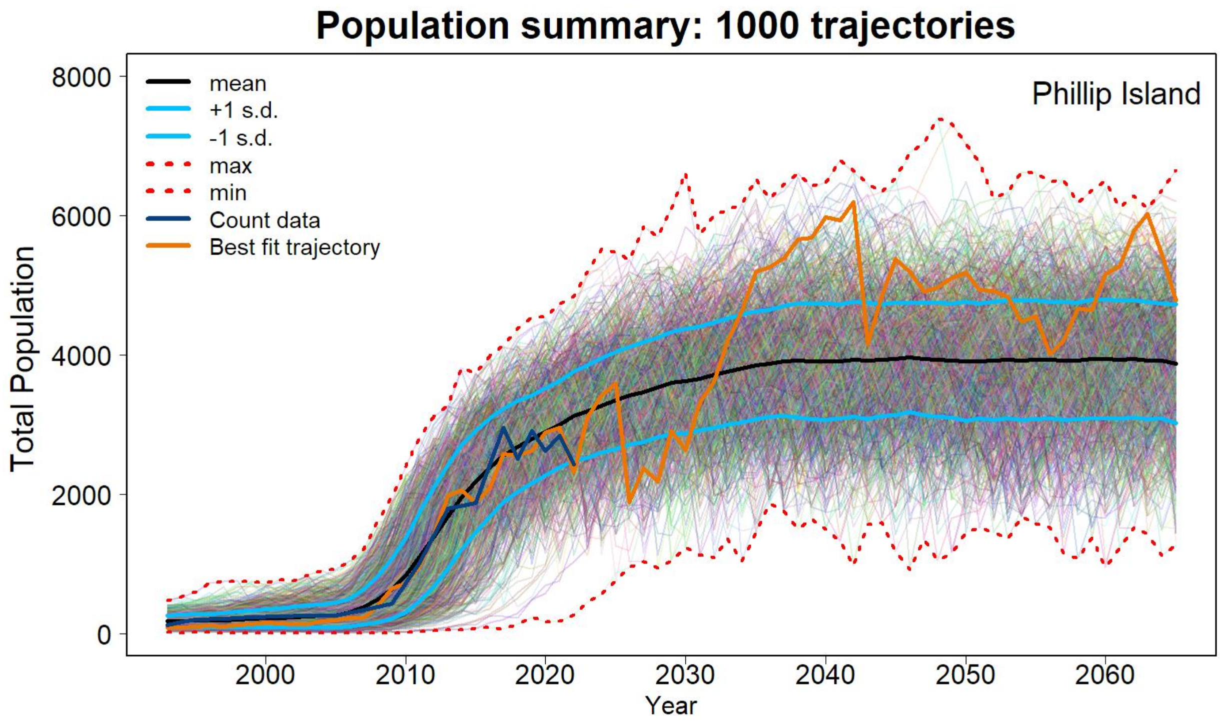

Figure 9. Modelled CBG trajectories on Phillip Island together with Count Data from Figure 3 overlaid with “best fit” trajectory extended to 2065.

Thin coloured lines are individual model trajectories, the thick black line is the mean modelled population trajectory, light blue lines present bounds (±1 standard deviation from the mean), and dotted red lines bound the lower and upper values in each year. The thick dark blue line displays observed population count data. The figure illustrates that modelled population dynamics generally captures the observed count data pattern with suppression of the population until fox control begins in 2006. With the addition of a best fit trajectory (minimum sum of squared errors between all modelled trajectories and observed population count data in Figure 3) extended to 2050. The mean trajectory indicates that the CBG population on Phillip Island may continue to increase in abundance despite a recent downturn in the observed population count data.

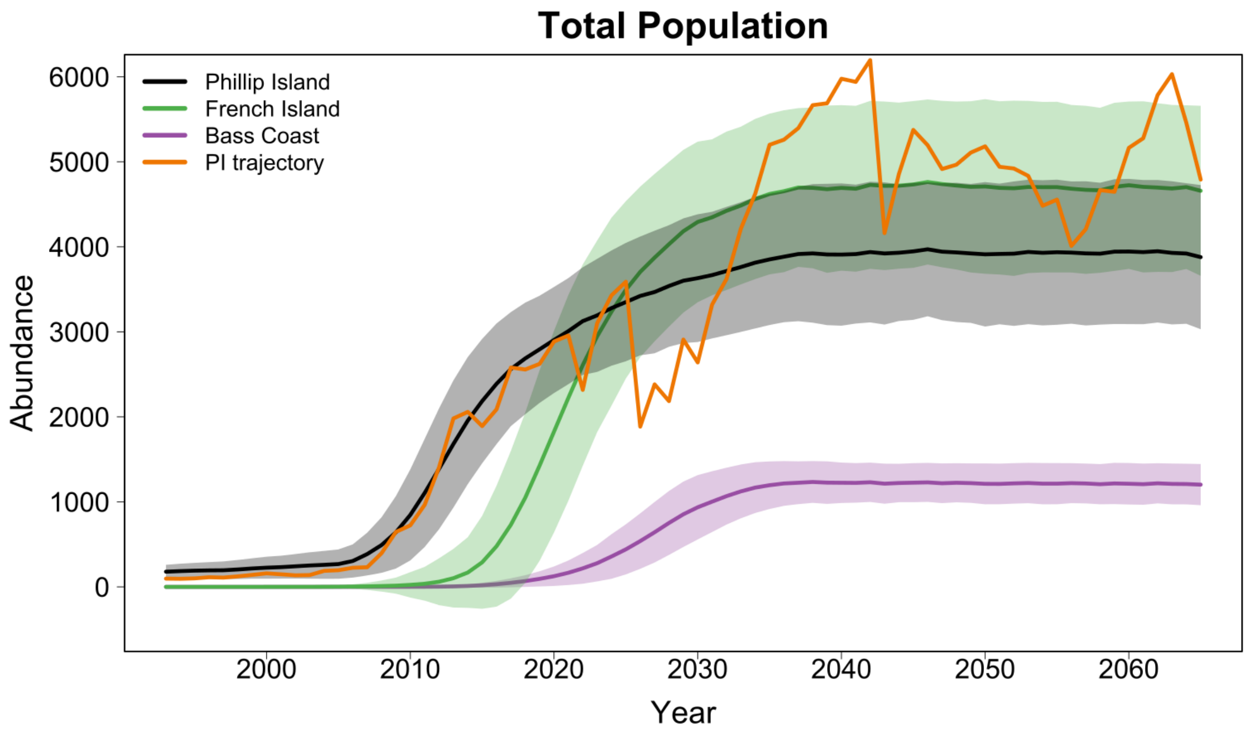

Figure 10. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the best fit trajectory for Phillip Island (i.e., the modelled trajectory that most closely aligns with observed population count data).

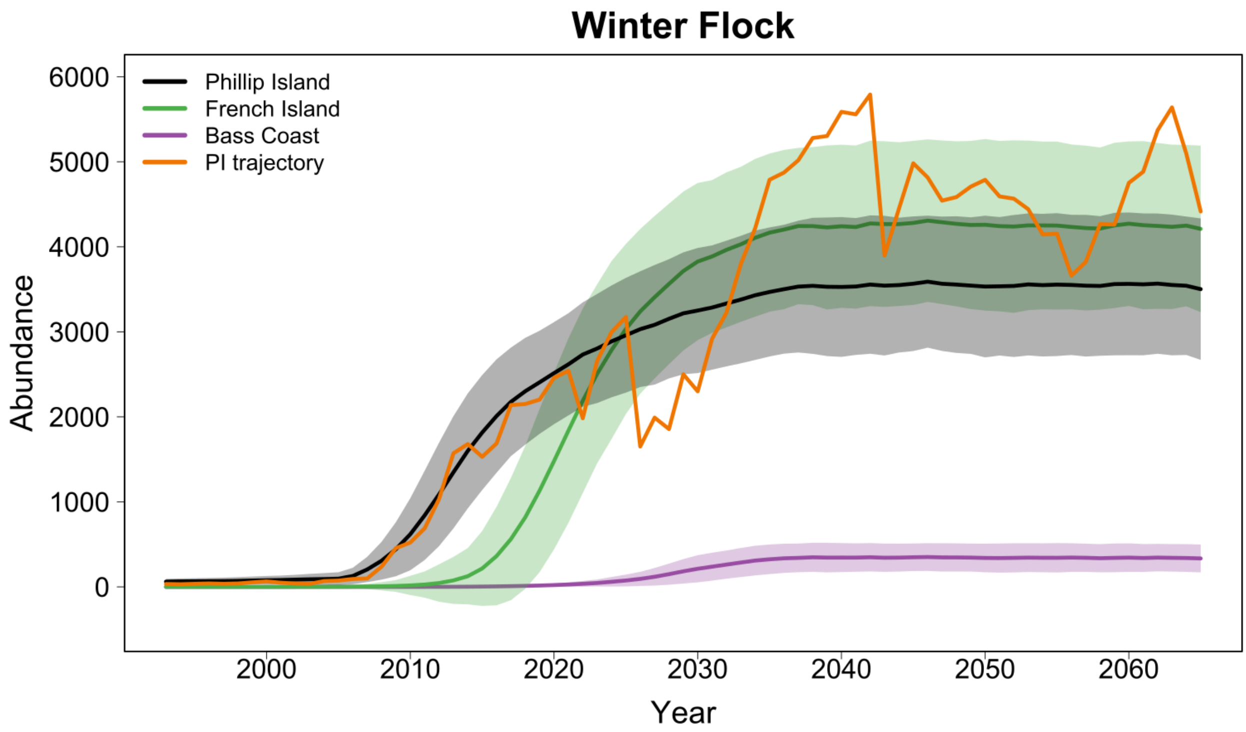

Figure 11. Modelled CBG winter flock trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is trajectory equivalent to the best fit trajectory for Phillip Island in Figures 9 and 10.

3.3 Control scenarios

We tested several control scenarios: control applied on Phillip Island only (S1 – S5: Table 5); applied to both Phillip Island and French Island as Winter Flock removal only (S6 – S10: Table 5); applied to Phillip Island and French Island as Winter Flock and egg removal combined (S11 – S13: Table 5); applied to Phillip Island as Winter Flock and egg removal combined and to French Island as removal of all Winter Flock (S14 – S15: Table 5); and applied to Phillip Island and French Island as Winter Flock and gosling removal combined (S17 – S19: Table 5). We define 3 goals to assess whether a strategy was successful: 1) an acute goal; 2) a moderate goal; and 3) a relaxed goal being the same as or less than the mean of the 2065 level of the measure examined (Phillip Island: Total Population, Winter Flock, Emigrants, Nesting Population).

We define 3 goals to determine whether a strategy was successful: 1) a acute goal comparing the mean of the 2005 level of the measure examined with the mean of the 2065 level of the measure examined, 2005 aligning with the pre-fox eradication programme; 2) a moderate goal with a total population size of 492 geese in 2008 and equivalently for the other measures; and 3) a relaxed goal higher than what famers will tolerate with a winter flock target of 619 which is the mean modelled level of winter flocking geese in 2010.

The largest reductions in the total population of CBG on Phillip Island were associated with Scenarios S3 – S5, S8 – S10, S12, S13, S15, S16, S18 and S19 (Figure 12). However, S3 – S5 do not meet the defined goal of the mean trajectory in 2065 being at the level of the 2005 population mean, prior to the implementation of the fox eradication programme. Scenarios S8 – S10, S12, S13, S15, S16, S18 and S19 (Table 6, Figure 12) do meet the goal for successful control of CBG on Phillip Island. Furthermore, these scenarios also met the specified goal for the three other measures tested (Winter Flock, Emigrants, Nesting Population; Figures 13 – 15).

Table 6. Successful control scenarios for the CBG metapopulation model based on outcomes from Figures 12 – 15.

Control scenario	Winter flock removal		Average no. of eggs removed per detected nest		Average no. of goslings removed per detected nest	
	PI	FI	PI	FI	PI	FI
S8	750	750	0	0	0	0
S9	1000	1000	0	0	0	0
S10	All	All	0	0	0	0
S12	500	500	4	4	0	0
S13	750	750	4	4	0	0
S15	500	All	4	0	0	0
S16	750	All	4	0	0	0
S18	500	500	0	0	4	4
S19	750	750	0	0	4	4

Control applied to Phillip Island only

Scenarios S3, S4, and S5 reduce the Phillip Island total population but not to the goal of 259 geese, however S3 and S5 meet the moderate goal of 492 and S4 meets the relaxed goal of 846 (Figure 12). Scenarios S3, S4 and S5 make little difference to the French Island population (Figure 12). Scenario S3 and S5 reduce the Winter Flock to the goal ~92 geese, and S4 meets the moderate goal ~307 geese. Again, scenarios S3 and S4 make little difference to the Winter Flock on French Island (Figure 13). Additionally, in S3, S4 and S5 emigration from Phillip Island is reduced, S3 and S5 meets the relaxed goal ~5 and S4 does not meet any goal and French Island emigrants remain high (Figure 14). Scenarios S3, S4 and S5 fails to meet all goals for Nesting Birds on Phillip Island and only produces marginal declines in the number of nesting birds in either population (Figure 15).

Control applied to Phillip Island and French Island

The control strategies that met all goals for successful control of CBG on Phillip Island implemented control strategies on both Phillip Island and French Island (scenarios S8 – S10, S12, S13, S15, S16, S18 and S19:

Table 6, Figure 12). Removing winter flock geese only, required a large removal target to be set at both Phillip Island and French Island, for the goals to be met. Once the goals were met, an ongoing commitment was required to maintain the Phillip Island population by removing on average approximately 300 winter flock birds per year on Phillip Island and approximately 370 (S8) and 325 (S9 and S10) winter flock birds per year on French Island (Table 7; Figures A13 – A18). Removing a combination of winter flock geese and eggs or goslings required a lower removal target to be set but also required the removal of eggs or goslings. Once the goals were met for the combined strategies, the required ongoing commitment was removing on average 220 and 240 winter flock geese (S12 and S13) and the removal of 90 and 95 eggs (S12) or 80 and 85 eggs (S13) on Phillip and French Islands respectively (Table 7; Figures A21 – A24). Applying a combined control strategy to Phillip Island and removing all winter flock geese from French Island, once the goals were met, required an ongoing commitment by removing on average 220 and 325 winter flock geese on Phillip and French Islands respectively and the removal of 90 eggs on Phillip Island (S15 and S16) (Table 7; Figures A27 – A30). Targeting goslings may have some advantages, applying a combined control strategy of removing winter flock geese and goslings once the goals were met, required an ongoing commitment by removing on average 220 and 240 winter flock geese on Phillip and French Islands respectively and the removal of 90 goslings from both islands (S18) and on average 215 and 240 winter flock geese and the removal of 80 and 90 goslings on Phillip and French Islands respectively (S19) (Table 7; Figures A33 – A36).

Table 7. Ongoing commitment to maintain Phillip Island population once goal has been met, approximate mean and confidence interval.

Control scenario	Winter flock removal per year		Average no. of total eggs per year		Average no. of total goslings removed per year		Total average removals	
	PI	FI	PI	FI	PI	FI	PI	FI
S8	~300 [103.97, 610.02]	~370 [106.98, 750]	0	0	0	0	~300	~370
S9	~300 [79, 599]	~330 [100, 759.12]	0	0	0	0	~300	~330
S10	~310 [84.95, 630.05]	~325 [96.97, 749.02]	0	0	0	0	~310	~325
S12	~220 [69.93, 421.07]	~240 [70.93, 500]	~90 [0, 208]	~95 [0, 232]	0	0	~310	~335
S13	~220 [67.97, 419.05]	~240 [68.97, 513.05]	~80 [0, 204]	~85 [0, 212]	0	0	~300	~325
S15	~220 [69.97, 410.07]	~325 [87.95, 737.07]	~90 [0, 216]	0	0	0	~310	~325
S16	~225 [70.98, 441.02]	~330 [92, 748.27]	~90 [0, 204]	0	0	0	~315	~330
S18	~220 [62.95, 414]	~240 [72, 500]	0	0	~90 [0, 212]	~90 [0, 216]	~310	~330
S19	~215 [68, 406.02]	~240 [73.93, 549.02]	0	0	~80 [0, 204]	~90 [0, 212.1]	~295	~330

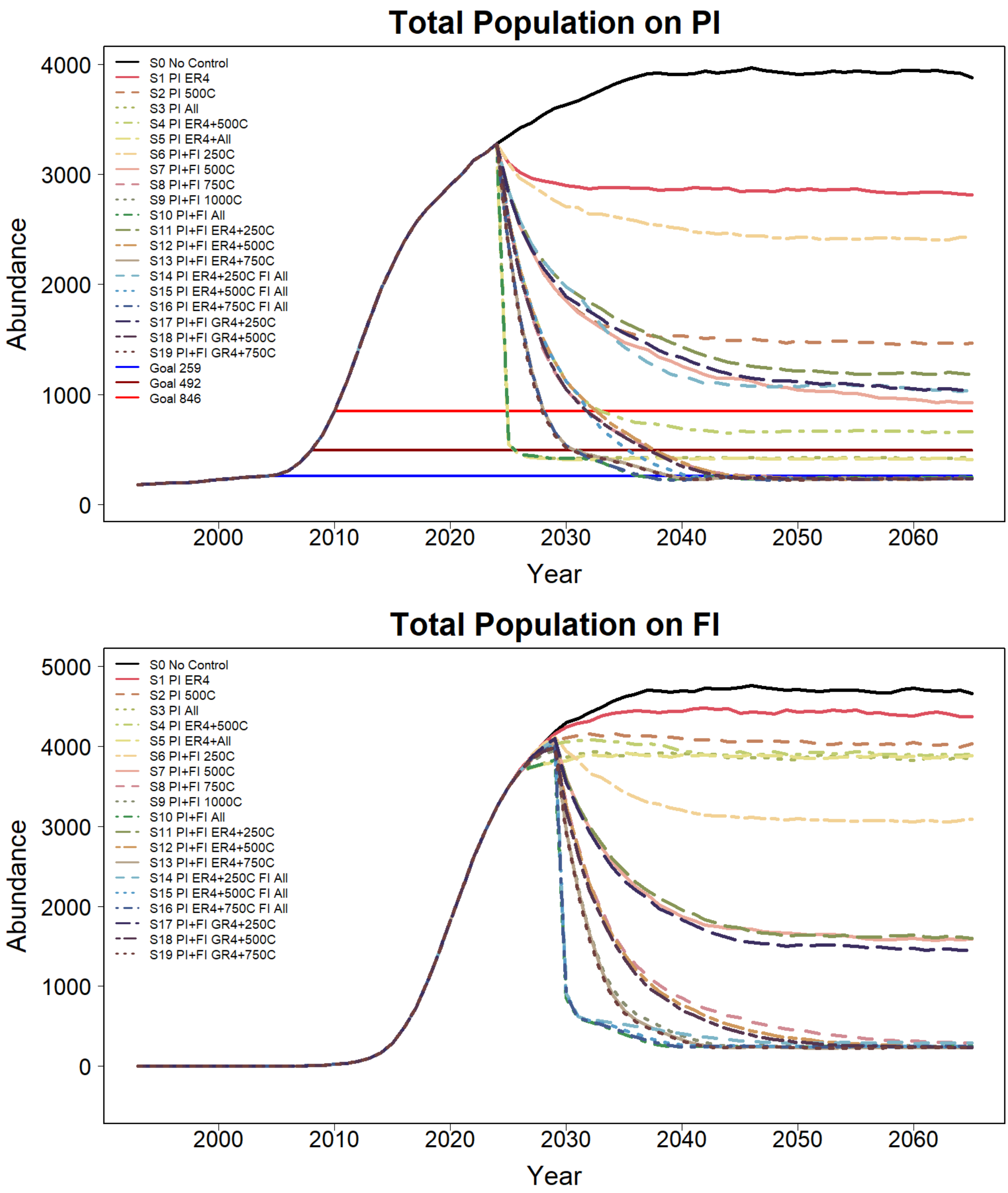

Figure 12. Modelled CBG mean total population trajectories (projected to 2065).
Top panel is Phillip Island and bottom panel is French Island.

