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Further knowledge and urgent action required to save Orange-bellied Parrots from extinction

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ABSTRACT

Only three wild-bred female Orange-bellied Parrots returned from migration in the 2016/17 breeding season, representing the lowest point of a long-term decline. In this context of imminent extinction risk we (i) update knowledge of population parameters, (ii) critically evaluate current recovery actions, and (iii) identify new management options. We present new data from the 2016/17 breeding season. Orange-bellied Parrots were only observed at the last known breeding site where fire suppression may havecaused shortage of natural food. Recently burned habitat elsewhere support abundant food, but no parrots. Fecundity of captive-bred individuals was significantly worse than wild-bred individuals (0.8 vs. 3 fledglings respectively), mostly due to infertility. Bacterial septicemia due to contaminated food caused mortalities of at least four nestlings. Fostering captive-bred nestlings to the wild showed some potential as a recovery tool, with 2 of 4 nests accepting a foster nestling, and one of these fledging successfully. Captive-bred birds had poorer feather condition than wild birds. Addressing food shortages and the addition of new managementactions to improve population recruitment are critical and urgent recovery priorities. We suggest recovery priorities for the species arising from our results, including emergency intervention to prevent imminent extinction.

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Neophema chrysogaster; endangered species; conservation action; reintroduction; extinction; captive breeding

Introduction

Orange-bellied Parrots (*Neophema chrysogaster*) are arguably the most threatened parrot species in the world because in the 2016/2017 breeding season the wild-bred population declined to only 3 females and 13 males (Troy 2017). They migrate annually between coastal, south-eastern mainland Australia in the winter and south-western Tasmania in the summer, where they breed (Higgins 1999). Although subject to conservation management since 1984 (Department of Environment, Land, Water and Planning 2016), there is considerable uncertainty about the causes of decline and which actions are effective for protecting the species. Habitat loss, migration mortality, and Allee effects (e.g. sex ratio bias and low female breeding participation) may be key drivers of decline (Crates *et al.* 2017). However, empirical evidence to support these assumptions, aid decision-making and evaluate outcomes of action is limited (Department of Environment, Land, Water and Planning 2016). This is reflected in the limited number of peer-reviewed studies on the species' ecology and threats (Table S1), despite the intensive, long-term conservation attention directed at its protection (Department of Environment, Land, Water and Planning 2016).

In 1986 a population of Orange-bellied Parrots was established in captivity (Smales *et al.* 2000) and later supplemented with new genetic material (Martin *et al.* 2012). Captive-bred birds have been repeatedly released (Department of Environment, Land, Water and Planning 2016) but this effort has not had a demonstrated lasting positive impact on the wild population. For example, 423 Orange-bellied Parrots were released at Birch's Inlet between 1999 and 2009, but that subpopulation died out and releases ceased at that site (Department of Environment, Land, Water and Planning 2016). Likewise, at the last known wild breeding site (Melaleuca; Figure 1), release of captive individuals has not improved migration return rates (Troy 2017).

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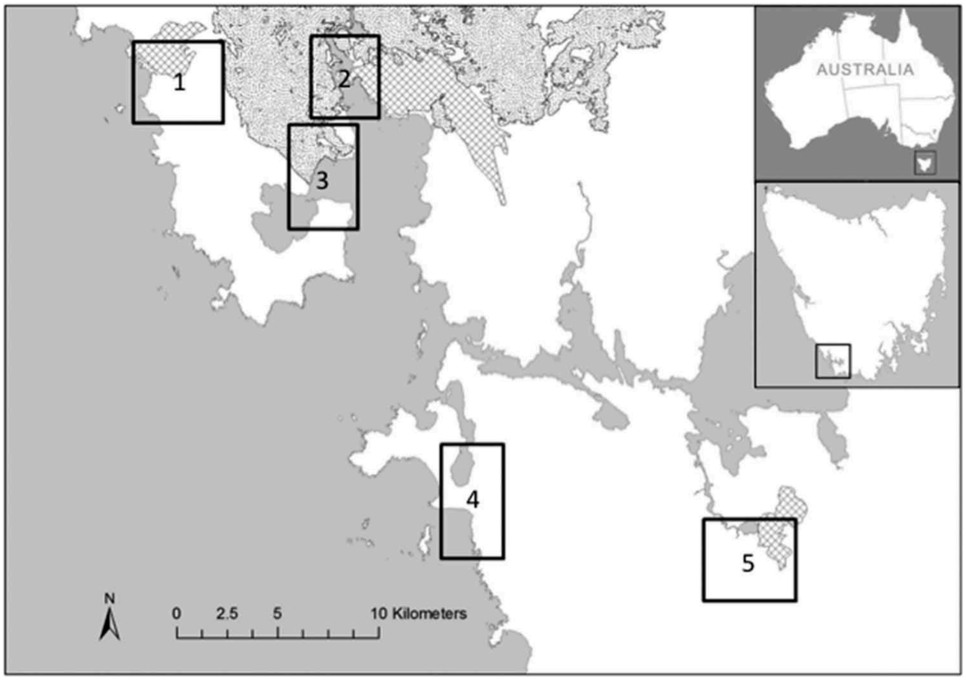

