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Ecological Risk Assessment for seabird interactions in Western and Central Pacific longline fisheries

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ABSTRACT

The risk of seabird–fishery interactions in the Western and Central Pacific Ocean (WCPO) was examined by analysing the overlap of seabird distributions with tuna and swordfish pelagic longline fisheries managed by the Western and Central Pacific Fisheries Commission (WCPFC) and its constituent members. The study used spatially-explicit Productivity–Susceptibility Analysis (PSA). Key data inputs were species productivity, fishing effort, likelihood of capture and species density by region. The outputs tailored results to the needs of fisheries- and wildlife-managers, indicating areas of greatest risk of species interactions, species of greatest concern for population impacts, and the flags or fisheries most likely to contribute to the risk. Large albatross species were found to be most likely to suffer population effects when exposed to longline fishing activity, followed by the larger petrels from the genuses *Procellaria*, *Macronectes* and *Pterodroma*. A mixture of coastal states with nesting seabird populations in their Exclusive Economic Zones (New Zealand, Australia and United States of America), distant water fishing nations (Japan, Taiwan) and flags of convenience (Vanuatu) contributed 90% of the risk to seabird populations. Recommendations include enhancing the level of fisheries observer monitoring in areas indicated as high to medium risk for seabird interactions, and consideration of spatial management tools, such as more intensive or more stringent seabird bycatch mitigation requirements in high- to medium-risk areas. The methods used, and similar studies conducted in the Atlantic Ocean could lead to improved targeting of monitoring resources, and greater specificity in the needs for seabird-mitigation measures. This will assist in reducing seabird mortality in longline fishing operations and with more effective use of resources for fishery managers in both domestic fisheries and RFMOs.

1. Introduction

1.1. Seabird fishery interactions

Seabird interactions with fisheries are a high-profile issue in many jurisdictions and for many Regional Fisheries Management Organisations (RFMOs) [1]. During fishing with longlines, seabirds may be caught on baited hooks or entangled in fishing lines, resulting in mortality. Three billion longline hooks are set annually around the globe, and it is estimated that 300,000 or more seabirds may be killed annually [2]. International agreements assert the need to reduce adverse effects of fishing mortality on non-target catch and seabird populations, and to safeguard populations during migrations. These include the Convention on the Conservation of Migratory Species of Wild Animals [3], the Fish Stocks Agreement [4], the Code of Conduct for Responsible Fisheries [5], the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) [6], the Western and Central Pacific Fisheries Commission (WCPFC) [7],the Indian Ocean Tuna Commission (IOTC) [8] and the Agreement for the Conservation of Albatrosses and Petrels (ACAP) [9]. To assist RFMOs in the aim of minimising impacts on non-target species, the Food and Agriculture Organisation of the United Nations has published best-practice guidelines for domestic fisheries and RFMOs [10], detailing effective methods and processes for reduction of seabird bycatch demanded by the FAO International

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Plan of Action for Reducing Incidental Catch of Seabirds in Longline Fisheries established 10 years earlier [11]. Defining the spatial and temporal aspects of incidental seabird catch is an important aspect of these guidelines. Some Ecological Risk Assessment methods have potential to assist RFMOs in prioritising actions to species, locations and seasons where impacts may be highest.

Defining the extent and importance of incidental seabird catch and mortality is a priority issue for the WCPFC, which is responsible for management of the tunas and billfish fisheries for the western section of the Pacific Ocean (Fig. 1). The Inter-American Tropical Tuna Commission (IATTC) covers complementary fisheries in the east of the Pacific. The Pacific Ocean hosts 60% of the world's 346 species of seabird, including a high diversity of Procellariiform seabirds centred on New Zealand and the Tasman Sea (Fig. 1). Our focus in this study was the WCPFC pelagic longline fisheries.

Twenty-eight percent of seabird species are threatened with extinction according to the International Union for the Conservation of Nature (IUCN) [12] and there is a potential for seabird–fishery interactions in the Pacific Ocean to damage populations, and particularly albatrosses, where a considerable proportion of the species overlap with fisheries in the WCPFC region [13,14]. ACAP [13] noted that several species of seabird spend over 75% of their time in the areas within the WCPFC zone: Antipodean albatross *Diomedea antipodensis*, Chatham albatross *Thalassarche eremita*, Laysan albatross *Phoebastria immutabilis*, northern royal albatross *Diomedea sanfordi*, short-tailed albatross *Phoebastria albatrus*, shy albatross *Thalassarche cauta* and sooty shearwater *Puffinus griseus*. All of these species are listed by the IUCN as threatened with extinction [12].

Albatrosses are particularly vulnerable to adverse population effects of fishing mortality, partly due to their long-ranging foraging habits, which expose them to fishing activity throughout large areas of ocean, and partly because of their extreme life-history traits. For example, some albatross species breed at most once every two years, and take up to one year to raise a chick, with age at maturity over 10 years. Should one adult die during its breeding period, the chick will most likely not survive, and the widowed mate may take several years to find another mate. Due to this low reproductive output, even occasional captures in fisheries can put pressure on seabird populations and contribute, long term, to declines in numbers of birds at breeding colonies. These declines have been seen in albatross populations, which are the most threatened family of birds globally, with 18 of the 22 species threatened with extinction [12].

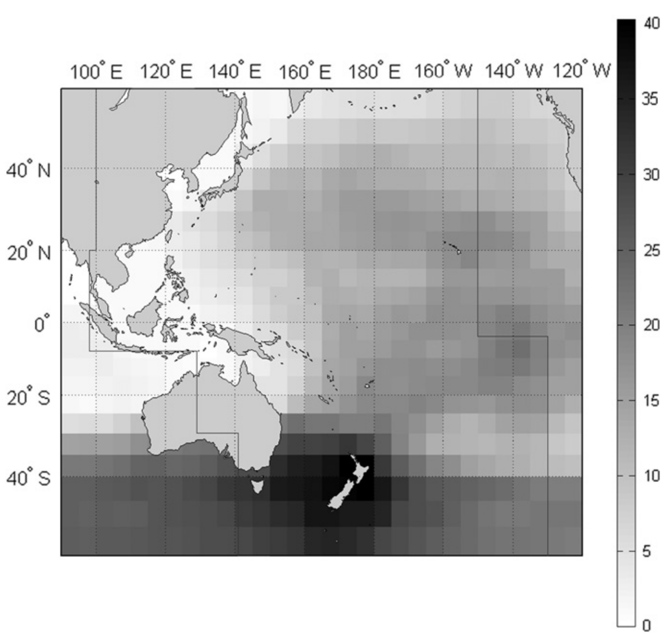

Fig. 1. Plot of seabird diversity (number of species per 5×5 degree area) for 70 species of albatross and petrel found in the WCPFC Convention Area. This factor was based on distributions defined during this analysis combining BirdLife International Range Maps, data from the BirdLife International Global Procellariiform Database remote tracking studies, and colony locations and other literature based information about foraging distances.

1.2. Ecological Risk Assessment (ERA)

To implement the environmental management called for under international agreements, such as the United Nations' Fish Stocks Agreement [4], Code of Conduct for Responsible Fisheries [5] or more specifically in management measures for the Pacific Ocean, where our study focuses, managers are required to consider which of a suite of non-target species populations may be affected by fishing mortality [7]. ERA approaches have been developed to make the best use of patchy, and at-times, highly uncertain information. Productivity–Susceptibility Analysis (PSA) is a semi-quantitative ERA methodology, developed to identify the risks that fishing poses of adverse population effects to non-target species, and to help prioritise management across a broad suite of non-target taxa, such as turtles, sharks, non-target fish and marine birds or mammals, exposed to different fishing methods [15]. The need for detailed analysis, which considers a suite of population factors along with catch data is reinforced by recent research showing that species population collapse may occur, even where fishery-catch levels are closely monitored for highly fishery-impacted species [16].

We developed spatially-explicit PSA methodologies to estimate the relative effects of seabird–fisheries interactions and the potential for adverse effects of fisheries mortality on populations of seabirds [17–20]. Here we report on a recent iteration of these analyses, which we consider appropriate for application to many RFMO fisheries. The 'risk' in this analysis refers to the probability of adverse effects on seabird populations as a result of fishing mortality.

Our approach maximises the use of robust data within the systems concerned, and can be applied wherever there is a minimum of information about the fishing effort concerned, such as fishing effort data. In many bycatch-management contexts, data about the frequency of capture and species composition of discarded, non-target catch is highly unreliable. The species information we chose are parameters, which can be easily and robustly estimated and rely on the conservatism imposed by demographic constraint in seabirds such as breeding frequency (annual or biennial) or clutch size (one-, two- or multiple-egg clutches depending on the family), and does not need parameter estimates from long-term research programmes.

PSAs are a semi-quantitative method of examining the vulnerability of populations based on two essential axes: one which describes the productivity of the species, the other its susceptibility (or exposure) to adverse effects. Those species, which are most inherently productive (e.g. breeding at earlier ages, more fecund) are considered better to tolerate and recover from fisheries removals than slower-breeding ones. Susceptibility is conceptually represented by the opportunities for mortality events. In this case we estimated susceptibility through the overlap of species' ranges with fishing effort, and we then applied a factor termed 'vulnerability' to correct this exposure with species-specific coefficients indicating the relative likelihood of a species (or group of species) to be caught when exposed to fishing events of a certain method ('catchability' in fisheries terms) (see Section 2 for description of the calculation of the factor ‘vulnerability’). By combining information on both productivity and susceptibility, the relative exposure of species to fishing effort, and the differential effects of removals by a particular fishery on a species population are assessed.

