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Drivers of colony failure in a vulnerable coastal seabird, the Australian Fairy Tern (*Sternula nereis nereis*)

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ABSTRACT

Context. Understanding breeding success and site threat profiles is critical to conservation planning, particularly for species of conservation concern. Regular surveillance is fundamental to observing spatiotemporal changes at breeding colonies. Still, it can be challenging for species with broadly distributed, unpredictable populations susceptible to various threats. In these cases, cooperative networks and citizen science programs offer an opportunity to support monitoring and conservation efforts. **Aims.** This study aimed to assess the outcomes, threats and sources of breeding failure at Australian Fairy Tern (*Sternula nereis nereis*) colonies. **Methods.** Through collaborative surveillance, this study identified the outcomes and threats at 77 monitored colonies over five breeding seasons between 2017/18 and 2021/22. The leading causes of nest failure were then considered against the *Recovery Plan for the Australian Fairy Tern* to understand how the observed threats compare with the identified risks in this plan. **Key results.** Nearly half (48%) of all colonies failed, with predation (32%) and inundation (27%) being the biggest causes of failure. At least 10 native and four invasive/domestic species contributed to the mortality of eggs, chicks, and/or adults or complete colony failure. Disturbance, including off-road vehicles, was identified as a recurring threat, impacting at least 30% of colonies. **Conclusions.** These identified threats have the potential to drive population-level effects and were consistent with those identified under the Recovery Plan. **Implications.** This study highlights the importance of developing practical solutions, including habitat protection, the control of invasive species and education programs to safeguard colonies and boost breeding success.

Keywords: Australian Fairy Tern, beach-nesting birds, breeding failure, conservation planning, inundation, Laridae, predation, site threat profiles, *Sternula nereis nereis*.

Introduction

Understanding breeding success and site-specific threat profiles is a core component of population monitoring and recovery planning (Burger 1989; Martin *et al.* 2012). For some long-lived seabirds, population declines associated with breeding failure can be difficult to detect because populations can remain relatively stable for many years, despite low levels of recruitment, before effects of poor breeding success are realised, i.e. cryptic population decline (Burger 1989; Piper *et al.* 2020).

The habit of nesting on shorelines, often just beyond the high-water mark, exposes beach-nesting birds such as *Sternula* (small terns) to a range of threats, with predators, extreme weather events and disturbance from human activities identified globally as the major threats to breeding success (Burger 1989; Gochfeld and Burger 1992; Zavalaga *et al.* 2008; Ratcliffe *et al.* 2008; Garnett *et al.* 2014, 2021; Lacey and O'Brien 2015; Greenwell *et al.* 2019*a*; Wilson *et al.* 2020; BirdLife International 2021; Greenwell 2021). Documenting site-specific threats and sources of breeding failure among *Sternula* can be difficult due to their unpredictable nesting locations, which can occur over expansive areas of coastline and islands, and their tendency to periodically shift colony sites between breeding seasons (Baling *et al.* 2009; Greenwell *et al.* 2021*b*). Collaborative approaches and citizen science programs offer a chance to support management efforts and increase the opportunities for monitoring through time (Tulloch *et al.* 2013). These data, collected over the longer term, may allow new or emerging threats to be identified and mitigation strategies that enhance breeding success to be developed.

The Fairy Tern (*Sternula nereis*) has three distinct and geographically isolated populations found in Australia (*S. n. nereis*), New Zealand (*S. n. davisae*) and New Caledonia (*S. n. exsul*) (BirdLife International 2018; Baling and Brunton 2022). Globally, the species is considered Vulnerable to extinction (BirdLife International 2018). The Australian Fairy Tern (hereafter Fairy Tern) is listed as Vulnerable under the *Australian Environment Protection and Biodiversity Conservation Act 1999* (Cth), with fewer than 7600 mature individuals estimated Australia-wide (Greenwell *et al.* 2021*e*).

Historically, the loss of breeding habitat and disturbance of colonies, associated with an increasing coastal human population, have contributed to poor breeding success, low recruitment and decreased populations, particularly in the eastern states of Australia (Baling *et al.* 2009; Commonwealth of Australia 2020). Additionally, contractions in the distribution of suitable prey following a reduction in water quality associated with the Millennium Drought (a drought that affected much of southern Australia) contributed to dramatic population decreases in the Coorong, SA, between 2000 and 2007 (Paton and Rogers 2009; Paton *et al.* 2009). Nonetheless, the key threatening processes affecting the Fairy Tern are numerous and also include predation by invasive species, native birds, changes in water levels and extreme weather events, which are likely to be more severe in the future as a result of anthropogenic climate change (Indian Ocean Climate Initiative 2012; Garnett *et al.* 2013; Commonwealth of Australia 2020; Greenwell *et al.* 2021*e*). Based on peer-reviewed literature and expert opinion, a qualitative threat prioritisation matrix was developed under the *National Recovery Plan for the Australian Fairy Tern* (hereafter Recovery Plan), which outlines the risks posed to Fairy Terns at regional and population scales (Commonwealth of Australia 2020).

In Western Australia, a winter breeding and, possibly, sedentary population occurs off the Pilbara coast, and a semi-migratory spring/summer breeding population occurs from ~North West Cape, south to Israelite Bay (Commonwealth of Australia 2020; Dunlop and Greenwell 2021). The population (~5000–6000 mature individuals) is considered stable in the evidence of any time series to the contrary (Commonwealth of Australia 2020; Dunlop and Greenwell 2021; Greenwell *et al.* 2021*e*). Yet, the loss of historically important breeding habitat due to intense recreational activity (Singor 1998, 2021), rising sea and estuary levels, and changes in sedimentation patterns (e.g. Peel-Harvey Estuary and Pelican Point in Swan-Canning Estuary) (Dunlop 2016; Dunlop 2018) leading to frequent breeding failure in some locations has triggered targeted management intervention over the past decade, particularly in the south-west. Considering the numerous threats that have the potential to impact a Fairy Tern colony during any single breeding attempt, almost all publicly accessible colonies are likely to require some protective measures to reduce threats at breeding sites (Greenwell *et al.* 2021*b*) – key objectives under the Recovery Plan (Commonwealth of Australia 2020).

