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Quantifying the cumulative impact of winter habitat loss on a critically endangered migratory parrot

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Abstract

Habitat loss is a major driver of biodiversity decline, often occurring in a slow-paced, piecemeal way. The cumulative impacts of such loss can be substantial for threatened species but are challenging to quantify and thus factor into planning decisions—particularly for mobile species with large ranges and irregular settlement patterns. We combined remote sensing and population viability analysis to estimate the cumulative impact of various winter habitat loss scenarios on the critically endangered, migratory swift parrot *Lathamus discolor* in south-eastern Australia. Swift parrots suffer from predation during nesting and logging of their Tasmanian breeding habitat, but the Hunter-Central Coast (HCC) of New South Wales is an important wintering area for the species and also amogst the most rapidly developing. If threats from predation and logging in Tasmania are addressed but habitat loss occurs throughout the species' wintering range at the rate observed in the HCC, the swift parrot population is expected to decline by 16% over 50 years. If observed rates of habitat loss in the HCC continue, halve, or double, the additional impact from that region alone on the swift parrot population could lead to a decline of 32% over 100 years. Our study emphasizes the need to avoid cumulative impacts across the full range of mobile species to help prevent their extinction.

KEYWORDS

environmental impact assessment, environment protection, ornithology, population modelling, significant impacts, threatened species

1 | INTRODUCTION

Habitat loss is one of the greatest drivers of global biodiversity decline, and native vegetation clearing associated with urban development, agriculture, and resource exploitation remains a pervasive and large-scale threat (Díaz et al., 2019; Pereira et al., 2010; Ward et al., 2022). Recent research suggests much contemporary habitat loss is occurring with little legislative scrutiny and that current environmental laws may be ineffective in helping governments achieve their commitments to preventing further biodiversity loss that is driven in large part by habitat destruction (Ward et al., 2019).

Devising effective ways to minimize biodiversity loss over the coming decades will require evidence-based conservation to be complemented with sufficient funding and strong political leadership (Reside et al., 2024; Wintle et al., 2019). There is increasing global recognition of the need for national and international policies that specifically aim to halt and reverse biodiversity decline (Rounsevell et al., 2020). For example, the Australian government has made a commitment to no new extinctions (Department of Agriculture, Water, & Environment, 2021). To achieve this goal while meeting demand for sustainable development will require a thorough understanding of not only the threats facing endangered species, but also the effectiveness of conservation actions to prevent and reverse declines in their populations (Robinson et al., 2018).

A major challenge for legislative and planning processes is that under current frameworks, planning applications are generally assessed on a case-by-case basis, often on a local or regional scale much smaller than the extent of occurrence of many threatened species (Hawke, 2009; Samuel, 2020). In this instance, the potential impacts associated with individual planning applications on threatened entities may well be minimal, but the cumulative impacts of multiple development applications could have serious and irreversible impacts on threatened entities (Maron et al., 2010; Maron & Fitzsimons, 2007). Accurately forecasting potential cumulative impacts is an important conservation goal; by explicitly considering cumulative impact risks, planning processes will be better placed to first avoid their occurrence, second minimize their magnitude, and third offset them effectively (Whitehead et al., 2017).

Life-history traits are a major factor affecting the ease with which cumulative impacts facing threatened entities can be identified and quantified. Perhaps the most challenging such trait is the mobility of the species in question (Runge et al., 2014). Forecasting potential cumulative impacts of habitat loss for sedentary, range-restricted species is relatively straightforward (Adhikari et al., 2019); their area of occupancy is invariably static and their abundance and distribution can be predicted with a high degree of confidence, making avoidance and minimization theoretically simple to achieve. In contrast, quantifying potential cumulative impacts of habitat loss is much more challenging for nomadic species, because their large ranges and dynamic distributions generate high levels of uncertainty around what habitats they might occupy, when they might occupy them, and the extent to which they may be able to tolerate some loss of habitat by occupying alternative areas of suitable habitat (Runge et al., 2014). Cumulative impacts can be linear and nonlinear, and non-linear impacts create a risk of rapid, irreversible population decline if cumulative impacts exceed a species' threshold ability to persist in increasingly modified environments (Halpern et al., 2008).

Nomadic species have evolved large ranges and irregular movement patterns to be able to persist in environments such as Australia's with high environmental variability (Runge et al., 2015; Webb et al., 2017). Thus, while the spatial extent of their fundamental niche may be very large, this is because only a small fraction of the habitats they have the potential to occupy will provide the resources they require for foraging or breeding, such as eucalypt blossom, at any given time (Soberón, 2007; Webb et al., 2017). These fractions of a species' fundamental niche are termed their realized niche or "functional habitat" (Soberón, 2007), and the extent and distribution of functional habitat will vary both spatially and temporally (Maron et al., 2010; Webb et al., 2014, 2017). Furthermore, a nomadic species must have the ability to exploit the resources in their realized niche, but this is not always the case given the intensified interspecific competition for those resources (i.e., niche space) in modified environments (Bennett et al., 2015; Scheele et al., 2017). Cumulative impacts have the potential to occur when what appear to be small-scale developments lead to the loss of what would in fact be a substantial proportion of a species' realized niche.

Here we combine remote sensing and population viability analysis (PVA) with the aim to predict the potential cumulative impacts of sequential loss of important (i.e., potentially functional) wintering habitat for the critically endangered swift parrot *Lathamus discolor*. Swift parrots epitomize the challenges that rare and highly mobile species pose to planning processes that seek to ensure developments do not lead to significant and irreversible impacts (SAII) on threatened entities. Swift parrots breed in Tasmania in the austral spring where they are subject to severe threats, including habitat loss and introduced predators (Stojanovic et al., 2014; Webb et al., 2018). Much research has focused on the threats the species faces in its breeding grounds, but the entire population then migrates to SE mainland Australia for the autumn and winter where the birds become nomadic in search of nectar and lerp from *Eucalyptus*, *Corymbia*, and *Angophora* tree species, among others (Saunders & Heinsohn, 2008). Their range in mainland Australia is vast (>400,000 km^2) extending from inland and coastal areas of Victoria to southern Queensland. The Hunter-Central Coast area of New South Wales (hereafter HCC) is one of the most important swift parrot wintering areas. In New South Wales, important swift parrot winter habitat is defined as all native vegetation communities containing a known swift parrot feed tree species occurring within 2 km of the sighting location of 10 or more swift parrots (NSW Department of Planning, Industry and Environment). Important habitat mapping indicates 29.13% of all important habitat for the species in New South Wales occurs within the HCC (Department of Planning & Environment NSW, 2022, see Section 3). The

HCC is also the subject of substantial housing development pressure, which could lead to cumulative impacts on the viability of the swift parrot population. Current understanding of the potential contribution of winter habitat loss to the species' decline remains a significant knowledge gap. This creates a headache for decision-makers seeking to balance the needs for development with avoidance of serious and irreversible impacts on threatened entities.