PSA studies sit in a suite of ERA methods that range from qualitative, such as through expert opinion based assessments, to fully age-structured population models. Each method has its constraints. For example, expert-based workshops, sometimes termed Level 1 Risk Assessment, such as that undertaken for CCAMLR fisheries [21], may be constrained by the inherent biases in the dataset or knowledge of participants, and may not provide reproducible results. More complex modelling approaches, such as those undertaken for some species in the Atlantic Ocean require high quality (and often long-term) datasets to define parameters for modelling of population inputs and outputs [22,23], and hence may be applicable to only a small subset of the species potentially affected within a system. Semi-quantitative (or Level 2) ERA methods, such as those explored here, allow room for measures of environmental or biological variables to be included, but enable assessment of risk for a broad suite of species or systems, which can be updated and improved through time as new information becomes available. They can be used to highlight where better quality information is needed. Management responses in relation to ERA findings can result in implementation of mitigation measures, while detailed monitoring data may be gathered to provide more detailed assessments of the nature of risks.

2. Materials and methods

We analysed fishing effort data sourced from the Western and Central Pacific Fisheries Commission. Our study area includes the waters within the WCPFC jurisdictional boundaries in the Western and Central Pacific Ocean (west of 130°W longitude in the southern hemisphere and west of 150°W in the northern hemisphere) and includes waters within Exclusive Economic Zones (EEZs) as well as high seas. Seabird species data were collated from literature review and through accessing databases of multi-research data holdings. We chose to concentrate on pelagic longline fisheries to explore the PSA methodology as this fishing method has known seabird bycatch problems, and detailed observer data were available to inform estimation of some parameters. All analyses were conducted for annual and quarterly periods, to examine seasonal effects with shifting fishing- and species-distributions. Results presented are average annual outputs, unless indicated otherwise.

2.1. Fishing effort and distribution

Fishing effort data for pelagic longline vessels targeting tuna and swordfish were extracted from databases held by the Secretariat for the Pacific Community (SPC) for the WCPFC. These data were the number of hooks for five-degree longitude by five-degree latitude square for the period 2002–2009, stratified by flag-state. We plotted fishing effort density within 5-degree squares as thousands of hooks per km^2. We summed the fishing effort within each square across 8 years of data (Fig. 2), thus integrating through the three phases of the El Niño Southern Oscillation (ENSO), which is the dominant driver of inter-annual variability in the spatial distribution of fishing effort.

2.2. Study species and their distributions

We analysed data for 70 species, which included albatrosses and petrels occurring in both tropical and temperate oceanic systems (Table 1). Thirty-six of these species have previously been recorded as captured by longline fisheries in the region (SPC and Ministry of Fisheries unpublished data). The 70 species were selected on the basis of those species occurring within the study area, whose families or genera are known to be captured in longline fishing, and for which information on species biology and populations were available.

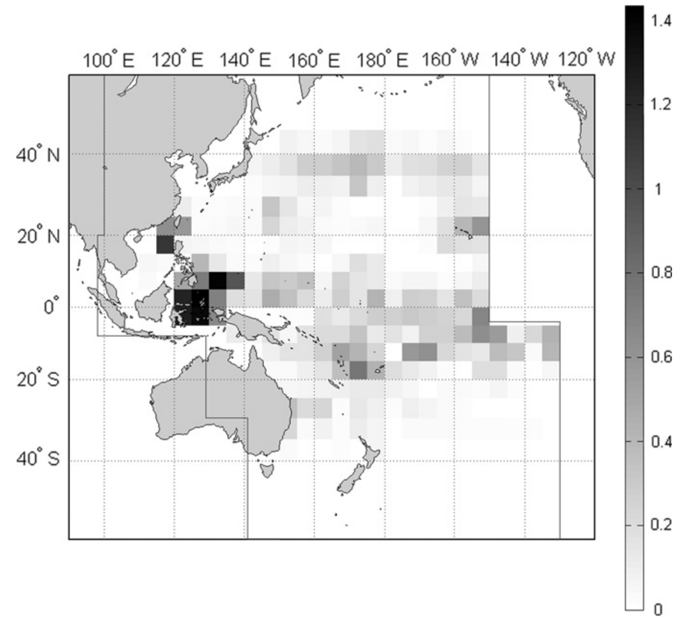

Fig. 2. Fishing effort density for WCPFC longline fisheries by 5-degree square (2002–2009) (scale bar is hundred hooks/km^2).

We used BirdLife International’s Range Maps as a basis for the species global distributions [24]. These represent the likely maximum range of a species throughout all seasons. They provide presence/absence information at a global scale by species.

We established seasonal (quarterly) distribution maps for the species by taking into account the known breeding colonies at a global scale, the breeding period, and using an estimate of distribution of breeding distribution as follows:

a. Remote-tracking information: for 14 species, we used remote-tracking data from the BirdLife International Global Procellariiform Tracking Database, which consisted of ARGOS satellite telemetry locations, geo-locator system fixes, or Global Positioning System (GPS) logger locations. We used 50%, 75%, 90% and 95% utility distributions (see [14] for methods to determine kernel distributions of birds on the basis of these data), for non-breeding and breeding ranges.
b. The species foraging radius approach: for 66 species where colony locations and literature-based mean maximum foraging radii were known, we assumed that the non-breeder birds occupied the full species’ range, while the breeder birds are only spread around their breeding colonies. Where only average foraging range was available, we used this value. We chose to use an exponential decay function to describe the way that birds cluster around colony areas due to their central-place foraging pattern during breeding, extending up to their maximum foraging range radius. We tested this function for two species for which we had extensive primary datasets (Buller’s and Southern Royal Albatrosses, *Thalassarche bulleri* and *Diomedea epomophora*, respectively), and found an exponential decay function best described the data (Fig. 3). This approach is similar to that advocated by BirdLife International for describing areas of particular importance for populations

Table 1
Species attributes for 70 species of albatross and petrel included in the analysis, sorted by scientific name. Species group is the group of birds considered to have similar behaviours, to which *Vulnerability* values were estimated. Code is the species code generated for this study and used in other figures; Age maturity is the average age at first breeding by species S—average annual survival rate; Life History Strategy 3 = biennial breeder with single egg; 2 = annual breeder with single egg; 1 = annual breeder with multiple eggs; Threat status is the IUCN threat ranking for the species. Radius—maximum foraging distance from colony (km). World population individuals are the estimated population sizes for individual birds for the species, globally.