To better understand breeding success and the threats impacting Fairy Terns, this study quantified the sources of failure at 77 monitored colonies over five breeding seasons (2017/18–2021/22) from data collected through the Western Australian Fairy Tern Network. Additionally, observations of threats and individual nest failure were summarised to better understand the sources of mortality of Fairy Tern eggs, chicks and/or adults during the breeding season. Finally, the leading causes of nest failure were considered against the Recovery Plan's threat prioritisation matrix to understand how the observed threats compare to the identified risks in this plan.

Methods

In total, 84 known Fairy Tern colonies from 54 locations were recorded along the Western Australian coast between 2017/18 and 2021/22, and where possible, were monitored (Fig. 1, Table 1). Easily accessible sites near population centres or land manager offices were regularly monitored, i.e. daily or ≥weekly (Table 1). These sites included Point Walter, Rous Head, Penguin Island, Rottnest Island, Woodman Point, Becher Point, Mandurah, Peel Inlet, Dawesville, Bunbury and Irwin Inlet. Attempts were made to document the outcomes at each colony, i.e. whether the colony was successful and how many chicks were produced. However, this was not always possible due to site accessibility and limited numbers of observers for remote locations. Observations were made by land and wildlife managers and researchers, and, to a lesser extent, volunteers from the Western Australian Fairy Tern Network (for further detail, see Dunlop and Greenwell 2021; Greenwell *et al.* 2021*b*). All records were collated by C. Greenwell.

Fairy Tern colonies were observed using binoculars or spotting scopes from the outskirts of the colonies at distances that minimised the potential for disturbance. Brooding behaviour, i.e. sitting adults or the presence of chicks within a nest cup, was the metric used to estimate the total number of nests. In some instances, nests were mapped, allowing colony growth to be tracked over time (Greenwell *et al.* 2021*b*, 2021*c*, 2021*d*). The total numbers of nests and/or chicks were recorded on most visits, noting that some colonies were observed intensively as part of other research projects (Greenwell *et al.* 2021*b*, 2021*c*, 2021*d*).

Seven colonies could not be revisited during the active nesting period and outcomes at those sites were not determined, leaving a total of 77 colonies from 49 locations where observations were recorded. Consequently, those seven colonies were excluded from the analysis.

In this study, colony failure was defined as the abandonment by at least 90% of all breeding pairs, noting that one or two chicks may have fledged from two of the colonies that were classified as having failed. Single-pair nesting attempts ($n = 3$) were included in the analysis because nests

