

Sentinel seabirds

A guide to using marine birds to monitor marine ecosystems in Western Australia

Prepared by J.N. Dunlop for the Northern Agricultural Catchment Council



National
Landcare
Programme



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FOREWORD

The Northern Agricultural Catchments Council (NACC) is very proud to be associated with this invaluable research and, on their behalf, I extend my congratulations to all who have contributed in some way to *Sentinel Seabirds*.

The NACC NRM Region is bounded on its western side by about 550 kilometres of coastline, featuring numerous river mouths and small estuaries and about 140 continental islands, most of which have seabird colonies. It is also adjacent to a marine area of approximately 180,000 km² under Australian jurisdiction. Monitoring environmental change and the condition of natural resources over such an area is a daunting proposition. Seabirds may provide a relatively cost-effective way of fore-warning and tracking threats to the region's marine ecosystems caused by climate change, changing ocean conditions, fishing and contaminants.

Sentinel Seabirds is a guide to using our seabirds to monitor changes in the marine environment. Its author – Nic Dunlop – has dedicated decades of his working life to the study of seabirds in the eastern Indian Ocean, and has succinctly combined results of his own studies with those of other researchers to produce this contemporary guide. Inclusion of the results of numerous longitudinal studies clearly show the relationship between a changing oceanic environment and seabird populations, and his work on seabirds as monitors of pollutant contamination in our marine food chains is as astonishing as it is concerning. The guide concludes with clear frameworks for establishing seabird monitoring programs aimed at addressing particular management issues, thereby laying the groundwork for this important work to continue.

NACC has had a long and productive history of collaboration with Nic Dunlop and the Conservation Council of WA, and is proud to have contributed to this work.

Richard McLellan, CEO, NACC

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Seabirds as indicators of marine ecosystems

INTRODUCTION

Marine ecosystems are vast, dynamic and beyond our terrestrial realm. Sampling these systems to monitor environmental change is typically challenging, time consuming and expensive. This guide details the various ways seabirds can be utilised as effective and efficient 'bioindicators' of change in marine environment.

A **bioindicator** (biological indicator) is an attribute at any level of biological organization that by its presence, absence, quantum, condition or behaviour indicates something about the state of the environment (Spellerberg 2005, Conservation Council WA 2009).

Bioindicators have some advantages over the measurement of physical or chemical parameters in monitoring environmental change. Firstly, they have

the potential to integrate changes in ecosystems at different levels and over a range of spatial and temporal scales. Mobile, long-lived species near the apex of food-chains, like seabirds, may be particularly useful in this regard. Secondly bioindicators have the capacity to capture and retain information on the incidence of past events (eg. a short term spike in a pollutant or a resource failure) or reflect trends from accumulating impacts (eg. from eutrophication or changes in ocean climate).

The monitoring of physical or chemical attributes may detect a stress or pressure (eg. rising sea-temperature, presence of marine debris) but provide no information of the biological or ecological consequences. Bioindicators however may incur the consequences of these stresses and lead to the identification, characterization or quantification of threats.

CURRENT KNOWN THREATS TO MARINE ECOSYSTEMS

Threat	Potential impact
Changes in ocean climate	Changes in the distribution and abundance of marine biota, shifts or declines in primary productivity and fishery resources.
Fisheries	Stock or local scale resource depletion, bycatch depletion or fishery / aquaculture food supplementation.
Marine Contaminants	
a. Marine debris	Habitat alteration, mortality from entanglement or ingestion, transport of invasive organisms.
b. Micro-plastics	Bio-accumulation of persistent organic pollutants, phthalates and heavy metals in marine food chains.
c. Persistent Organic Pollutants (POPs)	Bio-accumulation of toxic or hormone disrupting compounds (eg. organochlorine pesticides, PCBs, PAHs).
d. Heavy metals	Bio-accumulation of toxic compounds, mercury, lead and cadmium. Particularly mercury magnification in higher order consumers.
e. Oil pollution	Physical fouling, plumage damage, ingestion of toxic hydrocarbons.
f. Ionizing radiation	Reduced anti-oxidants, impaired immunity, disease & population decline.
g. Introduced pathogens	Pandemics in fish stocks



Many bioindicators can be measured by observers without the need for specialised, high precision or automated technology. This reduces the cost and makes them more accessible to volunteers or 'citizen-scientists'. Finally, some bioindicators may utilize subjects that are of greater social significance or popularity (eg. Little Penguins, Fairy Terns, dolphins) facilitating the engagement of communities in the collection of monitoring data.

ADVANTAGES OF SEABIRDS AS INDICATORS OF CHANGE IN MARINE ECOSYSTEMS

Seabirds are marine animals deriving their energy and nutrition from the open ocean, coastal waters or estuaries. They have a number of advantages over other potential bioindicators if, and only if, sufficient information on life history, seasonal movements, foraging locations and trophic (food related) ecology is available. Specifically the advantages of using seabirds to monitor marine ecosystems are as follows (Conservation Council WA 2009).

- Most seabirds are **higher order consumers** foraging near the apex of food webs and as such integrate biophysical processes operating through their marine ecosystems.
- Generally they are **colonial nesters** (usually on islands) and can therefore be sampled at predictable locations and times facilitating the repeated sampling necessary for effective, long-term, monitoring programs.
- When breeding, seabirds are **central place foragers** with different species having specific foraging ranges on spatial scales from 10^1 to 10^4 km².
- Different species are **functional components of a variety of marine ecosystems** from benthic estuarine and coastal to planktonic continental shelf and oceanic.

- The high energy demands associated with rearing young lead to marked marine productivity related variations in reproductive output. **Breeding performance can be a robust indicator of prevailing, within season, oceanographic and trophic conditions.**
- **Seabirds generally have conservative life histories.** i.e. philopatric (returning to natal area), are long-lived, delay maturity, have a low capacity for increase and may defer breeding under adverse conditions. As a result changes in population size or distribution **reflect longer term trends** in marine ecosystems rather than short term seasonal factors.
- Off central and south-western Australia there is a **unique assemblage of tropical, sub-tropical and temperate water species** sharing breeding islands due to the influence of the Leeuwin Current. Changes in the composition and structure of the seabird communities are potential indicators of shifts in ocean climate.
- Seabirds are **visible and popular subjects for observation** increasing the potential to recruit participants for monitoring programs.
- The central and south-west coasts of WA have a **useful historical record** of seabird breeding distribution dating back to the colonial period.

Twenty- seven seabird species have breeding populations along the coast of Western Australia. Many of these have attributes that could be measured to monitor the various threats to marine ecosystems that may be operating in different regions.

WESTERN AUSTRALIA'S BREEDING SEABIRD SPECIES

Common name	Systematic name	Breeding distribution
Little Penguin	<i>Eudyptula minor</i>	Numerous coastal islands from Perth region to Recherche Archipelago.
Wedge-tailed Shearwater	<i>Ardenna pacificus</i>	Numerous islands from Carnac I. off Perth to the Kimberleys.
Fleshy-footed Shearwater	<i>Ardenna carneipes</i>	Numerous islands along the south coast from Cape Leeuwin to the eastern Recherche.
Short-tailed Shearwater	<i>Ardenna tenuirostris</i>	Some islands in the eastern Recherche.
Little Shearwater	<i>Puffinus assimilis</i>	Numerous islands from the Houtman Abrolhos south to the Recherche Archipelago.
Great-winged Petrel	<i>Pterodroma macroptera</i>	Islands from the King George Sound east to the Recherche Archipelago.
White-faced Storm-petrel	<i>Pelagodroma marina</i>	Numerous islands from the Houtman Abrolhos to south to the Recherche Archipelago.
Australian Pelican	<i>Pelicanus conspicillatus</i>	Islands in Shoalwater Bay (Rockingham) and in Peel and Wilson Inlets.
Pied Cormorant	<i>Phalacrocorax varius</i>	Islands off the west coast from Warnbro Sound to Shark Bay.
Black-faced Cormorant	<i>Phalacrocorax fuscescens</i>	Small, rocky islands in the Recherche Archipelago.
Masked Booby	<i>Sula dactylatra</i>	Adele and Bedout Islands off NW coast
Brown Booby	<i>Sula leucogaster</i>	Islands off north-western WA
Red-footed Booby	<i>Sula sula</i>	Adele Island
Great Frigatebird	<i>Fregata minor</i>	Adele Island
Lesser Frigatebird	<i>Fregata ariel</i>	Adele I. Lacepede Islands and Bedout I.
Red-tailed Tropicbird	<i>Phaethon rubricauda</i>	Eruptive, small colony at Rowley Shoals. Breeding pairs recorded on some Houtman Abrolhos islands, Rottne Island and Sugarloaf Rock (Cape Naturaliste).
Pacific Gull	<i>Larus pacificus</i>	Mostly single pairs in territories on islands from Shark Bay south to the Recherche Archipelago.
Caspian Tern	<i>Hydroprogne caspia</i>	Small colonies or single pairs, on islands all along the Western Australian coastline.
Crested Tern	<i>Thalasseus bergii</i>	Colonies, often intermittent, on islands all along the Western Australian coastline
Lesser Crested Tern	<i>Thalasseus bengalensis</i>	Colonies, often intermittent, on islands from Shark Bay northwards.
Sooty Tern	<i>Onychoprion fuscata</i>	Colonies on Islands in the Easter and Pelsaert Groups in the Houtman Abrolhos, at Lancelin Island and Bedout Island off the NW Coast.
Bridled Tern	<i>Onychoprion anaethetus</i>	Colonies on islands all around the western Australian coastline. Less frequent and relatively recent on the south coast.

WESTERN AUSTRALIA'S BREEDING SEABIRD SPECIES (continued)

Common name	Systematic name	Breeding distribution
Roseate Tern	<i>Sterna dougallii</i>	Breeding along the west coast from the Kimberley Islands south to Warnbro Sound in Perth metro region.
Little Tern	<i>Sternula albifrons sinensis</i>	Breeding in colonies on some Kimberley islands
Australian Fairy Tern	<i>Sternula nereis</i>	Breeding in colonies on islands, and on sandy coastal mainland sites, from the Dampier Archipelago south and east to Point Malcolm (Cape Arid).
Common Noddy	<i>Anous stolidus</i>	Breeding colonies on Pelsaert Island in the Houtman Abrolhos, at Lancelin Island and Bedout Island off the NW Coast.
Lesser Noddy	<i>Anous tenuirostris</i>	Breeds in colonies on mangroves in the Easter and Pelsaert Groups in the Houtman Abrolhos



Common Noddies can reclaim pair bonds for many years returning to the same nest site.

INTRODUCTION

Seabird populations exist in a dynamic balance with the availability of marine resources. One theory, referred to as 'Ashmole's halo', proposes that competition for food resources within foraging range of breeding colonies regulates the number of birds that are sufficiently competent to reproduce. This manifests at the individual level in deferred reproduction (a delay in recruitment after reaching sexual maturity) and in 'rest years' in pairs when prey availability is insufficient to support a breeding attempt. At the population level it results in a breeding population that tracks the carrying capacity of the surrounding marine environment and generates a 'non-breeding pool' of sexually mature but latent individuals. Reduced adult survival or breeding output will initially lead to changes in age structure, as younger birds are able to recruit into the colonies, rather than a decline in the breeding population. Understanding these characteristics of seabird population regulation is essential to framing appropriate indicators for monitoring.

ADULT & NATAL PHILOPATRY

Philopatry is the tendency of individuals to return to their original location. In seabirds 'adult philopatry' or 'site fidelity' is the frequency with which breeding birds return to the same nest site or breeding zone. Natal philopatry is the tendency of birds to commence reproduction at, or near, the colony in which they were raised. This probably results from the imprinting of the colony environment during the latter stages of development. The structure of seabird populations will be strongly influenced by the degree to which individuals return to colony sites / areas or move between them.

Burrow-nesting petrels, shearwaters and storm-petrels typically have high nest-site and mate fidelity and natal philopatry. Little Penguins have similar, although less reliable, relationships to nest sites, mate and sand colonies. The breeding adults of other seabird species adopt two contrasting strategies, that can be classified as '**high site fidelity**' and '**synchronized area fidelity**'.

High site fidelity

Adult pairs of Bridled Terns, and Common and Lesser Noddies and Pacific Gulls return to the same nest location each season, provided the physical environment remains stable and each partner survives. These species coordinate breeding within the nest territory whilst interacting with their regular neighbours. Bridled Terns, for example, normally return to their natal colonies as they approach breeding age (at around 3 years old) and many recruit to their original neighbourhoods, sometimes within a few metres of the location at which they were reared.

Synchronized Area Fidelity

Most terns, Australian Pelicans and Pied Cormorants coordinate the timing and location of breeding colonies within a broader geographic area through social interactions within flocks of reproductively active (nuptial) individuals. This strategy may have several functions including locating colonies within range of prey resources (in coastal species), synchronising the timing of colonies with the onset of prey-resources and the 'swamping' of terrestrial predators. Seabirds that follow this strategy periodically shift colony locations (often between traditional sites). Social behaviour in pre-breeding display flocks facilitates pairing or re-pairing and synchronizes the timing and location of settlement in a suitable colony area. Breeding pairs may settle progressively in tightly synchronized groups or clusters through the breeding season with the earliest groups made up of 'neighbourhoods' of individuals probably of similar age and experience.

If changes in seabird populations are to be monitored to detect trends in marine ecosystems then different sampling strategies are needed for 'high site fidelity' and 'synchronized area fidelity' species. High site fidelity species can be monitored at predictable colony locations year after year. By contrast, populations of species without fixed nesting locations will have to simultaneously counted (and traced using banding programs) across zones that encompass all the potential nesting habitat.



SITE FIDELITY IN *ONYCHOPRION* SPECIES

Tropical Bridled and Sooty Terns are closely related sibling species (genus *Onychoprion*) that sometimes nest in close proximity on the same breeding islands. Although similar in appearance the two species have markedly different foraging ecologies that have influenced the response of their populations to changes in ocean climate. The two species also have contrasting patterns of colony formation.

Bridled Terns show high site fidelity. Young birds are strongly philopatric returning, generally in their 3rd year, to the colony within which they were reared. Most will ultimately recruit to their original colony although some have been found on nearby islands. However changes in ocean climate and prey availability around south-western Australia have reduced the normal tendency towards philopatry. The increased dispersal of pre-breeding age Bridled Terns (prospectors) has evidently driven one of the largest expansions of breeding range recorded in a seabird (see Section 3).

Once established, adult Bridled Terns maintain their nest territories from one season to the next and maintain long-term pair bonds. Retaining the same nesting territory within the same neighbourhood likely facilitates the relocation and retention of mates from one season to the next.



Illustration by Dr Elizabeth Rippey



Illustration by Dr Elizabeth Rippey

Sooty Terns demonstrate 'synchronized area fidelity'. Pre-breeding social flocks congregate at night (therefore called nightclubs) over their potential breeding islands. Noisy paired and group aerial courtship continues until contagious flocks (neighbourhoods) settle in closely packed colonies (often with more than one nest per m²). Highly synchronised laying follows within the neighbourhood with spatial and temporal gaps between groups.

Observations on Rat I. in the Abrolhos between 2011 and 2016 have shown that the Sooty Terns have selected different nesting areas each year and have now utilised almost all the available space. The night clubs however were observed to form over the colony areas used in the preceding season. Pairing, or re-pairing, and the coordination of settlement was apparently facilitated by terns in the neighbourhood meeting where they finished in the previous season. This settlement pattern has also been observed in other 'synchronized area fidelity' species including Crested and Fairy Terns during the pre-laying period.

Sooty Terns are capable of maintaining long term pair bonds and young are philopatric at least to the same population if not colony of origin.

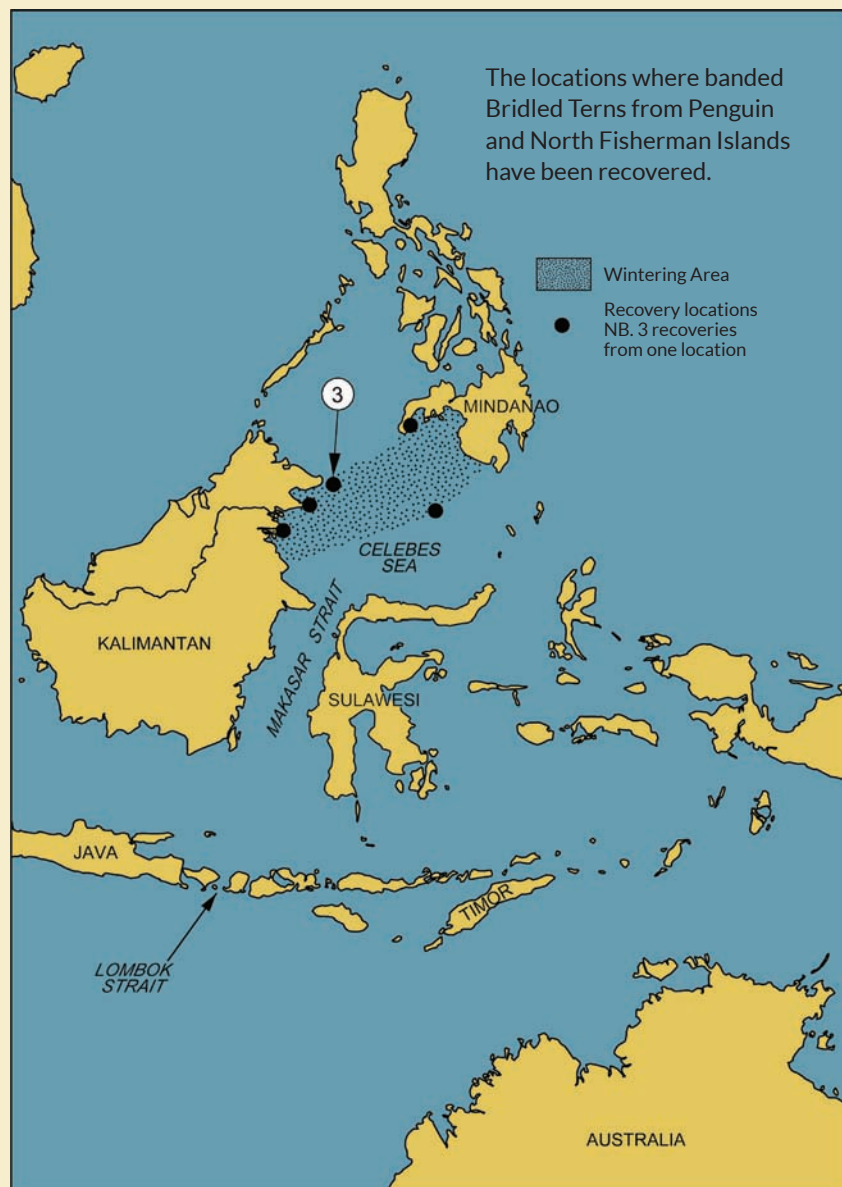
DISPERSAL AND MIGRATION

Monitoring programs based on seabirds are usually undertaken at breeding colonies. However the movements of seabirds outside the breeding season may bring them into contact with different marine environments and threats. Factors operating at these locations or regions may influence adult body condition in the following breeding season, survival and recruitment rates and exposure to contaminants. If a seabird species is to be the subject of an environmental indicator it will be necessary to know enough about the pattern of post-breeding dispersal or of migration.

Migration is the regular seasonal movement of a population between locations. A number of the seabirds breeding on islands of south-western Australia are known to be migratory. Flesh-footed

Shearwater move from breeding islands off the south coast of WA over spring and summer to winter in the north-western Indian Ocean. White-faced Storm-petrels from the south and mid west-coast cross the Indian Ocean to the Arabian Sea / Gulf of Oman. Bridled Terns breeding on islands between Dongara and Perth move north in April / May to winter in the North-west Sulawesi (Celebes) Sea between Mindanao in the Philippines and Sabah in Borneo (see box) returning through September. Sooty Terns, Common Noddies and Wedge-tailed Shearwaters from the Abrolhos move northwards into the tropical waters off north-western Australia. Some south-west Roseate and Fairy Tern populations have regular seasonal movements up and down the western Australian coastline, whilst other northern populations are apparently sedentary.

MIGRATION OF BRIDLED TERNS BREEDING ON THE LOWER WEST COAST OF WA



Non-migratory species usually still show an expansion of the area they occupy outside the breeding season, when they are no longer tied to nesting territories or developing young. Immature seabirds from non-migratory populations tend to disperse further from the breeding colonies than adults, converging back towards their natal areas as they become sexually mature. This radial expansion of the area occupied by a population is referred to as dispersal.

A number of essentially sedentary but locally dispersive seabird populations breed on islands along the western Australian coastline. These include populations of Great-winged Petrels, Little

Shearwaters, Little Penguins, Caspian and Crested Terns, Pacific Gulls and Pied Cormorants.

Some populations may have local and dispersive movements that lead to them foraging in compromised marine ecosystems where monitoring is a high priority. For example, Caspian Terns, from the colony on Penguin Island, spend periods of their annual cycle in highly eutrophic environments including Peel Inlet and Cockburn Sound. Their prey, and the foodchains in these environments may be contaminated with heavy metals. As top predators these terns are potentially useful indicators of the condition of these ecosystems (see section 7).