Scientific name	Common name	Species group	Code	Age maturity (yr)	S	LHS	Threat status	Radius	World population individuals	Vulnerability
Bulweria bulwerii	Bulwer's Petrel	Other petrels	BUB	5	94.7	2	LC	120	750,000	0.000344
Daption capense	Cape Pigeon	Other petrels	DAC	6	94	2	LC	360	4,000,000	0.000344
Diomedea antipodensis	Antipodean Albatross (Antipodes Island)	Large albatrosses	ANA	7	95.4	3	VU	1500	1,000,000	1.000000
Diomedea epomophora	Southern Royal Albatross	Large albatrosses	DIP	7	97	3	VU	1000	7,000,000	1.000000
Diomedea exulans	Wandering Albatross	Large albatrosses	DIX	9	96	3	VU	1800	150	1.000000
Diomedea gibsoni	Antipodean Albatross (Auckland Island)	Large albatrosses	GBA	7	97	3	VU	1500	25	1.000000
Diomedea sanfordi	Northern Royal Albatross	Large albatrosses	DIS	7	94.6	3	EN	1250	20,000	1.000000
Fulmarus glacialoides	Antarctic Fulmar	Large shearwaters	FUG	5	95.5	2	LC	n.d	30,000	0.001100
Halobaena caerulea	Blue Petrel	Other petrels	HBE	5.4	84	2	LC	n.d	75,000	0.000344
Lugensa brevirostris	Kerguelen Petrel	Other petrels	LUB	5.5	90	2	LC	n.d	5500	0.000344
Macronectes giganteus	Southern Giant Petrel	Small albatrosses	MAI	7	93	2	LC	189	3,000,000	0.307899
Macronectes halli	Northern Giant Petrel	Small albatrosses	MAH	7.5	93	2	LC	550	110,880	0.307899
Pachyptila belcheri	Thin-billed Prion	Other petrels	PAB	6.7	84	2	LC	n.d	12,000	0.000344
Pachyptila crassirostris	Fulmar Prion	Other petrels	PCC	4.5	84	2	LC	161	400,000	0.000344
Pachyptila desolata	Antarctic Prion	Other petrels	PWD	5	84	2	LC	300	135	0.000344
Pachyptila turtur	Fairy Prion	Other petrels	XFP	4.5	84	2	LC	161	20,000	0.000344
Pachyptila vittata	Broad-billed Prion	Other petrels	XPV	5.4	84	2	LC	200	100,000	0.000344
Pelecanoides urinatrix	Common Diving-Petrel	Other petrels	GDU	2	81	2	LC	200	900,000	0.000344
Phoebastria albatrus	Short-tailed Albatross	Small albatrosses	PHA	6.77	95	2	VU	1500	625	0.307899
Phoebastria immutabilis	Laysan Albatross	Small albatrosses	PHI	8	95	2	NT	1000	500,000	0.307899
Phoebastria nigripes	Black-footed Albatross	Small albatrosses	PHN	4	95	2	EN	250	22,388	0.307899
Phoebetria fusca	Sooty Albatross	0.1 small albatrosses	PHF	7	97.3	3	EN	350	38,600	0.030790
Phoebetria palpebrata	Light-mantled Sooty Albatross	0.1 small albatrosses	PHE	7	97.3	3	NT	1516	5,200,000	0.030790
Procellaria aequinoctialis	White-chinned Petrel	Procellaria petrels	PRO	6.5	89	2	VU	1868	23,000,000	0.151234
Procellaria cinerea	Grey Petrel	Procellaria petrels	PCI	7	93	2	NT	600	1,998,000	0.151234
Procellaria parkinsoni	Parkinson's Petrel	Procellaria petrels	PRK	7	88	2	VU	522	4,764,000	0.151234
Procellaria westlandica	Westland Petrel	Procellaria petrels	PCW	6	88	2	VU	150	150,510	0.151234
Pseudobulweria becki	Beck's Petrel	Other petrels	PSB	5.5	93	2	CR	n.d	35,400	0.000344
Pseudobulweria macgillivrayi	Fiji Petrel	Other petrels	PSM	5.5	93	2	CR	195	225,000	0.000344
Pseudobulweria rostrata	Tahiti Petrel	Other petrels	PSR	5.5	93	2	NT	210	75,150,000	0.000344
Pterodroma alba	Phoenix Petrel	Other petrels	PLB	5.5	93	2	EN	210	5,100,000	0.000344
Pterodroma atrata	Henderson Petrel	Other petrels	PTT	5.5	93	2	EN	195	15,000,000	0.000344
Pterodroma axillaris	Chatham Petrel	Other petrels	PTA	5.5	93	2	EN	120	15,999,999	0.000344
Pterodroma brevipes	Collared Petrel	Other petrels	PTB	5.5	93	2	NT	195	1410	0.000344
Pterodroma cervicalis	White-necked Petrel	Other petrels	WNP	5.5	93	2	VU	400	1,774,068	0.000344
Pterodroma cookii	Cook's Petrel	Other petrels	PTC	5.5	93	2	VU	250	183,921	0.000344
Pterodroma externa	Juan Fernàndez Petrel	Other petrels	PTE	5.5	93	2	VU	600	3,723,000	0.000344
Pterodroma heraldica	Herald Petrel	Other petrels	PTH	5.5	93	2	LC	195	335,052	0.000344
Pterodroma inexpectata	Mottled Petrel	Other petrels	XMP	5.5	93	2	NT	250	9999	0.000344
Pterodroma leucoptera	Gould's Petrel	Other petrels	PTL	5.5	93	2	VU	195	900	0.000344
Pterodroma longirostris	Stejneger's Petrel	Other petrels	PTO	5.5	93	2	VU	600	450,000	0.000344
Pterodroma macroptera	Great-winged Petrel	Large Pterodroma petrels	PDM	6.5	93	2	LC	600	2,100,000	0.006256
Pterodroma magentae	Magenta Petrel	Other petrels	PTM	6.5	93	2	CR	400	1,230,000	0.000344
Pterodroma mollis	Soft-plumaged Petrel	Large Pterodroma petrels	PTS	5.5	93	2	LC	500	660,000	0.006256
Pterodroma neglecta	Kermadec Petrel	Other petrels	PVB	5.5	93	2	LC	400	1,500,000	0.000344
Pterodroma nigripennis	Black-winged Petrel	Other petrels	PTN	5.5	93	2	LC	195	4,980,000	0.000344
Pterodroma pycrofti	Pycroft's Petrel	Other petrels	PTP	5.5	72	2	VU	195	174,900	0.000344
Pterodroma sandwichensis	Hawaiian Petrel	Other petrels	PTW	5.5	93	2	VU	1300	9,000,000	0.000344
Pterodroma solandri	Providence Petrel	Other petrels	PTI	5.5	93	2	VU	210	15,000	0.000344
Pterodroma ultima	Murphy's Petrel	Other petrels	PTU	5.5	93	2	NT	260	900,000	0.000344
Puffinus assimilis	Little Shearwater	Other petrels	PUA	5.5	90	2	LC	210	900,000	0.000344
Puffinus bulleri	Buller's Shearwater	Other petrels	PBU	5.5	90	2	VU	60	648,000	0.000344

Puffinus carneipes	Flesh-footed Shearwater	Large shearwaters	PFC	5.5	93	2	LC	250	18,000,000	0.001100
Puffinus griseus	Sooty Shearwater	Large shearwaters	PFG	6	93	2	NT	100	282,000	0.001100
Puffinus heinrothi	Heinroth's Shearwater	Other petrels	PUN	5.5	93	2	VU	n.d	91,380	0.000344
Puffinus huttoni	Hutton's Shearwater	Other petrels	PHU	5	93	2	EN	70	37,755	0.000344
Puffinus lherminieri	Audubon's Shearwater	Other petrels	PUL	8	90	2	LC	70	13,725	0.000344
Puffinus nativitatis	Christmas Shearwater	Other petrels	PNT	5.5	93	2	LC	70	63,000	0.000344
Puffinus newelli	Newell's Shearwater	Other petrels	PUW	5.5	90	2	EN	450	1,805,058	0.000344
Puffinus pacificus	Wedge-tailed Shearwater	Large shearwaters	PUP	4	93	2	LC	80	95,841	0.001100
Puffinus tenuirostris	Short-tailed Shearwater	Large shearwaters	PUT	6	93	2	LC	n.d	291,333	0.001100
Thalassarche bulleri	Buller's Albatross	Small albatrosses	DNB	5	91.3	2	NT	413	22,022	0.307899
Thalassarche cauta	Shy Albatross	Small albatrosses	THC	9	93.5	2	NT	200	27,650	0.307899
Thalassarche chrysostoma	Grey-headed Albatross	0.1 small albatrosses	DIC	10	95.3	3	VU	800	28,175	0.030790
Thalassarche eremita	Chatham Albatross	Small albatrosses	DER	7	93.5	2	VU	600	18,427	0.307899
Thalassarche impavida	Campbell Albatross	Small albatrosses	TQW	10	94.5	2	VU	640	20,412	0.307899
Thalassarche melanophrys	Black-browed Albatross	Small albatrosses	DIM	9	92	2	EN	1100	48,615	0.307899
Thalassarche salvini	Salvin Albatross	Small albatrosses	DLS	9	93.5	2	VU	1500	79,138	0.307899
Thalassarche steadi	White-capped Albatross	Small albatrosses	XWM	7	94	2	NT	413	335,118	0.307899

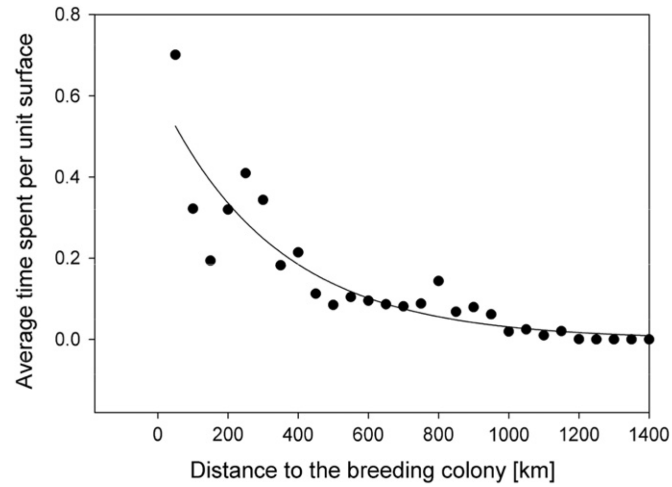

Fig. 3. Distance from the colony plotted against time spent by unit area for Southern Royal Albatross ($n=50$ tracks) shows an exponential decay pattern. This distribution of bird hours spent in relation to distance from breeding colonies was used to describe the distribution of birds from breeding colonies where remote tracking data were absent.

around major breeding sites [25]. This approach was also used for breeding localities of species for which remote-tracking data were available, at locations where birds had not been tracked, again using literature derived values for mean maximum foraging range.

The density of birds at a distance r from the colony following an exponential decay is defined with r representing the distance at the colony, thus, if $r >$ range_max then breeder_density$(r)=0$, where range_max is the maximum range for a species foraging from its breeding site, and breeder_density (r) is the density of breeding birds at a point location.

For $r \leq$ range_max

$$breeder_{density(r)} = e^{\frac{\ln(0.01)r}{range_{\max}}} \quad (1)$$

The maximum density of the foraging radius approach breeder layer, or the remote-tracking breeder layer was chosen to establish the species distribution map. Examples of the species layers considered are shown in Fig. 4 for Murphy's petrel, *Pterodroma ultima*, for one quarter of the year.

We assumed that the breeder component of the population in any year was 0.4 of the whole population for biennial breeding albatrosses, and 0.5 for annual breeding species. These were concentrated around the breeding colonies during the breeding season. The non-breeder population included pre-breeders and juveniles, and all birds outside of breeding months. The non-breeding population was spread evenly throughout their global range for the months when the population was not breeding, or throughout the year for non-breeding individuals.

