Text S1: Investigation of the impacts of the 2011 MHW on the northern and southern foraging grounds

We tested for the difference in the percentage of penguins caught at each of the mark-recapture sites before the 2011 MHW (i.e. 2007, 2008 and 2010) and after (i.e. 2011, 2017 and 2019). For each site we obtained the percentage of penguins caught, before and after the MHW, using:

$$\left(\sum penguins\ caught\ at\ site\ i / \sum penguins\ caught\ at\ sites\ 1-4\right) * 100$$

Text S2 Specimen collection and necropsies

Between 2003–2013 and 2016–2019, 336 little penguin carcases were collected, of which 202 were necropsied. The carcases or injured birds were mainly opportunistically found on Penguin Island (32° 18' S, 115° 41' E), Garden Island (<10 km north, 32° 14' S, 115° 41' E) and the foreshores of southwest Western Australia. In 2006–2009, additional weekly surveys were generally undertaken at the mainland beaches from 32° 10' S, 115° 46' E to 32° 31' S, 115° 44' E. Injured birds were taken to a veterinarian and were euthanised if considered appropriate. Carcases were typically frozen prior to necropsy, and most necropsies were performed at the School of Veterinary and Life Sciences, Murdoch University. We included only those birds that died of starvation or protozoal parasite infections. Of this subset of necropsied birds (86 birds), 17% were microchipped or flipper banded and were from Penguin Island. All of the remainder were found on foreshores within the home range of little penguins from Penguin Island (Cannell 2016, 2019).

Text S3 Timing of peak egg laying and influence of MHW

Since the MHW in 2011, peak egg laying in June/July occurred in 5 of the 8 years (excluding 2012). Additionally, peak egg laying occurred in May in 2015 and 2018. There was no consistent month of peak egg laying in the years of the lowest overall breeding success, i.e. 1986 (August), 1994 (September), 1999-MHW (September), 2011-MHW (June) and 2013 (June and July). Occasionally there were two distinct peaks of egg laying e.g. 1996 (June and September) and 2018 (May and September) (Fig. S3). Prior to the MHW, peaks in egg laying in the austral winter months of June and July were associated with years with cooler than average ocean temperatures (e.g. 1987), or were generally < 0.5°C above average (e.g. 1988) (Figs. 4 and S3). A single peak of egg laying in spring, or a double peak in winter and spring were associated with above average SST (except for 1991). In the few years immediately following the MHW however, peaks of egg laying in winter were associated with much warmer than average SST (Figs. 4 and S3). An almost constant proportion of egg laying in most months were associated with cooler than average SST both before and after the MHW (e.g. 2003 and 2016) (Figs. 4 and S3).

Text S4 Discussion of timing of peak egg laying, and the relationship between this, success and SST

Eggs were laid in every month from April–November, though eggs were rarely laid in both April and November. However, there was a change in the association between SST and peak egg lay after the extreme MHW in 2011. Prior to this, a delay in breeding (i.e., peak egg lay in September (austral spring)) as occurred in 1989, 1991, 1994, 1999 and 2000, was generally associated with positive SOI, increased FSL and above average SST. This delay in breeding is likely due to the majority of penguins not attaining the body condition necessary for breeding earlier in the year (Wienecke et al. 1995). After the extreme MHW, the penguins did not delay breeding but had a peak of egg lay in June/July, and waters were warmer than average (2011, 2013, 2014 and 2017). Despite the earlier breeding, the CPP was below average (except 2014, when it was just above average). We presume that in years when SST were warmer than average, similar to 2011, scaly mackerel were available but much further from the colony. Penguins can forage further afield during pre-breeding and incubation than during the chick-rearing period. Cannell (2016, 2019) has shown that incubating penguins nesting on SE, SW and W Penguin Island regularly travel to foraging grounds in Geographe Bay, approximately 120 km south of Penguin Island. Furthermore, those nesting on the NE side of the island forage north, in Cockburn Sound, approximately 35 km north (accounting for their travel route). However, as central place foragers, they must have an abundant and reliable prey source close to colony to successfully raise chicks. Interestingly, the CPP was more likely to be above average in those years prior to the MHW when peak egg lay occurred in June/July.

Text S5 Future Research

Whilst the top predictors for the RF models make biological sense, the models have low performance and thus a lot of unexplained variance. This is because the only available environmental covariates that temporally match the dependent data have a narrow range of spatial and attribute resolution. RF results may reflect that 1) not all the appropriate covariates were included in the models, 2) the covariates used were not sampled over the appropriate temporal or spatial scale, and/or 3) there are other variables such as breeding experience and locality of prey that may induce skipped breeding or other yet latent variables, which would ultimately confound the results of our models. For example, we could not use chlorophyll *a*, an indicator of ocean productivity, in our models. This is because the penguins forage in coastal waters and the chlorophyll *a* data from remote sensing platforms are inaccurate in such shallow waters (Yu 2020). Incorporating other factors that not only influence fish assemblages but can also be species-specific, such as salinity, turbidity and pH (Mansor et al. 2012), would be beneficial. Additionally, whilst there are data on the dispersal of eggs and larvae of pilchards and sandy sprat in SW Australia (Gaughan et al. 1996, Lenanton et al. 2009), the relationship between variables such as SST on the presence of juvenile and adult baitfish within the home range of little penguins is unknown. The establishment of regular abundance and distribution surveys will improve hypothesis testing related to the ecological drivers of baitfish abundance and hence their influence on the population dynamics of penguins (Rivers et al. 2022).

The change in the number of penguins caught at the arrival beaches warrants further investigation. To understand if there is likely to be a shift in the distribution of penguins on the island, it is paramount to determine breeding success in relation to nesting location. Additionally, Cockburn Sound, where the penguins nesting on NE Penguin Island forage during incubation, is already one of the most heavily utilized marine zones in Western Australia. Numerous upcoming projects are intended for the Sound, such as the Australian Maritime Complex, a hydrogen plant and marine loading facility, and a freight port. Consequently, there is a need to examine the significance of foraging grounds situated north of the island in preserving the colony's sustainability, especially during La Niña events or MHWs. Such work could extend into more extensive eDNA surveys. For example, using eDNA surveys, Berry et al. (2019) detected biotic shifts in the 2011/12 MHW near Rottnest Island, 45 km NW of Penguin Island. The incorporation of tree-of-life approach to studying the biota around penguin breeding areas may provide a more nuanced picture regarding how ecosystems respond to MHWs as well as the overall increasing trends in SST.

Table S1. Dates of the mark-recapture sessions of little penguins in 2007, 2008, 2010, 2011, 2017 and 2019 on Penguin Island, Western Australia

Year	1	2	3	4
2007	12 –15 Oct	2–5 Nov	23–26 Nov	
2008	19–22 Sept	3–6 Oct	17–20 Oct	24–27 Oct
2010*	29 Oct–1 Nov	12–15 Nov	26–29 Nov	3–6 Dec
2011	7–10 Sept	23–26 Sept	5–8 Oct	20–23 Oct
2017	24–27 Sept	10–13 Oct	27–30 Oct	9–12 Nov
2019	22–25 Sept	6–9 Oct	20–23 Oct	3–6 Nov

*Unavoidable contractual issues led to a delay in timing of the mark-recapture sessions

Table S2. Covariates used in the analysis of the body condition, diet composition and breeding success of little penguins from Penguin Island. [a]used for analysis of body condition, [b]used for analysis of dietary differences between 2009–2012, l, [c] used for analysis of breeding success.

Variable	**Description**	**Potential relationship dependent variable**
Offshore SSTs [a,b, c,]	Mean sea surface temperatures were obtained for a rectangular area with the co-ordinates 115°E–115° 15' E and 32° 30'S–31° 30'S. This encompasses the Leeuwin Current, even in the summer when it flows further offshore. Derived from European Space Agency CCI v2. We obtained mean, SD and anomaly values for 1) the austral summer (December–February)[a], 2) Pre–breeding (January–April)[b] 3) April[a,c], and 4) Breeding (May–November)[b]	SSTs influence spawning, recruitment of baitfish species (e.g. Gaughan et al. 1996, Lindegren & Checkley Jr 2013), and elevated April SSTs negatively impact breeding success of little penguins on Penguin Island (Cannell et al. 2012)
Southern Oscillation Index (SOI), and 1 and 2 year lags[a,b,c,]	Annual mean (and SD) SOI, which gives an indication of the development of El Niño or La Niña events in the Pacific Ocean. Sustained negative values of the SOI <-7 often indicate El Niño episodes, whilst >+7 indicate La Niña events	The strength of the Leeuwin Current increases during La Niña events (Feng et al. 2003, Feng et al. 2021). A strong Leeuwin Current has been associated with poorer feeding conditions for fish larvae on the continental shelf and the large mesoscale eddies formed can remove large numbers of pelagic larvae (Gaughan 2007a). The larvae can be transported up to 1000 km (Gaughan et al. 2001)
Winter[c] and annual[a,b,] rainfall, 1 year lag annual rainfall, 2 year lag annual rainfalll[a,b,c,]	Total annual and winter rainfall, obtained from the Australian Bureau of Meteorology (http://www.bom.gov.au/wa/?ref=hdr). As records from a single station close to Penguin Island did not cover the entire study for the analyses, data were obtained from stations 9572 (1986–2001) and 9977 (2002–2019). The stations are 2 km apart. Rainfall data from the Perth	There is an association between rainfall and riverine input, which can affect nutrient input in coastal marine systems (Molony et al. 2011). Additionally, rainfall had a positive influence on sandy sprat abundance in Warnbro Sound, the embayment immediately south of Penguin Island (Gaughan et al. 1996). Anecdotal evidence from fishers suggests that schools of sandy sprat move upstream into the Swan Estuary after the

