

Short communication

Dynamic enforcement of bycatch via reproductive value can increase theoretical efficiency



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ARTICLE INFO

Keywords:

Bycatch
Dynamic enforcement
Dynamic ocean management
Monitoring
Reproductive value
Albatross

ABSTRACT

Managing marine systems is challenging, as many marine species are highly mobile. Albatross exemplify this paradigm, overlapping multiple threats at sea, including bycatch. The typical characterization of bycatch, the number of individuals, ignores the long-term, population-wide repercussions of bycatch. Including an estimate of the reproductive value (RV, the loss of future reproductive contributions, given bycatch) is a complementary tool, incorporating the population-wide repercussions of bycatch. While bycatch management via dynamic spatial management allows management boundaries to move, it requires monitoring and enforcement to be effective. We provide a proof of concept to optimize bycatch enforcement activities by dynamically targeting areas of concentrated future productivity characterized by RV. This paper examined a population of black-browed albatross (*Thalassarche melanophrys*) as a case study. We calculate RV and apply it to at-sea distributions. This creates spatiotemporally explicit surfaces used to prioritize times and locations for bycatch mitigation enforcement. Dynamic enforcement has greater theoretical efficiency than static enforcement, but this difference decreases with increasing population-wide RV subject to enforcement. Though there are implementation challenges, many can be reduced with existing tools providing various opportunities. Incorporating RV when characterizing the impacts of bycatch on a population and strategically applying dynamic bycatch enforcement based on RV can be a powerful, efficient component of dynamic ocean management.

1. Introduction

Marine systems are challenging to manage as many marine species are highly mobile and have spatially extensive ranges. This ability to cover broad areas, potentially resulting in threats occurring across multiple political or management jurisdictions is true for most albatross species. Albatross are seabirds that can cover 1000 s of km during a single provisioning event and can encounter a diverse array of conservation threats. Perhaps the most ubiquitous threat at sea for albatross is mortality from bycatch events in commercial fisheries, which have contributed to multiple population declines [1]. Increasing awareness of

the issue has promoted the development of best management practices for bycatch mitigation and fishery-specific solutions [2–4]. However, the level of compliance with mitigation measures is not characterized in many fleets, hindering mitigation efficacy and subsequently leading to continued exposure of albatrosses to bycatch across broad scales [1,5].

To effectively mitigate bycatch, its magnitude and impacts need to be measured, generally characterized by the number of individuals caught during an event or bycatch rate, per-hook, or per-target species. These metrics do not consider future, long-term impacts. Quantifying the loss of future reproductive contributions due to bycatch would provide a more holistic and relevant, though not a replacement, metric for

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characterizing population-wide bycatch impacts. Specifically, the reproductive value (RV) quantifies the loss of all future reproductive contributions for individuals in a population given age and sex, describing their respective contribution to the population [8]. Values are typically low for very young individuals, peak around the onset of sexual maturity, and decline with age [9].

The RV has been applied in a range of management contexts within the marine environment and has proved to be a novel, informative tool. In sharks, it has been used to investigate the population-level impacts of different harvest strategies on target species [6]. The RV of logger-headed turtles was used to estimate the impacts of bycatch [7]. Fisheries managers are aware of the significant, disproportionate reproductive contribution of older females in some species, known as BOFFFs: big old fat fecund female fish [8]. Some have even compared more common fisheries management targets to RV and advocated a role for RV in setting conservation priorities [9].

While the work above has used RV to assess the impacts of bycatch, none have applied it to albatross. Furthermore, combining RV with known at-sea distributions of albatross would provide an explicit description of RV across their marine range. The resulting information could be used to apply bycatch management activities. This characterization of RV across space could be viewed at a temporally fine, monthly 'dynamic' resolution, or the same data could be summed in space through the breeding cycle, providing a temporally broad, 'static' characterization of RV. This spatiotemporally explicit RV could be used as a metric to define the management thresholds guiding the placement of enforcement effort. Moreover, targeted enforcement of mitigation compliance, surveillance, and monitoring of fishing activities, hereafter 'dynamic enforcement,' could focus on areas with high cumulative RV.