To help inform future planning decision-making, we aimed to answer the following research questions:

1. How much important swift parrot winter habitat has been lost in the HCC over the past two decades?
2. How would swift parrot population viability change if threats in Tasmania are addressed but:
   a. the observed rate of winter habitat loss in the HCC were to continue, double, or halve *in the HCC only* over the next 50–100 years?
   b. the observed rate of winter habitat loss in the HCC were to continue, double, or halve *across the species' entire winter range* over the next 50–100 years?
3. What would be the additional impact on the swift parrot population if threats in Tasmania are not addressed and the observed rate of habitat loss in the HCC were to continue, double, or halve *over the species' entire winter range* over the next 50 years?

Together, remote sensing and PVA offer a useful approach to answering these questions; remote sensing can be used to estimate accurately the rate of swift parrot habitat loss in the HCC over recent years, thus providing an estimate of the rate of potential loss in the future. PVA can then model the potential future impact of this loss while accounting for uncertainties in demographic parameters through concurrent reductions in the simulated carrying capacity of the environment. Swift parrots are an ideal species for such an approach because long-term monitoring of the population mean accurate estimates of key demographic parameters—which are typically lacking for threatened nomads—are available for this species (Heinsohn et al., 2015; Owens et al., 2023). We envisaged that the growth of the simulated swift parrot population would be linked to (i) the rate and extent of important winter habitat loss; and (ii) whether or not key threats in the Tasmanian breeding grounds are addressed. Therefore, we predicted smaller (or more negative) swift parrot population growth rates in scenarios where threats in Tasmania remained unabated, where winter habitat loss (i.e., reductions in the carrying capacity) occurred at a faster rate, and where habitat loss occurred through the species' entire winter range.

2 | METHODS

2.1 | Study species

The breeding biology and dynamic breeding distribution of swift parrots have been well studied, such that key demographic parameters around breeding can be estimated with a high degree of confidence (Stojanovic et al., 2014; Webb et al., 2014). Existing population models based on the best available evidence suggest that swift parrots are headed for extinction within two decades if the threats they face are not addressed effectively (Heinsohn et al., 2015; Owens et al., 2023). These threats are primarily two-fold: In their Tasmanian breeding grounds, blue gum *Eucalyptus globulus* and black gum *Eucalyptus ovata* forests continue to be logged on a large scale, leading to the ongoing loss of both hollow-bearing trees and nectar resources upon which swift parrots depend for breeding (Webb et al., 2012, 2017). Habitat loss also appears to be interacting with high but spatially variable rates of nest predation by introduced sugar gliders *Petaurus breviceps* (Stojanovic et al., 2014). Sugar gliders predate not only swift parrot eggs and nestlings but also adult females, leading to a heavily male-biased adult sex ratio (Heinsohn et al., 2021). Consequently, swift parrots have higher breeding success rates on offshore islands, from which sugar gliders are absent, than they do on mainland Tasmania (Stojanovic et al., 2014).

In their wintering grounds in south-eastern mainland Australia, the principal threat facing swift parrots is the loss and degradation of foraging habitat. Habitat loss occurs primarily due to agricultural land clearing to the west of the species' wintering range and residential/commercial development to the east (Commonwealth of Australia, 2011). Habitat degradation is linked to eucalypt dieback associated with severe drought events (Losso et al., 2022) and wildfires (Ward et al., 2020). Both effects are linked to climate change, which is predicted to lead to a reduction in the extent of available swift parrot habitat as well as a south-easterly shift in its distribution over coming decades (Porfirio et al., 2016). In this instance, swift parrot habitat within the HCC will become increasingly important for the survival of the species as a drought and general climate change refuge (Saunders & Heinsohn, 2008). Such distributional changes are already being observed in other Australian parrot species, most notably the superb parrot *Polytelis swainsonii* (Manning et al., 2007).

2.2 | Overview of analysis

We implemented a five-stage approach to answer our research questions. First, we estimated the proportion of suitable swift parrot habitat in our focal study area of the

HCC based on (i) NSW government swift parrot important area mapping and (ii) a range-wide swift parrot habitat suitability model. Second, we synthesized public sightings data to estimate the proportion of the swift parrot population that spent the winter in the HCC each year between 2005 and 2018, as well as the annual variation in this proportion. Third, we used remotely sensed data to estimate the annual extent of loss of what would have been important swift parrot habitat within the HCC between 2001 and 2019 based on both the NSW government mapping and the habitat suitability model. Fourth, we used these data to estimate the observed rate of swift parrot habitat loss, which we used as a baseline for how much important habitat might be lost in the HCC over the next 50–100 years under different levels of development. Finally, we incorporated these estimates into population simulations to predict how cumulative habitat loss might impact the swift parrot population—modeled via reductions in the carrying capacity of the environment—under multiple development and conservation scenarios over the same 50- to 100-year timescale. Each stage is described in detail below.

2.3 | Modeling habitat suitability

To estimate the proportion of important swift parrot habitat within the HCC, we used two complementary datasets. We first used the NSW government's Biodiversity Assessment Method (BAM) important swift parrot habitat mapping (NSW Department of Planning, Industry and Environment) as our base layer (Figure S1). This map informs planning processes that may have a SAII on swift parrots. The BAM mapping is a binary measure and does not consider the relative importance of different plant community types to swift parrots. For the purpose of the models, we therefore considered all mapped habitat to be of equal importance to swift parrots. We calculated that 29.13% of BAM important swift parrot habitat in NSW fell within the HCC (Figure S1).