	Airport (9021) were also obtained, as the rainfall in this region flows into the Swan Estuary.	onset of winter rains, when freshwater outflow reaches the lower estuary (Gaughan et al. 1996).
Fremantle Sea Level (FSL)[a,b,c]	Daily values of Fremantle (32º 3' S, 115º 44' E) sea level (FSL) were obtained from http://uhslc.soest.hawaii.edu/data/. From these data, we determined mean and SD for 1) annual (January–December)[a,b], 2) the moult period prior to breeding (December–February)[a], 3) the pre-breeding period (March–May)[a], 4) the breeding season (April–November)[a], and 5) for the winter period (June–August)[b,c]. We also included a lag of 1 year for the annual FSL[c] and the winter FSL[c]	The FSL values can be used as a proxy for the strength of the Leeuwin Current (Pearce & Phillips 1988, Feng et al. 2003). A strong Leeuwin Current removes phytoplankton and zooplankton from continental shelf waters, reducing the feeding conditions of larvae on the shelf (Gaughan 2007b). Large mesoscale eddies that form within the Leeuwin Current can remove large numbers of pelagic larvae (Gaughan 2007b), and transport up to 1000 km (Gaughan et al. 2001). Commercial catches in some regions were positively correlated with a 1-year lagged winter FSL, and predicted commercial catches of sandy sprat were strongly positively correlated with the 1-year lag of the FSL (Gaughan et al. 1996). Elevated FSL in February, prior to penguin breeding, led to a later end of egg lay for first clutches (Cannell et al. 2012)
North/South component of the wind[a,c]	Monthly values for November to February of each year were obtained from the European Centre for Medium-Range Weather Forecasts ERA5 reanalysis model (Hersbach et al. 2023) for a point at Rottnest Island (32° 00' S, 115° 30' E). We also obtained the mean and SD values for November to February.	The North/South component of the wind is a proxy for the strength of the Capes Current (Hetzel et al. 2020), a wind-driven northward current that runs inshore of the Leeuwin Current, provides a cool-water conduit for the transport of larval and adult fishes and influences shelf dynamics (Pearce & Pattiaratchi 1999). Upwellings are induced by southerly wind speeds of 7m s^{-1} (equivalent to 25.2km h^{-1}) (Gersbach et al. 1999).

The number of days in summer with southerly winds >7 $m\ s^{-1}$ [a, b, c]	Wind data were obtained from the Australian Bureau of Meteorology (http://www.bom.gov.au/wa/?ref=hdr) at station 9519	Upwellings are induced by southerly wind speeds of $7m\ s^{-1}$ (equivalent to $25.2km\ h^{-1}$) (Gersbach et al. 1999), so the more days with upwelling may provide more favourable conditions for fish production and growth.
Annual commercial catch of baitfish[a,c,]	The annual commercial catch per unit effort (CPUE) of pilchards, anchovy, scaly mackerel, sandy sprat and blue sprat was determined for the three coastal regions used by penguins for foraging 1) the southwest region (34°S–33°S, 115°E–116°E), 2) Mandurah region(33°S–32°S, 115°E–116°E, excluding Cockburn Sound) and 3) Cockburn Sound (32° 18'S–32° 12'S, 115° 42'E–116°E) (Cannell 2016, 2019). Data obtained from the Department of Primary Industries and Regional Development (formerly Department of Fisheries).	The annual CPUE is an indicator of the amount of fish available within the little penguin home range

Table S3. Fish species identified and the numerical abundance (%N) of each species in the diet. Note the data for 2009 were collected by Oliver (2009) using cloning of DNA rather than High Throughput Sequencing (see Murray et al. 2011 for cloning methodology). The total number of samples for each year is noted under the year, in brackets. The species in bold type were the top five species in the diet samples from 2009-2012

	Species	Common name	1986 (212)	1989 (108)	1995 (147)	1996 (44)	1997 (94)	2009 (14)	2010 (24)	2011 (42)	2012 (20)
Fish	***Hyperlophus vittatus***	**Sandy sprat**	18.9	8.5	30.4	81.7	64.8	37.6	56.5	0	25.0
	Sardinops neopilchardus	**Pilchard**	6.1	6.0	5.4	0.2	0.4	9.7	27.7	39.3	23.0
	Engraulis australis	**Anchovy**	1.4	3.2	1.0	4.3	6.5	7.5	6.8	1.5	5.0
	Spratelloides robustus	**Blue sprat**	11.8	3.8	0.6	6.6	1.1	25.8	5.7	0	<0.1
	Hyporhamphus melanochir	Southern Sea Garfish	23.6	34.4	11.3	2.5	4.6				
	Sardinella lemuru	**Scaly mackerel**	0.5					4.3	<0.1	41.1	33.4
	Parequula melbournensis	Silverbelly							2.1	2.7	3.5
	Mugil cephalus	Sea Mullet	2.8		0.4		13.2				
	Pseudocaranx wright	Skipjack trevally			24.7	1.1	1.1		0.5	0.7	
	Sillago basensis	Southern school whiting	0.9	1.4	0.8	0.7		1.1	<0.1	0.4	<0.1
	Sillago schomburgkii	Yellow finned whiting	0.5	4.2							
	Arripis truttaceus	Southern Australian Salmon	0.5								
	Eubalichthys mosaicus	Mosaic Leatherjacket						4.3	<0.1	<0.1	
	Monocanthidae			1.4	4.6	0.9					
	Pranesus ogilbyi	Ogilby's Hardyhead	0.9		3.6		0.1				
	Aldrichetti forsteri	Yelloweye Mullet	0.5		0.2						
	Trachurus spp.			0.3				3.2	<0.1	<0.1	

	Etrumeus teres	Round herring							0.2		<0.1
	Pelates octolineatus	Western striped grunter							0.3	5.0	
	Sphyraena spp.				0.2						
	Perciformes (excl. *Sphyraena* spp.)	Perch-like fish		1.4	0.8	0.7	1.5	1.1		2.1	
	Atheriniformes (excl. Ogilby's Hardyhead)					0.2					
	Actinopthrygii	Ray-finned fish								1.0	
	Cheilodactylidae									<0.1	
	Pempheris spp	Bullseye	1.0	1.8	0.2						
	Pentapodus vitta	Butterfish			0.2						
	Gymnapistes marmoratus	Cobbler								<0.1	
	Kyphosus spp.	Drummer, Chub	0.5					4.3			
	Parapriacanthus sp.	Sweepers									5.0
	Hilsa kelee	Fivespot herring									5.0
Crustaceans	*Amphipoda*				1.2						
	Isopoda				3.8						
	Megalopa	Crab			1.0						
	Penaeidae	Prawn	0.5		0.2						
	Tatraclitella purpurescens	Barnacle						1.1			
Cephalopds	Loliginidae	Squid			1.2		0.1				
	Idiosepius notoides	Squid	0.9	9.2							
	Sepioteuthis	Reef Squid									3.2

Table S4. Model selection results using multistate open robust design mark-recapture models to evaluate demographic parameters of little penguins on Penguin Island from October–November 2007. Parameters are p, probability of recapture; pent, probability of entering the colony for the first time in a given session; phi, the probability of persisting at the colony from one session to another. Structures are (.), constant; t, time within season; tsa, time since arrival; linear tsa, linear time since arrival trend. Constant pent implies values are fixed. Median *c*-hat=1.15

Model	$QAIC_c$	Delta $QAIC_c$	AIC_c Weights	Model Likelihood	Number Parameters	QDeviance
p(t),pent(. ..33333),phi(.)	1338.656	0	0.25299	1	4	1330.59
p(t),pent(. ..33333),phi(tsa)	1339.176	0.5201	0.19506	0.771	5	1329.077
p(.),pent(t),phi(t)	1339.751	1.0949	0.14633	0.5784	5	1329.652
p(1=2),pent(t),phi(.)	1339.751	1.0949	0.14633	0.5784	5	1329.652
p(t),pent(. ..33333),phi(t)	1339.751	1.0949	0.14633	0.5784	5	1329.652
p(1=2),pent(t),phi(tsa)	1341.056	2.4004	0.07618	0.3011	6	1328.917
p(.),pent(t),phi(tsa)	1343.015	4.3592	0.02861	0.1131	5	1332.916
p(.),pent(t),phi(.)	1345.782	7.1262	0.00717	0.0283	4	1337.716
Closed Mt	1349.747	11.0913	0.00099	0.0039	3	1343.708
p(.),pent(. ..33333),phi(t)	1440.494	101.8381	0	0	3	1434.454
p(.),pent(. ..33333),phi(.)	1448.312	109.656	0	0	2	1444.292
p(.),pent(. ..33333),phi(ttsa)	1450.147	111.4911	0	0	3	1444.107

Table S5. Model selection results using multistate open robust design mark-recapture models to evaluate demographic parameters of little penguins on Penguin Island from September–October 2008. Parameters are p, probability of recapture; pent, probability of entering the colony for the first time in a given session; phi, the probability of persisting at the colony from one session to another. Structures are (.), constant; t, time within season; tsa, time since arrival; linear tsa, linear time since arrival trend

