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Title: Managing Ecosystem Uncertainty: Critical Habitat and Dietary Overlap of Top-Predators in the Ross Sea

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ABSTRACT

We summarize three types of data in order to increase appreciation among fishery managers of the close spatial and temporal ecological overlaps among top predators in the Ross Sea Shelf Ecosystem (RSShE). This includes data on diet, foraging behavior, and habitat use. Murphy (1995) demonstrated that space-time overlap is critical to predicting the degree to which a fishery might affect a food web. The fisheries that we contemplate are those for Antarctic toothfish and the Antarctic minke whale, though other species might also soon be exploited in the Ross Sea region. In addition to those two predators we also include other trophic competitors and (and in two cases predatory species): killer whale (type C), Weddell seal, Emperor penguin, Adélie penguin, and 4 species of flighted birds.

Using data from satellite tags attached to top predators that occur at colonies and haul outs along the coast of Victoria Land from 1990 through 2004, we summarize the foraging ranges from these sites and the habitats used for foraging. We also summarize data on diet and overlaps in foraging behavior among these predators from analyses of scats and stomach contents and time-depth-recorders collected from 1976 through 2002. Finally, we present results of ship-based surveys of birds and cetaceans made from 1976 through 1981. Though many of those species have not yet been studied using satellite telemetry, their diets have been investigated.

Most top predators in the Ross Sea feed at relatively great depths, perhaps because this affords them access to waters under sea ice, which persists in this region except for late summer. Three of them are able to exploit the entire water column of the shelf, with others foraging from near surface to mid-depths. The major geographic habitats used include waters that are or were part of the marginal ice zone that rings the Ross Sea Polynya during spring and summer when primary production is in full swing. Waters

over shallow banks, especially in the western region, also appear to be important habitats. Even for colonies of these predators that are near the shelfbreak, their foraging efforts appear to be restricted to waters overlying the upper slope and shelf although deeper waters are well within range. In the RSShE, the main prey species eaten by most of the listed predators is the Antarctic silverfish, which is a major predator of ice krill. Based on frequency of occurrence in the diet, the prevalence of silverfish among diving predators averages 70% (range 45-95%) and among near-to-surface predators averages 31% (range 4-53%). The other main prey species of RSShE top predators is ice krill. Antarctic krill replaces ice krill in the predators' diets over the Ross Sea continental slope and outer shelf waters.

The key, and perhaps critical, foraging habitats of the seals and penguins from the colonies and haul-outs studied so far along the Victoria Land coast occur almost entirely within CCAMLR statistical area SSRU 88.1J and the southern third of 88.1H, one of the main SSRUs for harvests of Antarctic toothfish. We make recommendations for research needs related to top predators, including further assessments of population size and diet (including studies of fatty acid composition) from autumn through early spring when sea ice is most extensive, and simultaneous tracking of toothfish and cetaceans, especially the toothfish-eating killer whale.

SUMMARY OF FINDINGS AS RELATED TO NOMINATED AGENDA ITEMS

Agenda Item	*Findings*
EMM06-7 (Other business; Ross Sea)	While the findings presented in this report apply to many of the agenda items, it is not a krill-centric System, which is a main criterion for much of the Agenda. Rather, in the context of designated SSRUs, it describes ecological overlap and the scale of habit use among top predators including the two fishery target species currently being taken in the Ross Sea, and relates them to the scale of SSRUs.

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MANAGING ECOSYSTEM UNCERTAINTY: CRITICAL HABITAT AND DIETARY OVERLAP OF TOP-PREDATORS IN THE ROSS SEA

David Ainley, Viola Toniolo, Grant Ballard, Kerry Barton, Joseph Eastman, Brian Karl, Silvano Focardi, Gerald Kooyman, Phil Lyver, Silvia Olmastroni, Brent Stewart, Ward Testa, Peter Wilson (1)

SUMMARY. We summarize three types of data in order to increase appreciation among fishery managers of the close spatial and temporal ecological overlaps among top predators in the Ross Sea Shelf Ecosystem (RSShE). This includes data on diet, foraging behavior, and habitat use. Murphy (1995) demonstrated that space-time overlap is critical to predicting the degree to which a fishery might affect a food web. The fisheries that we contemplate are those for Antarctic toothfish and the Antarctic minke whale, though other species might also soon be exploited in the Ross Sea region. In addition to those two predators we also include other trophic competitors and (and in two cases predatory species): killer whale (type C), Weddell seal, Emperor penguin, Adélie penguin, and 4 species of flighted birds.