Second, we used a range-wide swift parrot habitat suitability model (Figure 1) to address two limitations with the BAM mapping. These are: (i) the BAM mapping is based on the buffered location of verified swift parrot sightings and is therefore likely to omit important swift parrot habitat within the HCC due to a lack of observer coverage; and (ii) the BAM mapping is restricted to NSW whereas swift parrots also winter in Victoria and southern Queensland. The MaxEnt model combines public sightings data as well as “background data” (i.e., locations when/where bird surveys were undertaken, but swift parrots were not detected) with remotely sensed climate, vegetation and topographic data to predict the likelihood of swift parrot occurrence throughout its winter range. Further details of the MaxEnt modeling

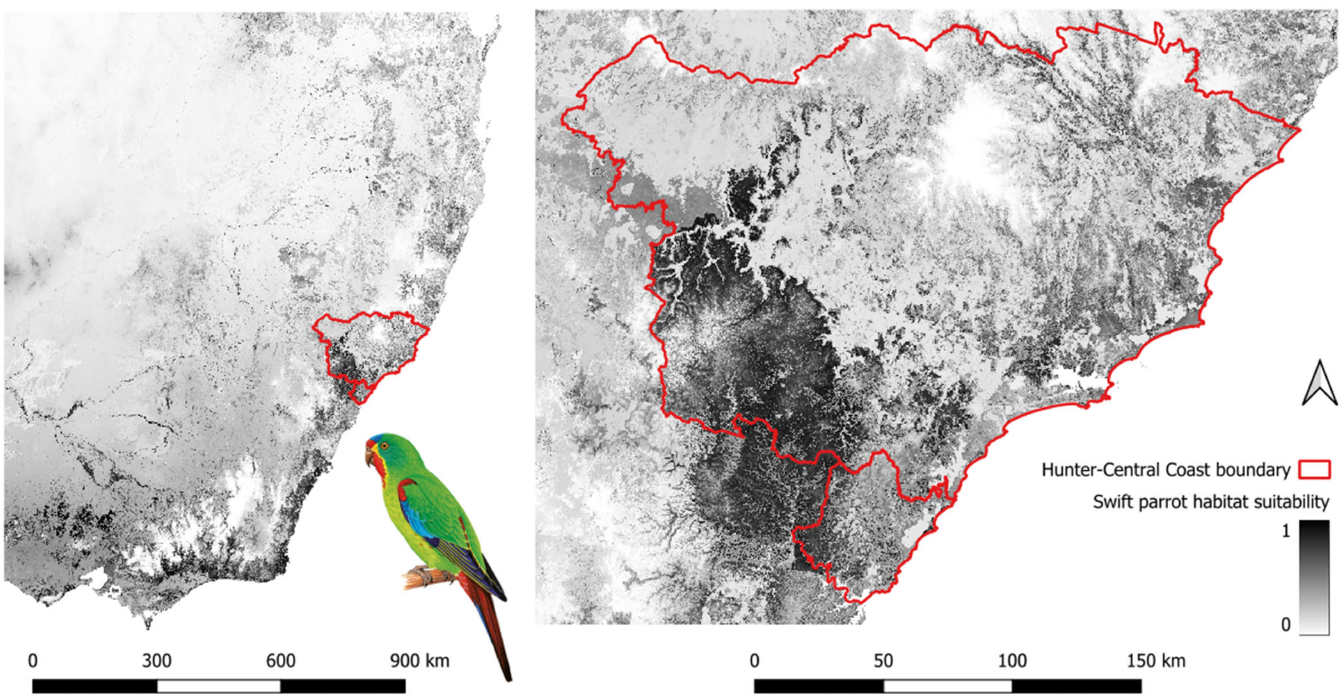

FIGURE 1 Distribution of important swift parrot habitat range-wide in south-east Australia (left) and at higher resolution within the Hunter-Central Coast (right) based on a logistic MaxEnt habitat suitability model. Lighter raster cells denote less suitable swift parrot habitat, darker cells denote more suitable swift parrot habitat. Larger red polygon to the north shows Hunter boundary, smaller red polygon to the south shows Central Coast boundary.

procedure are provided in File S1, Supporting Information S1. We used a logistic model (Figure 1) to calculate the proportion of suitable 1 km^2 raster cells in the swift parrot's winter range within the HCC, assuming cells with a predicted suitability of 0.7 or higher represented potentially important swift parrot foraging habitat. We calculated that 8.31% of the swift parrot's range-wide suitable wintering habitat fell within the HCC (Figure 1).

2.4 | Quantifying past and estimating future rates of important swift parrot winter habitat loss

To quantify past rates of important swift parrot habitat loss in the HCC, we used Google Earth Engine to calculate the annual area of what would have previously been important swift parrot habitat based on the current BAM and MaxEnt important habitat mapping lost to development over the past 20 years based on remote sensing data. Full details of the methodology used to calculate the extent of important swift parrot habitat that has been lost over the past two decades are provided in Crates et al. (2025) and File S2, Supporting Information S1. We therefore estimated an overall loss of 1% of suitable swift parrot habitat in the HCC between 2001 and 2019 (approximately 0.05% per year, see results). However, there was a significant upward trend in the proportion of habitat lost over 2001–2019, and so we used the trendline proportion lost (ha) $= 0.00006 \times \text{Year} + 0.0007$ to predict the proportion lost in the HCC each year up to 50 years. The corresponding trendline for the proportion of habitat lost range-wide was: proportion lost (ha) $= 0.0001 \times \text{Year} + 0.0003$.

We considered the best case in terms of reduced human development to be a 50% decrease in the observed annual rate of important swift parrot habitat lost within the HCC over the next 50 years, based on our own judgment from working in this region. We used half of the rate of loss in the above equations in best case scenarios. We considered the worst-case estimate to be a doubling of the current rate of loss, so we doubled the rate specified in the above equations.

2.5 | Cumulative impact scenarios

We used the software package VORTEX10 v1.3.2 (Lacy & Pollak, 2024); an individual-based population simulation program, to model swift parrot population trajectories over both 50 and 100 years. We used the demographic parameters applied in population viability analyses previously conducted by Heinsohn et al. (2015), and refined by Owens et al. (2022). All simulations were run 1000 times and all demographic parameters and their references are shown in Table 1. Mortality rates and number of offspring per female are assumed to be normally distributed and are presented as the mean ± standard deviation (SD).

To quantify cumulative impacts of habitat loss on the swift parrots, we modeled swift parrot populations under multiple scenarios within two broad themes. Theme one explored the impact of habitat loss in the HCC and further afield under “recovering population” conservation scenarios in the Tasmanian breeding grounds. Theme

TABLE 1 Swift parrot demographic parameters used in population viability analysis.