Model	AIC_c	Delta AIC_c	AIC_c Weights	Model Likelihood	Number Parameters	Deviance
p(.),pent(t),phi(.)	2622.764	0	0.30599	1	5	2612.689
p(.),pent(t),phi(linear tsa)	2623.841	1.0771	0.17857	0.5836	6	2611.736
p(t1=t2),pent(t),phi(linear tsa)	2624.471	1.7063	0.13037	0.4261	7	2610.329
p(t1=t2),pent(t),phi(.)	2624.702	1.9372	0.11616	0.3796	6	2612.596
p(.),pent(t),phi(tsa)	2625.874	3.1095	0.06464	0.2112	7	2611.732
p(t1=t2),pent(t),phi(tsa)	2625.999	3.2343	0.06073	0.1985	8	2609.817
p(t),pent(.25),phi(linear tsa)	2626.037	3.2723	0.05958	0.1947	5	2615.961
p(.),pent(t),phi(t)	2626.172	3.4077	0.05568	0.182	7	2612.031
p(t1=t2),pent(t),phi(t)	2628.212	5.4474	0.02008	0.0656	8	2612.03
p(t),pent(0.25),phi(tsa)	2630.086	7.3214	0.00787	0.0257	7	2615.944
p(t),pent(0.25t),phi(t)	2638.043	15.2787	0.00015	0.0005	7	2623.902
p(t),phi(t), deaths only	2638.082	15.3173	0.00014	0.0005	6	2625.976
p(t),pent(0.25t),phi(.)	2642.357	19.5928	0.00002	0.0001	5	2632.282
p(t1=t2),pent(t) births only	2643.919	21.1544	0.00001	0	4	2635.868
Closed Mt	2646.038	23.2735	0	0	4	2637.988
p(.),pent(0.25),phi(tsa)	2693.989	71.2243	0	0	4	2685.938
p(.),pent(0.25),phi(linear tsa)	2694.357	71.5931	0	0	3	2688.327
p(.),pent(0.25t),phi(.)	2703.196	80.4319	0	0	2	2699.181
p(.),pent(0.25t),phi(t)	2704.679	81.9149	0	0	4	2696.629

Table S6. Model selection results using multistate open robust design mark-recapture models to evaluate demographic parameters of little penguins on Penguin Island from October–December 2010. Parameters are p, probability of recapture; pent, probability of entering the colony for the first time in a given session; phi, the probability of persisting at the colony from one session to another. Structures are (.), constant; t, time within season; tsa, time since arrival; linear tsa, linear time since arrival trend. Median *c*-hat=1.57

Model	$QAIC_c$	Delta $QAIC_c$	AIC_c Weights	Model Likelihood	Number Parameters	QDeviance
p(t1=t2),pent(t),phi(linear tsa)	511.992	0	0.42075	1	7	497.5693
p(t1=t2),pent(t),phi(tsa)	514.113	2.1206	0.14573	0.3464	8	497.567
p(.),pent(t),phi(linear tsa)	514.323	2.3315	0.13114	0.3117	6	502.0076
p(t1=t2),pent(t),phi(.)	514.782	2.79	0.10427	0.2478	6	502.4661
p(.),pent(t),phi(.)	515.158	3.166	0.0864	0.2053	5	504.9332
p(.),pent(t),phi(tsa)	516.144	4.1517	0.05278	0.1254	7	501.721
p(.),pent(t),phi(t)	516.977	4.9849	0.0348	0.0827	7	502.5542
p(t1=t2),pent(t),phi(t)	517.780	5.7879	0.02329	0.0554	8	501.2344
p(t),phi(t), deaths only	525.216	13.2242	0.00057	0.0014	10	504.3764
p(t1=t2),pent(t) births only	528.349	16.3573	0.00012	0.0003	6	516.0334
p(t),pent(.25),phi(linear tsa)	528.601	16.6093	0.0001	0.0002	9	509.9168
p(t),pent(0.25),phi(tsa)	530.756	18.7645	0.00004	0.0001	10	509.9168
p(t),pent(0.25t),phi(t)	533.605	21.6131	0.00001	0	10	512.7654
Closed Mt	536.468	24.4756	0	0	10	515.6278
p(t),pent(0.25t),phi(.)	540.141	28.1493	0	0	8	523.5957
p(.),pent(0.25),phi(linear tsa)	614.442	102.4501	0	0	6	602.1262
p(.),pent(0.25),phi(tsa)	616.545	104.5535	0	0	7	602.1228
p(.),pent(0.25t),phi(.)	619.836	107.8438	0	0	5	609.611
p(.),pent(0.25t),phi(t)	622.583	110.5912	0	0	7	608.1604

Table S7. Model selection results using multistate open robust design mark-recapture models to evaluate demographic parameters of little penguins on Penguin Island from September–October 2011. Parameters are p, probability of recapture; pent, probability of entering the colony for the first time in a given session; phi, the probability of persisting at the colony from one session to another. Structures are (.), constant; t, time within season; tsa, time since arrival; linear tsa, linear time since arrival trend. Median *c*-hat=1.28

Model	$QAIC_c$	Delta $QAIC_c$	AIC_c Weights	Model Likelihood	Number Parameters	QDeviance
p(.),pent(t),phi(.)	1064.218	0	0.18763	1	5	1054.068
p(t1=t2),pent(t),phi(linear tsa)	1064.469	0.2518	0.16543	0.8817	7	1050.189
p(.),pent(t),phi(linear tsa)	1064.475	0.257	0.16501	0.8794	6	1052.265
p(t1=t2),pent(t),phi(t)	1065.333	1.1154	0.10742	0.5725	8	1048.971
p(t1=t2),pent(t),phi(tsa)	1065.414	1.1962	0.10317	0.5499	8	1049.052
p(.),pent(t),phi(t)	1065.641	1.4238	0.09207	0.4907	7	1051.361
p(t1=t2),pent(t),phi(.)	1066.029	1.8114	0.07585	0.4043	6	1053.819
p(.),pent(t),phi(tsa)	1066.515	2.2976	0.05948	0.317	7	1052.235
p(t),pent(.25),phi(linear tsa)	1068.414	4.1963	0.02302	0.1227	9	1049.961
p(t1=t2),pent(t) births only	1070.348	6.1306	0.00875	0.0466	6	1058.138
p(t),pent(0.25),phi(tsa)	1070.516	6.2985	0.00805	0.0429	10	1049.961
p(t),pent(0.25t),phi(.)	1072.453	8.2353	0.00306	0.0163	8	1056.091
p(t),pent(0.25t),phi(t)	1076.417	12.1992	0.00042	0.0022	10	1055.861
p(t),phi(t), deaths only	1076.715	12.4975	0.00036	0.0019	10	1056.16
Closed Mt	1077.284	13.0659	0.00027	0.0014	10	1056.728
p(.),pent(.),phi(tsa)	1094.741	30.5229	0	0	7	1080.46
p(.),pent(.),phi(linear tsa)	1096.753	32.5352	0	0	6	1084.543
p(.),pent(.),phi(t)	1100.158	35.9407	0	0	7	1085.878
p(.),pent(.),phi(.)	1101.641	37.4233	0	0	5	1091.491

Table S8. Model selection results using multistate open robust design mark-recapture models to evaluate demographic parameters of little penguins on Penguin Island from September–November 2017. Parameters are p, probability of recapture; pent, probability of entering the colony for the first time in a given session; phi, the probability of persisting at the colony from one session to another. Structures are (.), constant; t, time within season; tsa, time since arrival; linear tsa, linear time since arrival trend

Model	AIC_c	Delta AIC_c	AIC_c Weights	Model Likelihood	Number Parameters	Deviance
p(.),pent(t),phi(.)	726.2316	0	0.29001	1	5	715.9472
p(.),pent(t),phi(linear tsa)	726.4081	0.1765	0.26551	0.9155	6	714.0081
p(t1=t2),pent(t),phi(.)	727.8769	1.6453	0.12739	0.4393	6	715.4769
p(t1=t2),pent(t),phi(linear tsa)	728.4138	2.1822	0.0974	0.3359	7	713.8779
p(.),pent(t),phi(tsa)	728.5434	2.3118	0.09129	0.3148	7	714.0075
p(.),pent(t),phi(t)	730.2013	3.9697	0.03985	0.1374	7	715.6654
p(t1=t2),pent(t),phi(tsa)	730.5645	4.3329	0.03323	0.1146	8	713.8722
p(t1=t2),pent(t),phi(t)	730.9139	4.6823	0.0279	0.0962	8	714.2216
p(t1=t2),pent(t) births only	732.0933	5.8617	0.01547	0.0533	6	719.6933
p(t),pent(.25),phi(linear tsa)	733.7518	7.5202	0.00675	0.0233	9	714.8822
p(t),pent(0.25),phi(tsa)	735.9502	9.7186	0.00225	0.0078	10	714.8822
p(t),phi(t), deaths only	736.0663	9.8347	0.00212	0.0073	10	714.9983
p(t),pent(0.25t),phi(.)	739.4159	13.1843	0.0004	0.0014	8	722.7236
Closed Mt	740.2154	13.9838	0.00027	0.0009	10	719.1474
p(t),pent(0.25t),phi(t)	742.0238	15.7922	0.00011	0.0004	10	720.9559
p(.),pent(0.25),phi(linear tsa)	744.0536	17.822	0.00004	0.0001	6	731.6536
p(.),pent(0.25),phi(tsa)	746.0344	19.8028	0.00001	0	7	731.4985
p(.),pent(0.25t),phi(.)	751.756	25.5244	0	0	5	741.4716
p(.),pent(0.25t),phi(t)	754.9251	28.6935	0	0	7	740.3892

Table S9. Model selection results using multistate open robust design mark-recapture models to evaluate demographic parameters of little penguins on Penguin Island from September–November 2019. Parameters are p, probability of recapture; pent, probability of entering the colony for the first time in a given session; phi, the probability of persisting at the colony from one session to another. Structures are (.), constant; t, time within season; tsa, time since arrival; linear tsa, linear time since arrival trend