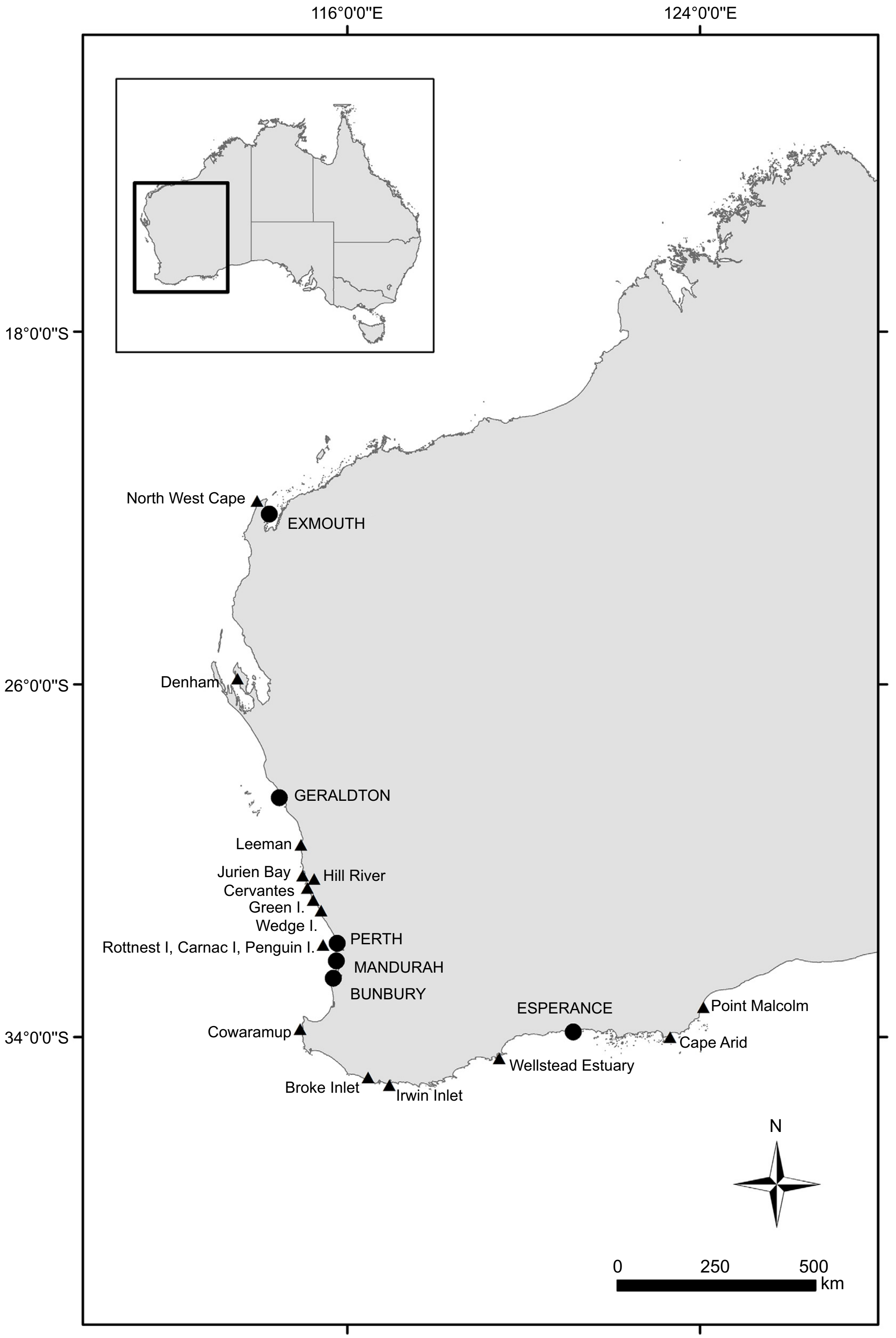

Fig. 1. Map identifying the locations of monitored Australian Fairy Tern (*Sternula nereis nereis*) colonies in Western Australia between 2017/18 and 2021/22. ▲ = breeding locations; ● = major Western Australian towns. Inset shows the extent of coastline where colonies were recorded in relation to the Australian continent.

Table 1. Outcomes and threats observed at 77 monitored Australian Fairy Tern (*Sternula nereis nereis*) colonies in Western Australia between 2017/18 and 2021/22.

Site	Season	Breeding pairs (*n*)	Colony outcome	Reason for failure (identification method)	Observed threats and sources of mortality	Monitoring routine	Observer(s)
Rous Head (Perth)	2017/18	250	High CP		Human disturbance, silver gull, black rat	≥Weekly	**CG**
Lake Bagdad, Rottnest Island	2017/18	176	Failed	Flooded (I)	**Flooded**, 1/500-year rainfall event (eggs, chicks)	≥Weekly	**CG**, RP, RIA
Carnac Island	2017/18	125	High CP			≥Monthly	DBCA
Mackenna Point, Bunbury	2017/18	70	High CP		Silver gull	≥Weekly	CT, DBCA
Point Walter (Perth)	2017/18	65	Moderate-high CP		Human disturbance	≥Weekly	TW
Cape Vlamingh, Rottnest Island	2017/18	50	Failed	Tidal Inundation (I)	**Tidal inundation** during storm front (eggs)	≥Weekly	RP, RIA
Causeway, Garden Island	2017/18	50	Moderate CP		**Vehicle strike** (adults, chicks)	≥Weekly	GD
Nairns, Peel Inlet (Mandurah)	2017/18	33	Failed	Tidal Inundation (DO)	**Tidal inundation** during storm front (eggs)	≥Weekly	CC, WAFTN
Milligan Island, Green Head	2017/18	20	Moderate-high CP			≥Weekly	AS, DBCA, SP
Causeway, Garden Island	2017/18	17	Moderate CP		Silver gull	≥Weekly	GD
Lake Thetis, Cervantes	2017/18	5	Failed	Unknown		≥Weekly	AS, DBCA
Hangover Bay, Cervantes	2017/18	5	High CP			≥Weekly	AS, DBCA
Lake Bagdad, Rottnest Island	2017/18	4	Moderate CP			≥Weekly	**CG**, RP, RIA
Rous Head (Perth)	2018/19	220	High CP		**Australian hobby** (adult), nankeen kestrel, cat, human disturbance, silver gull, black rat	Daily	**CG**
Lake Bagdad, Rottnest Island	2018/19	191	Moderate CP		Silver gull	≥Weekly	**CG**, RP, RIA
Wedge Island	2018/19	150	High CP		**Partial tidal inundation** (eggs)	≥Monthly	AS, ASh, DBCA
Mandurah Marina (sanctuary)	2018/19	111	Failed	Predation (WC, T, DO)	**Cat** (adults, chicks), **nankeen kestrel** (chicks), silver gull (eggs) beach erosion	Daily	**CG**
Carnac Island	2018/19	100	High CP		**Australian sea lion** (crushed eggs)	≥Monthly	DBCA
Leeman Lake	2018/19	95	Moderate-high CP			≥Weekly	AS, SP, DBCA
Point Walter (Perth)	2018/19	75	Low CP		**Red fox** (eggs, chicks), human disturbance	Daily	**CG**
Mandurah Marina (beach)	2018/19	43	Failed	Predation, erosion (WC, T, DO)	**Nankeen kestrel** (chicks), **silver gull** (eggs), dogs, human disturbance	Daily	**CG**
Parkin Pt, Garden Island	2018/19	40	Failed	Eggs buried (DO)	**Tidal inundation** checked after storm front (eggs)	≥Weekly	GD
Irwin Inlet, Peaceful Bay	2018/19	15	Moderate CP			≥Weekly	PM, JL
Causeway, Garden Island	2018/19	15	Failed	Predation (I)	**Black rat** (broken eggs)	≥Weekly	GD

(*Continued on next page*)

Table 1. (*Continued*).