BIRD BANDING

Knowledge about the movements of seabirds and their survivorship, potential longevity and recruitment has accumulated primarily by identifying and following individuals over long-periods of time. This requires the marking of individuals with uniquely numbered metal rings and / or colour coded rings, flags or patagial tags. In Australian this technique is referred to as bird-banding.

The capture and banding of birds is managed and regulated in Australia by the Australian Bird & Bat Banding Scheme (ABBBS) based within the Department of Environment in Canberra (www.environment.gov.au/science/bird-and-bat-blanding). The ABBBS operates a database for all birds banded in Australia and is linked to similar banding schemes in other countries to track international recaptures (living birds) or recoveries (reports of dead birds). Banders train under an apprenticeship system where trainees work with qualified practitioners until reaching the required levels of competency.



SEABIRD POPULATION STRUCTURE

The colonial behaviour and movements of seabirds produce a fairly typical, scale dependent, population structure.

Meta-populations may occupy large areas of the range of a species. They consist of a cluster or geographic spread of populations where there is, over time, a low level of exchange in individuals. Normally these individuals will be birds breeding for the first time outside their natal area. Given the philopatric tendencies of seabirds these movements are usually uncommon but the emigration rate may increase if there are persistent constraints around the natal colony, such as prey shortage or competition for nesting space.

Populations are regional clusters of colonies that regularly exchange some recruits and breeding adults (at least in species with synchronized area fidelity). In Western Australia there are some populations that overlap regionally (and even on the same islands) but have colonies separated by the timing of reproduction. For example Roseate, Crested and Bridled Terns and Pied Cormorants have distinct autumn/winter and spring/summer breeding populations or sub-populations.

Colonies are aggregations of breeding pairs with nesting territories in a specific geographic area (in most cases on a seabird island). The colonies of 'high site fidelity' species reform in the same areas each season whilst those of 'synchronised area fidelity' species may move around within an area of breeding habitat or to other (often traditional sites) within the geographical area used by the population.

Fairy Terns staging at a night roost on the Abrolhos Islands



Neighbourhoods are flocks or spatially contagious groups of breeding pairs that engage in the social phases of colony formation, often leading to synchronized settlement and timing of laying. There is some evidence that neighbourhoods contain pairs that have previously associated in breeding attempts and may involve individuals of similar age, breeding experience and quality.

CLUBS AND SOCIAL ROOSTS

During the pre-breeding period many seabirds gather at club sites. These are generally neutral zones (eg. sand-spits, rock-bars, mangroves) located outside, or on the periphery of, colony areas. At clubs individuals in breeding condition engage in the group and courtship displays that synchronize

and coordinate colony formation. Pairing and re-pairing usually occurs at such sites particularly in 'synchronized area fidelity' species.

Social roosts are aggregations of birds involving a range of age classes. Some migratory populations (eg. Australian Fairy Terns) form night roosts at traditional locations, particularly after arrival in a breeding area at the start of the season and whilst staging on migration. Such sites provide a cross-section of entire populations and may be useful for monitoring recruitment and changes in age structure.



CENTRAL PLACE FORAGING

Optimal foraging theory maintains that organisms will maximise the size and quality of their food intake whilst minimising the energy expended and time taken during foraging. Central place foraging is a special case of optimal foraging where the organism is constrained by the need to return at intervals to a particular location. When attending breeding colonies seabirds are **central place foragers** obtaining their resources from a marine area or 'prey field' around nesting sites. The radius of the foraging range depends on a variety of species-specific attributes including flight (travel) efficiency, foraging methods, and chick developmental periods. Environmental factors that influence prey density and distribution also constrain foraging behaviour as potentially does competition between breeders in the waters around the colony.

Foraging trip distance and duration changes with the species-specific pattern of colony attendance, through the pre-laying, incubation, chick provisioning, and in some cases post fledging (eg. some terns), stages of the breeding cycle. Within that context inter-annual and intra-seasonal variations may occur in response to shifts in prey density or distribution within the foraging range.

The application of central place foraging theory would predict significant differences in the dietary composition of breeding seabirds, between stages in the nesting cycle, and between breeding and maintenance periods. Foraging seabirds would be best able to target their preferred prey at times when the foraging range was least constrained (eg. during the pre-laying, incubation or moult periods) and more restricted during periods with short return intervals and high energy demands (eg. chick provisioning). Such dietary compromises would be greatest in years where the densities of preferred prey within the foraging range were at low levels.

It is these relationships between breeding seabird species and the aquatic environments within foraging range of their colonies that provide the opportunities to monitor change in the condition of marine ecosystems on a suite of spatial and temporal scales.

FORAGING ENVIRONMENTS

Seabird breeding locations (generally islands) are often hubs for a range of species each with its distinctive adaptations to provisioning adults and young from the surrounding marine ecosystems. Species may differ in method of prey capture, prey-type or species and foraging range and collectively this results in particular relationships with different marine food webs and ecosystems. Marine processes that increase prey-abundance or availability within these ecosystems are critical to foraging efficiency, adult condition and reproductive success.



Red-tailed Tropicbird



FORAGING ECOLOGY OF WESTERN AUSTRALIAN BREEDING SEABIRDS

Seabird species	Marine habitat & foraging range	Diet / prey resources
Little Penguin	Coastal embayments up to about 20km from the colony	Primarily small schooling fishes, Whitebait, Blue Sprat, Sardines and Garfish
Wedge-tailed Shearwater	Continental shelf waters with foraging range of 102 km.	Forage fishes (eg. Sardines and Scaley Mackerel) and squid. Also floating carrion.
Fleshy-footed Shearwater	Continental shelf waters with foraging range of 102 km.	Forage fishers (eg. sardines) and squid. Also floating carrion.
Short-tailed Shearwater	Continental shelf and Antarctic convergence (bimodal)	Forage fishes and krill.
Little Shearwater	Continental shelf waters with foraging range of 102 km.	Forage fishers (eg. Sardines) and squid
Great-winged Petrel	Oceanic waters off the continental shelf, foraging range of 102 km.	Nocturnal forager, large squid.
White-faced Storm-petrel	Continental shelf waters with foraging range of 102 km.	Surface zooplankton and neuston
Australian Pelican	Inshore waters and estuaries within about 30 km of breeding colonies	Mostly benthic fishes including mullet and seagrass species.
Pied Cormorant	Inshore waters and estuaries within about 30 km of breeding colonies	Mostly benthic fishes including mullet and seagrass species.
Black-faced Cormorant	Littoral waters and reef around rocky islands, generally within a few 100 metres of colonies	Benthic and reef fishes.
Masked Booby	Oceanic waters with 10 ² of breeding colonies	Flying-fish and squid captured over surface feeding tuna
Brown Booby	Oceanic waters with 10 ² of breeding colonies	Flying-fish and squid captured over surface feeding tuna
Red-footed Booby	Oceanic waters with 10 ² of breeding colonies	Flying-fish and squid captured over surface feeding tuna
Greater Frigatebird	Oceanic waters with 10 ² of breeding colonies	Flying-fish and squid captured over surface feeding tuna
Lesser Frigatebird	Oceanic waters with 10 ² of breeding colonies	Flying-fish and squid captured over surface feeding tuna
Red-tailed Tropicbird	Oceanic waters with 10 ² of breeding colonies	Flying-fish and squid

FORAGING ECOLOGY OF WESTERN AUSTRALIAN BREEDING SEABIRDS (continued)

Seabird species	Marine habitat & foraging range	Diet / prey resources
Pacific Gull	Reef platforms and shorelines within about 2km of nesting territories.	Crabs, molluscs, cephalopods, sea urchins, benthic reef fishes, other seabirds and carrion.
Caspian Tern	Sheltered, shallow coastal waters and estuaries within about 30 km of breeding sites / colonies.	Benthic fishes including Sea Mullet, Perth Herring and several Whiting species.
Crested Tern	Coastal and inner continental shelf waters up to 20 km of breeding colonies.	Adults take schooling forage fishes (eg. Sardines, Scaley Mackerel, Yellowtail Scad). Chicks are also fed smaller reef / seagrass fishes.
Lesser Crested Tern	Coastal and inner continental shelf waters up to 20 km of breeding colonies.	Adults take schooling forage fishes
Sooty Tern	Shelf edge and oceanic waters with a range of 10 ³ (at least during pre-breeding period and incubation)	Small mesopelagic post-larval fishes (eg. Lantern Fishes) and squid driven to the surface by foraging tuna.
Bridled Tern	Continental shelf up to about 80km from nesting colonies	Small forage fishes and larval fishes and crustaceans associated with <i>Sargassum</i> rafts (eg. Black-spot Goatfish post-larvae, leatherjackets and Columbus Crabs).
Roseate Tern	Continental shelf waters especially near reefs or in lagoons	Small forage fishes driven to the surface by predatory fishes (eg. Slender Sprats, Anchovies, Goatfish post larvae).
Little Tern	Sheltered, shallow coastal or estuarine waters within 2km of breeding colonies.	Small schooling forage fishes.
Australian Fairy Tern	Sheltered, shallow coastal or estuarine waters within 2km of breeding colonies.	Small schooling forage fishes (eg. Blue Sprats, Whitebait, Hardeyheads, Garfish, Goatfish post-larvae) and small benthic fishes (eg. Mullet and Gobies).
Common Noddy	Shelf edge waters up to 100km from breeding colonies	Post-larval fishes dominated by Beaked Salmon. Also Anchovies and squid. Often captured in association with surface feeding tuna.
Lesser Noddy	Shelf edge waters up to 100km from breeding colonies	Post-larval fishes particularly Black-spot Goatfish and Beaked Salmon. Often captured in association with surface feeding tuna.

LOCATING WHERE SEABIRDS FORAGE

If seabirds are to be used as bioindicators of processes occurring in marine ecosystems it is important to know where foraging is taking place at different stages in the nesting cycle. For inshore species this can often be ascertained by simple observation of feeding locations and foraging behaviour. Bird-banding can also be used (particular colour-marking) to trace individual movements from breeding colonies to temporary roosts close to foraging areas.

However many seabirds, particularly pelagic and oceanic species, forage at sea well beyond our view. Locating the foraging areas for these species is much more difficult. Historically investigators conducted offshore vessel-based surveys for foraging seabirds. These usually took the form of standardised (time-area) watches on pre-determined traverses across continental shelves or through the oceanographic features, such as currents, temperature fronts, upwellings, convergences, eddies and filaments, that control the composition of planktonic communities and marine productivity. At best these surveys were on multi-disciplinary expeditions that allowed collaboration between seabirders, oceanographers and marine biologists. Unfortunately opportunities to do vessel-based surveys were always scarce and research of this kind was time consuming and extremely expensive.

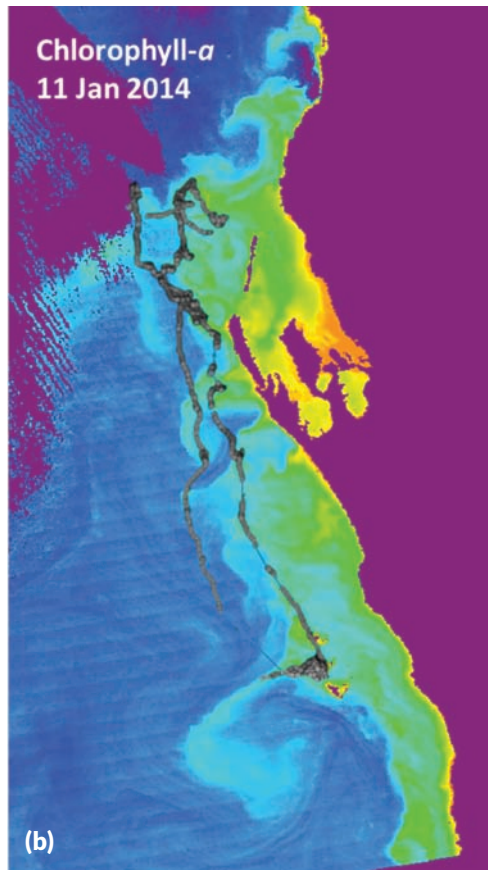
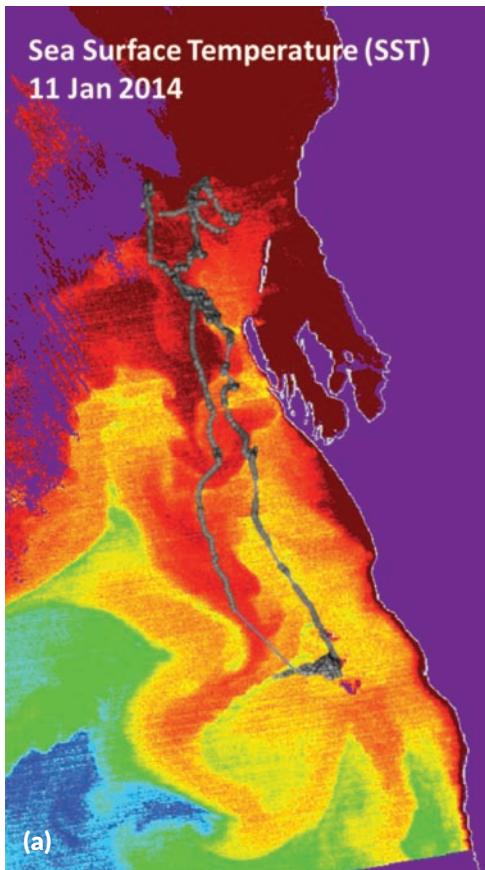
Advances in technology are increasingly making it possible to track seabirds using archival tags (that

operate on a sun compass) and GPS trackers (that use satellite fixes). Initially such investigations were restricted to large oceanic species like albatrosses and shearwaters but as these devices become smaller and lighter, and the software more sophisticated, these methods of exploring foraging ecology are becoming available for smaller species such as terns. Some require the birds to be recaptured to download the data, whilst others transmit data to satellites or to base stations close to the nest or roost. The more sophisticated devices can collect physiological information or information about activity such as flight patterns.

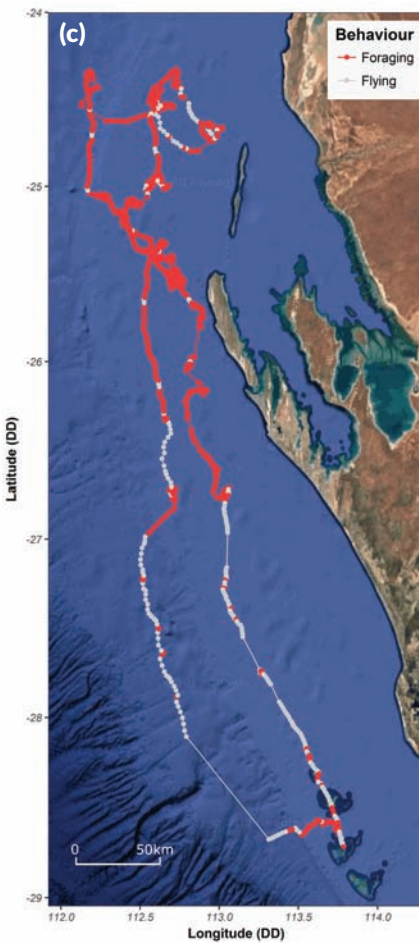
Increased miniaturisation has dramatically decreased the size of telemetry devices and opened the way to include additional on-board sensors to record behaviour, diving depth and physiology. Combined with environmental data from remote sensing information, movement data are a powerful way to indirectly 'observe' how seabirds are using the environment and partitioning resources both intra and inter-specifically. Changes in foraging movements and direction can be modelled against key oceanographic parameters such as sea surface temperature (SST), chlorophyll and bathymetry to identify factors that may be driving changes in foraging ecology. For example the foraging tracks of Sooty Terns on long and short foraging trips, both appear to track the edges of zones with high chlorophyll indicating areas of higher phytoplankton productivity. Tuna that drive the Sooty Tern's prey to the surface are also likely to concentrate in these areas.



Colour-banded Caspian Tern on Peel Inlet

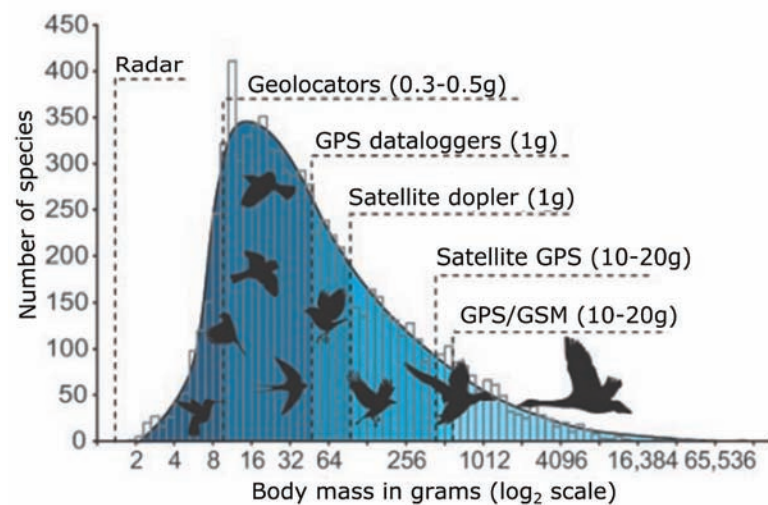


The foraging tracks of two Sooty Terns overlaid approximately over concurrent patterns of sea-surface temperature (a) and Chlorophyll-a (b) distribution. The third panel (c) shows the inferred locations of commuting flight and foraging.



(c) Movement track of a sooty tern on an eight day foraging trip from the Abrolhos Islands to Shark Bay. Using flight speed obtained through high resolution GPS it was possible to determine when this bird was actively foraging rather than commuting.

The diagram below shows the number of bird species that have been studied with each telemetry tag type according to bird body mass. Tag weights are current for 2017, but are continually getting lighter. Note the $\log_2$ scale (adapted from Bridge *et al.* 2011).



Current types of telemetry tag and their suitability to particular research questions.

Tag	Type	Weight	Accuracy	Attachment	Application
Geolocator (GLS)	Light sensor/ logger	~1.5g	150km	Surface, on body	Migration
Platform transmitter terminal (PTT)	ARGOS satellite	≥ ~5g	Location classes ≤250m +	Glue/Tape, collar, harness, implant	Landscape scale/ migration
Geographic positioning system (GPS)	Logger + base station/ recapture	≥1g	High	Glue/Tape, collar, harness	Fine scale and landscape scale. Broad range of research questions
Geographic positioning system (GPS)	GPS/GSM (retrieval through phone network)	10-20g	High	Glue/Tape, collar, harness	Fine scale and landscape scale. Broad range of research questions. Some behaviour.
Geographic positioning system (GPS) plus accelerometry, depth, temp, gyroscope, magnetometer	ARGOS, GSM, base station	~5g - 20g+	High	Glue/Tape, collar, harness	Fine scale and landscape scale. Broad range of research questions including behaviour and physiology.

TRACKING FORAGING COMMON NODDIES FROM LANCELIN ISLAND

About 2000 pairs of Common Noddies nest in a 'frontier' colony on Lancelin Island. This colony was initiated in 1991 and lies 300 km south of the historical limits of this species, at Pelsaert Island in the Houtman Abrolhos. Such range shifts probably indicate a redistribution of prey resources or foraging opportunities as a consequence of the observed changes in ocean-climate. Such shifts may have implications for fisheries and conservation management.

In 2014 and 2015 Common Noddies from the Lancelin Island colony were tracked using the **University of Amsterdam Bird Tracking System**. The data from these GPS tags can be downloaded in the field, when the birds return to the colony area, using a base station antenna and two relay stations. The tags were attached using a harness.

Attaching GPS Tags



Mounting a GPS tag on a common noddie on Lancelin Island.

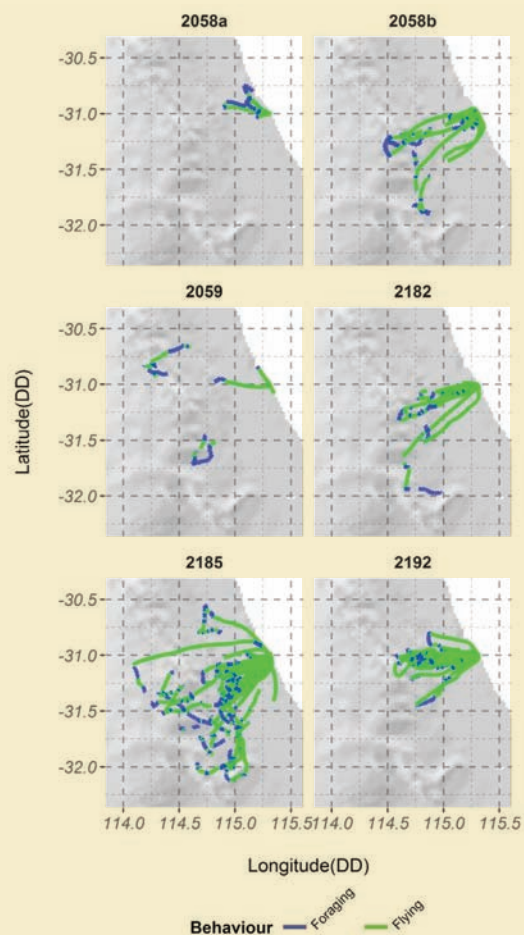


Noddy incubating back at the nest 30mins after tagging.