Demographic parameter	Value	Citation
Age of first reproduction (both sexes)	2 years	Bird et al. (2020)
Maximum lifespan	11 years	Bird et al. (2020)
Maximum age at reproduction	10 years	Bird et al. (2020)
Juvenile mortality (0–1 year, mean ± SD)	48.5% ± 8.1%	Stojanovic et al. (2021)
Background adult mortality (mean ± SD)	40.5% ± 8.1%	Bird et al. (2020)
Total adult female mortality (predation by gliders, mean ± SD)	52.8% ± 8.1%	Owens et al. (2022)
Maximum progeny per year	6	Owens et al. (2022)
Proportion of males at hatching	0.52	Heinsohn et al. (2021)
Percentage of adult females breeding	90	Heinsohn et al. (2021)
Percentage of adult males available for breeding	100	Heinsohn et al. (2021)
Number of offspring per female per year (no additional nest predation)	3.29 ± 1.44	Owens et al. (2023)
Mating system	Monogamy	Heinsohn et al. (2019)
Generation time	3.7	Bird et al. (2020)
Inbreeding depression	6.29 lethal equivalents	Heinsohn et al. (2021)
Initial carrying capacity[a]	1000–2000	Heinsohn et al. (2021)

Abbreviation: SD, standard deviation.
[a]Carrying capacity declines over time as a function of cumulative habitat loss- see further details in text below.

one scenarios assume threats from loss of breeding habitat and predation by sugar gliders are addressed by assuming a lower than current background mortality rate for both sexes of 40.5%.whereby they no longer contribute to population decline—the ultimate goal of the species' National Recovery Plan (Commonwealth of Australia, 2011).

Theme two scenarios we defined as "business as usual" scenarios. Under theme two, we assume that threats in the Tasmanian breeding grounds from logging and sugar glider predation still occur and continue to severely impact population growth rates through a female mortality rate of 52.8% (males kept at 40.5%; Heinsohn et al., 2015; Owens et al., 2022). For both themes, we set the initial carrying capacity of the environment to either 1000 or 2000, assuming mainland Australia could support a wintering swift parrot population of up to either 1000 or 2000 individuals. Two thousand individuals was the starting population size in previous PVAs before modeling the impact of sugar glider predation and habitat loss in Tasmania (Heinsohn et al., 2015). Although 2000 appears the most suitable carrying capacity for current modeling we also explore a carrying capacity of 1000 in case the ability of mainland Australia to support swift parrots has been more drastically reduced than realized due to drought, fire, land clearing, and development.

We accounted for the differing rates of habitat loss in the PVA scenarios as a range of annual changes to the carrying capacity of the swift parrot population either within the HCC only or throughout the swift parrots' winter range. We first held the availability of habitat elsewhere in the wintering range constant to isolate the effect of habitat loss in the HCC only, and for further models allowed habitat also to be lost elsewhere in the swift parrot's wintering range (Table 2). See also the formula in the following subsection for calculating the carrying capacity of the population in year *t*.

2.6 | Accounting for potential climate change impacts and swift parrot mobility

For both the recovering population and business as usual themes, we varied the annual proportion of the entire swift parrot population wintering within the HCC. We used public sightings data to estimate the proportion of birds occurring annually within the HCC between 2005 and 2018, which averaged 10.2% ± 0.90 SD and ranged from 0% to 31% (Table S2; Figure S2). To account for the impact of climate change (e.g., Manning et al., 2007), we allowed the proportion of swift parrots wintering in the HCC over the next 50 years to increase by 10% over that observed in the 2005–2018 data. We therefore used 11.2% as the proportion of swift parrot habitat represented in the HCC. To enhance biological reality, for example, related to variation in the abundance and distribution of flowering in key feed tree species (Saunders & Heinsohn, 2008), we varied the availability of habitat each year by adding a random function that added or detracted habitat from the trendlines for habitat availability above based on the standard deviation of the observed yearly sightings. The generalized formula for loss of future carrying capacity had the following form:

$$\text{Future carrying capacity for year } t = \text{Initial carrying capacity} - \text{total carrying capacity lost by year } t.$$

where

$$\text{Carrying capacity lost in year } t = \text{carrying capacity in year}(t-1) \times \frac{\text{predicted habitat loss}}{\text{total habitat}}.$$

"Predicted habitat loss" in this equation is modified by random fluctuations due to the birds' varying use of habitat. Values were drawn from a normal distribution with variance determined by the fluctuations in swift parrot sightings in the region. See Figure S2, for an example of simulated future carrying capacity due to habitat loss.

In total, we modeled 18 scenarios under the recovering population theme and 14 scenarios under the business as usual theme (Table 2). The four additional models in Table 2 were to examine the impact of habitat loss in the HCC only over a longer time period (100 years).

2.7 | Scenario assumptions

Our simulations assume that no gain of important swift parrot habitat occurs in the next 50 years through habitat restoration or sightings of swift parrot flocks in new areas. We also assume that the impacts of any future bushfires or droughts in important swift parrot habitat are temporary and do not lead to a long-term reduction in the carrying capacity of the environment (i.e., swift parrots have the capacity to utilize fire-affected important habitat once that habitat has had time to recover). Finally, we assume there is no change over the coming five decades to the current impact of noisy miners *Manorina melanocephala* (Maron et al., 2013) and bell miners *Manorina melanophrys* (Leseberg et al., 2015) on the

TABLE 2 Outcome of conservation and habitat loss scenarios modeled to explore potential cumulative impacts of developments on swift parrots in the Hunter-Central Coast (HCC) and beyond. Models assume pervasive threats of sugar glider predation and logging are addressed in theme one scenarios such that the swift parrot population recovers and remains unaddressed in theme two scenarios. Stoch-*r* = stochastic population growth rate; SD(*r*) = standard deviation of the stochastic population growth rate. PE = probability of extinction; *N*-all = final population size; SD(*N*-all) = standard deviation of the final population size.

