This is the peer reviewed version of the following article: Stojanovic, D., Alves, F., Cook, H., Crates, R., Heinsohn, R., Peters, A., Rayner, L., Troy, S.N., Webb, M. H. (2017). Further knowledge and urgent action required to save Orange-bellied Parrots from extinction. *Emu - Austral Ornithology*, 118(1): 126-134; which has been published in final form at https://doi.org/10.1080/01584197.2017.1394165

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

Dejan Stojanovic[1,4,5], Fernanda Alves[1], Henry Cook[1], Ross Crates[1], Robert Heinsohn[1], Andrew Peters[2] , Laura Rayner[1], Shannon N. Troy[3], Matthew H. Webb[1]

1. Fenner School of Environment and Society, Australian National University, Canberra
2. School of Animal and Veterinary Sciences, Charles Sturt University, Wagga Wagga
3. Department of Primary Industries, Parks, Water and Environment, Hobart
4. Coauthors listed alphabetically
5. Corresponding author: dejan.stojanovic@anu.edu.au

ABSTRACT

Only three wild-bred female Orange-bellied Parrots returned from migration in the 2016/17 breeding season, representing a new low point of a long-term decline. We address major gaps in knowledge about the species' ecology and conservation status. Orange-bellied Parrots may be extinct across most of their former breeding range despite the occurrence of apparently suitable habitat. Fire suppression in breeding habitat is likely to have resulted in scarce natural food, whereas equivalent but recently burned habitats elsewhere support abundant food, but no Orange-bellied Parrots. Wild-bred female Orange-bellied Parrots at the only known extant breeding site, Melaleuca, produced significantly more fledglings per nesting attempt than released captive-bred females (3 vs. 0.8 fledglings respectively). Fostering of captive-bred nestlings to the wild showed potential, with 2 of 4 nests accepting a foster nestling, and one of these fledged successfully. Captive-bred birds have poorer feather condition and lower fertility than wild birds. Bacterial septicemia attributable to provision of contaminated food caused mortalities of at least four nestlings at Melaleuca. Addressing shortages of natural food at Melaleuca, and the addition of further management opportunities for population recruitment are critical and urgent recovery priorities. We provide a list of recovery priorities for the species that arise from our results, including emergency intervention to prevent imminent extinction.

KEYWORDS

Neophema chrysogaster, critically endangered species, conservation action, reintroduction, translocation, extinction, captive breeding

INTRODUCTION

Parrots are among the most threatened bird orders and are a common focus of reintroduction and conservation programs (Olah, Butchart *et al.* 2016). Interventions in some species have been successful (Elliott, Merton *et al.* 2001), but not all recovery programs for parrots have succeeded. Most parrot species are site philopatric, range restricted or sedentary, which allows the conservation actions necessary for recovery to be carried out in one location. Most successful conservation programs for threatened parrots focus on islands (Powlesland, Merton *et al.* 2006; White 2005), where threats (e.g. introduced predators) can be proactively managed (Moorhouse, Greene *et al.* 2003). In contrast, reintroduction and population management of mobile and migratory birds are more complex because individuals use multiple habitats and may face a greater range of threats (Runge, Martin *et al.* 2014).

Orange-bellied Parrots *Neophema chrysogaster* are arguably the most threatened parrot species in the world because in the 2016/17 breeding season, the wild-bred population declined to only three females and 13 males (Troy 2017). They migrate annually between coastal, south-eastern mainland Australia in the winter and southwestern 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, sex ratio bias and low female breeding participation are thought to be key drivers of decline. 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 their protection (Department of Environment Land Water and Planning 2016).

In 1986 a population of Orange-bellied Parrots was established in captivity (Smales I. 2000) and later supplemented with new genetic material (Martin, Nally *et al.* 2012). Captive-bred birds have been repeatedly released (Department of Environment Land Water and Planning 2016) but this effort does not appear to have 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 (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).

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 2016/17 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 mostly in nest boxes provided by managers, and birds are monitored via observations at food tables where seed is provided *ad libatum* 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 (mean 22 birds ± 6 standard deviation, per year, Figure 2) (Troy 2017). At the start of the 2016 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).