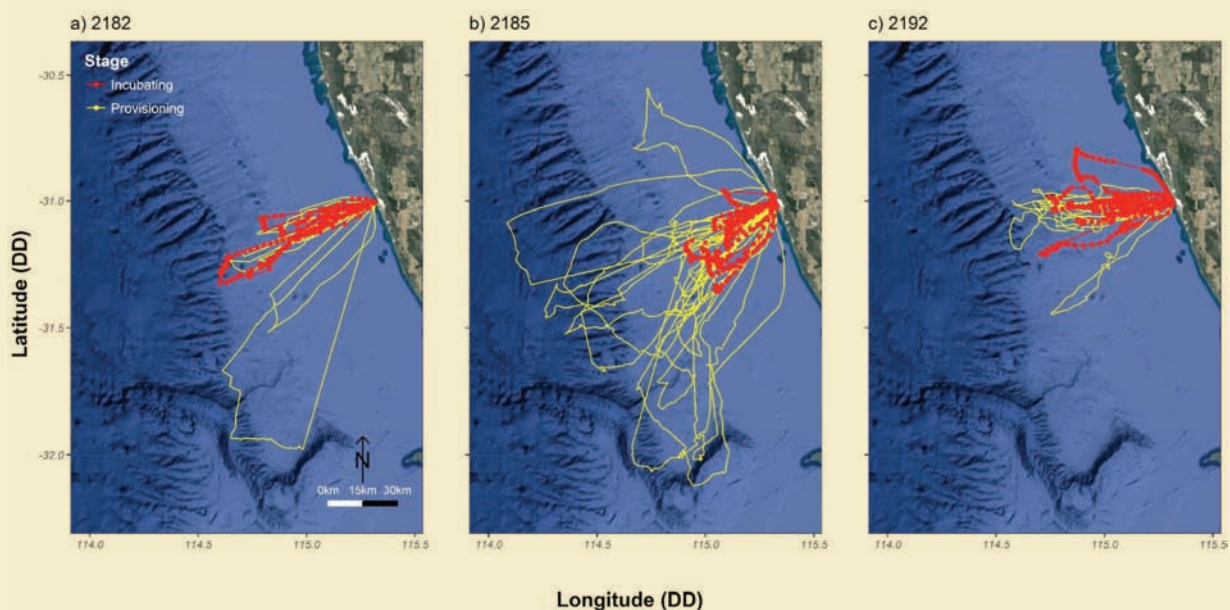
Noddy 2058 recaptured at the nest for tag removal 24 days later having made 14 foraging trips and flown 1261km.

Common Noddies breeding on Lancelin made day time foraging trips, generally changing over on the nest from late afternoon to early evening. During early chick-rearing, the Noddies commuted to the edge of the continental shelf, a journey of around 50 nautical miles. Foraging was often concentrated over complex canyon topography in the shelf break probably because these areas produced some local upwelling. These locations may also be areas where tuna schools concentrate. After hatching the Noddies foraged significantly further from the island, presumably to meet the demands of provisioning chicks.



Above: The foraging tracks of six individual Noddies from Lancelin with commuting and foraging locations inferred from flight speed and direction.

Below: Distances travelled by Noddies during provisioning were significantly longer than during incubation for birds tracked in 2015.



The foraging range of the Lancelin noddies was not far enough offshore to encompass warm or cold core eddies embedded in the Leeuwin Current. The bathymetric structure at the shelf edge was evidently a factor influencing prey location, at least early in the nesting cycle. Factors that are not coupled directly with Leeuwin Current behaviour appear to be operating including the life cycle of their main prey species.

Common Noddies breeding off the mid-west coast of WA take a very narrow range of prey types and unlike the other three species of dark pelagic terns do not switch prey types within or between seasons. Their prey is strongly dominated by the surface swimming (epipelagic) post-larvae of the Beaked Salmon (*Gonorhynchus greyi*). In some seasons there has been a significant component of post-larval Anchovies *Engraulis australis* in the regurgitates and squid are often a minority constituent.

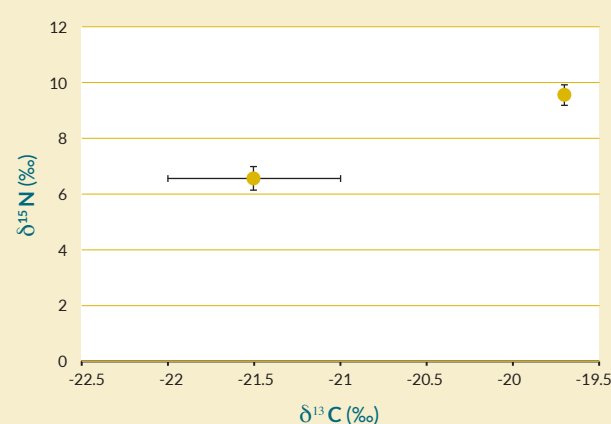
Adult Beaked Salmon are demersal fishes that occupy shallow, sandy substrates on the continental shelf. Spawning occurs near the shelf-edge over a protracted period and the pre-settlement stage (post-larvae) are normally present for an extended period during the spring to early summer months. They appear to be a significant prey resource because they shoal close to the surface and are likely also important food for a range of small / medium pelagic fishes.

At Lancelin Island the Common Noddies lay earlier in *La Nina* periods when the Leeuwin Current flow is relatively strong and sea-temperatures are higher and later in *El Nino* conditions when sea-temperatures are lower. It is likely that sea-temperatures control the timing of spawning in *Gonorhynchus* at the shelf edge and the subsequent appearance of the post-larvae at the surface. Changes in ocean climate (particularly rising sea temperatures) may be shifting the central spawning area for *Gonorhynchus* southwards to within range of the 'frontier' colony whilst increasing the foraging distance from the Abrolhos colony (where breeding activity has ceased tracking the Southern Oscillation).

Gonorhynchus post-larvae dominated the prey regurgitated by Lancelin noddies during the tracking project in 2014 and 2015. A sample of these fish

from 2015 was preserved and sent to a laboratory to measure the stable isotope ratios of carbon and nitrogen in the muscle tissue. A similar sample was taken at this colony on another project in the 2009 season.

The tracking in 2015 occurred during an *El Nino* period (annual Southern Oscillation Index was -134.8). The 2009 sample was taken in a neutral year (SOI was -3.9). This is reflected in the significantly higher $\delta^{15}\text{N}$ in 2009 which indicates the presence of more inorganic nitrogen from either upwelling or cross-shelf transport. The higher $\delta^{13}\text{C}$ values in 2009 would result from an increase in photosynthesis in the phytoplankton using up more of the heavy carbon isotope from the dissolved CO_2 , i.e. is an indicator of higher productivity in that year.



Stable isotope ratios of nitrogen ($\delta^{15}\text{N}$) and carbon ($\delta^{13}\text{C}$) in the tissues of Beaked Salmon (*Gonorhynchus greyii*) regurgitated by nesting Common Noddies on Lancelin Island (n=6) in 2009 and 2015 (n=17).

This analysis suggests that the Lancelin noddies follow a similar shelf-edge foraging pattern to find *Gonorhynchus* during both productive and relatively unproductive seasons. However, with the observed changes in ocean-climate, the preferred prey is a reliable resource within foraging distance of Lancelin Island but an increasingly unreliable one for the Abrolhos colony.

INVESTIGATING PREY SELECTION

The next step in understanding seabird foraging ecology is determining what prey types / species are taken in the foraging environments. Prey types connect seabirds to specific marine food-chains that may be affected by changes in climate, fisheries or contaminants.

A variety of methods are available to collect information on seabird diets depending on the species, resources available and ethical considerations. The simplest, and least intrusive, is the direct observation of prey being carried for courtship display or to provision mates or chicks. This application is limited to seabirds that carry their prey cross-wise in the bill, so called 'bill-loading' species. In WA the method is applicable to our coastal and plunge-diving Caspian, Crested, Lesser Crested, Roseate, Australian Fairy and Little Terns.

The advent of telephoto lens, digital cameras or digiscopes (digital cameras mounted on spotting scopes) has significantly improved these methods, providing 'vouchers' or reference photos to confirm the identity of prey species. The size of a prey item can also be estimated by comparing fish length to bill length, an observation also made more reliable by having a reference image. Digital cameras are now owned and utilised by many amateur bird-watchers allowing this method to be utilized in 'citizen-science' based monitoring projects.



Caspian Tern with Trumpeter Whiting

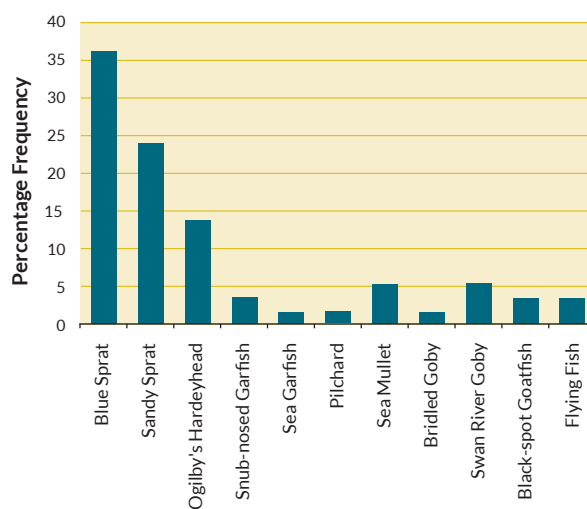


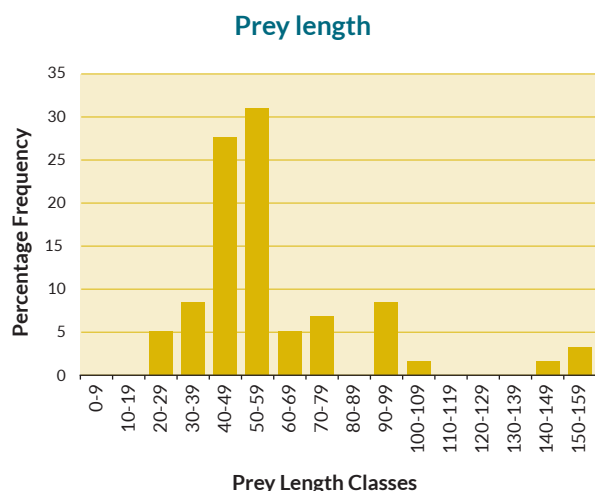
Fairy Tern with Ogilby's Hardeyhead



Crested Tern bring pilchard (sardine) to feed it's chick at the creche.

Carried fish species photographed by Network observers in 2016/17 season.





Prey species and prey lengths of fish carried by Fairy Terns during the 2016/17 breeding season based on photographs provided by birdwatchers with digital cameras.

All methods of assessing diet are biased to some extent. Adult terns, for example, do not necessarily ingest the same prey that they carry to mates or chicks. It is therefore beneficial to use more than one method to assess diet composition if possible.

Many seabirds will regurgitate the contents of the crop and stomach when handled or otherwise startled including terns, gulls, cormorants, boobies and tropicbirds. Samples vary in degree of digestion depending on species, time since ingestion and stage in the nesting cycle. Marine prey can usually be identified immediately from the largely intact remains although in some cases it may be necessary to use remaining hard parts, such as otoliths, fin rays or squid beaks. The species that readily regurgitate pre-digested meals will also produce 'pellets' or 'castings' that are usually found at roosting sites or on nest rims within the colonies. These are boluses of indigestible material typically bone, fins, skin, otoliths, chitin from crustaceans and squid beaks that can also be used to identify prey if sufficient reference material is available.



Caspian Terns take benthic fishes (in this case Sea Mullet) sometimes as large as 200mm



Regurgitated pellet on the rim of a Caspian Tern nest.



Pacific Gulls using the concrete pad from an abandoned shack at Rat Island in the Houtman Abrolhos as an 'anvil' site.

Pacific Gulls use flat, rocky pavement 'anvil sites' on the islands and mainland headlands to drop and break-open molluscs and sea-urchins. These prey are seized by 'duck-diving' over shallow reef and rock platforms or picked off at low tide. The accumulated 'middens' of broken shell material are not a comprehensive sample of the Pacific Gulls diet (which also includes free swimming fish and crustaceans and small seabirds) but may still be useful for monitoring changes in the relative abundance of some reef invertebrates.

Investigating seabird diets becomes more difficult in species that do not carry prey in the bill and rarely regurgitate when handled. This is the case with penguins, petrels, shearwaters and storm-petrels. Historically more invasive methods such as 'water off-loading', which involves flushing the stomach with water and/or an emetic, have been used. Such methods may not be considered ethical these days when alternatives are available. Prey remains collected by offloading methods was usually highly digested and

the identification of taxa usually relied on ‘hard parts’ including fish otoliths and cephalopod beaks.

Seabird faecal samples can now be genetically screened for prey species using DNA metabarcoding techniques. Samples need to be collected from individual birds that have detained for a short period in a bag or holding box free from sources of environmental DNA contamination. The analysis can be outsourced to specialist laboratories. The data is generally qualitative and the results depend on the DNA sequences being available in the international data bank. The sequences for many marine taxa are as yet unavailable.

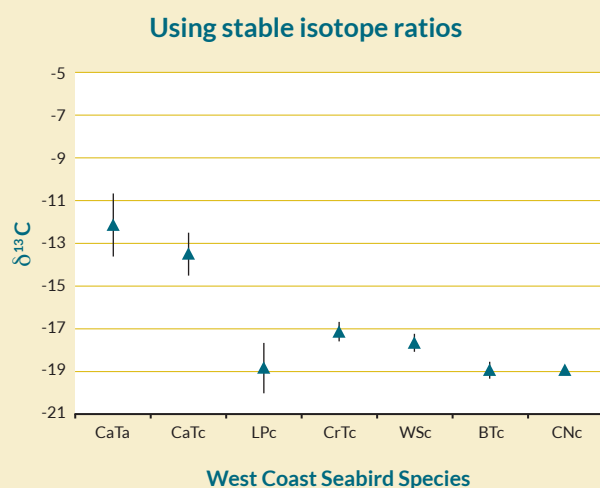
IDENTIFYING FOOD CHAINS AND ECOLOGICAL NICHES

Many elements exist in forms that vary in the number of neutrons in the nuclei of their atoms (isotopes). When these variations do not cause the atom to break-up and emit radiation (radio-isotopes) they are

known as stable isotopes and their effect is to make some atoms slightly heavier than the normal form. Biological processes such as photosynthesis, digestion and protein synthesis may sort these isotopes in ways that allow their origin to be traced.

Stable isotope analysis of carbon ($\delta^{13}\text{C}$ - the ratio of C^{13} to C^{12} atoms) and nitrogen ($\delta^{15}\text{N}$ - the ratio of N^{15} to N^{14}) atoms in consumer tissues can be used to infer the environmental origin of prey, the foraging habitat and / or the trophic level of seabirds. Collectively this information is referred to as the ‘isotopic niche’.

Broad groups of producers (terrestrial C3 plants including mangroves, C4 plants including seagrasses, macroalgae, phytoplankton, cyanobacteria and micro-phyto-benthos) all have distinctive ranges in $\delta^{13}\text{C}$ values. These values are transmitted (slightly upgraded) from the producers through to all consumers in a food chain. This allows the producer base for foraging seabirds to be inferred from the $\delta^{13}\text{C}$ values in their tissues (eg. in feathers or blood).



This Figure plots the $\delta^{13}\text{C}$ values from the feathers of six seabird species foraging from the lower west coast of Western Australia. These samples were from

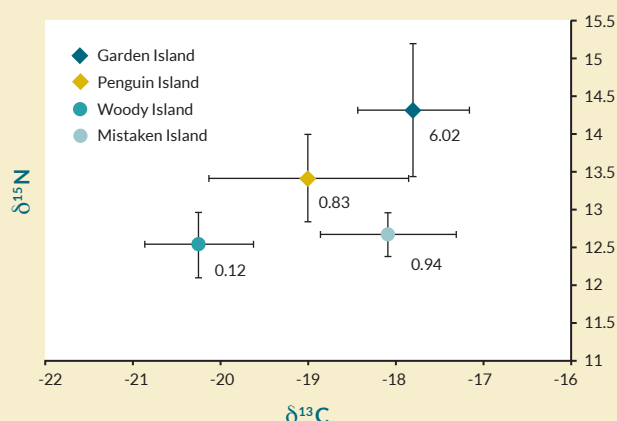
Caspian Tern adults (CaTa, n=39), Caspian Tern chicks (CaTc, n=10), Crested Tern chicks (CrTc, n=10), Little Penguin (LPc, n=104), Wedge-tailed Shearwater (WSc, n=23), Bridled Tern (BTc, n=12) and Common Noddy (CNc, n=11).

Caspian Terns forage in the shallow waters of coastal embayments and in the estuaries. The $\delta^{13}\text{C}$ values in their feathers are those of benthic producers, primarily seagrasses. The other species have the $\delta^{13}\text{C}$ values of the phytoplankton at the base of their food chains. The Crested Terns and Wedge-tailed Shearwaters pursue forage fishes (eg. pilchards) on the shelf. They have more enriched $\delta^{13}\text{C}$ values than Bridled Terns and Common Noddies that forage mainly on post-larval fishes closer to the shelf edge. The $\delta^{13}\text{C}$ values typically become more depleted with distance from the coast and the reduced carbon contribution from benthic ecosystems.

The $\delta^{15}\text{N}$ values in consumer tissues can be used to infer the sources of carbon (energy) in food-chains if the producer signatures (the isotopic baselines) are known. $\delta^{15}\text{N}$ values also show a stepwise increase with trophic level due to the tendency of animals to differentially excrete ^{14}N during digestion and assimilate ^{15}N during protein synthesis. The trophic position of consumer organisms can be inferred above a known producer baseline. The $\delta^{15}\text{N}$ values in marine producers such as phytoplankton will be dependent

on the fractionation of the nitrogen source. This in turn reflects the various nitrifying and de-nitrifying transformations occurring through the nitrogen cycle and on nitrogen availability. Inorganic (nitrate) nitrogen is relatively enriched in ^{15}N producing a high $\delta^{15}\text{N}$ value. Recycled (ammonia) nitrogen is less enriched and recently fixed (N_2) nitrogen is depleted in ^{15}N . The $\delta^{15}\text{N}$ value is a combined indicator of nitrate source, availability and uptake.

Stable isotopes as indicators of eutrophication



The results of the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analysis of mesoptile down samples from penguin chicks from colonies on Garden, Penguin, Mistaken and Woody Islands. The

$\delta^{13}\text{C}$ values of between -17.8 and -20.25 are consistent with these penguins foraging primarily on pelagic 'baitfishes' in phytoplankton based food chains. At the colony level the $\delta^{13}\text{C}$ values increase with increasing $\delta^{15}\text{N}$. The measured Chlorophyll A values reported for Cockburn Sound, Warnbro Sound (south of Penguin Island), King George Sound and the Recherche Archipelago are also shown. These indicate that in this case increasing $\delta^{15}\text{N}$ indicates higher availability of inorganic nitrogen. This suggests that the observed parallel increase in $\delta^{13}\text{C}$ is the result of increased primary production and the higher utilization of the heavier ^{13}C in the dissolved carbon dioxide during photosynthesis (i.e. with the depletion of available ^{12}C). The enriched $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values in the chick feathers in this case are indicators of eutrophication, with Cockburn Sound being the penguin foraging area with the highest inputs of inorganic nitrogen.



INTRODUCTION

Climate change is having a profound effect on bird populations around the world. The majority of the impacts have been detected as changes in distribution and / or in phenology (the timing of events in the seasonal cycle). Such changes generally relate to availability of food resources and have consequences for the size of bird populations or the structure of their biotic communities.

In marine ecosystems the relative impacts of changes in ocean climate and the harvesting of marine resources by fisheries can be difficult to discriminate. For example, changes in ocean climate have been implicated in the ultimate collapse of the overfished stocks of forage fishes in a number of regions. Despite these complexities the central-place foraging behaviour of colonially nesting seabirds can be utilised to infer spatially explicit changes in marine ecosystems caused by marine climate change, fisheries or their interaction.

The dynamics of ocean currents typically control sea -temperature, salinity, nutrient availability and ultimately primary productivity producing so called 'bottom-up' changes in fish biomass and in prey availability for seabirds. Climate change impacts on marine ecosystems will usually be manifested as shifts in marine community structure and / or productivity at a range of spatial scales.

CHANGES IN DISTRIBUTION

Colonial seabirds are strongly philopatric and breeding adults adopt 'high site fidelity' or 'synchronized area fidelity' behaviour (see Section 2). Changes in the rate at which recruits return to their natal area to breed or changes in colony locations generally indicate a persistent disruption in marine ecosystems. The break-down in the usual relationships with breeding sites usually follows protracted periods of reproductive failure caused by declining prey availability or prey quality within the range of the breeding colonies. Shifts in the distribution of

prey resources may be indicated concurrently by the appearance of individuals in waters outside their former range and ultimately by the establishment of colonies at novel locations, often outside the former breeding range.

The geographical distribution of conspicuous animals such as seabirds is relatively easy to monitor by either professional or amateur observers, particularly by those that routinely visit the breeding islands or engage in vessel-based pelagic surveys. Coordinated programs such as BirdLife Australia's Bird Atlas Project may enhance the strategic collection of such data although the changes to date have tended to be recorded and documented by researchers in seabird ecology. This is probably because amateur observers are less aware of the significance of their observations.