Model	AICc	Delta AICc	AICc Weights	Model Likelihood	Number Parameters	Deviance
p(.),pent(t),phi(.)	505.5377	0	0.23564	1	5	495.1377
p(.),pent(t),phi(tsa)	505.9234	0.3857	0.19431	0.8246	7	491.1667
p(.),pent(t),phi(t)	506.3999	0.8622	0.15312	0.6498	7	491.6431
p(t1=t2),pent(t),phi(.)	506.9822	1.4445	0.11444	0.4856	6	494.4185
p(.),pent(t),phi(linear tsa)	506.9897	1.452	0.11401	0.4838	6	494.426
p(t1=t2),pent(t),phi(tsa)	508.0665	2.5288	0.06655	0.2824	8	491.0869
p(t1=t2),pent(t),phi(t)	508.3941	2.8564	0.05649	0.2397	8	491.4145
p(t1=t2),pent(t),phi(linear tsa)	508.9682	3.4305	0.0424	0.1799	7	494.2115
p(t1=t2),pent(t) births only	510.4145	4.8768	0.02057	0.0873	6	497.8507
p(t),phi(t), deaths only	516.6193	11.0816	0.00092	0.0039	10	495.102
p(t),pent(0.25t),phi(.)	517.2302	11.6925	0.00068	0.0029	8	500.2506
p(t),pent(0.25t),phi(t)	518.9968	13.4591	0.00028	0.0012	10	497.4796
p(t),pent(.25),phi(linear tsa)	519.0317	13.494	0.00028	0.0012	9	499.7989
p(t),pent(0.25),phi(tsa)	520.161	14.6233	0.00016	0.0007	10	498.6437
Closed Mt	520.5726	15.0349	0.00013	0.0006	10	499.0553
p(.),pent(0.25t),phi(t)	529.2481	23.7104	0	0	7	514.4914
p(.),pent(0.25t),phi(.)	529.3483	23.8106	0	0	5	518.9483
p(.),pent(0.25),phi(tsa)	531.1543	25.6166	0	0	7	516.3976
p(.),pent(0.25),phi(linear tsa)	531.3522	25.8145	0	0	6	518.7884

Table S10. Estimated parameters of residency time (days), intensity of availability, $\hat{a}$, in each mark-recapture session, and arrival and departure times of little penguins on Penguin Island, Western Australia. 95% CI are given in the square brackets.

	Residency time	$\hat{a}_1$	$\hat{a}_2$	$\hat{a}_3$	$\hat{a}_4$	Arrival	Departure
2007	29 [24–32]	0.33 [0.33–0.33]	0.48 [0.42–0.54]	0.55 [0.43–0.67]		2 [2.00–2.00]	2.37 [2.18–2.54]
2008	26 [21–28]	0.51 [0.42–0.61]	0.59 [0.50–0.69]	0.56 [0.47–0.66]	0.51 [0.43–0.61]	1.86 [1.66–2.05]	3.05 [2.87–3.23]
2010	20 [17–24]	0.55 [0.43–0.67]	0.50 [0.39–0.61]	0.30 [0.18–0.42]	0.34 [0.16–0.52]	1.71 [1.42–2.01]	2.40 [2.01–2.79]
2011	34 [23–44]	0.61 [0.39–0.82]	0.62 [0.42–0.82]	0.58 [0.38–0.78]	0.56 [0.37–0.76	1.75 [1.39–2.16]	3.12 [2.72–3.52
2017	35 [19–51]	0.56 [0.28–0.86]	0.67 [0.36–0.99]	0.59 [0.30–0.87]	0.50 [0.25–0.76]	1.68 [1.05–2.31]	3.01 [2.50–3.53]
2019	36 [24–48]	0.59 [0.33–0.85]	0.65 [0.41–0.88]	0.73 [0.45–1.00]	0.58 [0.34–0.83]	1.65 [1.13–2.17]	3.20 [2.72–3.68]

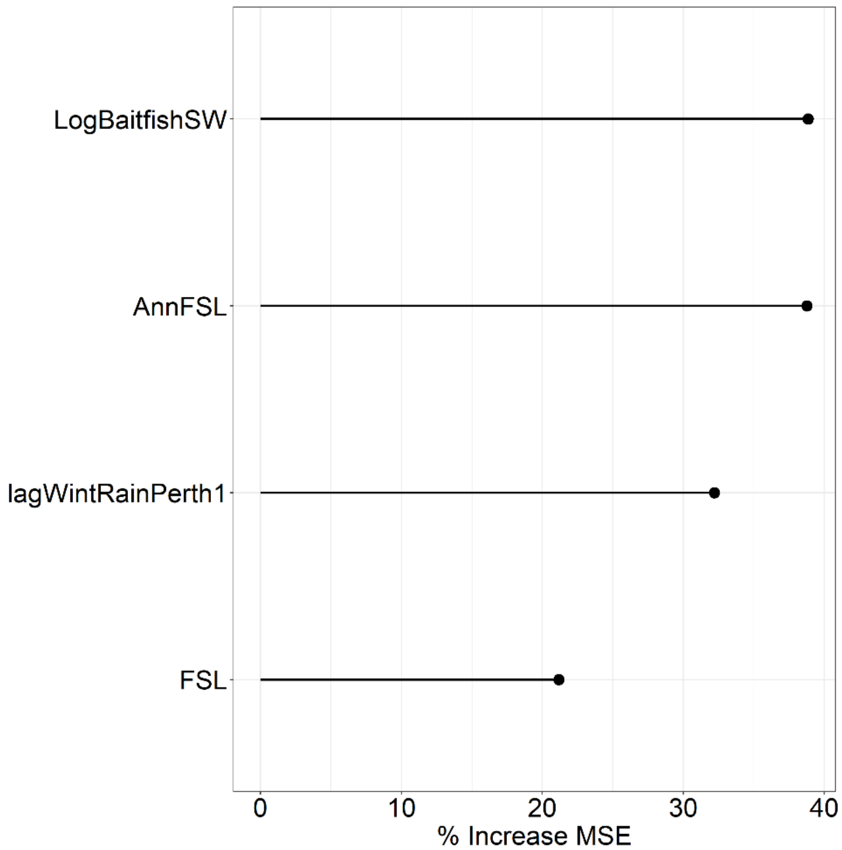

Fig. S1 Random forest variable importance plot of the top four predictor variables for the breeding participation by little penguins in all the nests checked on Penguin Island, Western Australia, from 1986–2018. LogBaitfish_SW is the log of the catch per unit effort for pilchards, anchovy, scaly mackerel, sandy sprat and blue sprat caught in the southwest region (34°S–33°S, 115°E–116°E), AnnFSL is the mean annual Fremantle Sea Level (FSL), a proxy for the strength of the Leeuwin Current, lagWintRainPerth1 is the 1 year lagged winter rainfall in Perth, and FSL is the mean FSL in June–August, MSE – mean square error

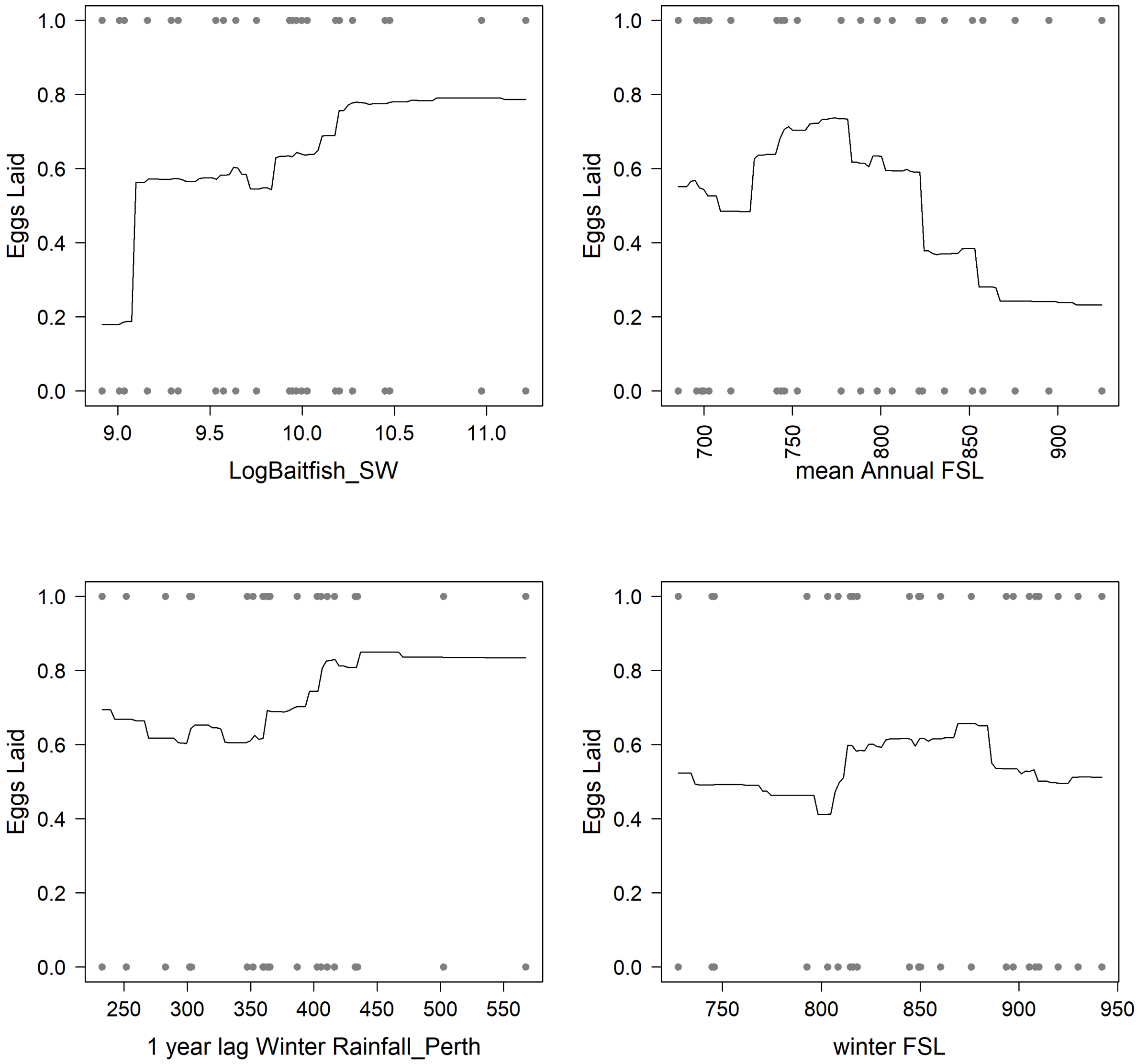

Fig. S2 Partial dependence plots for the effect of the top four predictors for the breeding participation, i.e. whether eggs were laid or not, by little penguins on Penguin Island, Western Australia, from 1986–2018. LogBaitfish_SW is the log of the catch per unit effort for pilchards, anchovy, scaly mackerel, sandy sprat and blue sprat caught in the southwest region (34°S–33°S, 115°E–116°E), FSL is the Fremantle Sea Level, a proxy for the strength of the Leeuwin Current, winter FSL is the mean FSL in June–August