Using data from satellite tags attached to top predators that occur at colonies and haul outs along the coast of Victoria Land from 1990 through 2004, we summarize the foraging ranges from these sites and the habitats used for foraging. We also summarize data on diet and overlaps in foraging behavior among these predators from analyses of scats and stomach contents and time-depth-recorders collected from 1976 through 2002. Finally, we present results of ship-based surveys of birds and cetaceans made from 1976 through 1981. Though many of those species have not yet been studied using satellite telemetry, their diets have been investigated.

Most top predators in the Ross Sea feed at relatively great depths, perhaps because this affords them access to waters under sea ice, which persists in this region except for late summer. Three of them are able to exploit the entire water column of the shelf, with others foraging from near surface to mid-depths. The major geographic habitats used include waters that are or were part of the marginal ice zone that rings the Ross Sea Polynya during spring and summer when primary production is in full swing. Waters over shallow banks, especially in the western region, also appear to be important habitats. Even for colonies of these predators that are near the shelfbreak, there foraging efforts appear to be restricted to waters overlying the upper slope and shelf although deeper waters are well within range. In the RSShE, the main prey species eaten by most of the listed predators is the Antarctic silverfish, which is a major predator of ice krill. Based on frequency of occurrence in the diet, the prevalence of silverfish among diving predators averages 70% (range 45-95%) and among near-to-surface predators averages 31% (range 4-53%). The other main prey species of RSShE top predators is ice krill. Antarctic krill

replaces ice krill in the predators' diets over the Ross Sea continental slope and outer shelf waters.

The key, and perhaps critical, foraging habitats of the seals and penguins from the colonies and haul-outs studied so far along the Victoria Land coast occur almost entirely within CCAMLR statistical area SSRU 88.1J and the southern third of 88.1H, one of the main SSRUs for harvests of Antarctic toothfish. We make recommendations for research needs related to top predators, including further assessments of population size and diet (including studies of fatty acid composition) from autumn through early spring when sea ice is most extensive, and simultaneous tracking of toothfish and cetaceans, especially the toothfish-eating killer whale.

2.0. INTRODUCTION

2.1. Description of the system. The Ross Sea Continental Shelf Ecosystem (RSShE) is the last Large Marine Ecosystem (2) on Earth that has not yet been severely affected by commercial or even artisinal fishing, introduction of alien species, mineral extraction and related disturbance, or wide-spread pollution (3). Yet, the RSShE has become one of the best studied stretches of the Southern Ocean because of efforts of three national Antarctic programs (Italy, NZ, US) over the past six decades. Physical and biological data sets that span several decades have been in the forefront of understanding organism adaptation to the Antarctic marine environment and ecosystem effects of a rapidly changing Southern Ocean climate (4). It is a far different system than that of the pelagic, continental slope "Antarctic Marine Ecosystem" where, for example, there is no appreciable benthic-pelagic coupling and where the fish fauna currently has little value to food-web structure, at least as it applies to top predators (5).

2.2. A brief history of the fishing. Under the regulatory umbrella of CCAMLR and IWC, the RSShE is experiencing increased extraction of biological resources, especially of ecologically key, top-trophic species like Antarctic minke whales (*Balaenoptera bonaerensis*) and Antarctic toothfish (*Dissostichus mawsoni*), which are slow to recover from population reductions (6). Management of the toothfish in the Ross Sea is based on data from the much different pelagic and insular Antarctic Marine Ecosystem, that of the area around South Georgia, and on different (though related) species (7). Moreover, the toothfish stock in area 58.4 has been fished for several decades and, thus, has been in a heavily-fished status for some time (8). Therefore, attributes would be expected to differ from a relatively unfished stock, which is the status believed to characterize the Ross Sea toothfish. It is unclear whether or not the Antarctic minke whale population was depleted during the industrial whaling targeting that species during the 1970s and early 1980s; it is also not clear what has led to an apparent decrease since the early 1990s (9). More recently, extraction equivalent to that of the industrial whaling era has resumed (6).