Theme	Scenario	Description	Carrying capacity	Years	Stoch-*r*	SD (*r*)	PE	*N*-all	SD (*N*-all)
One-threats in Tasmania are addressed	1A	Basic model, no future habitat loss in HCC or elsewhere	1000	50	−0.009	0.182	0.02	392	276
	1B	Half current rate of habitat loss in HCC only	1000	50	−0.008	0.184	0.03	397	279
	1C	Current rate of habitat loss in HCC only	1000	50	−0.008	0.183	0.01	393	274
	1D	Double current rate of habitat loss in HCC only	1000	50	−0.008	0.184	0.02	396	271
	1E	Half current rate of habitat loss in HCC, plus loss range-wide	1000	50	−0.008	0.183	0.01	323	201
	1F	Current rate of habitat loss in HCC, plus loss range-wide	1000	50	−0.009	0.185	0.02	311	201
	1G	Double current rate of habitat loss in HCC, plus loss range-wide	1000	50	−0.009	0.186	0.03	314	199
	2A	Basic model, no future habitat loss in HCC or elsewhere	2000	50	−0.008	0.184	0.02	724	585
	2B	Half current rate of habitat loss in HCC only	2000	50	−0.006	0.183	0.02	721	574
	2C	Current rate of habitat loss in HCC only	2000	50	−0.007	0.183	0.02	723	574
	2D	Double current rate of habitat loss in HCC only	2000	50	−0.007	0.184	0.02	716	577
	2E	Half current rate of habitat loss in HCC, plus loss range-wide	2000	50	−0.007	0.183	0.02	626	432
	2F	Current rate of habitat loss in HCC, plus loss range-wide	2000	50	−0.006	0.183	0.02	626	436
	2G	Double current rate of habitat loss in HCC, plus loss range-wide	2000	50	−0.007	0.184	0.02	614	445
	3A	Basic model, no future habitat loss in HCC or elsewhere	2000	100	−0.007	0.184	0.14	679	614
	3B	Half current rate of habitat loss in HCC only. 100-year timescale	2000	100	−0.018	0.192	0.26	606	574
	3C	Current rate of habitat loss in HCC only. 100-year timescale	2000	100	−0.021	0.189	0.30	509	483
	3D	Double current rate of habitat loss in HCC only. 100-year timescale	2000	100	−0.024	0.199	0.35	456	451
Two-business as usual in Tasmania	4A	Basic model, no future habitat loss in HCC or elsewhere	1000	50	−0.186	0.247	1	4	-
	4B	Half current rate of habitat loss in HCC only	1000	50	−0.186	0.249	1	5	-
	4C	Current rate of habitat loss in HCC only	1000	50	−0.187	0.249	1	4	-

(Continues)

TABLE 2 (Continued)

Theme	Scenario	Description	Carrying capacity	Years	Stoch-*r*	SD (*r*)	PE	*N*-all	SD (*N*-all)
	4D	Double current rate of habitat loss in HCC only	1000	50	−0.185	0.247	1	0	-
	4E	Half current rate of habitat loss in HCC, plus loss range-wide	1000	50	−0.185	0.249	1	4	-
	4F	Current rate of habitat loss in HCC, plus loss range-wide	1000	50	−0.187	0.251	1	4	-
	4G	Double current rate of habitat loss in HCC, plus loss range-wide	1000	50	−0.184	0.246	1	5	-
	5A	Basic model, no future habitat loss in HCC or elsewhere	2000	50	−0.188	0.250	1	5	-
	5B	Half current rate of habitat loss in HCC only	2000	50	−0.186	0.248	1	3	-
	5C	Current rate of habitat loss in HCC only	2000	50	−0.186	0.249	1	3	-
	5D	Double current rate of habitat loss in HCC only	2000	50	−0.187	0.247	1	5	-
	5E	Half current rate of habitat loss in HCC, plus loss range-wide	2000	50	−0.190	0.250	1	9	-
	5F	Current rate of habitat loss in HCC, plus loss range-wide	2000	50	−0.185	0.252	1	9	-
	5G	Double current rate of habitat loss in HCC, plus loss range-wide	2000	50	−0.187	0.250	1	9	-

capacity of swift parrots to utilize important habitat. Although habitat fragmentation may well lead to an increase in the abundance of noisy miners within the HCC (Rogers et al., 2021), there is no available data to accurately predict the rate nor the spatial configuration of changes in the abundance of this species. Under such circumstances, it is standard to assume a "best case" scenario (Heinsohn et al., 2019), acknowledging that the future impacts of miners on the availability of important swift parrot habitat within the HCC may well be worse than the modeled scenarios, but with a high degree of uncertainty. All VORTEX project files are provided in File S3, Supporting Information S1, to allow for full replication of the analysis.

3 | RESULTS

3.1 | Rate of loss of important swift parrot habitat within the hunter-central coast

The estimated total area of important swift parrot habitat lost to development within the HCC between 2000 and 2019 was 717.7 ha based on the BAM mapping and 10,081 ha based on the MaxEnt model (Table S1). These estimates equate to a proportional loss of 1.43% and 0.77% of the BAM and MaxEnt habitat respectively (Table S1).

3.2 | PVA theme one: Recovering population scenarios

In the absence of the severe threats known to presently occur in Tasmania (habitat loss and introduced predators), over 50 years and with an initial carrying capacity of 2000 birds, an accumulating loss of habitat only occurring in the HCC does not appear to cause major decreases in the swift parrot population (Figure 2a, Table 2). The basic model (2A) shows that the current estimated population of 750 will remain stable over the next 50 years. If habitat is lost at the current predicted rate in the HCC, the impact on the swift parrot population from this loss alone appears to be minimal (model 2C). However, if the observed rate of habitat loss occurring within the HCC occurred over the entire winter range, the swift parrot population will decline by 16% over 50 years (final

