Polar Biol (1998) 20: 273–280

ORIGINAL PAPER

K. Green · D.J. Slip · G.J. Moore

The take of fish species by seabirds and marine mammals in the Australian Fisheries Zone around Heard Island: the potential for competition with a commercial fishery

Received: 26 January 1998 / Accepted: 20 April 1998

Abstract. The number of predators from Heard Island foraging in shelf waters, their prey requirements, and the proportion of their diet that was commercial and non-commercial fish were estimated. The calculated annual consumption of commercial fish species varied between 36,360 and 84,166 tonnes. The non-commercial *Krefftichthys anderssoni* was the preferred prey for most predators, and when its occurrence in diets was low it was replaced by crustaceans and commercial fish species. The estimated annual consumption of *Champsocephalus gunnari* was approximately 2 and 6 times the highest and lowest estimates respectively of the biomass of this species, obtained from three fisheries research cruises. For *Dissostichus eleginoides*, the maximum estimate was 28% of the highest estimate of biomass. The current fishery for *D. eleginoides* will most likely impact on southern elephant seals, whose population decreased by 50% between the 1950s and the 1980s, possibly as a result of overfishing around Iles Kerguelen.

Introduction

There are major populations of macaroni penguins (*Eudyptes chrysolophus*), king penguins (*Aptenodytes patagonicus*), gentoo penguins (*Pygoscelis papua*), Heard Island shags (*Phalacrocorax nivalis*), Antarctic fur seals, (*Arctocephalus gazella*) and southern elephant seals (*Mirounga leonina*) present on Heard Island (53°05′S 73°30′E) and the McDonald Islands (53°03′S 72°35′E). All of these animals breed in this region and are to a large degree piscivorous, taking all or a part of their fish prey from waters near Heard Island (Woehler and Green 1992). There are also populations of albatrosses, petrels, prions and the Antarctic tern (*Sterna vittata*), which either do not consume fish from Heard Island shelf waters or consume an insignificant proportion, and the leopard seal (*Hydrurga leptonyx*) for which we do not have data on population or diet in the vicinity of Heard Island. Data for food consumption by these species (with the exception of the leopard seal) were presented by Woehler and Green (1992).

A fishery by Soviet, Polish, French and Ukrainian vessels has existed in the Iles Kerguelen region since the early 1970s. Most of this fishing has been outside the Australian zone (Fig. 1), except for some known exploratory fishing in 1975 (Slosarczyk and Wysokinski 1980; Sosinski 1985), and possibly a proportion of the Soviet fishery in the early 1970s (Williams and de la Mare 1995). The Kerguelen fishery depleted fish stocks, particularly of *Notothenia rossii*, which was fished during periods of spawning aggregation until it was totally protected in 1984 (Duhamel and Hureau 1990). Three out of four species of commercial interest were over-exploited (Duhamel and Hureau 1990) and, at present, only *Champsocephalus gunnari* and *Dissostichus eleginoides* are thought to have sufficient stocks to support a fishery (Williams and de la Mare 1995). Elephant seal populations in the Indian Ocean declined by about 50% from the 1960s to the 1980s (Laws 1994), and several authors have suggested that depletion of marine resources by commercial fisheries may have been responsible (van Aarde 1980; Pascal 1985; Wilkinson and Bester 1988). The slow population growth of Antarctic fur seals around Iles Kerguelen may also be due to depleted fish stocks (Bester and Roux 1986). Whilst speculative, these possibilities highlighted the need to assess the situation in the immediate seas around Heard Island before any licensed fishery was considered.

K. Green (✉)[1] · D.J. Slip · G.J. Moore[2]
Antarctic Division, Channel Highway, Kingston, Tasmania 7050, Australia

Present addresses:
[1] NPWS, Snowy Mountains Region, PO Box 2228, Jindabyne, NSW 2627, Australia
e-mail: ken.green@npws.nsw.gov.au, Fax: +02-6456-2240
[2] NPWS, Northern Zone, PO Box 914, Coffs Harbour, NSW 2450, Australia

