THE DEVELOPMENT OF FISHERIES AND STOCK ASSESSMENT OF RESOURCES IN THE SOUTHERN OCEAN

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Abstract: The paper describes the pattern of development of the fisheries in the Antarctic (roughly the area south of the convergence) in the light of statistics available to FAO. This data series starts with the 1969/70 season, but catches were very small before that. Total catches have fluctuated greatly, reflecting several distinct phases in the fishery, initially mainly on fish (*Notothenia* and *Chaenocephalus*), but with rapid increases in krill since 1978. Total catches were over half a million t in the 1979/80 season.

For recent years complete data are available on catches by species and by subarea, but the more detailed data (including statistics of fishing effort) required for stock assessment are not available for some of the biggest fishing countries. As a result, reliable assessments of the state of the stocks cannot be made, but the historical patterns suggest that the large catches of fish represented the removals of accumulated stocks, and that only a relatively small annual catch can be sustained. No conclusions can be reached from the short period of significant krill catches, although the preliminary reports from the FIBEX surveys suggest that current catches have been only a small proportion of the standing stock.

If the fish stocks have indeed been heavily fished, then management measures should be considered. This will require examination of the objectives of the measures (a pattern of "pulse fishing" may be more attractive than a steady but low annual catch), of the arrangements for providing scientific advice, and of the type of measures to be introduced (a limit on the number of vessels operating may be better than attempting to set a Total Allowable Catch).

1. Introduction

Man's interest in the Southern Ocean is of two main types–the scientific drive to know what is there, and how the natural system operates, and economic desires. These interact; the scientist, whatever his personal motives, usually has to demonstrate to his paymasters that his research could have some long-term practical benefit, while harvesting natural resources cannot continue successfully for along without some scientific understanding of the effects of the harvest on the resource. In the 1930s the scientific work of the U. K. Discovery Committee in the Southern Ocean was explicitly justified on the recognition of the importance of biological knowledge to the long-term health of the whaling industry. Nevertheless, since then scientific research and economic exploitation have to a large extent proceeded more or less in isolation–an isolation which was one important cause of the disasters which overtook whaling and the IWC in the 1960s. This isolation is now ending, and therefore no apology is necessary in this scientific meeting on touching on some of the practical and economic problems of harvesting the rich resources of the Antarctic Seas, and for which scientific advice, based on good scientific research, is needed.

This is not the place for a long discussion of the objectives of fishery management, but it is relevant to note that those determining the fishery policy of a country can have a variety of objectives in mind. These are likely to include increasing the net economic return from the fishery, the well-being of the individual fisherman, or the supply of protein to the country. Maximizing the yield from a particular resource (*i.e.*, achieving the Maximum Sustainable Yield, MSY) is likely to come some way down the list if it appears explicitly at all. This variety of objectives requires a corresponding complexity in the scientific advice. It is not sufficient, or indeed possible, to recommend some annual catch as being "correct", but the managers need to know about the impact of various policies on the pattern, over the next few years, of catches and of stock abundance (and hence costs of fishing and likely profits) of the stock being managed and, to the extent there is biological interaction between species, the impacts on the fisheries on other species.

Fortunately, since the information needed to make a comprehensive study of all possible aspects of scientific advice would be enormous, the detail and precision required depends on the state of the fishery, increasing as the fishery develops. At some stages very simple studies may be sufficient to provide useful advice, while later complex research may be needed.

The present paper does not attempt to make a comprehensive review of the fisheries of the Antarctic Seas, or a statement on what management measures–if any–seem necessary to achieve some objective or other. Its purpose is simpler–to outline the history of the fisheries; on the basis of the information available (principally the statistics reported to FAO), make a rough assessment of the state of exploitation, to identify, in general terms, possible management which seems desirable and, in particular, to discuss the extent to which current data and research is sufficient to reach useful policy decisions and where more data should be collected and more research done. The main source of information is the statistics reported by countries to FAO covering the period up to the 1979/80 season.