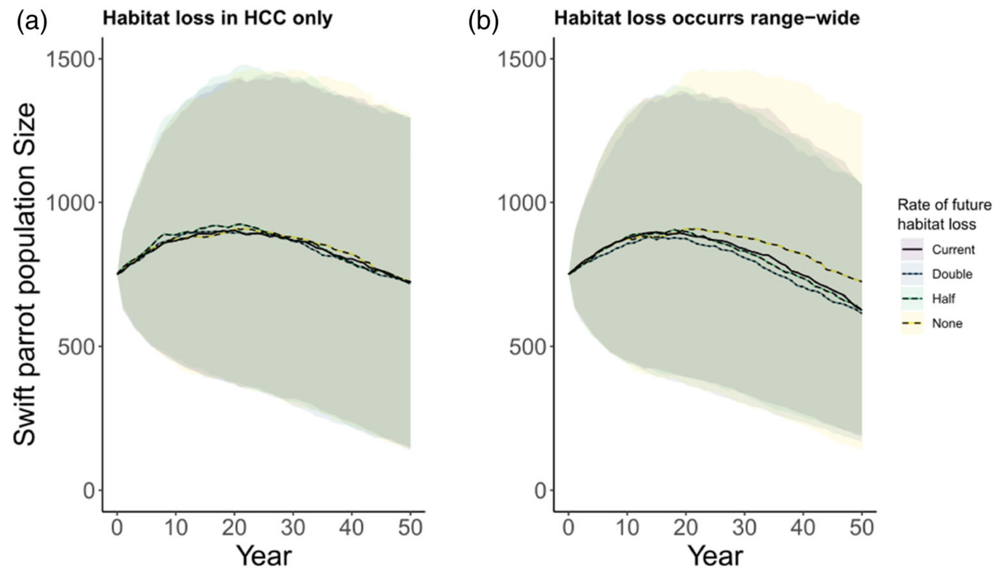

FIGURE 2 Swift parrot population trajectories assuming threats in the Tasmanian breeding grounds are addressed and a winter carrying capacity on mainland Australia of 2000 individuals. The trajectories show the impact on population size of future important habitat loss occurring: (a) within the Hunter-Central Coast only (scenarios 2A–D in Table 2); and (b) throughout the species' entire winter range (scenarios 2A and 2E–G in Table 2). The rates of future habitat loss estimates are derived from trends from 2001 to 2019 in the Hunter-Central Coast.

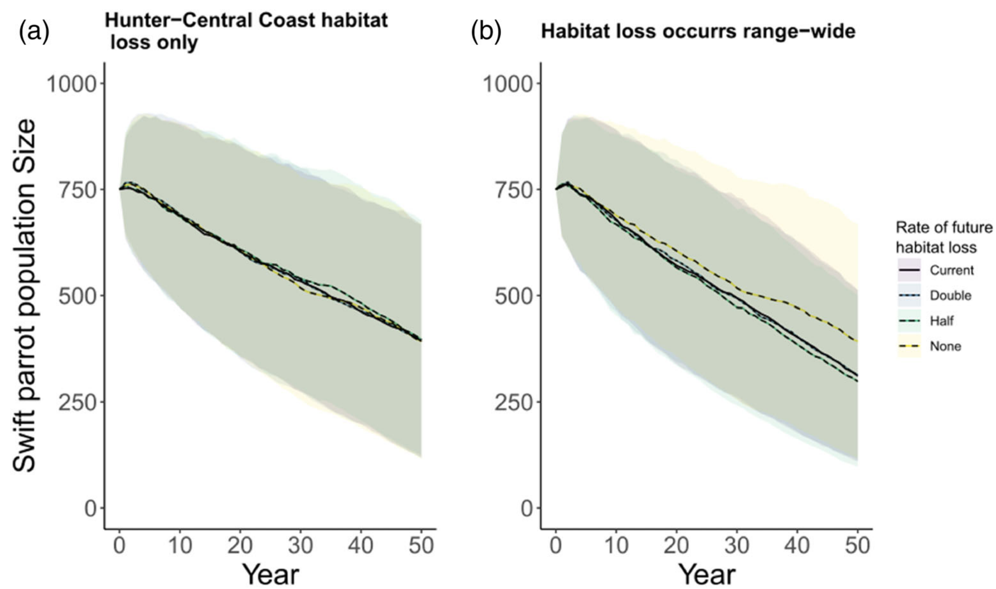

FIGURE 3 Swift parrot population trajectories assuming threats in the Tasmanian breeding grounds are addressed (i.e., recovering population theme one) and a winter carrying capacity of 1000 individuals. The trajectories show future important habitat loss occurring (a) within the Hunter-Central Coast only (scenarios 1A – D in Table 2); and (b) throughout the species' entire winter range (scenarios 1A & 1E - G in Table 2). The rates of future habitat loss estimates are derived from trends from 2001 to 2019 in the Hunter-Central Coast.

population = 626 in model 2F compared to the initial population of 750, Figure 2b). Halving (e.g., final population = 721 in model 2B) or doubling (e.g., 716 in model 2D) the rate of habitat loss in the HCC does not greatly alter the predictions of swift parrot population size over 50 years (Figure 2a), and this does not change when habitat loss also occurs range-wide (model 2E compared to 2G, Figure 2b).

If trends are examined over a 100-year period, the loss of habitat in the HCC alone is predicted to cause a reduction in swift parrot population size of about 32% (509 in model 3C compared to 724 in model 2A, Figures 3 and 4,

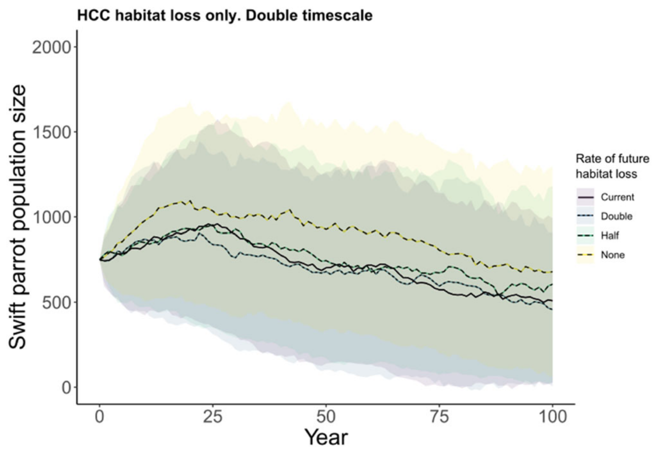

FIGURE 4 Swift parrot population trajectories over 100 years assuming threats in the Tasmanian breeding grounds are addressed. The trajectories assume (i) no future important habitat loss occurring; and (ii) future habitat loss occurring at half, double and the current loss rate within the Hunter-Central Coast only over a longer timescale of 100 years (scenarios 3A-D, Table 2). The rates of future habitat loss estimates are derived from trends from 2001 to 2019 in the Hunter-Central Coast.

Table 2). Greater effects of halving or doubling the rate of habitat loss are also apparent in the predictions made over 100 years (606 in model 3B vs. 456 in model 3D, Figures 3 and 4).

3.3 | PVA theme two: Business-as-usual scenarios

All models that incorporated the threats from habitat loss and introduced predators in Tasmania (4A-G, 5A-G) showed a precipitous decline as reported in Heinsohn et al. (2015) and Owens et al. (2022). The impact of these threats outweighs any additional impact of habitat loss on the mainland (Table S3, Figure 5). Under business as usual scenarios, the swift parrot is likely to be functionally extinct within 20 years.