1. Persistence of Orange-bellied Parrots and habitat suitability at historic sites

Vegetation dynamics in southwest Tasmania are shaped by fire history (Marsden-Smedley and Kirkpatrick 2000). Before 1830, Aboriginal burning regimes in Tasmanian moorlands were characterized 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 southwestern Tasmania are predominantly old-growth (Marsden-Smedley and Kirkpatrick 2000), and thus are poor habitats for food plants of Orange-bellied Parrots (e.g. *Actinotus bellidioides*, *Helichrysum pumilum, Eurychorda complanata*, *Boronia citriodora*) (Department of Environment Land Water and Planning 2016). These may be most abundant within eight 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 (M.H. unpublished data). Roaming searches were undertaken at each site in areas where birds and potential foraging habitat might occur (i.e. moorland). 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 to 150 sites per location), covering approximately 4 km^2 at each location. We did not attempt to quantify 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 the proportion of historical sites scored as medium/high density of food plants at recently burned/unburned locations using a generalized linear model (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 2-3 times by constantly visually scanning and listening for the calls of Orange-bellied Parrots. Orange-bellied Parrots 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 our aim was to establish presence/absence of the species at each site, we are confident 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.

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

All nest boxes deployed 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, Dettmann *et al.* 2011). At every nest, we recorded the number and fertility of eggs, number of hatchlings and fledglings. We compared clutch and brood data from 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.

3. 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 utilization of infertile captive-bred, released birds. Fostering of nestlings has been successfully used to improve breeding success in other parrots (Beissinger, Wunderle *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, (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 synchronized 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 minutes) 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 4 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).

4. Veterinary assessment of the population

A qualified avian veterinarian (AP) opportunistically examined Orange-bellied Parrots on 26-27th January 2017 at Melaleuca. Physical examinations were carried out on nestlings (1-3 per nest) from three active nests on 26th January and on six adults captured at food tables on 27th 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 27th January.

RESULTS

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

Survey effort totaled 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; F: 195.48, P: 0.005). 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 characterized 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 presence of dense dead, standing woody debris) or where shrub regeneration had established.

2. 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 breeding 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 1 foster fledgling; W: 4.5, P: 0.0237). The captive/captive pairing produced 5 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 these abandoned eggs were likely attributable to those females.

3. 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 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 *Pseudomonas aeruginosa* infection (cause of death only confirmed for the foster nestling, DPIPWE, unpublished data). The foster nestling in Nest 4 survived to fledge, and was subsequently seen with other fledgling Orange-bellied Parrots. Subsequent observations indicated that this individual successfully migrated to the wintering grounds. Nesting Orange-bellied Parrots were tolerant of intensive and repeated disturbance (including egg candling and regular nestling handling). The only nest abandonments recorded during this study were attributable to egg infertility.

4. 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, disheveled 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 no longer occupy suitable habitat across their historical breeding range. The likely extinction of the species away from Melaleuca reinforces the critical importance of improving management of this last wild population.

1. 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 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 well understood in southwest 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 Southwest 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 favors food plant growth requires urgent attention. We argue this can likely only be achieved by large-scale burning.

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

Two of three wild females attempted to breed in the 2016/17 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 were wasted during this study due to their 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 nine 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, behavioral or anthropogenic factors. Improving fertility is important for effective utilization of captive-bred females and maximizing reproductive opportunities for surviving wild males (eight nesting attempts involving a captive-bred female and a wild male failed due to egg infertility).

3. 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 utilization of infertile captive-bred birds. Causes of failure in foster nests were difficult to ascertain. One of our two surviving foster nestlings died due to bacterial septicemia (attributable to seed contaminated with *Pseudomonas aeruginosa* at food tables), despite having survived for a week. Other factors may have contributed 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 survivl. Parrots inherit vocal signatures from their parents (Berg, Delgado *et al.* 2011), so fostering eggs may be preferable to young nestlings because incubating females may communicate with eggs (Colombelli-Négrel, Hauber *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 utilization of captive-bred infertile birds released at Melaleuca.

4. 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 is likely to be energetically costly for wild birds, especially during cold weather or migration. However despite 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, Patterson *et al.* 2014) and *Pseudomonas aeruginosa* (DPIPWE, unpublished 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 (Hale and Briskie 2007; Hawley, Hanley *et al.* 2006). Although Orange-bellied Parrots could be genetically incompetent, other threatened species appear less susceptible to infectious and nutritional disease (Chen, Cosgrove *et al.* 2016; Ha, Alley *et al.* 2009).

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 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 their 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 $3.2 million dollars 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 is still 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, Nally *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.