2. The History of the Fisheries

The fisheries of the Southern Ocean–which to the participants comprise any harvest from the sea, regardless of the taxonomic status of the animals caught–started with sealing in the nineteenth century. Drastic though the effects were on the stocks of fur seals and others on the sub-Antarctic islands, the impact on the ecosystem as a whole was small. This is not the case of whaling, where the depletion of the larger baleen whales seems to have been followed by increases of several competing species. This interaction between species is discussed further in a later section. The history of whaling has been described many times from the various points of view. A good account from the industrial point of view is that of TØNNESSEN and JOHNSEN (1982). The biological aspects are discussed by LAWS (1962, 1977); the problems of management by GULLAND (1974) and SCHEVILL (1974), and the detailed population dynamics as well as management by ALLEN (1980). The most detailed information is available in the reports and meeting documents of the International Whaling Commission. Catches reached a peak of over 3 million t in 1938–whaling statistics have traditionally been expressed in numbers, rather than weight, which makes them difficult to compare with other catches, but HOLT (1976) has converted the published statistics to the more convenient form of weight. By 1973 catches had fallen to around half a million t, and are now much less (a few thousand minke whales). Within the rise and collapse of the industry as a whole, catches of each species (more or less in order of decreasing size) have reached a peak and declined. Catches of blue whales peaked (at a little under 30000 whales) in 1930/31; fin whales stayed at a plateau (at around 27000 whales, controlled by the IWC's quota) for most of the 1950s; sei whales had a short sharp peak of around 20000 whales in 1965/66. Catching of minke whales has only recently developed, and with catches being limited to less than 10000 whales annually, this species is still at least as abundant as it has ever been.

Exploitation of fishes has followed a similar pattern of boom and bust. The first boom period was on *Notothenia* (mostly *N. rossii marmorata*). Catches rose from very little to over 400000 t in 1969/70, declining almost as rapidly to 160000 t in 1970/71, and less than 10000 t in 1972/73. Catches in more recent years have increased again, but are still a little more than 10–15% of the peak years. Catches were taken almost entirely by the U.S.S.R. in the first few years of the fishery, but other eastern European countries now also take significant catches. The big catches in the 1969/70 season were taken in the South Atlantic–it is presumed most round South Georgia–but in the next year much of the fishing shifted to the Indian Ocean Sector (Kerguelen).

After low catches between 1971 and 1975, total fish catches rose again in the 1976/77 season with the growth of fishing on icefish (*Champsocephalus gunnari*), as well as the beginning of significant catches of krill. The fishing on icefish lasted little longer than that on *Notothenia*; catches rose from less than 10000 t in 1974/75 to 160000 t in 1975/76 and 180000 t in 1976/77, but then collapsed to 30000 t and 15000 t in the two following seasons. As for *Notothenia* the biggest catches have been in the South Atlantic (apparently mostly around the South Orkney Islands, rather than South Georgia), with smaller but still significant catches in the Indian Ocean Sector (Kerguelen). The Soviet Union has again taken big catches, with Poland and the German Democratic Republic also taking significant shares.

The most recent fishery to develop, and the one that seems potentially much the largest, and the one that has attracted greatest interest, is that for krill. Interest in krill, as a potential harvest, has existed for a long time, but krill did not figure in the reported statistics as an explicit item in the commercial catches until the 1973/74 season, when some 20000 t were caught. Subsequent growth in catches has been large, but irregular, with jumps to 120000 t in the 1976/77 season, and nearly 400000 t in 1978/79. The two principal countries have been Japan, whose catches have risen fairly steadily to a little less than 40000 t in 1979/80, and the U.S.S.R., which has become much the greatest producer with over 400000 t in 1979/80. The biggest catches have been in the Atlantic Sector, though Japanese vessels have fished mostly in the Indian Ocean Sector.