As global sea temperatures rise there would be a general expectation that the ranges of tropical seabird species would extend further into the higher latitudes whilst cold water species would retreat towards the poles. There is already clear evidence that this process is underway in a number of marine regions around the world. However the composition and availability of prey resources to seabird populations is controlled by a complex of oceanographic and biological factors that may confound predicted responses to marine climate change.

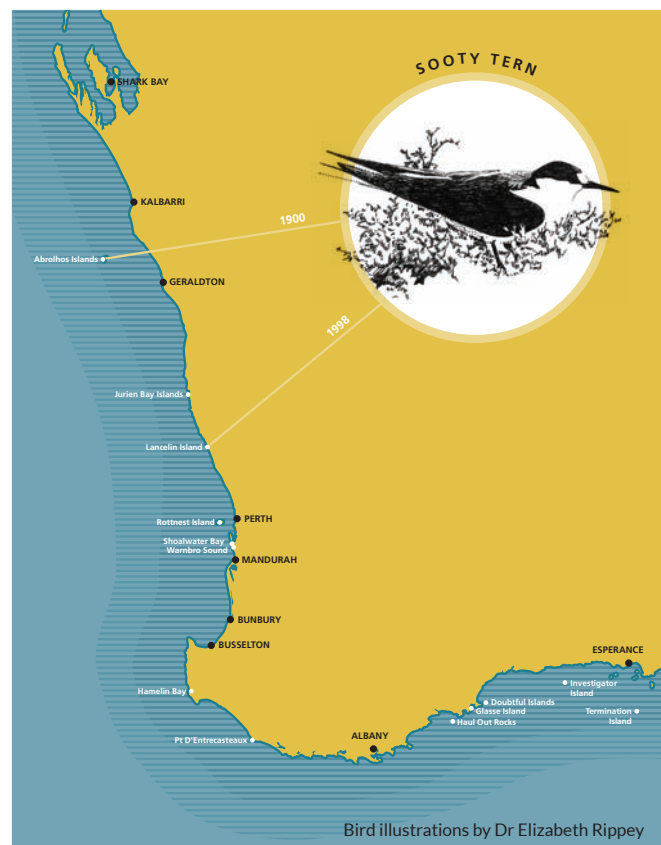
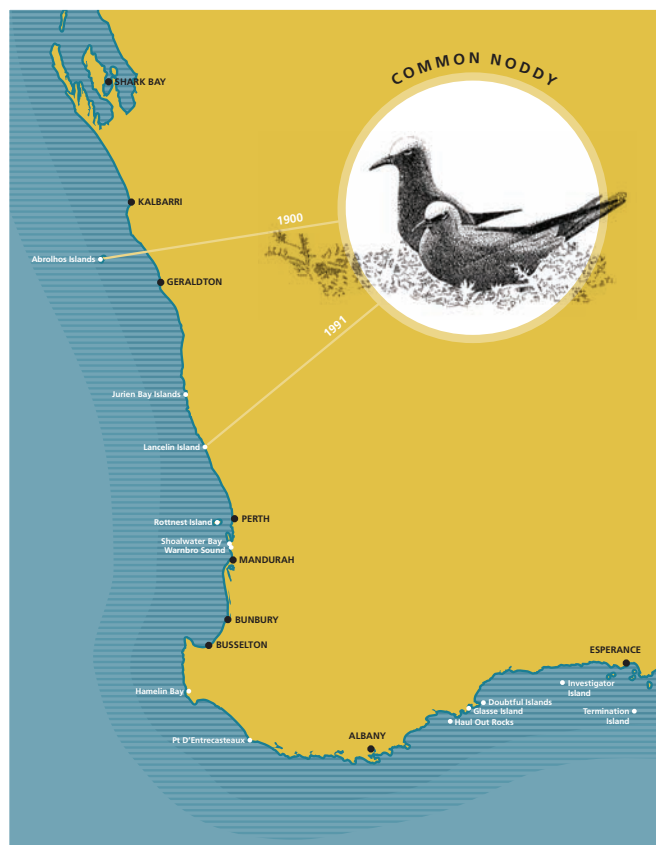
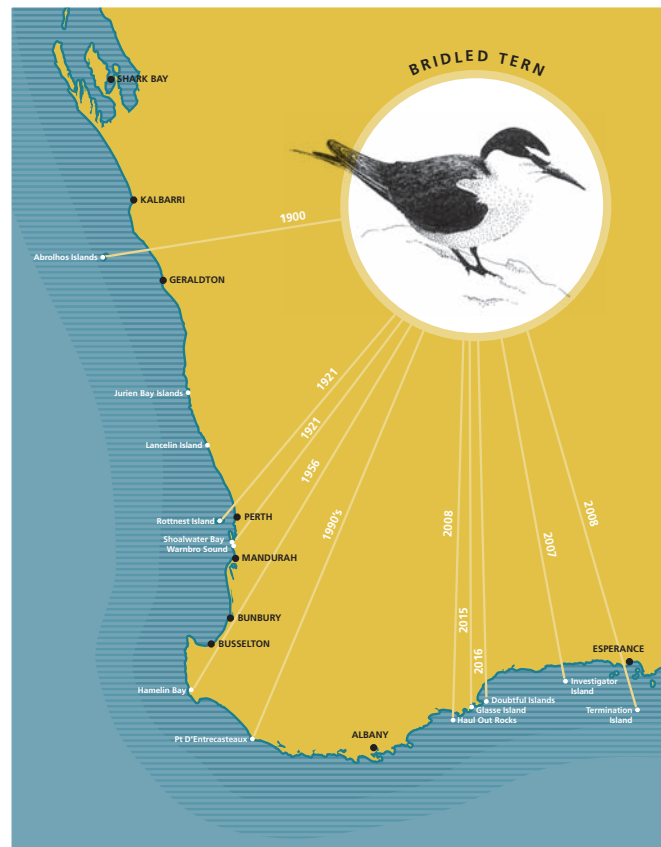
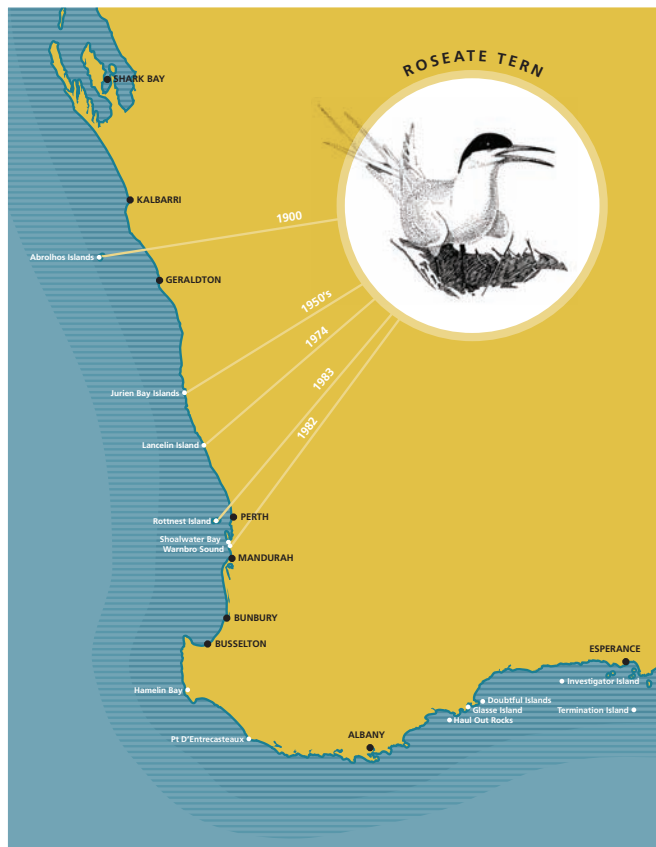


The Bridled Tern has extended its breeding range southward from the Abrolhos Islands since 1900 in response to changes in ocean climate.

THE CHANGING DISTRIBUTION OF TROPICAL TERNS IN SOUTH-WESTERN AUSTRALIA

In south-western Australia at least eight tropical pelagic seabird species-populations have shown either a southward shift in the distribution of breeding colonies or a rapid increase in the colony size at their southern limits. These changes have been occurring for nearly a century but have accelerated over the last 3 or 4 decades.

These figures show the recorded limits of the breeding distribution for four tropical tern/noddy species in the region at different times.



Bird illustrations by Dr Elizabeth Rippey

Range shift is usually driven by a persistent decline in prey availability at existing colonies within the historical distribution. Usually it will be initiated by the dispersal of younger pre-breeding age birds away from their natal areas in search of more productive foraging areas. Following extreme events the adults of 'synchronized area fidelity species' may also disperse in search of more productive areas. Uninhabited

potential breeding sites (usually small islands) within range of newly discovered prey resources may then be visited by these dispersing individuals or flocks. Observations of these 'prospectors' is typically the first indication of the potential establishment of 'frontier' colonies (outside the former breeding distribution) and an underlying long-term change in the distribution of marine resources.

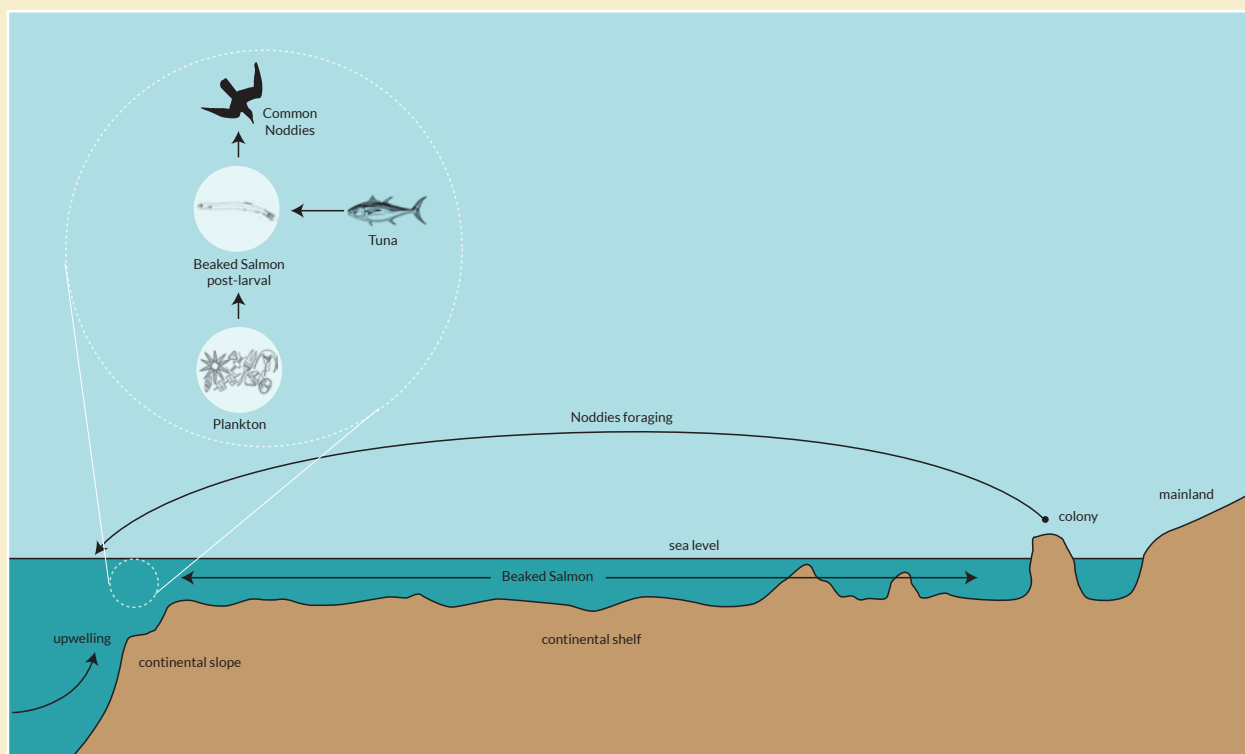


Range shifts in 'synchronised area fidelity' species can potentially involve adult birds with previous breeding experience. Sooty Terns have recently recolonized Rat Island in the Abrolhos after an absence of 73 years.

Although all four terns have formed frontier colonies south of the Houtman Abrolhos since around 1900 (when our ornithological history begins) the extent of the resettlement pattern differs markedly between species. The Bridled Tern has established 40-50 new colonies on islands and stacks all around the south-west coast to the Recherche Archipelago, arguably the longest range shift observed in any seabird to date. Many of the frontier colonies have continued to grow in size (to 3-5000 pairs) and some are now the largest known for this species. By contrast the Bridled Terns congener the Sooty Tern, and the Common Noddy, have only managed one leap of around 280km from Pelseart Island in the Abrolhos to Lancelin Island.

The contrasting responses to the changing oceanographic climate result from differences in foraging ecology. The three 'dark' tern species (Bridled & Sooty Terns and Common Noddy) all catch small, pelagic prey from the surface by 'contact dipping'. Roseate Terns however, like other coastal foraging black-capped species, 'plunge dive' shallowly to, or beneath, the surface to catch their prey. As the 'dark' terns have similar foraging methods and overlapping foraging habitats they are to some degree adapted to each other to avoid competition.

Common Noddies breeding off south-west coast of Western Australia conduct daily foraging trips to the shelf edge. Their prey is dominated by the surface swimming (epipelagic) post larvae of the Beaked Salmon (*Gonorrhynchus greyi*). Adult Beaked Salmon are demersal fishes that occupy shallow, sandy substrates on the continental shelf. Spawning occurs near the shelf-edge over a protracted period and the pre-settlement stage (post-larvae) are normally present for an extended period during spring to early summer months. Seasonal variations in oceanographic conditions apparently control the timing of spawning and the abundance of the post-larvae. The upwelling of relatively cold and nutrient rich water is probably forced by the southerly wind stresses (Ekman transport) and by features in the complex topography at the shelf edge. This in turn provides a more productive environment for larval development. The Noddies therefore depend on localized areas of enhanced marine productivity within foraging range of their breeding islands to meet the energy demands of reproduction.

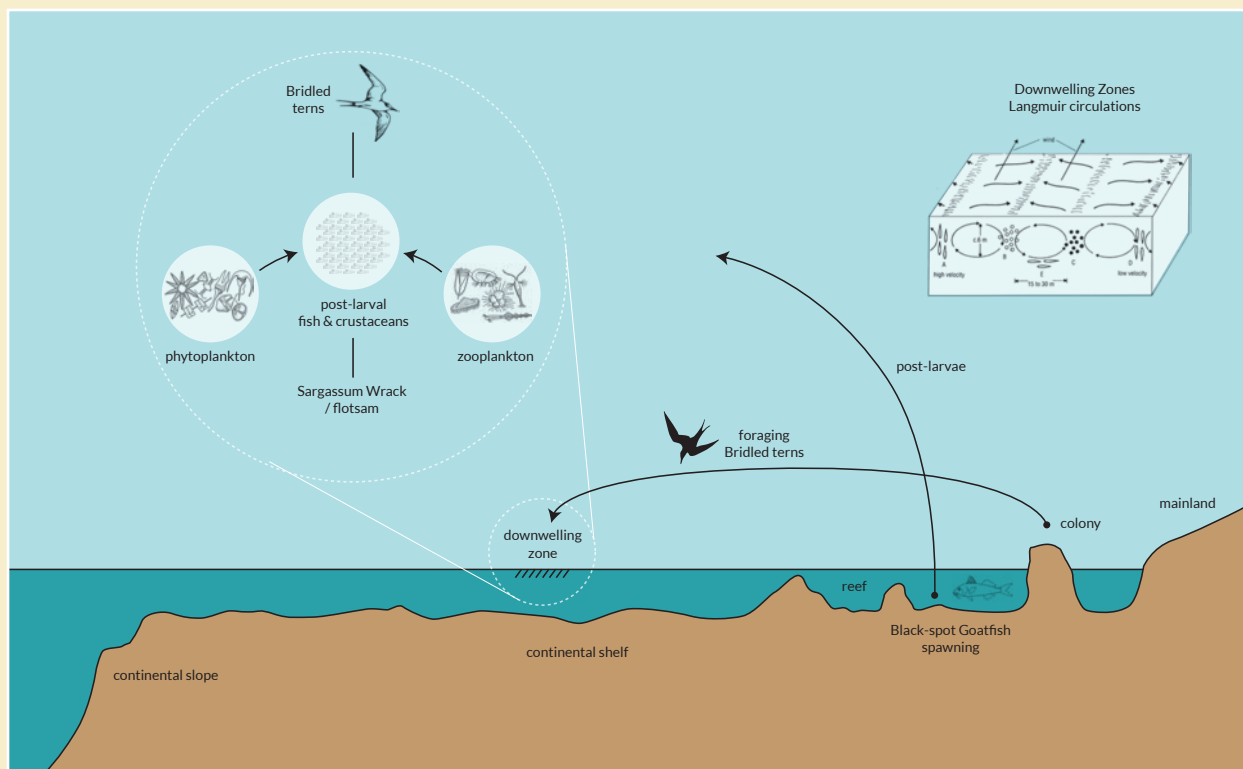


Foraging in the Common Noddy off Mid-Western Western Australia

Bridled Terns breeding on islands around south-western Australia take a wide range of small prey, dominated by juvenile or larval stages of fish and crustaceans. Most of these shelter amongst or aggregate around flotsam and in particular the floating rafts of seaweed found over the continental shelf. The seaweed includes the floating reproductive fronds (thalli) of the Brown Algae *Sargassum* and other macrophytes dislodged from the reefs. A common prey are the post-larvae of the

Black-spot Goatfish (*Parupeneus spilurus*) that aggregate in schools to settle on coastal reefs (or around *Sargassum* rafts) in the late spring and summer months.

On the continental shelf flotsam, and weakly swimming marine animals, are aggregated at the surface in downwelling zones. These form on some current boundaries, temperature fronts and, in shelf waters, on the Langmuir circulations set up by nearly constant southerly wind stress.



Foraging in the Bridled Tern of South-Western Australia

The breeding performance of Common Noddies at their core colony on Pelsaert Island in the Houtman Abrolhos has been frequently poor over the last couple of decades. However only one frontier colony has been established at Lancelin Island. The requirement this species has for relatively productive shelf-edge upwelling zones may not be replicated at many locations adjacent to potential breeding islands south of the Abrolhos. This may be restricting the redistribution of Common Noddies in this region.

Bridled Terns, by contrast, don't require areas of enhanced productivity and can make use of a wide selection of prey species that associate with flotsam. Rising sea-temperature will be expanding the distribution of its tropical prey types and allowing much of the continental shelf around south-western WA to become available for foraging. The redistribution of Bridled Terns in response to changing ocean climate has not been constrained by the generally declining marine productivity in the region.

CHANGES IN PHENOLOGY

The timing (phenology) of seasonal events such as arrival, laying, fledging and migration can also be quite readily monitored by both professional and amateur observers. In seabird species with some elasticity in their reproductive cycles the timing of laying is usually a good indicator of prey availability. This is because the females need to have attained a nutritional condition that supports the production of the egg or clutch. The onset of laying is influenced primarily by the timing

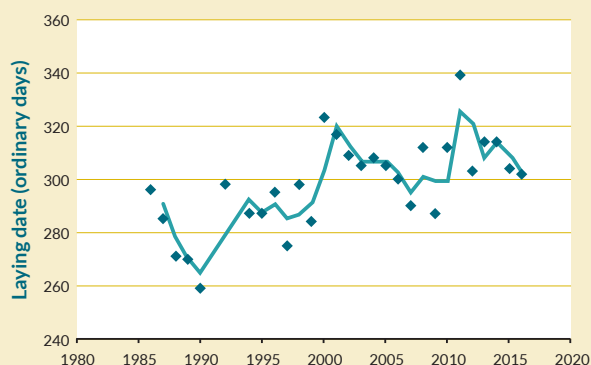
of prey availability within foraging range but also to some extent by the timing of reproduction in previous seasons (resetting the rhythmic internal cycle) and the cost of previous breeding attempts on female body condition. Collapses in prey availability may prevent laying altogether or lead to breeding failure later in the nesting cycle (eg. through mass starvation of nestlings or fledglings) depending on when they occur.

LAYING PHENOLOGY IN THE BRIDLED TERN OFF SOUTH-WESTERN AUSTRALIA

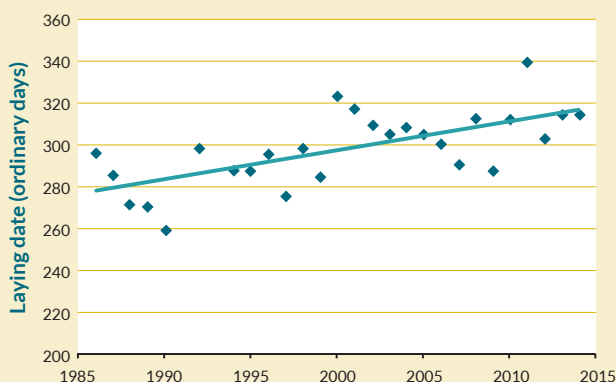
The date on which the first egg was laid has been monitored in the Bridled Tern colony on Penguin Island since 1986. When the rolling average is plotted it shows how these dates track the *El Nino* Southern Oscillation (ENSO), a widespread climatic pattern that influences the strength of the Leeuwin Current off Western Australia. The Bridled Terns tend to lay earlier and breed more successfully during *El Nino* periods when the Leeuwin Current is weaker. The oscillating pattern in the laying dates overlays another trend towards progressively later breeding. Bridled Terns appear to be adjusting to changes in the timing in availability of their prey resources, eg. delayed spawning in the Black-spot Goatfish.