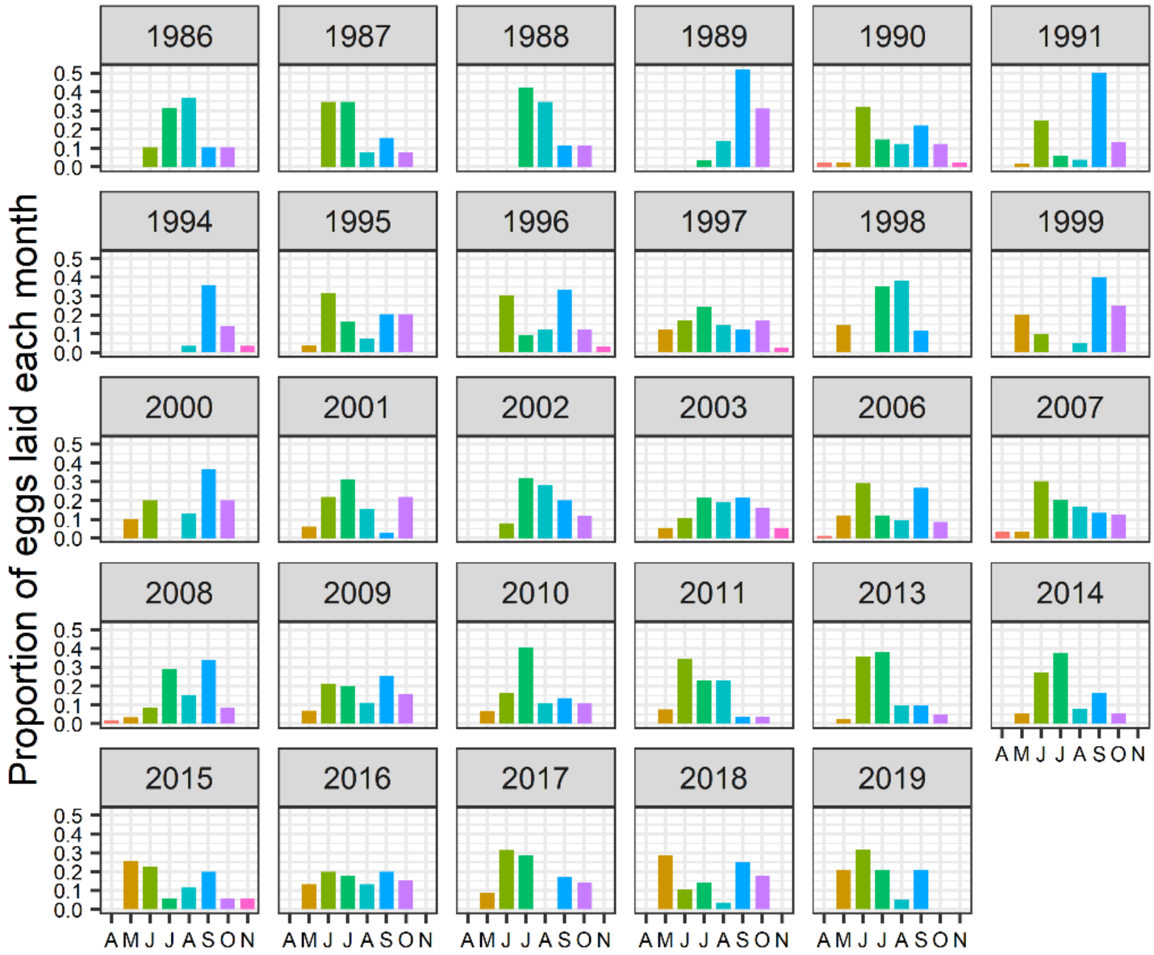

Fig. S3 The proportion of eggs laid by little penguins on Penguin Island, Western Australia, each month from April–November, 1986–2019. There are no data for 1992 (breeding success available but not timing of breeding), 1993, 2004, 2005 and 2012. April( ), May ( ), June ( ), July( ), August ( ), September ( ), October ( ), November ( )

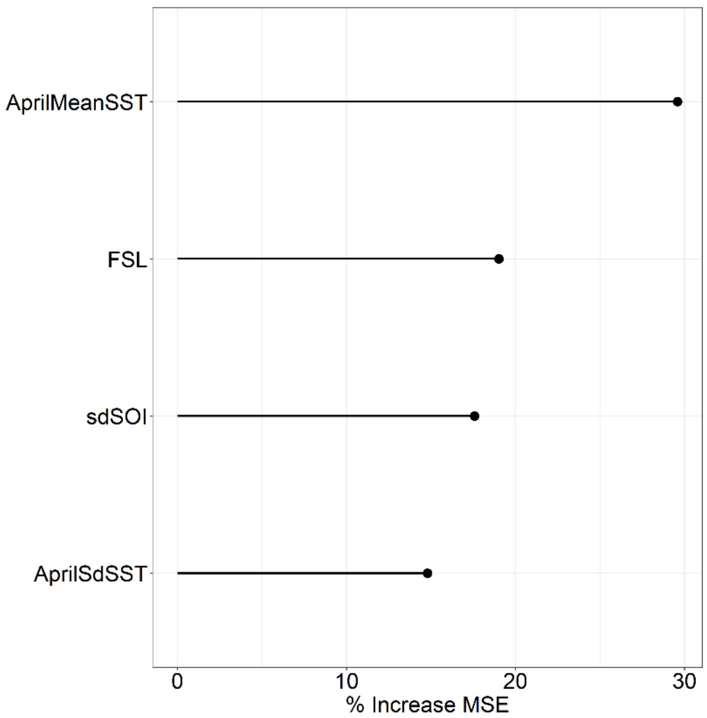

Fig. S4 Random forest variable importance plot of the top four predictor variables of whether chicks were successfully raised or not in the nests in which eggs were laid on Penguin Island, Western Australia, from 1986–2018. AprilMeanSST is the mean April SST each year in an area bounded by 115°E–115.25°E and 32.5°S to 31.5°S, FSL is the mean Fremantle Ssea Level (FSL)- a proxy for the strength of the Leeuwin Current, in June–August. sdSOI is the standard deviation of the annual Southern Oscillation Index, AprilSdSST is the standard deviation of the mean April SST each year

