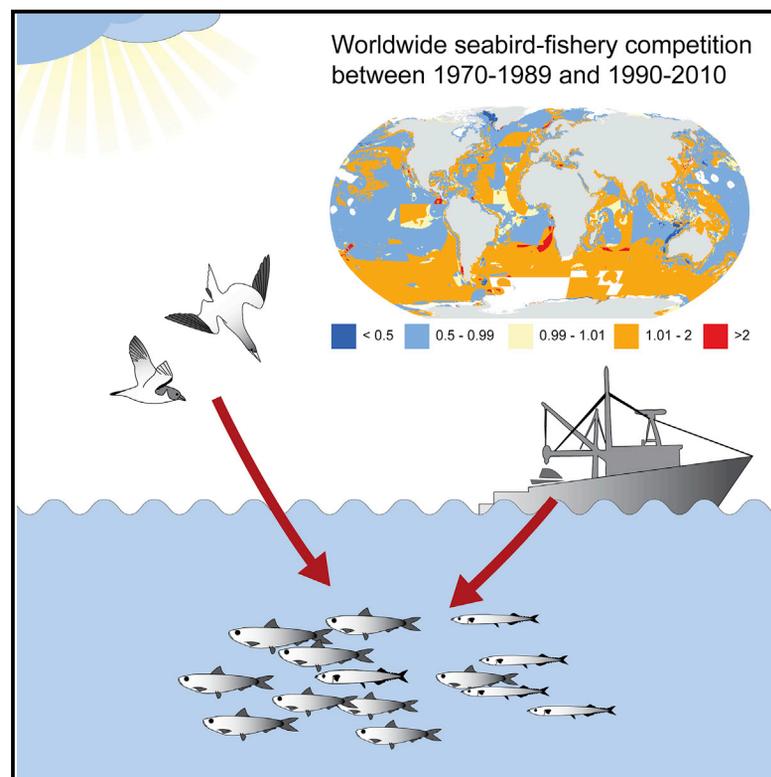


Persisting Worldwide Seabird-Fishery Competition Despite Seabird Community Decline

Graphical Abstract



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In Brief

Using global seabird and fisheries data of the Sea Around Us project, Grémillet et al. demonstrate that fishery catch on potential seabird prey increased from 59 to 65 million metric tons between 1970–1989 and 1990–2010 and that seabird-fishery competition persisted across these four decades, significantly constraining a vanishing seabird community.

Highlights

- Worldwide seabird-fishery competition persisted across 1970–1989 and 1990–2010
- Global seabird food consumption decreased by 19% between the two periods
- Global catch of fisheries competing with seabirds synoptically increased by 10%
- Competition with fisheries significantly constrains a vanishing seabird community



Persisting Worldwide Seabird-Fishery Competition Despite Seabird Community Decline

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<https://doi.org/10.1016/j.cub.2018.10.051>

SUMMARY

Fisheries transform marine ecosystems and compete with predators [1], but temporal trends in seabird-fishery competition had never been assessed on a worldwide scale. Using catch reconstructions [2] for all fisheries targeting taxa that are also seabird prey, we demonstrated that average annual fishery catch increased from 59 to 65 million metric tons between 1970–1989 and 1990–2010. For the same periods, we estimated that global annual seabird food consumption decreased from 70 to 57 million metric tons. Despite this decrease, we found sustained global seabird-fishery food competition between 1970–1989 and 1990–2010. Enhanced competition was identified in 48% of all areas, notably the Southern Ocean, Asian shelves, Mediterranean Sea, Norwegian Sea, and Californian coast. Fisheries generate severe constraints for seabird populations on a worldwide scale, and those need to be addressed urgently. Indeed, seabirds are the most threatened bird group, with a 70% community-level population decline across 1950–2010 [3].

RESULTS

We tested temporal trends in global seabird-fishery competition. To this end, we used an updated version of the Sea Around Us seabird database [3] (see STAR Methods) and focused on the time period for which seabird population data were the most abundant, 1970 to 2010. This period was split into two eras: 1970–1989 (era 1) and 1990–2010 (era 2). During this time global marine fishery catches doubled [2], and the overall period therefore seems ideal to test seabird-fishery competition. Our analysis encompassed 276 seabird species in 1,482 populations, with 0.53 and 0.47 billion individuals for era 1 and era 2, respectively, corresponding to 62% and 60% of the world's seabird population (see STAR Methods for an analysis of the representativeness of this sample). Using bioenergetics modeling to draw

from regional seabird population numbers, species-specific distributions, metabolic rates and diets, we estimated that annual seabird food consumption decreased by 19%, from 70 to 57 million metric tons between era 1 and era 2 (Figure 1). This decrease primarily occurred in the Southern Ocean and in the North Atlantic and was most marked in diving petrels (–66%), terns (–48%), and frigatebirds (–47%). The cephalopod (primarily squid) consumption of seabirds dropped by 31%, and their consumptions of euphausiids (primarily Antarctic krill, *Euphausia superba*) and small pelagic fish declined by 21% and 16%, respectively.

We then mapped seabird predatory pressure on marine organisms, using estimated seabird at-sea home ranges during and outside of the reproductive season. This information was confronted with global maps of reconstructed fisheries catches of taxa targeted by both seabirds and fisheries [2, 4] (see STAR Methods). In striking contrast to the observed declining trend of the global seabird community, overall yields of the world's fisheries increased from 59 to 65 million metric tons annually between era 1 and era 2 (Figures 2 and 3), with a 5% increase in the catch of small pelagic fish, an 8% increase for other fish, a 91% increase for squid, and a 48% decrease for krill. Fishery catches decreased between era 1 and era 2 in some areas (e.g., North West Atlantic and Bering Sea). This might be due to a reduction in fishery effort but more likely, to a decrease in prey availability.