The latest laying date recorded in the Bridled Terns followed the 2011 marine heatwave, an extreme event causing a dramatic rise in sea-temperature along much of the Western Australian coastline.

Running average laying date of Bridled Terns breeding on Penguin Island between 1986 and 2016



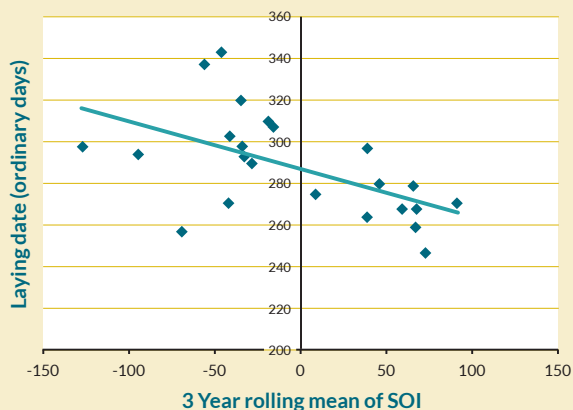
Laying dates of Bridled Terns on Penguin Island plotted against year showing progressive delay in the start of the breeding season ($R^2 = 0.6634$, $P < 0.01$).



The frontier colony of Common Noddies on Lancelin Island have been monitored continuously since 1994. The laying dates in this colony also track the ENSO pattern however unlike the Noddies, Bridled Terns breed earlier and do better during lengthy periods of *La Nina* conditions when the Leeuwin Current flow is relatively strong. This suggests that a strong Leeuwin Current forces more upwelling at the shelf edge, perhaps by driving the deeper and colder Leeuwin Counter Current.

LAYING PHENOLOGY IN THE COMMON NODDY AND THE EL NINO

The relationship between the 3yr Rolling Mean of the Southern Oscillation Index (SOI) and laying dates in Common Noddies on Lancelin Island between 1994 and 2016.



The core colony of Common Noddies on Pelsaert Island in the Houtman Abrolhos also tracked the ENSO through the 1990s. This relationship however disintegrated in around the mid-2000s. This change coincided with a major change in of Rock Lobster puerulus settlement in the region.

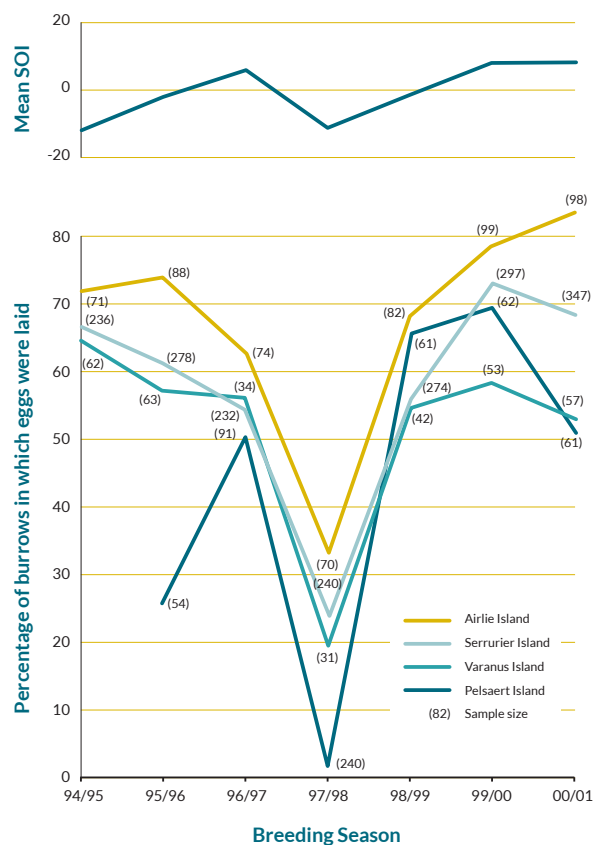
PARTICIPATION RATES

Individual seabirds vary in their foraging efficiency depending on genetic quality (or fitness) and upon age / experience. This variation in foraging efficiency may be reflected in the number of pairs within a colony or population breeding in a given season. The inter-seasonal fluctuations in breeding numbers are referred to as the participation rate.

Typically the higher quality, or older and more experienced birds, breed most frequently and can participate when foraging conditions are relatively poor. Younger or lower quality birds that are less skilled at foraging may not make a breeding attempt when prey availability is more limited, probably because the females have been incapable of building sufficient body condition. Participation rates are measured by counting the number of pairs within a colony or population that commence a breeding attempt by producing a clutch. In years of low prey availability this number is lower than the number of pairs that occupy nest territories or burrows at the start of the season (at least in high site-fidelity species).

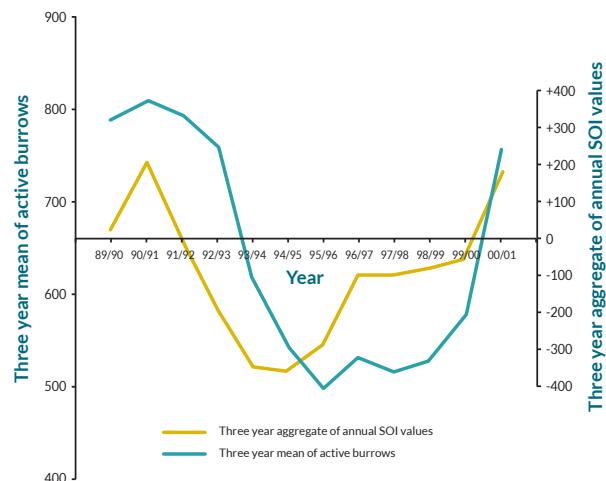
Shearwaters return to their previous nesting sites for a lengthy pre-laying period in which the burrows are dug or renovated and pair bonds established or renewed. The egg is large in comparison to female body weight, yolky and costly to produce. Females depart on a pre-laying exodus of 2-3 weeks to fatten at sea in order to produce the single egg. In shearwaters the laying period is short, usually occupying less than a fortnight. Participation rates, the number of burrows in which an egg is ultimately laid can vary widely from effectively zero to 80 %. In shearwaters the number of burrows excavated or refurbished each season is a useful index of the size of the breeding population whilst the 'participation rate' is related to the foraging conditions operating during the pre-laying exodus. Trends in excavated burrows and 'participation rates' were measured in colonies of the Wedge-tailed Shearwater between 1994 and 2000 showing the influence of the El Nino Southern Oscillation on breeding performance and colony size.

Laying phenology in the Wedge-tailed Shearwater and *El Nino*



The percentage of active burrows in which eggs were laid at four Western Australian Wedge-tailed Shearwater breeding colonies over seven seasons between 1994/95 and 2000/01. The number of burrows examined at each colony each season is shown in parentheses. Also plotted is the mean annual Southern Oscillation Index (SOI) for each year of the study.

The impact of *El Nino* on burrow numbers in Wedge-tailed Shearwaters



The time series of aggregate burrow counts for Airlie, Serrurier and Varanus Islands from 1988/89 to 2000/01. Numbers are expressed as percentages of the running mean. Also shown is the time series for the mean annual SOI.

REPRODUCTIVE PERFORMANCE

Tracking the fate of offspring through to fledging is very labour intensive and is generally the preserve of relatively short-term research projects. In many seabird species (eg. most surface nesters) the later stages of development and fledging often take place away from the original nest site making determination of the outcome uncertain. Tracking the progress of nesting attempts in the burrows of penguins, shearwaters and storm-petrels can be challenging even with specialised optical equipment (eg. burrowscopes) and usually requires the modification of natural cavities or the use of artificial chambers to facilitate observation. Generally the breeding success of seabirds is difficult to measure accurately and consistently enough to support the long term time-series needed for monitoring programs.

Collapses in prey availability may prevent laying altogether or lead to breeding failure later in the nesting cycle (eg. through mass starvation of nestlings or fledglings) depending on when they occur. The detection of mass failures in reproduction may indicate extreme ocean climate events associated with climate change.

INTRODUCTION

The harvesting of fishery resources produce 'top-down' effects on marine ecosystems by reducing the size of target consumer populations. If managed effectively this is sustainable as the reduced competition may increase the abundance of smaller, younger fish in the population and the rate of recruitment. However, if overfishing occurs, the spawner-biomass in the target species may be depleted to the point where there is insufficient egg production and recruitment, causing widespread decline in the stock. Seabird populations have been affected by the overfishing of forage fish stocks particularly in upwelling regions (eg. Sardines off South Africa, Anchoveta off Peru and Chile) and in other productive coastal waters (eg. Sandeels off the United Kingdom). Shifts in ocean climate also contributed in these cases. The industrial harvesting of krill in the Southern Ocean has been identified as a threat to seabirds and other marine predators. Nutrient rich, productive marine ecosystems typically have short, simple food-chains where the harvesting of the biomass at one trophic level can potentially have consequences for the others. By contrast the food chains in tropical, low productivity marine ecosystems (which are relatively species rich) intersect in complex webs, providing a range of alternative pathways for energy flow. This may isolate predators, including seabirds, from the overfishing of stocks in these systems.

At a more local scale fishing may cause temporary depletion, or disturbance, of prey species aggregations within range of seabird colonies. This type of interaction is more likely in Australian waters than overfishing at the stock level.

Changes in the abundance of some fish stocks from either 'bottom-up' or 'top-down' processes sometimes force a long-term regional shifts in the dominant fish species and the structure of biotic communities. Such wholesale changes in ecosystem function are referred to as 'regime shifts'.

The objectives of modern 'ecosystem-based fisheries management' (EBFM) include the sustainable utilization of fish stocks, the protection of non-target species and the maintenance of ecosystem function, including for example ensuring prey availability to marine predators. EBFM therefore may require the measurement of fishery-independent indicators that are based on sampling ecosystem components other than those captured in fishing operations. Appropriately designed, seabird-based indicators are a potential source of relatively cost-efficient fishery independent indicators.



The majority of prey-related interactions between fisheries and seabird populations involve forage fishes like Sardines.



Purse-seine operation off the south coast of Western Australia.

SEABIRDS AS INDICATORS OF STOCKS AND REGIME SHIFTS

Trophic (food-related) interactions between seabirds and fisheries are most likely to occur where the same target species (or a significant bycatch species) is being taken. Direct competition is possible when the same size / age classes are involved. At the stock level in the Australian context consequential interactions between stock depletion by fisheries and seabirds have not been demonstrated. However the mass Sardine (pilchard) mortality events across southern Australia in 1995 and 1998, caused by the introduction of a Herpes virus, did provide a natural experiment into seabird responses to both stock depletion and the subsequent ecological regime shifts.

Crested Terns typically utilise the most abundant forage fish stocks in the regions they occupy around the Australian coastlines. Sardines are usually a dominant prey species across southern Australia, particularly for provisioning the chicks. In South Australia in the years following the mass mortalities the growth and survival of Crested Tern chicks was much reduced and the cohorts from those years were under-represented in the population thereafter. This demonstrated that Crested Terns diet, chick growth and survival could all be used to monitor the stocks and functional importance of Sardines in this region.



Crested Terns carrying Sardines to feed their chicks at the creche.

The Sardine fishery is currently Australia's largest in terms of the harvested biomass primarily supplying feed for the tuna-ranching industry at Port Lincoln.

Little Penguins in Victoria suffered similar short term declines in reproductive performance and survival as the Crested Terns in South Australian waters. Other fish species substantially replaced Sardines as the major prey in Little Penguins after the mass mortality events. Little Penguins in Victoria now forage primarily on Barracouta, Anchovy, Red Cod, and Blue Warehou. Similarly Sardines comprised 60% of the diet of the Australasian Gannet in Victorian waters prior to the 1995 mass mortality but were replaced by Barracouta afterwards. These changes in diet indicated a regime shift in the pelagic ecosystem on the continental shelf in that area which may have had consequences for less flexible marine predators in the region.



The prey resources available for Little Penguins have changed significantly since the mass Sardine mortality events of the 1990s.

In south-western Australia there was little information on seabird diets in the years leading up to the pilchard mass mortalities. However half of the Crested Tern population in Perth metropolitan region (the sub-population breeding between April and June) disappeared after the collapse in the Sardine stock. The Crested Tern population is still rebuilding after those events and Sardines are again a conspicuous part of their diet.

SEABIRD INDICATORS OF RECRUITMENT STRENGTH

When seabirds are foraging on the size/age classes of target species prior to recruitment into the harvested population (the fishery) prey data can be used to measure recruitment strength. Bottom-up factors often produce significant variations in the survival of young fish and being able to predict recruitment rates assists in setting responsive allowable catches and avoiding the overfishing of the stock.

Foraging data has been road-tested as a technically robust means of predicting recruitment (as catches) in the Pacific Sardine and Northern Anchovy in the Gulf of California using the dietary intake of Brown Pelicans, Heerman's Gulls and Elegant Terns. Arctic Terns diets have similarly been correlated with subsequent catches of Herring and Great Cormorants with Norwegian Saithe. However, at this stage there is little evidence that these methods have been put into operation in any jurisdiction.

SEABIRDS AS INDICATORS OF LOCAL PREY DEPLETION / DISAGGREGATION

Intensive, localised fishing, may be sustainable on a regional scale and in the context of stock management. However, central placed foragers like breeding seabirds or other sedentary marine predators may be disrupted by the local, temporary depletion or dispersal of prey aggregations by fishing operations. Ecosystem-based Fisheries Management must have objectives to protect marine wildlife and local marine habitats from the consequences of local depletion regardless of the implications for fish stocks.

Seabird indicators of local prey depletion, or disaggregation, include changes in the length of foraging trips, the provisioning rates and growth rates for chicks, the prey species, foraging areas and ultimately in breeding performance.



Fleshy-footed Shearwaters forage closer to their colonies when provisioning older chicks, increasing interactions with the local purse-seine fishery.

SEABIRDS AS INDICATORS OF ECOSYSTEM SUBSIDIES

Some fishing methods can increase the food availability to some consumer organisms by providing foraging opportunities around catching operations. Trawling operations are the ones typically implicated in changes in seabird behaviour and increased colony sizes as the result of discarding fish bycatch. Crested Tern populations have increased around the Gulf of Carpenteria as the result of discarding by the northern prawn fishery. Trawlers may also make prey available by disturbing the seabed or corralling animals in their catching area. Bottom trawlers can have an impact on marine ecosystems by transferring benthic biomass (energy) to the pelagic system. This trophic subsidy could produce consequential changes in the structure of biotic communities.

Purse-seining operations simulate the bait ball interactions associated with multi-species prey aggregations and may be accompanied by the suite of species that participate in them. For example purse-seine shots around schools of Sardine on the south coast of WA corral fish, as hunting tuna would, and then attract Bottle-nosed and Common Dolphins, Dusky Whaler Sharks, Samson Fish, Fleshy-footed Shearwaters, Gannets, Crested Terns and Pacific and Silver Gulls. These fishing / predator aggregations can lead to some predators (particularly shearwaters and dolphins) becoming entangled and drowning in the nets, increasing the mortality rate in these populations. However the increased access to prey resources for predators could also subsidize local

populations increasing breeding performance and survival (particularly in immature animals).

Marine aquaculture activities such as fish-farming are another potential source of supplementation to marine ecosystems.

Seabird species that are more adept at scavenging are more likely to respond to fishery or aquaculture-based subsidies. Material levels of supplementation in marine ecosystems would first be detected in changes in seabird diet (eg. from pelagic to benthic prey species) and shifts in foraging behaviour. Ultimately changes may be detected in changes in breeding performance and population size.



The seabirds associated with mixed species 'bait ball' aggregations often attend purse-seine shots.

INTRODUCTION

Many pollutants are ingested and assimilated by marine organisms and if not efficiently excreted become more concentrated with each step in food-chains; from producers, to grazers or detritivores, to small predators, meso-predators and top-predators. As either meso or top predators seabirds may concentrate a wide variety of contaminants in their tissues allowing these substances to be detected and tracked in marine/estuarine ecosystems. The bio-accumulation or bio-magnification of these substances can produce concentrations in seabird tissues that have could also have a deleterious impact on the health of individuals, reducing reproductive success or survival.

Seabirds can provide indicators for monitoring a variety of contaminants. These include metals (particularly the 'non-essential' heavy metals mercury, lead and cadmium) and the Persistent Organic Pollutants (POPs). The POPs include the legacy organochlorine pesticides (e.g. DDT, DDE, Dieldrin, Chlordane, Heptachlor etc), PCBs, and phthalates from fabricated plastics and flame retardants. Seabirds have also been used to assess the extent of contamination of marine ecosystems by marine debris, nutrient inputs and even radionuclides from the Fukushima reactor meltdown.

METALS

The Sequestration of Metals in Bird Feathers

Seabirds sequester high proportions of their heavy metal burdens in their feathers during the moult, with some non-essentially, toxic metals including lead and mercury having a high affinity for the sulf-hydral bonds in keratin (the protein from which feathers and skin is constructed). Feathers provide efficient, repeatable and non-destructive tissues for heavy metal analysis. Since the moult is seasonal and progressive in most birds metal concentrations in the plumage can be correlated with the time, foraging location and /or prey being consumed during the period of feather growth. Completed feathers are isolated from the bloodstream and chemically inert preventing subsequent metals mobilization. Dry feathers can be stored indefinitely and can be 'banked' to support long-term baselines or benchmarks of contamination.

The concentration of non-essential metals in bird plumage is correlated with the internal burden during a particular time window. These metals may be mobilized into the blood stream from other tissues during the moult period and allocated progressively to the growing feathers. This is particularly the case with mercury (as methyl-mercury) in seabirds where the moult is the principal mechanism for detoxification.

Unlike mercury, selenium is an essential trace element in vertebrate animals and the concentrations in body tissues are actively regulated. It is an abundant constituent in seawater and marine organisms (particularly pelagic species) but naturally scarce in fresh and brackish ecosystems. Selenium (as organo-selenium compounds) can be substituted for mercury in vertebrate animals reducing the rate of bio-transfer or assimilation of the latter. There is evidence that the uptake of selenium is regulated in some seabirds to reduce exposure to methyl-mercury toxicity and there is often (but not always) a correlation between the two elements in bird feathers. The monitoring of mercury exposure in marine /estuarine ecosystems should be done in the context of selenium availability.

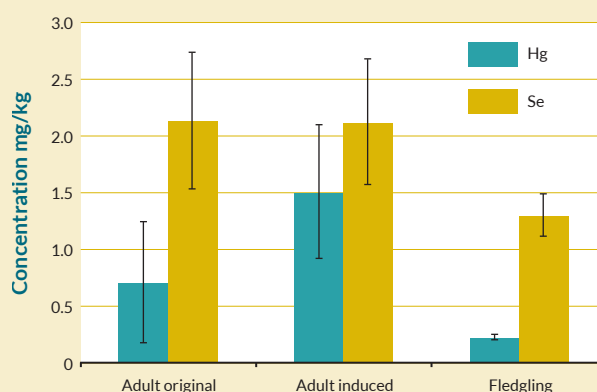


SEQUESTRATION OF MERCURY AND SELENIUM IN THE TAIL (R5- RECTRIX 5) FEATHERS DRAWN FROM BRIDLED TERNS

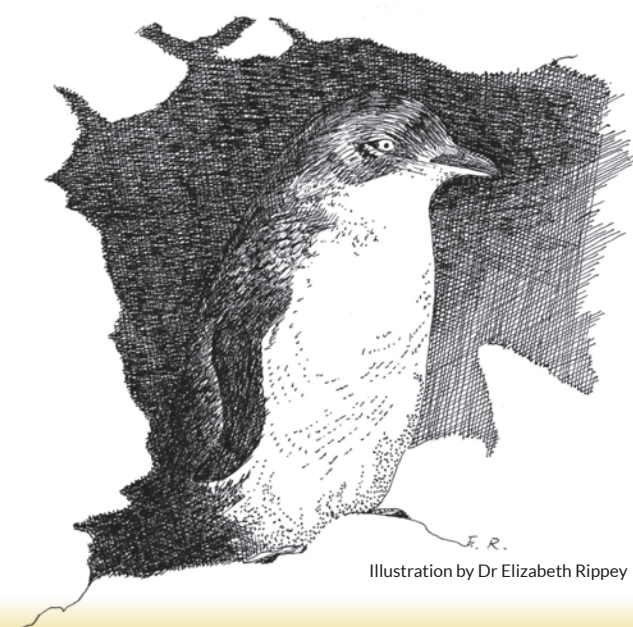
Tail feathers (rectrix 5) were drawn from adult Bridled Terns at the start of the breeding season. These 'original' feathers would have been replaced during the basic moult whilst the terns were 'wintering' in the north-west Sulawesi Sea (4-9° north of the equator). The mercury and selenium concentrations in these feathers reflect the annual mercury burden being sequestered in the plumage. These feathers were replaced by the same individuals during the breeding season providing 'induced' feathers (n=10). These were grown whilst the terns were foraging in the continental shelf waters off Perth, Western Australia. The feathers drawn from fledglings were produced during the development of the first flight feathers.