Figure 1. Map of the study area, focusing on the broader Tasmanian Southwest World Heritage Area, Tasmania, Australia. Our study sites were: 1 – Towterer Beach, 2 – Settlement Point, 3 – Bond Bay, 4 – Noyhener Beach, and 5 – Melaleuca (the location of the only known extant subpopulation). Boxes encompass the areas searched at each study site. Areas burned by fire in 2011 (cross-hatched) and 2013 (stippled) are indicated.

In this context of imminent extinction risk we aim to (i) update knowledge of population parameters, (ii) critically evaluate current recovery actions, and (iii) identify new management options. To achieve these aims, we present new data from the 2016/2017 breeding season, focusing on (1) persistence of spatially discrete subpopulations and habitat suitability at historical sites, (2) comparing fecundity of captive-bred vs. wild-bred individuals, (3) evaluation of fostering of nestlings as a recovery tool, and (4) veterinary observations of the health of wild- and captive-bred birds.

Methods

Study species and area

Orange-bellied Parrots nest in moorlands in the Tasmanian Wilderness World Heritage Area, Australia. The population is believed to survive at only one known location (Melaleuca; Figure 1, site 5), where it has been monitored since 1979 (Department of Environment, Land, Water and Planning 2016). At Melaleuca, breeding occurs almost entirely in nest boxes, and birds are monitored via observations at food tables where seed is provided ad libitum throughout the breeding season (Department of Environment, Land, Water and Planning 2016). Since 2013, release of captive-bred Orange-bellied Parrots has been undertaken at Melaleuca annually (annual mean 22 birds ± 6 SD; Figure 2) (Troy 2017). At the start of the 2016/2017 breeding season, the wild-bred Orange-bellied Parrot population was male biased (four males per female) before a spring release of captive-bred birds (n = 15 females, n = 8 males; Troy 2017). Spring release of captive-bred birds increases the number of nesting attempts recorded at Melaleuca because both wild-bred and captive-bred females attempt to breed (Troy 2017).

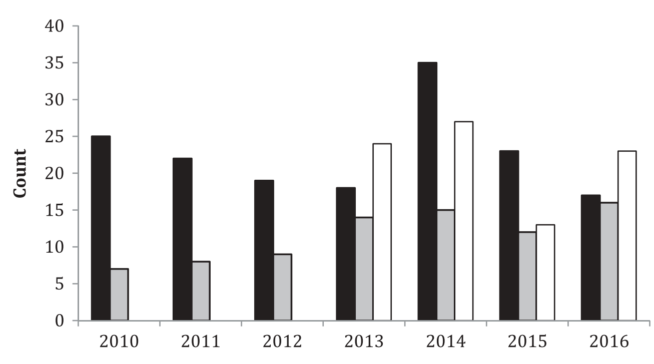

Figure 2. Time series showing the number of wild-bred and captive-bred Orange-bellied Parrots returning from migration (black), nesting attempts initiated (grey), and captive-bred individuals released (white). Derived from Troy (2017).