Site	Season	Breeding pairs (*n*)	Colony outcome	Reason for failure (identification method)	Observed threats and sources of mortality	Monitoring routine	Observer(s)
Green Islands, JBMP	2019/20	250	High CP			≥Monthly	AS, DBCA
Bunbury Outer Harbour	2019/20	168	Failed	Unknown	Presumably predation, unconfirmed. Cat (tracks), peregrine falcon.	≥Weekly	SK, RB, MP, DBCA
Parkin Pt, Garden Island	2019/20	144	High CP			≥Weekly	**CG**
Point Walter (Perth) (Colony 1)	2019/20	135	High CP		Human disturbance	Daily	**CG**
Lake Herschel, Rottnest Island	2019/20	120	High CP		Silver gull, Australian raven	≥Weekly	**CG**, RP
Carnac Island	2019/20	106	High CP		Human disturbance	≥Monthly	DBCA
Penguin Island	2019/20	90	Low CP	Predation (DO)	**Silver gull** (egg, chicks), **black-shouldered kite** (chicks), **greater crested tern** (chicks), arctic jaeger, white-bellied sea-eagle, human disturbance	Daily	**CG**, MP, WAFTN
Parkin Pt, Garden Island	2019/20	25	Failed	Predation (T, I)	**Black rat**, **ghost crab** (broken, missing eggs)	Daily	**CG**
Irwin Inlet, Peaceful Bay	2019/20	25	Moderate CP		Peregrine falcon, white-bellied sea eagle	≥Weekly	PM, JL, DBCA
Coal Point, Broke Inlet	2019/20	22	Moderate-high CP			≥Monthly	PM, JL, DBCA
Northies, Wanagarren	2019/20	19	Failed	Predation (T, I)	**Red fox** (eggs)	≥Weekly	AS, DBCA
Hangover Bay, Cervantes	2019/20	15	Failed	Predation (T, I)	**Red fox** (eggs)	≥Weekly	AS, DBCA
Cape Vlamingh, Rottnest Island	2019/20	12	Failed	Unknown	Possible tidal inundation, unconfirmed	≥Weekly	RP, RIA
Wellstead Estuary	2019/20	10	Failed	Predation (I)	**Silver gull** (eggs), human disturbance	≥Weekly	SE
Wedge to Grey Track	2019/20	10	Failed	Tidal Inundation (I)	*1 fledgling recorded	≥Weekly	AS, DBCA
Whitlock Island (Jurien Bay)	2019/20	6	Moderate CP			≥Monthly	AS, DBCA
Favourite Island, JBMP	2019/20	5	Moderate CP			≥Monthly	AS, DBCA
Kangaroo Point, Cervantes	2019/20	4	Failed	Predation (T, I)	**Red fox** (eggs)	≥Weekly	AS, DBCA
Cowaramup	2019/20	1	Failed	Disturbance (I)	**Human disturbance**	Twice	MS
Point Malcolm, Israelite Bay	2019/20		Moderate CP		Pacific gull *Colony with chicks/ fledglings found late in season	Once	SC, AD
Wedge Island	2020/21	270	High CP			≥Monthly	AS, ASh, DW, ER, **ND**, DBCA
Point Walter (Perth) (Colony 2)	2020/21	150	High CP		Partial tidal inundation, human disturbance	Daily-weekly	**CG**

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Table 1. (*Continued*).

Site	Season	Breeding pairs (*n*)	Colony outcome	Reason for failure (identification method)	Observed threats and sources of mortality	Monitoring routine	Observer(s)
Carnac Island	2020/21	150	Failed	Unknown	Possible tidal inundation, unconfirmed	≥Monthly	DBCA, SG
Pyramids Beach, Dawesville	2020/21	110	High CP		**Silver gull** (eggs), **dogs** (chicks), human disturbance, black rat	Daily	**CG**, WAFTN
Point Walter (Perth) (Colony 1)	2020/21	100	Failed	Tidal Inundation (I)	**Australian hobby** (adult), peregrine falcon, **Australian pied oystercatcher** (egg), human disturbance	Daily	**CG**
Point Peron (Perth)	2020/21	60	Failed	Predation (WC)	**Red foxes** (eggs), human disturbance	Daily	**CG**
Strickland Bay, Rottnest Island	2020/21	30	Failed	Tidal Inundation (I)		Daily-weekly	**CG**, RP, RIA
Leschenault Estuary, Bunbury	2020/21	18	Failed	Disturbance (I)	**Off-road vehicle(s)** (eggs)	≥Weekly	CT, PM, DBCA
Hill River	2020/21	17	Failed	Predation (T, I)	**Red fox** (eggs), dog, off-road vehicle(s)	≥Weekly	AS, DBCA
North West Cape	2020/21	10	Low CP		Human disturbance, off-road vehicles	≥Weekly	MP JG, GG
Becher Point, Warnboro (Perth)	2020/21	8	Failed	Predation (DO, I)	Red fox, Australian raven (eggs)	Daily	BM, CH
Green Islands	2020/21	7	Failed	Unknown		≥Monthly	AS, ASh, DW, ER, DBCA
Causeway, Garden Island	2020/21	7	Failed	Eggs removed	Eggs removed to prevent vehicle strike. Black rat	≥Weekly	**CG**, SB, DBCA
Parkin Pt, Garden Island	2020/21	5	Failed	Tidal Inundation (I)		≥Weekly	**CG**
Penguin Island	2020/21	4	Failed	Unknown	Possible egg burial, unconfirmed	Daily	DBCA, SG
Bunbury Outer Harbour	2020/21	1	Failed	Unknown		≥Weekly	CT, DBCA
Rous Head, North Fremantle	2020/21	1	Failed	Disturbance (WC)	**Human disturbance**	Daily	**CG**, MR, **MP**
Lake Herschel, Rottnest Island	2021/21	30	Failed	Predation (DO)	**Ruddy turnstone** (eggs), Australian raven, silver gull	Daily	**CG**
Collins Pt, Garden Island	2021/21	29	Failed	Tidal Inundation (I)		≥Weekly	**CG**, SB
Pyramids Beach, Dawesville	2021/22	350	High CP		**Australian hobby** (adult), **dugite** (chick), **cat** (chicks), **silver gull** (eggs), dog	Daily	**CG,** WAFTN
Pearse Lake, Rottnest Island	2021/22	168	High CP			≥Weekly	RP, RIA
Wedge Island	2021/22	140	Failed	Tidal Inundation (I)		≥Weekly	AS, TL, RW, DBCA
Leeman Lake	2021/22	140	High CP		Peregrine falcon (fledgling), red fox	≥Weekly	AS, DBCA
Point Walter (Perth)	2021/22	130	High CP		Human disturbance	Daily-weekly	**CG**

(*Continued on next page*)

Table 1. (*Continued*).