4 | DISCUSSION

Cumulative impacts of persistent, small-scale habitat loss are a pervasive threat for many endangered species

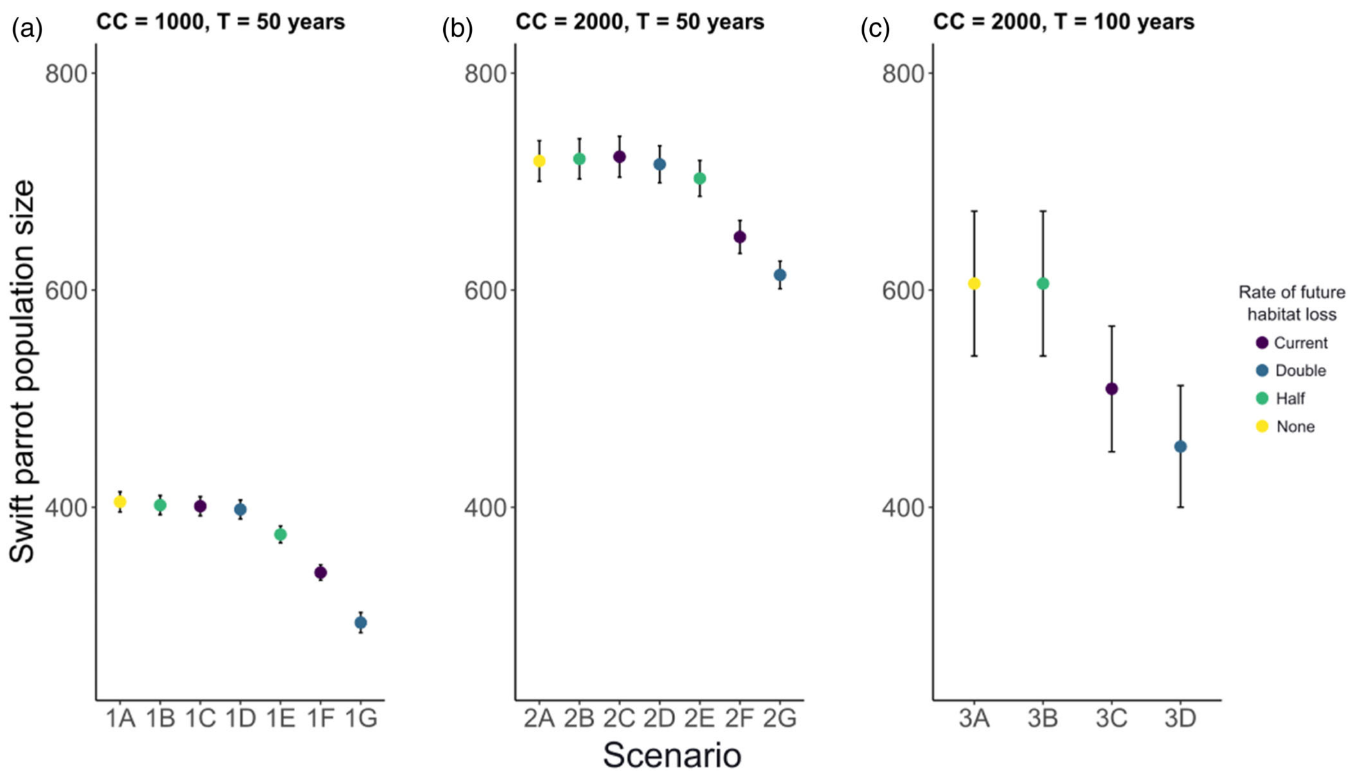

FIGURE 5 Final population estimates (± standard errors) for scenarios under theme one that assume recovery of the swift parrot population. Shown are estimates for (a) carrying capacity (CC) of 1000 and timescale (T) of 50 years.; (b) carrying capacity of 2000 and timescale of 50 years; and (c) carrying capacity of 2000, timescale of 100 years, habitat loss in Hunter-Central Coast only. See Table 2 for corresponding definitions of the scenarios. The rates of future habitat loss estimates are derived from trends from 2001 to 2019 in the Hunter-Central Coast. Scenarios are ordered according to increasing amount of winter habitat loss.

(Ward et al., 2019). Predicting the magnitude and timing of such impacts is challenging, particularly for highly mobile species with large ranges and nomadic movement patterns (Runge et al., 2014). This in turn makes it challenging to account for potential cumulative impacts in planning decisions (Whitehead et al., 2017). We used all available demographic and environmental data to try to predict the potential cumulative impact of the loss of important wintering habitat on the critically endangered swift parrot population. Assuming known threats in the Tasmanian breeding grounds are addressed, the rate of habitat loss predicted to occur within the HCC over the next 50 years is unlikely in itself to impact the swift parrot population. However, if: (i) the timescale of concern is doubled to 100 years; or (ii) habitat loss additionally occurs throughout the swift parrot's wintering range, the species is predicted to decline by between 16% and 32%.

Our business as usual models (4A-G, 5A-G, Table 2) reaffirm the urgent need to address the pervasive threats facing swift parrots in their breeding grounds (Heinsohn et al., 2015; Owens et al., 2023). If these threats are not dealt with, the swift parrot is predicted to be extinct in the wild within two to three decades (Figure 5). The federal government has committed to "no new extinctions," and there is much scientific evidence to show exactly what needs to happen to arrest the decline of swift parrots in their breeding grounds (Stojanovic et al., 2014; Webb et al., 2017, 2018). Landscape-scale management of sugar gliders and cessation of native forest logging in swift parrot breeding habitat are clearly challenging issues to manage from technological, financial, and political perspectives (Stojanovic et al., 2019; Webb et al., 2018). Yet we suggest with sufficient research, investment, and political will, it is fundamentally feasible to address these threats.

Assuming threats in Tasmania can be addressed within the coming decade and the swift parrot population stabilizes at a modest size of 750, our results suggest there will be a need to minimize cumulative impacts that habitat loss in their wintering grounds might have on an otherwise recovering population. As one of the most important areas within the species' winter range (Roderick & Stuart, 2010; Saunders & Heinsohn, 2008), the HCC is under high development pressure and decision-makers need to balance the need for development with the need to avoid and minimize impacts on threatened species such as the swift parrot. Public sightings data suggest that in some years, a significant proportion of the entire population can aggregate in the HCC. It is during these resource bottlenecks when food is limited in other parts of their winter range (e.g., severe drought) that habitat loss within the HCC is most likely to impact the swift parrot population in the medium term 50- to 100-year timescale. This timescale, even though relevant from a planning perspective, is still extremely short term in an evolutionary context (Wright et al., 2008). Thus, even though the predicted decline is relatively modest in comparison to contemporary threats the species is facing—namely logging of breeding habitat and predation by sugar gliders during breeding (Heinsohn et al., 2015; Owens et al., 2022)—they are still concerning for the species' longer-term persistence over coming centuries.