For each season, we computed a composite map, which was the combination of the seasonal breeder layer and the seasonal non-breeder layers on a global scale, assuming that 100% of the population of the species was distributed within the estimated range of the species.

2.3. Productivity–susceptibility analyses (PSA)

We used the distributions of fishing effort and species distributions to calculate seasonal and average annual risk scores based on (a) the *Susceptibility* indicator and (b) the *Productivity* indicator.

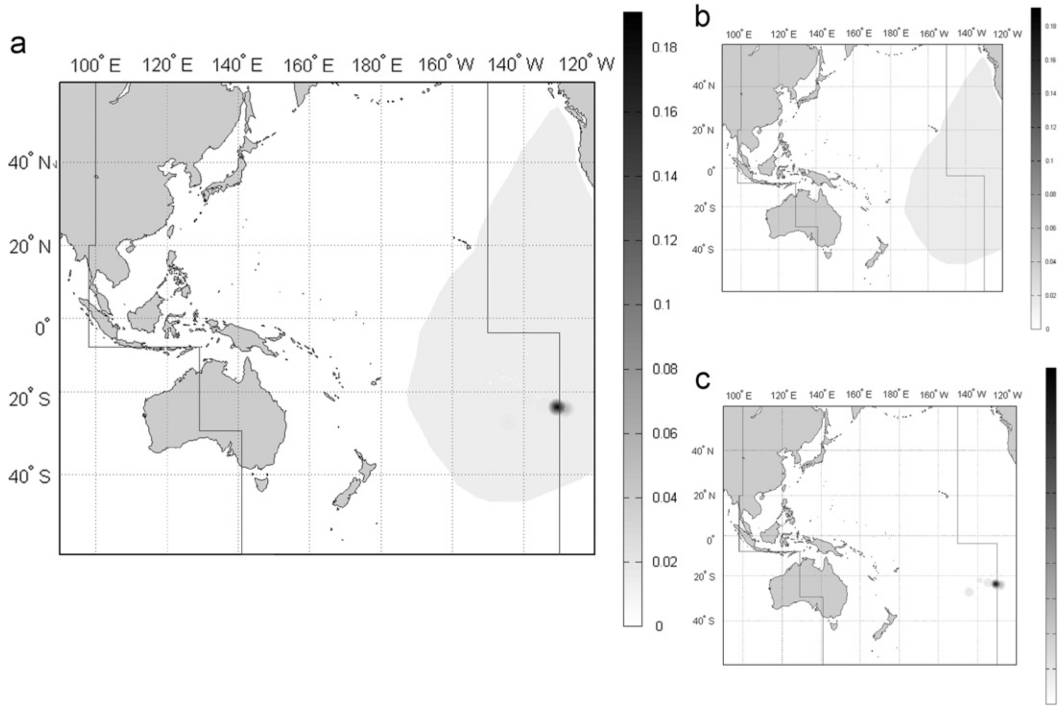

Fig. 4. Example of a composite bird density map for Murphy's petrel *Pterodroma ultima* in spring (birds/km^2). The composite spring (September–November) distribution map (a) for Murphy's petrel is a combination of (b) the spring non-breeder distribution layer and (c) spring breeder distribution layer with colony based information.

2.3.1. Susceptibility

The *Susceptibility* indicator was calculated as the product of fishing effort and normalised species distributions (i.e. proportion of a species' range). This was weighted with the *Vulnerability* of the different species to longline fishing gear:

$$susceptibility(sp,f,se) = \frac{vulnerability(sp) \times \int_{wcpfc}(bird_{density} \times effort_{density(f)})}{bird_{population_{wcpfc}}(sp,se)} \quad (2)$$

where *sp* is the species, *se* the season and *fl* the fishing flag.

2.3.2. Vulnerability

Vulnerability (V) relates the density of each species at the location where fishing is taking place, to the number of kills that occur. Depending on the behaviour of the birds, which differs among species (or species groups), differential mortality is expected for the same seabird density. If there are, on average, *K* birds killed on a fishing event then the vulnerability is

$$K = VD \quad (3)$$

V has been estimated for a set of seabird species of the New Zealand EEZ (NZ Ministry of Fisheries, unpublished data) and the values used in this analysis are presented in Table 1. *V* is equivalent to the average number of birds of a particular taxon group caught per 1000 longline sets.

The New Zealand Ministry of Fisheries' observer data provides a consistent data source that has been used to determine the number of birds killed per fishing event in the New Zealand EEZ for similar ERA studies [20], unpublished reports to Ministry of Fisheries, New Zealand. We considered that large vessel pelagic fisheries in New Zealand was a suitable proxy for the large-vessel longline fleet operating in the WCPFC fisheries for the temporal period in question (2002–2008), as it used similar methods and mitigation during the period studied (streamer lines, or night setting were commonly used, while line-weighting was uncommonly used), and targeted many of the same species of tuna and billfish. During the period of our study, the mitigation requirements for both fisheries were similar; therefore the propensity of fishing activity to catch seabirds from both areas may be similar. In other studies, the relative likelihood of capture between species was assessed on the basis of expert opinion (e.g. [28]), an approach, which may be justifiable in circumstances in which few bycatch data are available.

Here, captured birds were used (excluding deck captures) and no account is taken of whether or not the birds were released alive. The observers recorded birds that were either brought on board the vessel, or that the observers clearly saw being killed. This follows the methods used for estimating seabird captures in New Zealand fisheries [26]. Observer data from fishing years 2004–05, 2005–06 and 2006–07 were used to estimate *V*.

In order to calculate *V*, the species were first grouped together in the following groups based on similar behaviour and propensities to be captured in fishing gear: large albatrosses, small albatrosses, small shearwaters, large shearwaters, *Procellaria* petrels; large *Pterodroma* petrels and other petrels. The species groupings were necessary to reduce the sparseness of the capture dataset. For some species there were very few captures, but by grouping similar species together, a greater density of data within a group was achieved, resulting in more robust estimation of capture parameters. Due to lack of comparable data on Northern Hemisphere species during the period of the study, we substituted values for large albatrosses for these species.

V was then estimated for each species group by fitting a generalised linear model to the captures and density data, for observed fishing events from the surface longline fishery. Capture data are typically over-dispersed, particularly where there were few captures. To increase the stability of the fitting, the observed captures were assumed to be drawn from a Poisson distribution, with a mean proportional to the seabird density at the location of the fishing event. *V* was given by the constant of proportionality. No other covariates were included in the models. An exploration of the model fitting found that neglecting the possibility of over-dispersion had little effect on the model fit. The models were fitted using standard Bayesian methods (e.g., [27]), with a diffuse lognormal distribution being assumed as the prior for *V*.

V was not estimated for two species, as there was little observational data on which the estimate is based. For these, small values were used, e.g. 0.1 the *V* value used for large shearwaters was attributed to small shearwaters and other petrels, and 0.1 the *V* value for small albatrosses was attributed to two species of albatross known infrequently to attend vessels compared to others in that group: grey-headed albatross and light-mantled albatross. This approach is consistent with that of Phillips and Small [28], who assigned a low catchability to these species on the basis of expert opinion. These values were included to assess the potential for interactions of these species as they were all known to occur sporadically in the bycatch of trawl and longline fisheries.

2.3.3. Productivity

The *Productivity* risk indicator is an inverted index of species reproductive potential. During the evolution of the PSA methodology, several productivity measures have been explored. In previous PSAs for a wide range of taxon groups, including fish, turtles, mammals and seabirds [18,19,29,30] *Productivity* estimates were generated using several variables that describe reproductive output (e.g. age-at-maturity, size at maturity, breeding frequency), standardised and averaged in order to provide a scale-free indicator that approximates the intrinsic rate of population increase. The objective of these analyses is to differentiate species on the basis of their biological characteristics, and therefore choosing metrics that spread species along a productivity scale, from low to high productivity, is more important than defining productivity in an absolute sense for these studies.

In this study for seabirds, we compared two different methods of generating *Productivity*; 'R_{max}' and 'Fecundity Factors Index'. These have been used in earlier versions of this Pacific seabird ERA study [18,19] and in similar studies on seabirds in the Atlantic Ocean [28]. In the R_{max} method we used a set of life-history parameters to approximate the maximum rate of increase of a population with no resource limitation, predation or competition [31]. Niel and Lebreton [32] demonstrated that for birds there is a constant relationship between generation length and population growth rate. They established that maximum annual growth rate λ_{max} can be estimated for long-lived species using measures of age at first reproduction α and adult annual survival *s*. This methodology was first elaborated for seabirds by Dillingham and Fletcher [33], and subsequently for a wider group of species [34]. Applying their approach, we solved for λ_{max} to derive *Productivity*, based on the relationship between this parameter and age at first breeding and annual adult survival:

$$\lambda_{max} = e^{\left[\left(\alpha + \frac{s}{\lambda_{max} - s}\right)^{-1}\right]} \quad (4)$$

R_{max} was calculated from λ_{max} thus: $R_{max} = \lambda_{max} - 1$.

We estimated α and *s* values for each species based on parameter values found in the scientific literature. Where more than one value was available for a species, the value from the study likely to provide the most robust estimation of R_{max} was used, i.e. that with the largest sample size, or a longer-term study. Where severe colony-based threats (i.e. from factors other than fishing mortality) were apparent, which are likely to result in depressed *s* values, we excluded these values from the study. For species where data were absent, we substituted a value from a closely-related species. Just over 1/3 of α and *s* values were substituted in our study. R_{max} values were normalised, with a maximum value set at 1.

