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All the eggs in one basket: Are island refuges securing an endangered passerine?

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Abstract Refuges for threatened species are important to prevent species extinction. They provide protection from a range of environmental and biotic stressors, and ideally provide protection against all threatening processes. However, for some species it may not be clear why some areas are refuges and others are not. The forty-spotted pardalote (*Pardalotus quadragintus*) is an endangered, sedentary, cryptic and specialised bird endemic to the island of Tasmania, Australia. Having undergone an extreme range contraction over the past century the species is now mostly confined to a few small offshore island refuges. Key threatening processes to the species include habitat loss, wildfire, competition and predation. The ways in which these processes have molded the species' contemporary range have not been clearly evaluated. Furthermore, the security of the remnant population within refuges is uncertain. To overcome this uncertainty we assessed key threats and established the population status in known refuges by developing a robust survey protocol within an occupancy modelling framework. We discuss our results in the context of planning trial reintroductions of this endangered species in suitable habitat across its former range. We found very high occupancy rates (0.75–0.96) at two refuges and in suitable conditions, the species was highly detectable (p, 0.43–0.77). At a third location our surveys indicated a local extinction, likely due to recent wildfire. We demonstrate that all refuges are at high risk of one or more threatening processes and the current distribution across island refuges is unlikely to secure the species from extinction. We identified large areas of potential habitat across the species' former mainland range, but these are likely too distant from source populations for natural recolonisation. We propose that establishing new populations of forty-spotted pardalotes via reintroduction is essential to secure the species and that this is best achieved while robust source populations still exist.

Key words: conservation biology, forty-spotted pardalote *Pardalotus quadragintus*, refuges, threatening processes.

INTRODUCTION

The identification of refuges for at risk species is increasingly important to conservation biology (Keppel & Wardell-Johnson Grant 2012). In the Australian context, refuges can generally be defined as locations or habitat within a landscape that facilitate survival of species after disturbance events (e.g. fire, drought) or protection against introduced predators (Pavey *et al.* 2017). Refuges can originate through geographical isolation (e.g. islands), topographic position and vegetation types less prone to fire, or anthropogenic activities such as predator control, fencing and fuel reduction burning (Taylor *et al.* 2005). There are numerous cases where a species' survival hinges on its persistence within refuges (Morris 2000; Atkinson 2002; Webb *et al.* 2016). Understanding the processes that form refuges is critical to conservation management. Moreover, understanding the spatial and temporal nature of these processes is important to evaluate if the protection provided by a refuge is short-term (e.g. fire refuges, invasive species), or potentially long-term security (e.g. islands; Woinarski 2011). This will ultimately determine what actions can be undertaken to increase their effectiveness (e.g. fire management, reservation, biosecurity; Caughley 1994).

For small or rapidly declining populations, failure to act can quickly lead to extinction (Martin *et al.* 2012; Woinarski 2016). When a species has reached this critical stage, its distribution has often contracted to refuges (Lomolino & Channell 1995) and by default, these areas often become foci for conservation planning (Webb *et al.* 2016; Stojanovic *et al.* 2017). In such cases, conservation actions usually

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focus on the reservation of occupied habitat, increasing habitat area (Smith 2008) and evaluating how best to expand or protect refuges depending on spatial and temporal factors related to extinction risk (McCarthy *et al.* 2005; Schultz Courtney *et al.* 2013).

Typical approaches for threatened species in conservation are increasing population size (McCarthy *et al.* 2005); managing specific threats (Wilson *et al.* 2007), and *ex situ* conservation or translocations (Seddon 2015). If populations are viable but local habitat is at carrying capacity, creating 'new' populations (or restoring locally extinct populations) in suitable but unoccupied habitat may provide greatest cost-benefits rather than attempting to enlarge existing populations (McCarthy *et al.* 2005).

Despite islands being disproportionally represented in species extinctions (Blackburn *et al.* 2004; Tershy *et al.* 2015), conversely they can also provide critical refuges if threatening processes are absent (Taylor *et al.* 2005; Heinsohn *et al.* 2015; Lentini *et al.* 2018). Here, we examine the benefits of focusing management actions on the protection of refuges compared to actions that target threats, both historic, current and future. We use the case study of an endangered bird that now only occurs in refuges, primarily on islands (Threatened Species Section 2006). The forty-spotted pardalote (*Pardalotus quadragintus*) is a small, cavity nesting, leaf gleaning passerine dependent on white gums (*Eucalyptus viminalis*) for food, and primarily nests in tree cavities of eucalyptus species (Woinarski & Bulman 1985). Historically the species was widely distributed across Tasmania (Fig. 1) and it is now presumed extinct across most of its former range (Rounsevell & Woinarski 1983; Brown 1986). This range contraction has been occurring at least since the early last century and has continued over recent decades (Rounsevell &