3. Resource Evaluation

Even this brief examination of the history of the exploitation of Antarctic Waters raises two questions. The first is the practical question of whether it is possible to arrange for sustained harvesting over a period, or whether utilization of these resources is condemned to a succession of booms and crashes, until no resource is left that can support a viable industry. The second is the scientific question of the degree to which the violent changes in what is caught is reflected in changes in the ecosystem as a whole. To answer either of these questions it is necessary to evaluate the state of the resources (individually and collectively), though as discussed in a later section, the ability to have a sustained fishery also depends on the action taken by authorities in the light of the scientific findings.

3.1. Whales

The evaluation of whale stocks and the subsequent decisions on managing these stocks has probably attracted more controversy than that of any other natural resource, but this controversy has recently been mainly over sperm whales, and some of the minor stocks of baleen whales in the northern hemisphere, for which basic data are scarce. The single-species dynamics of baleen whales appear to be simple, compared with those of sperm whales (ALLEN, 1980). As exploitation reduces the abundance of the stock, whales mature at an earlier age (LOCKYER, 1972) and there is an increase in the pregnancy rate towards the theoretical maximum of one birth every other year (in practice it seems that a female producing a very early calf one year might occasionally be able to produce another calf late the next year, so the theoretical maximum could be exceeded). There is little evidence on the possible changes in the other important parameter–the natural mortality rates of young and adults–but any change is likely to be in the direction of a lower death rate in a smaller population. If catches were limited to the equivalent of the increased births, then the population abundance could be held at a constant level. This has hardly ever happened, though probably the fin whale catches in the early 1950s were not greatly in excess of the sustainable yield from the large stocks.

The practical difficulty in assessing the Antarctic baleen whales is to fix the scale, *i.e.*, to know the actual numbers in the stock, or to know what a given catch (in numbers) correspond to in terms of the mortality rate exerted. No one method has been entirely satisfactory. Direct counts from sightings from survey vessels (*e.g.*, DOI, 1974), while satisfactory for coastal stocks of gray or right whales, are extremely expensive in ships' time if attempted for Antarctic stocks. The surveys done, *e.g.*, for minke whales, give rise to estimates with large variance. The estimates may also be biassed due to difficulties in knowing what proportion of whales within a given distance of the ship's track are actually sighted, and in planning a statistically satisfactory survey grid.

The most satisfactory estimates are those (*e.g.*, for blue and fin whales) which match changes in observed abundance (as measured by catch-per-unit-effort) to those that would be expected in populations of different sizes due to the catches taken during the period of observation. This depends on having a good measure of effort, *i.e.*, one such that the c.p.u.e. will remain proportional to the stock abundance over a long time, and a range of population sizes. The number of days worked by the catchers attached to the factory vessels did provide a useful measure in the early period of analysis. It has since been adjusted at different times to take account of days lost by bad weather, the effect of weather on operational success (whales are harder to see in rough weather or poor visibility), the size and power of the individual catchers, the use of ASDIC, and (since the abundance of whales is clearly very close to being proportional to the numbers seen per unit time, so that the time actually spent actively searching for whales is probably the best unit of effort), the time lost from potential searching time due to chasing whales seen, killing them and bringing them to the factory vessel. There may be some elements of double counting in these adjustments–the size and power of a catcher may have little to do with how many whales are sighted per hour searched, but larger, more powerful vessels lose less time once a whale is seen. The points to be made here are first that the nature of whaling is such that a unit of effort that could be readily obtained from simple operational information (the number of catchers attached to each factory, and the number of days that factory worked) provided a useful first index of effort and c.p.u.e., and second, that adjustments made to this unit, on the basis of knowledge of how whaling is carried out, make the resultant figures of effort and c.p.u.e. even more reliable. The situation for fish and krill may not be so happy.