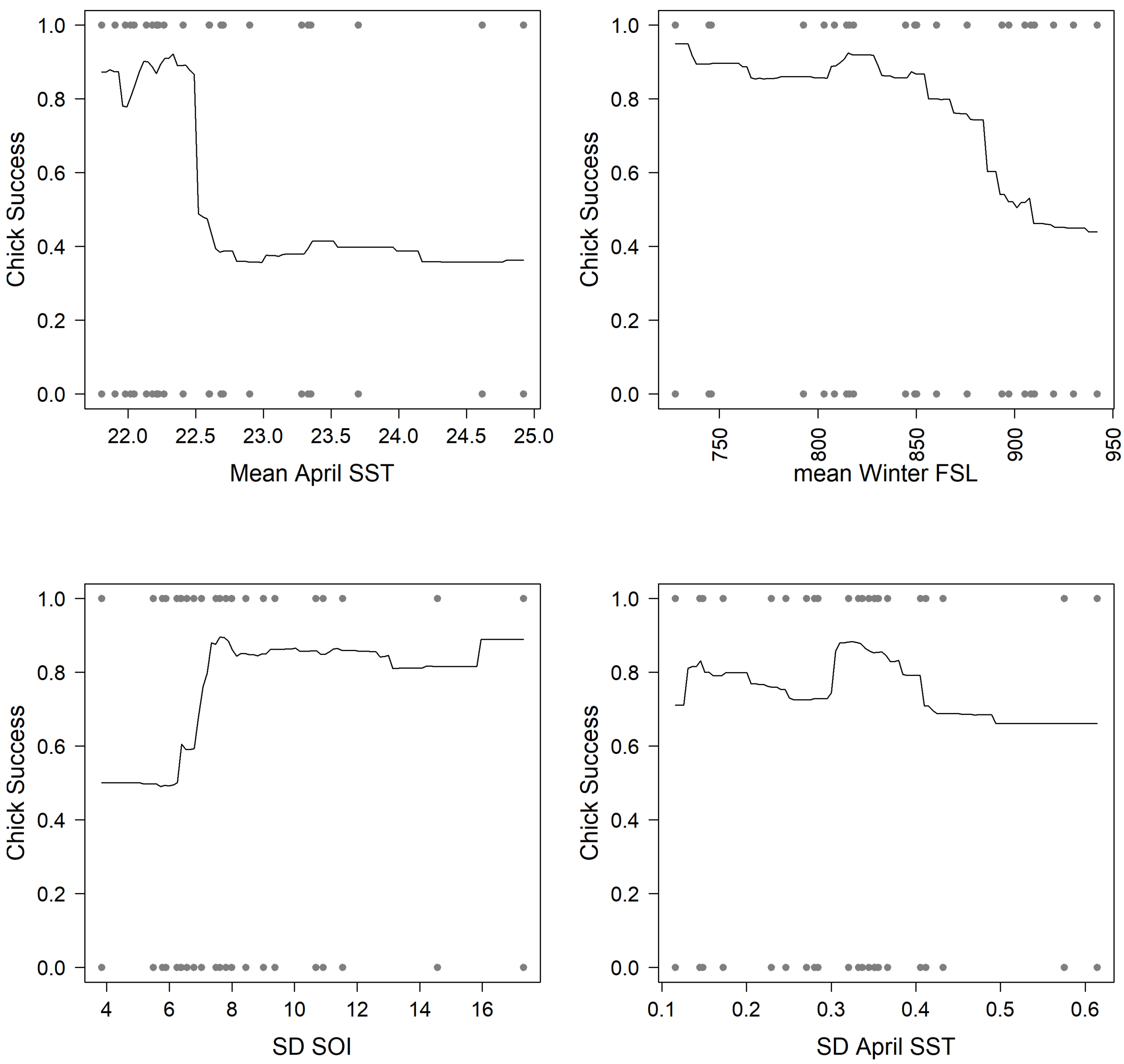

Fig. S5 Partial dependence plots for the top four predictors of whether chicks were successfully raised or not in the nests in which eggs were laid on Penguin Island, Western Australia, from 1986–2018. Mean April SST is for an area bounded by 115°E–115.25°E and 32.5°S–31.5°S, the mean winter FSL (Fremantle Sea Level- a proxy for the strength of the Leeuwin Current) is the mean FSL in June–August. SOI is the Southern Oscillation Index. SD- standard deviation

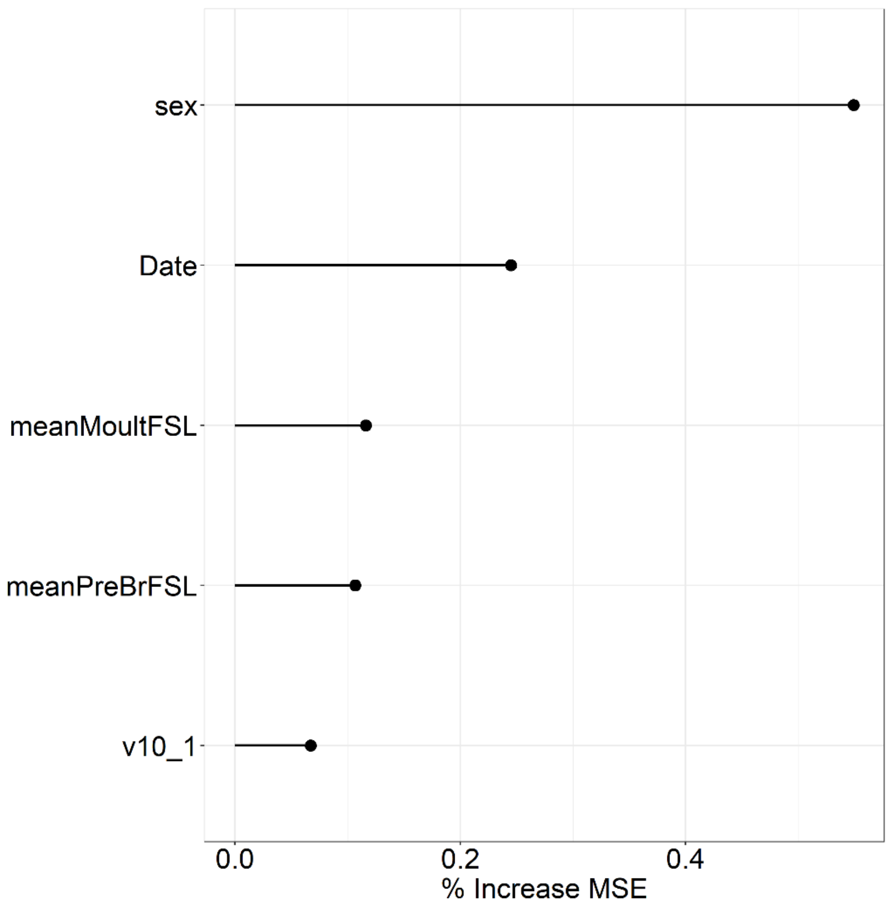

Figure S6 Random forest variable importance plot of the top five predictor variables for the body condition of non-moulting adult penguins on Penguin Island, Western Australia, from 1986–2019. meanMoultFSL is the mean Fremantle Sea Level (FSL) during the moult period (i.e. from December the preceding year to February of the year the adult was measured), meanPreBrFSL is the mean FSL during pre-breeding (i.e. from March–May) V10_1 is the north/south component of the wind (i.e. a proxy for the Capes Current) in January of the year a penguin was measured

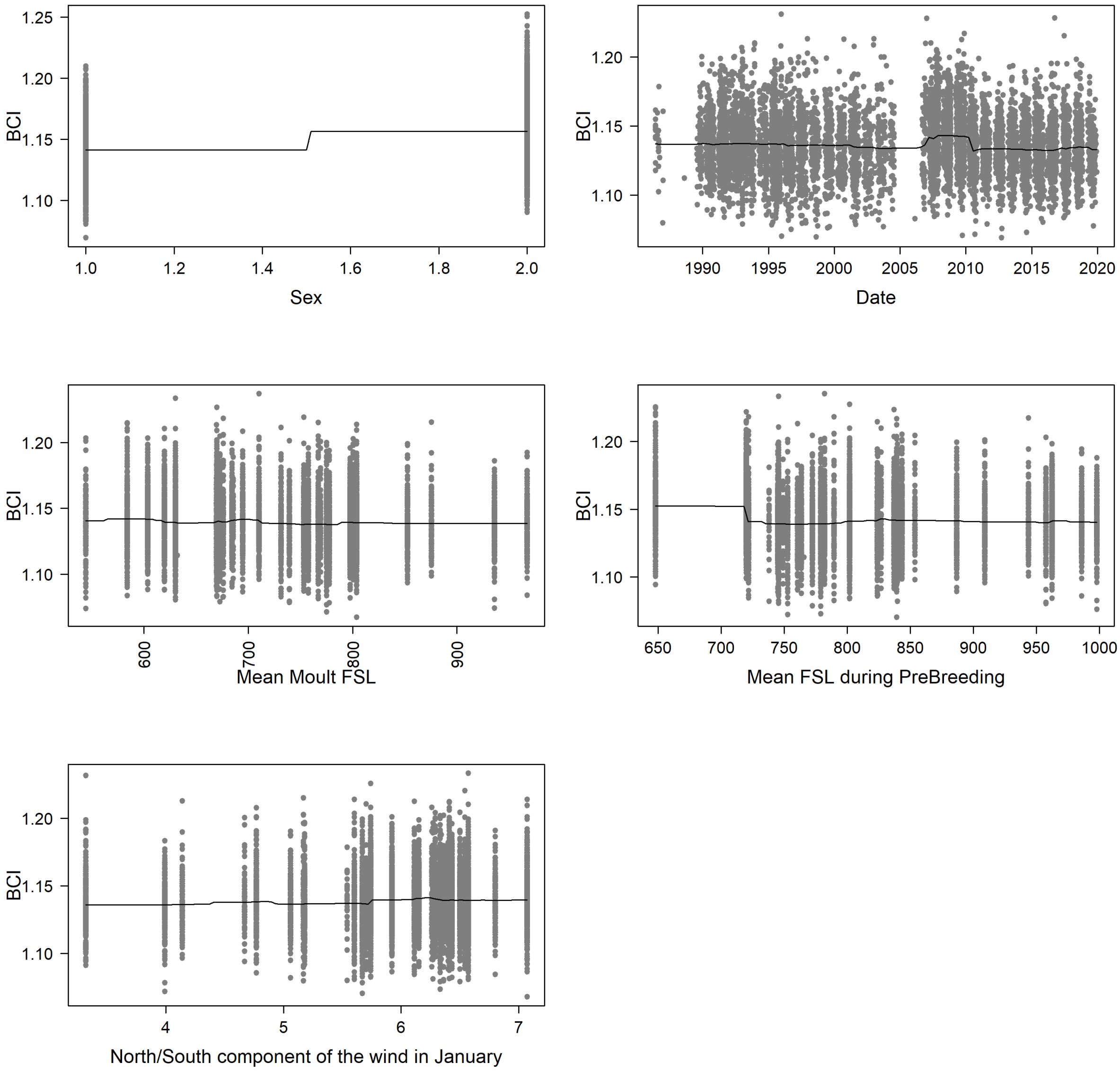

Fig. S7 Partial dependence plots for the top five predictors of the body condition of Little Penguins (BCI, measured as $\log_{10}$mass/ $\log_{10}$(culmen length*bill depth at gonys)) on Penguin Island, Western Australia, from 1986–2019. Sex- 1 : Males, 2: Females, Mean Moult FSL is the mean Fremantle Sea Level (FSL) during the moult period (i.e. from December the preceding year to February of the year the adult was measured), mean FSL during pre–breeding is the mean FSL from March–May), and the north/south component of the wind (i.e. a proxy for the Capes Current) in January is in the year a penguin was measured