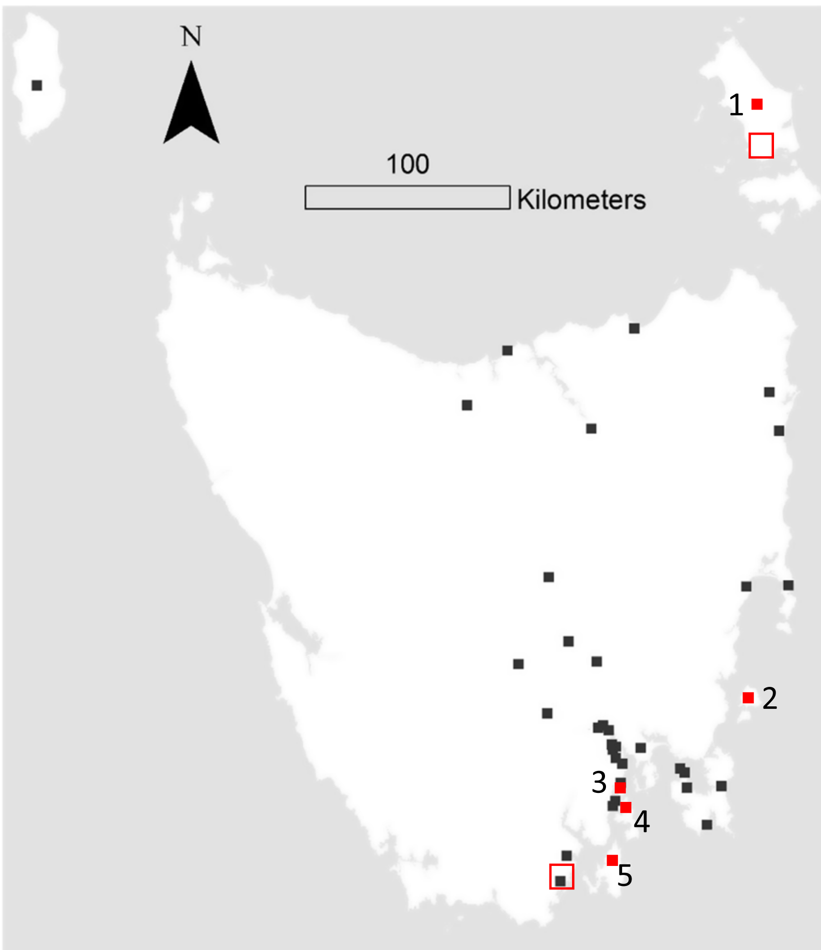

Fig. 1. Current refuges and historical locations of the forty-spotted pardalote; refuges (solid red squares), historical sites from Brown (1986) (black squares); 1, Flinders Island; 2, Maria Island; 3, Tinderbox; 4, North Bruny Island; 5, South Bruny Island; new sites identified during this study (open red squares). Historical locations obtained from (Table 1, Brown 1986). [Colour figure can be viewed at wileyonlinelibrary.com]

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Woinarski 1983; Threatened Species Section 2006; Bryant 2010). Three decades ago the species' area of occupancy was estimated to be <50 km^2, mostly on Bruny, Maria and Flinders Islands off the Tasmanian coast and a mainland location, Tinderbox Peninsula. Tinderbox Peninsula is <1.5 km from Bruny Island (Fig. 1; Appendices S1,S2), and based on genetic evidence is likely supported by birds dispersing from Bruny Island (Edworthy 2017). These locations are foci for the species' conservation, and 77% of refuge habitat has some level of statutory protection (Bryant 2010). Importantly, an implicit assumption of this approach is that the species can be secured from extinction at these locations.

The probable causes of the species' range contraction are diverse (Table 1). Likewise, it is not known whether forty-spotted pardalotes are now restricted to island refuges, or if they are capable of recolonising parts of their historical range on mainland Tasmania either naturally or through translocation (Threatened Species Section 2006). Here, we aim to: (i) quantify current threats to refuges and their security; and (ii) provide baseline population data. We use our results to examine management options to prevent further range contraction and evaluate potential for range expansion through reintroductions.

METHODS

Aim 1: quantifying the historical and future impact of threats and updating conservation assessments of refuge habitat

We focus on widespread threatening processes with strong evidence of direct impacts: (i) deforestation, (ii) wildfire, (iii) noisy miner *Manorina melanocephala* competition, and climate change (see Table 1), but also consider threats where impacts are more uncertain such as a newly discovered parasitic fly that can cause high nestling mortality (Edworthy 2018). For each threat, we evaluated the potential risk of it impacting refuges.