There are also two unsolved theoretical problems involved in whale assessment. One is the uncertainty that surrounds the form of the relation between the vital parameters (age at first maturity, pregnancy rate) and population abundance. This affects the level of abundance (as a proportion of the unexploited abundance) at which the sustainable yield is a maximum. If the relation were linear, then the MSY would occur at 50% of the unexploited level. It is believed that it is not linear, but much of the change occurs near the maximum population. In that case the maximum would occur at a higher population level, perhaps at 70% or 75% of the initial abundance. The difference is of practical importance, since the New Management Policy gives the highest priority to restoring the stock to the MSY level. Thus, if a stock was at 60% of the initial abundance, it would, on the linear model, be above the MSY and could be exploited, while on the other, and generally accepted model, it is below the MSY and should be protected, and catches set at zero.

The second problem is more interesting scientifically, and concerns the interaction between different species of whales. There are differences in the distribution of the species, with the blue and minke whales being found furthest south, nearest the ice, and the fin, humpback and sei whales progressively further north, and their food preferences and other characteristics differ in detail. However, there are also considerable overlap. All the Antarctic baleen whales eat krill, which is the predominant element in the diet of blue and minke whales, while sei whales also eat many copepods and other small zooplankton. One might therefore expect some reaction in one species when the abundance of another species change. This has possibly happened to the minke whales, where the age at maturity may have decreased before significant exploitation of this species began. It is therefore possible that the stock of minke whales has been increasing. This has two possible implications for management. One argument is that since the interaction between species works in both directions, the increased abundance of minke whales will have some negative influence on the rate of recovery of blue whales (and possibly other species). Therefore, on this argument, exploitation of minke whales should be encouraged, at least up to the point of maintaining their abundance at around the original level occurring at the beginning of this century. The other implication is that until the depleted stocks of the larger whales recover, the "carrying capacity" for minke whales is greater than it used to be. The level of abundance at which the MSY will occur is similarly increased, possibly above the current abundance, and therefore, according to the IWC's New Management Policy, no catching of minke whales should be allowed until the new MSY level is reached. The difficulty with both these arguments is that though the interaction between blue and minke whales has been established in a qualitative sense, there are no quantitative measures. It is not known what degree of "thinning out" of minke whales might be necessary to increase the recovery rate of blue whales. Nor is it known by how much the "carrying capacity" or MSY levels of minke whales have increased, or whether these levels are now decreasing (and if so, by how much) as the depleted stocks of larger whales recover.

3.2. Fish

The theoretical basis for assessing fish stocks is less complete than that for whales. Although the models currently used were mostly developed (notably during the classic period of the 1950s) with reference to fish stocks, some of the earliest applications were to whales (*e.g.*, HJORT *et al.*, 1933) and the models fit whales rather better than they do fish. For whales, the current models cover, at least to a reasonable first approximation, the whole life-cycle. For fish only the later stages, after they recruit to the fishery, can at present be studied satisfactorily, and there is a largely unknown period between the time when vast numbers of eggs are released into the plankton, and the time (some years later in the case of Antarctic fishes) when the survivors, reduced by several orders of magnitude, reach a fishable size. Analysis of fish stocks tend therefore to proceed in two stages, first of the events after recruitment, *e.g.*, the calculations of the yield to be expected under different patterns of fishing from a given number of recruits, and second, attempts to relate the recruitment to the abundance of the parent stock. In this the entire pre-recruit phase is generally treated as a "black box", with consideration given only to the input (size of spawning stock) and output (number of recruits). In practice it is often assumed that recruitment, under average environmental conditions, remains constant. The alternative approach, using the so-called surplus production models (SCHAEFER, 1954; PELLA and TOMLINSON, 1969), relates the sustainable yield directly to the abundance, or to the level of fishing effort (FOX, 1970) and virtually all the detailed population processes are treated as a simple "black box".