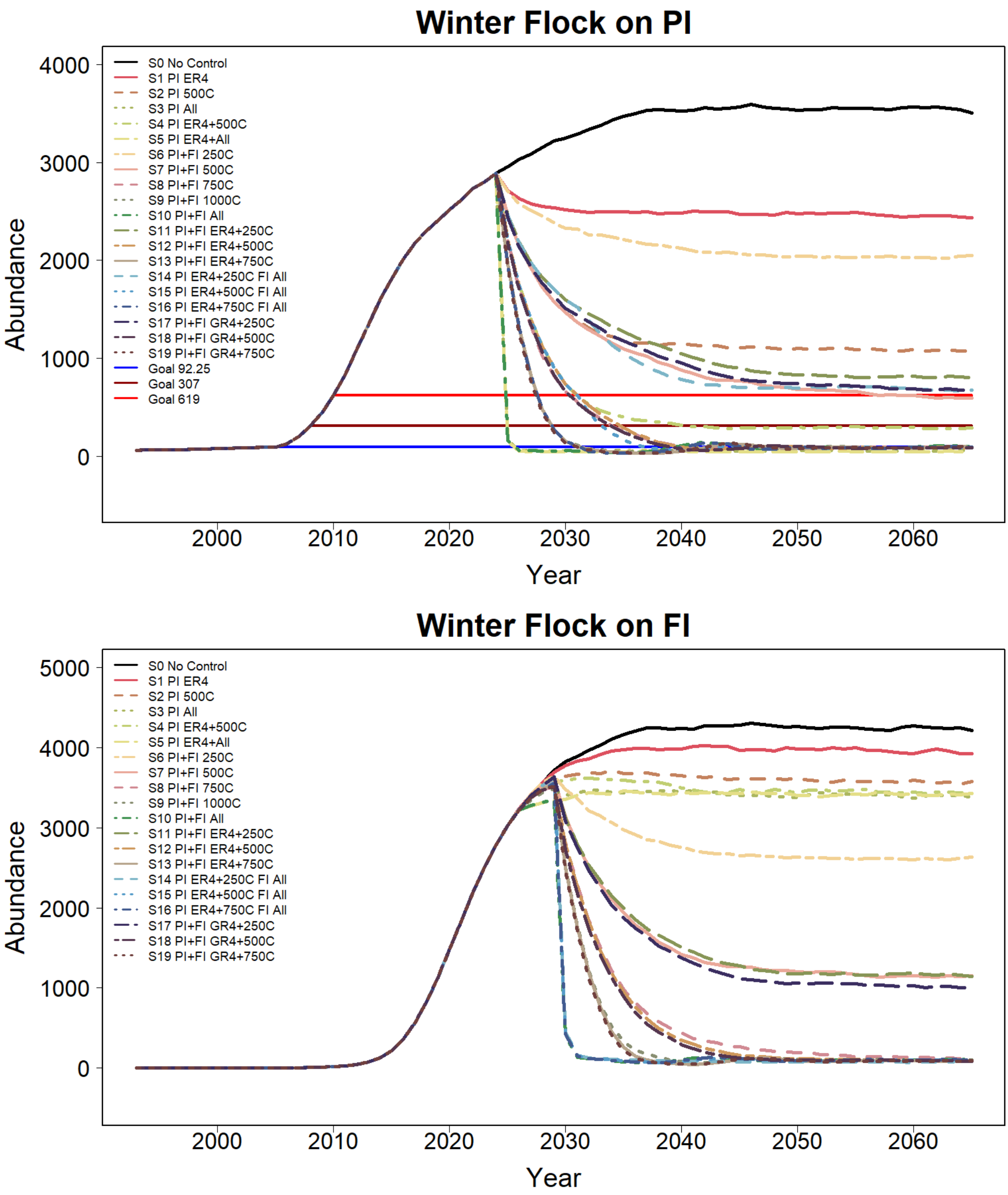

Figure 13. Modelled CBG mean winter flock trajectories (projected to 2065).
Top panel is Phillip Island and bottom panel is French Island.

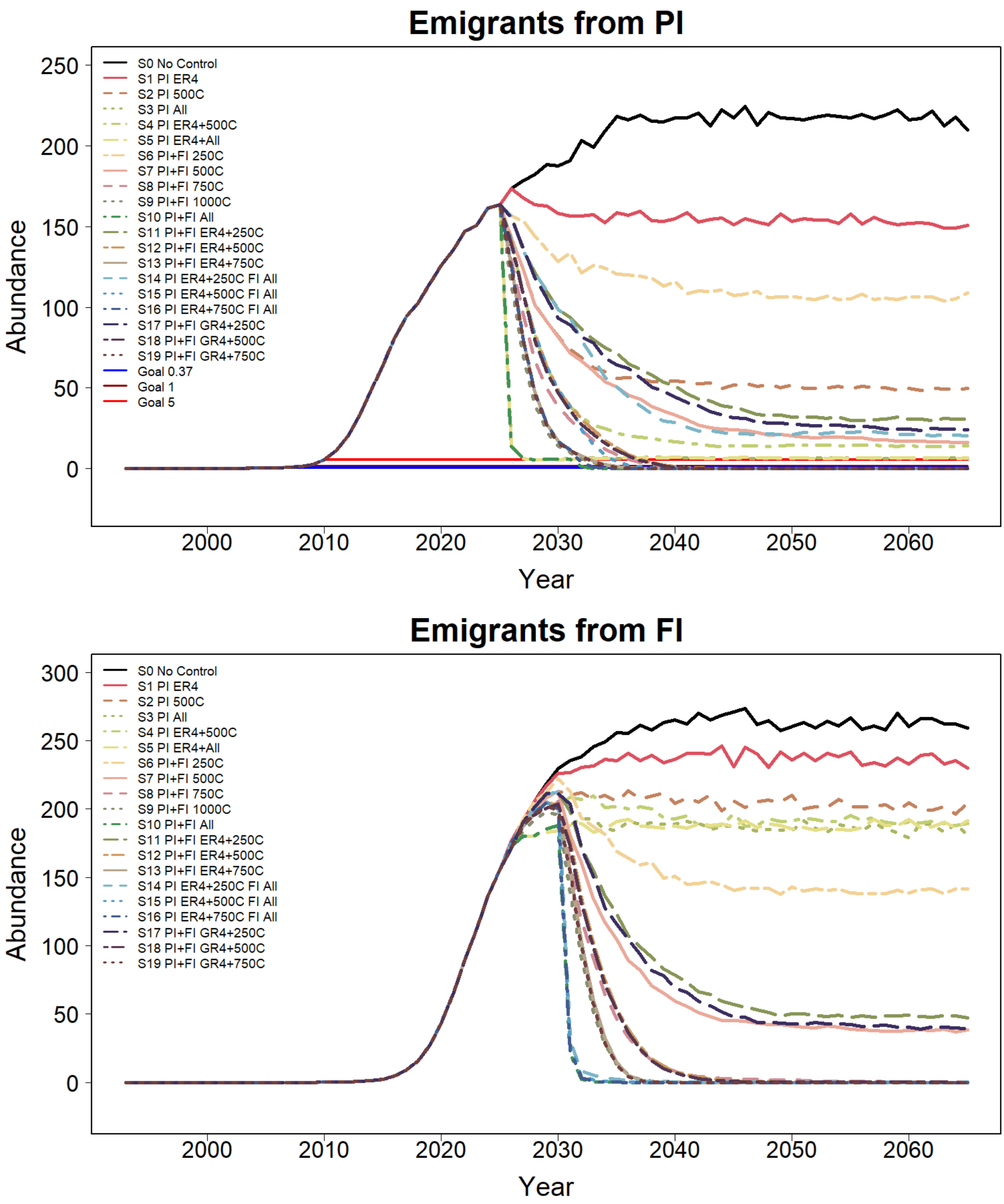

Figure 14. Modelled CBG mean emigrants trajectories (projected to 2065).

Top panel is Phillip Island and bottom panel is French Island.

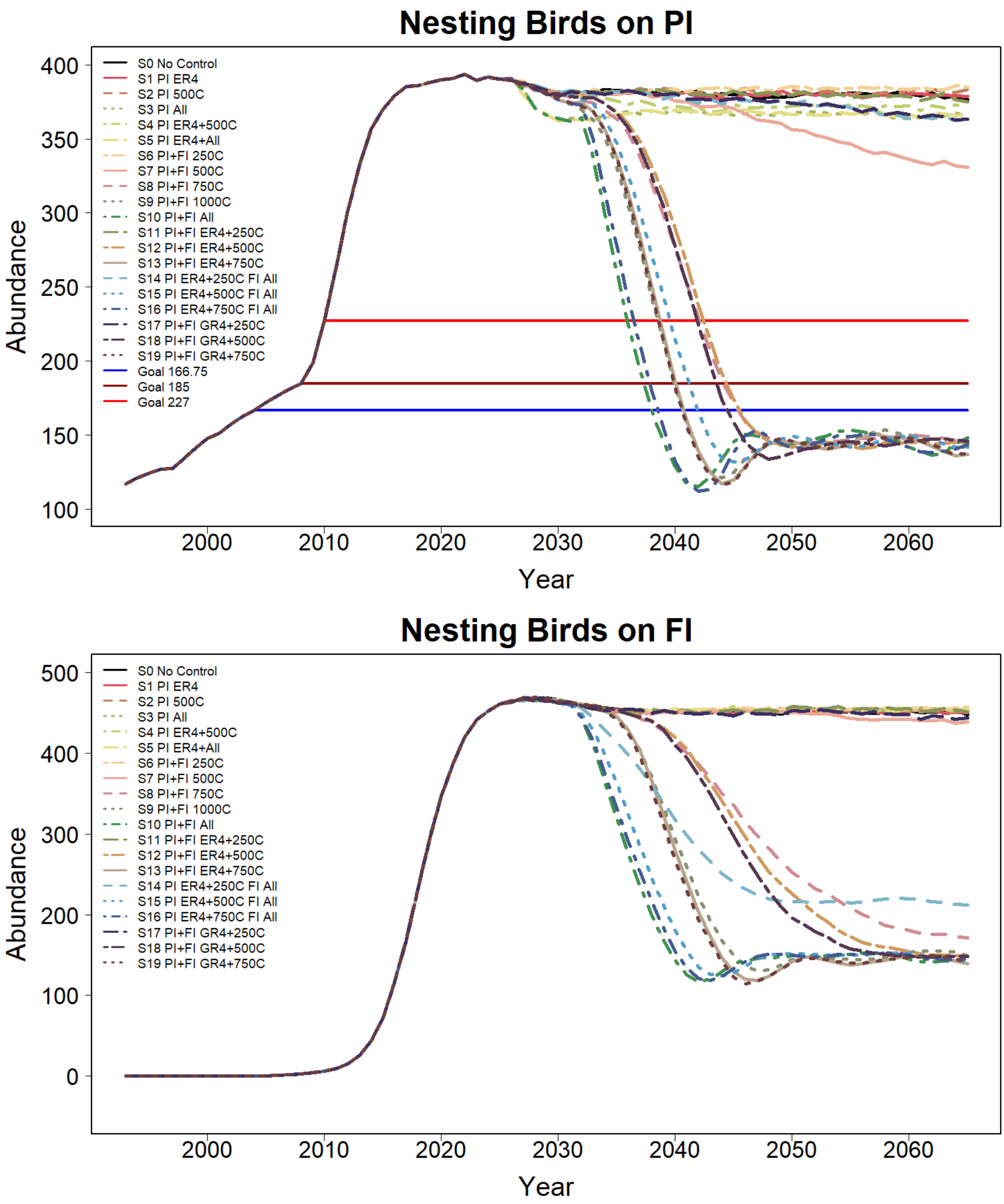

Figure 15. Modelled CBG mean nest birds (female and male) trajectories (projected to 2065).
Top panel is Phillip Island and bottom panel is French Island.

3.4 Sensitivity analysis

The sensitivity analysis (Figure 16) indicates the change (both proportional and absolute) in adult survival as having the largest impact on the population growth rate. Given a unit change in adult survival rate, either proportional or absolute, does not produce a change greater than 1 and hence the effect on the population growth rate is not multiplicative, i.e. a 10% increase adult survival produces 3.5% response in the growth rate for proportional change and adding 0.01 to adult survival produces a 0.0058 increase in the growth rate for absolute change. The reproductive value shows the contribution an age class to future generations, Figure 17 shows a high reproductive value for most of the adult life of CBG, this highlights the reproductive capacity of how the model is constructed and reflective of the species reproductive capacity and potential for population growth.

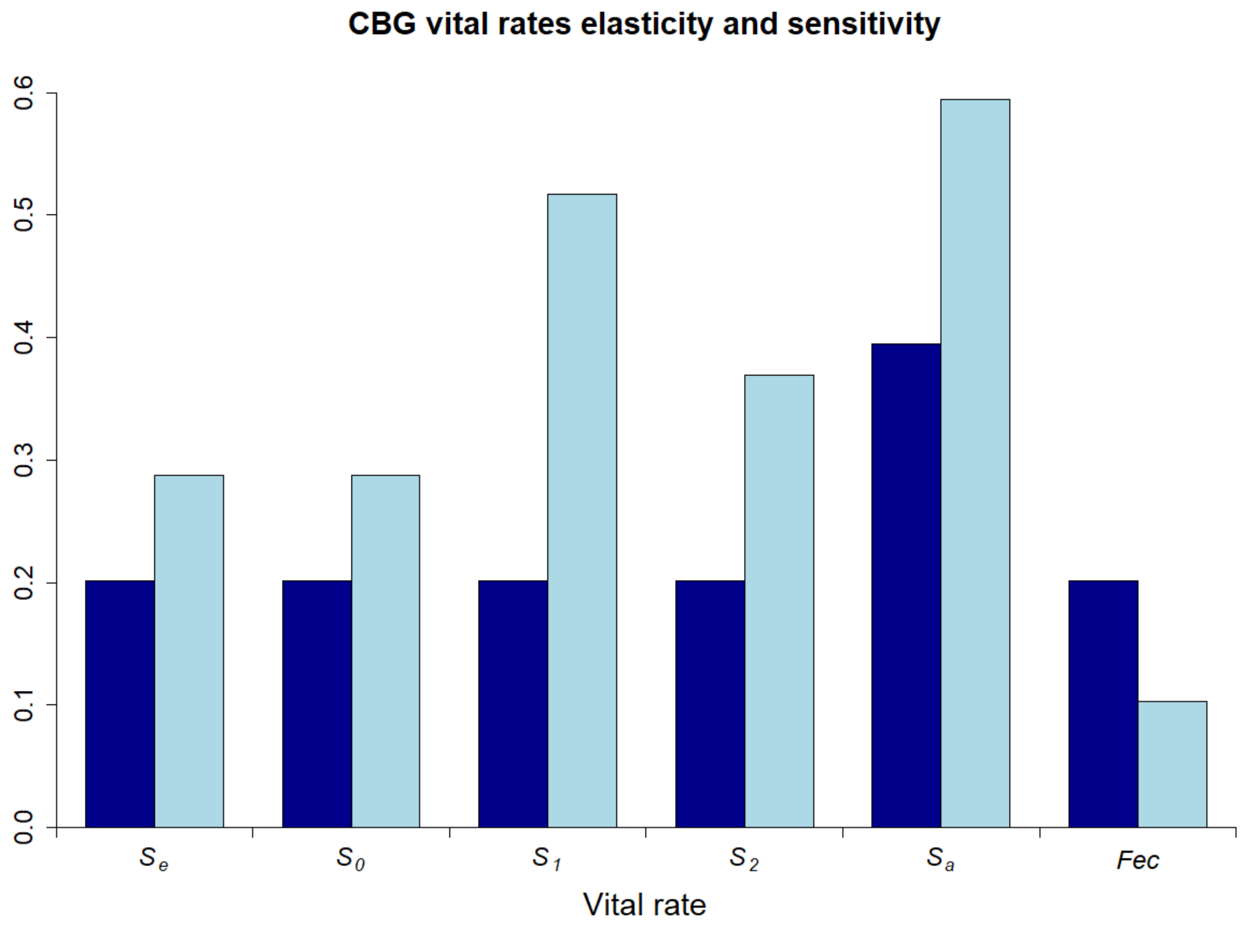

Figure 16. Sensitivity analysis for the CBG model using Set 3 with a growth rate of 1.39: elasticity analysis (dark blue – sensitivity of the growth rate to proportional change in the vital rates of survival and fecundity); and sensitivity analysis (light blue – sensitivity of the growth rate to the absolute change in the vital rates of survival and fecundity).