Further, seabird-fishery competition was evaluated as a resource overlap index [5]:

$$a = \frac{2 \cdot \sum_{i=1}^G P_{ij} \cdot P_{if}}{\sum_{i=1}^G P_{ij}^2 + \sum_{f=1}^H P_{if}^2},$$

where a ranges from 0 (no overlap) to 1 (complete overlap), P_{ij} is the proportion of a food group j to the total amount of food taken by a seabird i , P_{if} is the proportion of j in the total catch of the fishery f , G denotes the number of food groups taken by i , and H denotes the number of food groups caught by f .

Surprisingly, despite reduced seabird predatory pressure, our analyses indicate that overall competition between seabirds and fisheries remained at similar levels between era 1 and era 2. Specifically, we found that average seabird-fishery resource overlap was 0.429 ± 0.263 for era 1 and 0.436 ± 0.249 for era 2. Between



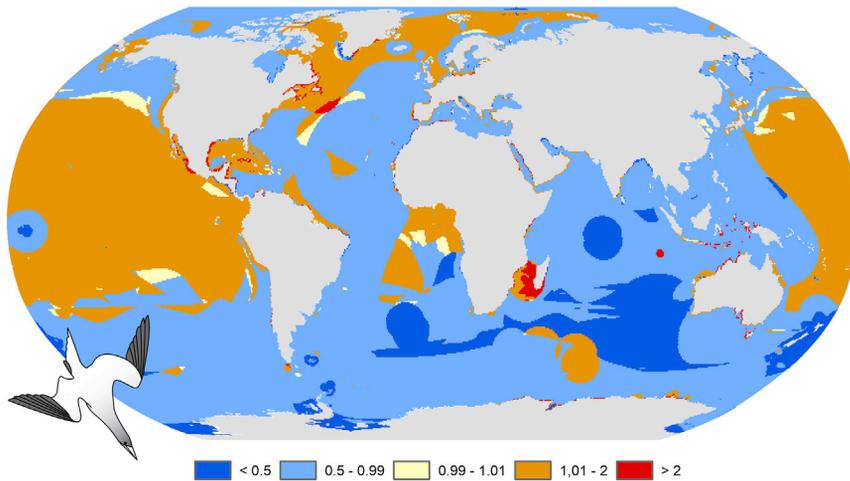


Figure 1. Declining Global Seabird Food Consumption

Distribution (0.5° cells) of the ratio between annual average seabird food consumptions for 1990–2010 (era 2) and 1970–1989 (era 1). Note the predominance of blue areas, indicating decreasing seabird predatory pressure upon marine resources.

the two eras, resource overlap decreased by at least 1% in 46% of all areas, increased by at least 1% in 48% of all areas, and remained stable (difference $<1\%$) in 6% of the marine realm (Figure 4). Enhanced seabird-fishery competition between the two eras was identified in numerous areas, notably most of the Southern Ocean, as well as in the Asian shelves, Mediterranean Sea, Norwegian Sea, and Californian coast. These results are coherent with regional analyses, notably within the California and Humboldt currents [6].

DISCUSSION

Fisheries have been demonstrated to significantly impact marine ecosystems [1, 7, 8] and to compete with the marine megafauna for fish and invertebrates. Yet, although fisheries throughout the world are being accused of “starving seabirds” [9], food competition between seabirds and fisheries had so far mainly been assessed regionally. For instance, an investigation performed for 14 seabird species feeding on small pelagic fish and krill in seven marine ecosystems demonstrated that their breeding performance was diminished and more variable when their prey base was depleted below one-third of its maximum abundance as determined through long-term studies [10]. Further, a

The authors estimated worldwide resource overlap for an average year of the decade, and identified a series of competition hotspots, notably the North Atlantic, the Mediterranean Sea, and the Asian shelves.

Our macro-ecological approach takes this matter substantially further by exploring temporal trends in global seabird-fishery competition, yet it includes a series of assumptions and limitations which require careful consideration. First, we acknowledge the imperfect nature of the global seabird database used in this study, despite 15 years of sustained efforts toward its maintenance and validation. Further improvements may be facilitated by the Seabird Information Network recently launched by the World Seabird Union. Nevertheless, our observed decreasing seabird population trends and reduced predation pressure are consistent with other global assessments [3, 12]. Importantly, the International Union for Conservation of Nature (IUCN) identified seabirds as the most threatened bird group: 38% of 346 seabird species are listed as globally threatened or near threatened, with almost half of all species known or suspected to experience population declines [13]. Second, seabird bioenergetics modeling was entirely based upon allometric relationships. Even though this method generally performs well [14], it could be replaced in many cases by empirical measurements

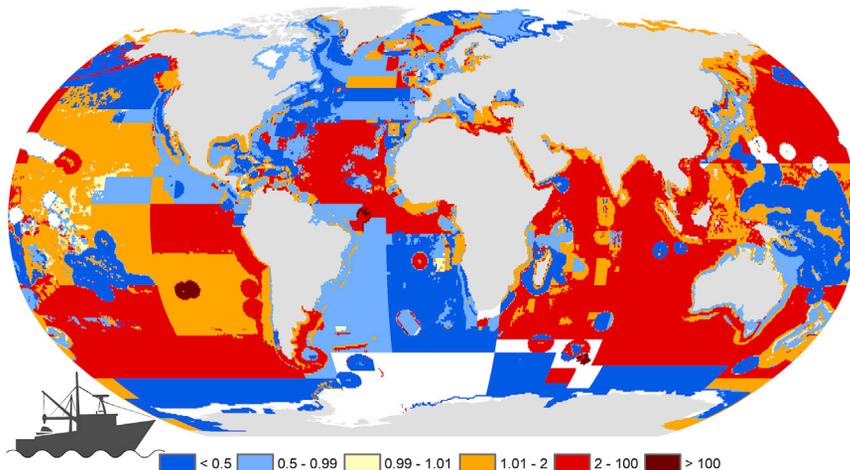


Figure 2. Increasing Global Fishing Pressure on Potential Seabird Prey

Distribution (0.5° cells) of the ratio between annual average fishery catches for 1990–2010 (era 2) and 1970–1989 (era 1). Note the predominance of yellow and red areas notifying increasing fishing pressure upon marine resources. Blue areas denote either an actual decrease in fishery pressure or a sustained fishery pressure on depleted resources.