ACKNOWLEDGEMENTS

This project was funded by 1609 people and organizations that supported our crowd-funding campaign “Operation OBP” - we are deeply grateful. The Tasmanian Government Department of Primary Industries, Parks, Water and Environment collaborated on this study, with thanks to Annika Everaardt, Andrew Crane, Jon DeLaine and Darren Page. We are grateful to Barbara Willson. Airlines of Tasmania (Par Avion), Friends of the Orange-bellied Parrot and the Tasmanian National Parks and Wildlife Service. Mark Holdsworth contributed to the fieldwork and critiqued the manuscript. Thanks to Gemma Deavin, James Da Costa, Matthew Eyles, Dave James, Nicole Gill, Jon Kudelka, Bronte Lee Lance, Andrew Marlton, Shane Pinner, Sue Robinson, Janneke Webb, Allan Wiltshire and Xinyu (Shirley) Zheng. Barry Baker, Michael McGrath and three reviewers provided helpful critiques of the manuscript. Funding was also received from the Australian Government National Environmental Science Programme. The research was conducted with approval from the Australian National University Animal Ethics Committee (A2016/48) and the Tasmanian Department of Primary Industries, Parks Water and Environment (TFA17037).

Literature Cited

Beissinger, S.R., Wunderle, J.M., Meyers, J.M., Saether, B.E., and Engen, S. (2008) Anatomy of a bottleneck: Diagnosing factors limiting population growth in the Puerto Rican Parrot. *Ecological Monographs* **78**(2), 185-203

Berg, K.S., Delgado, S., Cortopassi, K.A., Beissinger, S.R., and Bradbury, J.W. (2011) Vertical transmission of learned signatures in a wild parrot. *Proceedings of the Royal Society B: Biological Sciences*

Briskie, J.V., and Mackintosh, M. (2004) Hatching failure increases with severity of population bottlenecks in birds. *Proceedings of the National Academy of Sciences of the United States of America* **101**(2), 558-561

Brown, P., and Wilson, R. (1980) A survey of the Orange-bellied Parrot *Neophema chrysogaster* in Tasmania, Victoria and South Australia. The World WIldlife Fund, NPWS Tasmania, Hobart.

Chen, N., Cosgrove, E., Bowman, R., Fitzpatrick, J., and Clark, A. (2016) Genomic Consequences of Population Decline in the Endangered Florida Scrub-Jay. *Current Biology* **26**(21), 2974-2979

Colombelli-Négrel, D., Hauber, M.E., Robertson, J., Sulloway, F.J., Hoi, H., Griggio, M., and Kleindorfer, S. (2012) Embryonic learning of vocal passwords in Superb Fairy-wrens reveals intruder cuckoo nestlings. *Current Biology* **22**(22), 2155-2160

Department of Environment Land Water and Planning (2016) National Recovery Plan for the Orange-bellied Parrot *Neophema chrysogaster*. Canberra.

Elliott, G.P., Merton, D.V., and Jansen, P.W. (2001) Intensive management of a critically endangered species: The Kakapo. *Biological Conservation* **99**(1), 121-133

Ha, H.J., Alley, M.R., Cahill, J.I., Howe, L., and Gartrell, B.D. (2009) The prevalence of psittacine beak and feather disease virus infection in native parrots in New Zealand. *New Zealand Veterinary Journal* **57**(1), 50-52

Hale, K.A., and Briskie, J.V. (2007) Decreased immunocompetence in a severely bottlenecked population of an endemic New Zealand bird. *Animal Conservation* **10**(1), 2-10

Hawley, D.M., Hanley, D., Dhondt, A.A., and Lovette, I.J. (2006) Molecular evidence for a founder effect in invasive House Finch (*Carpodacus mexicanus*) populations experiencing an emergent disease epidemic. *Molecular Ecology* **15**(1), 263-275

Higgins, P.J. (Ed.) (1999) 'Handbook of Australian, New Zealand and Antarctic Birds ' (Oxford University Press: Melbourne)

Holdsworth, M., Dettmann, B., and Baker, G.B. (2011) Survival in the Orange-bellied Parrot (*Neophema chrysogaster*). *Emu* **111**(3), 222-228

Holdsworth, M.C. (2006) Reproductive success and demography of the Orange-bellied Parrot *Neophema chrysogaster*. School of Zoology, University of Tasmania, Hobart

Koutsos, E.A., Matson, K.D., and Klasing, K.C. (2001) Nutrition of birds in the order Psittaciformes: A review. *Journal of Avian Medicine and Surgery* **15**(4), 257-275

Mariette, M.M., and Buchanan, K.L. (2016) Prenatal acoustic communication programs offspring for high posthatching temperatures in a songbird. *Science* **353**(6301), 812-814

Marsden-Smedley, J. (1993) Orange-bellied Parrot Recovery Plan: operational prescriptions for habitat management burns. Hobart, Tasmania.