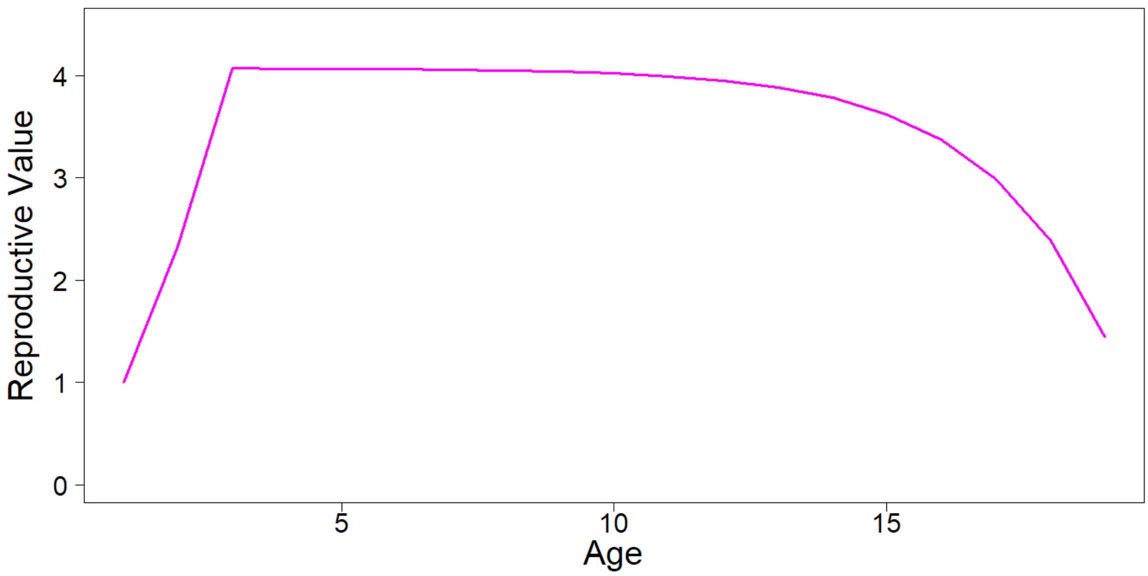

Figure 17. Reproductive value from the CBG model using Set 3 with a growth rate of 1.39.

4 Discussion

4.1 Insights from the metapopulation model

We developed a metapopulation model to examine management options for the control of the overabundant native species Cape Barren Geese on Phillip Island. The metapopulation model was constructed with three populations representing Phillip Island, French Island, and a third mainland population we labelled Bass Coast. We considered a mix of control options that included removal of winter flock geese, egg removal, and gosling removal (in various combinations). Model parameters were derived from (limited) available data and expert input, and the model was calibrated with a long-term data set comprising population counts on Phillip Island and observed immigration to French Island. We modelled population trajectories from 1993 to 2065, with fox predation on goslings reducing to zero between 2006 and 2015 and control options for overabundant Cape Barren Geese beginning in 2025. We assessed control options using several population metrics (Phillip Island Total Population, Winter Flock, Emigrants, Nesting Population) and defined 3 different targets (acute, moderate, and relaxed) for a successful strategy compared with the mean of the 2065 level of the metric examined for Phillip Island. Successful control strategies included winter flock removal on both Phillip Island and French Island (at least 500 individuals removed from each island), with lower rates of winter flock removal needing to be supplemented with egg or fledging removal.

Our modelling shows that there are clear consequences of not implementing management actions to control the Cape Barren Geese populations on both Phillip Island and French Island. Populations are likely to remain high and may continue to increase, resulting in continuing impacts on agriculture and protected wildlife such as impacting on nesting sites of the Little Penguin. Targeting Phillip Island but not French Island did not result in successful control of overabundant Cape Barren Geese (as per the criteria outlined in the previous paragraph). Although control efforts on Phillip Island alone did reduce the winter flock population on Phillip Island (under some scenarios; Table 5), none of these strategies significantly reduced the winter flock population on French Island or the nesting population on either Phillip Island or French Island. Under Scenario 3 (removing all winter flock on Phillip Island), requires the ongoing removal of approx. 800 winter flock per year on Phillip Island (confidence interval: [323.85, 1173.10]) to maintain winter flock levels (i.e., winter flock levels remained at approximately 800 individuals for all modelled years). Under Scenario 4 (removal of up to 4 eggs per nest and 500 winter flock per year on Phillip Island), requires the ongoing removal of approx. 470 winter flock per year [291.90, 500] and 290 eggs per year [204, 352] to maintain winter flock levels. These values were approx. 500 winter flock [248.95, 850.05] and approx. 280 eggs [191.80, 348] per year under Scenario 5 (removal of up to 4 eggs per year and all winter flock on Phillip Island). Equivalent control options but with removals on both Phillip Island and French Island reduced the level of ongoing winter flock and egg removals required to maintain winter flock levels (e.g., 800 removals under S3 vs 635 under S11). These results indicate that implementing controls on both Phillip Island and French Island is necessary for successful control and may have the added benefit of reducing the required effort for ongoing control measures.

There are methods immediately available for controlling Cape Barren Geese, such as culling via the use of Authority to Control Wildlife (subject to an application and assessment process by the regulator). By contrast, egg or gosling management (intended to reduce recruitment to the winter flock) would need to be demonstrated to be humane and effective via a research project before permissions may be considered as part of a management plan. However, egg or gosling management warrants consideration given our finding that combining winter flock removals with egg or gosling removals reduced the predicted number of winter flock that needed to be removed to achieve successful control. The removal of winter flocking geese requires the shooting of geese, and a potentially large number of geese may need to be removed to maximise the likelihood of successful control. For example, Scenario 8 targets up to 750 winter flock per year, whereas Scenarios 12 and 18 (which include egg or gosling removals) achieve equivalent or better outcomes but only target up to 500 winter flock per year (Figures 12–15). Shooting many geese may be problematic, particularly on Phillip Island with its high tourism exposure, and shooting may disperse geese, making it harder to achieve necessary targets. Therefore, control options that reduce the number of winter flock removals may be beneficial. However, control options aiming to reduce recruitment also present challenges. Hoysted et al. (1981) noted that the slightest interference will cause Cape Barren Geese to abandon their nests, and Guiler (1967) observed that nests from which eggs were removed were renovated or rebuilt nearby by the parents, followed by a further laying. Guiler (1967) made the additional observation that if one egg was left in the nest the parents did not rebuild. Alongside gosling removal, an alternative to egg removal is to cause egg death (e.g., by puncturing eggs or covering eggs in oil to block respiratory gas exchange) but leaving the dead eggs in situ to avoid nest abandonment or rebuilding (Curtis and Braband 2022). Alternatively, removed eggs can be replaced with fake eggs (Curtis and Braband 2022).

The model was constructed with Cape Barren Geese control beginning in 2025 on Phillip Island and in 2030 on French Island. Of the control scenarios predicted to be successful, the time taken to achieve success extends out to approximately 2045 in most cases. These outcomes indicate that control strategies for Cape Barren Geese on both Phillip Island and French Island may not achieve “success” for several decades. That is, control of Cape Barren Geese is not likely to be a short-term intervention and is dependent on ongoing control measures. The estimated reproductive value of Cape Barren Geese populations would suggest that the species has a very high reproductive capacity, such that populations can increase rapidly in the absence of control, particularly given the response of the Phillip Island population when fox control was introduced (Figure 3). Therefore, control of Cape Barren Geese is an ongoing challenge, noting that the effort required to maintain control may be relatively low after population numbers are reduced from their current high levels.

We did not consider the potential costs of different control options in our analysis. Doing so would support a cost-benefit analysis of the different strategies, which would provide an additional level of insight into the (cost) effectiveness of the proposed options. One study examining the costs of egg oiling compared with culling adults and fledglings found there was considerable variation in the costs of bird control (McGregor and Davis 2012). This study found that the start-up costs to establish a culling program were high compared with oiling eggs and, as populations decreased in abundance, culling became more expensive (McGregor and Davis 2012). Although we did not formally consider the costs of different strategies, it is relatively straightforward to assess strategy outcomes against estimated costs of implementation (e.g., as in our previous work modelling over-abundant koalas; Todd et al. 2008).

4.2 Recommendations for future data collection

When managers are required to make decisions about how to manipulate natural systems in the face of uncertainty, a natural framework for learning about how the system might respond is adaptive management (Walters and Holling 1990; Gerber and Kendall 2018). Adaptive management aims to improve decision-making around natural resources by decreasing the uncertainty about how systems respond to management. The model we have developed is information-rich, with several parameters that can be used to assess model accuracy and/or guide calibration. Ideally, models should be updated as new information comes to hand, particularly when used in an adaptive management framework (Bearlin et al. 2002, Schreiber et al. 2004). Adaptive management of Cape Barren Geese populations would be supported by monitoring of the populations on both Phillip and French Islands (winter flock, breeding birds, and total population), developing a protocol to undertake nest counts (e.g., using drone flyovers), and a mark-recapture study to estimate survival rates and movement probabilities (including emigration rates and destinations). The information gained from these activities would support an assessment of any control strategy adopted and would also inform estimates of important population model parameters.

Based on the above findings, we provide the following recommendations for data collection and monitoring:

1. Monitoring of the total population on Phillip Island (ongoing)
2. Monitoring of the winter flock on Phillip Island (ongoing) if this the decision metric for assessing the effectiveness of control
3. Urgent monitoring of the total population on French Island to establish its size and potential and then ongoing monitoring
4. Monitoring of the winter flock on French Island (ongoing) if this the decision metric for assessing the effectiveness of control
5. Nest counts on both Phillip Island and French Island. Nest counts will help identify the Nest Threshold and therefore provide an estimate of an important parameter used in the population model. Nest counts will also be beneficial in setting egg or gosling removal targets if using a combined control strategy. Note that a sampling technique will be required to be developed to conduct nest counts that do not disturb nesting geese for example the use of drones to take pictures and using computer analysis to determine nest locations.
6. Studies to quantify emigration rates and destination
7. Establish a mark-recapture program. Mark-recapture data can provide estimates of survival rates of different age classes, including juveniles, which are important to understanding the population growth rate and dynamics. In addition, a mark-recapture program can provide estimates of the rate at which juveniles transition to breeding territories (in conjunction with nest counts would be very informative about density dependence).

The above monitoring would resolve several uncertainties surrounding the Cape Barren Geese population on Phillip Island but does not explicitly inform the natural carrying capacity of CBG on Phillip Island. It is not unusual to contemplate what the natural Cape Barren Geese carrying capacity of Phillip Island might be. This, however, is the wrong concept to be considering. Both Phillip Island and French Island present modified habitat that greatly suits the life cycle of Cape Barren Geese and it is likely that both islands can support large populations and therefore maintain high impacts on agriculture and the habitat of protected wildlife. Consequently, the natural carrying capacity is likely to be quite high for Phillip Island, particularly due to potential immigration from French Island or the Bass Coast. Carrying capacity is likely to at least match current numbers (if not higher under a scenario with a large Cape Barren Geese population on French Island). Therefore, the goal of a control strategy is to artificially reduce the carrying capacity, and artificially reduce recruitment, to a level that is acceptable to stakeholders. Resolving the natural carrying capacity (in the absence of control) seems less important than determining stakeholder tolerance to different levels of impact from Cape Barren Geese.

4.3 Conclusions

Cape Barren Geese on Phillip Island will likely continue to increase, providing emigrants to other areas. Based on these findings, we provide the following recommendations and key findings:

1. Control should be implemented immediately if the Cape Barren Geese population on Phillip Island and the winter flock are to remain below current levels. Not implementing control options immediately is expected to lead to an increase in the number of Cape Barren Geese on Phillip Island, including the winter flock (approaching 3500 birds by 2025 under the current model assumptions).
2. If control is implemented immediately, the population on Phillip Island may be reduced to desirable levels by 2045. Reducing the Phillip Island population to desirable levels is contingent on removal of at least 500 winter flock per year (when combined with egg or gosling removals) or at least 750 winter flock per year (without egg or gosling removals). Importantly, reductions to desirable levels requires control measures on both Phillip Island and French Island.
3. Following successful control (e.g., reducing the Phillip Island population below 2005 levels), ongoing control measures will be required to maintain population numbers (particularly the winter flock) at these levels. Cape Barren Geese have a high capacity for population growth, which would suggest that numbers would increase rapidly if control were ceased. However, ongoing control measures may not need to remain at the levels used during the initial period of control (e.g., > 500 winter flock removed per year), with ongoing removals of 200–400 winter flock and 80–95 eggs or goslings per year predicted to maintain populations on Phillip Island and French Island.
4. A mix of control strategies was predicted to be successful, with egg and gosling removals reducing the culling rate of winter flock required to achieve successful control. We did not model the logistics of different strategies but note that culling can be implemented now (subject to an application and assessment process by the regulator), whereas egg or gosling management would require targeted research to demonstrate that the methods used are humane and effective (required before approvals can be sought to implement these methods).
5. Ongoing monitoring of the population of Cape Barren Geese on Phillip Island and increased monitoring of the French Island population are critical to refine current population estimates, establish baselines for any control measures, and assess the effectiveness of any implemented control actions. In particular, French Island may contribute significant numbers of Cape Barren Geese to the wider meta-population in coming years and requires immediate population assessment and management. Essential monitoring approaches are annual counts of the total population and winter flock, and potential additional targets for monitoring are nest counts (e.g., with drone flyovers and image analysis) and mark-resight/recapture studies to estimate survival rates, emigration rates and destinations (e.g., with a mark-recapture program), transition rates of juveniles to breeding territories, and density-dependent feedback.
6. Update the population model, in an adaptive management cycle, as new data and information are obtained through monitoring and further research.

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Appendix: Supplementary Figures

Implementing control strategies on Phillip Island only

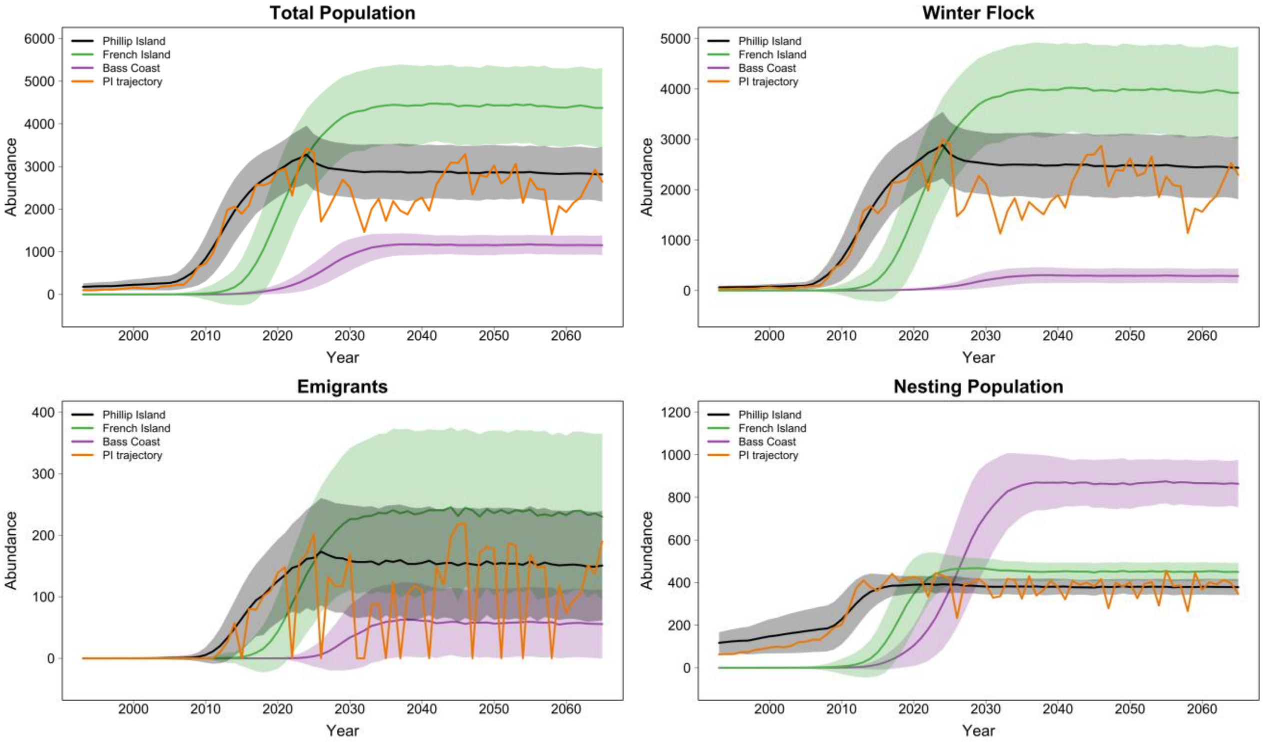

Figure A1. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S1 (Phillip Island: removal of 4 eggs from 40% of nests per year; French Island: no control).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