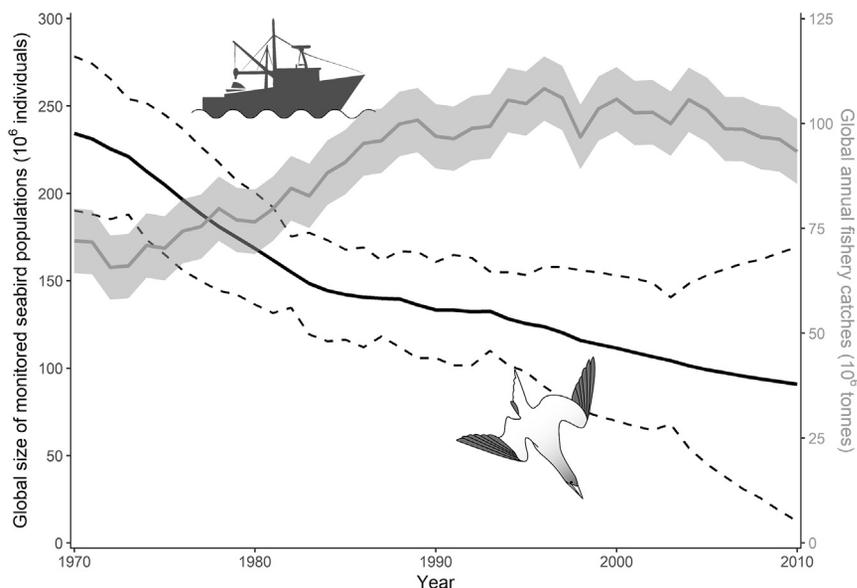


Figure 3. Declining Worldwide Seabird Community and Enhanced Global Fisheries

1970–2010 trends in global seabird population (black solid line with uncertainty ranges as dotted lines; adapted from [3]) and in catches by global fisheries (gray line with uncertainty ranges as gray shadow; adapted from [2]).

structured fisheries catch statistics, but those have been addressed in great detail in the literature [17] and will not be reiterated here.

Notwithstanding these potential limitations, our analyses reveal sustained seabird-fishery competition in recent decades, despite decreases in global seabird numbers. Competition with fisheries is noted for some declining seabird groups, such as terns, but not for others, notably diving petrels, which are also planktivorous. Nevertheless, it is the seabird community as a whole that is being significantly challenged by fisheries, and such pressure may further increase within balanced harvest schemes [18], which envisage exploiting all trophic levels, including zooplankton [19].

of field metabolic rates, or by outputs from mechanistic modeling tools [15]. Whether these extremely time-consuming refinements would lead to significant improvements of the overall calculations remains unclear. Third, seabird at-sea home ranges were primarily determined using atlases of their general distribution patterns, and we assumed even distributions of seabird predatory pressure across these surfaces. This approach could be substantially refined, by using electronic tracking studies of seabird movements at sea. For instance, the Tracking Ocean Wanderers database maintained by BirdLife International includes such information for 113 species (~32% of all seabird species). Yet, tracking studies have a strong bias toward larger-bodied species, to the neglect of smaller species. This is the case for species we identified as particularly vulnerable, such as diving petrels and terns. Regardless, we believe that the simultaneous electronic tracking of seabirds and fisheries [16] is a major forthcoming research topic on a worldwide scale. Finally, specific caveats are also linked to the use of recon-

community as a whole that is being significantly challenged by fisheries, and such pressure may further increase within balanced harvest schemes [18], which envisage exploiting all trophic levels, including zooplankton [19].

The seabird community is affected by a number of threats [20]. Historically, direct harvesting of adults, juveniles, and eggs probably led to the most important population declines, especially in the North Atlantic. Such additional mortality persists today, in the form of accidental bycatch by fishing gear, followed by the destruction of breeding habitat and its colonization by invasive species and pathogens, as well as the impacts of oil spills and chemical and plastic pollutions [21]. More recently, climate change has been shown to significantly impact seabird populations, directly and indirectly. In the latter case, this can result in changes in the spatiotemporal availability of seabird food [22], which may occur synoptically with fisheries impacts and complicate the attribution of seabird population declines to the consequences of either climate change or fisheries [23]. Yet recent

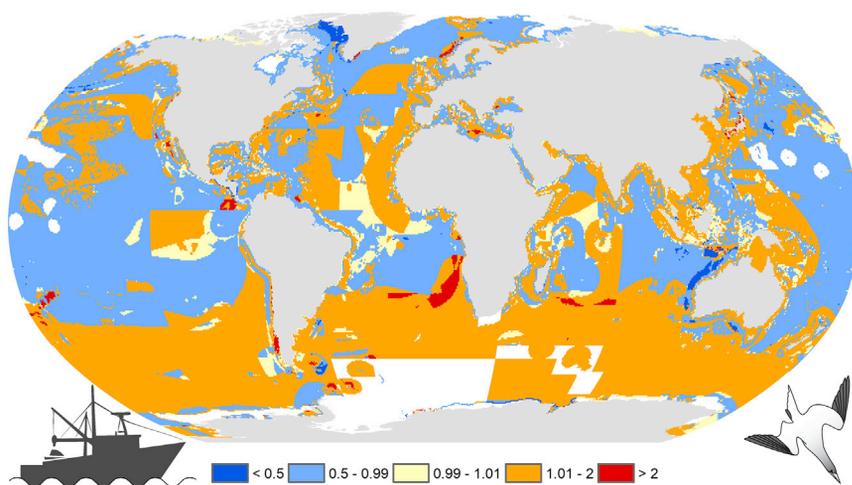


Figure 4. Persisting Worldwide Seabird-Fishery Competition

Distribution (0.5° cells) of the ratio of resource overlap indexes (seabird-fishery competition) between 1990–2010 (era 2) and 1970–1989 (era 1). Areas in orange and red denote marine regions in which seabird-fishery competition has increased (see also Table S1).

work demonstrated significant fisheries impacts on seabird abundance in the Peru upwelling, even when accounting for environmental factors [24]. Competition with fisheries should therefore be regarded as one of the numerous stressors acting upon the fitness of individual seabirds [9] and, ultimately, upon population trajectories [25]. As our study indicates, this threat should not be neglected as it is substantial and global. Signals from seabirds strongly call for improved management of the world's fisheries [26], with the aim of restoring marine ecosystem function and resilience.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental Information includes three figures and three tables and can be found with this article online at <https://doi.org/10.1016/j.cub.2018.10.051>.