To assess the impact of recent deforestation, we quantified the area of core forty-spotted pardalote refuge habitat using two data sources: (i) a 30-year-old spatial layer of core refuge habitat (Brown 1986; Natural Values Atlas www.naturalvaluesatlas.tas.gov.au, accessed 1 September 2015) and (ii) a recent map of vegetation types TASVEG 3.0 (Department of Primary Industries, Parks Water and Environment 2013) to identify key forest habitats. We assessed contemporary habitat loss/disturbance using a spatial layer of forest loss derived from Landsat imagery at 30 × 30 m resolution (Hansen *et al.* 2013). Hansen *et al.* (2013) classifies 'forest loss' as the result of land clearing, timber harvesting and wildfire. Here, we defined the cumulative area of impact of these processes as

Table 1. Key threatening processes for the forty spotted pardalote, derived from Brown (1986) and Threatened Species Section (2006)

Threat	Description	Current threat extent	Potential extent of impact
Deforestation	The species is reliant on white gums (Woinarski & Bulman 1985; Brown 1986). Habitat loss at refuges and across the historical range through deforestation for agriculture, logging and urban development is strongly implicated in the species decline (Threatened Species Section 2006)	Entire range outside of reserves	Entire range outside of reserves
Wildfire	The effect of wildfire can be devastating on wildlife (Webb *et al.* 2016). Fire has been implicated in local extinctions (Bryant 2010). Intense fire can kill white gums; lower intensity fire can scorch tree crowns reducing or eliminating food availability. Too frequent burning may exacerbate these issues (Brown 1986). Tree cavity abundance can also decline after wildfire (Stojanovic *et al.* 2016)	Entire range	Entire range
Competitive exclusion by noisy miner (*Manorina melanocephala*)	Noisy Miners negatively impact bird communities via hyper-aggressive competitive exclusion of other bird species, and are listed as a 'key threatening process (Threatened Species Scientific Committee 2014). Currently noisy miners are absent from all remaining forty-spotted pardalote refuges. Noisy miner occurrence has been implicated in recent local extinctions (Brown 1986). Noisy miner distribution has increased with landscape modification (MacDonald & Kirkpatrick 2003; Thomson *et al.* 2015)	Tasmania mainland	Unknown
Climate change	Climate change has the potential to exacerbate the threats listed above, particularly wildfire and tree dieback	Unknown	Entire range

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deforestation area. Using ArcMap 10.2, we estimated the total area of potential habitat of the forty-spotted pardalote and the total area of habitat affected by recent deforestation.

The forty-spotted pardalote's current and historical distribution is highly fire-prone (Appendices S3,S4). To assess the potential historical impacts of fire on refuges, we used a spatial layer of fires in Tasmania (1969–2016; Tasmanian Fire Service 2017) to estimate the area of forty-spotted pardalote habitat affected by wildfire during this period. We also assessed the future risk of fires occurring in refuges using the Tasmanian Bushfire Risk Assessment Model (Parks and Wildlife Service, unpubl. data, 2014–2016) by quantifying the area of each refuge and its respective 'fire ignition potential'. Ignition potential in this model is based on the number of historical fires, lightning probability and Bureau of Meteorology observations.

Noisy miners do not currently occur in forty-spotted pardalote refuges. However, they are widespread on the Tasmanian mainland, having expanded with land clearance (MacDonald & Kirkpatrick 2003). To examine possible historical impacts of noisy miners on pardalote populations and assess the future risk of noisy miner colonisation of refuge habitat, we compared noisy miner environmental suitability of forty-spotted pardalote refuges and their historical range. We modelled environmental suitability for noisy miners across Tasmania using MaxEnt (Phillips *et al.* 2006). We used verified occurrence data with a location accuracy <500 m downloaded from the Atlas of Living Australia (ALA, http://www.ala.org.au, downloaded 4/9/2016). We also included unpublished data collected by the authors, resulting in a total of 1550 noisy miner records for modelling. Predictor variables were total rainfall during the driest quarter, mean temperature of the warmest quarter, minimum temperature of the coldest period, temperature seasonality, vegetation cover (cleared or not), and ecosystem type (11 categories, reclassified from the Major Vegetation subgroups from the National Vegetation Information System v4.1, Australian Government 2012); these variables are known to relate to noisy miner prevalence and abundance (Maron *et al.* 2013; Thomson *et al.* 2015). Based on model outputs, we assessed the environmental suitability of forty-spotted pardalote refuges for noisy miners. We reclassified the Maxent logistic output into predictions of noisy miner presence or absence using equal sensitivity and specificity threshold values for each year (Liu *et al.* 2013). This resulted in a map of predicted suitable or unsuitable environments. This map aimed to represent current suitability and did not account for potential expansion of the species resulting from future disturbance or a changing climate. The potential impacts of climate change were considered in the context of the species' highly restricted distribution and likely exacerbation of other known threats (e.g. fire).