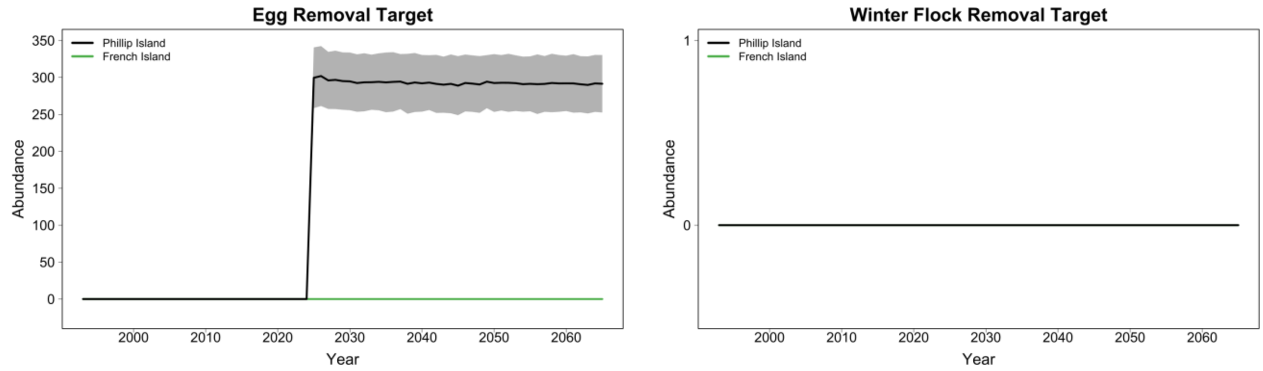

Figure A2. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S1 (Phillip Island: removal of 4 eggs from 40% of nests per year; French Island: no control).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

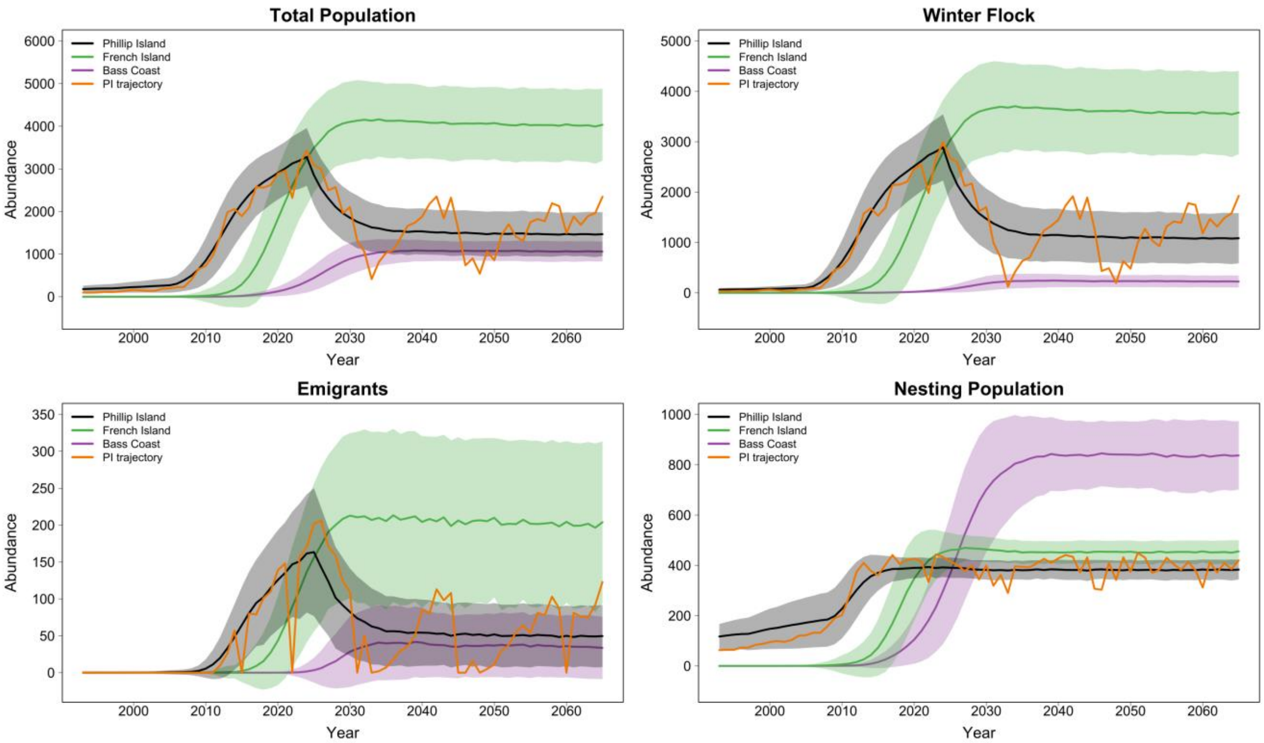

Figure A3. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S2 (Phillip Island: removal of up to 500 winter flock geese per year; French Island: no control).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

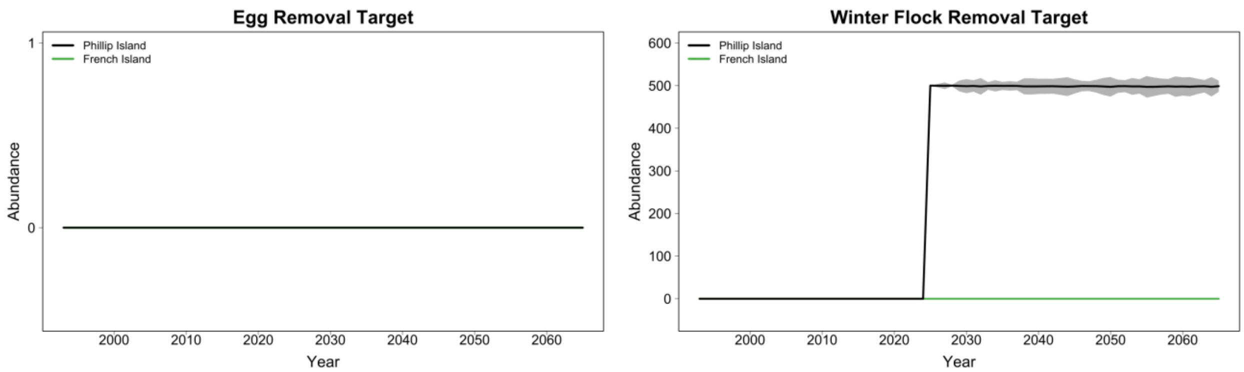

Figure A4. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line), under control scenario S2 (Phillip Island: removal of up to 500 winter flock geese per year; French Island: no control).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

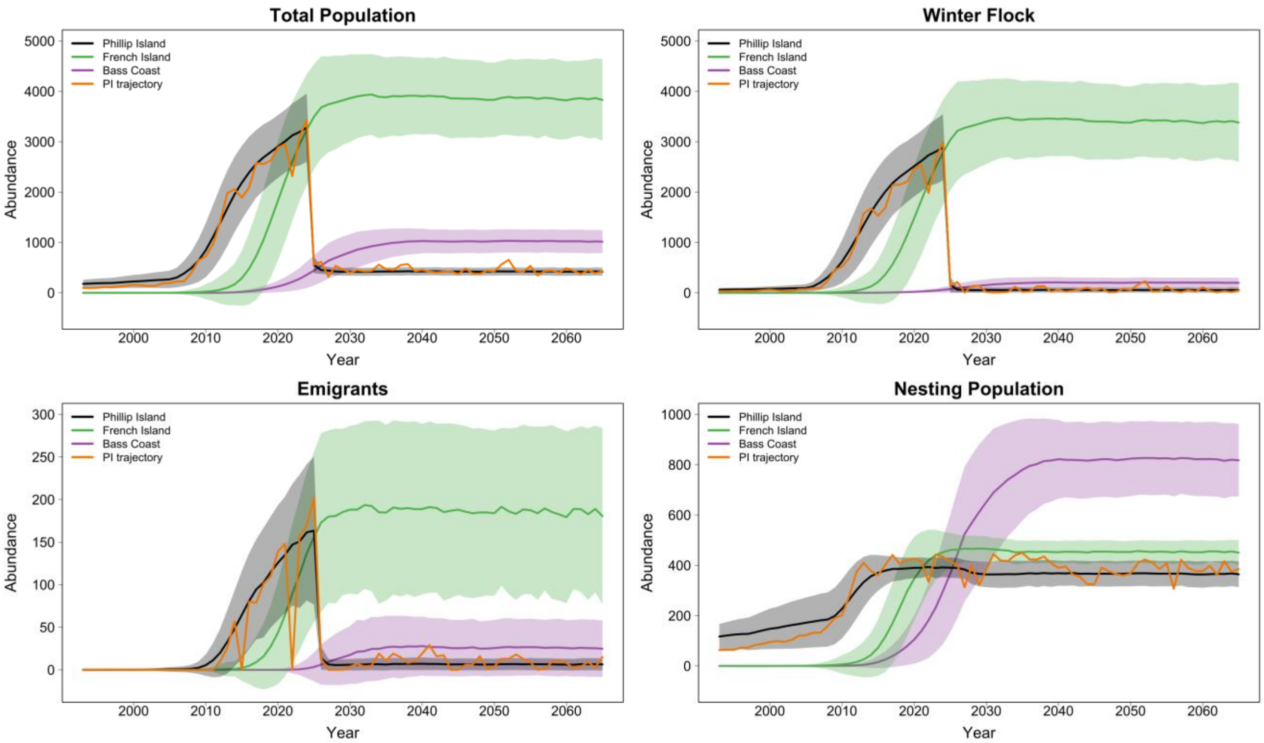

Figure A5. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S3 (Phillip Island: removal of all winter flock geese per year; French Island: no control).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

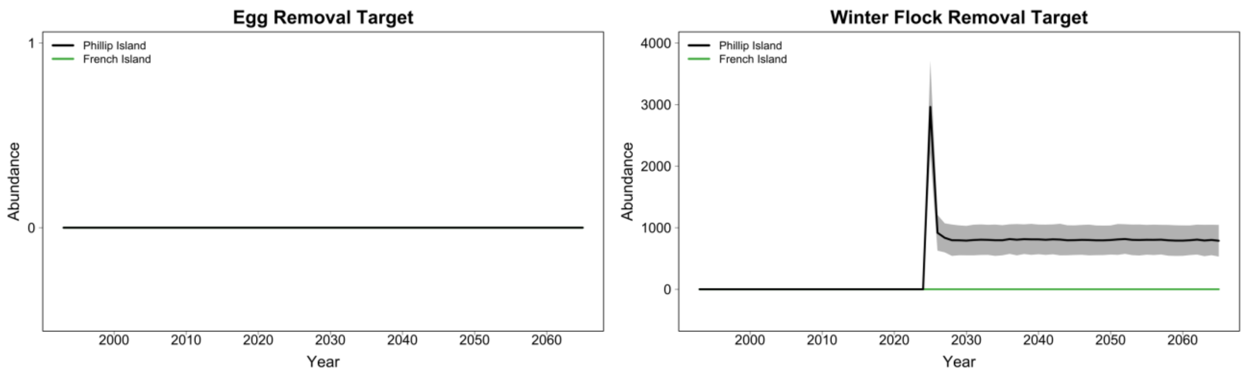

Figure A6. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S3 (Phillip Island: removal of all winter flock geese per year; French Island: no control).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

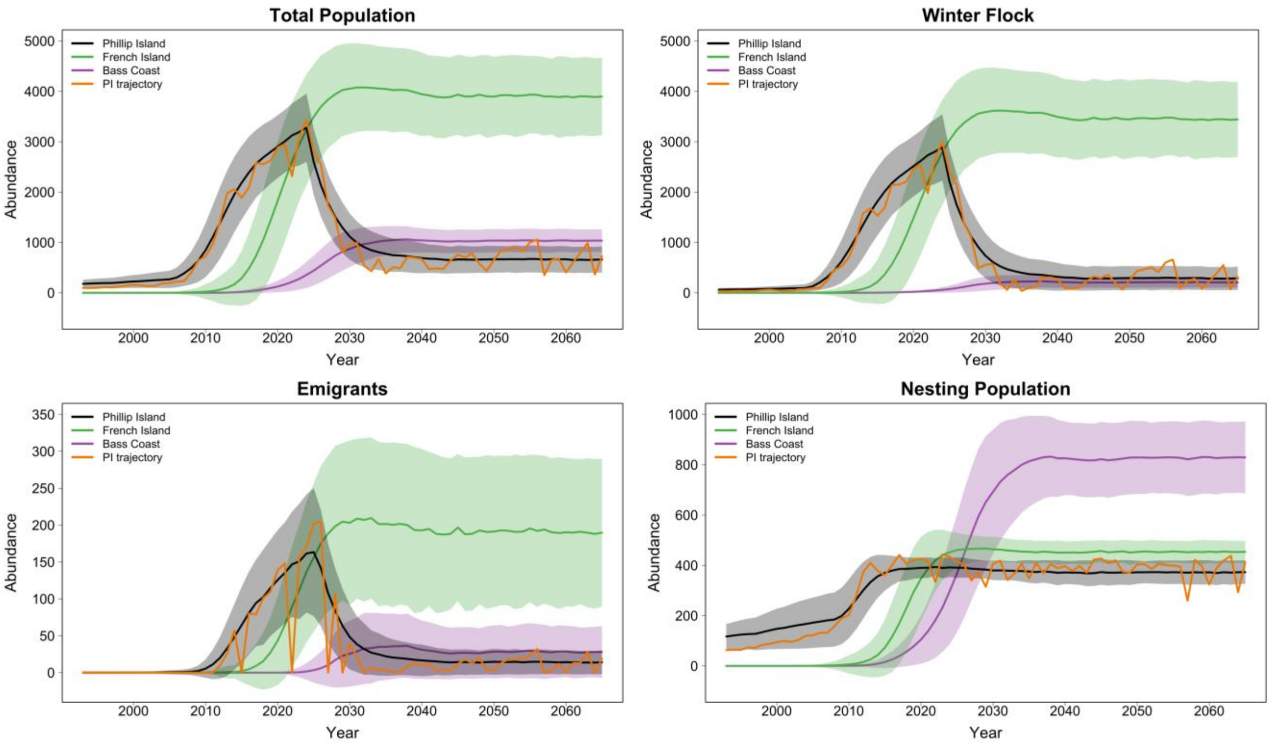

Figure A7. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S4 (Phillip Island: removal of 4 eggs from 40% of nests and removal of up to 500 winter flock geese per year; French Island: no control).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

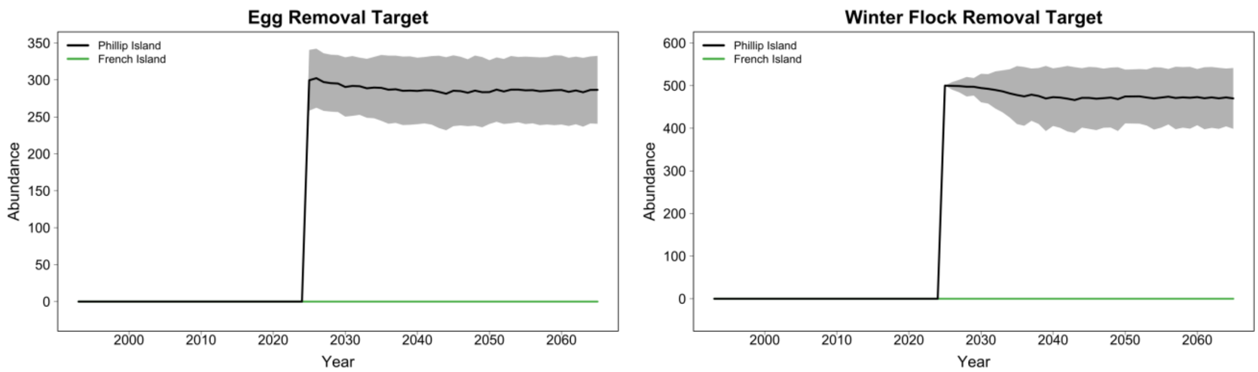

Figure A8. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S4 (Phillip Island: removal of 4 eggs from 40% of nests and removal of up to 500 winter flock geese per year; French Island: no control).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

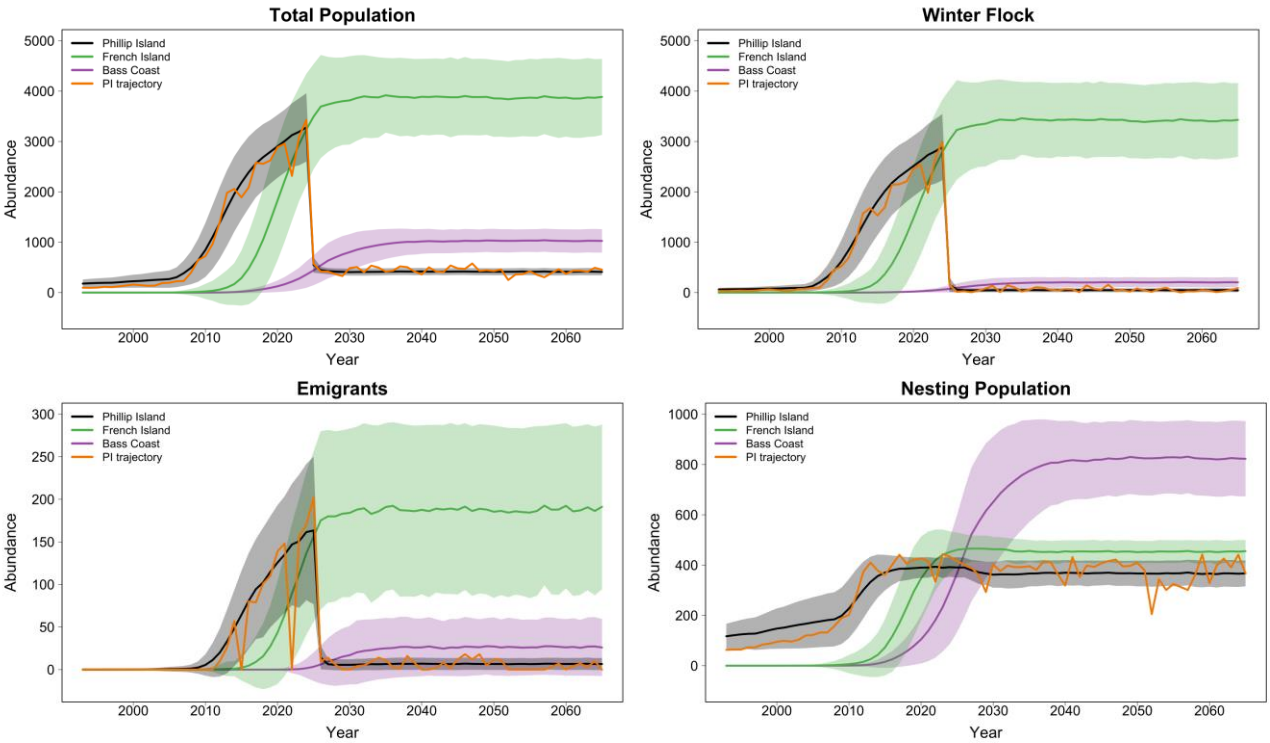

Figure A9. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S5 (Phillip Island: removal of 4 eggs from 40% of nests and all winter flock geese per year; French Island: no control).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