The mean mercury concentrations of the 'induced' feathers were 1.504 mg/kg (SD $\pm$ 0.59) significantly higher ($t = 3.15$, $p < 0.02$) than the 'originals' (0.712 mg/kg, SD $\pm$ 0.53) despite the relatively short period of exposure. This does not indicate higher mercury contamination of the waters in the breeding area but rather the sequestration of the accumulated

mercury burden into a single feather, rather than to all the actively growing plumage during the normal basic moult. The selenium levels do not vary between periods or foraging locations indicating that the intake or mobilization of this element is being regulated. The lower mercury and selenium in the fledglings reflects the short exposure period.



Unlike other birds penguins moult all their feathers simultaneously. In Little Penguins the moult takes place over a period of about 3 weeks during which they cannot return to the sea to forage. The birds spend some time fattening before the moult and become anorexic towards the end as they use up their stored reserves and some muscle tissue. The metal concentrations in penguin feathers therefore indicate the annual sequestered body burden where the moult is the main mechanism for excretion (eg. for mercury and lead).

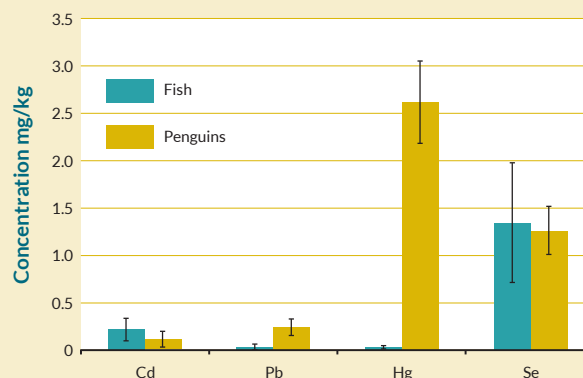


BIO-TRANSFER, BIO-ACCUMULATION & BIO-MAGNIFICATION OF NON-ESSENTIAL (HEAVY) METALS AND SELENIUM IN LITTLE PENGUIN FEATHERS

Unlike other birds penguins moult all their feathers simultaneously. In Little Penguins the moult takes place over a period of about 3 weeks when during which they cannot return to the sea to forage. The birds spend some time fattening before the moult and become anorexic towards the end as they use up their stored reserves and some muscle tissue. The metal concentrations in penguin feathers therefore indicate the annual sequestered body burden where the moult is the main mechanism for excretion (eg. for mercury and lead).

Captive penguins housed at the 'Penguin Experience' facility on Penguin Island were fed a consistent diet of small commercially supplied forage fish for several years. Monthly samples of these fish were analysed for cadmium (Cd), lead (Pb), mercury (Hg) and selenium (Se) concentrations through 2011. Moult feathers from captive individuals were collected in December 2011 (N=9) and December 2012 (N=7) to estimate the transference ratios of these metals from fish tissues to penguin moult feathers.

The mean cadmium, lead, mercury and selenium concentrations in the fish consumed by the captive Little Penguins can be compared to the mean concentrations in the moult feathers. The cadmium and selenium levels were not significantly different between fish and feathers indicating some **bio-transference** but not accumulation of these elements. Lead concentrations were significantly higher in the penguin feathers compared with the fish in the diet ($t=2.893$, $p<0.01$) indicating a level of **bio-accumulation** (a multiplier of 7.6). Mercury levels were 78 times the concentration in bird feathers compared with the fish that were consumed over

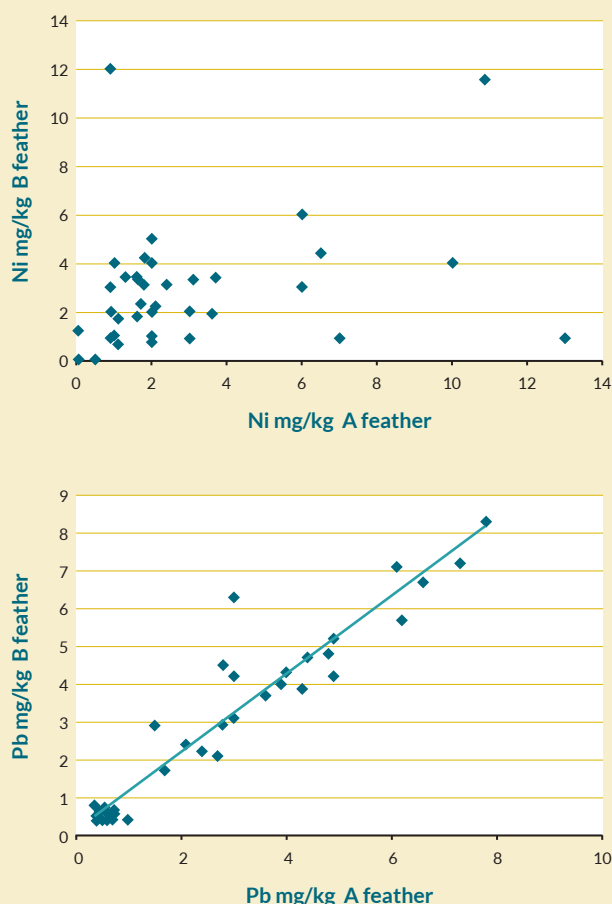


the year, demonstrating the propensity for mercury **biomagnification** in the food chain. These ratios may be more accentuated in penguins than in birds the moult progressively but the pattern of sequestration is similar in all seabirds.

The mean cadmium (Cd), lead (Pb), mercury (Hg) and selenium (Se) concentrations (mg/kg) in the fish consumed by the captive Little Penguins compared to the mean concentrations in the annual moult feathers.

Metallic particles can also bind quite strongly with the external structure of feathers and be difficult to remove when preparing feathers for analysis. Discriminating between endogenous, sequestered metals and ecotopic contamination is important if inferences are to be made about sources of contamination (eg. dietary verses dust from the air or terrestrial surfaces). One way of testing this is to sample a matching feather from each wing or both sides of the tail. The basic moult is more or less symmetrical with the equivalent feather on each side being replaced concurrently.

ENDOGENOUS (DIETARY) OR ECTOPIC (AMBIENT ENVIRONMENT) SOURCES OF METALS IN/ON BIRD FEATHERS



The bulk handling of metal concentrates at the Esperance Port between 2007 and 2010 produced dust fallout at locations downwind of ship-loading operations. Nickel concentrates were handled throughout that 4 year period. The shipping of lead carbonate concentrates started in 2006 and ceased in March 2007 after several incidents where the dust contaminated parts of the town. Feather sampling of bush birds was conducted over four years from October 2007 to October 2010.

The sixth primary feather (P6) was sampled on both the left (A) and right (B) wings of the individual birds sampled in 2009 and 2010. The nickel (Ni) concentrations in the A and B feathers showed no relationship ($R^2=0.1435$, $n=47$) indicating that exposure was from random contact with dust particles coating parts of the ambient environment. By contrast the lead concentrations in the same A and B feathers were strongly correlated ($R^2=0.9577$, $P<0.01$, $n=47$) indicating that the lead had bio-transferred from dietary sources and was being sequestered in the feathers.

SAMPLING AND ANALYSIS OF FEATHERS FOR METALS ANALYSIS

Moulted feathers can be collected from seabird colonies or roosts or recovered from dead individuals. Depending on the precision required this may be sufficient. However once in the environment feathers are subject to increased external contamination and more rapid degradation and there may be some uncertainty about the seabird species or the stage in the moult schedule. If the data needs to be standardized for the growth period or the stage in the moult sequence then feathers will need to be drawn from the relevant tracts.

There are a number of considerations in choosing the feather (or feathers) to be sampled. These include;

- providing sufficient sample weight for analysis LOR (laboratory 'Limits of Reporting'),
- potential for re-sampling the feather tract on the same individual,
- the approximate time window during which the feather was replaced,
- the moulting habitat during feather replacement (eg. local or migratory location), and
- the relative exposure to ambient / ectopic sources of the monitored metals.

Completed feathers are isolated from the blood stream and can be drawn from the follicle, usually with no discernible reaction from the bird. Growing feathers should not be extracted as that will cause the feather tract to bleed. The loss of feathers through extraction mirror as far as possible the pattern of missing and growing feathers resulting from the natural moult sequence. For example if more than one tail feather is needed then the equivalent feather on each side should be drawn to retain symmetry. Having the equivalent feather from each side also allows confirmation, from the relative concentrations, that the metals are being sequestered.

Mesoptile (middle) down can be easily lifted or brushed from developing chicks at the points where the final feathers are erupting into the plumage. Dry feathers can be stored indefinitely in air-tight containers without the need for preservatives or refrigeration.

Before processing feathers should be closely inspected, physically cleaned of any extraneous matter and, if there was any surface staining, washed in de-ionized water and air-dried. The use of solvents, such as acetone to clean feathers may not remove all the ectopic metals bound to feathers. Other methods (see above) are suggested to assess the extent to which the measured concentrations represent sequestered verses ambient sources of contamination.

The analysis of feather metal concentrations should be carried out by a NATA accredited laboratory, like Chemistry Centre of Western Australia. Feathers are typically analysed by mixed acid microwave digestion followed by inductively coupled plasma mass spectrometry (ICPMS). Results are reported as mg/kg dry weight.

SEABIRDS AND METALS CONTAMINATION

Metals pollution is a significant issue, particularly in inshore waters and estuaries adjacent to urban and industrial areas and ports. Common coastal contaminants in Western Australia include copper, zinc, aluminium, arsenic, iron, manganese, nickel,

selenium, cadmium, lead and mercury. Some of these are important trace elements for vertebrates and the intake and mobilization of these metals is regulated. For example both copper and zinc are important in the co-enzymes that synthesise keratin (the feather protein) and are only toxic in extremely high doses. Selenium, by contrast, is an important anti-oxidant and is used to reduce mercury assimilation but rapidly becomes toxic above an optimal intake level. Elevated levels of arsenic and aluminium have toxic impacts on animals lower in the food chain reducing the potential for bio-accumulation into predators like seabirds.

Seabirds are most useful for monitoring the non-essential ('heavy') metals that have no biological function and therefore are not readily regulated and build up in animal tissues. These elements, cadmium, lead and mercury are transferred from prey to predator to top-predator and bio-accumulate or bio-magnify in food chains.

Arguably of greatest concern has been the build-up of mercury in marine ecosystems. Mercury is a volatile metal generated primarily by natural weathering and from the burning of fossil fuels (particularly coal). It enters aquatic ecosystems via precipitation from the atmosphere and through the hydrological system. Metallic mercury enters food-chains when converted by anaerobic bacteria to organic forms (eg. methyl-mercury). This process happens in the deeper layers of the ocean and mercury is naturally more concentrated in the meso-pelagic biota of oceanic ecosystems than in epi-pelagic or coastal organisms. Health warnings emphasize avoiding eating the flesh of top predators from oceanic ecosystems, such as large tuna, billfish and sharks. The inputs of mercury to the global atmosphere and oceans are continuing to rise and eventually lower levels in marine food-chains may also become unsafe for consumption. The sampling of 'banked' seabird feathers was utilized very effectively to demonstrate the build-up of mercury in European waters over the century following the start of the industrial revolution.

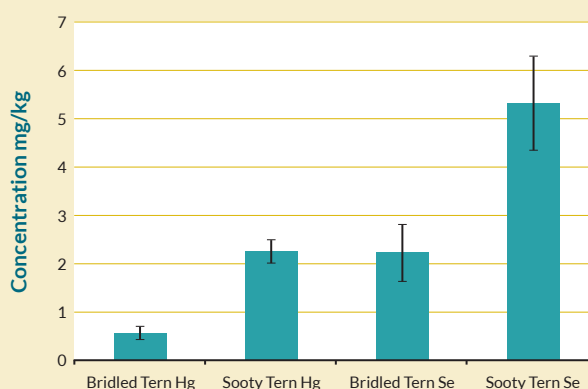
MERCURY EXPOSURE IN TWO ONYCHOPRION SPECIES

Nearly all the mercury in seabird tissues is in the potentially toxic organic forms, principally as methyl mercury. Exposure can be influenced by a number of factors including trophic level (place in the foodchain), the foraging habitat and the availability of selenium in the diet. A critical habitat factor is the extent to which the ambient elemental mercury is being converted to methyl-mercury at the base of the foodchain. Oceanic seabirds typically have a higher mercury exposure than littoral species as their prey (eg. meso-pelagic fish and squid) forage on organisms that have assimilated methyl-mercury from the deeper anoxic layers in the water column. Fortunately, protective selenium also appears to be more abundant in the diet of oceanic species.

The Sooty Tern *Onychoprion fuscatus* and Bridled Tern *O. anaethetus* are sibling species which forage by 'contact dipping' to capture fish, squid and small crustaceans at the water surface. The two species nest together on islands off mid-western Australia, particularly at the Abrolhos Islands. The Sooty Tern is a long-range, oceanic forager that relies on feeding tuna to make its prey available. The Bridled Tern is an offshore, continental shelf forager that searches

down-welling zones where the currents aggregate flotsam and prey near the surface.

Outer tail feathers (rectrix 5) from 12 Sooty Terns and 12 Bridled Terns from the region were sampled and analysed to determine mercury and selenium concentrations. The oceanic Sooty Terns had significantly higher feather mercury (Hg) levels in their outer tail feathers compared with the sympatric, shelf foraging Bridled Terns ($t=2.48$, $P<0.02$). Selenium concentrations are also significantly higher in the Sooty Tern tail feathers.



Methyl-mercury may also be produced in the coastal zone and estuaries where anoxic conditions are created by the decomposition of excessive deposits or organic matter. Such conditions develop in eutrophic (overfed) waterways subject to excessive nutrient inputs from agriculture, industry and urban development. The monitoring of mercury in coastal seabirds provides information on local rather than the ocean basin scale sources of contamination.

HEAVY METALS EXPOSURE IN THE COASTAL WATERS OF SOUTH-WESTERN AUSTRALIA

Little Penguins forage in near-shore coastal waters close to their breeding colonies on continental islands. When breeding, foraging ranges are normally within about 20km. In Western Australia their prey consists primarily of schooling forage fishes such as Sardines *Sardinops sagax*, Sandy Sprat *Hyperlophus vittatus*, Blue Spat *Spratelloides robustus* and Sea Garfish *Hyporhamphus melanochir*.

After breeding the adults forage at sea to build-up their fat reserves. Then they return to their breeding colonies in mid-late summer to spend a period of about three weeks ashore to moult all their feathers. Deposits of freshly shed feathers can be located in the nesting burrows or other sheltered hollows and can be readily collected without the need to capture and handle the birds. The concentrations of 'non-essential' metals in the new plumage represents the annual body burden, mobilized from the organs (eg. liver) fat deposits and blood stream and sequestered in the growing feathers during the moult.

PROFILING HEAVY METALS EXPOSURE IN THE COASTAL WATERS OF SOUTH-WESTERN AUSTRALIA

Penguin moult feathers were collected from four colonies in distributed around south-western Australia between 2009 and 2012 to profile heavy metals (and selenium) exposure at different locations. Woody Island in the Recherche Archipelago was relatively isolated from land-based sources of heavy metals. Mistaken Island in King George Sound was adjacent to the city of Albany and connected to Princess Royal Harbour (which has an industrial history of mercury exposure) and Oyster Harbour (which is a eutrophic estuary within an agricultural catchment). The penguins from the Penguin Island colony forage in the southern metropolitan waters off Perth and the birds from Garden Island forage in Cockburn Sound (a sheltered embayment impacted by urban development, Fremantle Port and heavy industry).

Location of Little Penguin colonies where adult moult feathers were analysed for cadmium, lead, mercury and selenium.



The results, at one level, reflect the degree to which the heavy metals are sequestered in feathers. Cadmium is bio-transferred from prey to predators in foodchains but concentrates in other tissues such as the kidney. Feathers are not the best tissues to track cadmium exposure in ecosystems. Lead is most concentrated in bone tissue but is also sequestered in the feathers (and may also bind to the outside

of feathers from the atmosphere or contact with contaminated soil). The moult is the most important pathway for methyl-mercury elimination in seabirds. Selenium concentrations are regulated but might exceed the normal range if excessive amounts are present in the environment. Selenium tends to accumulate in aquatic invertebrates (foraging lower the foodchain) before being transferred to predators, including seabirds.

Feather cadmium (Cd) concentrations were low and highly variable with no significant differences between locations. There were a few slightly elevated lead (Pb) samples (that may reflect external contamination from the soil on the islands) but levels were generally low and again there was no significant variations between breeding colonies.

Mercury (Hg) concentration in adult penguin feathers on Woody Island in the Recherche Archipelago were 0.609 mg/kg (SD $\pm$ 0.17). This probably represents the background level of mercury contamination in the coastal waters around south-western Australia. The penguins in the other three colonies all showed elevated mercury concentrations with the metropolitan colonies having significantly higher levels than Woody Island. The Garden Island birds foraging in Cockburn Sound had the highest concentrations, these were significantly higher than Woody and Mistaken Islands but not nearby Penguin Island. The level of mercury contamination is almost certainly related to the proximity of urban and industrial coastal development. The particularly elevated levels in Cockburn Sound may be related to mercury methylation occurring in anoxic sediments in areas of degraded and decaying seagrass meadow rather than any specific, undocumented point source.

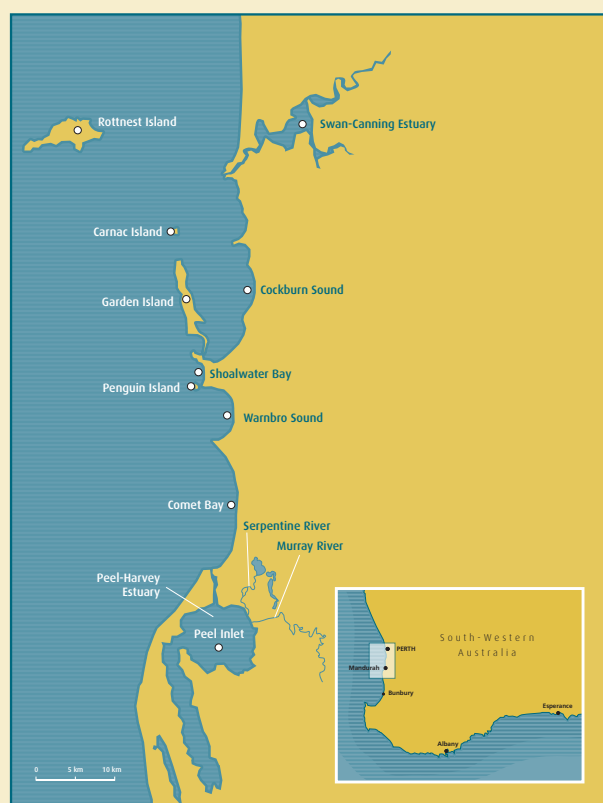
The selenium concentrations were similar at Woody, Penguin and Garden Island between 2.73 and 3.41 mg/kg, but were significantly higher at Mistaken Island in King George Sound at 5.9 mg/kg (SD $\pm$ 1.41). Mercury and selenium concentrations had a significant positive correlation at Woody ($R^2=0.736$, $P<0.02$) and Penguin Island ($R^2=-0.7808$, $p<0.01$) but there was no relationship between the two elements at Mistaken and Garden Islands.

These apparently conflicting results seem to indicate that mercury can be substituted with selenium where this is abundant in the diet. Conversely mercury may dominate in the feathers when it is present at concentrations that exceed the threshold selenium availability. Selenium appears to be more abundant in the diet at Mistaken Island. Whilst the principal prey for Little Penguins on the south coast are sardines, and these are a rich source of selenium, these fish will also dominate the diet of Woody Island birds.

Prey type alone doesn't explain the elevated levels in King George Sound. Selenium may be a contaminant entering King George Sound via Oyster Harbour as it is an additive to fertilizers, soil treatments and stock feeds in its catchment and may be leaching into the rivers and estuary. Alternatively the high selenium concentrations in Mistaken Island penguins may be masking ongoing mercury contamination from Princess Royal Harbour.

Both mercury and selenium concentrations are naturally higher in the deep ocean than in coastal waters. This is the result of mercury methylation in the mesopelagic (deep water) foodchains and increasing mercury emissions to the atmosphere on a global scale. Elevated mercury in seabirds foraging in coastal waters and estuaries is likely to be an indicator of point source geological sources of mercury or of local background pollution from coastal cities or industries.

Selenium is abundant in pelagic, oceanic organisms but becomes less abundant in near coastal waters and becomes scarce, or even limiting, in unpolluted brackish or fresh-waters. Elevated selenium concentrations in inshore waters (from activities such as mining, solar salt bitterns and irrigated agriculture) can bio-accumulate in aquatic invertebrates and reach toxic levels in vertebrates, including birds. A lack of selenium in prey organisms could make coastal seabirds and shorebirds more vulnerable to elevated mercury concentrations.



CASPIAN TERNS AS SENTINELS OF AN ESTUARINE ECOSYSTEM

Caspian Terns inhabit coastal and inland waters in sub-tropical and temperate regions around the world. These terns are piscivorous mesopredators foraging by plunge-diving into shallow water. A breeding colony on Penguin Island in the southern metropolitan coastal waters of Perth, Western Australian, dispersed primarily onto the nearby Peel-Harvey estuary. These terns preyed on benthic fishes associated with marine seagrass meadows and estuarine shallows. The diet was dominated by detritivores, in particular sea mullet *Mugil cephalus* and Perth herring *Nematalosa vlaminghi*. Stable isotope values from adult feathers also indicated the importance of perennial or annual seagrass habitats for foraging.