Using the information outlined above and the combined expert knowledge of the authors we used a standard threat risk assessment process (Hart *et al.* 2005) to identify the relative future risk posed by each threat to each refuge (and habitat in the historical range) over a 30-year period. Each threat was assessed for the consequence to the species and the likelihood of that consequence happening (Supporting Information). Consequence was defined by the expected magnitude of the impact of a threat and the overall threat footprint. For example, habitat clearance in reserved refuges would be major but only small areas (i.e. threat footprint) are likely to be affected. Overall risk posed by each threat was then assessed using the consequence and likelihood ratings in a standard risk matrix (Supporting Information).

Aim 2: develop a monitoring protocol to provide baseline population data for refuges

There is currently no systematic monitoring program for the forty-spotted pardalote. To account for false absences (i.e. imperfect detection) we adopted a standard occupancy modelling approach (MacKenzie *et al.* 2002). We undertook baseline surveys on known pardalote refuges Maria Island, North Bruny Island and Flinders Island (Appendices S1–S3), which combined supports ~79% of the species contemporary area of occupancy, with the remainder occurring on South Bruny Island and Tinderbox Peninsula (calculated in ArcMap 10.2 using the spatial layer of habitat outlined above (Natural Values Atlas 2015). The number of sites and site visits is summarised in Table 5. As our objective was to estimate occupancy in critical habitat (i.e. forest containing white gum, *E. viminalis*), we used the spatial layer of refuge habitat outlined above as a guide for site selection. All sites had at least one white gum present, and were selected as follows: from a random starting point the nearest white gum was located which became the first sampling site. Subsequent sites were established by following a random compass bearing to the nearest white gum ≥200 m from the previous site. For logistical reasons the locations of sites on North Bruny Island were influenced by access and on Maria Island sites were restricted to within ~100 m of existing walking tracks (Appendix S1). We used repeated five-minute visits to record the presence/absence of birds within 100 m of the site (based on calls and observation). Monitoring was conducted intermittently between 2010 and 2016. Other locations in the historical range were surveyed opportunistically.

The forty-spotted pardalote is extremely cryptic owing to its soft call, small size, and two other sympatric pardalote species (*Pardalotus striatus* and *Pardalotus punctatus*; Rounsevell & Woinarski 1983). During the species' breeding season (i.e. spring/summer), several avian migrants and other resident species, can form noisy aggregations that can drown out the soft vocalisations of the forty-spotted pardalote. To increase and control for variation in detectability, we restricted our surveys to still, clement weather in the non-breeding season (i.e. autumn/winter, when migratory species had left the study area) to maximise the likelihood of detecting the soft calls of the target species. We used occupancy modelling to estimate overall occupancy (Ψ) in critical habitat for each refuge. We fitted simple constant occupancy models using the package *unmarked* in R (R Development Core Team 2008; Fiske & Chandler 2011). We used estimates of detectability (p) to assess the reliability of absences at other locations where data were too sparse.

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RESULTS

Aim 1: quantifying the historical and future impact of threats and updating conservation assessments of refuge habitat

The species' area of occupancy based on mapped habitat (Natural Values Atlas www.naturalvaluesatlas.tas.gov.au, accessed 1 September 2015) was estimated as ~42 km^2, but only 35.5 km^2 of this area is currently eucalypt forest and woodland. According to our overall risk assessment, all refuges face high, very high, or extreme risks from multiple threats (Table 2). Consequence and likelihood ratings for each threat in each refuge are provided in Appendix S6.

Only 0.82 km^2 (<2%) of refuge habitat has been affected by deforestation since ~1996. Overall, deforestation through habitat clearance is likely to be relatively low risk to refuge populations, as 77% (Bryant 2010) of refuges has some level of statutory reservation and risk level was identified to vary depending on the location (Table 2). Furthermore, fire is likely the cause for ~75% of the disturbance classified as deforestation (Hansen *et al.* 2013).

Historical fire mapping indicates that of all refuge habitat has burned since 1969 (17%, 7.1 km^2), with most of this (62%, 4.1 km^2) attributable to the 2003 fire on Flinders Island (Appendix S3). Other fires in refuge habitat were smaller (mean 0.12 km^2; range 0.0002–1.2 km^2) and 83% of extant habitat has not burned for >45 years. The Tasmanian Bushfire Risk Assessment Model identifies 83% of refuge habitat as having a moderate to very high ignition potential (Table 3).