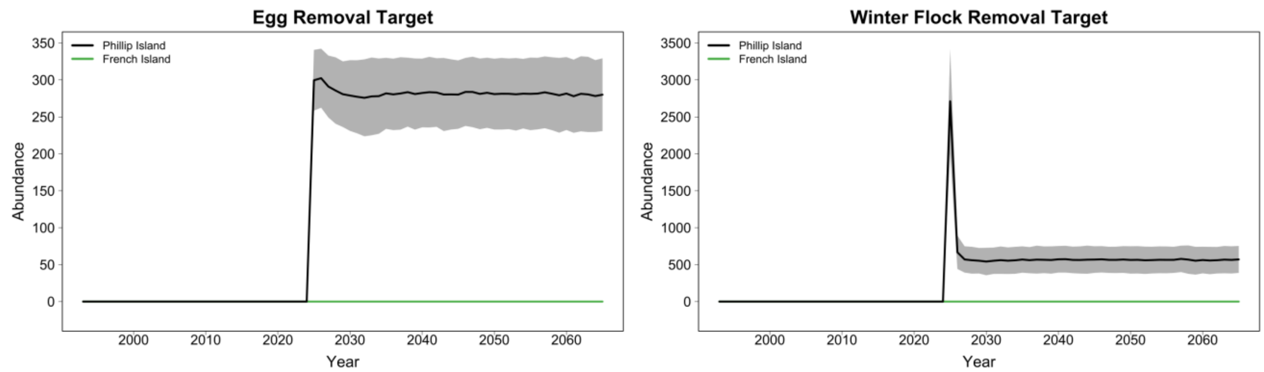

Figure A10. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S5 (Phillip Island: removal of 4 eggs from 40% of nests and all winter flock geese per year; French Island: no control).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

Implementing winter flock removal strategies on Phillip Island and French Island

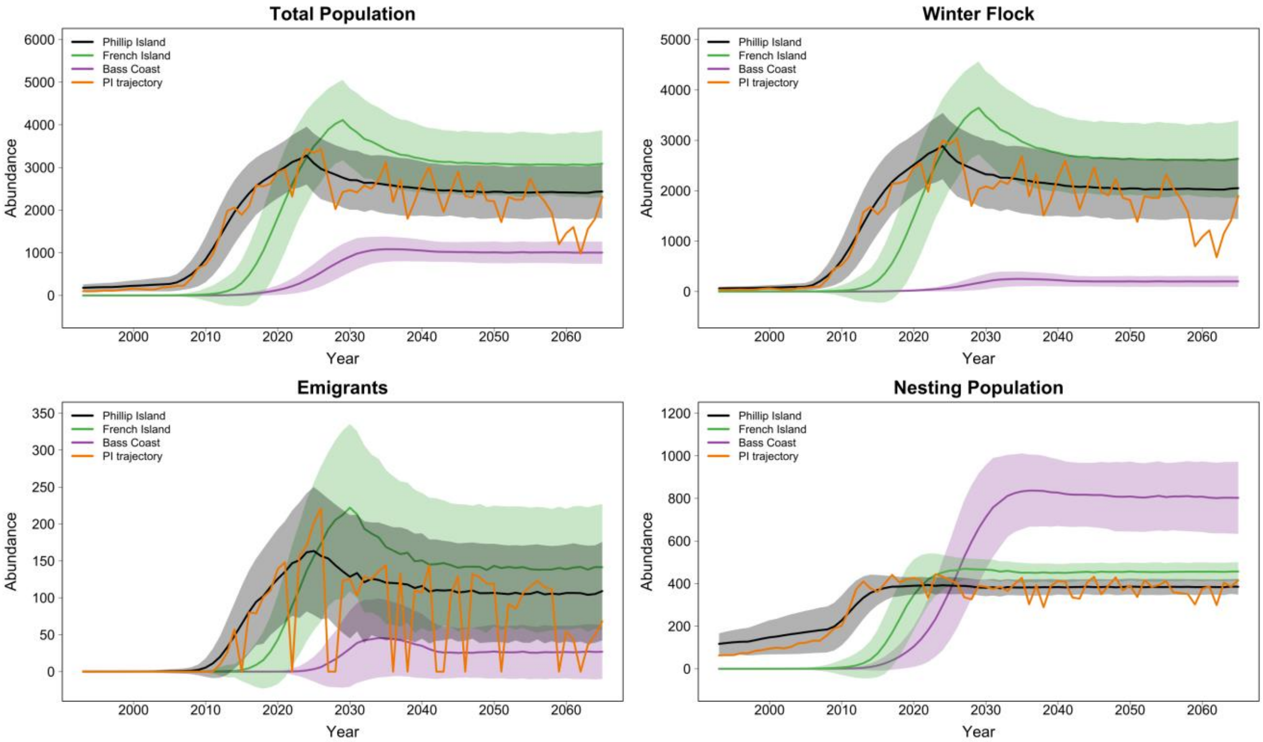

Figure A11. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S6 (Phillip Island and French Island: removal of up to 250 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

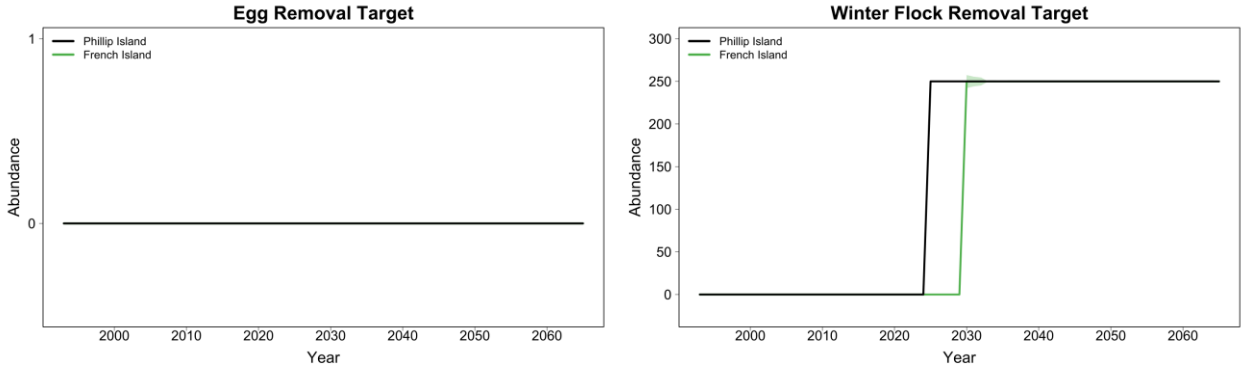

Figure A12. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S6 (Phillip Island and French Island: removal of up to 250 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

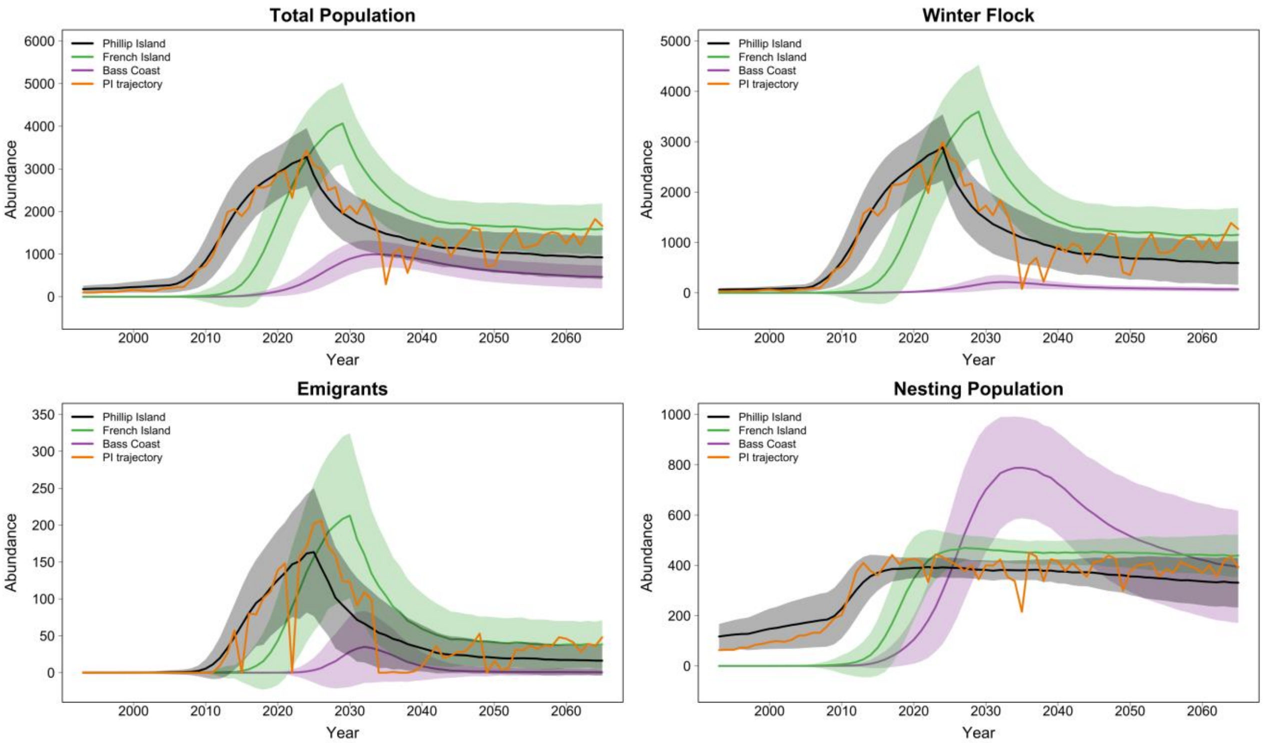

Figure A13. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S7 (Phillip Island and French Island: removal of up to 500 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

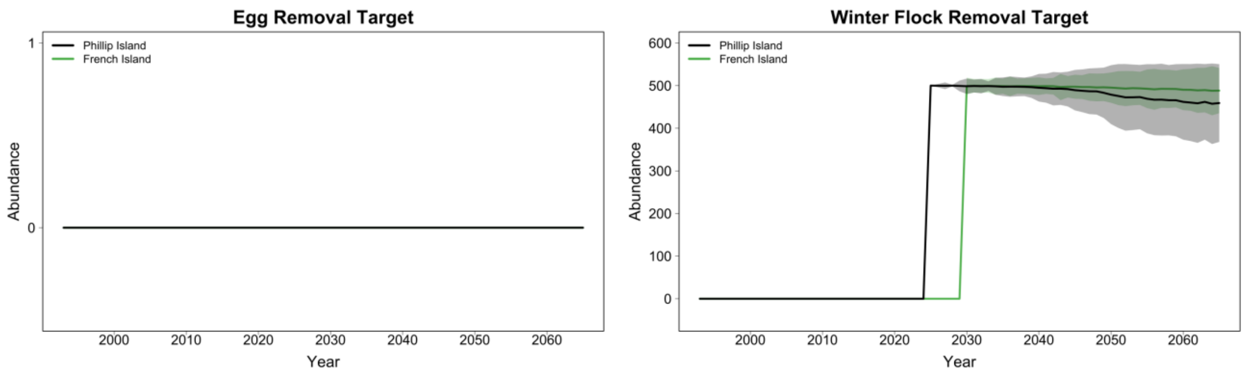

Figure A14. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S7 (Phillip Island and French Island: removal of up to 500 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

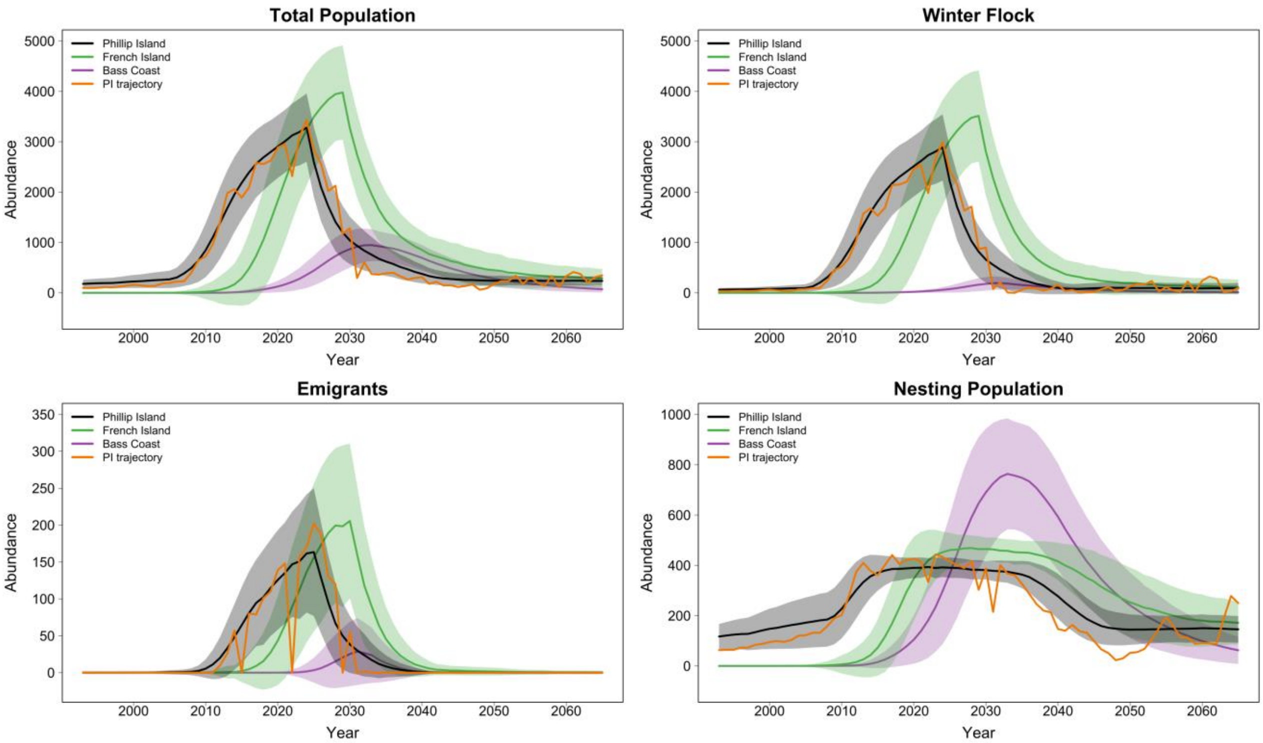

Figure A15. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S8 (Phillip Island and French Island: removal of up to 750 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

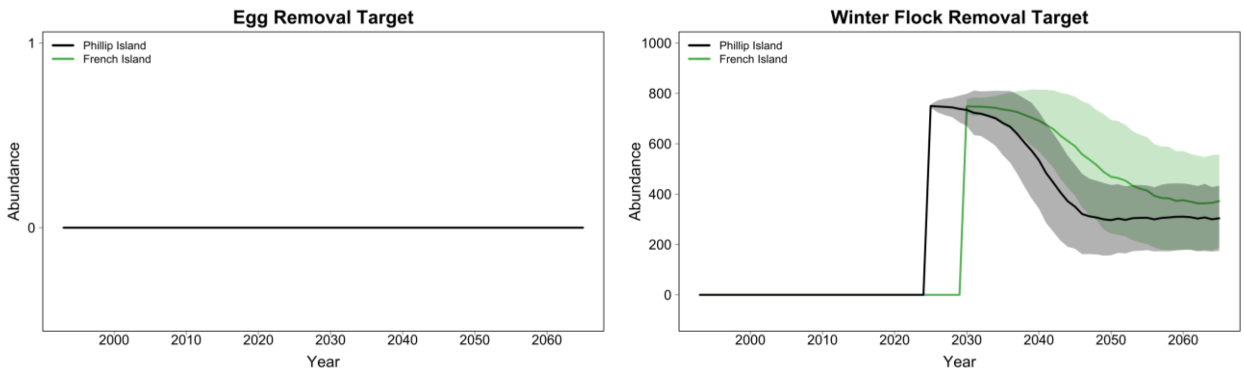

Figure A16. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S8 (Phillip Island and French Island: removal of up to 750 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