2.3. Purpose of this report. CCAMLR is charged with striking a balance between harvesting and conservation, protecting the needs of dependent species, and avoiding changes that are irreversible in 20–30 years (10). In the current absence of ecosystem monitoring in the Ross Sea related to existing fisheries (and whaling), which are

extracting top-trophic species, we present a summary of the patterns of spatial and food-web relationships exhibited by these and competing species of the RSShE. Establishing spatial and temporal connections between food web components and biotic extractions is an important first step in gauging potential impacts (11). Such an analysis could be compared against the target areas of the extractive industries in assessing the relative values of the Ross Sea's biotic resources. The expansive spatial coverage of the research results that we summarize is equal to or, in most cases, greater than any analogous efforts elsewhere in the Southern Ocean (the ocean south of the Antarctic Polar Front), where tracking efforts have not had the opportunity to research regional patterns.

3.0. METHODS

This paper is a summary of results, mostly published elsewhere, for the first time related to one another from the perspective of gauging habitat use and trophic overlap among competing species, including those in the fisheries, in one region: the Ross Sea. The reader is referred to the pertinent publications for full details of methods (see Notes and Literature Cited).

We summarize the two fishery target species and trophic data for the killer whale (type C; *Orcinus orca)*, Weddell seal (*Leptonychotes weddellii*), emperor penguin (*Aptenodytes forsteri*), Adélie penguin (*Pygoscelis adeliae*), mottled petrel (*Pterodroma inexpectata*), snow petrel (*Pagodroma nivea*), Antarctic petrel (*Thalassoica Antarctica*), Wilson's storm-petrel (*Oceanites oceanicus*), and south polar skua (*Stercorarius maccormicki)*. The main prey species eaten by those predators in the RSShE are Antarctic silverfish (*Pleuragramma antarcticum*), ice krill (*Euphausia crystallorophias*), and Antarctic krill (*E. superba*).

Data for diet are presented as frequency of occurrence or percent of samples containing a prey species, whether the latter are stomach or scat samples. This measure is the only one common to all the studies that we summarize here.

4.0. RESULTS AND DISCUSSION

The following summarizes the existing data on the dietary and spatial overlap among top predators in the RSShE. As indicated above most of data summarized have been published, but much of it has been brought together here for the first time.

4.1. Foraging behavior and diet. There is clear, close overlap among these predators in diet, foraging behavior and foraging habitat during summer and autumn. The major aspect of these species' foraging strategies, resulting in reduced competition, involves dive depths and, to some extent, differences in prey size (related to predator size). All of these predators, except the toothfish (not known for sure), Weddell seal and emperor penguin, vacate the RSShE in winter and early spring.

Among the most ecologically important top predators (i.e., high biomass), all forage by diving and can use a significant portion of the water column in the RSShE (Figure 1).

All depend greatly on the availability of Antarctic silverfish, either directly or indirectly, as well as ice krill (Figures 2, 3). Along the shelfbreak, Antarctic krill replace ice krill in the diet. The silverfish is the primary forage species among top predators in this ecosystem.