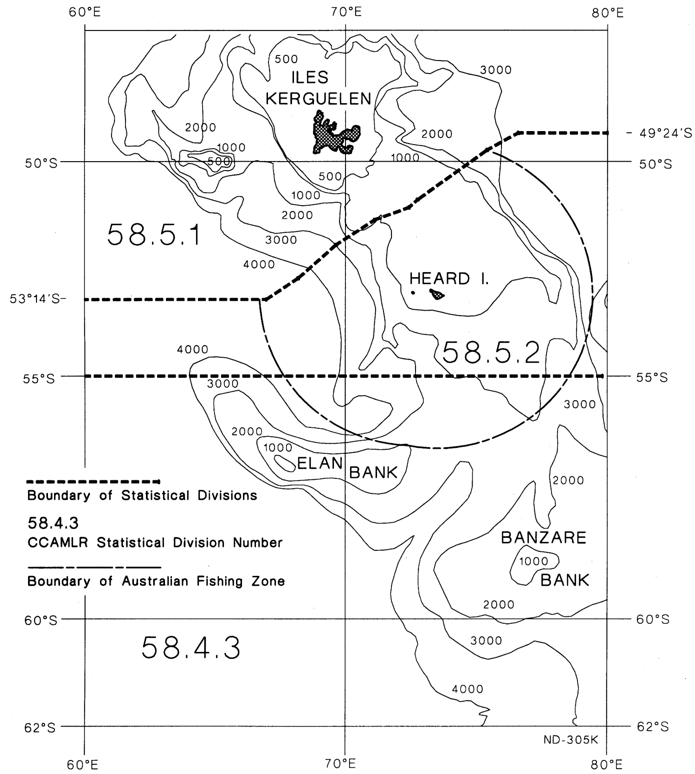

Fig. 1 Location of the Australian Fishery Zone around Heard Island. The line follows the boundary of the CCAMLR Statistical Divisions between Heard Island and Iles Kerguelen

The main objective of the Australian National Antarctic Research Expeditions program on Heard Island from January 1992 to March 1993 was to collect data on the feeding ecologies of the major shore-based predators of fish and to provide baseline data on their ecologies in the absence of a nearby fishery. This paper aims to synthesise those data, to quantify the prey requirements of bird and seal populations, and to examine the potential for competition with a commercial fishery that has since been established.

Materials and methods

Foraging and dietary data

Data on the diet of piscivorous species were obtained using water offloading of stomach contents (southern elephant seals, Slip 1995; macaroni penguins, Green et al. in press; king penguins, Moore and Robertson 1993a), collection of Antarctic fur seals' faeces (Green et al. 1997) and regurgitated casts from Heard Island shags (Green and Williams 1997). Data on foraging locations were obtained using time-depth recorders for king penguins (Moore and Robertson 1993b), macaroni penguins (Green et al., in press), Heard Island shags (Green and Williams 1997), Antarctic fur seals (Green et al. 1997) and southern elephant seals (Slip 1997a, b): methods of attachment and analyses are described in these papers.

Commercial fish species and minimum commercial size within the study area were considered to be: *Notothenia rossii* 450 mm, *Lepidonotothen squamifrons* 300 mm, *Champsocephalus gunnari* 280 mm and *Dissostichus eleginoides* 400 mm (R. Williams, personal communication).

Calculations

Estimates of annual food consumption were obtained by multiplying the number of animals by the number of days spent foraging around the island and the daily food requirements. The amount of the diet that was fish, commercial fish species and commercial size was calculated (Table 1). In an attempt to allow for inter-annual variability, three estimates (low, medium and high) of the proportion of fish in the diets were used. Studies with the highest total fish intake for a given predator species were allocated to the high year and those with the lowest to the low year. Where possible, estimates were based on empirical data but, where this was not possible, one of the rates was estimated.

Macaroni penguin

The time spent around the island by 2 million pairs of macaroni penguins (Woehler and Green 1992) was based on a full breeding season from October to March (Green et al. in press) with the non-breeding season ignored because there was no evidence that the penguins remained in the vicinity of Heard Island. The estimate by Brown (1989) of food requirements of macaroni penguins was used to estimate the total food requirement of this population. Fish consumption estimates were based on Klages et al. (1989) for the low estimate and on samples taken in 1991/1992 and in 1992/1993 for the medium and high estimates respectively (Green et al. in press). Only Klages et al. (1989) recorded the presence of commercial fish species (45.9% of fish mass) but none were of commercial size.

King penguin

A figure of 10,745 breeding pairs of adult king penguins in 1992/1993 (Moore and Robertson 1993c) has been taken as the minimum estimate of king penguins foraging around Heard Island. Food consumption by king penguins was taken from Woehler and Green (1992) and scaled up for an increased population but down to allow for a 123-day winter period when penguins are thought to forage off the plateau (G. Moore unpublished work). Two measures of total fish consumption by mass were 71.6% (G. Moore unpublished work) and 99.4% (Klages et al. 1990). Assuming that 71.6% is a medium intake the low intake was set at a further 28% below this mark (99.4–71.6%).

By mass, *C. gunnari* constituted 3.2% of the total diet in 1992, with 11.3% of this being of commercial size (Moore and Robertson 1993a). In 1986/1987, *K. anderssoni* made up 96.5% of the food by mass (Klages et al. 1990). For the present study, it was assumed that the remainder of the fish were represented once per occurrence in stomachs and that their average mass was equal to that for *Electrona carlsbergi*. This meant that *C. gunnari* made up 1.8% of fish by number but 25.1% by mass, but none were of commercial size.