To apply any of these models some measure of the stock abundance, either in absolute terms or as an index reflecting changes over a period, is essential. (A measure of fishing effort or fishing mortality is equally essential, but provided total catch is known one flows directly from the other, and it is easier to consider the measurement of abundance). Most often this has been obtained from the catch and effort data of the commercial fisheries. For the Antarctic FAO has circulated statistical forms–STATLANT B forms–based on the requirements identified in the North Atlantic and other fishery regions with major multi-national fisheries. These forms, which are similar to those used in other regions, ask for information on the catches and fishing effort (days on the grounds and hours fishing) according to the month and fishing area (South Georgia, Antarctic Peninsula, etc.). These detailed statistics have been reported to FAO for recent seasons by a number of countries (Bulgaria, Japan, Poland) but the U.S.S.R., which takes much the greatest catches (89% of the total in 1979/80, has not reported effort data. Without these data any assessment is extremely difficult and uncertain.

Even if the catch and effort statistics were available in the detail required, it cannot be assumed that the question of monitoring abundance would be solved. Only in the most favourable cases (and whales are moderately favourable) will the c.p.u.e. derived directly from the readily available statistics reflect adequately changes in abundance. In the case of the factory trawlers operating in the Southern Ocean the amount of fish that can usefully be caught each day is limited to what can be processed, so that fishing stops once the processing lines are full. Then the catch per day reflects the processing capacity, rather than the abundance. The catch per hour fishing (*i.e.*, with the trawl net actually on the bottom) will be much more closely related to the fish density. However, this will be the density at the point of fishing, which (since fishermen do not fish at random) will not be the average density of the population. To the extent to which fishermen can stay on patches of high density, or the reduction in stock abundance is reflected by a shrinkage of the area inhabited (rather than a lowering of density in the inhabited area), the catch per hour fishing may fail to reflect adequately reductions in stock abundance. This is not to say that high priority should not be given to improving the available statistics, but it must be pointed out that even with good statistics, accurate assessment of the state of the stock may not be easy.

The abundance may be also estimated, and changes monitored, by means of surveys. Acoustic surveys are probably not suitable for fish close to the bottom in deep water. Several trawl surveys have been done round South Georgia (by Poland and the Federal Republic of Germany, reported to the second meeting of the BIOMASS Working Party on Fish Biology), and round Kerguelen (by France, HUREAU, 1979). The density, at least for the German data, was calculated on the assumption that all the fish in the path swept by the line between the extreme wings of the net were caught, *i.e.*, a catchability of 1. This may give an underestimate of the true density to the extent that fish escape from the path of the net, but this may be balanced by the shepherding effect of the trawl doors and bridles. The estimates have–inevitably given the small number of hauls possible on any one survey–a high variance, and there are also substantial differences in surveys taken a few months apart. Nevertheless, some clear information emerges from the surveys made around South Georgia.

(a) The abundance in 1975/76 (*i.e.*, before the second period of intense fishing) was around 1 million t (900000 t in a Polish survey in March 1976, 1300000 t in the German 1975/76 survey).

(b) There was a very big decline between 1975/76 and 1978/79, which matches very well the large catches of fish taken in the 1976/77 and 1977/78 seasons.

(c) The abundance by 1978/79 may be less than 100000 t (3 Polish surveys in December 1978, and January and March 1979 gave estimates from 42000 t to 97000 t). The stock round Kerguelen was estimated by HUREAU as some 130000 t.

The situation regarding the biological data needed for analytical assessments is rather better. The ages of Antarctic fish can be determined–though with some difficulties (EVERSON, 1980). Length and age data have been collected from both research and commercial catches, and other basic biological investigations carried out (*e.g.*, HUREAU, 1970; FREYTAG, 1980; KOCK, 1981).

Antarctic fish seem to be only moderately long-lived. Samples of *Notothenia rossii* collected by OLSEN in 1950/51 (before any fishery had taken place) contained fish between 4 and 14 years of age. More recent samples, reported to the BIOMASS Working Party, have somewhat similar ranges of age, though, as might be expected, rather fewer older fish. Samples of *Chaenichthys rhinoceratus* and *Notothenia magelleniea* contained fish from 2 years up to 10 years in age. In comparison stocks of some northern temperate or subarctic fish contain individuals of much higher ages–the Arcto-Norwegian cod does not mature until 9–10 years old, and before the stock was heavily fished 10-year old fish were quite common even among North Sea herring.