Persistence of Orange-bellied Parrots and habitat suitability at historical sites

Vegetation dynamics in south-west Tasmania are shaped by fire history (Marsden-Smedley and Kirkpatrick 2000). Before 1830, Aboriginal burning regimes in Tasmanian moorlands were characterised by frequent, small-scale, high-frequency, low-intensity fires. Since European settlement, altered fire regimes have resulted in larger, less frequent, more intense fire (Marsden-Smedley 1998). Consequently, moorlands across south-western Tasmania are predominantly old-growth (Marsden-Smedley and Kirkpatrick 2000), and thus are poor habitats for the food plants of Orange-bellied Parrots (e.g. *Actinotus bellidioides*, *Helichrysum pumilum*, *Eurychorda complanata*, *Boronia citriodora*) (Department of Environment, Land, Water and Planning 2016). Food plants may be most abundant within 8 years after fire (Brown and Wilson 1980).

We aimed to identify areas of historical habitat that (i) support extant Orange-bellied Parrot subpopulations and (ii) support abundant food plants. We undertook field surveys during late January/early February 2017 when Orange-bellied Parrots are more detectable due to increased activity of fledglings and post-breeding adults. We used helicopters to access four remote locations where potential breeding habitat occurs (Noyhener Beach, Towterer Beach, Bond Bay, Settlement Point; Figure 1) based on information from the species recovery plan (Department of Environment, Land, Water and Planning 2016). Fire has affected these sites to different extents over the last decade (Figure 1). A large wildfire burned Bond Bay and Settlement Point in 2013. Smaller fires affected Melaleuca and Towterer Beach in 2011. Noyhener Beach has not been burned in the last decade. These sites have not been surveyed for Orange-bellied Parrots in 5–10 years, and the species has not been detected breeding away from Melaleuca since 2008 (Holdsworth, unpub. data). Roaming searches were undertaken at each site in potential foraging habitat (i.e. moorland) and the edges of potential nesting habitat (*Eucalyptus* dominated forest patches). Although seeds and flowers of many plants are eaten by Orange-bellied Parrots, we focused on *Actinotus*, *Helichrysum*, *Eurychorda* and *Boronia* because they are considered key foods during breeding (Department of Environment, Land, Water and Planning 2016). We undertook a rapid survey of the relative abundance of these four plants at ~150 m intervals during roaming searches (125–150 sites per location), covering approximately 4 km^2 at each location. We did not attempt to quantify the abundance of edible parts of food plants. Vegetation composition of food plants was visually estimated as absent/low density (0–10% vegetation cover) or medium/high density (>10% vegetation cover) at each survey point. We compared food availability at historical sites relative to fire history (burned/unburned within the last decade) using generalised linear models (quasibinomial distribution, logit link) with food abundance as a response variable and burned/unburned as a fixed effect (implemented in R; R Core Development Team 2016). Following the same track as taken on the first survey, each route was surveyed two to three times by constantly visually scanning and listening for the calls of Orange-bellied Parrots. They are easily identified in their breeding range because they are vocal and few other similar parrot species occur in the area, reducing the risk of observer error. Our survey was undertaken late in the breeding season when fledglings (if present) were expected to have just left the nest; at this time Orange-bellied Parrots are easily detectible due to their increased activity. Given that our aim was to establish the presence/absence of the species at each site, we are confident that our method accounted for potential problems associated with failure to detect parrots had they been present. By repeating surveys we attempted to account for potential problems associated with false absences; however, no standardised observational survey method exists to account for imperfect detection.

Reproductive success of captive-bred vs. wild Orange-bellied Parrots

All nest boxes deployed at Melaleuca as part of the ongoing recovery effort (n = 74) were checked at approximately 10-day intervals early in the breeding season to detect nesting attempts by Orange-bellied Parrots. We used motion-activated cameras (Hyperfire HC600 and Ultrafire XR6; Reconyx Inc.) and direct observations to monitor nests. We deployed cameras within 1 m of all nest boxes occupied by Orange-bellied Parrots from the day the nest was found until fledging/death of the last nestling. We identified the provenance of all individuals that attempted to breed, i.e. captive-bred or wild-bred, based on their unique leg rings (Holdsworth *et al.* 2011). At every nest, we recorded the number and fertility of eggs, and the number of hatchlings and fledglings. We compared clutch and brood data from the nests of captive-bred and wild-bred birds using Wilcoxon signed rank tests implemented in R (R Core Development Team 2016). Egg fertility was determined by candling using a small flashlight or dissection of unhatched eggs.