Rockhopper penguins

The estimated population figure of 1010 pairs of rockhopper penguins used by Woehler and Green (1992) was used to estimate total food consumption. The diet of rockhopper penguins consisted of 8% fish by mass (mainly *K. anderssoni*) with no commercial fish species taken (Klages et al. 1990). Based on this, rockhopper penguins took approximately 8.8 tonnes of fish per year (Woehler and Green 1992). Separate estimates were not made for low, medium and high predation.

Table 1 Estimated fish consumption by predators on the shelf around Heard Island

Species	Number	Number of days	Food required (tonnes)	% bony fish by mass	Total bony fish (tonnes)[a]	Commercial fish species (tonnes)	Commercial fish size (tonnes)
Macaroni penguin	4,000,000	200	592,277				
Low				23.2	137,408	63,076	0
Medium				41.4	245,203	0	0
High				76.8	454,869	0	0
King penguin	21,490	242	11,557				
Low				43.6	5,039	161	18
Medium				71.6	8,275	265	30
High				99.4	11,487	2,883	0
Rockhopper penguin	2,020	365	110	8	9	0	0
Gentoo penguin	26,900	365	8,692				
Low				97.9	8,640	0	
Medium				97.9	8,640	475	
High				97.9	8,640	1,469	
Heard Island shag	500	365	173	See methods	116	3	
Antarctic fur seal	21,536	See methods and Table 2	20,065				
Low					13,569	3,943	21
Medium					17,228	9,188	3,983
High					19,872	14,039	27
Elephant seal	77,000	See methods					
Low			122,870	25	30,368	16,983	14,491
Medium			106,585	45	47,559	26,428	22,553
High			88,873	75	66,395	36,653	31,283
Total low					195,149	84,166	
Total medium					327,030	36,359	
Total high					561,388	55,047	

[a] Total fish is calculated as % fish multiplied by food required

Gentoo penguins

The whole-island estimate of gentoo penguins was 13,450 breeding pairs in the 1992/1993 season (Moore 1993). The diet was investigated in summer 1986/1987 (Klages et al. 1990) and in winter 1990 (Green and Wong 1992). In 1986/1987, fish made up 99.4% of the diet (Klages et al. 1990) with the most common species being *K. anderssoni* (present in 65.5% of stomachs). *Champsocephalus gunnari* remains occurred in 30.9% of stomachs, though none were of commercial size. In winter 1990, *K. anderssoni* was the most important fish species contributing 80.4% of identifiable otoliths, with no *C. gunnari* present (Green and Wong 1992). Food consumption by gentoo penguins was scaled down from the requirement for 16,574 pairs (Woehler and Green 1992). Using estimated masses from Klages et al. (1990), and assuming a minimum estimate of one otolith per occurrence in stomachs, two figures were estimated for commercial fish species: 5.5% based on the numbers of measured otoliths and 17% based on occurrence. These, together with the absence of commercial fish species (Green and Wong 1992), gave a spread of estimates for commercial fish take (Table 1).

Heard Island shags

Data for food intake were scaled up from 89 pairs (Woehler and Green 1992) to 500 individuals (Green et al. 1990), 100 pairs of which were assumed to breed. Only one figure for total consumption was calculated. The diet of non-breeders was calculated at 60.1% fish for the whole year based on casts and regurgitated stomach samples from two non-breeding adults (Green and Williams 1997). It was assumed that the diet of 200 breeding birds was 100% fish for the period October to February (Green and Williams 1997), and 60.1% fish for the remainder of the year. Unidentified nototheniids in Green et al. (1990) were allocated to identified species according to their proportional representation and all fish were assumed to be of the same mass (100 g).

Antarctic fur seals

The number of Antarctic fur seals used for calculations was the minimum number known to be in the vicinity of Heard Island in each quarter of the year (Green 1993). Consumption estimates were calculated quarterly (Table 2). The proportion of fish in the diet was similar in three studies (Green et al. 1989, 1991, 1997) and was close to 100% by mass. Estimates of fish consumption were calculated for a composite year made up of data from 1987/1988 and 1990 (Green et al. 1989, 1991). Because of the differences in diet between the March quarters of 1992 and 1993 (when the numbers of seals ashore were at their highest), the 1992/1993 data were examined as 2 quite different years: 1992 including March of that year, and 1992/1993, which included the March quarter for 1993. For 1992/1993, average commercial fish consumption as a percentage of bony fish was 71.4%, while for 1992 it was 59.5%. The figure for the composite year was 42.5%.

Difficulties arose in determining the contribution made by skate, which do not leave remains suitable for calculating either numbers or size. Two estimates of the importance of skate were made: the first assumed a representation of skate directly proportional to the frequency of occurrence (1992/1993 model), while the second (1992 model) assumed that skate were 16 times more likely to be represented than bony fish (32 thorns for *Bathyraja murrayi*, Gon and Heemstra 1990, vs 2 identifiable otoliths per bony fish). For the medium model, the skate proportion for the composite year was divided by 8. The contribution by commercial fish species was calculated each quarter for the 3 years, out of the fish remaining after skate had been deducted (Table 2).