Marsden-Smedley, J. (1998) Changes in southwestern Tasmanian fire regimes since the early 1800's. *Papers and Proceedings of the Royal Society of Tasmania* **132**, 15 - 29

Marsden-Smedley, J.B., and Kirkpatrick, J.B. (2000) Fire management in Tasmania's Wilderness World Heritage Area: Ecosystem restoration using Indigenous-style fire regimes? *Ecological Management & Restoration* **1**(3), 195-203

Martin, T.G., Nally, S., Burbidge, A.A., Arnall, S., Garnett, S.T., Hayward, M.W., Lumsden, L.F., Menkhorst, P., McDonald-Madden, E., and Possingham, H.P. (2012) Acting fast helps avoid extinction. *Conservation Letters* **5**(4), 274-280

Moorhouse, R., Greene, T., Dilks, P., Powlesland, R., Moran, L., Taylor, G., Jones, A., Knegtmans, J., Wills, D., Pryde, M., Fraser, I., August, A., and August, C. (2003) Control of introduced mammalian predators improves Kaka *Nestor meridionalis* breeding success: reversing the decline of a threatened New Zealand parrot. *Biological Conservation* **110**, 33-44

Olah, G., Butchart, S.H.M., Symes, A., Guzmán, I.M., Cunningham, R., Brightsmith, D.J., and Heinsohn, R. (2016) Ecological and socio-economic factors affecting extinction risk in parrots. *Biodiversity and Conservation* **25**(2), 205-223

Peters, A., Patterson, E.I., Baker, B.G.B., Holdsworth, M., Sarker, S., Ghorashi, S.A., and Raidal, S.R. (2014) Evidence of Psittacine beak and feather disease virus spillover into wild critically endangered Orange-bellied Parrots (*Neophema chrysogaster)*. *Journal of Wildlife Diseases* **50**(2), 288-296

Powlesland, R.G., Merton, D.V., and Cockrem, J.F. (2006) A parrot apart: The natural history of the Kakapo (*Strigops habroptilus*), and the context of its conservation management. *Notornis* **53**(1), 3-26

R Core Development Team (2016) R: A language and environment for statistical computing R Foundation for Statistical Computing, Vienna, Austria.

Reardon, S. (2016) The CRISPR zoo. *Nature* **531**(7593), 160-163

Runge, C.A., Martin, T.G., Possingham, H.P., Willis, S.G., and Fuller, R.A. (2014) Conserving mobile species. *Frontiers in Ecology and the Environment* **12**(7), 395-402

Smales I., B.P., Menkhorst P., Holdsworth M. and Holz P. (2000) Contribution of captive management of Orange-bellied Parrots *Neophema chrysogaster* to the recovery programme for the species in Australia. *Inernational Zoo Yearbook* **37**, 171-178

Troy, S. (2017) Tasmanian Orange-bellied Parrot Program: Report on the Tasmanian Wild Population 2016/17. Department of Primary Industries, Parks, Water and Environment, Hobart.

Wedekind, C. (2002) Manipulating sex ratios for conservation: short-term risks and long-term benefits. *Animal Conservation* **5**(1), 13-20

White, T.R., Collazo J.A. and Vilella F.J. (2005) Survival of captive-reared Puerto Rican Parrots released in the Caribbean National Forest. *The Condor* **107**, 424-432