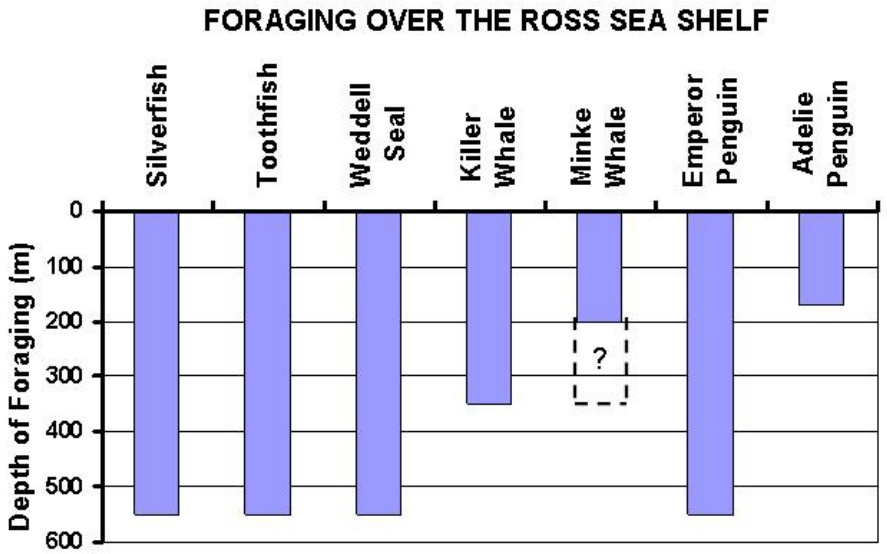

Figure 1. Overlap in the maximum diving depths exhibited among sub-surface foraging top-trophic predators, and correspondence of these depths to that of the primary RSShE forage species: Antarctic silverfish. As silverfish age classes are stratified by depth (youngest are shallower), some diet and behavioral partitioning in this respect may occur (12). In general, deepest depths in the Ross Sea are about 550 m.

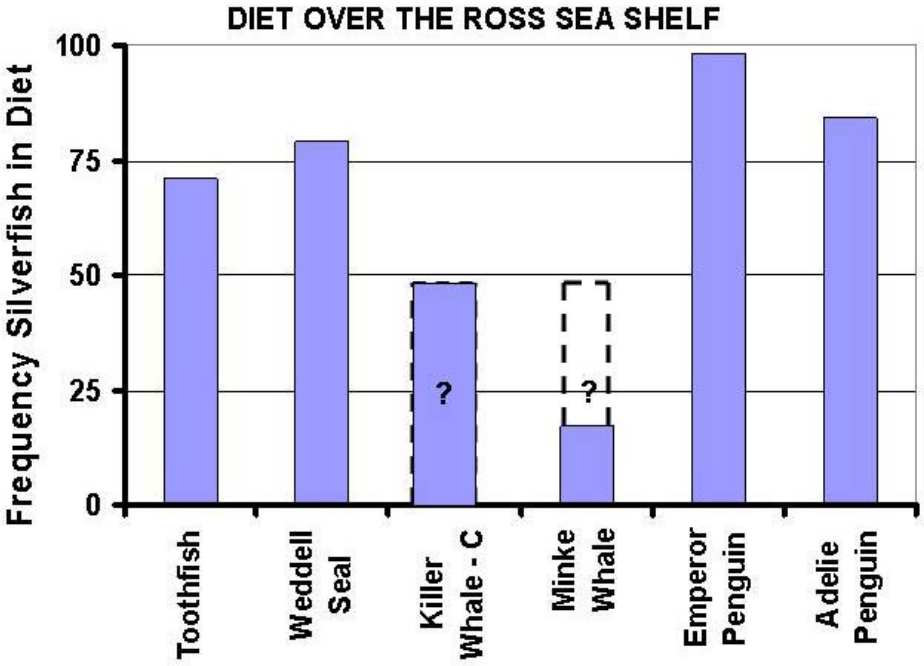

Figure 2. Prevalence of Antarctic silverfish in the diet of subsurface-foraging top predators in waters of the RSShE. The most important alternate prey are mysid shrimp and ice (crystal) krill (13, 14).