Dynamic enforcement could be applied within a dynamic ocean management (DyOM) context. This spatially and temporally targeted approach to management has become a valuable tool in bycatch and fisheries contexts as it incorporates the dynamic nature of the marine environment [10–12]. Research also indicates that relatively fine-scale fisheries closures can be more efficient at meeting management thresholds than broad-scale closures [13]. Identifying relevant metrics to define management thresholds is critical to implementing and assessing DyOM. Though often implicit, enforcement is vital to the success of DyOM [14]. Dynamic enforcement is a natural and essential partner to DyOM and could be applied based on RV's spatial and temporal distribution.

We characterize the spatial distribution of RV across the marine range of an albatross population and explore the trade-offs in theoretical enforcement efficiency (time per area) of dynamic (monthly allocation) versus static (annual allocation) enforcement. Our analysis involves two objectives: 1) assess how monthly dynamic versus annually aggregated static characterization of RV impacts the spatial and temporal distribution of RV, and 2) understand the theoretical efficiency of dynamic enforcement allocated based on the dynamic versus static characterization of RV above. Using black-browed albatross *Thalassarche melanophris* breeding on îles Kerguelen as a case-study, we present a proof of concept for the application and relative benefits of dynamic enforcement allocated based on the distribution of RV. We describe theoretical efficiency as relative as opposed to absolute value. Acknowledging challenges in its broader application, we highlight tools and examples of recent work that can be leveraged, producing opportunities, including the potential for multi-species application of dynamic enforcement based on RV.

2. Materials and methods

2.1. Population context

Since the late 1970s/early 1980s, the population has overall remained stable at Kerguelen, with a period of relatively low numbers from about 2002–2015. The number of breeding pairs shows important

inter-annual variations, which is, in part, due to climate sensitivity in both the breeding and wintering grounds and fisheries bycatch [15–17] and fisheries bycatch. Bycatch monitoring is performed by the Muséum National d'Histoire Naturelle in collaboration with Terres Australes et Antarctiques Françaises as part of the management of the Patagonian toothfish fisheries in the French EEZ around Kerguelen and Crozet, ~1400 km northwest of Kerguelen. In contrast to Kerguelen, the black-browed albatross population on Crozet has notably declined [18]. Bycatch numbers are also reported to Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) and Terres australes et antarctiques françaises (TAAF) and recorded when ringed specimens are reported or received.

2.2. Data sources

Data were obtained from a range of sources described below.

2.2.1. Demographic data

Demographic data are the same as those used in [19]. These data were annually collected from 200 albatross nests in a colony of approximately 1000 pairs at Cañon des Sourcils Noirs, Kerguelen (48° 14'S 68° 13'E) [20]. Albatross were ringed since 1967, and capture-mark-recapture has been undertaken annually during the breeding season since 1979 and used to measure age, sex, breeding status, and breeding success. Both Centre d'Etudes Biologiques de Chizé-Le Centre National de la Recherche Scientifique (CEBC-CNRS), with support from the French Polar Institute as part of the long-term program "Seabirds and marine mammals as sentinels of global changes in the Southern Ocean", and the Réserve Naturelle Nationale des Terres Australes monitor population counts. The CEBC-CNRS also operates the capture-mark-recapture program.

2.2.2. Sea-surface temperature data

Sea-surface temperature is known to impact this population's breeding success (e.g. [21]). The model used to project the demographics of the focal population (explained below) assumed a previously characterized positive linear relationship of SST with breeding success [19]. To incorporate the potential impacts of future temperatures on this population, we used forecast SST from the BLUELink model [22]. This model is based on corrected output from the CSIRO Mk.3.5 output, forced by the A1B scenario for the 2060s [23].

2.2.3. At-sea distribution

The distribution of birds at sea during the breeding season (October through April: Austral summer) is closely associated with the Kerguelen Plateau, particularly the eastern shelf. Non-breeding (Austral winter) at-sea distribution occurs, south of Australia, with some birds traveling to western New Zealand or southwest of South Africa [24]. Seasonal at-sea distribution was modelled as time-spent-per-square (TSS; [25]), which converted tracking data to gridded data and defined the proportion of time spent by each bird within a 2° cell to account for Geolocation error [26–29]. Fifteen unique TSS layers were created based on known sex, breeding status, month, and age class. Age and class-specific distributions included juveniles, immature, adult: breeding, current failed breeder, non-breeding previously failed breeder, non-breeding previously successful breeder. See Appendix [Fig. A.1a–u] for further details. Classes were identified through the demographic monitoring program and capture-mark-recapture program at the colony. These gridded data were then applied across relevant months [Table A.1].