The BIOMASS Working Party attempted to estimate the various parameters (growth pattern, age and size at first maturity, total mortality, etc.). For some of these acceptable estimates are possible, but it was not possible to get a good estimate of the total mortality, still less determine the division of the total mortality into that due to fishery, and to natural causes. It is therefore possible to predict the general nature of the reaction of the stock to fishing, *i.e.*, the shape of the yield curve, but not, with much precision, the present location of the fishery on this curve. Because growth is slow, and natural mortality comparatively large, there is not much advantage in letting fish grow before catching them, *i.e.*, the greatest yield per recruit is taken with a low age at recruitment and moderately high fishing rate. However, because recruitment in most species occurs before, sometimes years before, the fish become mature, such a fishing pattern would lead to a great decrease in spawning stock, with the risk of recruitment failure.

It is clear, therefore, that it is not possible to make a full scientific assessment of the state of the Antarctic fish resources. At the same time some general statements can be made. Both the declines in the survey catches and, perhaps more conclusive, the short duration of the peak fisheries, strongly suggest that the stocks are not capable of sustaining the catches of the peak years such as 1969/70 or 1975/76–1976/77. Much of these catches must represent the fishing out of an accumulated stock. Altogether in the 11 seasons from 1964/70 to 1979/80 a little less than 1.8 million t of fish have been reported. If up to 1 million t comes from the accumulated stock (the survey results suggest that the decrease round South Georgia since 1969, much of which would have occurred before the first reported surveys were made, could have been approaching this level), then the net annual production, and the sustainable yield, could be less than 100000 t annually. More research is needed to get a better figure, and to determine what pattern of fishery might be necessary to maintain the productivity of the stock, as well as to promote a viable fishery. This might not necessarily be a fishery remaining constant from year to year. So-called 'pulse fishing', with large catches for short periods, followed by little if any fishing, can make economic sense for fleets operating a long way from their bases, but require careful control if the biological productivity of the resource is to be maintained.

3.3. *Krill*

Assessment of krill resources faces the same difficulties as assessment of fish, with some additional problems. Monitoring of changes in abundance is likely to be difficult. Experience during FIBEX has shown that acoustic methods can be used for surveying krill, but also that its patchy distribution, as well as other uncertainties (*e.g.*, how much krill is outside the main patches) make it difficult to get accurate results, without a large variance. The patchy distribution is also likely to cause great difficulties in interpreting catch and effort data from commercial fisheries. The catch per trawl haul, or per hour fishing will probably reflect the density within a patch. To monitor changes in the number of patches–and hence the overall abundance in a region–it may be necessary to look at such things as the time spent looking for patches (comparable to the searching time for whales), the number of patches seen per unit searching time, and the average size of the patch.

Another problem is that it is not possible to tell the age of individual krill. It is therefore difficult to apply many classical assessment methods. This is a difficulty that is being faced by many fishery scientists, particularly in tropical areas. Much progress is being made in using length-frequency data directly to estimate growth and mortality rates, and to assess the effect of fishing on the resource. For example, the ELEFAN computer program developed by Daniel PAULY (PAULY and DAVID, 1981) enables very extensive length frequency data to be examined to find the modes, and to determine growth curves that give the best overall fit to these modes. These methods might well be applied to krill data. One important application could be to look at the pre-war ('Discovery') and post-war length data to see if there is evidence of a reduction in mortality rates which could be the result of reduced predation by whales.