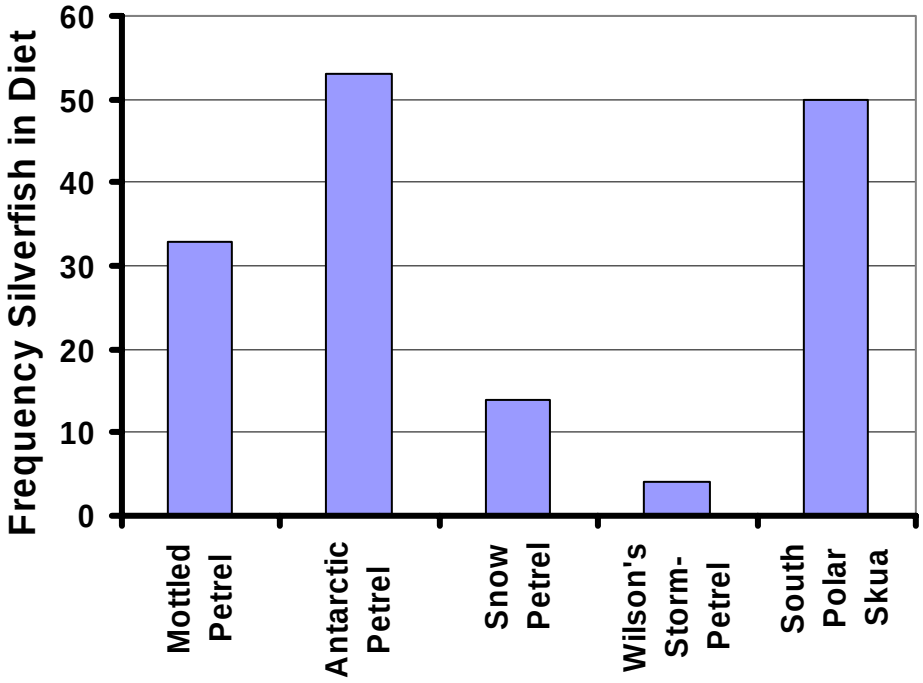

Figure 3. Prevalence of Antarctic silverfish in the diet of near-to-surface feeding flighted birds in waters of the RSShE (and lower continental slope in the case of Mottled petrel). The most important alternate prey include other species of fish and krill (including *E. superba* over the slope; 14).

4.2.1. Foraging habitat: general patterns. It is clear that the concentration of top predators in waters that coincide with the *marginal ice zone* that rings the very large Ross Sea Polynya (Figure 4). In summer, most important is the polynya boundary that lies in the western one-third of the RSShE. Birds and mammals are concentrated in this area (dominated by diatoms) unlike that of the central, open-water portion of the Polynya, which is dominated by *Phaeocystis*. Blooms of the latter are much shorter in duration and much earlier in the spring. These blooms, therefore, lead to a food-web less suited to the needs of top-trophic species (15).

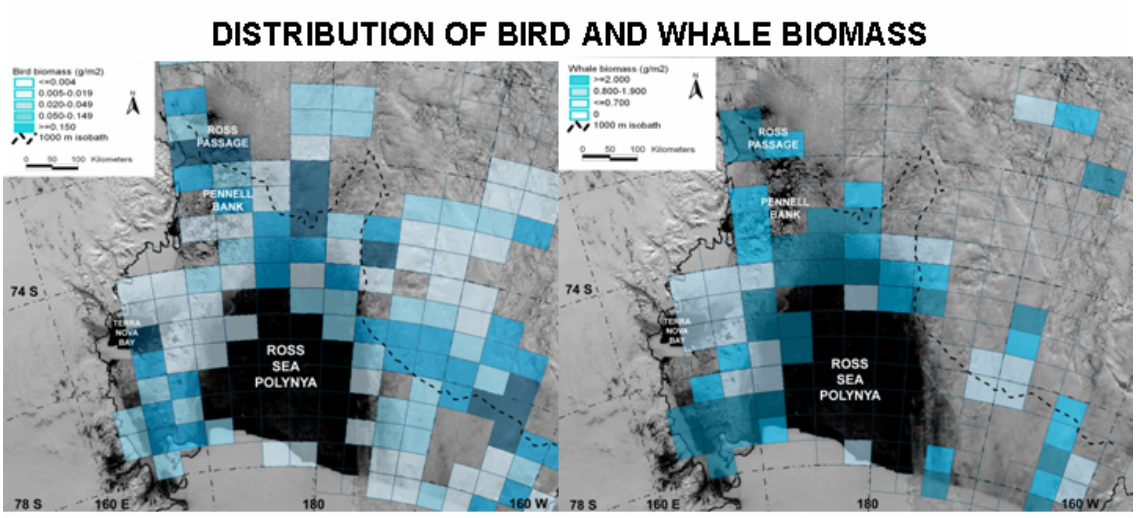

Figure 4. The Ross Sea in early December showing sea-ice cover and location of (post-) polynyas, and (left panel) the distribution of marine birds (about 9 million individuals) and (right panel) cetaceans (about 14 thousand minke and killer whales (16). The pattern for Weddell seals is similar (19). About 3 million penguins and 57 thousand Weddell seals breed along the Victoria Land coast, the highest concentrations of these species anywhere in the high latitude Antarctic (17).

4.2.2. *Foraging habitat: species-specific patterns*. Weddell seals from breeding concentrations in the southwestern Ross Sea (McMurdo Sound) confine movements to the RSShE, concentrating in waters that earlier had been the marginal ice zone along the western boundary of the Ross Sea Polynya (c.f., Figs 4, 5). There is some correspondence of foraging in the troughs between shallow banks during middle and late winter. The foraging areas of juveniles and adults, once away from McMurdo Sound, appear not to overlap although confirmation requires tracking of both age classes simultaneously.