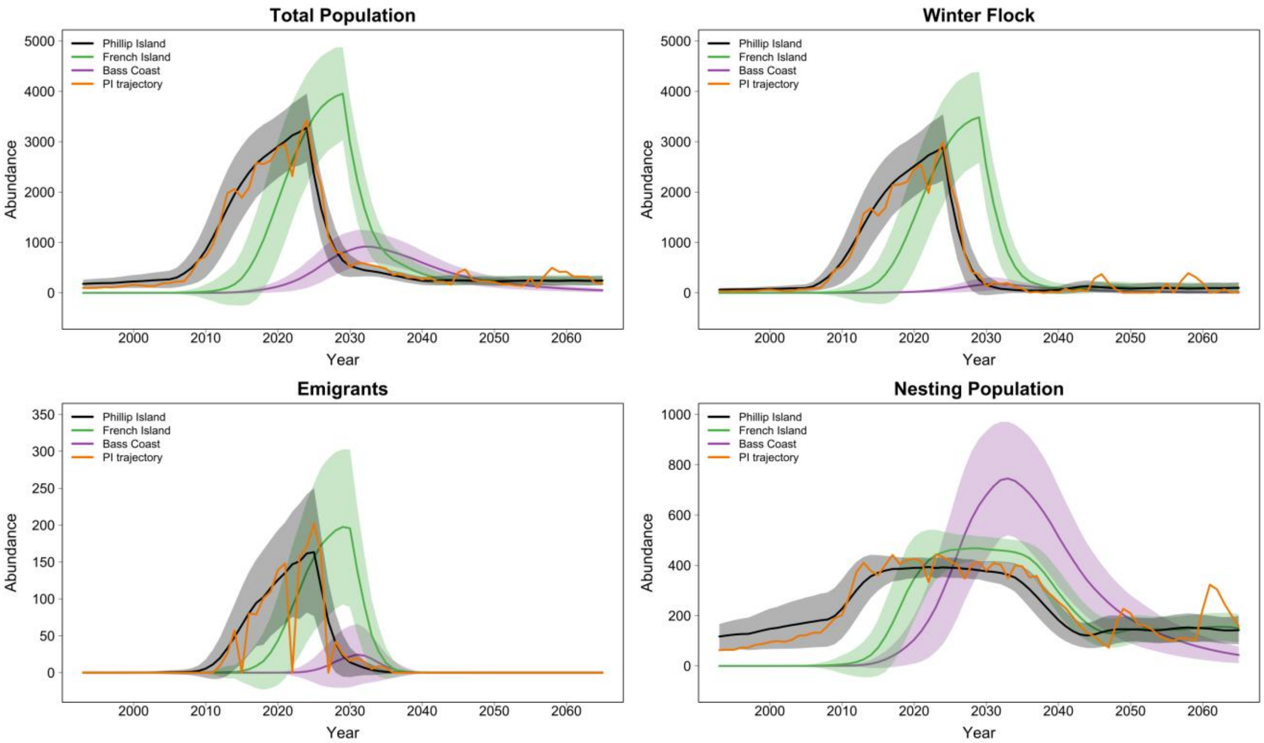

Figure A17. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S9 (Phillip Island and French Island: removal of up to 1000 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

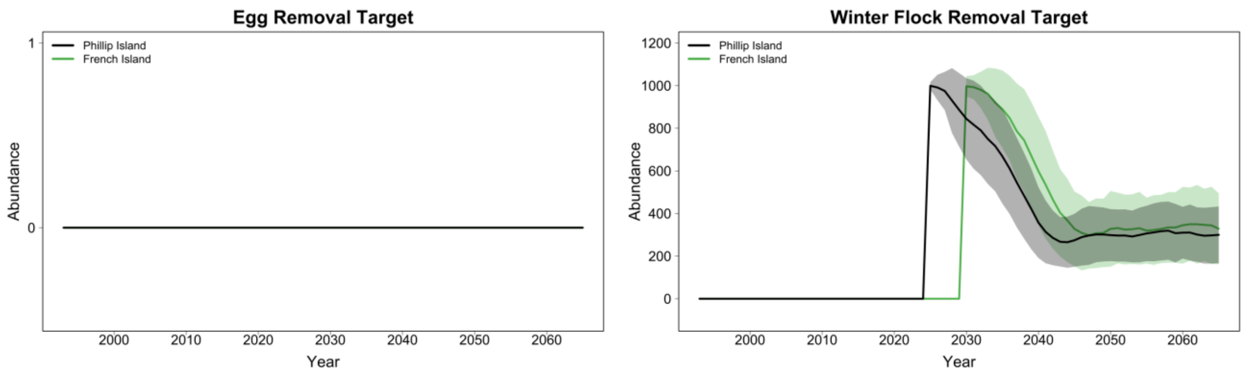

Figure A18. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S9 (Phillip Island and French Island: removal of up to 1000 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

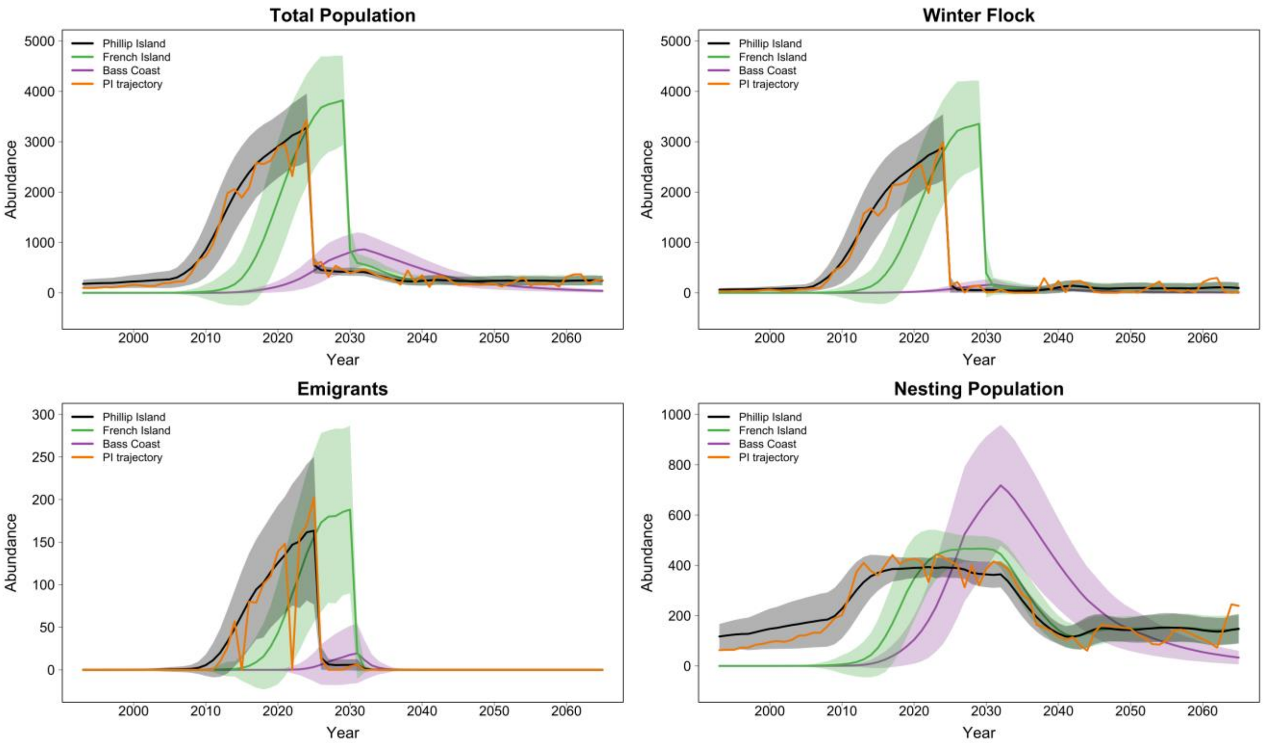

Figure A19. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S10 (Phillip Island and French Island: removal of all winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

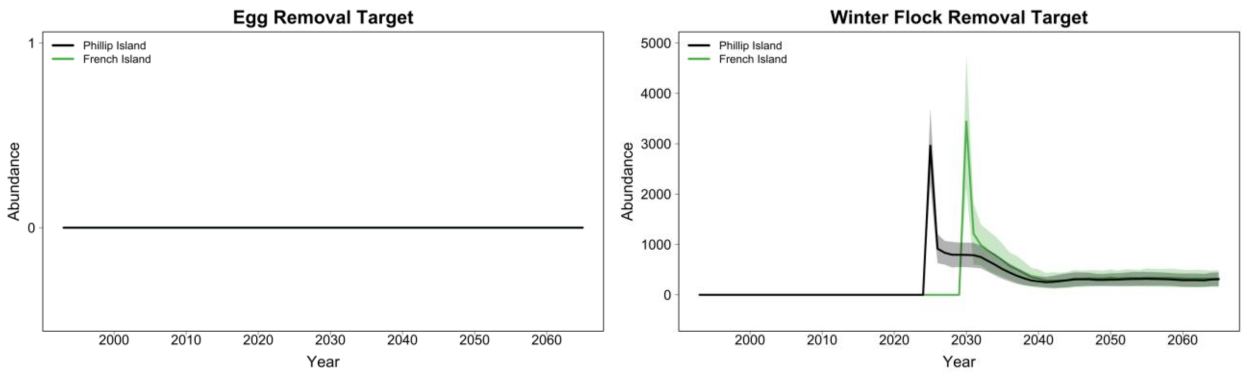

Figure A20. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S10 (Phillip Island and French Island: removal of all winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

Implementing combined egg and winter flock removal strategies on Phillip Island and French Island

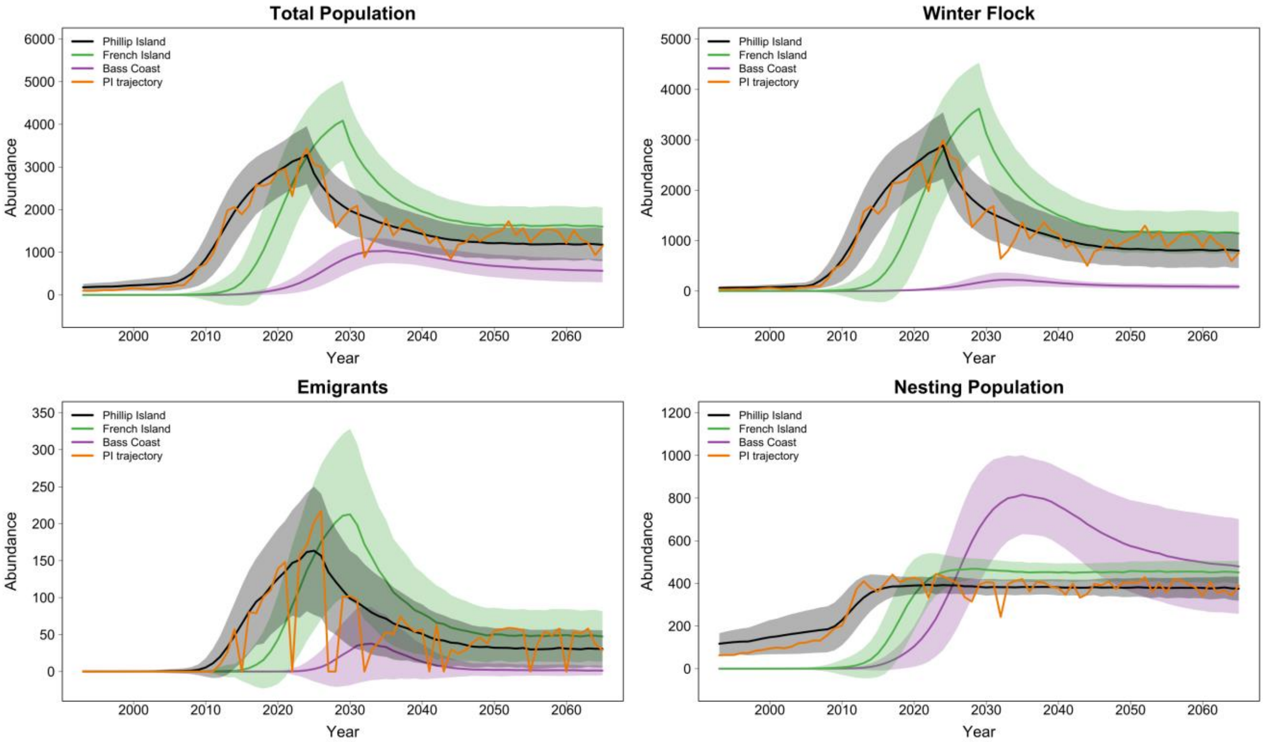

Figure A21. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S11 (Phillip Island and French Island: removal of 4 eggs from 40% of nests and removal of up to 250 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

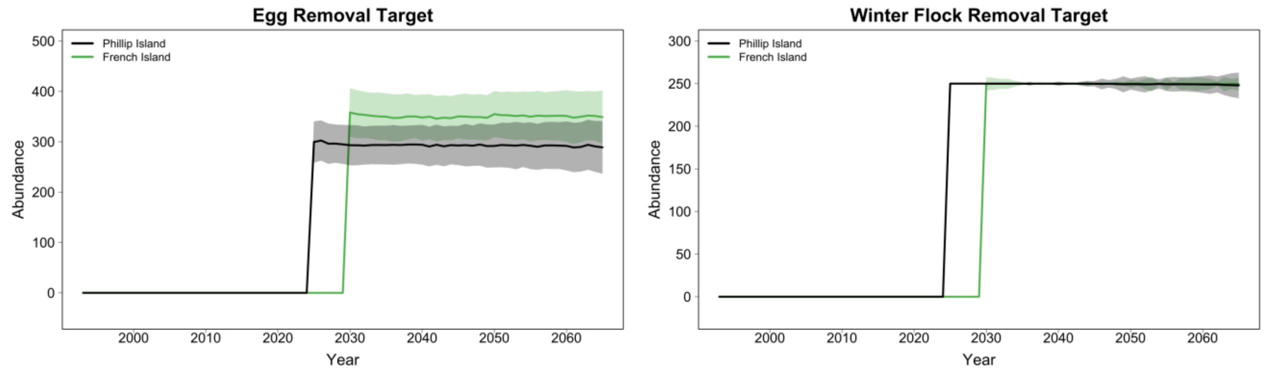

Figure A22. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S11 (Phillip Island and French Island: removal of 4 eggs from 40% of nests and removal of up to 250 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

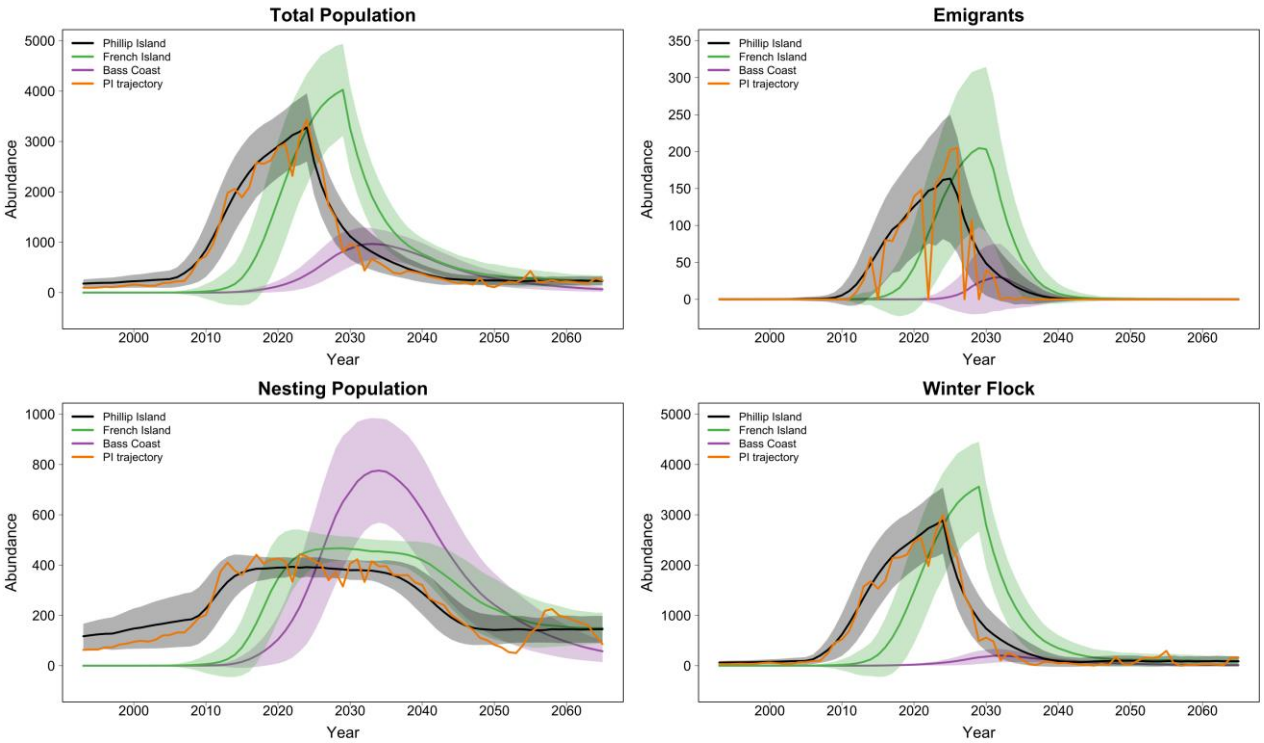

Figure A23. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S12 (Phillip Island and French Island: removal of 4 eggs from 40% of nests and removal of up to 500 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