Secondly, we adapted the *Productivity* measure developed by Phillips and Small [28] who used a simpler (and arguably more robust) formation to provide a species-specific metric of relative productivity. This 'Life History Strategy' score differentiated species in relation to reproductive frequency and potential output of progeny. This was then weighted by the median age at first breeding recorded for the species, or similar species where information was unavailable. This methodology has been used in ERA studies for Atlantic tuna fishery-seabird interactions, and considered an equivalent metric to the PSA productivity factor discussed earlier where multiple factors were averaged [28]. It was less likely to suffer from bias, and did not provide an impression of a more detailed understanding of species' biology might be supposed, as might be the construed from the R_{max} methodology. We adapted the Phillips and Small [28] methodology, which scored species into three groups for two variables: Life-history strategy (annual breeding, multiple-egg clutches = 1; annual-breeding, single-egg clutches = 2; biennial-breeding, single-egg clutches = 3) and median age at first breeding (< 5 years = 1, 5–7.5 years group = 2, ≥ 7.5 years = 3). Our study did not require equal weighting of the indices, so we simply multiplied the observed age at maturity for a species with the life-history strategy score. These values were then normalised, so that the maximum value was 1. We called this new productivity index the Fecundity Factors Index (FFI).

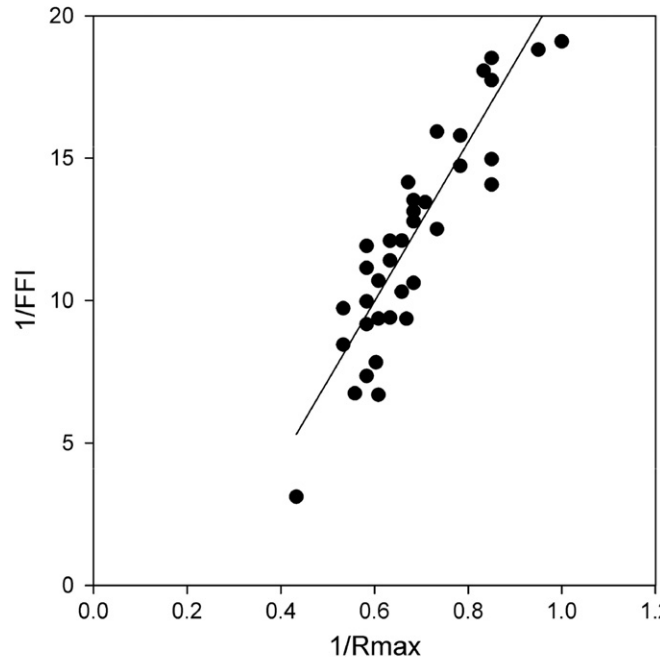

Fig. 5. Comparison of productivity scores between R_{max} method (*x* axis) and FFI method (*y* axis) for 70 species. Inverse FFI values were plotted to provide a comparable metric to the R_{max} (Pearson's $r = 0.91$).

When we compared the values generated from the R_{max} index with the FFI, and found a good correlation between the two indices (Pearson's $r = 0.91$, $P < 0.0001$, $n = 70$) (Fig. 5). This is to be expected to a degree, as both use a common metric of age at maturity. We report PSA results using the FFI method only.

2.3.4. PSA scores

Seasonal risks of adverse effects on seabird populations were calculated by combining both *Productivity* and *Susceptibility* indicators. In previous studies by our team the risk was defined as below [19]:

$$risk = (1/Productivity^2 + Susceptiblity^2)^{1/2} \quad (5)$$

This had the advantage of being the direct measure of the risk scores for a species from the origin of the PSA plot (Euclidean distance). However, following this formulation, in some extreme cases, seabird species with low-productivity, but extremely low susceptibility could be highly ranked, despite very little exposure to fishing events. Clearly, the combination of both parameters has importance in defining the overall risk score, and a means of balancing the weighting of the productivity and susceptibility was sought. To overcome this problem, we defined risk as the product of the two indicators, but noting that the inverse of the *Productivity* score is used so that the axes move intuitively from lowest risk near the origin to higher risk at higher values. In this way, birds with low productivity, but very little exposure to fisheries interactions could not achieve a high risk score:

$$risk = Susceptibility/Productivity \tag{6}$$

We normalised outputs of the overall seasonal PSA, combining both *Susceptibility* and *Productivity* indicators, so that values fell between 0 and 1. Values plotted were also square-root transformed twice to normalise the distribution of the data. Five levels were attributed to the outputs based on the actual frequency distribution of the transformed PSA scores, dividing the range of scores into six groupings, in order to ease interpretation. Negligible levels of risk (0–0.001); low (0.001–0.2); low to moderate (0.2–0.4); moderate (0.4–0.6); moderate to high (0.6–0.8); high (0.8–1.0). The first level (negligible) was set at a low level (0.001) to remove 'noise' from the results, and the remaining scores were divided into five even-sized brackets of risk scores. Risk scores by 5 degree square were calculated as:

$$Risk(area, season) = \sum_{all_{species}} \sum_{all_{flags}} Risk(species, flag, season) \tag{7}$$

Finally, to ease interpretation for fishery and wildlife managers, we present the results in a set of tables and maps. For species, the taxa are ranked in relation to the cumulative risk from the fisheries examined, and for fisheries, the cumulative risk across all species is the ranking variable. To examine risk by area, the cumulative scores of risk for all species is calculated, and mapped by five degree latitude by five degree longitude square. We calculated quarterly maps for the fishery-risk score outputs, and present these, along with quarterly maxima, and average annual scores.

3. Results

The main concentration of fishing effort was in the western tropical zone (Fig. 2) while the centres of Procellariiform seabird diversity (Fig. 1) and density (Fig. 6) were in southern temperate waters. However, despite relatively low fishing effort in the temperate regions, the high vulnerability of species to capture still results in areas for concern in managing seabird–fishery interactions.

3.1. Species of most concern

The species for which the product of their scores along each access axis is greatest were most at risk. Table 2 shows the ranking of species for average annual risk. Among the top 10-ranked species, Northern and Southern Hemisphere large albatrosses predominate (*Diomedea* and *Phoebastria* spp., comprising eight of the top 10 ranked species), along with black petrel, and Chatham Albatross, both species from southern temperate regions. The species that complete the list of top 25 species (or the top 1/3 of species in the analysis) include many smaller albatrosses (*Thalassarche* and *Phoebetria* spp.), larger petrels (*Procellaria* petrels and Giant petrels *Macronectes* spp., and great-winged petrels), one sub-tropical shearwater (Buller's shearwater) and one tropical petrel (Fiji petrel). Species with medium or low risk ranking (ranked 26–69) include many of the gadfly petrels *Pterodroma* and *Pseudobulweria* spp., and small petrels, shearwaters and prions (*Puffinus* and *Pachyptila* spp.) along with grey-headed and sooty albatrosses.

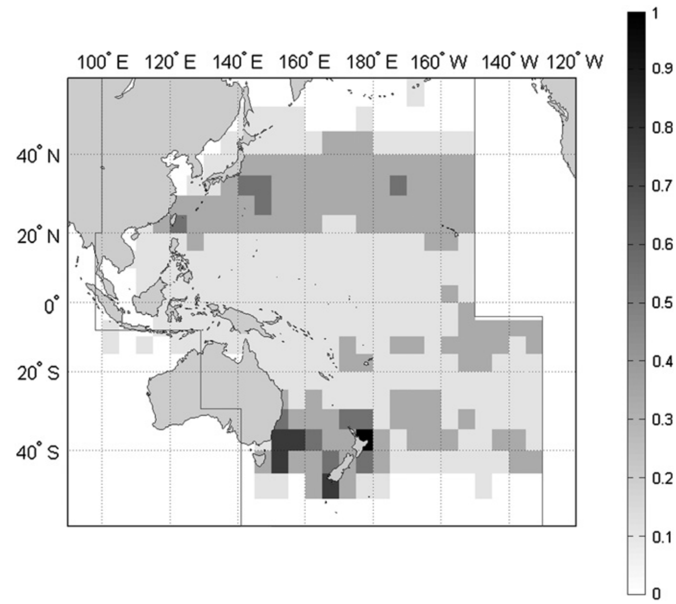

Fig. 6. Annual plot of seabird numbers (individuals per 5 × 5 degree area) for 70 species of albatross and petrel found in the WCPFC Convention Area (log 10 (birds/km^2)).

3.2. Areas of greatest risk of seabird–fishery interactions

The zones that were identified with the greatest risk of adverse effects of fishing mortality on seabird populations were in the temperate areas of the study area (Fig. 7). In the Northern hemisphere, the areas of moderate risk (0.2–0.4) were between 20 and 40°N. In the Southern Hemisphere, the medium- and high-risk areas were mainly between 25 and 50°S. Highest risk areas, when considered on an average annual basis, were to the east and south of the New Zealand mainland, and to the east of Australia.

We further considered risk on a season-by-season basis, as fishing and seabird distributions are known to vary considerably throughout the year. Four seasonal analyses, analogous with the annual analysis, were conducted (Fig. 8). These outputs showed that areas of greatest risk change throughout the seasons. Winter and autumn plots showed a concentration of higher risk areas in the Northern Hemisphere, to the west and east of temperate latitudes in winter, and in the east and central areas in autumn. An additional high risk area to the east of the New Zealand mainland is indicated in autumn. Spring and summer plots showed highest risk areas in southern temperate waters in the west of the WCPFC zone, in temperate areas.