2.3. Integrated population model

To obtain the parameters required to estimate population-wide RV, we applied an integrated population model framework to estimate demographic rates. This framework allows multiple time-series of observational data: breeding success, survival rates, bycatch mortality

observations, etc., to be simultaneously estimated in a single maximum likelihood estimation framework [19,30]. We assume a closed system. The current study utilized parameter estimates for the focal population obtained by Michael et al. [19], projected them into the future, and calculated age- and class-specific numbers by month to estimate RV in space and time (below). Specifically, we included mortality (adult and pre-breeding), productivity, and density dependence [Table 1]. As RV is intended to guide the application of dynamic enforcement of bycatch mitigation, as opposed to the trajectory of the population given projected bycatch (e.g., [31]), we characterize RV in the absence of bycatch. Including bycatch in RV would create a circular argument, with dynamic enforcement effort allocated away from areas of high bycatch due to reduced RV caused by the estimated bycatch. The model was run from 1997 through 2067.

2.4. Reproductive value calculation

The RV can be calculated in many ways [32]. To calculate RV, we adapted definitions previously applied to wild bird populations [33,34], permitting non-stationary dynamics, following:

$$RV_a = \sum_{x=a}^M \frac{l_x}{l_a} r_x s_x \quad (1)$$

Here, RV is the reproductive value at age a , M is the last age of reproduction, l_x is survival to a given age, l_a is survival at current age a , r_x is the probability of attempting to breed in a given year, and s_x is the probability of breeding successfully in a given year. The RV was calculated for each class and month then distributed across space relative to the corresponding at-sea distribution (TSS layer) assuming a constant, class-specific age distribution. For details on RV, numbers at age, and assumption impacts, see B.1 (Fig. B.1, B.2).

2.5. Characterizing RV and dynamic enforcement

The following objectives guide our assessment of RV.

2.5.1. Distribution of monthly dynamic versus annually aggregated static RV

To investigate how the temporal scale used to summarize population-wide RV would impact the spatial and temporal distribution of RV (objective 1), we compared the population-wide percent of RV (% RV) at two different temporal resolutions: monthly and annual. As each class's RV reflects the number of individuals in that class, the % RV is calculated by summing the RVs of all classes for each grid at the corresponding temporal scale. These values were scaled to a percent of the

Table 1

Demographic parameter estimates derived from the integrated population model used in [19] were then projected to calculate the reproductive value (RV) in the current study. All bycatch parameters in the current study are set to 0. Therefore, reproductive value estimates assume no bycatch. Demographic information to this level of detail is not a prerequisite to estimate RV.

Parameter	Study	
	[19]	Current
Number of birds in the population	1107	1107
Mortality		
adult		
juvenile, immature	8.8	8.8
chicks, density dependent	0.551	0.551
SST slope	chick mortality during incubation	–0.552
Productivity		0.551
Bycatch rates		0.551
	Japanese pelagic longline	3.58E–10
	other pelagic longline	3.58E–10
	demersal longline	5.92E–10
	trawl	7.55E–08
	illegal, unreported, unregulated	1.57E–08

total RV, where all grids across all months sum to 100% at the monthly resolution and all grids at the annual resolution sum to 100%. We hypothesized that relative peak in % RV would be similar across temporal scales. However, variability in the timing of departure from the breeding colony, relating to age class and breeding status, would distribute moderately high % RV across the population's range at a monthly relative to the annual resolution.

2.5.2. Dynamic enforcement efficiency

We assessed characterized the theoretical enforcement efficiency: percent of % RV per kilometer² *month under dynamic enforcement (objective 2; (Table 2)) using the following equation:

$$\text{theoretical efficiency} = \frac{\% RV}{\text{area} * \text{months} \text{ subject to dynamic enforcement}} \quad (2)$$

with the denominator approximating costs, producing %RV per km²month. This can also be thought of as relative cost-effectiveness. The exact costs associated with implementing dynamic enforcement would involve additional factors, such as the extent to which existing management frameworks can be used versus the establishment of new enforcement infrastructure and potentially incentivizing participation in collaborative enforcement. Costs could differ relating to spatial and temporal factors linked with the above, physical location, and seasonal variation. While not comprehensive, our approximation of costs defines an investment in enforcement that is easy to understand and avoids assumptions related to the above's relative or absolute costs, which could be associated with additional enforcement.