The biggest difficulty in evaluating with any precision the level of a possible krill harvest is that the present krill harvest is so small. For precision and reliability in knowing what the effect is of exploitation on a natural resource, there is no substitute for exploitation and direct observation of what happens. Nevertheless, various attempts to predict the potential krill harvest have been made. In conventional fisheries it is usually assumed that the potential yield from an unexploited resource, for which estimates of biomass are available will be proportional to the unexploited biomass, B_0, and to the turn-over rate of the stock, as measured by the natural mortality, M. This, using a factor of 0.5, gives rise to the formula $Y=0.5\ MB_0$, which has given useful results, though recent analysis suggests it may be too high. Applied to the South Georgia fish stocks (biomass 1 million t, natural mortality perhaps 0.2–0.3) thus gives a potential annual yield of 100–150000 t-higher, but not outrageously higher, than the figures suggested earlier. For krill, with a total life span of 1–2 years, M is higher, perhaps 0.5–1.0, which would suggest potential yields of 25–50% of the unexploited biomass.

Most existing attempts to estimate the potential harvest of krill have gone a little deeper into the biological system, and considered the impact on the possible harvest by man, of the reduced consumption by whales. For example, LAWS (1977) gives estimates of krill consumption by whales before exploitation of some 190 million t, compared with 43 million t now. This difference has been taken as implying that there is a 'surplus' of 150 million t available for harvest. The broad general argument is clear enough, but the specific details of how the 'surplus' becomes available are less clear. If the replacement of whales by factory ships was exact so that the 150 million t were harvested at the same time and places, and consisted of the same sizes and conditions of krill as the original consumption by whales, then it would be reasonable to assume the impact on the krill population would be the same. Then the krill stocks–and the stocks of other consumers of krill–would be unchanged, though the dynamics of the whales would not presumably react to the reduced whale population. In practice fishing vessels will not harvest krill in precisely the same way as whales, and the 150 million t cannot be considered a precise estimate of potential yield.

Nevertheless, the figure of 150 million t and other figures of a similar order of magnitude derived from FIBEX acoustic surveys, or consideration of primary production, do show the order of magnitude of the krill stocks, and their gross production. It is highly unlikely that present catches, or even larger catches of a few million tons will, if spread throughout the Southern Ocean, have an effect on the stock that would be easily detectable. If, however, catches of these magnitudes were concentrated on a separate stock of krill that was only a small fraction of the total, then it would be more reasonable to hope to detect an effect. There is not enough information on the stock structure of krill to know whether this would be practicable.

3.4. Interactions between species

Much of the scientific interest in krill harvesting comes, of course, not from krill per se, but from the possible impact of the harvest on whales and other animals that eat krill. This interest in species interactions, and the effects of fishing several species in the same ecosystems is not confined to the Antarctic, but is a pressing issue in many areas. Many stocks of small pelagic fish have collapsed (*e.g.*, sardine off California in the 1930s, anchovy off Peru in 1972, MURPHY, 1977) and these collapses have coincided, more or less precisely with the rise of other similar species (anchovy off California, sardine off Peru). In the North Sea there have been big changes in the species composition in the last couple of decades, with declines in herring and mackerel being matched by increases in a number of demersal species, several of which (cod, haddock, plaice) have been heavily fished for the best part of a century (HOLDEN, 1978). A number of complex models have been constructed to describe these events (*e.g.*, ANDERSEN and URSIN, 1977), but with a dozen or more species involved, and a variety of possible kinds of interactions between species, these models must still be considered as providing descriptions of possible patterns of interaction, rather than as definitive statements. It is still not possible to say to what extent, if at all, stocks and catches of one species, *e.g.*, cod in the North Sea, or sardine off California, can be increased by adjusting the pattern of fishing on other species (*e.g.*, by heavy fishing on herring or anchovy).

Paradoxically the practical problems may be least in some of the tropical demersal fisheries in which a hundred or more species may be involved. In these fisheries it may be quite impracticable for either the fisherman or the scientist to treat single species individually. Instead it may be sufficient to look at total biomass, and the total weight (or value) of the catch, and relate them to the amount of fishing. This type of analysis seems to provide perfectly adequate information on the desirable management strategy for the heavily exploited demersal stocks of the Gulf of Thailand, even though more detailed analysis shows that there have been great changes in the species composition.