Site	Season	Breeding pairs (*n*)	Colony outcome	Reason for failure (identification method)	Observed threats and sources of mortality	Monitoring routine	Observer(s)
Carnac Island	2021/22	30	Moderate CP		Human disturbance	Weekly-Fortnightly	ME, SG, DBCA
Jorndee Creek, Cape Arid	2021/22	25	High CP		Pacific gull, silver gull, rat (probably native brown rat), cat, swamp harrier, white-bellied sea-eagle	Twice	TM, KN, PN, DBCA
Broke Inlet	2021/22	23	Moderate CP		**Unidentified snake** (chick)	≥Monthly	JL, DBCA
Fishermans Island, Jurien Bay	2021/22	22	Failed	Tidal Inundation (I)	**Australian sea lion** (eggs)	≥Monthly	RW, AS, TL, DBCA
Peel Inlet (Mandurah)	2021/22	14	Low CP			Daily-weekly	JVJ, SVJ
Hangover Bay, Cervantes	2021/22	6	Failed	Predation (T, I)	**Red fox** (eggs), off-road vehicle(s)	≥Weekly	RW, AS, DBCA
Denham	2021/22	4	Failed	Tidal Inundation (I)	**Tidal inundation** (eggs)	Daily	DW
Boundary Island, Mandurah	2021/22	4	Low CP		Red fox, Australian raven	≥Weekly	JVJ, SVJ, NG
Woodman Point, Cockburn	2021/22	3	Failed	Unknown	Red fox, kite surfers, human disturbance, dogs, cats (2), silver gull	Daily	SH, WG, WFTN

Under Colony Outcome, CP = chick production. Observed threats that resulted in egg, chick or adult mortality are shown in bold face, and the associated life history stage in brackets. Under Reason for Failure, method of identification is recorded as direct observation (DO), wildlife camera (WC), animal tracks (T) or the outcome was inferred (I) from other evidence at the site (see methods). Under Observer, initials are shown in bold face where monitoring was undertaken by a researcher, observations by a land manager are shaded grey and white space indicates observations were made by volunteers.
Observers: TW, Toni Webster; WAFTN, WA Fairy Tern Network; CC, Cherilyn Corker; DBCA, Department of Biodiversity, Conservation and Attractions; RP, Ron Priemus; RIA, Rottnest Island Authority; GD, Georgia Davies; AS, Alanna Smith; CG, Claire Greenwell; CT, Christine Taylor; PM, Peter Moore; JL, Janine Liddelow; AS, Annie Shaw; ND, Nic Dunlop; SP, Sean Plozza; SE, Steve Elson; MS, Marcus Singor; SK, Sue Kalab; RB, Rebecca Bloomfield; MP, Merryn Pryor; SC, Sarah Comer; AD, Alan Danks; PM, Peter Morris; RW, Roger Whitelaw; ER, Emma Rowe; BM, Brad Marayan; CH, Cathy Hurst; SB, Steve Booth; MP, Mark Panhuyzen; JG, John Greer; GG, Grant Griffin; MR, Mackenzie Rowtcliff, DW, Drew Wassam; JVJ, Jamie van Jones; SVJ, Sebastian van Jones; NG, Natalie Goddard; ME, Melissa Evans; TL, Toby Larke; TM, Tessa Murray; KN, Kim Norris; PM, Pam Norris; SH, Sumedha Herath; WG, Wayne Gerrard.

at those sites failed soon after egg-laying, presumably in the early stages of colony development, and may have gone on to support a larger number of breeding pairs had they not failed. Understanding the sources of failure during this vulnerable early colony formation period is critical to informing conservation management.

Threats and causes of colony failure were determined through direct observations and wildlife cameras, or in some cases, predation was evidenced by tracks in the sand and broken eggs (inferred predation). Occasionally, direct observations of red foxes (*Vulpes vulpes*) close to colonies, in addition to tracks and broken eggs supported the determination of inferred predation. Tidal inundation was inferred by observing the high-water mark, algal wrack and/or the movement of eggs past the highest tide, sometimes on consecutive days of monitoring (Table 1).

To reduce the potential for colony disturbance, the number of chicks produced per pair was not an obtainable measure. However, breeding success at each site was subjectively categorised as having low (<30% of pairs), moderate (~40–70% of pairs) or high (>70% of pairs) chick production, i.e. few to many chicks produced, based on the apparent number of chicks observed relative to the number of breeding pairs around the peak of nesting. The causes of nest failure were then considered against the Recovery Plan's threat prioritisation matrix to understand how the observed threats compared to the identified risks in this plan.

Results

Colony outcomes

From the 77 colonies monitored, 27% (n = 21) had high breeding success, 18% (n = 14) were moderately successful, 7% (n = 5) had low breeding success and 48% (n = 37) failed (Fig. 2, Table 1). Among those that failed, predation (32%, n = 12) and inundation (27% n = 10) were, purportedly, the biggest causes of colony failure, followed by human disturbance, i.e. fishing, walking, camping, kite surfing (8%, n = 3, Fig. 2). The sources of failure were not able to be determined at 22% (n = 8) of the monitored colonies (Fig. 2).

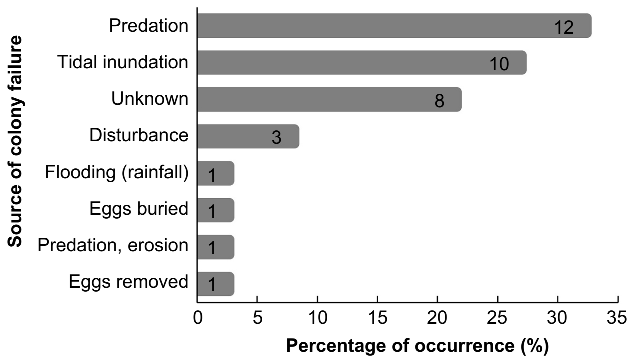

Fig. 2. Sources of colony failure (percentage of occurrence) at 77 monitored Australian Fairy Tern (*Sternula nereis nereis*) colonies in Western Australia between 2017/18 and 2021/22. Numbers shown inside bars indicate the number (*n*) of occurrences the source of failure was observed.