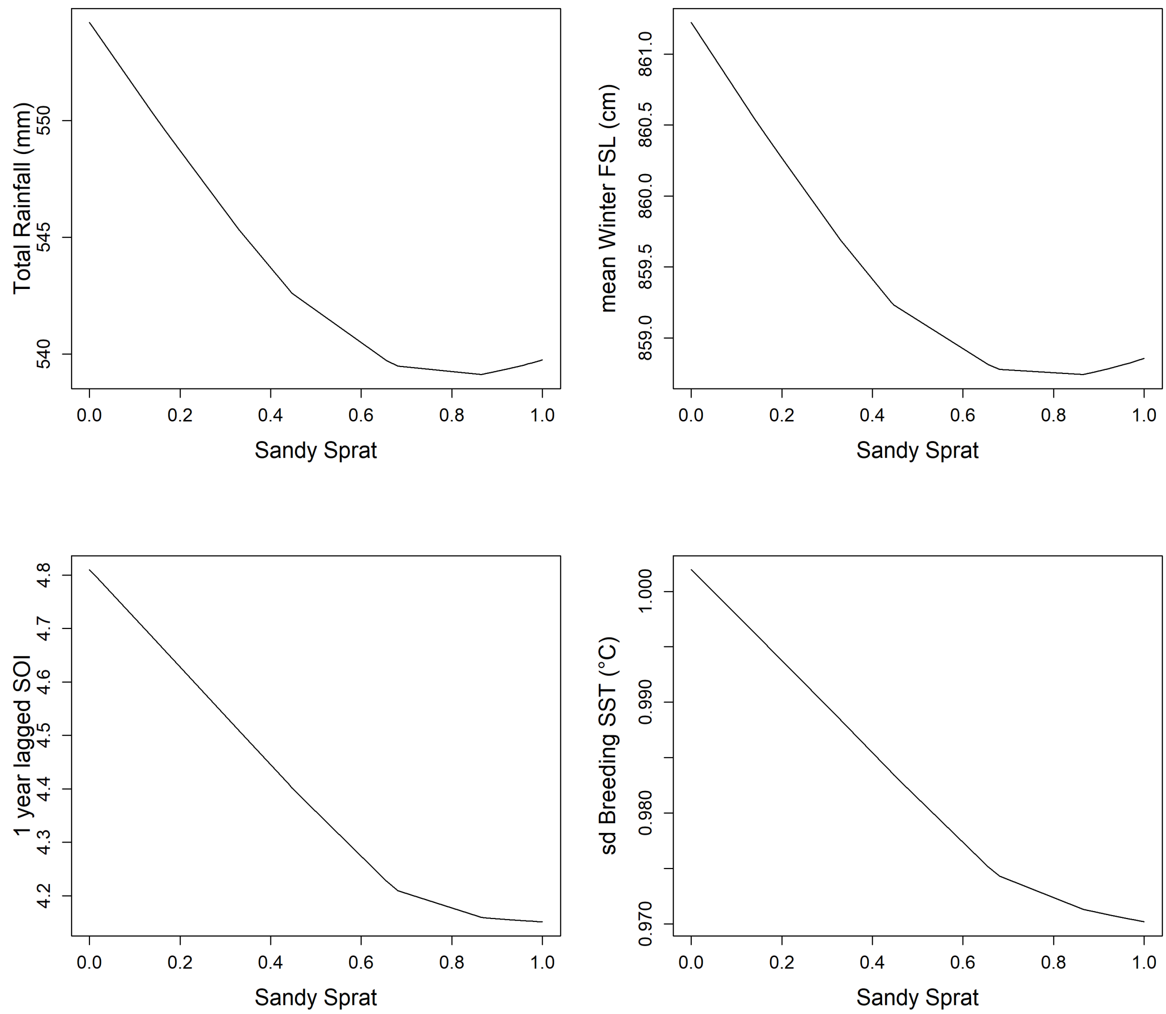

Fig. S8 Partial effect plots for the most influential environmental variables on the proportion of sandy sprat in the diet of Little Penguins, Western Australia from 2009–2012

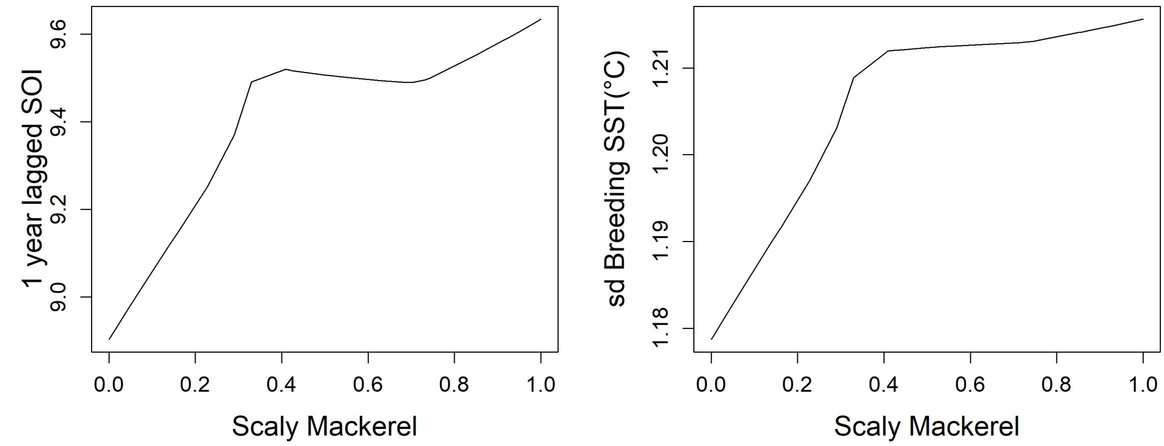

Fig S9. Partial effect plots for the effect of the 1 year lagged SOI and SD of the sea surface temperatures during breeding on the proportion of scaly mackerel in the diet of little penguins, Western Australia from 2009–2012

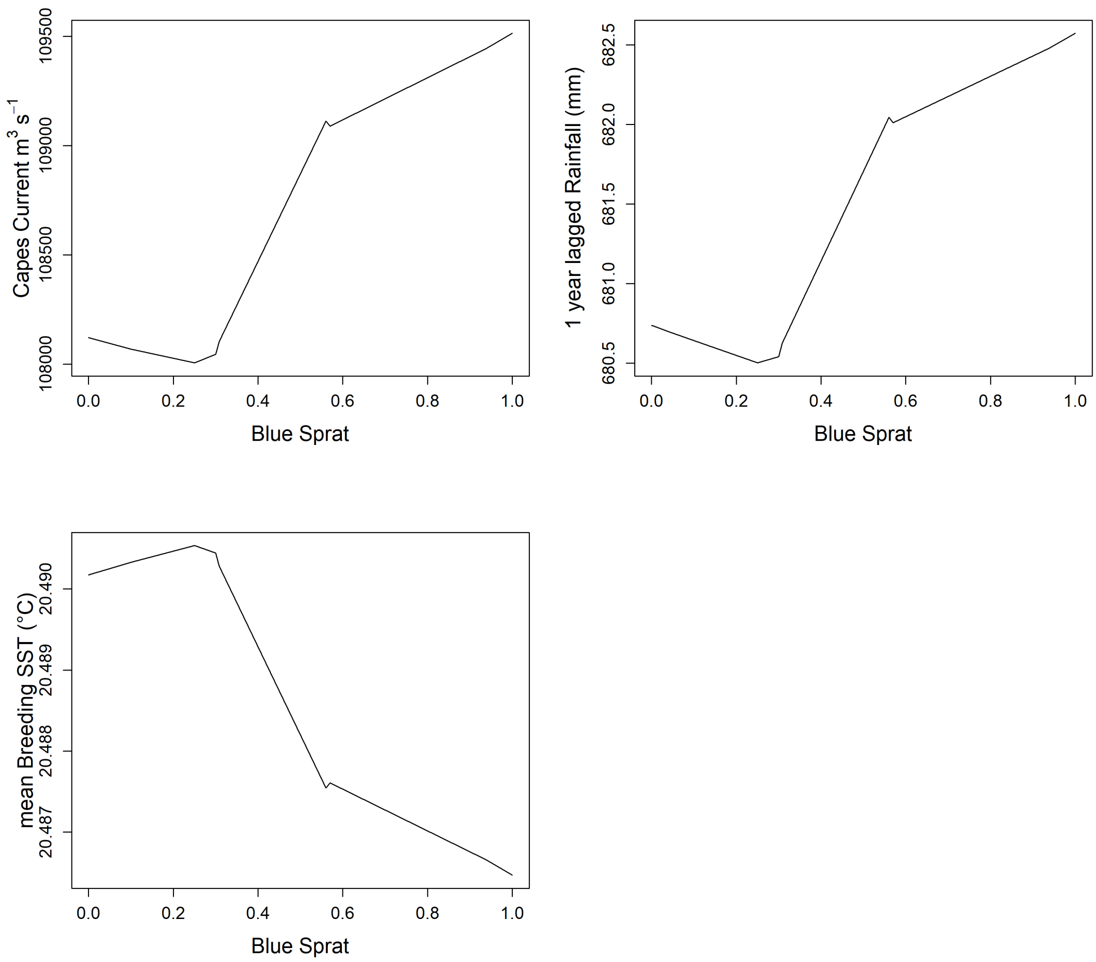

Fig S10. Partial effect plots for the effect of the Capes Current, the 1 year lagged annual rainfall and the mean SST during breeding (i.e. May–November) on the proportion of blue sprat in the diet of little penguins, Western Australia from 2009–2012