Our MaxEnt model of noisy miner distribution indicates that an area of 10 587 km^2 across Tasmania is climatically suitable for the generalist noisy miner (Fig. 2, see Supporting Information for model details). Environmental suitability for noisy miners is high across most of the former and present distribution of the forty-spotted pardalote and they are well-established <4 km from all refuges except Flinders Island (Fig. 3). The percentage area above the threshold value of noisy miner environmental suitability for each pardalote refuge varied from 0% to 81% (Table 4).

Table 3. Ignition potential of forty-spotted pardalote refuge habitat (km^2) as per the Tasmanian Bushfire Risk Assessment Model (DPIPWE 2017)

	Ignition potential area (km^2)				
Location	Very low	Low	Moderate	High	Very high
Maria Island	1.8	0	18.5	0	0
Bruny Island	0	1.1	2.8	0	9.6
Tinderbox Peninsula	0	0	0	0	4.4
Flinders Island	0	0	0	3.3	0
Total area	1.8	1.1	21.3	3.3	14

Aim 2: develop a monitoring protocol to provide baseline population data for refuges

On North Bruny Island and Maria Island estimates of pardalote Ψ were high in all years (range 0.75–0.96, Table 5). Detectability for a single site visit was also high but more variable (0.43–0.77). Over the entire study period the species was recorded at 59 of 67 sites (88%) on Maria Island, 55 of 61 sites (90%) on Bruny Island, and only 7 of 115 of sites (6%) on Flinders Island. The mean number of birds counted at a site (given presence) was 2.2 (range 1–6).

No birds were detected at any previously known forty-spotted pardalote sites on Flinders Island despite visiting these sites more often than other areas (up to five site visits in each year). A 'new' location was discovered on Flinders Island but is separated from the previously known refuge by >20 km of primarily agricultural land (Appendix S3). The species was also found in small patch of habitat (~10 ha) near Southport, on the Tasmanian mainland (Fig. 1). The last record of the species in the vicinity of Southport was >120 years ago. Too few data (and birds) were available to model Ψ or p at these locations (Table 5).

Table 2. Threat risk assessment for forty-spotted pardalote refuges and habitat in its former range in the next 30 years

Location	Fire	Noisy miner colonisation	Deforestation	Climate change
Maria Island	Very high	Moderate	Moderate	Very high
North Bruny Island	Very high	Very high	High	Very high
Tinderbox	Very high	Very high	Very high	Very high
South Bruny Island	Very high	Very high	High	Very high
Flinders Island	Extreme	Low	High	Very high
Southport	Extreme	Moderate	High	Very high
Large patches of intact habitat in former range	Unknown	Low	Unknown	Very high

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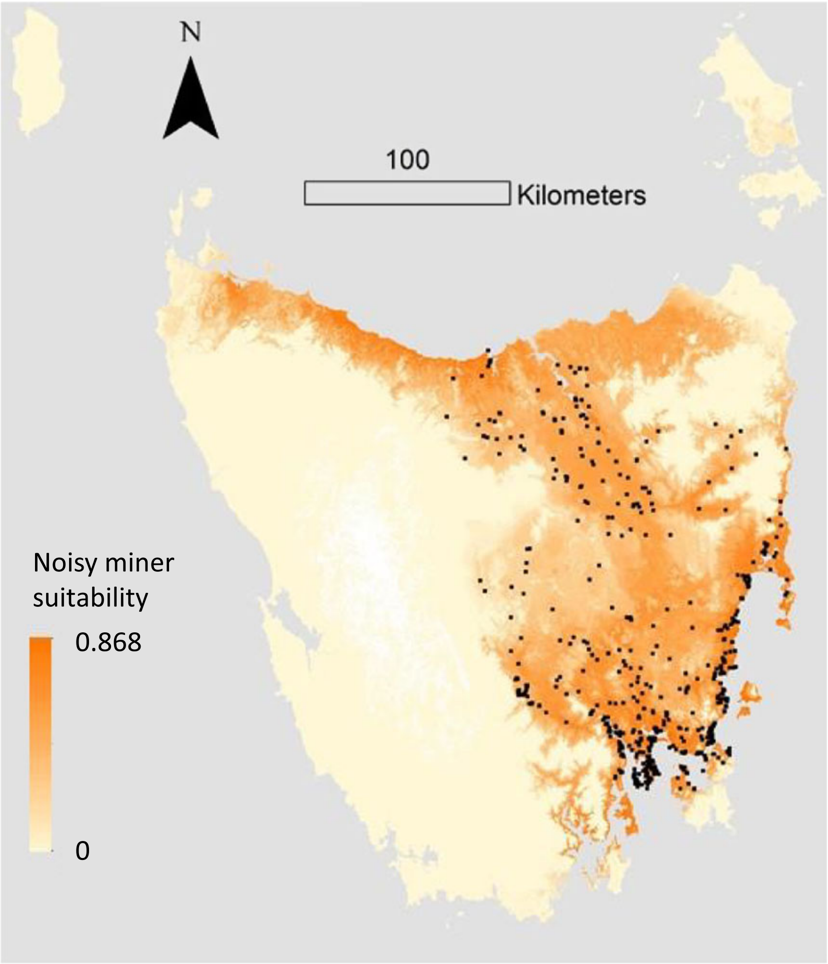