We combined the data from these seasonal plots, and created an output that combined the seasonal maxima for any five-degree square (Fig. 9). In this representation, which gives an overall picture of which five-degree squares may require special consideration for careful bycatch management throughout the year, we note that the areas of moderate risk (0.2–0.4) are spread throughout temperate and eastern tropical waters of the WCPFC zone. High risk areas occur throughout the temperate areas of the Northern hemisphere, and in the east and south of the New Zealand mainland and east of Australia in the Southern hemisphere.

3.3. Fleets contributing to the risk

We summed the PSA scores for each species, and examined which fishing fleets (flags) contributed most risk at an average annual level (Fig. 10). New Zealand was the top-ranked flag,

Table 2
Risk scores by seabird species for WCPFC longline fisheries.

Common name	Code	Threat status (IUCN)	Rank	Risk ranking
Wandering Albatross	DIX	VU	1	High
Gibson's Albatross	GBA	VU	2	High
Southern Royal Albatross	DIP	VU	3	High
Short-tailed Albatross	PHA	VU	4	High
Antipodean Albatross	ANA	VU	5	High
Parkinson's Petrel	PRK	VU	6	High
Northern Royal Albatross	DIS	EN	7	High
Laysan Albatross	PHI	VU	8	High
Black-footed Albatross	PHN	EN	9	High
Chatham Albatross	DER	VU	10	High
Buller's Shearwater	PBU	VU	11	High-to-medium
Buller's Albatross	DNB	NT	12	High-to-medium
Salvin Albatross	DLS	VU	13	High-to-medium
Campbell Albatross	TQW	VU	14	High-to-medium
White-capped Albatross	XWM	NT	15	High-to-medium
Westland Petrel	PCW	VU	16	High-to-medium
Southern Giant Petrel	MAI	LC	17	High-to-medium
Northern Giant Petrel	MAH	LC	18	High-to-medium
Shy Albatross	THC	NT	19	High-to-medium
White-chinned Petrel	PRO	VU	20	High-to-medium
Grey Petrel	PCI	NT	21	High-to-medium
Light-mantled Sooty Albatross	PHE	NT	22	High-to-medium
Great-winged Petrel	PDM	LC	23	High-to-medium
Black-browed Albatross	DIM	EN	24	High-to-medium
Fiji Petrel	PSM	CR	25	High-to-medium
Short-Tailed Shearwater	PUT	LC	26	Medium
Phoenix Petrel	PLB	EN	27	Medium
Beck's Petrel	PSB	CR	28	Medium
Flesh-footed Shearwater	PFC	LC	29	Medium
Audubon's Shearwater	PUL	LC	30	Medium
Pycroft's Petrel	PTP	VU	31	Medium
Grey-Headed Albatross	DIC	VU	32	Medium
Wedge-tailed Shearwater	PUP	LC	33	Medium
Tahiti Petrel	PSR	NT	34	Medium
White-headed Petrel	XWH	LC	35	Medium
Providence Petrel	PTI	VU	36	Medium
Newell's Shearwater	PUW	EN	37	Medium
Collared Petrel	PTB	NT	38	Medium
Christmas Shearwater	PNT	LC	39	Medium
Gould's Petrel	PTL	VU	40	Medium
Sooty Shearwater	PFG	NT	41	Medium
Hawaiian Petrel	PTW	VU	42	Medium
Bulwer's Petrel	BUB	LC	43	Medium
Stejneger's Petrel	PTO	VU	44	Medium
Soft-plumaged Petrel	PTS	LC	45	Medium
Mottled Petrel	XMP	NT	46	Medium
Hutton's Shearwater	PHU	EN	47	Medium
Heinroth's Shearwater	PUN	VU	48	Medium
Cook's Petrel	PTC	VU	49	Medium
White-necked Petrel	WNP	VU	50	Low
Murphy's Petrel	PTU	NT	51	Low
Kermadec Petrel	PVB	LC	52	Low
Henderson Petrel	PTT	EN	53	Low
Chatham Petrel	PTA	EN	54	Low
Black-winged Petrel	PTN	LC	55	Low
Magenta Petrel	PTM	CR	56	Low
Juan Fernàndez Petrel	PTE	VU	57	Low
Little Shearwater	PUA	LC	58	Low
Cape Pigeon	DAC	LC	59	Low
Fairy Prion	XFP	LC	60	Low
Broad-billed Prion	XPV	LC	61	Low
Thin-billed Prion	PAB	LC	62	Low
Antarctic Fulmar	FUG	LC	63	Low
Kerguelen Petrel	LUB	LC	64	Low
Antarctic Prion	PWD	LC	65	Low
Common Diving-Petrel	GDU	LC	66	Low
Blue Petrel	HBE	LC	67	Low
Herald Petrel	PTH	VU	68	Low
Fulmar Prion	PCC	LC	69	Low
Sooty Albatross	PHF	EN	70	Low

followed by Japan, Taiwan, Australia, Vanuatu and United States of America. These six flags contributed 90% of the risk of seabird–fishery interactions in WCPFC fisheries.

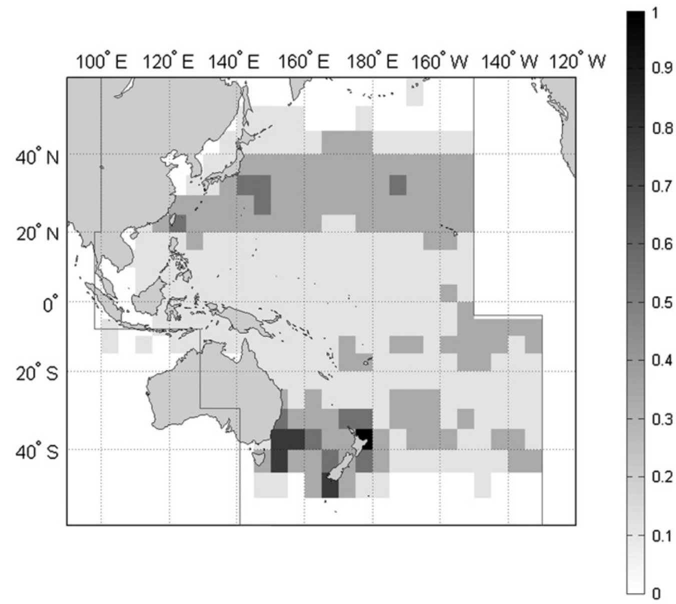

Fig. 7. Annual risk areas for the WCPFC Area. Black—highest risk, white—lowest risk. Risk scores are normalised.

4. Discussion

The key findings of the study were that particular areas of the WCPFC zone are likely to show greater risk of seabird-fishery interactions than others. In particular, the temperate areas in the Tasman Sea and to the east of New Zealand are a particular hotspot for seabird-fishery interactions, as are temperate Northern Hemisphere waters. The importance of these areas varied by season, with southern areas being more prone to risk in spring and summer than northern areas, at a time of year when most southern hemisphere seabirds are nesting, and hence concentrated in areas near to their breeding sites. Conversely, the northern temperate waters show a broad band of medium- to high-risk areas in the Northern Hemisphere summer, again coinciding with the concentration of Northern Hemisphere albatrosses around nesting grounds, but also a time when many Southern Hemisphere petrels migrate to northern waters, in their non-breeding seasons. The one area east of New Zealand that was shown as having high risk in autumn is a zone were many albatrosses congregate or migrate through following fledging in the late first quarter of the year. Many of the Southern Hemisphere albatrosses that were indicated as being at highest risk migrate to the east of the Pacific and the Indian Ocean outside of their breeding seasons. It would be beneficial to analyse risk across all areas of the Southern Ocean, to assess the relative importance of bycatch for migrating species throughout their oceanic habitat.

The areas of medium-to-high risk identified are largely covered by the WCPFC Conservation and Management Measure that defines seabird bycatch mitigation requirements in WCFPC longline fisheries (WCPFC Conservation and Management Measures (CMM2007-04) [7]). The southern hemisphere areas identified fall within the zone covered by CMM2007-04, which operates south of 30°S. However, waters south of the Hawai'ian archipelago in the Northern Hemisphere are only partly covered, as CMM2007-04 operates from 23°N and northward. This may be an issue of data resolution, as fisheries data were only available at the scale of five-degree squares for this study, and this point warrants further investigation for Northern Hemisphere areas.