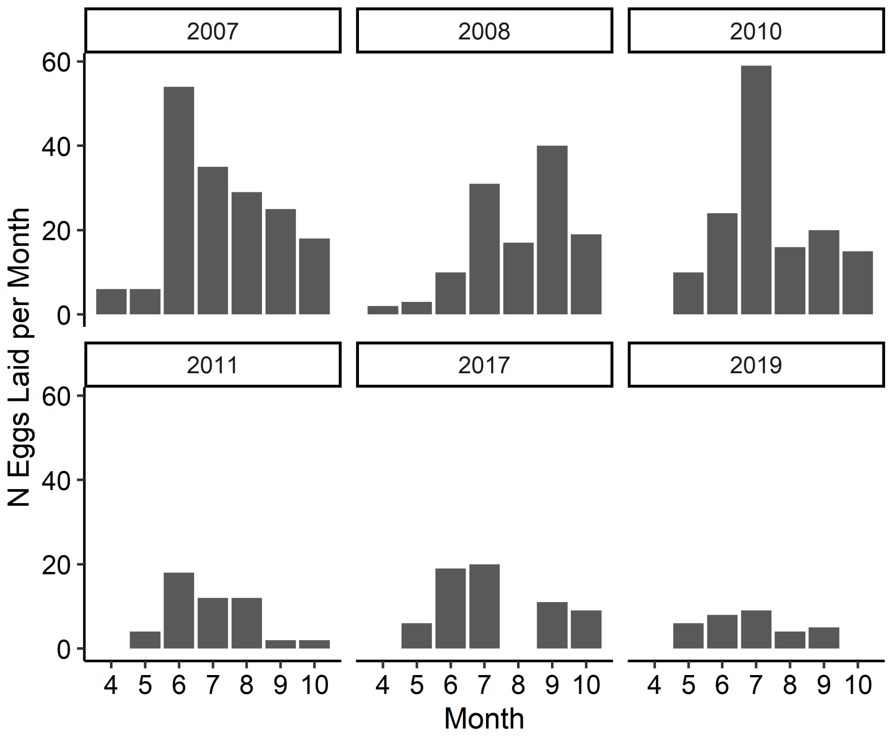

Fig. S11. The number of eggs laid per month in the years the population estimates were conducted on Penguin Island, Western Australia. A similar number of nestboxes were monitored in each of these years

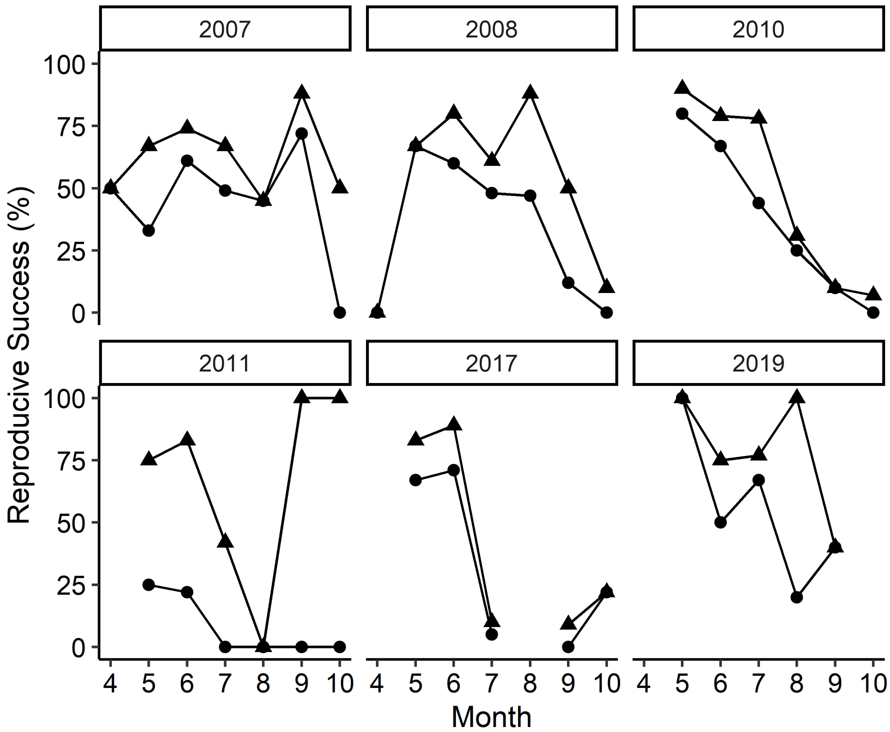

Fig. S12 The percentage of eggs that hatched (▲) and overall breeding success, i.e. the percentage of chicks fledged/eggs laid (●) each month for the years that a population estimate of of little penguins on Penguin Island, Western Australia was determined

LITERATURE CITED

Berry TE, Saunders BJ, Coghlan ML, Stat M, Jarman S, Richardson AJ, Davies CH, Berry O, Harvey ES, Bunce M (2019) Marine environmental DNA biomonitoring reveals seasonal patterns in biodiversity and identifies ecosystem responses to anomalous climatic events. PLoS genetics. 15:e1007943

Cannell B (2016) How resilient are the Little Penguins and the coastal marine habitats they use. Report Year 3. Report for Fremantle Ports and the City of Rockingham, Murdoch University, Perth,

Cannell B (2019) Understanding the toll of consecutive years of warm waters on Little Penguins and refining their capacity as bioindicators of the marine coastal ecosystem. Report for Fremantle Ports and the City of Rockingham, Murdoch University, Perth,

Cannell BL, Chambers LE, Wooller RD, Bradley JS (2012) Poorer breeding by little penguins near Perth, Western Australia is correlated with above average sea surface temperatures and a stronger Leeuwin Current. Mar Freshw Res 63:914–925

Feng M, Meyers G, Pearce A, Wijffels S (2003) Annual and interannual variations of the Leeuwin Current at 32°C. J Geophys Res 108

Feng M, Caputi N, Chandrapavan A, Chen M, Hart A, Kangas M (2021) Multi-year marine cold-spells off the west coast of Australia and effects on fisheries. J Mar Sys 214:103473

Gaughan DJ (2007a) Potential mechanisms of influence of the Leeuwin Current eddy system on teleost recruitment to the Western Australian continental shelf. Deep-Sea Res II 54:1129–1140

Gaughan DJ (2007b) Potential mechanisms of influence of the Leeuwin Current eddy system on teleost recruitment to the Western Australian continental shelf. Deep-Sea Res II 54:1129–1140

Gaughan DJ, Fletcher WJ, Tregonning RJ, Goh J (1996) Aspects of the biology and stock assessment of the whitebait, *Hyperlophus vittatus*, in south western Australia.Fisheries Research Report No. 108, Department of Fisheries Western Australia, Perth

Gaughan DJ, White KV, Fletcher WJ (2001) The links between functionally distinct adult assemblages of *Sardinops sagax*: larval advection across management boundaries. ICES J Mar Sci 58:597–606

Gersbach GH, Pattiaratchi CB, Ivey GN, Cresswell GR (1999) Upwelling on the south-west coast of Australia—source of the Capes Current? Cont Shelf Res 19:363–400

Hersbach H, Bel, B, Berrisford P, Biavati G, Horányi A, Muñoz Sabater J, Nicolas J, Peubey C, Radu R, Rozum I, Schepers D, Simmons A, Soci C, Dee D, Thépaut J-N (2023): ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). doi:10.24381/cds.adbb2d47 (Accessed 22-Jul-2020)

Hetzel Y, Cosoli S, Pattiaratchi C (2020) Inter-annual circulation variability along Western Australia’s continental shelf. Proc Aust Meteorol Ocean Soc, 10–14 Feb 2020, Fremantle (Abstract)

Lenanton R, Caputi N, Kangas M, Craine M (2009) The ongoing influence of the Leeuwin Current on economically important fish and invertebrates off temperate Western Australia-has it changed? J R Soc West Aus 92:111-127

Lindegren M, Checkley Jr DM (2013) Temperature dependence of Pacific sardine (Sardinops sagax) recruitment in the California Current Ecosystem revisited and revised. Can J Fish Aquat Sci 70:245–252

Mansor M, Mohammad-Zafrizal M, Nur-Fadhilah M, Khairun Y, Wan-Maznah W (2012) Temporal and spatial variations in fish assemblage structures in relation to the physicochemical parameters of the Merbok estuary, Kedah. J Nat Sci Res 2:110-127

Molony BW, Newman SJ, Joll L, Lenanton RCJ, Wise B (2011) Are Western Australian waters the least productive waters for finfish across two oceans? A review with a focus on finfish resources in the Kimberley region and North Coast Bioregion. J Roy Soc West Aust 94: 323–332

Oliver RK (2009) Development of Molecular Tools for the Dietary Analysis of Little Penguins (*Eudyptula minor*) in the Perth Metropolitan region. BSc (Hons) dissertation, Murdoch University, Perth

Pearce A, Pattiaratchi C (1999) The Capes Current: a summer countercurrent flowing past Cape Leeuwin and Cape Naturaliste, Western Australia. Cont Shelf Res 19:401–420

Pearce AF, Phillips BF (1988) ENSO events, the Leeuwin Current, and larval recruitment of the western rock lobster. J Cons Int Explor Mer 45:13–21

Rivers JW, Bailey Guerrero J, Brodeur RD, Krutzikowsky GK, Adrean LJ, Heppell SA, Jacobson KC, Milligan K, Nelson SK, Roby DD, Sydeman WJ (2022) Critical Research Needs for Forage Fish within Inner Shelf Marine Ecosystems. Fisheries. 47:213-21

Wienecke BC, Wooller RD, Klomp NI (1995) The ecology and management of little penguins on Penguin Island, Western Australia. In: Dann P, Norman I, Reilly P (eds) The Penguins. Surrey Beatty & Sons, Chipping Norton, NSW, p 440-467

Yu, Y, Chen S, Qin W, Lu T, Li J, and Cao Y (2020) A Semi-Empirical Chlorophyll-*a* Retrieval Algorithm Considering the Effects of Sun Glint, Bottom Reflectance, and Non-Algal Particles in the Optically Shallow Water Zones of Sanya Bay Using SPOT6 Data. Remote Sens 12: 2765.