Non-native species were recorded at 29 colonies during the study period (Fig. 3). Red foxes, black rats (*Rattus rattus*) and cats (*Felis catus*) were believed to be implicated in the failure of at least nine colonies, and in all cases, predation was evidenced by tracks in the sand and broken eggs (inferred predation), direct observations and/or wildlife cameras (Table 1). Red foxes appear to have contributed to the failure of at least six colonies (Table 1) and the partial failure of a colony at Point Walter in 2018/19 (Greenwell *et al.* 2021*b*). Predation by a single, free-roaming cat purportedly led to the failure of one colony of 111 pairs in Mandurah in 2018 (Greenwell *et al.* 2019*a*), and black rats are believed to have predated eggs (inferred predation) at two colonies at Garden Island (Table 1, C. Greenwell, pers. obs; G. Davies, pers. comm.). Two colonies purportedly failed following predation by native species – one by ruddy turnstone (*Arenaria interpres*) at Rottnest Island (Greenwell 2021) and the other by silver gulls (*Chroicocephalus novaehollandiae*) at Wellstead Estuary (S. Elson, pers. comm.).

Natural weather events, i.e. inundation, flooding (heavy rainfall) and egg burial from strong winds, contributed to the failure of at least 33% ($n = 12$) of colonies and were recorded in all years (Table 1). Tidal inundation (27%, $n = 10$) was the most persistent source of 'natural' failure, recorded in 4 of the 5 years of observation (Fig. 2, Table 1). In 2017/18 on Rottnest Island, a 1/500-year rainfall event caused the flooding and abandonment of an entire colony of 176 pairs. In 2018, beach erosion and predation by a nankeen kestrel (*Falco cenchroides*) contributed to the failure of a colony in Mandurah, following predation by a cat at a nearby colony (Table 1, Greenwell *et al.* 2019*a*).

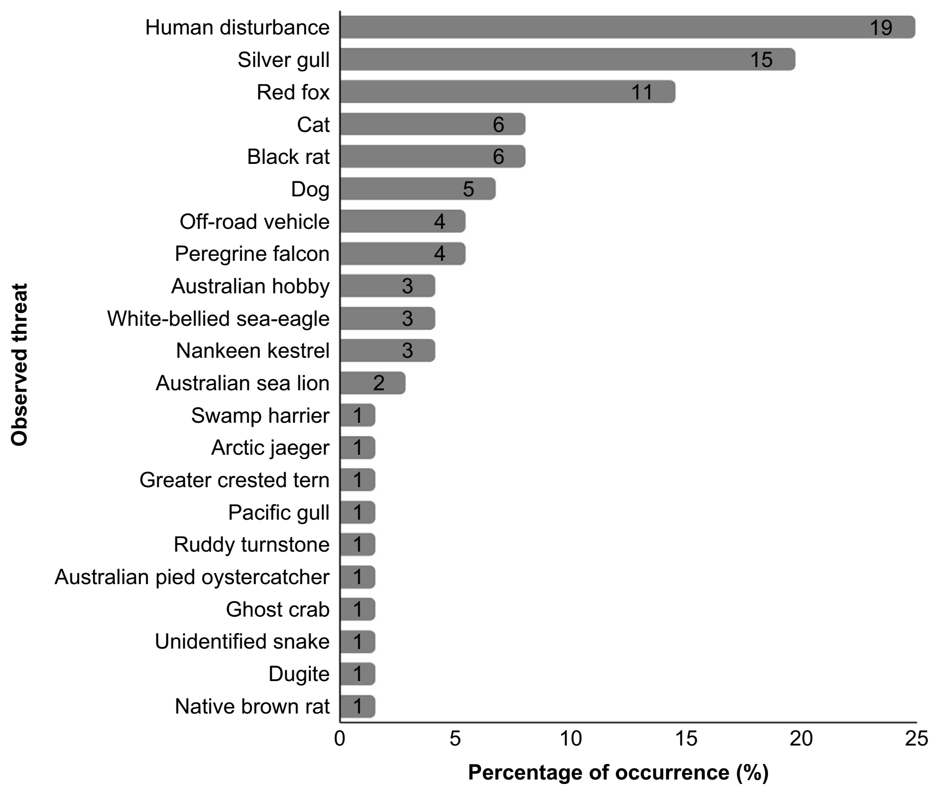

Fig. 3. Threats observed (percentage of occurrence) at 77 monitored Australian Fairy Tern (*Sternula nereis nereis*) colonies in Western Australia between 2017/18 and 2021/22. Numbers shown inside bars indicate the number (*n*) of occurrences the threat was observed.

Human disturbance, including off-road vehicles, caused the failure of 8% ($n = 3$) of colonies (Fig. 2). On two occasions, off-road vehicles were implicated, evidenced by tyre tracks through the nesting area (Table 1). At the Leschenault Estuary mouth, near Bunbury, a colony in the early stages of development consisting of ~18 nests was destroyed by a vehicle(s) that drove, in circles, within the sign-posted nesting area (Table 1, C. Taylor, P. Morris, pers. comm.). At Rous Head in 2020/21, the first nest to be established was abandoned between Christmas Day and Boxing Day due to human disturbance. A beach towel, empty beer bottles and a beach ball were found in the fenced breeding area, and these activities were detected on wildlife cameras (M. Pryor, pers. comm.). On a beach in Cowaramup, a single nest was abandoned before it could be fenced off, presumably due to disturbance (Table 1, M. Singor, pers. comm.).