To track the difference in relative theoretical efficiency of dynamic enforcement using the population-wide percent of monthly and annually aggregated % RV, we assessed a range of dynamic enforcement targets. A dynamic enforcement target is the minimum % RV that management aims to protect under dynamic enforcement. For example, if the dynamic enforcement target was 20%, dynamic enforcement would be allocated to the minimum number of grids which sum to a minimum of 20% RV. At the annual resolution of % RV, we assumed spatial enforcement was constant throughout the year, i.e., a given location is subject to enforcement for 12 months. Data sources and definitions are summarised in Table 2. All analyses were performed using R version 3.6.0, with 'trip', 'adehabitatLT', 'sp', and 'tidyverse' packages used in data processing [35–40].

3. Results

3.1. Distribution of monthly versus annually aggregated % RV

To investigate differences in the spatial distribution of % RV at monthly dynamic versus annually aggregated static resolutions (objective 1), we visually compared annually aggregated values to months representing different stages of the breeding cycle (Fig. 1a–d). When annually aggregated, the greatest % RV was broadly distributed around îles Kerguelen and southeast of Australia (Fig. 1a). Relatively high values occurred on the Kerguelen plateau, extending north, slightly west, and into the EEZ around île Amsterdam. Similarly, high % RV was also generally centered northwest of Tasmania. These high values span the central and southwest Great Australian Bight, around Tasmania, extending south to nearly 60° S.

At a monthly resolution, the location of elevated % RV shifted and occurred in similar locations with a much smaller footprint relative to annually aggregated values (Fig. 1a–d). During the breeding season, % RV was concentrated around the Kerguelen plateau, slightly to the east (Fig. 1b). At the end of the breeding season, the % RV around the Kerguelen plateau decreased and slightly increased off northwest Tasmania relative to the breeding season [Fig. 1b, c]. By the middle of the non-breeding season, % RV values were distributed west and northwest of

Table 2

Summary of data sources and analysis as relative to Michael et al. [19] and key terms defined in the current study. ‘SST’ indicates sea-surface temperature. ‘Further details’ indicates the corresponding manuscript section.

Data or term	[15]	Source	Analysis	Further details
Data		Current study		
albatross demographics	mark capture-recapture analysis	same used in [19]	parameter estimates used in [19]	Section 2.2.1, Section 2.3, Table 1
SST	NOAA 1° monthly optimum interpolation dataset	Forecast, BLUELink model [22]	linear interpolation	Section 2.2.2
albatross at-sea distribution	time spent per cell	same used in [19]	increased resolution from $5^{\circ} \times 5^{\circ}$ to $2^{\circ} \times 2^{\circ}$	Section 2.2.3, A.1, Table A.1, Fig. A.1a–u
bycatch	published literature or reports	assumed absent	assumed absent	Section 2.3, Table 1
Term	[19]	Current study	Analyses	Further details
RV	not calculated	same parameter estimates as in [19], Eq. (1)	equations in published literature [33,34]	Section 2.4, Table 2
dynamic enforcement	not used	defined by authors	temporally and spatially dynamic application of enforcement measures	Section 2.5, Table 2
enforcement target	not used	defined by authors	management target for population-wide % RV under dynamic enforcement; minimum area	Section 2.5.2, Table 2
theoretical enforcement efficiency	not used	defined by authors, Eq. (2)	percent of RV per km^2/month under dynamic enforcement	Section 2.5.2, Table 2