In reality, loss of important swift parrot is not restricted to the HCC. Although it may be lower than within the HCC, development pressure is likely to impact swift parrot wintering habitat throughout south-eastern Australia over the next half century (Ward et al., 2019). Our results indicate this loss is predicted to lead to around a 16% decrease in the swift parrot population over the same timescale under our recovering population theme. In addition, our model scenarios are somewhat "best case" because they do not account for additional loss of important habitat due to factors such as megafire (Crates et al. 2022), drought-associated eucalypt dieback (Losso et al., 2022) and potential expansion of noisy miner and bell miner populations, which aggressively exclude swift parrots from potential foraging habitat (Leseberg et al., 2015; Mac Nally et al., 2012). It is extremely difficult to model the impacts of these factors with accuracy, however it is safe to assume they are all likely to further reduce the availability of important swift parrot habitat (i.e., realized niche space) over coming decades, particularly with the effects of climate change set to become more pronounced (Hartmann et al., 2013).

Uncertainties around the impacts of climate change on future habitat availability are but one way modeling approaches such as ours must be interpreted with a degree of caution. Swift parrots have been extensively studied in their breeding grounds over the past decade, so key demographic parameters can be estimated with a high degree of confidence (Heinsohn et al., 2015, Owens et al., 2022). However, uncertainties exist around the movement patterns of highly mobile species such as the swift parrot (Cottee-Jones et al., 2016). The degree to which most mobile species exhibit some fidelity to wintering sites or regions is largely unknown, and this makes it challenging to determine whether their populations can tolerate a degree of habitat loss by finding alternative winter foraging sites (Runge et al., 2014). The ability of animals to find alternative winter foraging sites will be determined by the carrying capacity of the environment (Chapman & Byron, 2018). This is also unknown because the swift parrot population is currently clearly most limited by threats in its Tasmanian breeding grounds. For this reason, we modeled two carrying capacity scenarios (cc = 1000 and 2000) which we considered the most plausible values

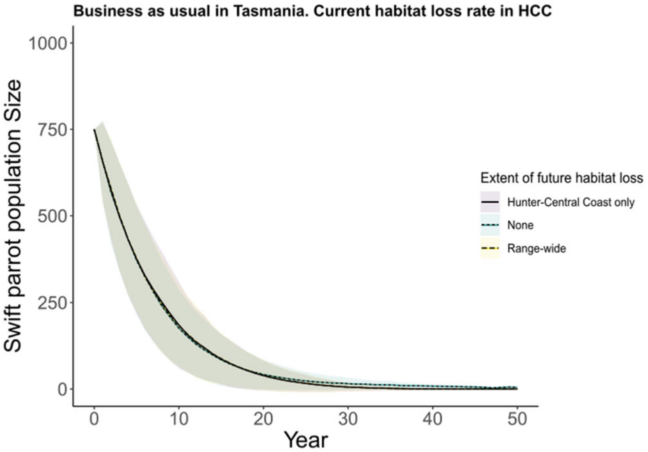

FIGURE 6 Swift parrot population trajectories assuming threats from sugar glider predation and logging in Tasmanian breeding grounds are not addressed. Trajectories assume either that (1) the current rate of swift parrot habitat loss continues within the Hunter-Central Coast (HCC) only (Scenario 4C); (2) the current rate of loss within the HCC occurs throughout the swift parrot's winter range (Scenario 4F); and (3) no future loss of important swift parrot habitat within the HCC or elsewhere (Scenario 4A).

based on our expert judgment. While the outcome of these scenarios differed in terms of final swift parrot population sizes, the proportional change in population size and overall trends under various levels of habitat loss were broadly similar across both carrying capacity scenarios (Figures 2 and 6). The initial increases reflect an elimination of the threats in Tasmania allowing the population to initially recover, which is more apparent in the scenarios with higher carrying capacity. This gives a degree of confidence that the cumulative impact estimates of our models in terms of proportional change in the size of the swift parrot population are relatively robust to variation in the swift parrot carrying capacity of mainland Australia.

An additional challenge to account for in the models is that different plant community types will vary in their relative importance to swift parrots (Roderick & Stuart, 2010). Even within plant community types, some areas will be more favorable than others due to the influence of microhabitat features such as soil moisture, elevation, and aspect (Watson, 2011). This information is currently not considered in government assessment of important swift parrot habitat in New South Wales. However, loss of key plant communities that produce rich nectar resources (e.g., low elevation spotted-gum-ironbark forest in the lower Hunter Valley) is likely to have a greater cumulative impact on the swift parrot population than the loss of an equivalent extent of habitats that occupy less fertile soils (e.g., red bloodwood-scribbly gum forest on dry sandstone ridges) and thus flower less prolifically (Watson, 2011). Devising ways to accurately assess the relative importance of all vegetation communities that are currently considered important foraging habitat for listed species is an important way of increasing the capacity of planning processes to avoid, minimize, and (as a last resort) offset potential cumulative impacts through future losses of important habitat.

Our results present the best evidence currently available that the long-term persistence of a highly mobile species could be jeopardized by the cumulative impacts of the loss of important foraging habitat. Such threats are of global relevance to a large number of taxa beyond birds. We therefore encourage decision-makers to explicitly consider potential cumulative impacts on listed species when assessing development proposals on a case-by-case basis, and ensure all reasonable measures are taken to avoid and minimize their occurrence. Our approach of estimating observed rates of important habitat loss and incorporating these loss rates into population models under a range of development scenarios could be used to help base planning decisions on the best available evidence. For instance, decision-makers could use the information to evaluate the potential longer-term cumulative impact of multiple concurrent development proposals (e.g., housing and infrastructure each in the tens to hundreds of hectares) on threatened species' habitats and their populations at the regional scale. This in turn could be used to better justify requests to revise individual development plans to minimize habitat loss locally. Models are only as good as the data available to construct them, however, so improved population monitoring is also needed to minimize assumptions and ensure models can predict threatened species' responses to habitat loss as accurately as possible.

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DATA AVAILABILITY STATEMENT

The study models demographic data synthesized from other empirical studies cited and presented within Table 1 of the manuscript.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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