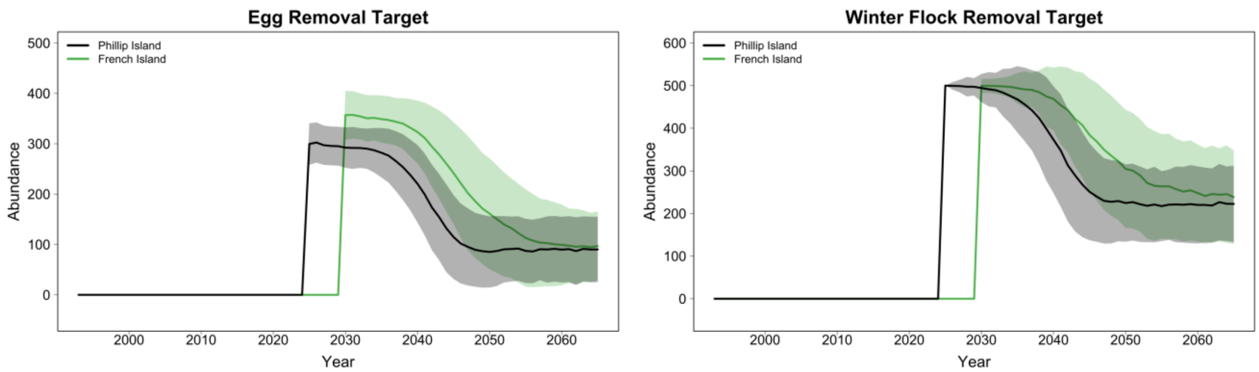

Figure A24. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S12 (Phillip Island and French Island: removal of 4 eggs from 40% of nests and removal of up to 500 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

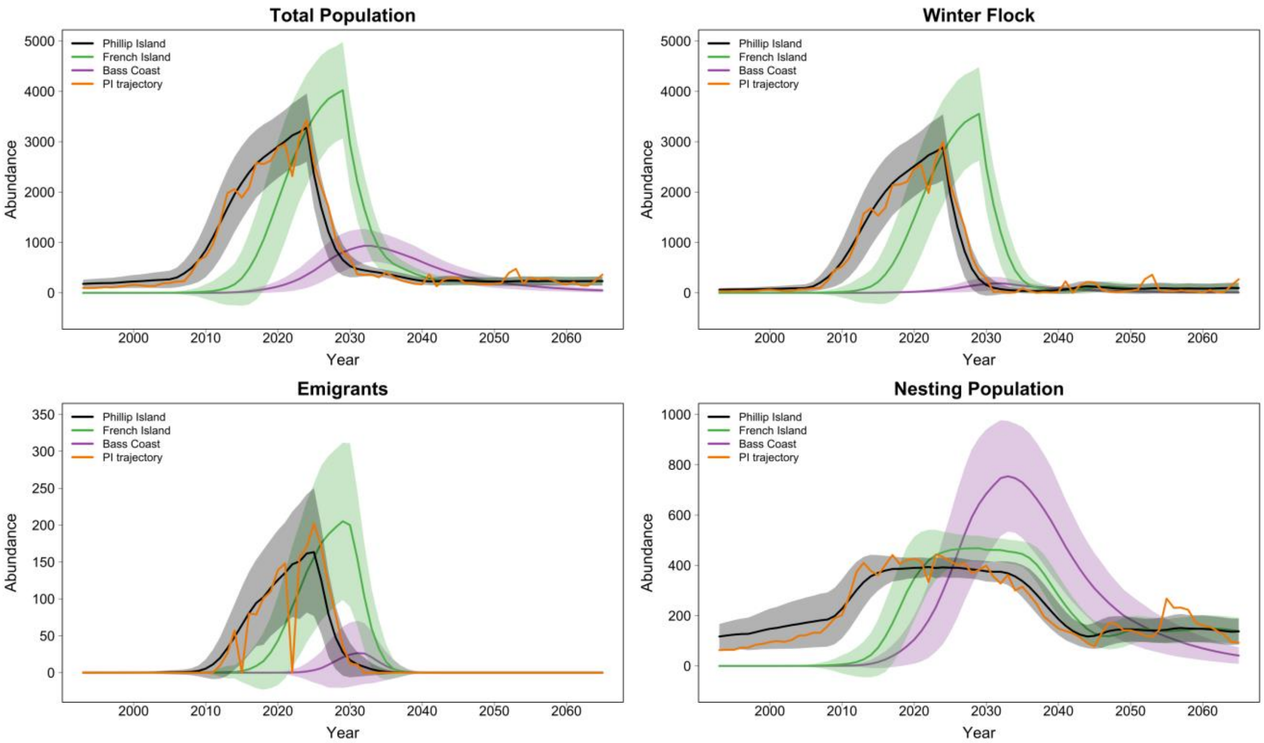

Figure A25. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S13 (Phillip Island and French Island: removal of 4 eggs from 40% of nests and removal of up to 750 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

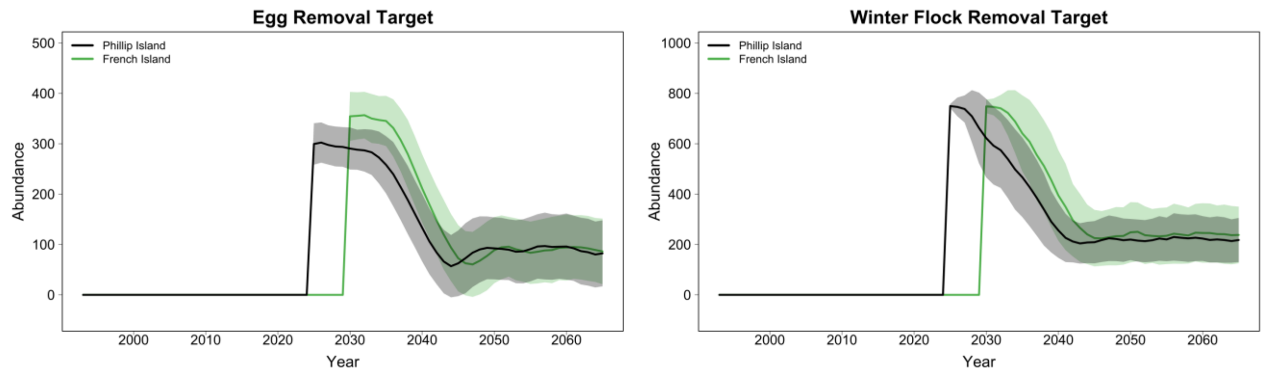

Figure A26. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S13 (Phillip Island and French Island: removal of 4 eggs from 40% of nests and removal of up to 750 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

Implementing egg and winter flock removal strategies on Phillip Island and removing all winter flock on French Island

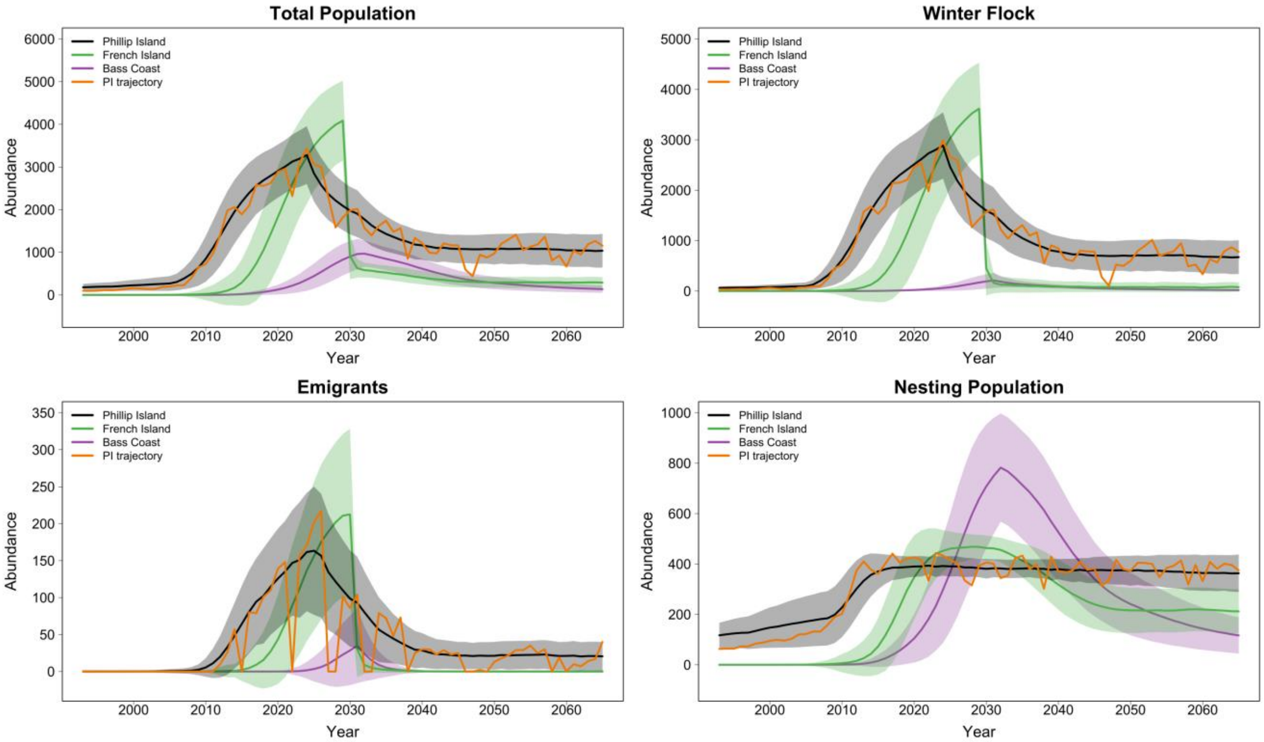

Figure A27. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S14 (Phillip Island: removal of 4 eggs from 40% of nests and culling up to 250 winter flock geese per year; French Island: removal of all winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

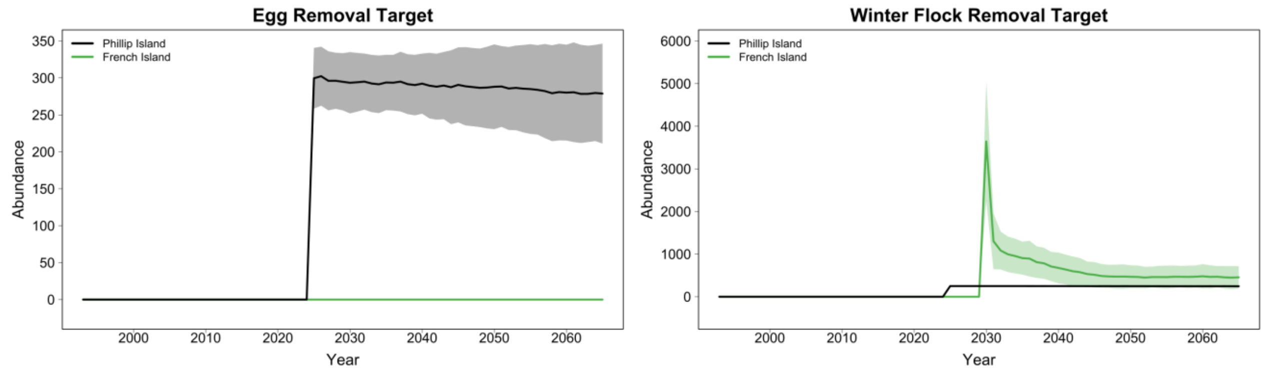

Figure A28. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S14 (Phillip Island: removal of 4 eggs from 40% of nests and culling up to 250 winter flock geese per year; French Island: removal of all winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

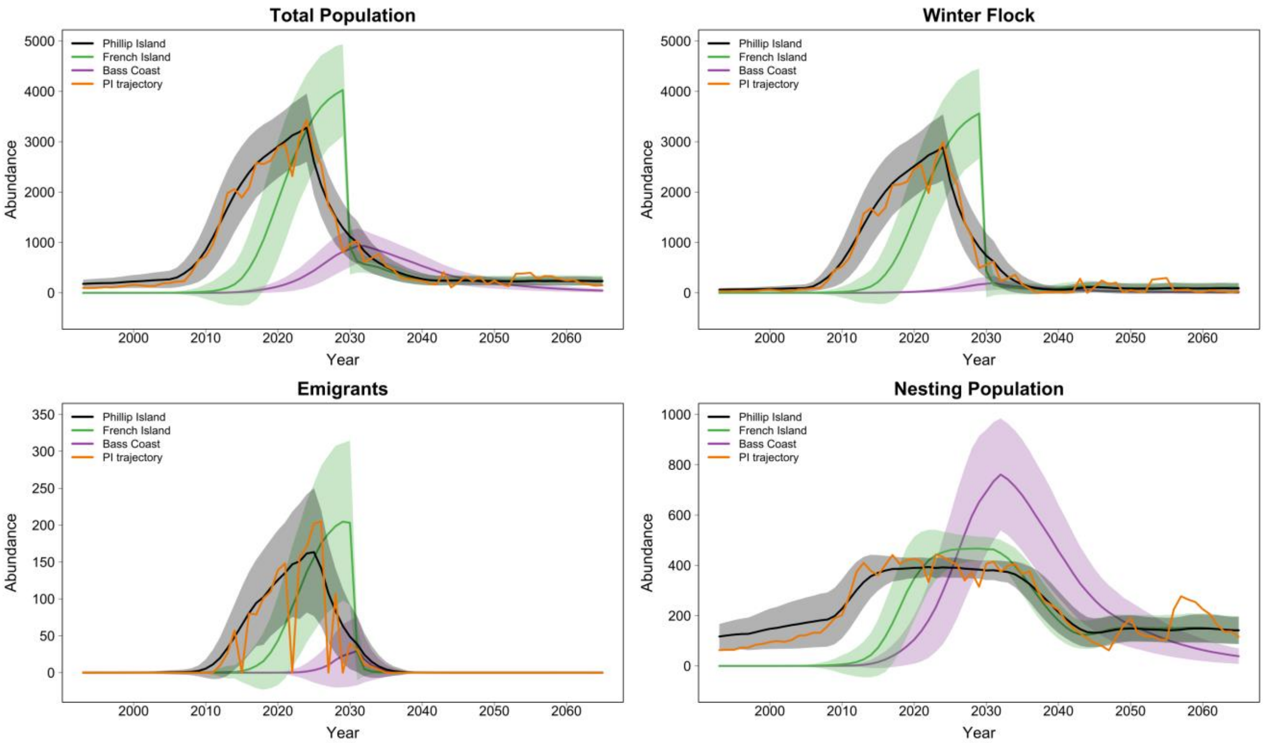

Figure A29. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S15 (Phillip Island: removal of 4 eggs from 40% of nests and culling up to 500 winter flock geese per year; French Island: removal of all winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

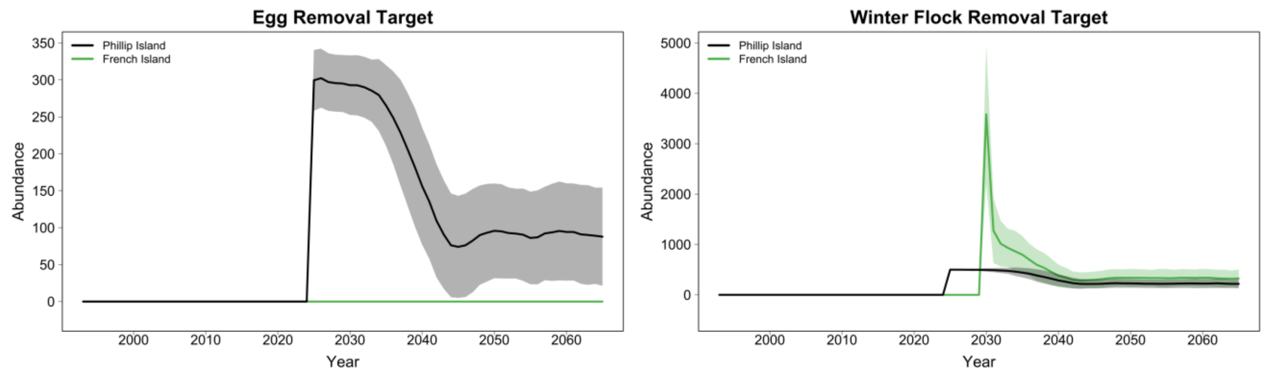

Figure A30. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S15 (Phillip Island: removal of 4 eggs from 40% of nests and culling up to 500 winter flock geese per year; French Island: removal of all winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

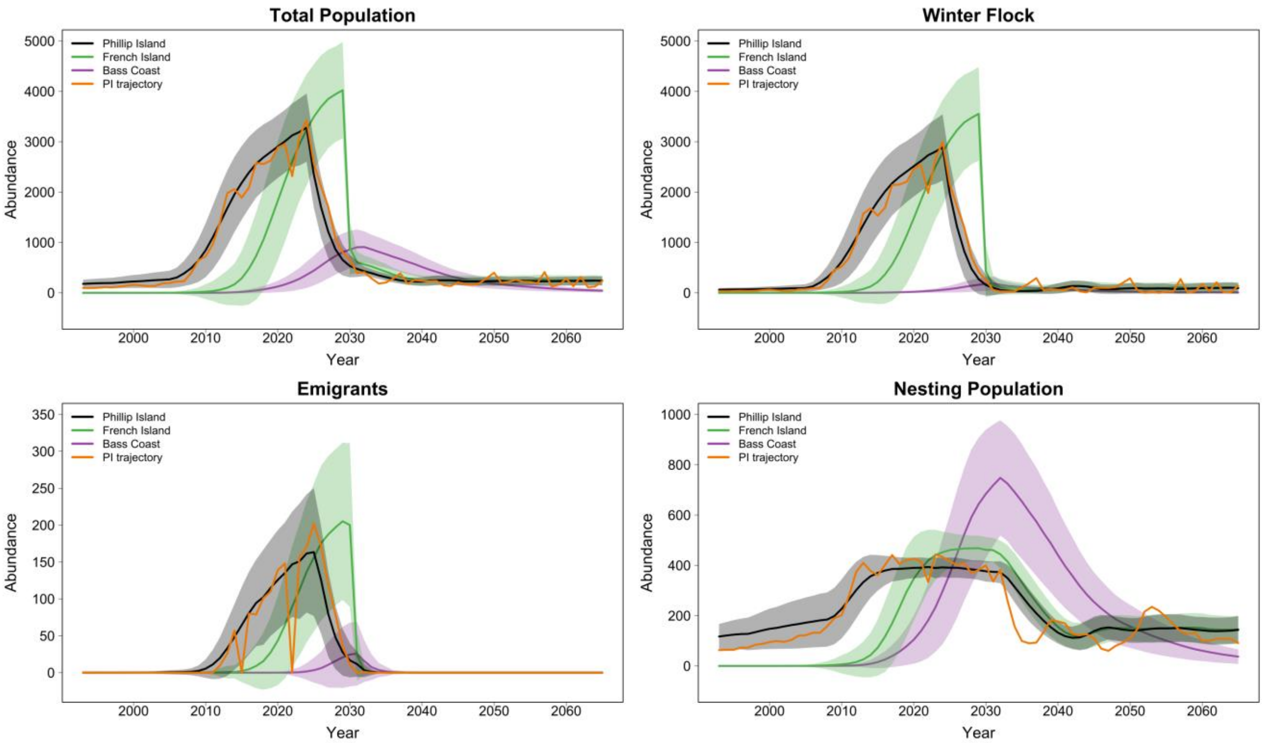

Figure A31. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S16 (Phillip Island: removal of 4 eggs from 40% of nests and culling up to 750 winter flock geese per year; French Island: removal of all winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