Individual nest failure, predation and colony disturbance

Human disturbance was observed at many monitored sites, including Mandurah Marina, Dawesville, Penguin Island, Point Walter, Rous Head, Carnac Island, Wedge Island, Hangover Bay and North West Cape (Table 1). For example, at Point Walter, fishers and other recreational users intermittently breached the fenced exclusion zone and disturbed nesting Fairy Terns as they walked along the narrow sandbar in all years (C. Greenwell, pers. obs.). At Rous Head, fishers and beachgoers were often observed or detected on wildlife cameras, walking through the fenced site (C. Greenwell, pers. obs.). At Woodman Point, numerous disturbances were documented, including off-leash dogs, recreational fishers that walked through the nesting site and kite surfers (S. Herath, W. Garrard, pers. comm.). At Point Walter in 2018/19, predation of eggs and chicks by a red fox contributed to the partial failure of the colony, and on Penguin Island in 2019/20, predation by silver gull(s) and a juvenile crested tern (*Thalasseus bergii*) contributed to a high incidence of individual nest failure (≥70%; Fig. 4, Table 1).

Numerous native species were observed predating Fairy Tern eggs, chicks or adults (Fig. 4, Table 1). Predators included Australian pied oystercatcher (*Haematopus longirostris*; C. Greenwell, pers. obs.), ruddy turnstone (Greenwell 2021), silver gull (Greenwell *et al.* 2021*b*; S. Elson, C. Corker, pers. comm.); juvenile greater crested tern (Greenwell *et al.* 2021*b*), nankeen kestrel (C. Corker, C. Greenwell, pers. obs.), Australian hobby (C. Greenwell, pers. obs., A. Loffler, pers. comm.), dugite (*Pseudonaja affinis*; D. Martin, pers. comm.).

Arctic jaeger (*Stercorarius parasiticus*; S. Goodlich, pers. comm.), pacific gull (*Larus pacificus*; K & P Norris, pers. comm.), peregrine falcon (*Falco peregrinus*; C. Greenwell, pers. obs.; A. Smith, S. Kalab, pers. comm.), swamp harrier (*Circus approximans*), white-bellied sea-eagle (*Haliaeetus leucogaster*; C. Greenwell, pers. obs., P. Moore, pers. comm.) were observed near or harassing colonies, and despite obvious disturbance to terns, no cases of predation by these species were confirmed (Fig. 4, Table 1). In addition, Australian sea lions (*Neophoca cinerea*) purportedly crushed several nests on Carnac Island in 2018/19 and Fisherman's Island in 2020/21 (Table 1, S. Goodlich, A. Smith, pers. comm.).

In 2020/21, domestic dogs were a common source of disturbance at a colony in Dawesville, and are suspected of having injured or killed at least two Fairy Tern chicks (Fig. 4*g*, *f*, P. Fenton, pers. comm.). Subsequently, the beach was rezoned from an on-leash area to a dog prohibited area. At the same site in January 2022, a deceased 5-day-old chick with punctures in the body and four wing sets belonging to fledgling Fairy Terns were found (Fig. 4*e*, *f*, J. White, pers. comm.). On further investigation, animal tracks suspected of belonging to a cat were found on the colony's outskirts. The following evening, a cat was trapped by the City of Mandurah (B. Beal-Richardson, pers. comm.). The cat was not collared, desexed, nor microchipped, and was believed to be semi-feral/unowned due to its poor body condition (i.e. an animal that is partially provisioned by people, deliberately or incidentally through garbage; Cove *et al.* 2018) (B. Beal-Richardson, pers. comm.). No further mammal tracks or instances of terrestrial predation were found following the trapping and removal of the cat in the 2021/22 season.

Discussion

Nearly half of all known and monitored Fairy Tern colonies in Western Australia failed between 2017/18 and 2021/22. Predation, inundation and to a lesser extent, human disturbance, were the biggest drivers of failure, accounting for ~68% of colony failures, and were observed across the State.

Predation

At least 14 predators (10 native and 4 invasive/domestic) were observed at Fairy Tern colonies during the 5 years of monitoring and contributed to egg, chick and/or adult mortality or complete colony failure. The high incidence of colony failure associated with invasive and domestic predators reinforces the need for monitoring and targeted predator removal or deterrence, both in the lead-up to and during the breeding season, i.e. pre-emptive and reactive controls. This is particularly important at frequently used sites, which may be subject to a build-up of predators or where the locations of colonies become predictable to predators over time (Ward *et al.* 2011; Dunlop 2018; Greenwell *et al.* 2019*b*). Red foxes, black rats and cats have been identified as key invasive predators impacting the breeding success of Fairy Terns elsewhere on mainland Australia (Trees and Natural Resources 1997; Maguire 2008; Paton and Rogers 2009; Lacey and O'Brien 2015; Commonwealth of Australia 2020). The development of local/regional protocols by land management agencies may be useful for informing predator control

Fig. 4. Examples of disturbance, predation and colony failure at Australian Fairy Tern (*Sternula nereis nereis*) colonies in Western Australia between 2017/18 and 2021/22. (*a*) Red fox (*Vulpes vulpes*) at Point Peron, (*b*) adult silver gull (*Chroicocephalus novaehollandiae*) predating a chick at Penguin Island, (*c*) juvenile greater crested tern (*Thalasseus bergii*) predating a chick at Penguin Island, (*d*) Australian hobby (*Falco longipennis*) predating an adult tern at Dawesville, (*e* and *f*) dead Fairy Tern runner and fledgling following suspected predation and trapping of a cat at Dawesville, (*g*) incursion by an off-leash dog at Dawesville and (*h*) Fairy Tern chick with an injured wing from a suspected dog attack at Dawesville. Image credits: (*a*) Peter Moore; (*b* and *c*) Claire Greenwell; (*d*) Amy Loffler; (*e*–*g*) Julie White; (*h*) Paul Fenton.

efforts, particularly at short notice, to prevent swift colony decline (Greenwell *et al*. 2019*a*; Commonwealth of Australia 2020). Improved regulation of pet animals, i.e. dog prohibition and/or strict leashing requirements and cat containment, in areas adjacent to colony sites would also likely improve outcomes for nesting terns.