Southern elephant seals

Total biomass of the population of elephant seals for estimates of food consumption was calculated by multiplying the number of seals within each age class by the mean mass of individuals within that age class for a population of 72,000 seals (Slip 1997a).

The main foraging areas of adult southern elephant seals from Heard Island are close to the Antarctic continental shelf in winter, and along the southeast edge of the Kerguelen Plateau for adult females in summer (Slip 1997a,b). The most likely foraging areas on the plateau are therefore in the vicinity of Heard Island rather than Iles Kerguelen. Assuming the locations of tracked animals (Slip 1997a,b) were representative of the population, juvenile seals ≤2 years old spent about 60% of their time on or at the edge of the Kerguelen Plateau, while adult females and subadult males spent 30% of their time at sea there and adult males 29% (Slip 1997a).

Because so few dietary data were available for elephant seals the results of the two studies at Heard Island (Green and Burton 1993; Slip 1995) were not considered representative of interannual differences and the results of both studies were combined to calculate the composition of the diet. In 1992/1993, 4 species of fish (*E. carlsbergi*, *Electrona antarctica*, *D. eleginoides* and *Gymnoscopelus nicholsi*) were identified from otoliths in 11 of 65 elephant seal stomachs containing food remains (Slip 1995). There were few data on the sizes of fish in 1987/1988 due to the degraded state in which the few otoliths present were found (Green and Burton 1993). Size estimates for three species (*C. gunnari*, *Channichthys rhinoceratus* and *Gymnoscopelus braueri*) were available from otoliths, but otoliths of six other species were too degraded to measure. Fish taken by elephant seals were all close to or above the age of sexual maturity, whereas those of Antarctic fur seals were below the age. For *L. squamifrons*, the standard length at maturity was 28% larger than fish taken by Antarctic fur seals so this length was adopted for individuals of this species taken by elephant seals. The relative importance of all fish species in the diet was determined by Slip (1997a).

Laws (1960) estimated that 25% of the diet of elephant seals was fish whereas, based on the ratio of fish eyes to squid beaks in Green and Burton (1993), 77.5% of the diet could be fish. Slip (1997a), using the same presence/absence method of Laws (1960), estimated a figure of 45% fish. Three estimates for the percentage of fish in the diet were therefore used: 25%, 45% and 75%. Because the energy densities vary between fish and squid the total food requirement will vary with different proportions of each in the diet (Table 1).

Results

The quantity of fish in the diet varied for three species (macaroni penguins, king penguins and southern elephant seals) that commonly preyed on other food sources (zooplankton and squid), but not for two other species (gentoo penguin and Antarctic fur seal) whose diet was almost completely fish (Table 1). A wide variation in the estimated consumption of commercial fish species occurred, regardless of whether the percentage of fish in the diet varied (Tables 3, 4). One result to be highlighted from the calculations was that while there was a threefold increase in fish consumption between low and high total fish take (Table 1), the take of commercial fish species declined by 34.6% over the same range. Much of this reduction was due to a high intake of *Champsocephalus gunnari* by macaroni penguins at low overall fish consumption. Predation by macaroni penguins on commercial-sized fish was nil and so the amounts of fish of commercial size that were taken among the three estimates varied by a factor of over 2 (Table 4).

Discussion

Studies of piscivore-fisheries interactions have generally concentrated on single species or taxa of seals or birds (for example, Furness 1982; Nettleship et al. 1982;

Table 2 Quarterly calculations of fish requirements for Antarctic fur seals at Heard Island at three levels of fish consumption

	Total food (tonnes)	Fraction of non-bony fish	Total bony fish (tonnes)	Commercial species (%)	Commercial size (%)	Commercial species (tonnes)	Commercial size (tonnes)
1992							0
March	17,144	0.312	11,795.1	23.13	0	2,728.2	0
June	1,336	0.397	805.6	53.94	0	434.5	0
September	1,021	0.46	551.3	81.43	0	449.0	20.6
December	564	0.26	417.4	79.34	4.93	331.1	20.6
Total for year	20,065		13,569.4	59.46		3,942.8	
1987/88/90							
March	17,144	0.141	14,726.7	57.16	23.73	8,417.8	3494.6
June	1,336	0.085	1,223.1	13.79	5.87	168.7	71.8
September	1,021	0.207	810.2	40.50	32.0	328.1	259.3
December	564	0.171	467.6	58.41	33.68	273.1	157.5
Total for year	20,065		17,227.5	42.47		9,187.7	3,983.2
1992/93							
March	17,144	0.007	17,024.0	71.01	0	12,088.7	0
June	1,336	0.025	1,302.6	53.94	0	702.6	0
September	1,021	0.029	991.4	81.43	0	807.3	0
December	564	0.017	554.4	79.34	4.93	439.9	27.3
Total for year	20,065		19,872.4	71.43		14,038.5	27.3

Beddington et al. 1985; Thompson 1989; Duffy and Schneider 1994). Few studies have attempted to consider a wider range of taxa for the examination of interactions, possibly due to the complexity of the task or the restricted taxonomic interests of the researcher. Most studies (e.g. Thompson 1989) are made after the commencement of a fishery. The present study is one of the few that was initiated as an attempt to collect data in the absence of a nearby fishery and it was aimed at all fish predators that were amenable to study by a land-based operation.