In some cases (e.g., emperor and Adélie penguins), individuals from certain colonies have the capacity to be exploiting slope or deeper waters, yet they confine their foraging during the breeding season to waters overlying the shelf and upper slope (Figures 6, 7). These patterns indicate that the shelf is perhaps more reliable as a source of prey than waters overlying deeper depths. In the case of penguins, foraging farther north may also in part be a function of interference competition from large colonies in extreme northern Victoria Land (see below).

Emperor penguins confine foraging to waters of the RSShE, especially the western third, during the spring/early summer chick-feeding season and the initial late-summer period of pre-molt fattening. Foraging appears to be associated with shallow banks to some degree. After that they move to molt among the large, stable ice floes that exist only in the eastern Ross Sea, and especially farther east. Foraging during summer often coincides with shallow banks. There is little overlap among the foraging areas of adjacent colonies. That pattern suggests interference competition similar to that described for Adélie penguins in the southwestern most part of the Ross Sea (around Ross Island; 18).

Adélie penguins confine their foraging to waters of the western RSShE during summer and the eastern RSShE during the period of pre-molt fattening. There is little overlap among the foraging areas of adjacent colonies, congruent with interference competition among adjacent, large colonies (18). Following the breeding season, the penguins move to stable ice floes in the east to molt.

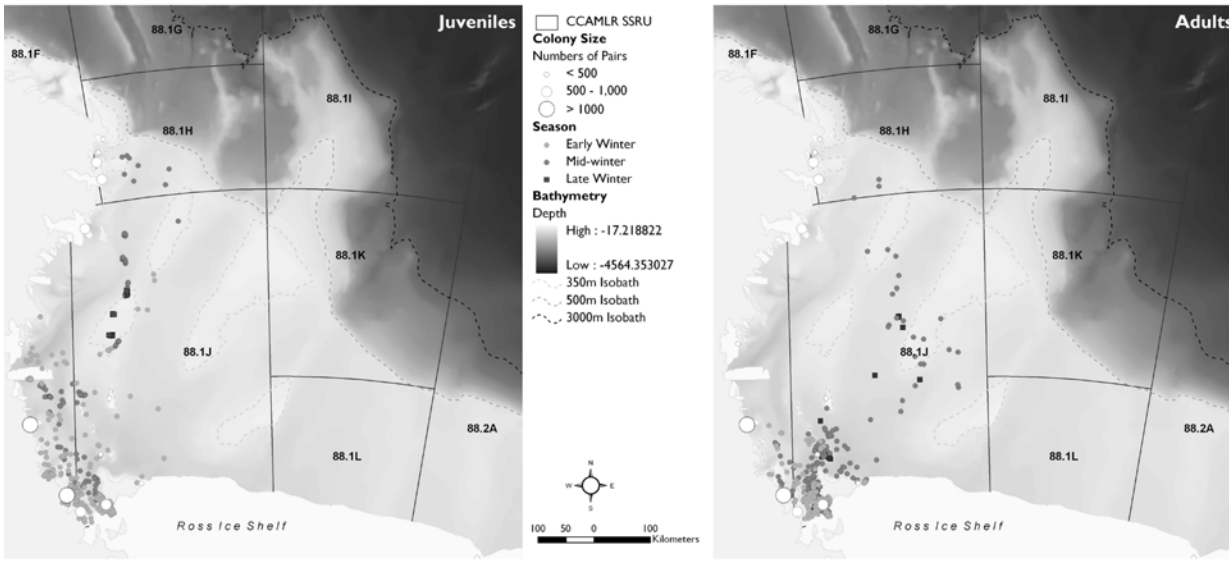

Figure 5. Movements of Weddell seals from breeding sites in McMurdo Sound, as tracked by ARGOS satellites, including both adult females (left panel) and weaned pups (3 to 12 months old; right panel) during early- (April-May), middle- (June-July) and late-winter (August-September) following the spring breeding season, 1990-2000 (19). CCAMLR SSRUs also shown.