PENGUIN ISLAND CASPIAN TERN IN THE PEEL HARVEY ESTUARY



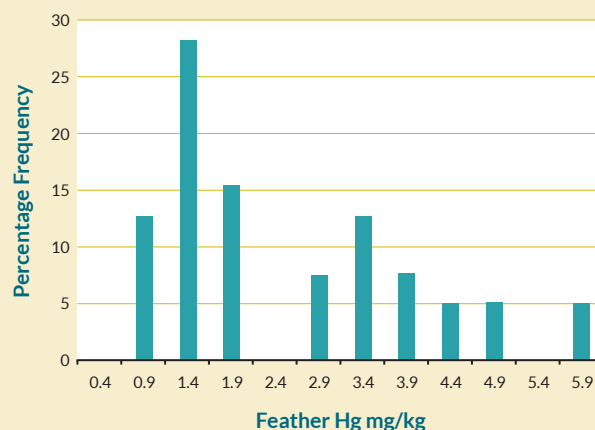
Caspian Terns are being used as a 'sentinal' species for the southern metropolitan coastal waters.

Cadmium and lead concentrations in feathers were low. However most breeding adults had elevated levels of mercury in their tail feathers. Mercury concentrations were strongly correlated with selenium in the adult feathers suggesting that selenium was being regulated possibly to assist with the sequestration of mercury. The mechanism for mercury elimination with selenium apparently differs from that used by Little Penguins. The negative (antagonistic) relationship in the penguin feathers suggests that the two elements are being substituted for each other at receptor sites. In Caspian Terns the positive correlation suggests that the selenium compounds are attached to the mercury ones, perhaps at the sulph-hydral bonds in the feather keratin.

The mean feather mercury concentration in adult Caspian Terns breeding on Penguin Island was 2.27. Bridled Terns foraging over the shelf waters off south-west WA had concentration of around 0.7mg/kg and even oceanic Sooty Terns averaged around 1.5mg/kg. All but two (n=39) adult Caspian Terns sampled on Penguin Island had feather mercury levels above 0.7 as an indicator of uncontaminated conditions. Two of the sampled Caspian Terns had feather mercury levels above the threshold considered capable of producing deleterious effects which is 5mg/kg and four individuals registered above 4mg/kg. One bird with a feather mercury of 5.8 mg/kg was observed dying on the Peel inlet about 3 months after sampling with symptoms consistent with nervous disintegration caused by mercury intoxication. These observations indicate that the Caspian Terns foraging in the southern metropolitan coastal waters of Perth may well be subject to an elevated level of mercury exposure.

The mercury concentrations in the adult Caspian Tern feathers were not normally distributed indicating the possible existence of more than one sample population in the data. These differences in exposure patterns are probably the result of differences in foraging behaviour and locations between adult individuals. Indeed Caspian Terns have been reported to occupy temporary foraging territories and this might underpin individual variations in mercury contamination.

The distribution of Hg values in the adult Caspian Tern R5 feathers. Percentage Frequency (n=39)



Microbial methylation of mercury tends to occur in high carbon, anoxic environments in surface sediments or biofilms. Such conditions frequently develop in the upper reaches of the Peel-Harvey estuary due to the de-oxygenation of the surface sediments from the decomposition of excessive algal biomass and the oxidation of mono-sulphidic black ooze. The detritivorous fishes consumed by the Caspian Terns ingest contaminated surface sediment and are likely to assimilate methyl-mercury from affected areas into their tissues. It is therefore probable that the principal source of mercury contamination in Caspian Terns in the southern metropolitan coastal waters is the Peel-Harvey Estuary. The variations in exposure probably relate to the time different individuals spend foraging in the estuary.

It is likely the high selenium availability from marine prey provides some protection to Caspian Terns from mercury toxicity whilst in the estuaries and may also mask some of the environmental exposure. Individual terns with a high mercury burden may be more at risk when they shift from mostly marine foraging when breeding to estuarine environments with lower selenium availability.

PLASTICS AND PLASTIC RESIDUES

Introduction

Plastic objects are a major component of marine debris and have become a significant threat to aquatic life and marine ecosystems. Fugitive materials include fabricated plastic products and packaging, resin beads or nurdles (which are the polymer raw materials used for plastics fabrication) and micro-beads, which are microscopic particles used as industrial scourers and cosmetics. The main source of the plastics in marine debris is trash from human settlements on the coast or along river systems. The material is either, casually discarded into the environment, deliberately dumped or collected and distributed by wind or storm water. Plastics are also discarded or lost from vessels at sea or generated by commercial and recreational fishing activities. Most of the marine plastic in Australian waters originates locally from Australian urban populations.

People are now familiar with the problems associated with fish, sea-turtles, marine mammals and seabirds ingesting plastic materials confused with prey items, or becoming entangled in ghost fishing nets, ropes or self-tightening packaging straps. The ingestion of plastic objects or fragments can prevent vertebrate animals from swallowing or breathing, block the alimentary canal or interfere with digestion. Sharp plastic objects may perforate the gut causing death. Adult seabirds are generally capable of regurgitating indigestible material such as bone and scales and large plastic particles. The developing young however typically lack this reflex and are more vulnerable to the consequences of plastics ingestion.

The threat posed by plastic debris is highly visual and demonstrable. Less well understood however is the impact of the tiny plastic particles (< 5mm) that are now becoming abundant in all the world's oceans and waterways. These 'microplastics' are the result of either the long-term weathering of fabricated plastic materials (some of which have been in the marine environment for decades) or from more recent contamination with small diameter particles, such as nurdles and micro-beads.

Microplastics derived from fabricated materials contain chemical plasticisers, a family of compounds known as phthalates (i.e. dimethyl phthalate, dibutyl phthalate & bis { 2-ethylhexyl}-phthalate). Similar compounds are on Navy and Air Force bases as flame retardants. Laboratory studies have shown these compounds to be powerful hormone disruptors in animal models and have now been banned in most jurisdictions for use in food packaging. Once ingested

by animals these compounds could enter the blood-stream through the processes of digestion and then be assimilated into body tissues. It has recently been demonstrated that marine zooplankton will ingest micro-plastic particles raising the possibility that phthalates may be transferred up the food chain and bio-accumulate in top predators, including seabirds. The impact on the reproductive potential or survival of marine animals has yet to be investigated.

Tiny microplastic particles attract lipophilic (fat soluble) compounds in water and bind them to their surfaces. Many of the bio-accumulating, hormone disrupting and toxic substances manufactured by humans as pesticides or industrial chemicals, known collectively as Persistent Organic Pollutants POPs, are lipophilic. Microplastic particles concentrate these pollutants and if ingested facilitate transfer into the foodchains, increasing the rate of contaminant bio-accumulation.

Organic forms of heavy metals, such as methyl mercury, also bind to the surface of microplastic particles concentrating at levels far above the background seawater. The ingestion of microplastics by marine organisms could therefore be exacerbating the existing problems with mercury bio-magnification in oceanic and unhealthy estuarine ecosystems.

Monitoring Plastics Exposure in Seabirds

The rate of plastics ingestion in seabirds has been most frequently assessed by the necropsy of specimens found within colonies or washed up on shorelines. Sampling this way is limited by the availability of specimens and biased towards birds that have had their survival compromised either by the plastics burden or by some other factor (eg. storms or starvation from a lack of prey). Statistically robust samples from a specific population or a particular area are difficult to accumulate. Seabird 'wrecks', where there are large number of simultaneous wash-ups, have been used to provide larger samples. Large wrecks of Short-tailed Shearwaters and Prions are not uncommon around the southern Australian coastline.

In recent years the Flesh-footed Shearwater bycatch from the South Coast Purse-seine fishery has been utilized to assess exposure to the ingestion of plastic debris. Each year between about 50 and 150 adult Shearwaters were being drowned in fishing nets and landed to verify the accuracy of the bycatch reporting system. These otherwise healthy birds were dissected and plastic fragments were extracted from the crop and stomach. Each plastic particle was measured and the colour and type of plastic recorded. The results have yet to be reported.

Seabirds may regurgitate plastics fragments with their dietary intake when handled (e.g. gulls, terns, cormorants). Fragments may also be found within regurgitated pellets of indigestible prey remains such as bone, skin and scales found at nest sites or roosts. However many seabirds (eg. penguins, shearwaters, petrels, storm-petrels) rarely regurgitate when handled or at the nest site and sampling the contents of the stomach or crop requires water-offloading. This method involves pumping water or an emetic into the stomach and sampling the refluxed material. This is a rather invasive process that could compromise survival and would require strong justification from an ethical perspective.

Plastic fragments and particles may be imported into colony areas and end up littering the soil surface or nesting burrows. This material may have been in regurgitated material of the bodies of birds, particularly chicks, that have died and decomposed within the colony area. Such littering may be the earliest indication of heavy plastics contamination in foraging habitats. Monitoring programs can record the amount of material per unit area using plots or transects or measure accumulation rates by removing plastic material from sample areas. Microplastic sand-grain size (<3mm) particles might be monitored by extraction and quantification from soil samples taken from burrow entrances or nest sites.

PLASTICS INGESTION IN THE FLESH-FOOTED SHEARWATER

Shearwaters appear to be vulnerable to the ingestion of plastic debris. On Lord Howe Island off the coast of New South Wales plastics transported by the breeding birds were first observed littering the ground surface. Chicks were receiving 0.13-3.21 g of plastic with each feed brought in by their parents from foraging trips in the Tasman Sea. Most of this plastic would be retained in the gut during growth and development. Chicks with high levels of ingested plastic showed decreased body condition, presumably leading to lower fledging success, post-fledging survival or adult fitness. The waters between Australia and New Zealand are evidently highly contaminated with plastic debris.

Flesh-footed Shearwaters in the population breeding on islands off the south coast of Western Australia are also ingesting plastic fragments. However, at this stage, it appears the incidence is much lower than at Lord Howe Island. This indicates that contamination from plastic debris is currently not as serious in the waters south of Australia compared with the Tasman Sea.

Historically sampling seabirds for lipophilic pollutants required killing birds to sample their body fats or using dead specimens. These contaminants also report to the yolks of eggs.

Recently non-destructive biochemical methods have been developed to detect phthalate assimilation in seabirds from the ingestion of fragments of fabricated plastics. As phthalates are lipophilic (POPs) they will be found primarily in body fats and oils. These methods therefore utilise the oily or waxy secretions seabirds produce from the uropygial (green) gland located just above the tail. The preen oil is used to maintain and water-proof the feathers and is stimulated by the birds bill during bouts of preening.



Sampling terns for phthalate exposure on Rat Island in 2013

Plastics are now ubiquitous in our environment and considerable care needs to be taken during sampling to avoid false positives from contact with plastic aerosols or surfaces (eg. clothing). The uropygial gland is stimulated with clean fingers or with the copper spatula used to collect the sample (a smear of oil or small glob of wax is sufficient). The spatula with the oil sample is transferred directly to an autoclaved glass test tube. The top is sealed with an aluminium sheet before sealing with a screw top cap. Control tubes with copper spatulas are left open during sampling operations to detect possible contamination from plastic aerosols. The samples must be kept cold, preferably frozen, to prevent decomposition before the biochemical analysis.



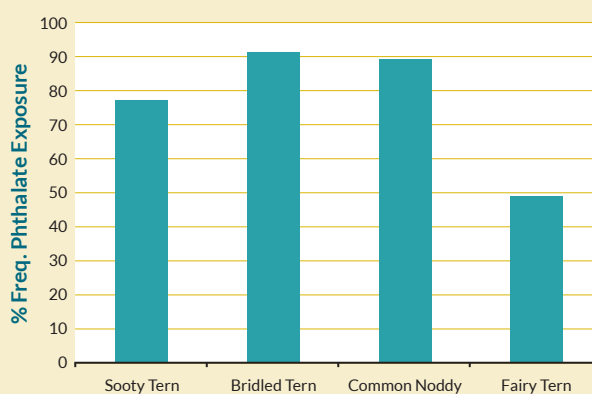
Expressing green oil from the uropygial gland of a Red-tailed Tropicbird

PHTHALATE EXPOSURE IN TERNS AT THE HOUTMAN ABROLHOS

Terns forage on motile marine organisms including fish, cephalopods and crustaceans and are unlikely to ingest floating plastics like species that sometimes scavenge food, such as shearwaters. So far WA researchers have not noticed plastic particles in meals regurgitated by our tern species. In December 2013 the CCWA Citizen Science Program assisted Dr Denise Hardesty (CSIRO Oceans & Atmosphere Program) in sampling four tern species for phthalates at the Abrolhos Islands. Surprisingly all the species indicated exposure to phthalates with the incidence varying from 49% in the coastal foraging Fairy Tern to 98% in the offshore, flotsam foraging Bridled Tern. The oceanic Common Noddy and Sooty Terns also had high rates of exposure.

These results tend to indicate that phthalate exposure in some seabirds is not the result of direct ingestion of plastic fragments. Phthalates may be

being transferred from microplastic particles in the guts of prey species or from contaminated prey tissues. The latter possibility could have serious implications for the human consumption of seafood and warrants further investigation.



PERSISTENT ORGANIC POLLUTANTS (POPS)

Aquatic predators including fish-eating raptors and seabirds accumulate persistent organic pollutants (POPs), such as polychlorinated biphenyls (PCBs), organochlorine pesticides (including dichlorodiphenyltrichloroethane (DDT) and its metabolites), organo-chlorines and hexachlorocyclohexanes (HCHs), in their tissues. Egg-shell thinning in Ospreys and Sea-eagles was one of the first consequences of DDT bio-magnification in aquatic ecosystems and shell thickness was subsequently used as a long-term indicator of organochlorines in the environment.

The toxic effects of POPs on vertebrates vary greatly between compounds and even between forms (isomers) of the same compounds. Sub-lethal effects are usually related to hormone disruption and particularly of the reproductive system. These may manifest as changes in embryo development, in abnormalities in the gonads or sexual organs (eg. the feminization of genetic males), changes in clutch size, reduced hatching or fledging success and in incompetent or aberrant behaviour. Biological indicators for POPs pollution could be developed based on these predicted responses to contamination if a potential risk is identified.

ROSEATE TERNS AND PCB CONTAMINATION

On Bird Island in Massachusetts USA Roseate Terns forage in waters contaminated with PCBs from a former industrial site. The problem was initially detected with observations of super-normal clutches consisting of 3 or 4 eggs rather than the usual 1 or 2. Genetic tests demonstrated that these clutches were produced by female - female pairs and the sex ratio in the colony had become significantly skewed towards females. The Roseate Tern eggs and tissues

were contaminated with PCBs however the exact mechanism by which high PCB concentrations produced the skewed sex ratios remains uncertain.

A survey of sex ratios in Roseate Terns breeding on islands in the unindustrialized waters off mid-western Australia (mainly Lancelin Island and Abrolhos Islands) in 1997 showed normal clutch-sizes and a 1:1 sex ratio.



Breeding Roseate Tern from Lancelin Island sexed using DNA methods in 1997.



Roseate Terns normally have clutches of one or two eggs.

POPs are lipophilic and are most concentrated in body fats and oils. This had made non-invasive sampling methods largely unavailable and monitoring body burdens has been dependent on collecting specimens, using dead birds (eg. washups) or egg yolks. Recently biochemical techniques have been developed to measure POPs at low sample weights from preen oils excreted from the uropygial. This non-invasive sampling technique was described in relation to phthalates (which are also POPs) in the previous section. Unfortunately the laboratory analyses for these contaminants are very expensive.

EUTROPHICATION

Nutrient pollution can change the character of coastal and estuarine ecosystems in ways that may benefit or threaten seabird populations. For example, the high nitrogen inputs into Cockburn Sound from contaminated groundwater have substantially changed an oligotrophic, seagrass based ecosystem into a more productive phytoplankton-based one. This has evidently favoured Little Penguins that forage on small pelagic forage fishes that are part of plankton-based foodchains.

Little Penguins established a new breeding colony at HMS Stirling on Garden Island in Cockburn Sound

within range of these new prey resources. Breeding pairs on Garden Island produce more broods and are more successful than penguins at the long established nearby colony on Penguin Island in Shoalwater Bay. The increases in the metropolitan population of the Pied Cormorant that occurred through the 1970s and 80s are also likely attributable to increased prey abundance in eutrophic coastal waters and the Peel Harvey Estuary.

Eutrophication typically increases the biomass in marine and estuarine ecosystems but reduces water clarity and biodiversity. In estuaries excessive nutrient inputs lead to a build up of organic matter, periods of high biological oxygen demand and the development of anoxic sediments.

The water quality of the Peel Harvey Estuary is highly compromised by high phosphorus inputs and the consequential algal blooms, high organic carbon, anoxic and reducing surface sediments and the consequential development of toxic, monosulphidic black ooze. These conditions are particularly evident near the river deltas in the upper reaches of the Peel Inlet. Frequent fish-kills occur in this region no doubt depleting the prey stocks for marine birds that rely on these resources such as Pied Cormorants, Australian Pelicans and terns.



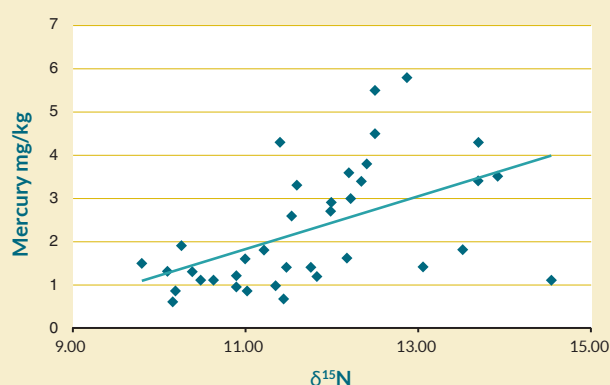
Caspian Tern on the Peel Harvey Estuary (NB. algal film the muddy surface).

EUTROPHICATION AND MERCURY EXPOSURE IN CASPIAN TERNS

Mercury (Hg) concentrations in Caspian Terns foraging in the Peel Harvey Estuary were elevated compared to predicted background levels and potentially hazardous in some individuals (see Heavy Metals section).

There was a highly significant positive correlation in $\delta^{15}\text{N}$ values against mercury (Hg) concentrations for the Caspian Tern R5 feathers ($R^2=0.51$, $p<0.005$, $n=37$; Fig. 3), i.e. mercury sequestration increased with increasing $\delta^{15}\text{N}$.

The mercury concentrations observed were strongly
Linear regression of $\delta^{15}\text{N}$ values against mercury concentrations for the Caspian Tern R5 feathers ($R^2 = 0.51$, $p<0.005$, $n = 37$).



correlated with the $\delta^{15}\text{N}$ values in the same feathers. This suggests that, rather than being determined by individual differences in trophic level in adult Caspian Terns, variations in the relative abundance of mineralised nitrogen in the food chain at different locations may be more important. The $\delta^{15}\text{N}$ values in the Caspian Tern feathers were probably indicative of the level of nitrate contamination in the foraging habitat. High mercury exposure would appear to be related to the increased eutrophication in these aquatic ecosystems.

The bio-transference and amplification of mercury into aquatic food-chains is facilitated by microbial conversion of elemental forms into organic forms, principally methyl-mercury. Almost all the mercury in birds and bird feathers is in organo-mercury compounds. Microbial methylation of mercury tends to occur in high carbon, anoxic environments in surface sediments or biofilms. Such conditions frequently develop in the upper reaches of the Peel-Harvey Estuary due to the de-oxygenation of the surface sediments from the decomposition of excessive algal biomass and the oxidation of mono-sulphidic black ooze. The detritivorous fishes consumed by the Caspian Terns are likely to ingest contaminated surface sediment and assimilate methyl-mercury from affected areas into their tissues. It is therefore probable that the principal source of mercury contamination in Caspian Terns in the southern metropolitan coastal waters was the Peel-Harvey Estuary. The variations in exposure probably relate to the time different individuals spend foraging in the estuary.



Caspian Tern colony used as 'sentinels' for the Southern Metropolitan Coastal Waters.

OIL POLLUTION

Oil pollution was one of the flagship issues for the emerging environmentalism of the 1960s. The highly visual character of seabirds coated in oil still dominated the public's perception of water pollution until more recently with the increasing awareness of plastics in marine debris. Major oil spills and deliberate releases are relatively uncommon these days. Early seabird monitoring of the incidence of oil spills was based on 'beach-sweeping' for stranded individuals. These days the emphasis has been on monitoring the impacts of oil-spill incidents on the impacted ecosystems and on sub-lethal effects of chronic, low level contamination.

In Western Australia seabirds sometimes visit colonies or roosts with oil-staining on their plumage. Such observations may be an indicator of an offshore spill or deliberate (and illegal) release from shipping. Beach-washed birds may also have had contact with oil.

Monitoring for sub-lethal chronic hydro-carbon pollution has largely relied on the use of dead or moribund birds (eg. liver tissue) or eggs (yolk) to analyse for concentrations of Poly Aromatic Hydrocarbons (PAHs) or their metabolites. These compounds are a component of oil, can bio-accumulate, are toxic and functional endocrine disrupters. Most recently blood samples have been used successfully to track the persistence of PAHs in gulls in the area impacted by the Prestige oil spill.