Evaluation of nestling fostering as a recovery tool

Infertility in wild- and captive-bred Orange-bellied Parrots is a problem that wastes breeding effort and conservation resources. We aimed to address this issue by evaluating whether fostering of captive-bred nestlings to nests initiated at Melaleuca is a potential on-ground management tool for improving utilisation of infertile captive-bred, released birds. Fostering of nestlings has been used successfully to improve breeding success in other parrots (Beissinger *et al.* 2008). Fostering was undertaken within three key licensing constraints: (i) only nestlings – not eggs – could be fostered; (ii) only nests of captive-bred birds released at Melaleuca could be used as hosts – i.e. nests of wild-bred birds were excluded; and (iii) foster nestlings could be harvested from only three captive pairs (housed *ex situ* in Hobart). Nests at Melaleuca were selected for the trial if they were synchronised with the Hobart captive nests (n = 4 nests were chosen based on similar dates of egg laying).

On 15 January 2017 we used a helicopter to transfer five foster nestlings from Hobart to Melaleuca (~110 km, drive plus flight time = 60 min) in heated containers. We selected the youngest possible foster nestlings (0.5–4 days old). Older foster nestlings were allocated to nests where hatchlings were already present (wing length was used to identify similarly aged nestlings). The youngest nestlings were allocated to nests with infertile eggs that were within 5 days of expected hatch dates. Nests were checked on the first day after 6 h (except for nest four which was checked at 3 h, then again at 6 h). After 24 h, checks were reduced to the same frequency as other nests (see above).

Veterinary assessment of the population

A qualified avian veterinarian (A.P.) opportunistically examined Orange-bellied Parrots on 26–27 January 2017 at Melaleuca. Physical examinations were carried out on nestlings (one to three per nest) from three active nests on 26 January and on six adults captured at food tables on 27 January. Examination included visual assessment of behaviour, respiration and plumage characteristics and physical assessment of body condition, oropharyngeal cavity and plumage. Feathers were collected from captured adult birds, including contour feathers from each individual and two broken flight feathers from captive-bred birds, and examined stereomicroscopically. Fresh Orange-bellied Parrot faeces were visually examined at two food tables on 27 January.

Results

Persistence of Orange-bellied Parrots and habitat suitability at historical sites

Survey effort totalled 20 survey days (5 days per site, 8–10 h survey effort per day) and covered moorland (potential foraging habitat) and forest edges (potential nesting habitat) at each location. Orange-bellied Parrots were not detected at any of the four sites. Because no birds were observed it was not possible to estimate detectability or any other parameters. Historical locations were significantly more likely to support food plants if they were recently burned (proportion of sites with medium/high food plant abundance was 48% for burned vs. 5% unburned; df = 2, residual deviance 0.0115, $\chi^2 < 0.001$). At Melaleuca, which experienced a small fire in 2011, only 28% of surveyed sites supported medium-/high-density food plant abundance. Within burned areas, food plant distribution was patchy. When present, food plants could comprise >25% of survey site vegetation cover, and these sites were characterised by low vegetation height (<50 cm) and cover (<60%). Most sites where food plants were absent/low density supported >15 year unburned scrub or steep rocky hillsides with skeletal soils. Food plants were also generally absent where dense scrub occurred prior to recent fire (identified by the presence of dense dead, standing woody debris) or where shrub regeneration had established.

Reproductive success of captive-bred vs. wild Orange-bellied Parrots

We monitored 17 nesting attempts by 13 female parrots (Table 1). Two of three wild/wild pairings were attributable to the same wild female, and only two of three wild-bred females that returned from migration attempted to breed. We observed nesting attempts by (i) wild-bred females with wild-bred males (wild/wild: n = 2 pairs), (ii) captive-bred females with wild-bred males (captive/wild: n = 13 pairs), and (iii) captive-bred females with captive-bred males (captive/captive: n = 1 pair). Wild/wild pairs had more than double the breed-

Table 1. Reproductive parameters of Orange-bellied Parrot nests initiated at Melaleuca in 2016/2017. 'Provenance' indicates whether the breeding female was captive- or wild-bred. Data are mean values and parentheses indicate range.