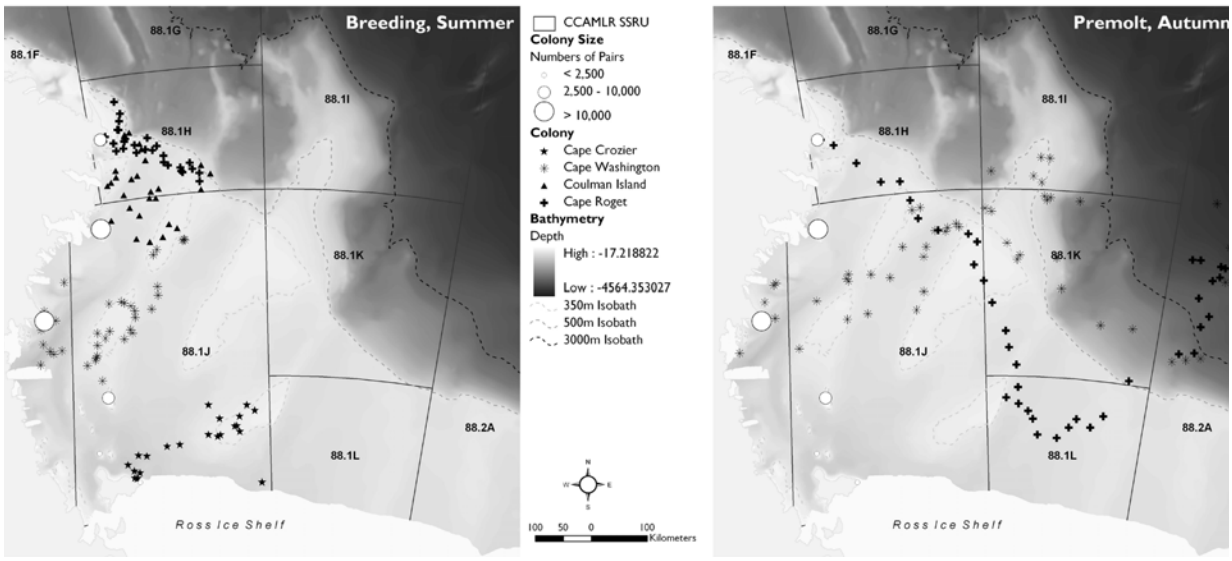

Figure 6. Locations of foraging adult emperor penguins, as tracked by ARGOS satellites, from Victoria Land colonies during (left panel) October-December 1990-94, the summer chick-rearing season; and (right panel) January, when adults are fattening just before their annual molt. Molt takes place on the large stable ice floes characteristic of waters east of the Ross Sea (20); the penguins do not feed while molting. CCAMLR SSRUs also shown.