IONIZING RADIATION

Marine pollution by radionuclides is not a problem that is likely to occur on the Western Australian coastline in the absence of nuclear power generation. We do however have nuclear powered warships using our ports (eg. Garden Island) and exercising off our coast.

The melt-down at the Fukushima Daiichi Nuclear Power Plant in Japan has however seen seabirds utilized to monitor the extent and distribution of radiocaesium pollution from contaminated water released during the incident. The blood of pre-fledging chicks of Streaked Shearwaters *Calonectris leucomelas* from two Japanese colonies were sampled for Vitamin A (retinol). This compound along with carotenoides and Vitamin E are important antioxidants. At the cellular level exposure to radionuclides produces oxidative stress and animals respond to this by mobilizing and then depleting protective anti-oxidates. A decline in blood levels of Vitamin A in the Streaked was therefore an indicator of exposure to radionuclides in the foraging areas. Adults most likely transferred radiocaesium to their chick through feeding them contaminated prey.

The foraging area of one of the Streaked Shearwaters colonies was evidently within the oceanic area impacted by the pollution plume from the Plant. The food chain in this area at least was contaminated. The Shearwaters from the other colony foraged in another area and were relatively unaffected. About 60% of the population of the world's population of Streaked Shearwaters was exposed to the radiation generated from Fukushima. The consequences of that in terms of individual fitness and reproductive output will take years to play out.

Streaked Shearwaters from Japan are regular migrants to the seas off northern Australia and are commonly seen off the NW coast of WA and off the Abrolhos Islands. In years with a strong Leeuwin Current they have been observed off the Cape Naturalist / Leeuwin region. It would be prudent to bank beach-washed specimens of this species to collect longer term data on the impact of radiation on seabirds.

Construction of seabird-based marine monitoring programs

INTRODUCTION

Most seabird monitoring is designed to provide long time series for research projects or as part of conservation programs. This guide is focussed on using what we know about seabird foraging patterns and breeding biology to monitor changes in marine ecosystems. The two approaches are of course both sympathetic and interrelated.

Seabird islands are effectively 'information hubs' where indicators or the condition of a range of different marine ecosystems can be monitored strategically from a central location. Suitable seabird-based marine monitoring hubs would have the following characteristics:

- Provide a variety of accessible seabird species foraging at a range of scales encompassing all the marine ecosystems in the region.
- Adequate knowledge of the biology and foraging ecology of the potential indicator species in the region.
- Sufficient numbers of breeding individuals in each indicator species population to meet experimental and statistical requirements. N.B. Threatened species would generally not be ideal subjects for monitoring environmental changes as their numbers may have been depleted by historical factors unrelated to marine processes (eg. disturbance at breeding colonies, fisheries bycatch).
- Sufficient protection from land-based threats including introduced predators, breeding habitat loss and unregulated human disturbance.
- A research base with accommodation, transport and communications infrastructure, to reduce the logistical cost of field operations collecting monitoring data (eg. Saville Kent Centre in the Abrolhos Islands, Rottneest Field Station).

- The ability to utilise seabird monitoring data in marine management processes (eg. as indicators in environmental, fisheries and/ or marine reserve management processes).
- Funding resources from agencies, institutions or science-based ecotourism products. Citizen-science volunteers may also need to participate in the program to reduce labour costs.

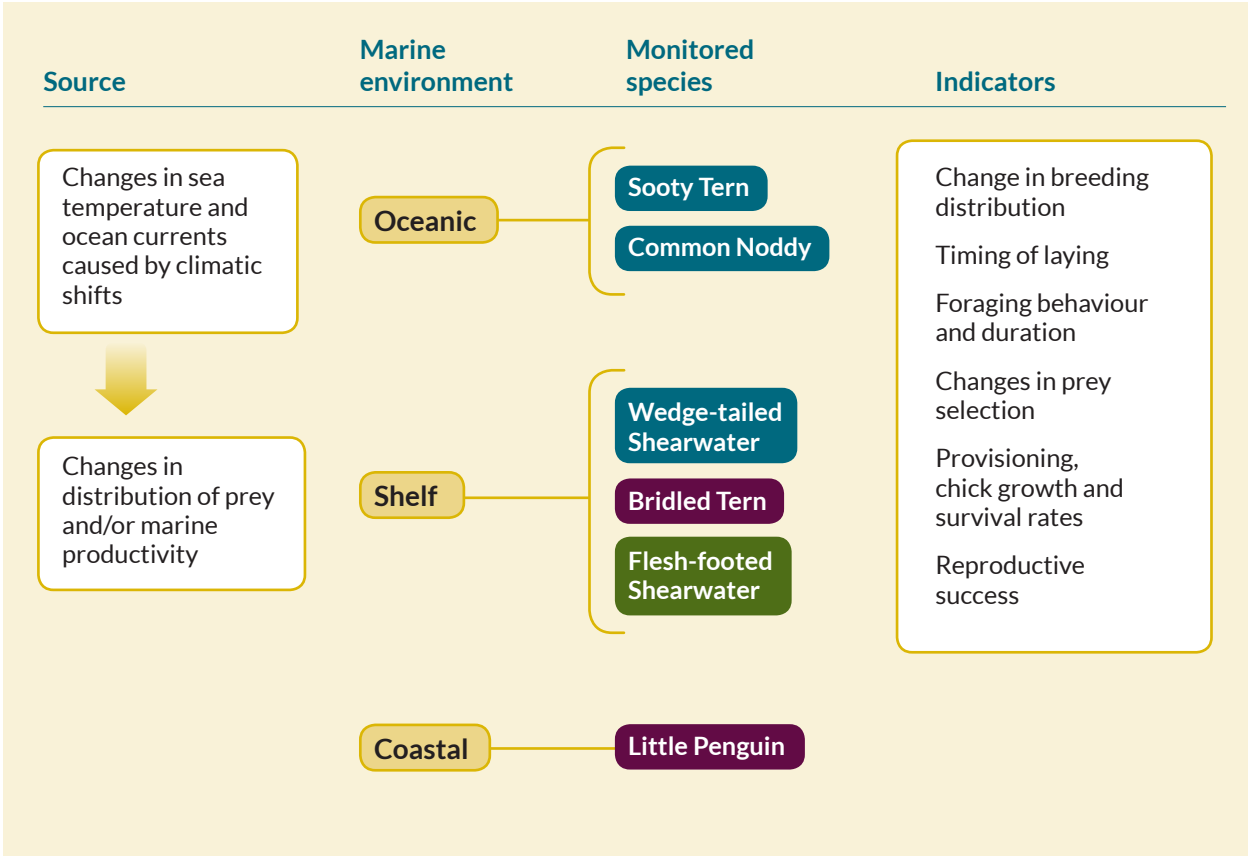
FRAMEWORKS FOR SEABIRD-BASED MONITORING OF MARINE ECOSYSTEMS

Frameworks can be developed around threats to marine ecosystems. The following examples relate to potential threats operating in Western Australian marine ecosystems including the changes in ocean climate, wild fisheries and aquaculture activities, plastics contamination from marine debris and mercury biomagnification in food chains. The frameworks identify;

- the potential sources for the threatening processes,
- the broadly defined marine environment in which the impacts are likely to occur (oceanic including the continental slope, shelf waters, coastal waters and estuaries).
- the selected seabird indicator species (coded for West Coast, South Coast or both), and
- the indicator (i.e. the measured attribute of seabird behaviour, biology, population or contamination burden).



IMPACT OF OCEAN CLIMATE ON MARINE PRODUCTIVITY



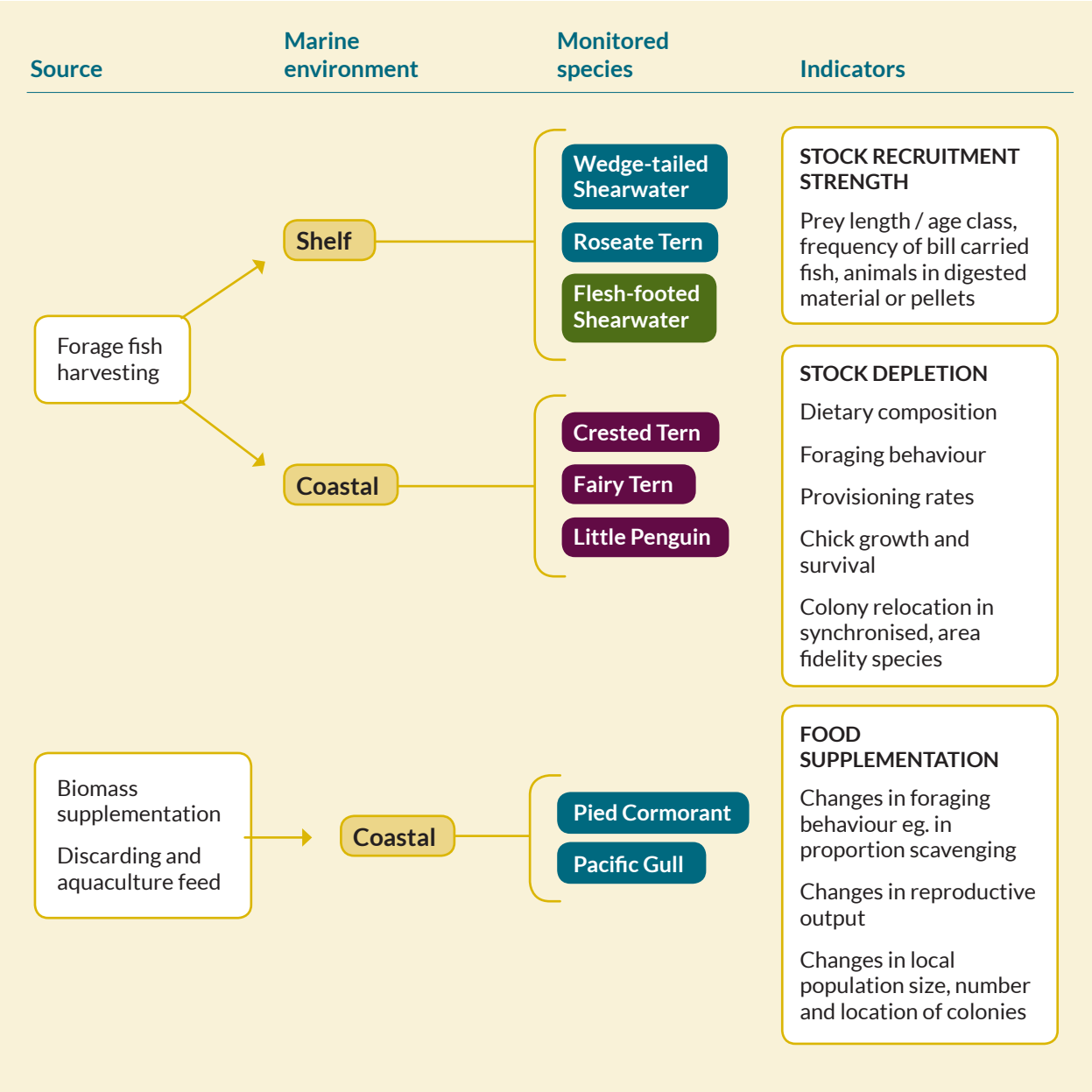
KEY

West Coast

South Coast

West & South Coast

FISHERIES / AQUACULTURE IMPACTS



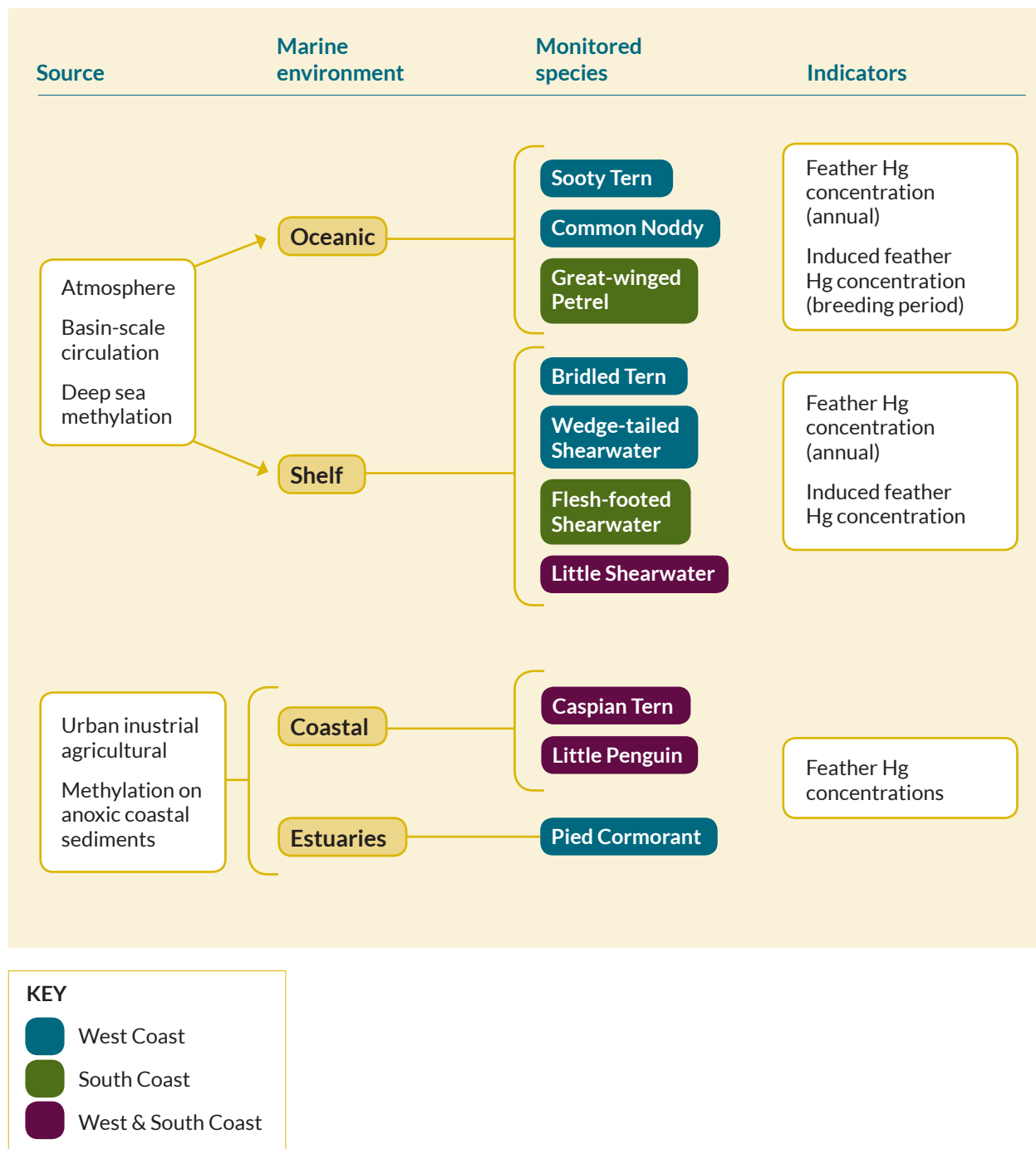
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West Coast

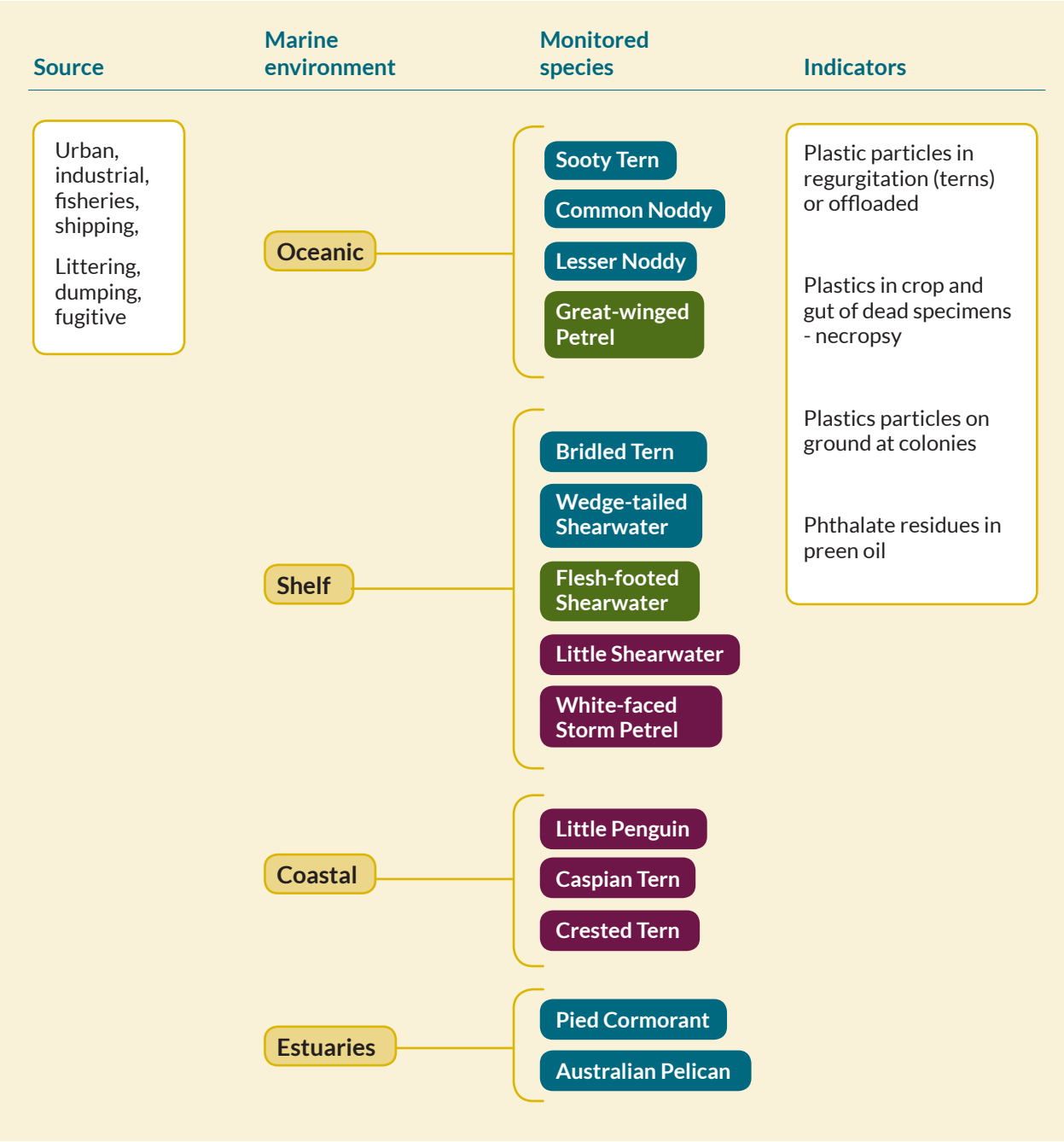
South Coast

West & South Coast

MERCURY CONTAMINATION



PLASTICS CONTAMINATION

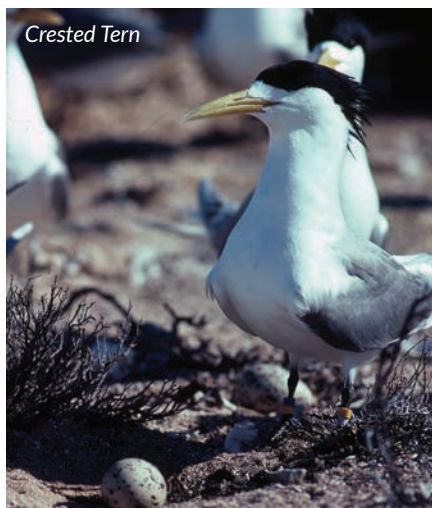


KEY

West Coast

South Coast

West & South Coast



Crested Tern



Pacific Gull



Great-winged Petrel



White-faced Storm-petrel



Common Noddies

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ABOUT THE CONSERVATION COUNCIL OF WA

The Conservation Council of WA (CCWA) is the State's foremost non-profit, non-government conservation organisation. We are an umbrella group for over 100 affiliate conservation groups and have been an outspoken advocate for environmental protection and a sustainable WA for over 40 years.

The CCWA Citizen Science program supports community groups and individuals in undertaking ecological monitoring in order to build the knowledge and understanding that is critical to the conservation and management of our natural environment.

You can find out more, and support CCWA's conservation and citizen science work by visiting the CCWA website at www.ccwa.org.au

Piers Verstegen
Director



THE CO-AUTHORS



Dr. J.N. (Nic) Dunlop is CCWA's ecologist and Citizen Science Coordinator and has been studying seabirds in Western Australia and elsewhere for over 30 years. During this time Nic has advised many agencies and community organisations on seabird conservation and published numerous reports and journal articles on seabird ecology. One line of research has focussed on how seabirds can be used to detect and monitor changes in the marine environment.



Jill Shephard (left) attaching a GPS tracker to a Common Noddy.

Dr Jill Shephard is an Ecology Lecturer and Researcher at Murdoch University, Australia, and an affiliate researcher in the Murdoch University Conservation Medicine Research Group. She is particularly interested in movement and spatial ecology, and uses a range of genetic, satellite and GPS tracking, and chemical markers to identify and understand the drivers of population distribution; particularly among avian species.