Fig. 2. Estimated environmental suitability for noisy miners in Tasmania; noisy miner records (black squares). [Colour figure can be viewed at wileyonlinelibrary.com

DISCUSSION

The forty-spotted pardalote is now predominantly confined to island refuges. The species is at risk from multiple threats across this highly restricted range. We have established baseline population data and quantified the historical impacts and future potential risks of threats to refuge populations. We demonstrate that occupancy rates are very high at two refuges (Maria and Bruny Islands) and that the Flinders Island population is almost extinct. This provides the first standardised quantitative assessment of refuge populations providing a baseline for assessing change in population size using Ψ as a surrogate for abundance (MacKenzie & Nichols 2004). Deforestation in refuges has abated in recent decades and these areas appear to currently support viable populations. However, our threat risk assessment (Table 2) found all refuges are extremely vulnerable to multiple threats including wildfire, colonisation by the hyper-aggressive noisy miner and climate change. Islands have clearly provided critical refuges from threatening processes; however, our results indicate that these refuges are not secure from these threats despite being extensively reserved.

Fire frequency, intensity, and extent are expected to increase with climate change in this ecosystem (Fox-Hughes *et al.* 2014; Grose *et al.* 2014). In this case, the islands have clearly provided protection from fire; however, most refuge habitat has not burnt for a long time(and therefore currently support high fuel loads) and has a high ignition potential suggesting severe fire(s) are likely under suitable weather conditions (Table 3 & Appendix S4). Hence, refuges have only provided temporary protection at different spatial scales, but not security. The impact of fire will depend on fire severity, frequency and the spatial configuration and extent of burned and unburned habitat (Prowse *et al.* 2017). For example, a single severe fire on Flinders Island in 2003 (Appendix S3) that burned an entire patch of refuge habitat has likely resulted in another local extinction. Despite

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some forest recovery, the location remains unoccupied by forty-spotted pardalotes over a decade later. In contrast, several decades ago a fire burned all of south Maria Island (Appendix S1), but was recolonised 2 years later likely due to immigration from nearby refuge habitat (<1 km) on the north of the island (Rounsevell & Woinarski 1983). Importantly, when compared to the size of many large fires the small size of refuges means that they are all at risk of being totally destroyed with little chance of recolonisation.

The value of a refuge for forty-spotted pardalotes post fire will also depend on interactions with other biota including competition, predation, and parasitism (Lindenmayer *et al.* 2006; Kirkpatrick *et al.* 2011). Under post-fire conditions introduced herbivores may suppress regrowth and structural complexity of forest (Driscoll *et al.* 2010; Kirkpatrick *et al.* 2011), thus increasing environmental suitability for noisy miners (MacDonald & Kirkpatrick 2003; Maron & Kennedy 2007; Maron *et al.* 2011) or result in increased predator abundance (Hradsky *et al.* 2017). While high nestling mortality is caused by the newly discovered native parasitic fly (Edworthy 2017) it is unknown what the overall potential threat this poses. However, its effect likely varies in time and space depending on environmental conditions (e.g. Antoniazzi *et al.* 2010) and may be exacerbated under post fire conditions and climate change (Møller *et al.* 2014). Longitudinal (and larger scale) studies are required to determine the role of the parasitic fly on population dynamics for the forty-spotted pardalote.

We identify a large area of climatically suitable habitat for noisy miners across Tasmania (Fig. 2). The high bioclimatic suitability of most forty-spotted pardalote refuges for noisy miners, and their proximity to refuges (<4 km) suggests there is a very high likelihood of colonisation (Fig. 3). Given that noisy miners favour fragmented environments (MacDonald & Kirkpatrick 2003; Maron *et al.* 2013), the impacts of colonisation of refuges may vary depending on local forest fragmentation (Appendices S1,S2). Since most occupied habitat on Bruny Island is adjacent to fragmented agricultural land, noisy miners could penetrate most pardalote refuges. By contrast, forest on Maria Island is more intact providing less opportunities for miner expansion, but historically cleared areas maybe ideal for noisy miners. Furthermore, intense grazing by introduced herbivores across large parts of Maria Island severely suppresses understory vegetation, reducing (or eliminating) cover which may advantage noisy miners (Maron & Kennedy 2007; Maron *et al.* 2011). Thus, our use of vegetation mapping likely provides an optimistic view of the area of 'intact' forest.