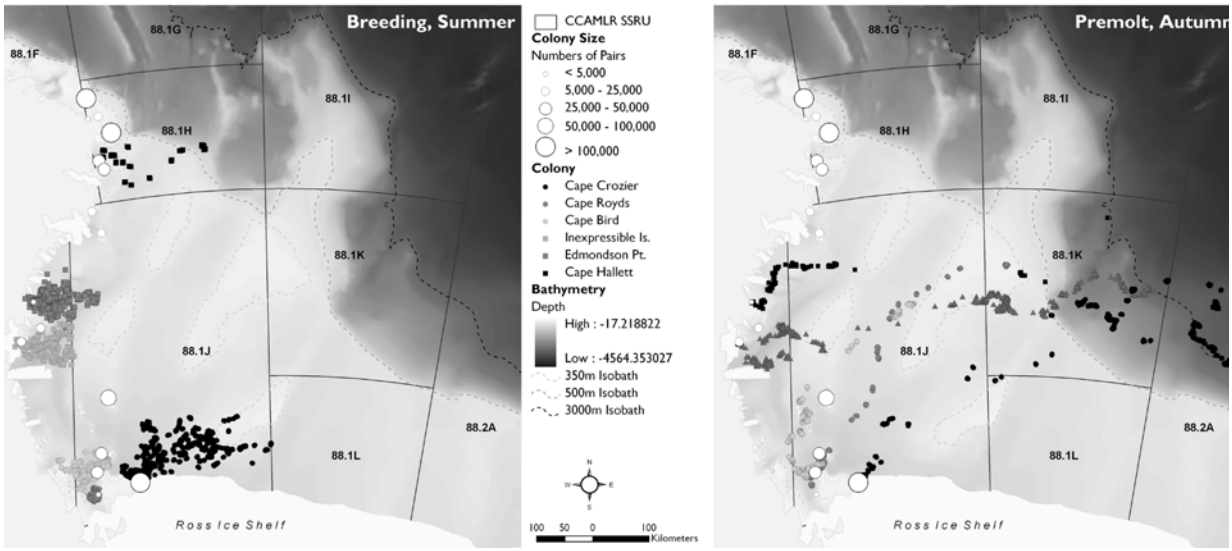

Figure 7. Locations of foraging adult Adélie penguins, as tracked by ARGOS satellites, from Victoria Land colonies during (left panel) December-January 1994-2004, the summer chick feeding period; and (right panel) during January-February, when adults are fattening just before their annual molt (21). Molt patterns similar to those described for emperor penguins (Figure 5 caption). CCAMLR SSRUs also shown.

5.0. CONCLUSIONS AND RECOMMENDATIONS

Top predators, minimally separated by either diet or by foraging (diving) behavior, partition the RSShE by intra-specific spatial segregation of foraging area from spring to summer and autumn, using the western third of the shelf (the southern third of CCAMLR SSRU 88.1H and all of 88.1J; 23) especially. Intra- and interspecific competition for prey has been confirmed in this ecosystem to the extent that a given predator (cetaceans) can alter the foraging patterns of other predators (penguins; 18, 22). In general, predators seem to resist foraging in the central and southern portion of the Ross Sea Polynya area. Likely there is much less food there to interest them owing to the phytoplankton patterns discussed above (15). In this context, it seems likely that the food-web structure of the RSShE, as it applies to top predators and ecological relationships among them, is highly sensitive to perturbation. Any substantial decrease in prey or predator prevalence may likely have significant compensatory effects on all other species.

When data become available, the latitude and longitude of fishing vessels, at the time of successful resource extraction, should be plotted over the foraging tracks of top predators. This will allow an assessment of the potential for trophic competition between humans and other top predators (11). Most recently, the toothfish fishery has been centered in waters over the continental slope of the western Ross Sea (70^{o}-72.5^{o} S) with highest catch rates in lines set at 1000-2000 m in areas SSRU 88.1H and 88.1I; 23). Location of recent minke whale extractions are not publicly known and perhaps never will be, as catch area information is closely guarded.

Additional data are needed on a number of subjects to better manage ongoing and potential fisheries in the Ross Sea region:

(1) assessment of Weddell seal breeding populations and their foraging habitats throughout all of Victoria Land;
(2) diet of Weddell seals, using scats and fatty-acid signatures, when they are foraging in waters north of McMurdo Sound;
(3) movements and diet of Weddell seal breeding populations along northern Victoria Land, in part to determine whether or not, like in Adélie penguins (18), there is lack of overlap in the foraging areas used by populations up the coast from the McMurdo Sound population (interference competition);
(4) breeding season foraging areas of the very large colonies of Adélie penguins that occur in the extreme northern Victoria Land (e.g., Cape Adare; these colonies may be responsible for southern penguins not foraging as far north as they could, i.e. along the continental slope);
(5) foraging movements of cetaceans, residence times at different spatial scales, of both minke and fish-eating killer whales;
(6) study of cetacean diet using fatty acid signatures of prey, and non-lethal, micro-tissue samples from predators;
(7) spatial variation in density, movement patterns and residence time of adult and subadult toothfish in the RSShE; and
(8) the role of fast ice and heavy pack ice in offering refuge of toothfish from mammalian predators.

6.0. ACKNOWLEDGMENTS

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7.0. NOTES AND LITERATURE CITED

1. Authors' institutions: (DA) HT Harvey & Associates, San Jose CA USA; (VT, GB) PRBO Conservation Science, Stinson Beach CA USA; (KB, BK, PL, PW) LandCare Research NZ, Nelson, Christchurch & Auckland NZ; (JE) Ohio University, Athens OH USA; (GK) Scripps Institution of Oceanography, La Jolla CA USA; (SO) University of Siena, Siena Italy; (BSS) Hubbs-SeaWorld Research Institute, San Diego CA USA; (JWT) NOAA Fisheries, Seattle, WA USA.

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