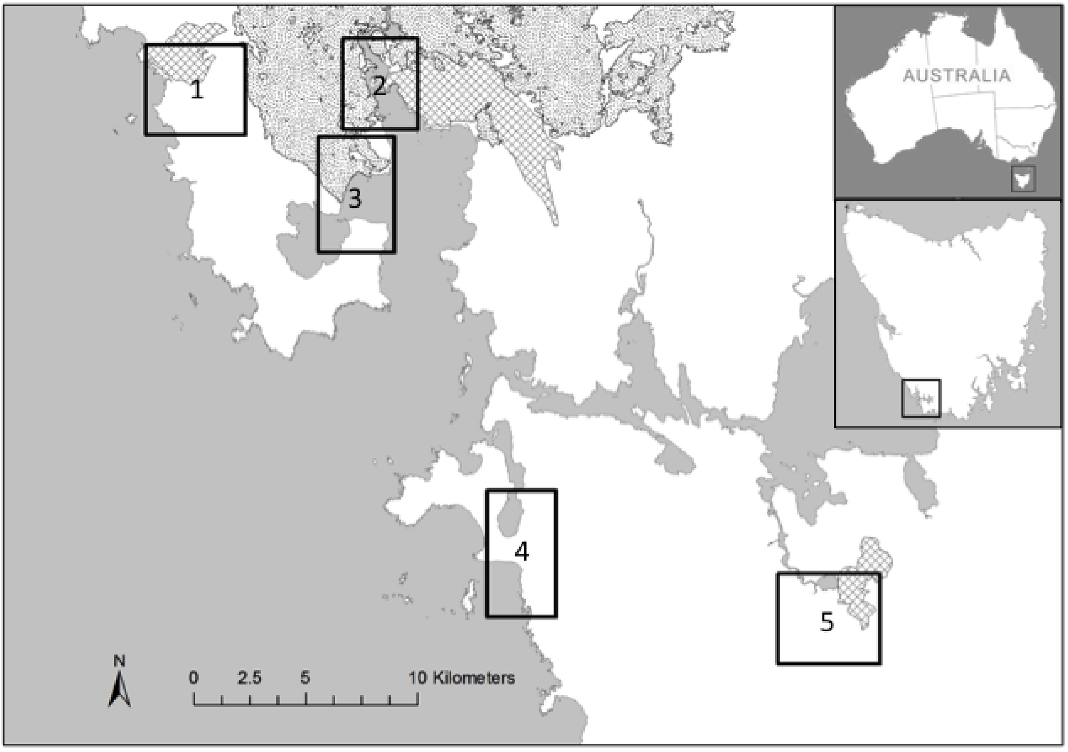

Figure 1. Map of the study area, focusing on the broader Tasmanian Southwest World Heritage Area, Tasmania, Australia. Our study sites were: 1- Towterer Beach, 2- Settlement Point, 3- Bond Bay, 4- Noyhener Beach, and 5- Melaleuca (the location of the only known extant subpopulation). Boxes encompass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

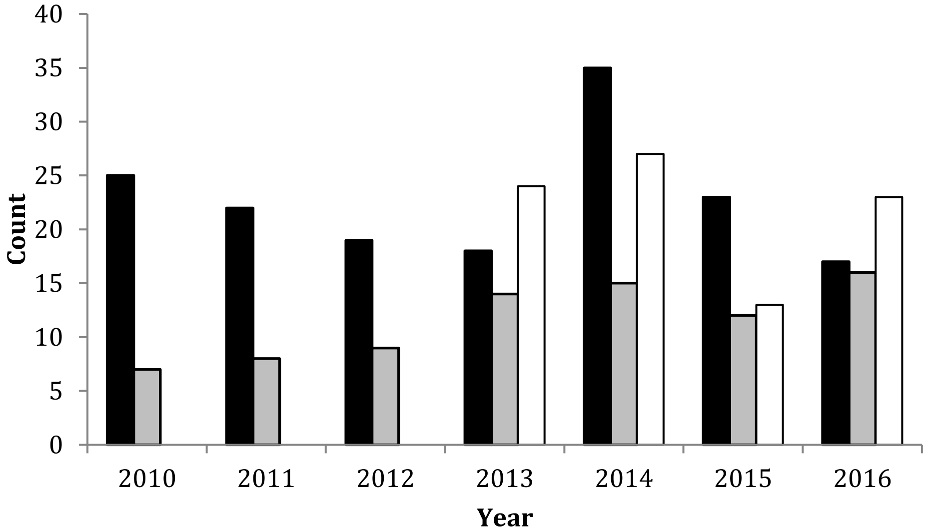

Figure 2. Time series showing the number of wild-bred and captive-bred Orange-bellied Parrots returning from migration (black), nesting attempts initiated (grey), and captive-bred individuals released (white). Derived from Troy (2017).