Methodological constraints

This is not the place for a review of dietary and energetic or consumption models. The literature abounds in critiques (e.g. Jobling and Breiby 1986) and here we concentrate on the species-specific problems. Within the limitations of consumption models, estimates for the penguin species (particularly king and macaroni) are realistic. The dietary studies were of reasonable sample size and the methodology did not vary greatly between years. The major difference was in the presentation of results, particularly the lack of data on the numerical composition of otoliths in Klages et al. (1989, 1990).

One major problem with estimating fish consumption by elephant seals was the low number of otoliths recovered from stomachs. This meant that inter-annual variation in the diet could not be incorporated into the model. Additionally, there were few data on the size distribution of fish species, particularly for *D. eleginoides*, but it is known that elephant seals take larger fish than Antarctic fur seals (which do take commercial-sized *D. eleginoides*) and elephant seals have been recorded consuming *D. eleginoides* of 650 mm standard length (Slip 1995).

Most of the foraging areas of southern elephant seals documented by Slip (1997a,b) were well away from Heard Island. Time was spent over the shelf, and this was estimated by making assumptions based on time-depth-location data (Slip 1997a,b). Additionally, Krockenberger and Bryden (1994) calculated a rate of passage of digesta for captive elephant seals of about 9 h. Together, these findings suggest that the prey identified in the stomachs of elephant seals from Heard Island were caught close to the island.

There are two biases with regard to otoliths that are of concern, one of which is peculiar to fur seals. Selective non-representation of fish types has generally been discussed in terms of otoliths being preferentially digested because of their size (i.e. smaller otoliths are lost first), or composition, or surface area to volume ratio. However, fur seals may also break up larger fish and discard the fish heads before consumption (David 1987), introducing biases against the representation of larger fish.

Veracity

The results here are comparable to other calculations for the same species (Croxall et al. 1984; Woehler and Green 1992). Croxall et al. (1984) made an estimate for 8 million pairs of macaroni penguins at South Georgia for 365 days. Assuming (for ease of calculation) a linear

Table 3 Estimates of the take of commercial fish (tonnes) by fish species at three different levels of consumption by predators around Heard Island and estimates of fish biomass that are averages of three estimates from Williams and de la Mare (1995)

Predator/fish	Predator population and estimated fish biomass	Fish species	Low predation (tonnes)	Medium predation (tonnes)	High predation (tonnes)
Macaroni	4,000,000	*C. gunnari*	63,076	0	0
King	21,490	*C. gunnari*	161	265	2,883
Rockhopper	2,020		0	0	0
Gentoo	26,900	*C. gunnari*	0	475	1,469
Shag	500	*N. rossii*	3	3	3
Fur seal	21,536	*C. gunnari*	3,792	8,213	13,805
		D. eleginoides	50	6	76
		N. rossii	2	295	2
		L. squamifrons	99	674	156
Elephant seal	77,000	*D. eleginoides*	15,315	23,808	32,982
		C. gunnari	351	552	773
		L. squamifrons	1,317	2,069	2,899
Champsocephalus gunnari	13,133 tonnes	Total *C. gunnari*	67,380	9,505	18,930
Dissostichus eleginoides	10,925 tonnes	Total *D. eleginoides*	15,365	23,814	33,058
Notothenia rossii	No estimate	Total *N. rossii*	5	298	5
Lepidonotothen squamifrons	14,752 tonnes	Total *L. squamifrons*	1,416	2,743	3,055
Total	38,810 tonnes		84,166	36,360	55,048

Table 4 Estimates of the mass of commercial-sized fish (tonnes) by fish species at three different levels of consumption by predators around Heard Island

Predator	Population	Fish species	Low predation	Medium predation	High predation
Macaroni	4,000,000		0	0	0
King	21,490	*Champsocephalus gunnari*	18	30	0
Rockhopper	2,020		0	0	0
Gentoo	26,900		0	0	0
Shag	500		0	0	0
Fur seal	21,536	*C. gunnari*	0	3,402	0
		Dissostichus eleginoides	21	6	27
		Notothenia rossii	0	284	0
		Lepidonotothen squamifrons	0	490	0
Elephant seal	59,805	*D. eleginoides*	12,906	20,063	27,793
		C. gunnari	351	552	773
		L. squamifrons	1,234	1,939	2,717
		Total *C. gunnari*	369	3,984	773
		Total *D. eleginoides*	12,927	20,069	27,820
		Total *N. rossii*	0	284	0
		Total *L. squamifrons*	1,234	2,429	2,717
Total			14,530	26,766	31,310

relationship between the number of days and food consumption and recalculating the South Georgia data for 200 days and 2 million pairs, the estimated consumption would be 548,000 tonnes, very close to the estimate for Heard Island.