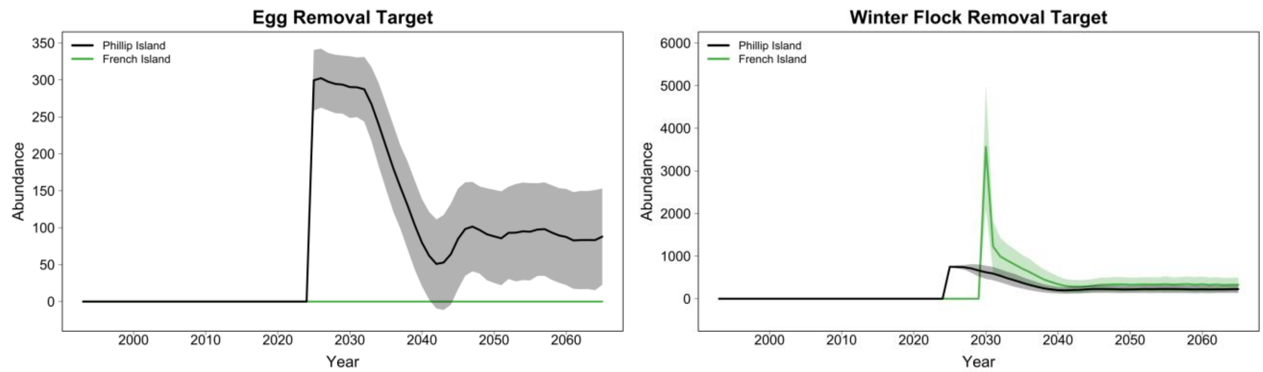

Figure A32. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S16 (Phillip Island: removal of 4 eggs from 40% of nests and culling up to 750 winter flock geese per year; French Island: removal of all winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

Implementing gosling and winter flock removal strategies on Phillip Island and French Island

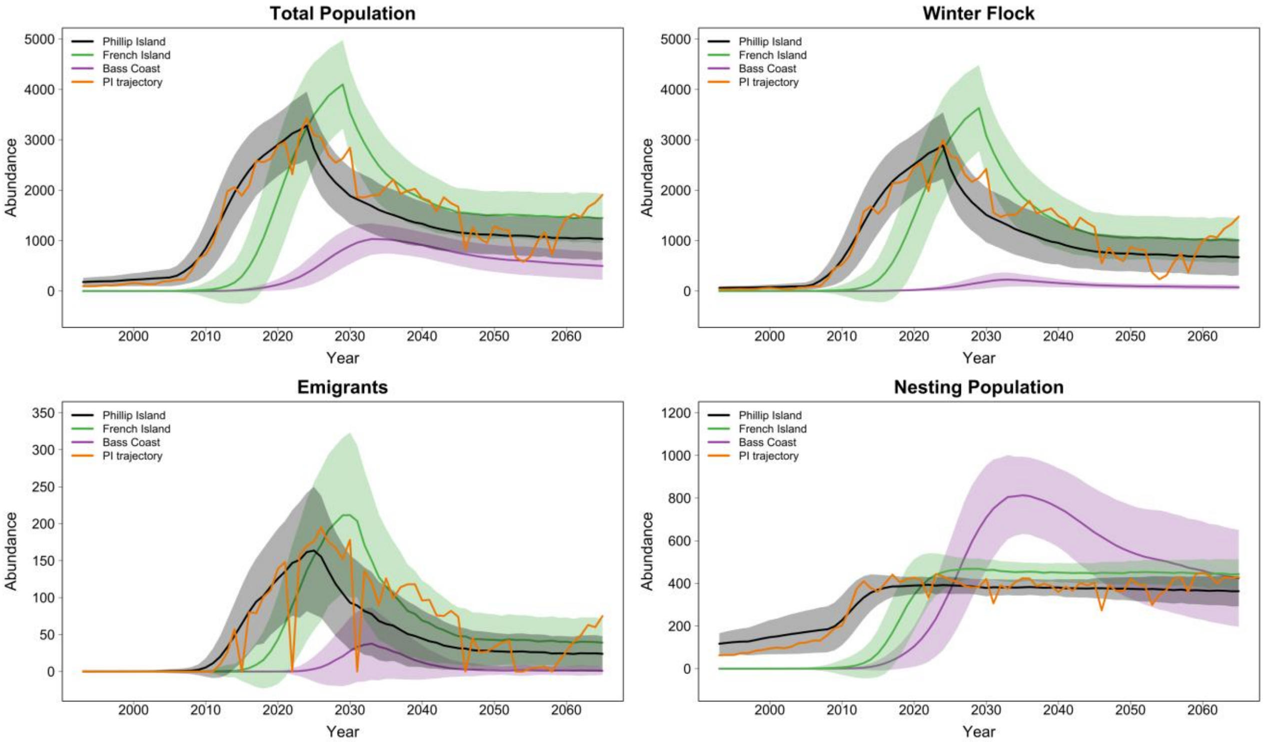

Figure A33. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S17 (Phillip Island and French Island: removal of 4 goslings from 40% of nests and culling up to 250 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

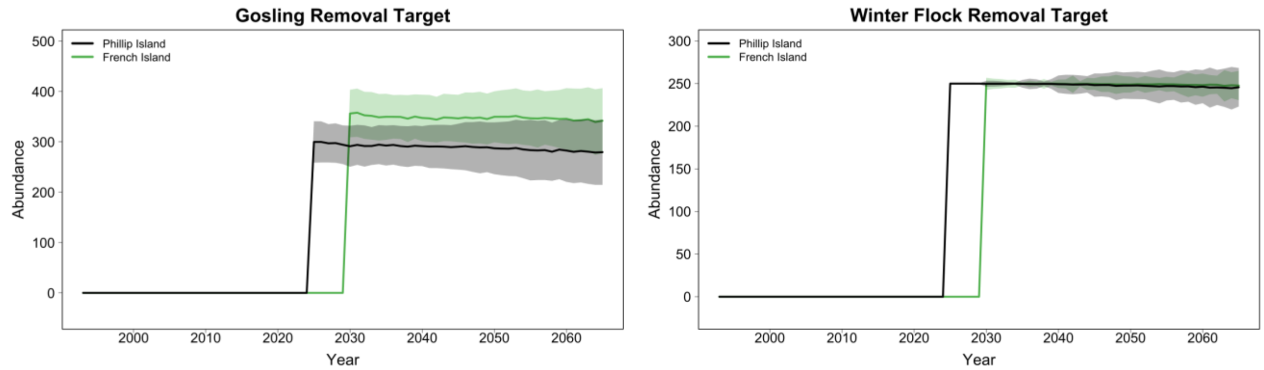

Figure A34. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S17 (Phillip Island and French Island: removal of 4 goslings from 40% of nests and culling up to 250 winter flock geese per year)

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

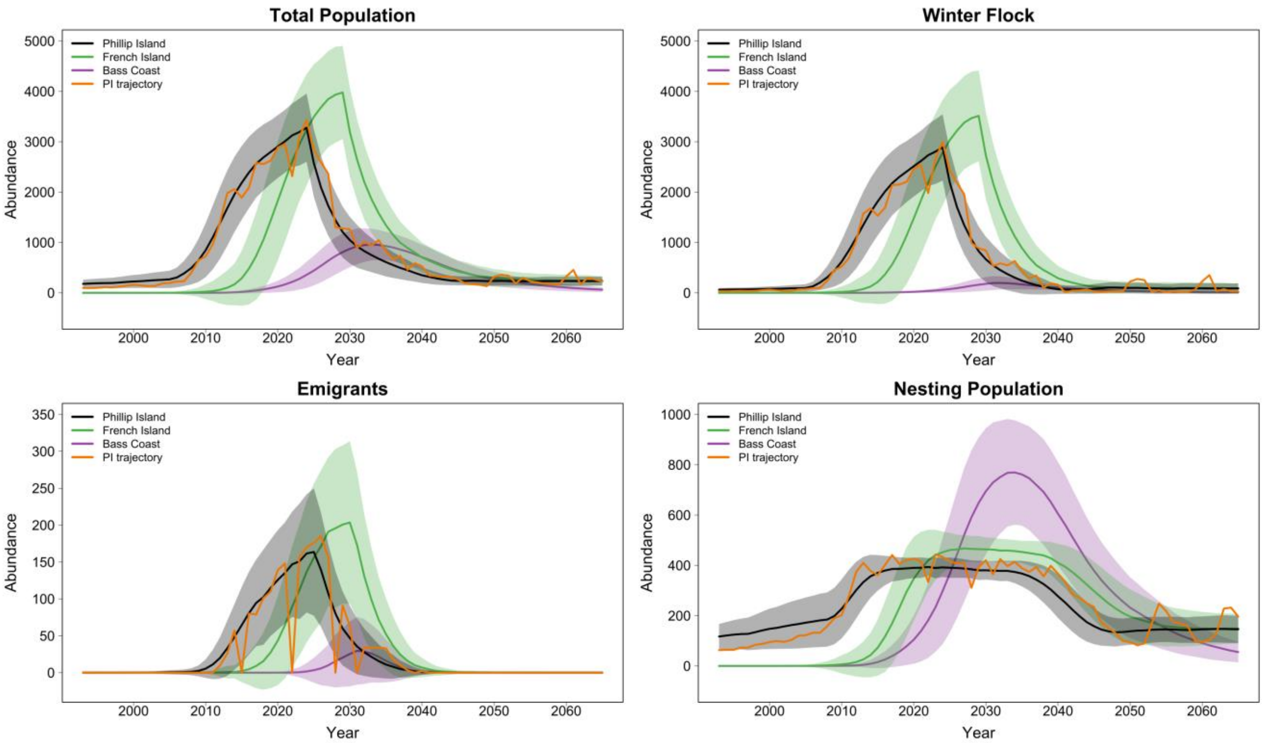

Figure A35. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S18 (Phillip Island and French Island: removal of 4 goslings from 40% of nests and culling up to 500 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

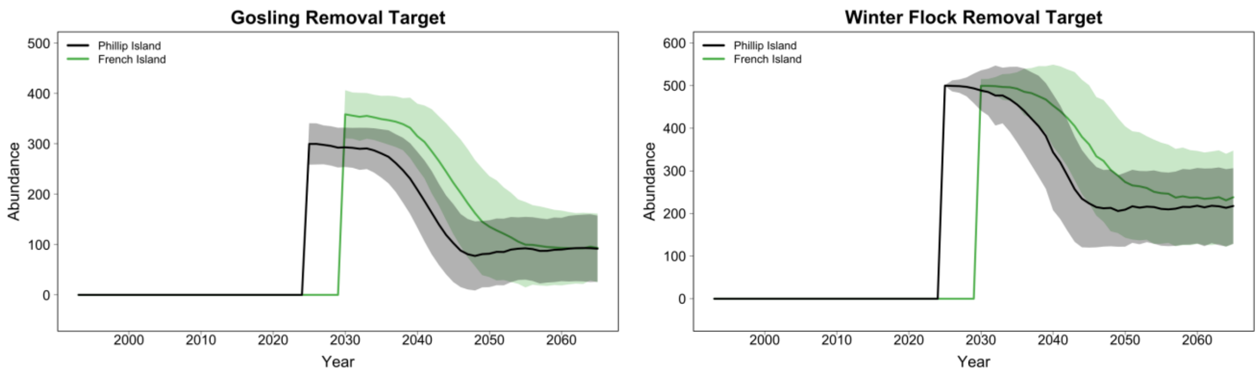

Figure A36. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S18 (Phillip Island and French Island: removal of 4 goslings from 40% of nests and culling up to 500 winter flock geese per year)

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

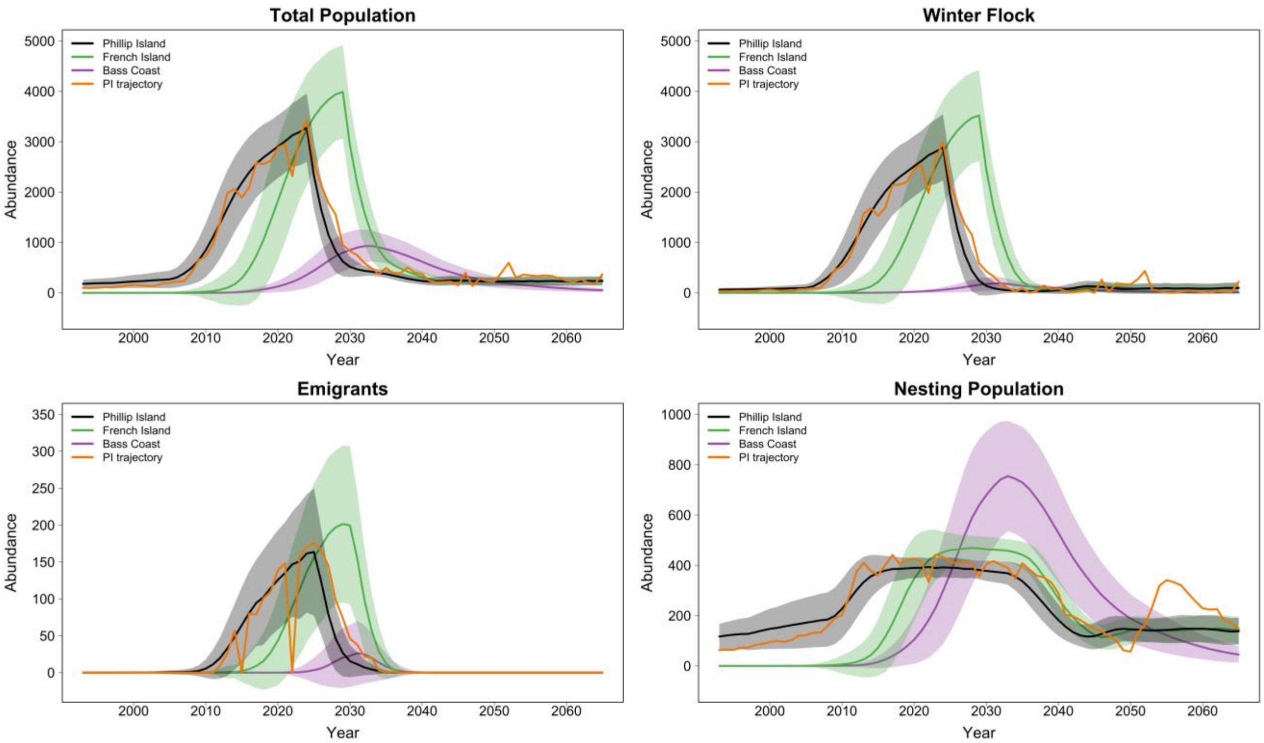

Figure A37. Modelled CBG trajectories (projected to 2065) on Phillip Island (black line), French Island (green line), and the Bass Coast (purple line) under control scenario S19 (Phillip Island and French Island: removal of 4 goslings from 40% of nests and culling up to 750 winter flock geese per year).

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean. The orange line is the equivalent trajectory of the best fit trajectory for the Total Population Phillip Island (i.e., the modelled trajectory that most closely aligns with count data).

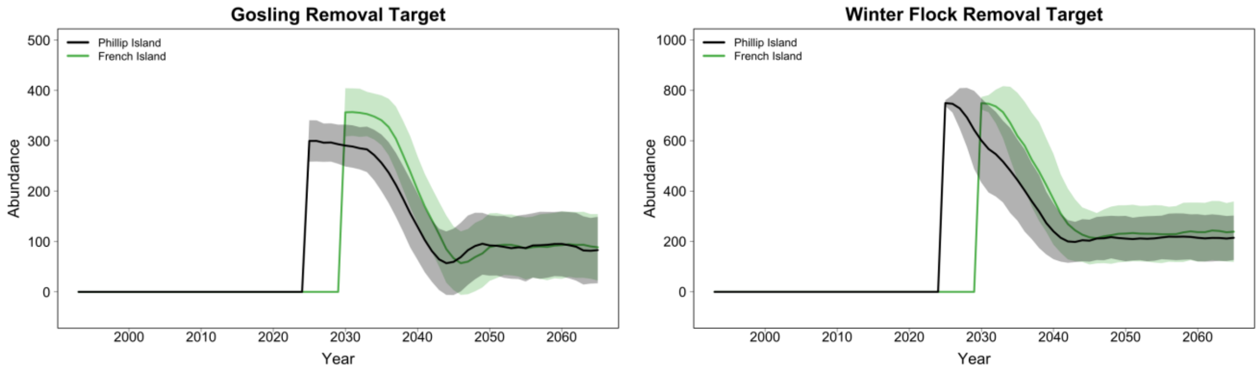

Figure A38. Modelled CBG removals (projected to 2065) on Phillip Island (black line) and French Island (green line) under control scenario S19 (Phillip Island and French Island: removal of 4 goslings from 40% of nests and culling up to 750 winter flock geese per year)

Solid lines are mean trajectories and shaded regions bound ±1 standard deviation from the mean.

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