ACKNOWLEDGMENTS

This is a contribution of the Sea Around Us project, a scientific collaboration between the University of British Columbia, the Pew Charitable Trusts, and the Paul G. Allen Family Foundation. D.G. acknowledges the support of the French National Center for Scientific Research (CNRS), the French Polar Institute IPEV (program 388 ADACLIM), the Belmont Forum, and the French National Research Agency ANR (TAMANI program), as well as of Jean-Christophe Auffray for the Office for Science, French Embassy in Canada. We are grateful for the analytical assistance of Doris Gomez, Eric Sy, Sarah Popov, and Christopher Hoornaert, for the illustrative assistance of Bénédicte Martin and Evelyn Liu, and for the constructive comments of three anonymous reviewers.

AUTHOR CONTRIBUTIONS

D.P. and D.G. conceived the research. All authors performed the research. D.G. wrote the manuscript, with substantial inputs from all authors.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: April 18, 2018

Revised: August 17, 2018

Accepted: October 23, 2018

Published: December 6, 2018

REFERENCES

1. Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., and Torres, F., Jr. (1998). Fishing down marine food webs. *Science* 279, 860–863.
2. Pauly, D., and Zeller, D. (2016). Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nat. Commun.* 7, 10244.
3. Paleczny, M., Hammill, E., Karpouzi, V., and Pauly, D. (2015). Population trend of the world's monitored seabirds, 1950–2010. *PLoS ONE* 10, e0129342.
4. Pauly, D. (2016). *Global Atlas of Marine Fisheries: A Critical Appraisal of Catches and Ecosystem Impacts* (Island Press).
5. Horn, H.S. (1966). Measurement of “overlap” in comparative ecological studies. *Am. Nat.* 100, 419–424.
6. Sydeman, W.J., Thompson, S.A., Anker-Nilssen, T., Arimitsu, M., Bennison, A., Bertrand, S., Boersch-Supan, P., Boyd, C., Bransome, N.C., Crawford, R.J., et al. (2017). Best practices for assessing forage fish fisheries-seabird resource competition. *Fish. Res.* 194, 209–221.
7. Jackson, J.B., Kirby, M.X., Berger, W.H., Bjorndal, K.A., Botsford, L.W., Bourque, B.J., Bradbury, R.H., Cooke, R., Erlandson, J., Estes, J.A., et al. (2001). Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293, 629–637.
8. Worm, B., Barbier, E.B., Beaumont, N., Duffy, J.E., Folke, C., Halpern, B.S., Jackson, J.B., Lotze, H.K., Micheli, F., Palumbi, S.R., et al. (2006). Impacts of biodiversity loss on ocean ecosystem services. *Science* 314, 787–790.
9. Grémillet, D., Péron, C., Kato, A., Amélineau, F., Ropert-Coudert, Y., Ryan, P.G., and Pichegru, L. (2016). Starving seabirds: unprofitable foraging and its fitness consequences in Cape gannets competing with fisheries in the Benguela upwelling ecosystem. *Mar. Biol.* 163, 35.
10. Cury, P.M., Boyd, I.L., Bonhommeau, S., Anker-Nilssen, T., Crawford, R.J., Furness, R.W., Mills, J.A., Murphy, E.J., Österblom, H., Paleczny, M., et al. (2011). Global seabird response to forage fish depletion—one-third for the birds. *Science* 334, 1703–1706.
11. Karpouzi, V.S., Watson, R., and Pauly, D. (2007). Modelling and mapping resource overlap between seabirds and fisheries on a global scale: a preliminary assessment. *Mar. Ecol. Prog. Ser.* 343, 87–99.
12. Paleczny, M., Karpouzi, V., Hammill, E., and Pauly, D. (2016). Global seabird populations and their food consumption. In *Global Atlas of Marine Fisheries: A Critical Appraisal of Catches and Ecosystem Impacts*, D. Pauly, and D. Zeller, eds. (Island Press), pp. 83–87.
13. IUCN (2018). *The IUCN Red List of Threatened Species, Version 2018-2*. <http://www.iucnredlist.org>.
14. Fort, J., Porter, W.P., and Grémillet, D. (2011). Energetic modelling: a comparison of the different approaches used in seabirds. *Comp. Biochem. Physiol. A Mol. Integr. Physiol.* 158, 358–365.
15. Amélineau, F., Fort, J., Mathewson, P.D., Speirs, D.C., Courbin, N., Perret, S., Porter, W.P., Wilson, R.J., and Grémillet, D. (2018). Energyscapes and prey fields shape a North Atlantic seabird wintering hotspot under climate change. *R. Soc. Open Sci.* 5, 171883.
16. Weimerskirch, H., Filippi, D., Collet, J., Waugh, S.M., and Patrick, S. (2018). Use of radar detectors to track attendance of albatrosses at fishing vessels. *Conserv. Biol.* 32, 240–245.
17. Zeller, D., Palomares, M.D., Tavakolie, A., Ang, M., Belhabib, D., Cheung, W.W., Lam, V.W., Sy, E., Tsui, G., Zyllich, K., et al. (2016). Still catching attention: Sea Around Us reconstructed global catch data, their spatial expression and public accessibility. *Mar. Policy* 70, 145–152.
18. Garcia, S., Rice, J., and Charles, A. (2015). Balanced harvesting in fisheries: a preliminary analysis of management implications. *ICES J. Mar. Sci.* 73, 1668–1678.
19. Pauly, D., Froese, R., and Holt, S.J. (2016). Balanced harvesting: the institutional incompatibilities. *Mar. Policy* 69, 121–123.
20. Croxall, J.P., Butchart, S.H., Lascelles, B., Stattersfield, A.J., Sullivan, B., Symes, A., and Taylor, P. (2012). Seabird conservation status, threats and priority actions: a global assessment. *Bird Conserv. Int.* 22, 1–34.
21. Wilcox, C., Van Sebille, E., and Hardesty, B.D. (2015). Threat of plastic pollution to seabirds is global, pervasive, and increasing. *Proc. Natl. Acad. Sci. USA* 112, 11899–11904.
22. Cristofari, R., Liu, X., Bonadonna, F., Cherel, Y., Pistorius, P., Le Maho, Y., Raybaud, V., Stenseth, N.C., Le Bohec, C., and Trucchi, E. (2018).