The similarity in the amount of commercial fish taken at low and high rates of predation on fish was unexpected. The pelagic *K. anderssoni* was the preferred fish species for three species (king and macaroni penguins and Antarctic fur seal). If the abundance of pelagic prey in the region varies interannually there may be years when *K. anderssoni* is not present in high numbers. Under these circumstances, macaroni penguins may forage more closely to Heard Island on euphausiids and fish as they did in 1986 (Klages et al. 1989), when stomach contents were less digested and contained more shelf species (the major species being *C. gunnari*). Macaroni penguins are estimated to be responsible for over 75% of the consumption of marine resources around Heard Island by land-based predators (Woehler and Green 1992). One consequence of macaroni penguins foraging on the shelf is that while there may be low predation levels on fish generally there is high consumption of commercial fish, mainly of small individuals.

For Antarctic fur seals, confidence in the results obtained is lower due to the difficulties in quantifying the contribution of skate to the diet. Total fish consumption was similar across all base studies of fur seals (Green et al. 1989, 1991, 1997). However, the occurrence of skate varied widely from 52.6% in 1987/1988 to only 18.5% in 1990 (Green et al. 1991). At high total fish predation, the take of *C. gunnari* was 13,805 tonnes but the take of commercial-sized *C. gunnari* was zero. By recalculating the composite year at the same level of total bony fish intake, the comparable total consumption would increase from 8213 to 12,549 tonnes and the take of commercial-sized *C. gunnari* would be 5199 tonnes. In this respect it is likely that the calculated consumption of commercial-sized *C. gunnari* presented here is conservative.

Comparison with stock estimates

The estimates of both the maximum and minimum total consumption of *C. gunnari* by all predator species are between approximately double the highest and 6 times the lowest estimates, respectively, of biomass estimated from three research cruises (Williams and de la Mare 1995). It is not unusual for these types of estimates to differ widely, and Reid (1995) estimated that the winter take of *C. gunnari* at South Georgia by fur seals alone was over 4 times the estimated biomass. The highest figure for *C. gunnari* in the present study was largely due to a single high figure for consumption by macaroni penguins. The estimated consumption of *C. gunnari* by Antarctic fur seals was influenced by the quantity allocated to skate consumption. This quantity varied between 193 tonnes in the year of high total bony fish consumption and 6496 tonnes in the year of low total bony fish consumption, with the average figure of 3175 tonnes being about half the average of the estimated 6083 tonnes of available skate (Williams and de la Mare 1995). It seems, therefore, that there is little room for adjustments to the estimates for predation on *C. gunnari*.

For *D. eleginoides* and *L. squamifrons*, our estimates of consumption are 1.9 and 0.07 times the highest estimates of biomass for these two species (17,715 and 41,380 tonnes respectively) by Williams and de la Mare (1995). Their estimated biomass for *D. eleginoides* stocks at Heard Island has recently been increased by an order of magnitude to 120,000 tonnes from the same survey data (W.K. de la Mare personal communication) and, as a consequence, the estimated proportion of this taken by fish predators from Heard Island is between 12.8 and 27.5% (Table 3).

Extension to the Kerguelen Plateau fishery and possible competition with predators

A formal proposal for a commercial fishery within the Heard Island region was made in 1994 and a Total Allowable Catch (TAC) of 295 tonnes was set for *D. eleginoides* in 1995, but this was increased to 3800 tonnes in 1996 on the basis of revised estimates of biomass (120,000 tonnes) for this species (SC-CAMLR XV). The extension of a fishery into Heard Island waters was thought likely to lead to competition with fur seals by Green et al. (1989). However, it is extremely difficult to measure the degree of competition between a fishery and vertebrate predators. Duffy and Schneider (1994) suggested the use of the Schaefer Ratio (in the present context the ratio of total intake by predators to the commercial catch); if it was greater than 0.25 this would seem to indicate considerable potential for competition. An examination of only commercial-sized *D. eleginoides* in the diet of predators compared with the TAC of 3800 tonnes gives a Schaefer Ratio of between 3.4:1 and 7.3:1. The conclusion from this analysis, that there will be intense competition for available fish between the licenced fishery and predators, especially southern elephant seals, is inescapable. The additional harvest by vessels fishing illegally for *D. eleginoides* of unknown size can only increase this competition.