Provenance	Count	Eggs	Hatched	Fledged	Fledglings/eggs (%)
Wild	3	4.7 (4–6)	3.7 (3–4)	3.0 (2–4)	64
Captive[a]	14	3.1 (1–5)	1.0 (0–4)	0.8 (0–4)	26

[a]Includes any pairing where one or both breeders was captive-bred.

ing success (fledglings/eggs) of pairs involving captive-bred females (64% vs. 26%). Compared against wild-bred females, captive-bred females produced comparable clutch sizes (W: 9, P: 0.1302), but significantly fewer hatchlings (only 14/43 eggs hatched; W: 3, P: 0.0192) and fledglings (n = 10 fledglings, plus one foster fledgling; W: 4.5, P: 0.0237). The captive/captive pairing produced five infertile eggs, but successfully fledged a foster nestling (below). Seven clutches of eggs laid by captive-bred females were completely infertile. Captive-bred females incubated infertile eggs up to a week beyond their expected hatch dates. Although presented here as nesting attempts, we twice detected individual eggs abandoned in nest boxes. Nearby these abandoned eggs, captive-bred females subsequently attempted to nest, so abandoned eggs were likely attributable to those females.

Evaluation of nestling fostering as a recovery tool

Two of four fostering attempts were successful, and one of these nests successfully reared a foster nestling to fledge. Outbreak of *Pseudomonas aeruginosa* following provision of contaminated seed at Melaleuca (Troy 2017) contributed to the death of at least one foster nestling. Nestling fates and the characteristics of host nests (nests 1–4) are outlined in Table 2. On the first check, we found the foster nestling dead in nest 1 (unknown cause). At nest 2, both the foster and host nestlings appeared healthy and normal. Both nestlings in nest 3 were cold, lying separate from one another and away from the female parrot that was present in the box at the time of the check. At a subsequent check these nestlings appeared neglected despite the ongoing presence of the female parrot in the box, so after warming them we moved them to nest 2, where they died overnight (unknown cause). The original foster chick and the host sibling in nest 2 survived for a further week, before succumbing to *P. aeruginosa* infection (cause of death only confirmed for the foster nestling; DPIPWE unpub. data). The foster nestling in nest 4 survived to fledge, and was subsequently seen with other fledgling Orange-bellied Parrots. This individual was later observed at the wintering grounds. Nesting Orange-bellied Parrots tolerated intensive and repeated disturbance (including egg candling and regular nestling handling). The only nest abandonments recorded during this study were attributable to egg infertility.

Veterinary assessment of the population

Orange-bellied Parrots (n = 6) were trapped and physically examined. Five were adult captive-bred birds and feather condition ranged from mildly to severely weathered. Captive-bred released Orange-bellied Parrots had noticeably poorer plumage quality than their wild-bred counterparts (Figure 3). Feathers were variably affected between individuals but were generally dull, dishevelled and excessively weathered. Some individuals showed dramatic loss of barbs at the ends of contour feathers, remiges and rectrices. Loss of refractory ultrastructure was microscopically evident proximal to the regions of barb loss (Figure 3). The one wild-bred adult had very little feather weathering. All birds handled were assessed to be in reasonable to good body condition based on pectoral muscle mass, fat deposits and general appearance. Faeces examined at food tables were grossly normal. The faecal mass was pale khaki-green, well-formed and tubular in shape and urates were moderate and white. Nestlings appeared in good condition with normal plumage although hippoboscid flies were present. Choanal papillae were moderately developed on one individual.

Discussion

Our study provides worrying new information about the conservation status of Orange-bellied Parrots, habitat quality at their breeding grounds and the efficacy of reintroducing captive-bred birds under the current paradigm. Orange-bellied Parrots are absent in areas of their historical breeding range even where natural

Table 2. Summary data for each nest involved in the fostering trial.

Nest ID	Provenance	Host nest contents	WI (mm) H: host F: foster	Fail	Notes
1	F: Captive M: Wild	3 nestlings, 1 fertile egg, 1 infertile egg	H: 14.2; 12.3; 13.7 F: 13	Yes	Foster nestling died – unknown cause. Host nestlings all fledged
2	F: Captive M: Wild	1 nestling, 1 infertile egg	H: 12.7 F: 11	Yes	Host and foster nestlings died after 5 days from *Pseudomonas*
3	F: Captive M: Unknown	1 infertile egg	H: N/A F: 6, 7	Yes	Foster nestlings were removed to prevent death by chilling
4	F: Captive M: Captive	5 infertile eggs	H: N/A F: 7	No	Foster nestling fledged successfully