Table 4. Total area of each forty-spotted pardalote refuge and the percentage of each refuge above the equal test sensitivity and specificity threshold for Noisy Miner environmental suitability

Location	Area (km^2)	Area above environmental suitability threshold (%)
Maria Island	20.3	81
North Bruny Island	8.6	91
South Bruny Island	6.9	17
Tinderbox Peninsula	4.4	16
Flinders Island	1.2	0
Total area	41.4	63

Historical range contraction

Failure to account for historical processes that have resulted in a species' current range can lead to misleading inferences about a species' ecological niche (Warren *et al.* 2014). Since European settlement, waves of local extinctions caused by large scale land clearance, subsequent habitat fragmentation and stochastic events (e.g. wildfire) and habitat fragmentation most likely resulted in no refuge populations to recolonise recovering habitat. We argue that these processes probably disrupted pre-existing extinction-

Table 5. Occupancy (Ψ) and detectability (*p*) estimates in forty-spotted pardalote refuges surveyed between 2010 and 2016

Location	Year	No. sites	Site visits	Naïve Ψ	Ψ	SE	*p*	SE
Maria Island	2010	37	3	0.784	0.96	0.114	0.432	0.069
	2011	67	2	0.806	0.869	0.059	0.730	0.054
	2012	66	2	0.667	0.750	0.075	0.667	0.067
	2016	66	2–3	0.727	0.757	0.058	0.773	0.046
North Bruny Island	2011	61	3	0.754	0.937	0.094	0.420	0.055
	2016	61	3	0.787	0.814	0.055	0.678	0.433
Flinders Island	2010, 2011, 2012	115	2–10	0.061	–	–	–	–
Southport	2014, 2015	6	4	1.0	–	–	–	–

Naïve Ψ (proportion of sites birds detected), Ψ (modelled occupancy), *p* (detectability); occupied locations at Southport and Flinders Island were discovered during this study.

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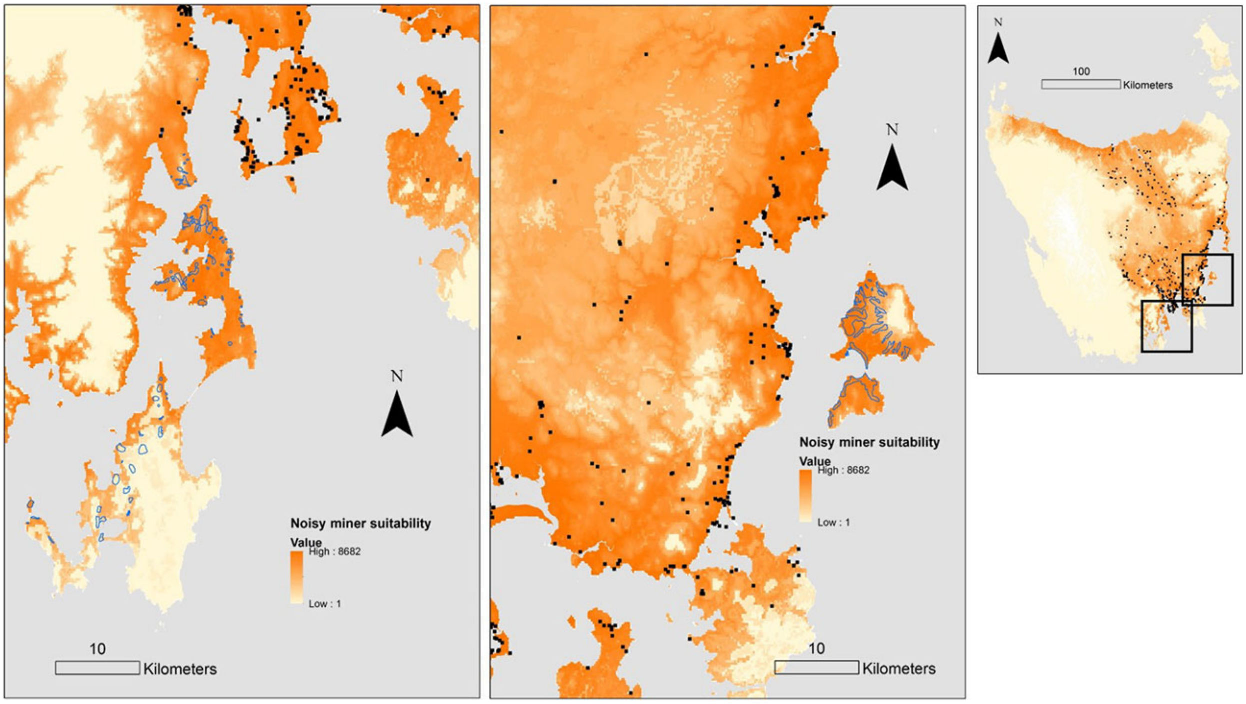