- Climate-driven range shifts of the king penguin in a fragmented ecosystem. *Nat. Clim. Chang.* 8, 245.
23. Frederiksen, M., Wanless, S., Harris, M.P., Rothery, P., and Wilson, L.J. (2004). The role of industrial fisheries and oceanographic change in the decline of North Sea black-legged kittiwakes. *J. Appl. Ecol.* 41, 1129–1139.
 24. Barbraud, C., Bertrand, A., Bouchón, M., Chaigneau, A., Delord, K., Demarcq, H., Gimenez, O., Torero, M.G., Gutiérrez, D., Oliveros-Ramos, R., et al. (2018). Density dependence, prey accessibility and prey depletion by fisheries drive Peruvian seabird population dynamics. *Ecography* 41, 1092–1102.
 25. Krüger, L., Ramos, J., Xavier, J., Grémillet, D., González-Solís, J., Petry, M., Phillips, R., Wanless, R., and Paiva, V. (2018). Projected distributions of Southern Ocean albatrosses, petrels and fisheries as a consequence of climatic change. *Ecography* 41, 195–208.
 26. Lescroëil, A., Mathevet, R., Péron, C., Authier, M., Provost, P., Takahashi, A., and Grémillet, D. (2016). Seeing the ocean through the eyes of seabirds: A new path for marine conservation? *Mar. Policy* 68, 212–220.
 27. Brooke, M. de L. (2004). The food consumption of the world's seabirds. *Proc. Biol. Sci.* 271 (Suppl 4), S246–S248.
 28. Ellis, H., and Gabrielsen, G. (2004). Energetics of free-ranging seabirds. In *Biology of Marine Birds*, E.A. Schreiber, and J. Burger, eds. (CRC Press), pp. 359–407.
 29. Jackson, S. (1986). Assimilation efficiencies of White-chinned petrels (*Procellaria aequinoctialis*) fed different prey. *Comp. Biochem. Physiol. A Physiol.* 85, 301–303.
 30. Palomares, M.L.D., Cheung, W.W., Lam, V.W., and Pauly, D. (2016). The distribution of exploited marine biodiversity. In *Global Atlas of Marine Fisheries: A Critical Appraisal of Catches and Ecosystem Impacts*, D. Pauly, and D. Zeller, eds. (Island Press), pp. 46–58.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited Data		
Raw and analyzed data	This paper	https://github.com/SeaAroundUs
Software and Algorithms		
R		N/A
Access		N/A
QGIS		N/A

CONTACT FOR REAGENT AND RESOURCE SHARING

Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, David Grémillet (david.gremillet@cefe.cnrs.fr).

METHOD DETAILS

Mapping worldwide seabird food consumption Seabird population and distribution data

We used the *Sea Around Us* seabird database, which encompasses 3218 breeding populations belonging to 324 seabird species [3, 11, 12]. Therein, we considered the 1970–1989 and 1990–2010 time periods (hereafter era 1 and era 2), for which the best population count data were available [3]. We retained populations which had at least one recorded number of individuals per era, leading to a sub-sample of 1482 populations from 276 species. For each population we used the average number of individuals per era, with 0.53 and 0.47 billion individuals for era 1 and era 2, respectively, corresponding to 62% and 60% of the world's seabird population. We assessed the representativeness of the 1482 sampled populations in comparison with the 3218 populations included in the *Sea Around Us* seabird database. We considered the latter to be the “global seabird population,” as it corresponded closely to other world seabird population estimates [27]. Sampled populations included data for 46% (i.e., 1482 of 3218) of all populations, 85% (i.e., 274 of 324) of all species and 100% (i.e., 14 of 14) of all families. We summarized global population data using available records nearest 1980 for era 1 and available records nearest 2000 for era 2 per population in the *Sea Around Us* seabird database. We found that the proportion of global populations included in our analysis ranged from *Pelecanoididae* (3%–7%) and *Stercorariidae* (10%–12%) for poorly studied families, to above 80% for well-studied families (*Diomedidae*, *Alcidae*, and *Spheniscidae*) (Fig.S1). Overall population size changes were similar between the sampled and global populations: Between era 1 and era 2 the seabird population was reduced by 11% in the sampled population, in comparison to 8% in the global population. By family, the direction of change between eras was the same between sampled and global populations (–8% and –11%, respectively, see Table S2). The difference in extent of change between sampled and global populations was $\leq 20\%$ for 11 out of 14 families. Exceptions were *Pelecanoididae* with a population decline 47% more pronounced in sampled than in global populations, *Hydrobatidae* whose population increase was 41% more pronounced in sampled than in global populations, and in *Phalacrocoracidae*, with a population increase 36% more pronounced in sampled than in global populations (Table S2). We also assessed the spatial distribution of sampled versus global populations (Table S3): The percentage of each population sampled within a given FAO area ranged from less than 33% for Arctic Seas, Atlantic Antarctic Ocean, Southern and Antarctic Indian Ocean and East Central Pacific Ocean, to over 80% for North East Pacific Ocean, North West, South West and South East Atlantic Ocean.