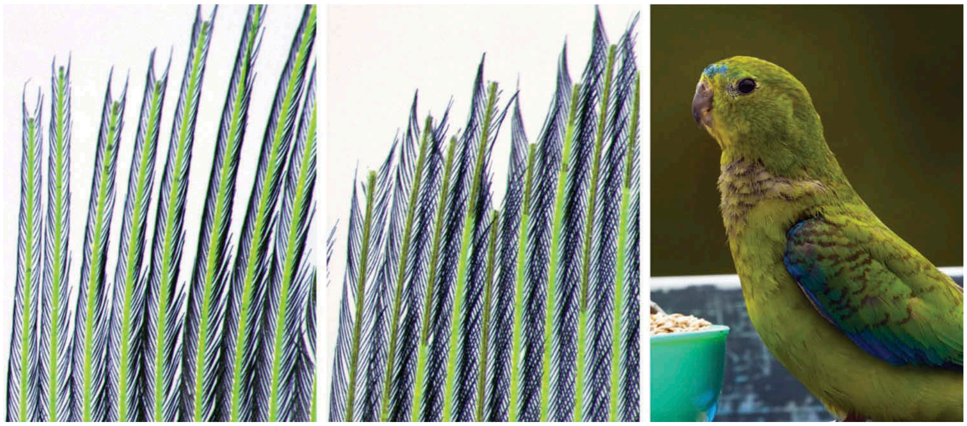

Figure 3. Ultrastructural light refraction of feather barbs of wild-bred (left) and captive-bred (centre) wild Orange-bellied Parrots. Loss of yellow-green refraction advances further proximally along the barb in the captive-bred parrot. This resulted in dull plumage and was associated with excessive weathering of both contour and flight feathers in many captive-bred birds (right).

food and nesting sites are abundant. The likely extinction of the species away from Melaleuca reinforces the critical importance of improving management of this last wild population.

Persistence of Orange-bellied Parrots and habitat quality at historical sites

Our survey of four historical sites failed to detect any birds. It is possible a small number of birds may persist away from Melaleuca, however our surveys (and negligible numbers of unmarked individuals in the population; Troy 2017) suggest that this is unlikely. Recently burned historical sites supported significantly more food plants than unburned sites. However, fire did not necessarily equate to uniform, widespread and abundant food plant regeneration. Less than half of recently burned survey sites at Bond Bay and Settlement Point supported abundant food plants. Likewise, despite recent small-scale fires at Melaleuca and Towterer Beach, food plants were uncommon. Patchy occurrence of food plants may negate the potential benefit of small-scale fires if the wrong locations are burned (e.g. where viable seedbanks are absent). Fire ecology is reasonably well understood in south-west Tasmania (Marsden-Smedley and Kirkpatrick 2000) and operational prescriptions for ecological burning already exist (Marsden-Smedley 1993). Unfortunately, these plans have not been implemented as scheduled and old-growth moorlands now dominate the Tasmanian Wilderness World Heritage Area (Marsden-Smedley and Kirkpatrick 2000). The high fuel loads of old-growth moorlands suppress food plant abundance and increase wildfire risk. Evaluating the effects of changes to fire frequency and scale on Orange-bellied Parrot survival and recruitment, and implementing a fire regime that favours food plant growth, requires urgent attention. We argue this can likely only be achieved by large-scale burning.

Reproductive success of captive-bred vs. wild Orange-bellied Parrots

Two of three wild females attempted to breed in the 2016/2017 season, including the first recorded second within-season nesting attempt for a wild bird (Holdsworth 2006). All other nests were initiated by captive-bred females. Spring releases of captive-bred females to correct sex ratio imbalances have strong merit based on the extent of captive/wild pairings we observed. However, conservation resources expended to produce and release captive-bred birds did not benefit the wild population in this study due to infertility. The two wild-bred females in this study performed comparably to historical data (3.0 vs. 3.1 fledglings/nest respectively; Holdsworth 2006), rearing 9 of the 20 fledglings. Captive-bred females produced significantly fewer hatchlings and fledglings per nest than wild-bred birds, despite their comparable clutch sizes. Prolonged incubation of infertile eggs by captive-bred females wasted time in the short breeding season and resulted in lost opportunities for population recruitment (Briskie and Mackintosh 2004). Why nests involving captive-bred females suffered such low fertility is not clear, but may be attributable to individual or cumulative impacts of genetic, nutritional, pathological, behavioural or anthropogenic factors. Improving fertility is important for effective utilisation of captive-bred females and maximising reproductive opportunities for surviving wild males (eight nesting attempts involving a captive-bred female and a wild male failed due to egg infertility).