Fig. 3. Noisy miner environmental suitability estimated from MaxEnt model; forty-spotted pardalote refuge habitat on Bruny Island and Maria Island (blue lines), noisy miner records (black squares). [Colour figure can be viewed at wileyonline library.com

colonisation dynamics, causing the species' range contraction. Some potential habitat in the species' historical range appears to be suitable forty-spotted pardalote habitat (M.H. Webb, F. Alves, S. Bryant & D. Stojanovic, pers. obs.). However, the threatening processes (outlined above) allowed the concomitant expansion of noisy miners (and other aggressive birds with a similar niche), thus preventing dispersal through the agricultural matrix and recolonisation of suitable habitat. Considering the spatial and temporal nature of the processes that caused the species range contraction, we suggest that suitable habitat may be available, but natural recolonisation is no longer possible.

Translocations in the species historical range

We call for immediate action to identify and prioritise potential reintroduction sites for the forty-spotted pardalote and attempt to establish new populations while apparently viable source populations exist within refuges. Moreover, reintroducing individuals from wild sources can be more effective since even small amounts of genetic adaptation in captive-bred individuals may negatively impact long-term wild population size and genetic diversity (Willoughby & Christie 2018). We propose that any attempt would undertake a structured decision-making process to identify an optimal source population (as per Wauchope *et al.* in press). There are well-established protocols to inform conservation reintroducitons (IUCN/SSC 2013) and many precedents to inform a pardalote program (e.g. Taylor *et al.* 2005; Ortiz-Catedral & Brunton 2010; Collen *et al.* 2014).

Revegetation programs usually result in small areas of the landscape being revegetated (Thomson *et al.* 2015), require large investments (Atyeo & Thackway 2009; Menz *et al.* 2013) and take many years to achieve their objectives. Targeted revegetation programs (Understorey Network 2011) at refuges may eventually increase the area of occupancy, but this will not address the immediate threats to these refuges.

The creation of new populations via translocation may provide substantial opportunities to secure the species, particularly we are proposing reintroductions into the species former range. There is currently >1100 km^2 of white gum forest across the species former range, 610 km^2 of which occurs in patches >1 km^2 in area (mean, 3.1 km^2; SD 4.4 km^2) and often form a part of larger forest remnants (Harris & Kitchener 2005; Fig. S5). Despite the high climatic suitability of much of the former range for noisy miners, they rarely occur in the intact interior of larger forest patches (Maron *et al.* 2013); these areas may be ideal for creating new populations. In this context, a common failure in conservation planning is that

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locations designated as critical habitat rarely include suitable but unoccupied locations (Camaclang *et al.* 2014) and currently unoccupied potential habitat within the species' former range is afforded no legislative protection.

While reintroductions may be perceived as a 'risky' strategy (Ricciardi & Simberloff 2009) and the outcomes uncertain in some instances (e.g. persistence, population growth rate), they may be essential for the species' long-term survival and knowledge gained from undertaking such actions may be extremely valuable (Rout *et al.* 2009). Because of the current threats to refuges we believe any risks associated with translocations far outweigh the risks of not acting. Moreover, our assessments show that this opportunity could rapidly be lost due to collapse of refuge populations (e.g. Flinders Island), or clearance of potential reintroduction sites and action must be undertaken promptly.

CONCLUSION

Our study highlights the need to consider the processes that create refuges for endangered species, and if they provide long-term security or merely represent the final locations to be affected by threatening processes. Diagnosing the processes that have led to a species current distribution is extremely valuable because previous local extinctions does not necessarily mean these sites remain permanently unsuitable, and vice-versa.

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SUPPORTING INFORMATION

Additional supporting information may/can be found online in the supporting information tab for this article.

Appendix S1. Occupied forty-spotted pardalotehabitat (blue)on Maria Island and North BrunyIsland, eucalypt forest and woodland (green); survey sites (black squares).

Appendix S2. Forty-spotted pardalote habitat (blue) on South BrunyIsland, eucalypt forest and woodland (green).

Appendix S3. Summary of Forty-spotted Pardalote surveys on Flinders Island in 2010, 2011 and 2012. Black circles are sites where the species was detected; grey circles are sites where it was not detected; grey stippling, wild fires since 2002.

Appendix S4. Extent of the most recent fire since 1969 (red), current forty-spotted pardaloterefuges in southeast Tasmania (blue lines).

Appendix S5. White gum dominated forest (red), human modified environments (light green), other forest and woodland (grey), other systems (white); derived from TASVEG 3.0.

Appendix S6. Threat risk assessment process for the Forty-spotted pardalote (following Hart *et al.* 2005).