The fisheries management system most commonly adopted has been termed reactive management, action only being taken when it is seen to be necessary, and typically leading to the collapse of resources (Nicol and de la Mare 1993). This has already happened at least once in the Heard Island region (Duhamel and Hureau 1990). The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has taken an ecosystem approach to the management of areas south of the Antarctic Polar Front, using control-systems theory to examine a single species harvest, Antarctic krill, *Euphausia superba* (Nicol and de la Mare 1993). A fundamental component of such feedback management is a model of the ecosystem that incorporates consumption by the predators of the target species. However, there are no long-term monitoring programs in place for predators in the Heard Island region such as CCAMLR's Ecosystem Monitoring Program in the Antarctic. There are, therefore, no means of measuring the impact of the fishery on vertebrate populations, particularly the southern elephant seals which are most at risk. Because of the threat posed by a fishery there are some obvious weaknesses in this study that need to be addressed by further research programs to gain a more complete picture of the potential for competition. These include: (1) a more accurate measure of the fish component of the diet of southern elephant seals and the amount of skate taken by Antarctic fur seals, (2) a determination of the interannual variation in reproductive success, diet and foraging patterns of predators in response to variations in the food supply, and (3) an examination of the biomass and interannual fluctuations in *K. anderssoni* stocks. Any changes in the fish stock resulting from the removal of larger commercial fish must also be modelled to give a better understanding of ecosystem changes resulting from the commencement of a fishery.

Acknowledgements We thank E.J. Woehler, R. Williams, W. de la Mare and H.R. Burton for their discussions and for commenting on the manuscript. R. Williams, G. Hosie and M. Stolp (Antarctic Division) provided various measurements.

References

Aarde RJ van (1980) Fluctuations in the population of southern elephant seals *Mirounga leonina* at Kerguelen Island. S Afr J Zool 15:99–106

Beddington JR, Beverton RJH, Lavigne DM (1985) Marine mammals and fisheries. Allen & Unwin, London

Bester MN, Roux JP (1986) The second survey of Antarctic fur seals *Arctocephalus gazella* on the Courbet Peninsula, Iles Kerguelen. S Afr J Antarct Res 16:33–37

Brown CR (1989) Energy requirements and food consumption of *Eudyptes* penguins at the Prince Edward Islands. Antarct Sci 1:15–21

Croxall JP, Ricketts C, Prince PA (1984) Impact of seabirds on marine resources, especially krill, of South Georgia waters. In: Whittow GC, Rahn H (eds) Seabird energetics. Plenum, New York, pp 285–315

David JHM (1987) Diet of the South African fur seal (1974–1985) and an assessment of competition with fisheries in southern Africa. S Afr J Mar Sci 5:693–713

Duffy DC, Schneider D (1994) Guide to seabird-fishery interactions. In: Nettleship DN, Burger J, Gochfeld M (eds) Seabirds on islands – threats, case studies and action plans. Birdlife International Conservation Series 1, Cambridge, pp 26–38

Duhamel G, Hureau J-C (1990) Changes in fish populations and fisheries around the Kerguelen Islands during the last decade. In: Kerry KR, Hempel G (eds) Antarctic ecosystems. Ecological change and conservation. Springer, Berlin Heidelberg New York, pp 323–333

Furness RW (1982) Competition between fisheries and seabird communities. Adv Mar Biol 20:225–307

Gon O, Heemstra PC (eds) (1990) Fishes of the Southern Ocean. JLB Smith Institute of Ichthyology, Grahamstown

Green K (1993) Counts for biomass calculations of Antarctic fur seals *(Arctocephalus gazella)* at Heard Island, 1992/1993. In: Green K (ed) Heard Island 1992 ANARE Report. Antarctic Division, Hobart, pp 11–13

Green K, Burton HR (1993) Comparison of the stomach contents of southern elephant seals, *Mirounga leonina*, from two breeding populations. Mar Mamm Sci 9:10–22

Green K, Williams R (1997) Biology of the Heard Island shag, *Phalacrocorax nivalis*. 3. Foraging, diet and diving behaviour. Emu 97:76–83

Green K, Wong V (1992) The diet of gentoo penguins *Pygoscelis papua* in early winter at Heard Island. Corella 16:129–132

Green K, Burton HR, Williams R (1989) The diet of Antarctic fur seals *Arctocephalus gazella* during the breeding season at Heard Island. Antarct Sci 1:317–324

Green K, Williams R, Woehler EJ, Burton HR, Gales NJ, Jones RT (1990) Diet of the Heard Island cormorant *Phalacrocorax (atriceps) nivalis*. Antarct Sci 2:139–141

Green K, Williams R, Burton HR (1991) The diet of Antarctic fur seals during the late autumn and early winter around Heard Island. Antarct Sci 3:359–361

Green K, Williams R, Burton HR (1997) Foraging ecology of Antarctic fur seals (*Arctocephalus gazella* Peters) around Heard Island. In: Hindell MA, Kemper C (eds) Recent marine mammal research in Australia and New Zealand. Surrey Beatty, Sydney, pp 105–113