Evaluation of nestling fostering as a recovery tool

Based on the two of four foster nestlings being accepted by the host nest, we consider this technique a potentially viable tool to improve utilisation of infertile captive-bred birds. The causes of failure in foster nests were difficult to ascertain. One of our two surviving foster nestlings died due to bacterial septicaemia (attributable to seed contaminated with *Pseudomonas aeruginosa* at food tables), despite having survived for a week. Other factors may have contributed to the deaths of the other foster nestlings, but chilling after rejection by foster mothers likely contributed to other nestling mortalities. Our results warrant evaluation of fostering either eggs or older nestlings to improve survival. Parrots inherit vocal signatures from their parents (Berg *et al*. 2011), so fostering eggs may be preferable to young nestlings because incubating females may communicate with eggs (Colombelli-Négrel *et al*. 2012; Mariette and Buchanan 2016), thus preventing potential vocal mismatch. Fostering older nestlings should be tested because this technique may be useful to address population sex bias (Wedekind 2002), assist ailing nestlings by assigning them to nests where they will be more competitive, or to improve genetic management of the wild population. Although our sample size was very limited, we argue that, if the above challenges can be overcome, fostering may improve utilisation of captive-bred infertile birds released at Melaleuca.

Veterinary assessment of the population

Observations of poor plumage in captive-bred birds were not consistent with viral, bacterial or parasitic causes of feather dystrophy. More likely causes include poor nutrition during feather growth or feather mutilation due to underlying skin hypersensitivities or behaviour. Loss of feather integrity could be energetically costly for wild birds, especially during cold weather or migration. However, despite the low survival of captive-bred Orange-bellied Parrots in the wild, this health issue is unstudied. Disease outbreaks, for example *Beak and Feather Disease Virus* (Peters *et al*. 2014) and *Pseudomonas aeruginosa* (DPIPWE unpub. data), are major causes of mortality of Orange-bellied Parrots. Population bottlenecks (e.g. as a result of recurrent disease outbreaks in an already small population) are likely to result in loss of genetic diversity and to exacerbate genetic and phenotypic incompetence (Hawley *et al*. 2006; Hale and Briskie 2007). Although Orange-bellied Parrots could be genetically incompetent, other threatened species appear less susceptible to infectious and nutritional disease (Ha *et al*. 2009; Chen *et al*. 2016).

Conservation implications

New approaches need to be implemented now to prevent extinction of the Orange-bellied Parrot. Although release of 87 captive-bred Orange-bellied Parrots at Melaleuca since 2013 has increased the number of nesting attempts initiated (Figure 2) the population trajectory remains negative. We argue that simply releasing captive-bred birds has proven inadequate at reversing population declines. The low rates of breeding success we report highlight that recruitment and breeding habitat quality are critical unresolved issues.

Failure to stop Orange-bellied Parrot population decline warrants urgent revision and change of management actions. We suggest conservation actions for urgent consideration (Table 3). Some have already recently been implemented (e.g. correct spring sex ratios, recapture of captive-bred birds; Troy 2017), may soon be implemented (e.g. burning, population genetic management) or are under consideration (e.g. revise and reduce supplementary feeding) by the Tasmanian Department of Primary Industries, Parks, Water and Environment and its collaborators. Although not intended as a comprehensive review of all recovery actions necessary to recover the species, we present these ideas alongside additional priorities identified during this study, which the authors consider will collectively contribute to the improving conditions at the breeding grounds.

Business as usual will result in the extinction of the Orange-bellied Parrot. Multiple interacting processes, both historical and contemporary, have led to their population collapse. The Tasmanian government recently invested an additional A$3.2 million to support the recovery of the Orange-bellied Parrot, including relocating captive breeding facilities to allow expansion of the insurance population and increased translocation of captive-bred birds to the wild. If further resources become available to implement effective recovery actions in the wild, there may still be hope that extinction of the Orange-bellied Parrot can be avoided. It is possible that in the 2017 season, no wild-bred female Orange-bellied Parrots will return from migration to breed. Acting fast may have helped avoid extinction in the past (Martin *et al*. 2012), but urgent action and additional resources to address the issues we have identified may help prevent the imminent extinction of the Orange-bellied Parrot in the wild.