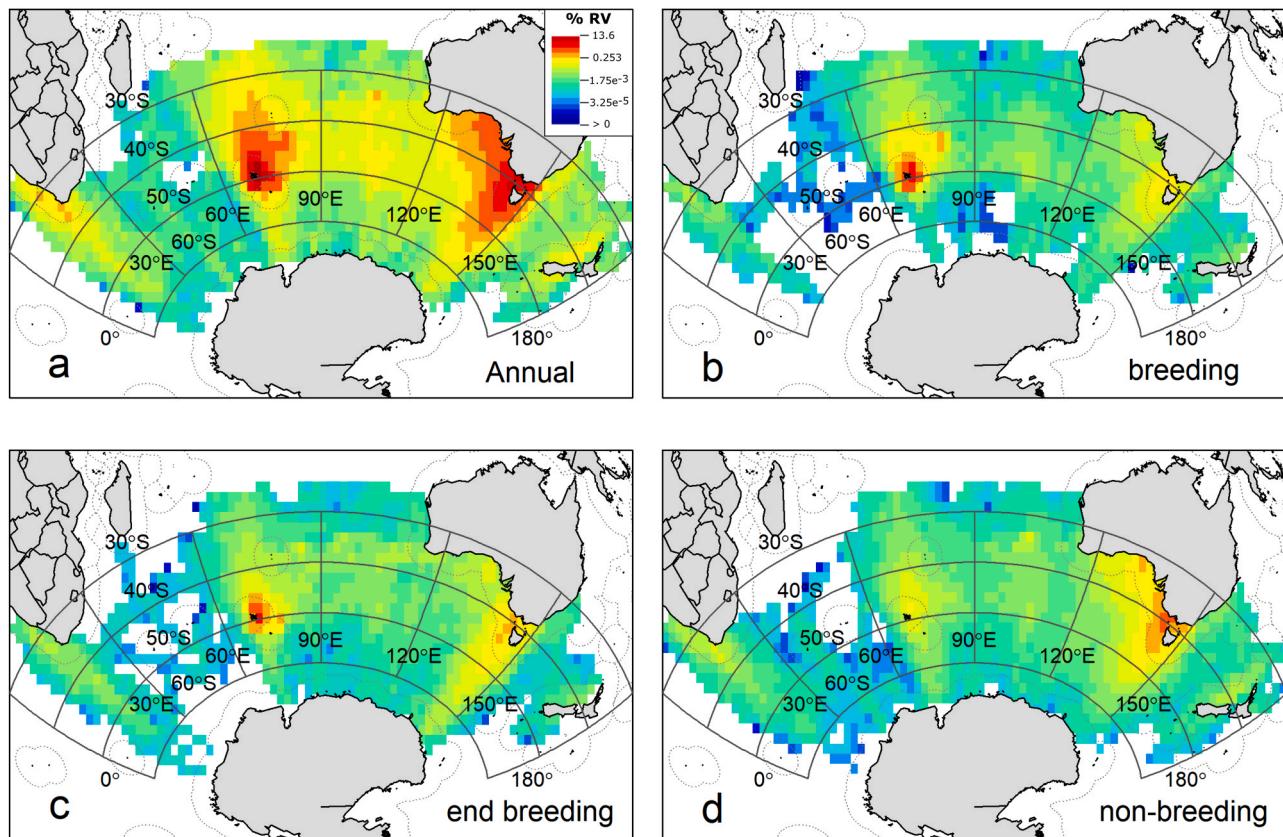


Fig. 1. The distribution of the (a) static, annually aggregated, and (b – d) dynamic monthly (breeding = October, end breeding = April, non-breeding = September) population-wide percent of reproductive value (RV, Eq. 1). At-sea distributions of the monthly % RV are shown in the Appendix [Figs B.4a–l]. Grey dotted lines are exclusive economic zones. The percent of RV was calculated by month and location, with all months and locations summing to 100 (%).

Tasmania and into the eastern Great Australian bight (Fig. 1d). Key terms are defined in Table 1. See Appendix for the spatial distribution of each class and season combination (Fig. A.1a–u), distribution at age (B.1, Fig. B.1), by class (Fig. B.2), age-specific RV by class (Fig. B.3), and the spatial distribution of % RV (Fig. B.4).

3.2. Dynamic enforcement efficiency

Our assessment of the relationship between the theoretical efficiency

(%RV per km^2/month) of enforcement across a continuum of enforcement targets indicated the theoretical efficiency of dynamic, monthly over annually static % RV (objective 2) was greater at small targets but declined exponentially (Fig. 2). The theoretical efficiency of using dynamic monthly versus annually aggregated % RV was very high at small enforcement targets; > 15% RV and remained slightly greater from 15% to 25% RV. Monthly theoretical efficiency relative to annually aggregated was minimally greater from 25% to 40% RV and essentially equal at > 40% RV.