Green K, Williams R, Green MG (in press) Foraging ecology and diving behaviour of Macaroni penguins *Eudyptes chrysolophus* over the breeding season of 1992/93 at Heard Island. Mar Ornithol

Jobling M, Breiby A (1986) The use and abuse of fish otoliths in studies of feeding habits of marine piscivores. Antarct Sci 71:265–274

Klages NTW, Gales RP, Pemberton D (1989) Dietary segregation of macaroni and rockhopper penguins at Heard Island. Aust Wildl Res 16:599–604

Klages NTW, Pemberton D, Gales RP (1990) The diets of king and gentoo penguins at Heard Island. Aust Wildl Res 17:53–60

Krockenberger MB, Bryden MM (1994) Rate of passage of digesta through the alimentary tract of southern elephant seals (*Mirounga leonina*) (Carnivora: Phocidae). J Zool Lond 234:229–237

Laws RM (1960) The southern elephant seal (*Mirounga leonina* Linn.) at South Georgia. Nor Hvalfangst Tid 49:466–476, 520–542

Laws RM (1994) History and present status of southern elephant seal populations In: Le Boeuf BJ, Laws RM (eds) Elephant seals: population ecology, behaviour, and physiology. University of California Press, Berkeley, pp 49–65

Moore GJ (1993) Distribution, population size and breeding success of the gentoo penguin (*Pygoscelis papua*) at the eastern end of Heard Island during the 1992/93 breeding season. In: Green K (ed) Heard Island 1992 ANARE Report. Antarctic Division, Hobart, pp 120–131

Moore GJ, Robertson G (1993a) The diet of king penguin (*Aptenodytes patagonicus*) at Heard Island over the 1992 breeding season: diet composition, feed mass and feeding frequency. In: Green K (ed) Heard Island 1992 ANARE Report. Antarctic Division, Hobart, pp 72–101

Moore GJ, Robertson G (1993b) Diving ecology of the king penguin (*Aptenodytes patagonicus*) at Heard Island for 1992 and 1993: adults feeding chicks from brood to fledging. In: Green K (ed) Heard Island 1992 ANARE Report. Antarctic Division, Hobart, pp 107–114

Moore GJ, Robertson G (1993c) Population parameters of the king penguin (*Aptenodytes patagonicus*) at Heard Island over the 1992 and 1993 breeding seasons: population size, patterns of chick mortality, fledging patterns and morphometrics. In: Green K (ed) Heard Island 1992 ANARE Report. Antarctic Division, Hobart, pp 67–71

Nettleship DN, Sanger GA, Springer PF (eds) (1982) Marine birds: their feeding ecology and commercial fisheries relationships. Minister of Supply and Services, Canada

Nicol S, Mare WK de la (1993) Ecosystem management and the Antarctic krill. Am Sci 81:36–47

Pascal M (1985) Numerical changes in the population of elephant seals (*Mirounga leonina* L.) in the Kerguelen Archipelago during the past 30 years. In: Beddington JR, Beverton RJH, Lavigne DM (eds) Marine mammals and fisheries. Allen & Unwin, London, pp 171–186

Reid K (1995) The diet of Antarctic fur seals (*Arctocephalus gazella* Peters 1875) during winter at South Georgia. Antarct Sci 7:241–249

Slip DJ (1995) The diet of southern elephant seals (*Mirounga leonina*) at Heard Island. Can J Zool 73:1519–1528

Slip DJ (1997a) Foraging ecology of southern elephant seals at Heard Island. PhD Thesis, University of Tasmania

Slip DJ (1997b) Diving and foraging behaviour of juvenile southern elephant seals from Heard Island. In: Hindell MA, Kemper C (eds) Recent marine mammal research in Australia and New Zealand. Surrey Beatty, Sydney, pp 114–124

Slosarczyk W, Wysokinski A (1980) Ichthyological and fishery studies of the shelf fishing grounds in the region of Kerguelen Islands (Antarctic). Pol Polar Res 1:173–190

Sosinski J (1985) Some data on taxonomy and biology of Antarctic icefish *Champsocephalus gunnari* Lonnberg 1905. Acta Ichthyol Piscatoria 15:3–54

Thompson KR (1989) An assessment of the potential for competition between seabirds and fisheries in the Falkland Islands. Falkland Islands Foundation, Brighton

Wilkinson IS, Bester MN (1988) Is onshore human activity a factor in the decline of the southern elephant seal? S Afr J Antarct Res 18:14–17

Williams R, Mare WK de la (1995) Fish distribution and biomass in the Heard Island zone (Division 58.5.2). CCAMLR Sci 2:1–20

Woehler EJ, Green, K (1992) Consumption of marine resources by seabirds and seals at Heard Island and the McDonald Islands. Polar Biol 12:659–665