Seabird bioenergetics calculations

Populations were then divided in two groups: Those which utilize the same at-sea areas year-round (hereafter ‘pelagic’, $n = 230$ populations of 70 species), and those which have distinct breeding and non-breeding at-sea ranges (hereafter ‘non-pelagic’, $n = 1252$ populations of 206 species). For each species, we calculated required daily food intake (DFI) following [11]:

$$DFI_i = \frac{ER_i}{\sum_{j=1}^G DC_{ij} \cdot ED_j} \cdot \frac{1}{AE_i}$$

Where DFI_i is the daily food intake for each seabird species i , ER_i are the energy requirements for each i , calculated with allometric relationships [28] using species-specific body masses to estimate basal and field metabolic rates (BMR and FMR, respectively) for each species, DC_{ij} is the fraction of food item j in the diet of each i , ED_j is the mean energy density of each prey j [11]. ED_j values were available either at the species or the taxon level for prey items [11]. AE_i is the mean food assimilation efficiency for each i , and G the total number of food groups encountered in the diet of each i .

For the breeding and non-breeding seasons, energy requirements were estimated as equal to FMR and as 2.5 x BMR, respectively, and used to calculate breeding and non-breeding daily food requirements. Dietary information was gathered per species if available, otherwise per family, using all information available from the literature, being from stomach contents, pellet analyses, or direct feeding observations. Such information included, whenever available, diet shifts between seasons (breeding/non-breeding) and between the two eras. An average assimilation efficiency of 75% was assumed [29], unless more specific information was found in the literature.

We calculated annual food requirements for each species by taking into account the lengths of the breeding and non-breeding seasons, and mapped their predatory pressure using species-specific at-sea home ranges. For non-pelagic species during the breeding season, these were defined as foraging buffers around each coastal breeding area, assuming that 70% of the birds present within the at-sea range of breeders during the breeding season were breeders, and the remaining 30% non-breeders [11]. For non-pelagic species during the non-breeding season, and for pelagic species across the year cycle, at-sea home ranges were defined as the overall range extent of the species [12]. Seabird predatory pressure (metric tons) per year and surface unit was then calculated for each era, by evenly distributing seabird food requirements across home ranges. Total consumed prey volumes (metric tons) were estimated for the following six seabird food groups: 0 = fishery discards, 1 = other fish, 2 = krill, 3 = squid, 4 = other prey (e.g., molluscs, jellyfish), 5 = forage fish.

Mapping worldwide human marine fisheries

We used the *Sea Around Us* global fisheries database, which provides estimated, spatialized fishery catch volumes for the 1950–2010 time period [2, 4]. This information integrates three distinct sources [17]. The first features catch volume reconstructions, performed on the basis of existing officially reported statistics (at the national level, or through the FAO), to which initially missing information is added using all publically-available information sources. This leads, using conservative assumptions, to the reconstruction of comprehensive catch time series, by fishing sector/taxon and year. Catch reconstructions were performed country by country, and also included the activities of foreign fleets, as well as high-sea fisheries. Second, data from FishBase (<https://www.fishbase.de>) and SeaLifeBase (<http://www.sealifebase.org>) were used to map the likely distributions of all organisms targeted by sea fisheries, using occurrence data along with species distribution models [30]. Finally, a global fishing agreements table assembled in the *Sea Around Us* database [17], which was used to cross-check where fisheries actually operated. As for the seabird analysis, we focused on the 1970–1989 and 1990–2010 time periods (era 1 and era 2, respectively), and used marine organisms targeted by fisheries and consumed by seabirds, without fishery discards. Average seabird predatory pressure and average fishing pressure (expressed in metric tons year⁻¹) were calculated for era 1 and era 2, and mapped using 0.5 degree grid cells.

QUANTIFICATION AND STATISTICAL ANALYSIS

Sensitivity analysis of seabird-fishery competition

To map seabird-fishery competition across space and time, we used a resource overlap index (see main text). This metric (a) is strongly driven by P_{ij} and P_{fj} , which describe how seabird and fishery predation pressure is spread across the different food groups. For each 0.5° geographic cell and for each era, we therefore identified the main food group taken by seabirds, and we subtracted 10% from the proportion currently allocated to this main food group. These 10% were then randomly allocated to another food group. If there was only one food group for this cell/era, we created a second token food group, to which the 10% food proportion was allocated. This allowed us to visualize the impact of potential errors in food group assignments of preys consumed by seabirds and thus, in the worldwide distribution of resource overlap indexes during both eras (Figure S2). Those showed that overall patterns remained unchanged, notably the predominance of areas within which seabird-fishery competition has increased between the two eras. Further, we plotted, for each era, manipulated values of (a), calculated as detailed above across 0.5° grid cells for all considered at-sea areas, against the unmanipulated values of (a) in the same 0.5° grid cells (Figure S3). The Pearson correlation coefficient was 0.9810 (95% confidence interval: 0.9808–0.9812; $p < 0.001$) for era 1 and 0.9790 (95% confidence interval: 0.9788–0.9792; $p < 0.001$) for era 2. This confirmed the strong coherence and robustness of our results.