Inundation

Inundation was a major source of colony failure due to the tern's preference for breeding sites in low-laying sandy beach habitat, often just above the intertidal zone. Inundation frequency is predicted to increase with climate change, driven by sea-level rise and higher sea surface levels (Indian Ocean Climate Initiative 2012; Garnett *et al.* 2013), engineering impacts (e.g. the Dawesville Cut influencing water levels on the Peel Inlet), and more severe and frequent summer storm events. Flood mitigation strategies, such as raising the height of colony areas or encouraging settlement in low flood risk areas, should be developed and implemented as a priority to provide a safe habitat for beach-nesting species, including Fairy Terns, and to improve breeding productivity (Garnett *et al.* 2013).

In New Zealand, options used to reduce inundation risk for Fairy Terns (*Sternula nereis davisae*) have included sand-bagging nests from tidal surges, ditch and dyke systems to reduce flooding risk of low laying nests and oyster shell banks to increase substrate height and reduce the impacts of tides and storm surges (Ferreira *et al.* 2005; Department of Environment and Conservation New Zealand 2019). Alternatively, managed and/or engineered sites (generally on dredge-spoil) dedicated specifically to breeding may provide an effective long-term solution, with elevated sites removing the potential for inundation (Krogh and Schweitzer 1999; Jenniges and Plettner 2008; Pakanen *et al.* 2014; Greenwell *et al.* 2019*b*, 2021*a*).

Human disturbance

Although human disturbance only accounted for 8% ($n = 3$) of colony failures, disturbance was recorded at ≥30% ($n = 23$) of colonies. The incidence of disturbance may be underestimated, particularly during the settlement and early egg-laying periods before the colony site has been identified or at remote sites that are difficult to monitor regularly. In these cases, colony abandonment is more likely to occur before protective measures are introduced, such as the installation of temporary fencing and signage. During the early settling period, site attachment is relatively low due to the low investment of time and energy into egg laying or incubation and moving to an alternative site may outweigh the risk of remaining at a disturbed site (Nisbet 1981; Safina and Burger 1983; Burger and Gochfeld 1991; Nisbet 2000; Greenwell *et al.* 2021*b*).

In the early stages of colony formation, the first eggs to be laid are often intermittently incubated or deserted at night, potentially as a mechanism for assessing potential nest predators or increasing egg synchrony and reducing the time the colony is detectable by predators (Gochfeld 1980; Atwood 1986; Nisbet 2000; Jovani and Grimm 2008; Greenwell *et al.* 2019*b*). During this period, fewer terns may be present at the breeding site, thus group defence strategies, including dive-bombing intruders, are likely to be lower (Brunton 1999).

Fairy Terns often form colonies on spits and wide sandy beaches located near estuary mouths, on nearshore islands or salt lakes, or within sheltered coastal embayments where small baitfish are abundant (Higgins and Davies 1996; Paton *et al.* 2009; Lacey and O'Brien 2015; Greenwell *et al.* 2021*b*, 2021*d*). The protection of these important coastal landforms should be prioritised to improve the long-term conservation needs of Fairy Terns and other beach-nesting species, such as Australian pied oystercatchers and red-capped plovers (*Charadrius ruficapillus*), and to preserve their high natural value. Reducing the impact of recreational activities, particularly from off-leash dogs and unregulated, highly destructive off-road vehicles in these sensitive habitats, is critical for maintaining ecosystem function (Williams *et al.* 2009; Schlacher *et al.* 2015; Maguire 2018).

When breeding behaviour is anticipated or identified, pre-emptive or proactive management interventions may be used to reduce human disturbance. Interventions such as seasonal site closures and restricting human access by erecting temporary fencing and signage near nesting areas are often effective in reducing disturbance, facilitating an increase in reproductive success (Burger and Leonard 2000; Lafferty *et al.* 2006; Medeiros *et al.* 2007; Maguire 2008).

Unidentified failures

Outcomes could not be documented at several colonies due to their remoteness or a lack of resources to undertake regular monitoring. Documenting the outcomes of breeding success is a key objective under the Recovery Plan to better target management actions (Commonwealth of Australia 2020). Engaging local observers, including commercial operators, and/or expanding the opportunities for citizen science programs may effectively support monitoring and management efforts (Tulloch *et al.* 2013; Greenwell *et al.* 2021*c*).

Conservation implications

This study highlighted the numerous threats Fairy Terns face during a breeding attempt. The observed threats were consistent with those identified under the Fairy Tern Recovery Plan risk matrix and recognised as having major consequences, i.e. at the population level (Commonwealth of Australia 2020). To address these threats and maintain or increase the current population trajectory, practical solutions, including the development of effective predator control and flood mitigation strategies are critical for addressing the major sources of colony failure. Identifying the beaches most at risk of sea-level rise and inundation – and those that may act as refuge sites (i.e. likely to be relatively unaffected by sea level rise before 2100) or retreat pathways (i.e. where the affected natural value has the capacity to retreat landward, enabling birds to nest elsewhere), similar to work completed in Tasmania – is urgently needed (DPIPWE 2015).

Disturbance was intermittently observed in at least one-third of colonies but was identified as the only cause of abandonment at three sites. It is possible that increased education, early identification and protection of colonies and pre-emptive management at regularly-used sites have helped to reduce (but not completely eliminate) the impacts of disturbance compared with historical levels (Singor 1998; Dunlop 2016; Singor 2021), particularly in the higher population centres in the south-west, where Fairy Tern conservation now has a large network of active volunteer observers, managers and wider community support.

The community-led, collaborative approach adopted for management and monitoring in Western Australia has enabled the early identification and protection of breeding sites and the collection and reporting of information on the threats faced by Fairy Terns during the breeding season. Strategies that raise awareness and educate the general public about Fairy Tern conservation are likely to further reduce disturbance at breeding colonies, help foster stronger community stewardship and increase citizen scientist participation over time.

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