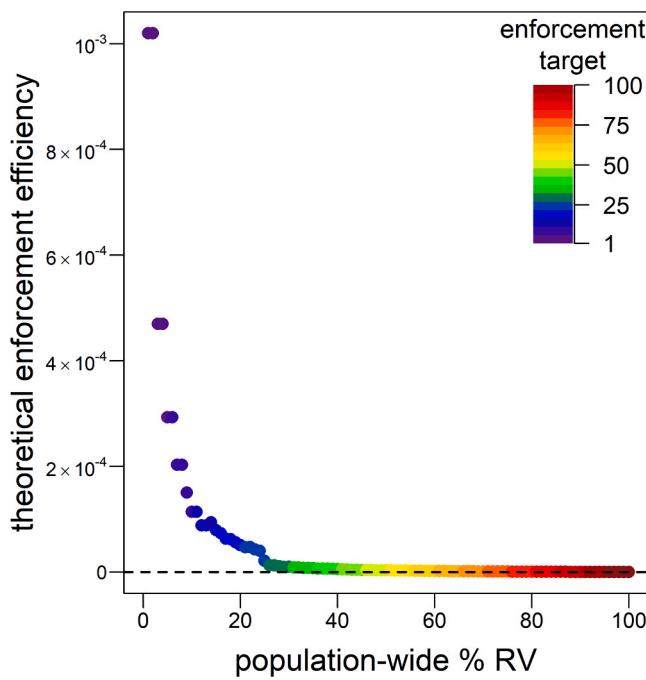


Fig. 2. The theoretical efficiency (Eq. (2)) of dynamic (monthly) minus static (annually aggregated) enforcement based on the population-wide percent of RV across a range of enforcement targets. The enforcement target is indicated by the color bar. Theoretical efficiency is defined as %RV per km²month. The % RV and enforcement target are closely related [Section 2.5.2, Table 2] but can differ when the area required to encompass a given enforcement target covers a greater %RV.

4. Discussion

We provide a proof of concept to optimize bycatch enforcement activities by dynamically targeting areas of concentrated future productivity characterized by RV. Using RV as a spatiotemporal tool to guide the distribution of bycatch mitigation enforcement efforts builds upon earlier work characterizing RV's impact on populations and applying RV and reproductive potential as a monitoring and management tool [6,7, 9]. Incorporating projected productivity via RV provides a more accurate characterization of the potential impacts of bycatch or other mortality events on a population than the traditional approach of quantifying the loss of individuals [32]. Moreover, our approach reduces the footprint of dynamically managed areas, increasing efficiency while still meeting management targets [13].

Others have also found that non-static enforcement can be more efficient than temporally or spatially static enforcement [41–43]. While theoretical efficiency was greatest with the smallest enforcement targets, we caution that the smallest targets may not be sufficient to sustain this or another population or to meet DyOM aims. Defining actual versus theoretical efficiency and identifying a target appropriate for any DyOM scenario would involve considering and balancing many costs and additional factors. These factors include but are not limited to other species or habitats of interest, territorial and legal obligations, and human impacts [41,42,44]. Depending on these circumstances, it may be unrealistic or infeasible to enforce bycatch mitigation in some situations. The magnitude and distribution of fishing effort and fleet-specific bycatch rates would need to be considered as well. Nevertheless, we have demonstrated that including temporal variation in the spatial dynamics directing enforcement effort increased theoretical efficiency relative to static enforcement allocated based on annually aggregated % RV.

4.1. Addressing challenges and creating opportunities

There are many challenges to operationalizing the approach presented here as well as opportunities once put into force.

4.1.1. Quantifying RV and spatial distribution

While we applied a highly detailed demographic model, RV can be estimated and informative with less detail. The number of classes could be reduced, recruitment, productivity, and survival rates could be approximated based on the current state of knowledge, historical observations, or populations suspected to have similar demographic rates. Instead of using Eq. (1), any of a range of approaches, such as those outlined in Kindvater et al. [32], could be used to calculate RV depending on the information available. Fine-resolution spatial distributions can be costly to obtain, but 'assumed range' maps could be used. There is always the potential to add greater detail, but it is often not a prerequisite to providing valuable insight, provided it is considered along with the associated assumptions. As with all data informing management decisions, it is critical to periodically, if not continuously, re-evaluate and update the information characterizing RV and spatial distributions to the extent possible.

4.1.2. Collaboration, implementation, and maintenance

For the case-study population, spatially and temporally distinct areas of high RV were identified in regions under French and Australian government management authority. Historical success reducing IUU fishing and continued cooperation, monitoring, and coordinated dynamic enforcement between these nations and fisheries remains critical and supported on the Kerguelen plateau and neighboring maritime areas into the near future [45,46]. The benefits of combining information on bycatch numbers, times, and locations with up-to-date demographics from the capture-mark-recapture program would be two-fold; accurate characterization of the population-wide RV given known bycatch and tracking the fraction of future productivity lost. The latter has been advocated as a metric to characterize harvest impacts on a population [6] and could be equally informative applied to non-harvested populations.