Current Biology, Volume 28

Supplemental Information

Persisting Worldwide Seabird-Fishery Competition

Despite Seabird Community Decline

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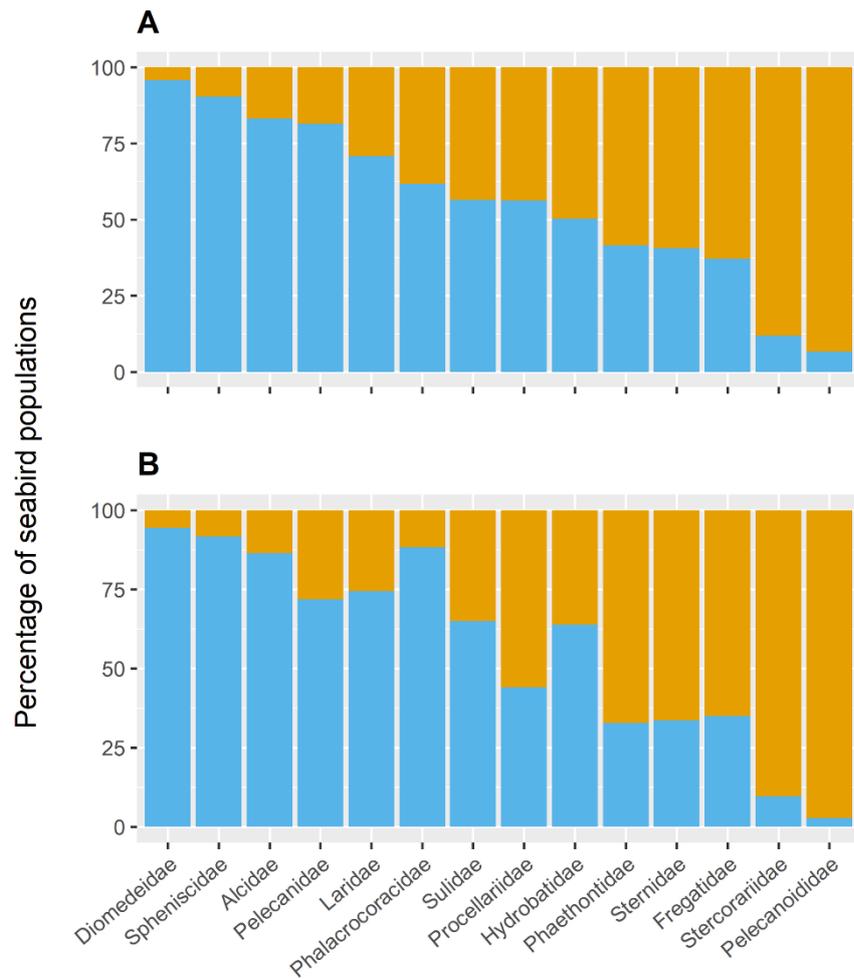


Figure S1. Extent of populational monitoring effort by seabird family. Related to STAR

Methods.

Percentage of seabird populations which were monitored (blue) and unmonitored (orange) by family for 1970-1989 (era1; Panel A) and 1990-2010 (era2; Panel B).

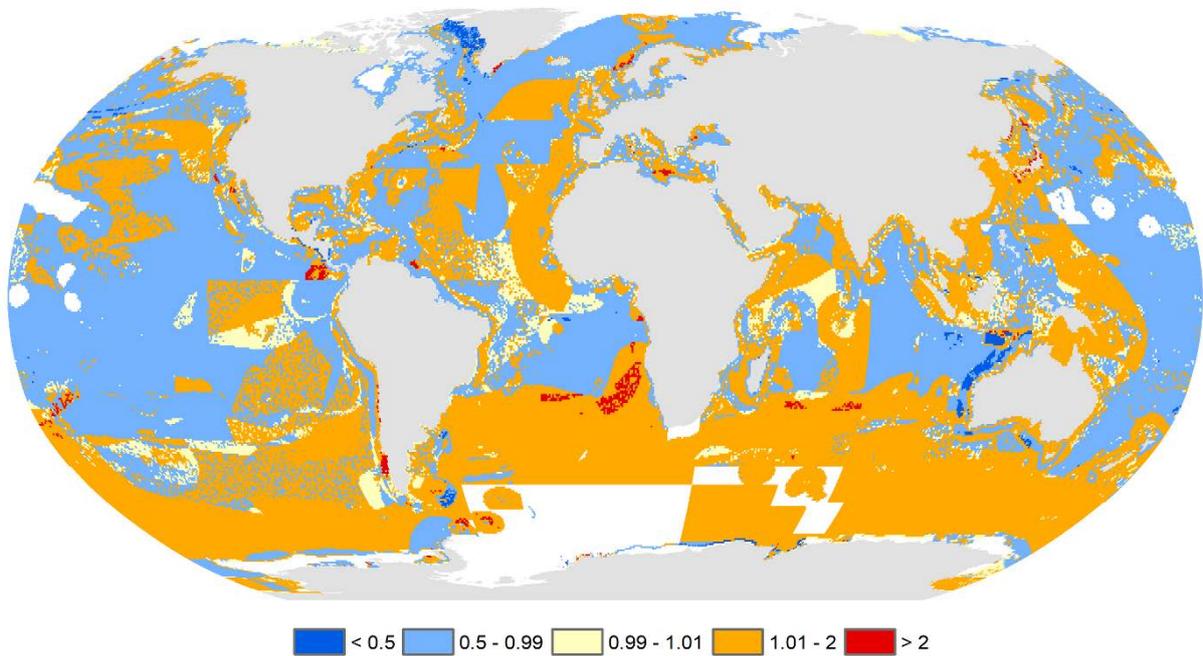
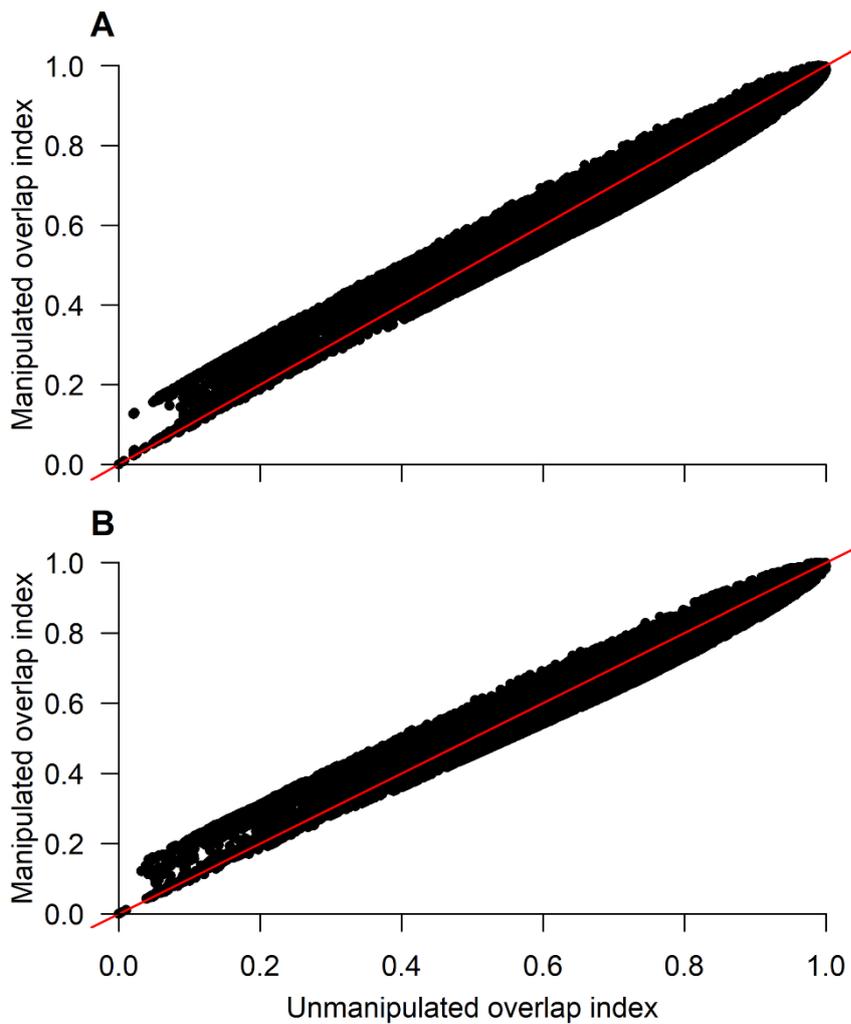