CMM2007-04 applies only to large longline vessels in the Northern Hemisphere with measures required to avoid seabird bycatch in these areas not mandatory on vessels of less than 24 m

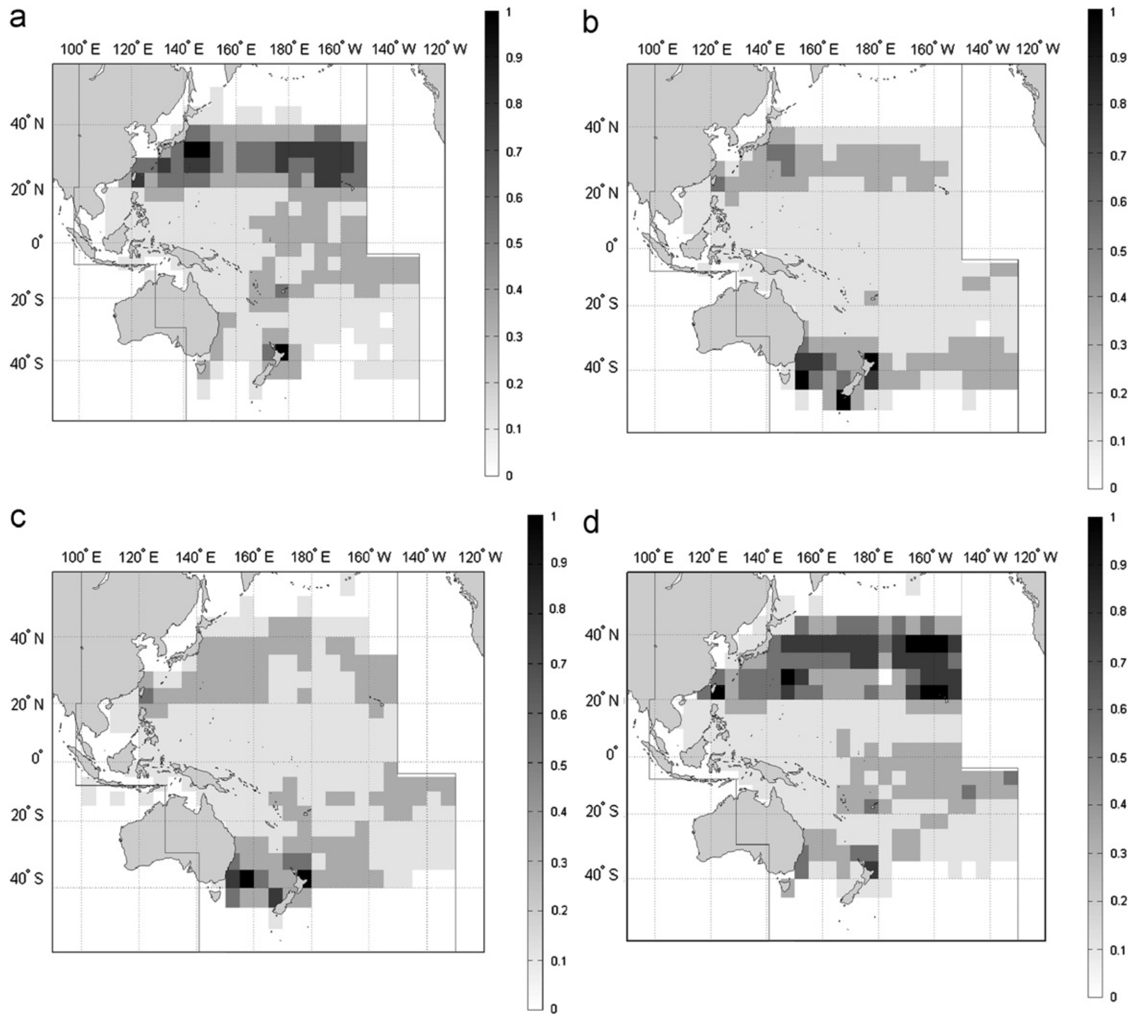

Fig. 8. Four seasonal analyses of risk for 70 species of Procellariiform seabird, showing southern hemisphere (a) winter (June–August), (b) spring (September–November), (c) summer (December–February) and (d) autumn (March–May) and risk scores. Black—highest risk, white—lowest risk. Risk scores are normalised.

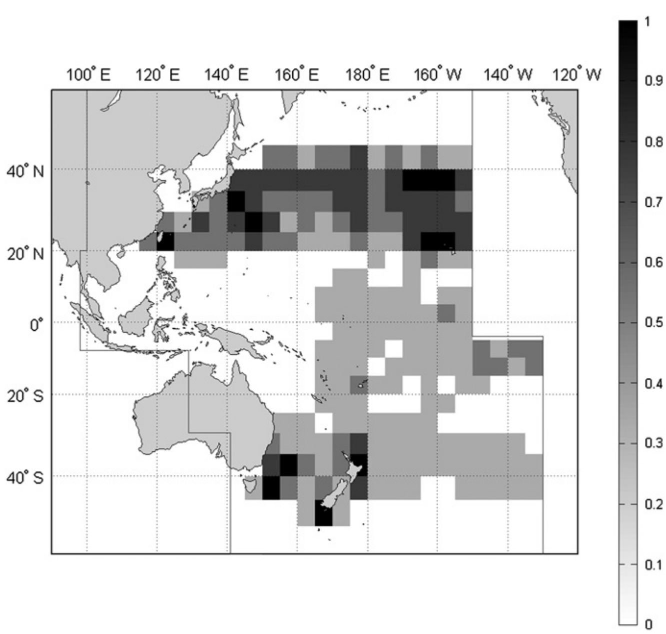

Fig. 9. Quarterly maximum risk scores for each 5×5 latitude by longitude square for WCPFC longline fisheries. Black—highest risk, white—lowest risk. Risk scores are normalised.

in length. The scientific rationale for excluding Northern Hemisphere small vessels from CMM2007-04 is unclear, especially as there is a lack of empirical evidence to demonstrate that smaller vessels are less likely to catch seabirds than large ones.

Albatrosses and large petrels were shown to be the most vulnerable to WCPFC longline fisheries impacts in this study. In particular, the large albatrosses (*Diomedea* and *Phoebastria* spp.), small albatrosses (*Thalassarche* spp.) large petrels (*Procellaria* spp. and *Macronectes* spp.) were found to be particularly vulnerable to population impacts from WCPFC longline fishing. The times of year when these effects were most likely to occur were during the breeding seasons for most of these species, which may have a reinforced effect of resulting in death of nestlings as well as any breeding bird killed during this season. Birds foraging activity during breeding can be highly concentrated, particularly during early chick-rearing phases. At these times, particular populations may be strong affected by fishing activity if their zones of activity coincide. As all of the 10 species most at risk, and all but three of the species listed in the top 25 most at risk species in this study are threatened with extinction, it is an urgent conservation problem to address bycatch of these species.

Relatively few of the fishing nations operating in the WPCFC zone were likely to be affecting seabird populations, with only six flags contributing 90% of the risk. It is therefore feasible to consider targeted monitoring activity in some particular areas and fleets to address any potentially damaging bycatch. The contribution of

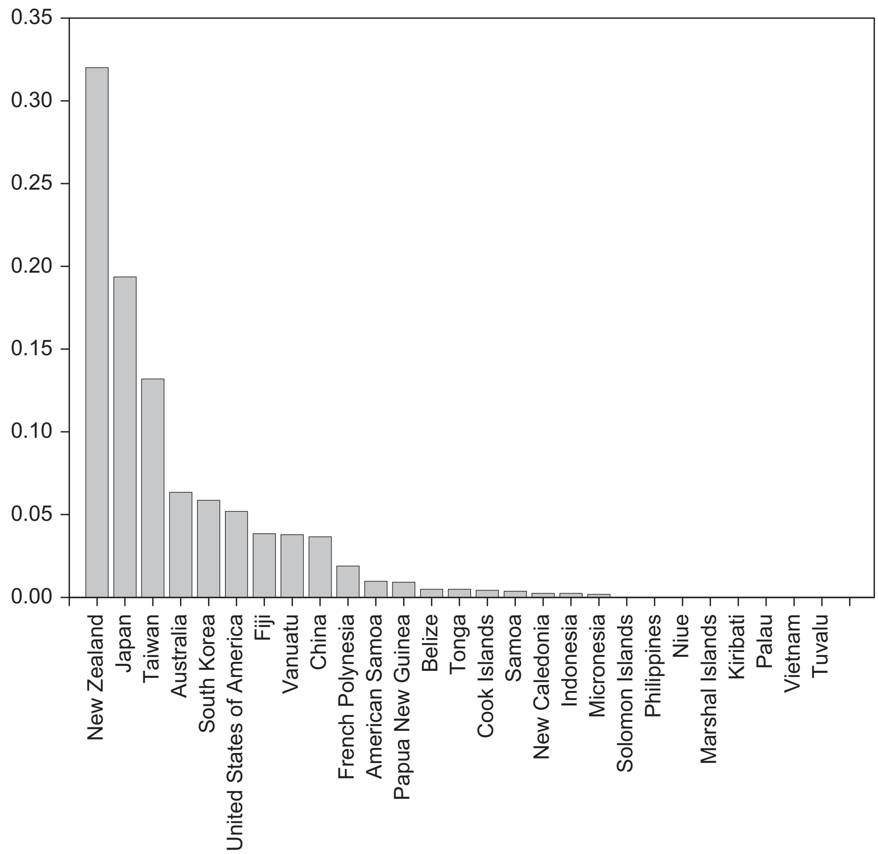

Fig. 10. Percentage of risk for WCPFC longline fisheries by flag for the average annual analysis.

illegal, unreported and unregulated (IUU) fishing to seabird bycatch is unknown, as this is poorly quantified for WCPFC fisheries. Even in CCAMLR fisheries, where estimates of catch of IUU fishing are developed annually, bycatch of seabirds from this source was not included in ERA research outputs due to lack of detail about season and locality of IUU fishing [21].