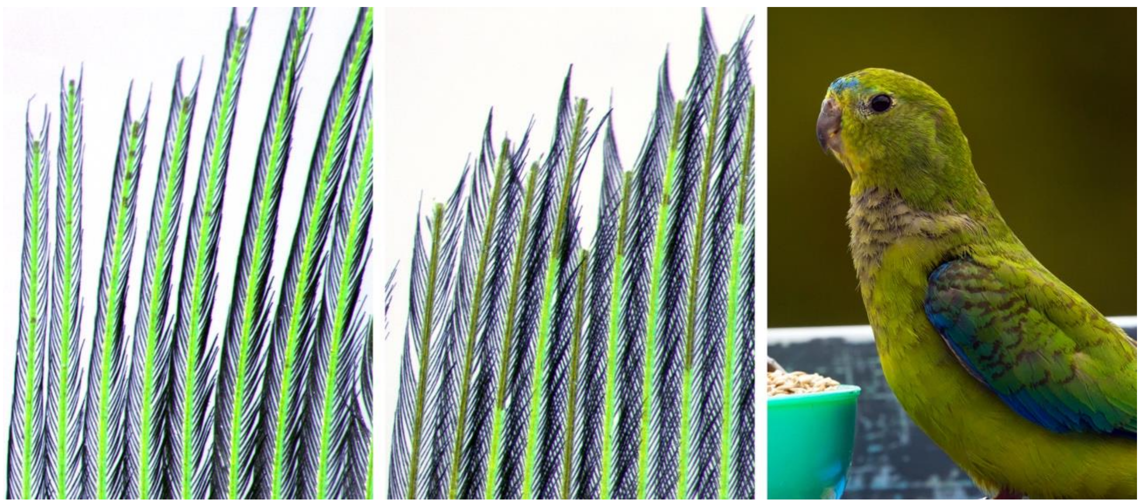

Figure 3. Ultrastructural light refraction of feather barbs differs between wild-bred (left) and captive-bred (centre) wild Orange-bellied Parrots. Loss of yellow-green refraction can be seen advancing much further proximally along the barb in the captive-bred parrot. This resulted in dull plumage and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

Table 1. Reproductive parameters of Orange-bellied Parrot nests initiated at Melaleuca in 2016/17. 'Provenance' indicates whether the breeding female was captive or wild-bred. Data are mean values and parentheses indicate range. * Includes any pairing where one or both breeders was captive bred.

PROVENANCE	COUNT	EGGS	HATCHED	FLEDGED	FLEDLINGS/EGGS
Wild	3	4.7 (4-6)	3.7 (3-4)	3.0 (2-4)	64 %
Captive*	14	3.1 (1-5)	1.0 (0-4)	0.8 (0-4)	26 %

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

Nest id	Provenance	Host nest contents	Wl (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.

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 2017/18 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 occur undetected elsewhere.
Revise and reduce supplementary feeding	Nutrient deficiencies of seed diets (as provided at Melaleuca) are well known (Koutsos, Matson *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 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, and 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	Motion activated 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 do not diminish 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	Restoring lost genetic diversity to the wild population may be achieved in the short term via selective release of captive birds

intervention options	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 program difficult. Public archiving of data (if they are available) and recovery team documentation will improve transparency and address knowledge gaps.

Table S1. Peer reviewed publications relating to the ecology, threats and population trajectory of Orange-bellied Parrots, identified by searching the Scopus and Web of Science Databases for "*Neophema chrysogaster* or Orange-bellied Parrot".

AUTHOR	TITLE	YEAR	JOURNAL
Peters A. et al.	Evidence of Psittacine beak and feather disease virus spillover into wild critically endangered Orange-bellied Parrots (*Neophema chrysogaster*)	2014	Journal of Wildlife Diseases 50: 288-296
Weston M.A. et al.	Hope for resurrecting a functionally extinct parrot or squandered social capital? Landholder attitudes towards the Orange-bellied Parrot (*Neophema chrysogaster*) in Victoria, Australia	2012	Conservation and Society10: 381-385
Martin T.G. et al.	Acting fast helps avoid extinction	2012	Conservation Letters 5: 274-280
Holdsworth M.et al.	Survival in the Orange-bellied Parrot (*Neophema chrysogaster*)	2011	Emu 111: 222-228
Drechsler M.	A model-based decision aid for species protection under uncertainty	2000	Biological Conservation 94: 23-30
Drechsler M. et al.	Uncertainty in population dynamics and its consequences for the management of the Orange-bellied Parrot *Neophema chrysogaster*	1998	Biological Conservation 84: 269-281

Drechsler M.	Spatial conservation management of the Orange-bellied Parrot *Neophema chrysogaster*	1998	Biological Conservation 84: 283-292
Loyn R.H. et al.	Ecology of Orange-bellied Parrots *Neophema chrysogaster* at their main remnant wintering site	1986	Emu 86: 195-206