In addition to current collaborations with CCAMLR, spatially overlapping enforcement frameworks in Regional Fisheries Management Organizations (RFMOs), like the Indian Ocean Tuna Commission and the Southern Indian Ocean Fisheries Agreements, could also be leveraged. For example, given the elevated RV outside the Australian EEZ, prioritizing collaborative relationships with these RFMOs could expand the dynamic enforcement footprint while maintaining spatial connectivity. This and similar partnerships could be incentivized by highlighting the potential to advance public perception of participating fisheries by adding this component to existing conservation and ecosystem-based management practices. Maintaining extensive and diverse collaborations is challenging to maintain. Fortunately, critical features and guidance on forming and sustaining collaborative relationships in a marine-based context are growing. It is essential to maintain trust and a shared sense of purpose while addressing contentious issues and acquire sufficient funding [47,48].

Accurately characterizing costs could involve bioeconomic or business models, facilitating the decision-making process [49]. Work with cooperating vessels would likely involve local fisheries management as well as RFMOs and should foster collaborative relationships, which are crucial to successful bycatch reduction and enforcement [12,50]. A shared feature of many organizations involved in IUU fishing reduction is a central agency coordinating and maintaining protocols and rapid communication across organizations [48]. Identifying non-cooperating and IUU fleets will likely involve a suite of surveillance tools, such as aperture and embedded radar, space-based optical imagery, and Electronic Intelligence, and patrol vessels; manned and autonomous [44,51]. Furthermore, all fleets, including IUU, are dynamic and adaptable, capable of shifting effort into areas with a lesser capacity to monitor or

enforce regulations [52]. For parties and vessels spanning the range of participation and compliance, vigilance, and timely response to violations are needed and can be facilitated by cooperation and coordination across the region.

4.1.3. Cross-taxa applications

Prioritization of areas for dynamic enforcement based on the distribution of RV could be applied across a suite of populations, species, and taxa sensitive to bycatch, in the Southern Ocean or other regions. Current demographic information [53–55] with recent tracking syntheses [56,57] could be used to characterize the spatially explicit distribution of RV across a range of taxa. Extensive collaborations and significant investments were required to acquire and analyse these data; synthesizing their spatial and demographic insights will bring additional value. Moreover, the relative cost of bycatch enforcement effort per-population or species could decrease as the number of overlapping species increases. Creating and sharing the resulting synthesis would promote a collaborative, participatory, future-forward bycatch management perspective.

5. Conclusions

Dynamic enforcement is complementary to and a requirement of effective DyOM. The areas and times subject to dynamic enforcement can be based on the population-wide RV, representing the population's cumulative loss via bycatch. Considering the factors involved in broad-scale enforcement, the investment can be optimized and adjusted over time. While bycatch mitigation continues to be a powerful and critical conservation tool, dynamic enforcement of bycatch mitigation can enhance the protection of bycatch prone species or communities in areas where RV, representing the potential future population, is concentrated.

CRediT authorship contribution statement

Pamela Michael: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing. **Chris Wilcox:** Conceptualization, Methodology, Writing – review & editing. **Christophe Barbraud:** Data curation, Writing – review & editing. **Karine Delord:** Data curation, Writing – review & editing. **Michael Sumner:** Visualizations. **Henri Weimerskirch:** Data curation.

Data Availability

Data entered into the integrated population model used to calculate the RV are available upon request.

Acknowledgments

We are particularly grateful to all the field workers involved in the monitoring program over the past 40 yr on the black-browed albatross at Cañon des Sourcils Noirs, îles Kerguelen. We are grateful to R. Thomson for the use of the demographics model and S. de Grissac for processing juvenile data. Fieldwork and animal tagging were supported financially and logistically by the Institut Polaire Français Paul Emile Victor (program 109), Terres Australes et Antarctiques Françaises, Zone Atelier de Recherches sur l'Environnement Antarctique et Subantarctique (CNRSINEE), and has been approved by the ethics committee of IPEV and by the Comité de l'Environnement Polaire. Demographic data collection and animal tagging were also partly supported by a grant to Stéphanie Jenouvrier from the National Science Foundation no. 1246407. We thank D. Besson for the data management. We also thank P and JMichael and PGR Jodice for feedback on an earlier version of the manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2021.104684.

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