4.1. ERA work in the context of RFMO fisheries management

This study shows that even with basic information about species and fishery activities, it is possible to identify areas and groups of vessels that can be targeted for increased monitoring and mitigation efforts. We used a set of information about species, which should be available for many fishery situations globally, even for species and areas where there has been little direct research undertaken. Fishery data used in this study is at a spatial and temporal resolution that should be available in most regions; i.e. monthly records of 5×5 degree longitude and latitude. If finer scale information is available, more targeted outputs can be generated. Data about catch of species, or their relative propensity to interact with fishing gear may be lacking in some areas, but we considered that use of data from similar fisheries (here New Zealand metrics were used) or expert opinion on catchability of species (as used in Atlantic studies of a similar nature [28]) is appropriate.

The Pacific Region is a very important area for seabird conservation, with 60% of the world's seabird species, and a high proportion of seabirds occurring in this region are threatened with extinction. RFMOs such as the WCPFC play an important role in contributing to conservation of marine resources and marine-dependent species. The latter part of the 20th Century saw international law-makers define many environmental standards and set in place principles for management of shared resources such as the Convention on Migratory Species, the Convention on Biological Diversity, the Agreement for the Conservation of Albatrosses and Petrels, the Fish Stocks Agreement, and the FAO's Code of Conduct for Responsible Fisheries. RFMOs are some of the primary institutions through which the principles of these agreements are put into practice.

In 1999, the Food and Agriculture Organisation of the United Nations published an International Plan of Action for seabirds [11] and in 2008 defined a set of guidelines, identifying best practice in management of seabird mortality in longline and other fisheries, noting that these approaches were equally applicable in national fisheries management systems and RFMOs [10]. Assessment of seabird mortality problems for a fishery was one of the fundamental steps identified by this guideline. This was recommended for all longline, gillnet and trawl fisheries. Monitoring of mortality and implementation of appropriate mitigation strategies on board vessels were other key steps. ERA studies such as the one described here are a vital tool in assessing where bycatch in fisheries poses a conservation problem, and help to target monitoring and mitigation activity. This approach has been adopted in some national fisheries, and forms the basis for management actions [35].

The ERA approach explored in this study is a semi-quantitative one, using a mix of readily-available biological parameters and low-resolution fishery data, to allow a wide coverage of species and areas of interest. More complex approaches, involving dedicated modelling efforts and long-term datasets are justifiable for some particular species–fishery interactions, such as those where a single fishery is likely to impact a particular species. The approach explored here allows managers to address questions in broader context, such as

- Which species out of a suite of several are most likely to be experiencing adverse effects of fishing mortality?

- Which fisheries out of several operating in an area are most likely to be contributing to impacts for non-target species populations?

Alternative approaches may be more appropriate for other management contexts. For example, in New Zealand domestic fisheries, methods have been developed that examine the availability of individuals from populations to capture and assess the likelihood that sustainable levels of take are exceeded, as a means to prioritising research and monitoring activity (Ministry of Fisheries, unpublished reports). In the appropriate management context, where species are protected by legislation, and a policy mandate enforces continual reduction of non-target take as a management objective, such an approach may be justifiable, and serves as a method of prioritising management actions. However, these methods rely on ongoing collection of detailed observer data of non-target catch rates and species composition, and demographic modelling requiring a high number of assumptions about species biology to be met, and/or long-term and high quality datasets.

In a precautionary management context, where the availability of good quality information is limited, less detailed but robust methods that allow targeting of monitoring or mitigation are entirely appropriate, as envisaged in the FAO Code of Contact for Responsible Fisheries [5]. This is particularly the case where the data required to develop more complex analyses are prohibitively time-consuming or expensive to obtain.

The metrics derived by the study do not replace estimation of bycatch; rather they indicate where relative likelihood of catch may be more or less important, for a given species, area, fishing method or flag. They can therefore be seen as complimentary to detailed bycatch estimation work.

4.2. Shortcomings and limitations of the approach

We recognise that the approach used here may be criticised as it does not use the most sophisticated modelling approaches available, or fully explore one or two very detailed datasets which exist in relation to a few seabird species covered in this study. Nor does our approach attempt to assess uncertainty. There are shortcomings inherent in the dataset such as the lack of precision in species distributions or population size estimates. We contend that for a broad-brush approach that attempts to assess information about a suite of species, some of which are very poorly known, the approach used is adequate and useful. It may also be instructive to explore high-quality datasets by alternative modelling methods. Studies, which incorporate uncertainty in the model outputs may also be useful, but for the type of analysis presented here, some simple sensitivity assessments can be carried out by including alternative plausible parameter estimates.

Our initial research in this area [19,20] followed the principles of the Hobday et al. approach [15], with the key divergence from their methodology being that we used best average estimates for parameters, whereas the Hobday et al. [15] advocated for use of a high-risk rating where information was lacking or uncertain.

In order to avoid correlation between the two axes of the PSA we have avoided using aggregate descriptors of species status, such as IUCN rankings, as these often combine multiple factors about a species, such as its range, abundance, population size and trend, many of which we have described discretely. We examined two methods of assessing productivity for populations. One required data relating to average annual survivorship of species ($R_{\max}$ method), information, which is available for only a very few populations by direct estimation. The other used data on clutch-size, breeding frequency and age at maturity (FFI), which are easier and more robust measures to obtain in the field, and are in large part deterministic for seabirds. There was a strong correlation between the two indices, and little influence on the outputs of the study between the two approaches. We therefore recommend that the simpler, more robust measure of Fecundity Factors Index be applied in further ERA studies of this type.

Our approach assumes that sets by all fishing fleets have equal likelihood of capturing birds. This is unlikely to be true. However, information is lacking to provide finer definition of the relevant parameters. This would require detailed reporting on the mitigation used and catch of species in specific fleets, data which in the case of WCPFC fisheries are required to be collected from 2011 onwards. Further, reporting of event-by-event details of fishing activity are not yet a requirement under this Fishery Commission, with members of WCPFC reporting annual catches and summary details of mitigation only in their annual reports. To better understand individual catch problems and fleet-specific solutions, both detailed data collection and reporting is required.

We consider that ERA studies should be conducted iteratively, to incorporate new information as it becomes available. Changing fishing practice should be assessed, as should new information about the distribution of species and the status of their populations. We consider that for fisheries where our study indicates a high potential for seabird interactions, more detailed research should be initiated, including recording current fishery practice, mitigation efficacy, and detailed recording of the catch composition and magnitude of seabird bycatch. Likewise, it would be desirable to conduct monitoring of the populations and their fishery interactions, for those species whose populations are most likely to be impacted by fishery activity, such as the albatrosses, *Procellaria* petrels, giant petrels, Buller's shearwater and Fiji petrel.

5. Conclusions

In respect of management of seabird mortality in WCPFC fisheries, the study highlighted several important factors:

1. Risk is not evenly spread among the fishing nations participating in the fishery. A mix of coastal states (where seabirds occur within EEZ waters, such as New Zealand, Australia and United States of America) and distant water fishing nations (e.g. Japan, Taiwan) and flags of convenience (Vanuatu) contribute important proportions to the overall risk. Therefore managing the problem of seabird bycatch can be seen as a global issue, requiring cooperation among nations. Targeting of observer coverage on these fleets would be desirable. A pilot observer programme to gather such data was discussed in 2010 at the WCPFC Commission meeting, but has not yet to be implemented [36].
2. Risk is not simply proportional to the amount of fishing effort in the region, as differential vulnerability of species, and populations' ability to recover from occasional removals leads to effects being concentrated in some areas more than others. Areas where species with high vulnerability and low productivity coincided with even moderate levels of fishing effort were identified as the highest risk areas in the WCPFC zone. These were in the temperate Northern Hemisphere from 20 to 40°N, and in the Southern Hemisphere from 30 to 50°S. This area roughly coincides with the zones specified for seabird conservation measure CMM2007-04 of the WCPFC [7], but further examination of the zones of overlap of Northern Hemisphere albatrosses and fishing effort south of 23°N may be warranted.
3. Specific hotspots of seabird–fishery interaction varied seasonally, and highlighted the importance of using a seasonal-based

approach. The seasonal approach we applied identified a wider set of high-risk areas than the average annual outputs, although largely in the same general zones (temperate areas). However, a wider spread of areas in the Northern Hemisphere was identified as having a high to medium level of risk seasonally than on an average annual basis, highlighting the need for measures and monitoring to be applied in this area. Currently in WCPFC fisheries, Northern Hemisphere fleets of vessels (in particular vessels less than 24 m in length) are exempted from mitigation measures [7]. We would recommend that best practice mitigation measures be required in any medium-to-high risk areas of the WCPFC Convention Area, identified at a seasonal level. Best practice mitigation is recommended in all RFMOs by the FAO Best Practice Guideline [10].

4. Some EEZs (or parts of EEZs) that comprise part of the WCPFC Area, with a long history of managing seabird bycatch (e.g. Australia and New Zealand) are also identified as high-risk areas. It would be appropriate for best-practice mitigation, such as that applied in New Zealand and Australian longline fisheries (including combinations of night setting, line weighting and streamer lines) to be a requirement in the wider suite of high-risk areas within the WCPFC Convention Area. Current WCPFC requirements allow room for a suite of other, possibly less effective measures to be used in WCPFC fisheries [37]. In the spirit of precautionary management of seabird mortality in medium-to-high risk areas, we would recommend at least two measures among the following be applied (line weighting, night setting, streamer lines) in these areas, until monitoring data are available to assess the nature and extent of seabird bycatch in these zones.

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