Table 3. Recovery actions for urgent implementation aimed at preventing extinction of the Orange-bellied Parrot.

Action	Details
Burn moorland in breeding range	Burn plans should be implemented before the 2017/2018 breeding season to address food limitation at Melaleuca. To augment habitat in the short term, targeted small-scale burns may need to be implemented in areas where food plants are likely to regenerate (e.g. moorlands where food plants occur). Alternatively, larger-scale burns may be required to reveal patches/locations where food plants return to high densities. Away from Melaleuca, maintaining appropriate burning regimes is essential to (i) support the possibility of establishing a second subpopulation, and (ii) provide habitat for parrots that may still survive undetected elsewhere
Revise and reduce supplementary feeding	Nutrient deficiencies of seed diets (as provided at Melaleuca) are well known (Koutsos *et al*. 2001), but impacts of supplementary food on population health is unstudied in Orange-bellied Parrots. If burning is achieved, use of food tables should be limited to population monitoring purposes only (i.e. cease ad-lib feeding). Dry, formulated food will reduce disease risk associated with wet food. Food tables may be situated where natural food occurs to encourage natural foraging
Formulation of a diet based on wild food	If provision of supplementary food is continued (e.g. for monitoring), nutritional profiles of natural foods should be developed to guide production of a formulated diet. Experimental feeding trials may be undertaken using the captive population to evaluate formulated diet performance compared to existing diets
Increase the number of captive-bred birds released to the wild	Increasing the number of captive-bred birds released to the wild is necessary to facilitate some of the actions that aim to increase the size of the wild Orange-bellied Parrot population. Spring release of captive-bred adults is necessary to (i) correct sex ratio bias to ensure all wild returns have the opportunity to contribute to recruitment, and (ii) increase the number of nests initiated in the wild. More nests initiated in the wild may improve recruitment, and create opportunities for fostering of captive-bred eggs to improve breeding success, compensate for infertility, and allow fostering of nestlings to address sex ratios. Expanding the Orange-bellied Parrot population beyond Melaleuca will require spring releases of adult captive-bred birds and probably eggs in excess of those required at Melaleuca for (i) and (ii) above
Intensively monitor wild nests	Cameras and frequent observation will improve capacity to confirm breeder provenance, likely nest parentage, egg fertility and nestling health and survival. Higher monitoring intensity improves capacity of managers to respond earlier to problems
Improve recruitment using fostering	Releasing infertile captive-bred birds wastes scarce conservation resources. Infertile eggs or small broods may be remedied by fostering fertile captive-bred eggs or nestlings. This would reduce abandonment of infertile nests, and facilitate additional manipulations (e.g. swapping nestlings to address sex ratio bias, or increase representation of particular genotypes)
Extend studbook to wild nests	Wild nests should be included in the species studbook. Two-way flow between captive and wild populations may improve representation of remaining wild genotypes in the captive population, and ensure that captive releases improve genetic diversity in the wild population
Prevent migration of captive-bred birds	Captive-bred released birds (particularly females) should be recaptured at the end of each breeding season, held over winter, and then be released again the following spring. This will increase the number of birds available each year to initiate nests in the wild and resolve resource waste imposed by high migration mortality of captive-bred birds
Capture of under-represented wild genomes	Capture of important genotypes that could still appear in the wild may be achieved by (i) egg or nestling harvesting or (ii) capturing important individuals for captive breeding. Harvesting eggs may induce a second nesting attempt and reduce the impact of this action on the wild population
Identify genetic intervention options	Restoring lost genetic diversity to the wild population may be achieved in the short term via selective release of captive birds retaining such diversity. If such diversity has also been lost, technology such as CRISPR cas9 may offer a mechanism to restore ancestral allelic diversity (Reardon 2016)
Improve transparency	Documentation about decision-making, reporting on outcomes of actions (both successful and failed) and limited public access to information makes evaluating strengths and weaknesses of the recovery programme difficult. Public archiving of data (if they are available) and recovery team documentation will improve transparency and address knowledge gaps

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