Figure S2. Sensitivity analysis of seabird-fishery resource overlap index. Related to STAR Methods.

Distribution (0.5° cells) of the ratio of resource overlap indexes (seabird-fishery competition) between 1990-2010 (era2) and 1970-1989 (era1) after subtracting 10% of the main seabird food group and randomly allocating it to another food group.



FigureS3: Robustness of seabird-fishery resource overlap indexes. Related to STAR Methods.

Regression of manipulated resource overlap indexes obtained from the sensitivity analysis, and of unmanipulated resource overlaps indexes as presented in the main text, for era1 (panel A) and era2 (panel B). The red line represents $y=x$. When points are above the red line, unmanipulated resource overlaps indexes tend to be underestimated while when they are below, they tend to be overestimated.

Table S1. Amplitude of seabird-fishery competition by FAO area. Related to Figure 4.

FAO Area	FAO Area Name	% of area with increased overlap	Maximum overlap ratio
18	Arctic Sea	2.9	1.17
21	Atlantic, NW	32.8	2.52
27	Atlantic, NE	34.0	3.25
31	Atlantic, WC	57.2	3.21
34	Atlantic, EC	46.7	5.07
37	Mediterranean and Black Sea	41.6	3.29
41	Atlantic, SW	59.5	2.66
47	Atlantic, SE	68.1	2.50
48	Atlantic, Antarctic	69.7	2.80
51	Indian Ocean, Western	62.5	4.65
57	Indian Ocean, Eastern	55.3	7.93
58	Indian Ocean, Antarctic and Southern	95.1	3.08
61	Pacific, NW	28.4	3.59
67	Pacific, NE	36.3	2.46
71	Pacific, WC	33.5	2.06
77	Pacific, EC	18.8	4.69
81	Pacific, SW	59.2	4.48
87	Pacific, SE	51.3	3.83
88	Pacific, Antarctic	79.5	2.83

Percentage of the FAO regions in which the seabird-fisheries overlap increased by at least 1% between era1 and era2 and maximum overlap ratio.

**Table S2. Rates of seabird population changes per seabird family.
Related to STAR methods.**

Family	% change sampled pop	% change global pop	diff in % change
<i>Alcidae</i>	+16	+11	5
<i>Diomedeidae</i>	+14	+16	2
<i>Fregatidae</i>	-45	-42	3
<i>Hydrobatidae</i>	+82	+43	39
<i>Laridae</i>	-17	-21	4
<i>Pelecanidae</i>	-20	-10	10
<i>Pelecanoididae</i>	-66	-19	47
<i>Phaethontidae</i>	-32	-13	19
<i>Phalacrocoracidae</i>	+20	-16	36
<i>Procellariidae</i>	-28	-8	20
<i>Spheniscidae</i>	-26	-27	1
<i>Stercorariidae</i>	-21	-3	18
<i>Sternidae</i>	-48	-36	12
<i>Sulidae</i>	+21	+5	16
TOTAL	-8	-11	3

Percent population change between era1 and era2 observed in the sampled population in comparison with the global population, and difference between the two.

Table S3. Percentage of breeding seabird populations sampled by FAO area. Related to STAR methods.

FAO Area	FAO Area Name	% Sampled for era1	% Sampled for era2
18	Arctic Sea	15	19
21	Atlantic, NW	100	100
27	Atlantic, NE	73	80
31	Atlantic, WC	36	36
34	Atlantic, EC	56	33
37	Mediterranean and Black Sea	37	44
41	Atlantic, SW	100	79
47	Atlantic, SE	100	96
48	Atlantic, Antarctic	31	24
51	Indian Ocean, Western	60	50
57	Indian Ocean, Eastern	68	82
58	Indian Ocean, Antarctic and Southern	25	31
61	Pacific, NW	40	46
67	Pacific, NE	84	84
71	Pacific, WC	40	44
77	Pacific, EC	30	25
81	Pacific, SW	52	52
87	Pacific, SE	60	80
88	Pacific, Antarctic	54	37