The Antarctic system, which seems to be sufficiently simple to be understandable, is therefore of considerable interest. Whether or not it is understandable, and understood is not clear. Two simplified systems can be examined–the exploitation of two species–predator ("whale") and prey ("krill"), and the dynamics (with or without exploitation) of two or more species ('whales' and penguins or two species of whales) preying on the same species dynamics. Models of these systems have been developed by MAY *et al.* (1979) and others. They probably bear a similar relation to the reality of multispecies dynamics as the simpler production models, *e.g.*, the logistic, bears to single species. That is, at worst, they provide a useful first conceptual model of what is going on. With reasonable fortune they should also provide practical guidance on how fishing on one species should be adjusted to take account of the effects on other species, *e.g.*, whether catches of krill of 1 million or 10 million t, or 100 million t, can be reasonably expected to have a significant effect on the recovery rate or sustainable yield of whales. Even under favorable circumstances they will give little or no insight into the actual processes that determine the interaction. Nor is it simple to incorporate additional biological information, *e.g.*, on the growth rate of krill, into the models to refine the conclusions. For example, the simple models may be able to show that if krill catches were to rise into the range of 20–40 million t, effects on whale stocks would become significant, but more complex models, using more information, will be needed to quantify the impact, and, if this is serious, to determine where in the range of krill catches between 20 million and 40 million t controls should be applied.

Similar conclusions apply to interactions at the same trophic level. It is generally accepted that several species (minke whales, some seals, some penguins) that eat krill have increased as a result of the depletion of the larger whales. These changes can be described in a qualitative way by simple multi-species models. What is less easy to establish is the quantitative interaction between particular pairs of species (does indeed the abundance of blue whales have any influence on the dynamics of sei whales), and the actual mechanisms of the interaction. Is the total abundance of krill the important factor, or does, say, the growth or pregnancy rate of blue whales depend much more on local factors such as the existence of high density patches in certain key locations? It may be argued that the adverse effect on whales of krill harvesting could, through the breaking up of patches on which whales feed, be much greater than suggested simply by the weight caught.

This uncertainty extends even to the density-dependent effects within a single species. Earlier maturity and increased pregnancy rates are certainly associated with decreased abundance, and it is commonly assumed that this is an indirect effect, acting through the chain of events of decreased abundance–lower krill consumption–more krill available–more krill eaten by each whale–early maturity, but there is no evidence that some of the effects might be more direct, acting through some social behaviour.

4. Discussion

This paper has reviewed the development of Southern Ocean fisheries against the background of the possible need for management, and the degree to which the present data and biological understanding are sufficient to provide advice for management.

Management of whales has gone through some disastrous periods, but the present situation is better. Sensible actions regarding the Antarctic stocks are now being taken and the chief arguments are mainly political, regarding the basic objectives of whale management, and the relative weights that should be given to possible future uses of whales, and current operations. One outstanding scientific problem relating to management has already been noted, and that is the degree of interaction between species, and of the adjustments that should be made to the allowable catch of minke whales due to their interaction with other species. Another problem that may become more pressing, as the blue whales and other species currently depleted and protected recover, is the difficulty in monitoring this recovery. The only available method is from sightings, and these are highly variable. At some stage the recovery of these stocks should reach the stage at which catching could be resumed, but the available data are far from adequate to show when this could occur, or at which level catches might be permitted.

For fish it is clear that some management action is needed, but far from clear what specific measures should be introduced. Controls should be applied separately for each stock, *e.g.*, within the Atlantic Sector separately for South Georgia, South Orkney Islands, and the Peninsula, as well as for each species. The obvious step would then be to set annual quotas by species and areas, but experience in other areas suggest that control and verification of such quotas in a long-range multi-national and multi-species fishery could be very difficult. Consideration should therefore be given alternative types of control, *e.g.*, on the numbers of vessels operating, as well as to quotas extending over longer period (*e.g.*, a limit of 40000 t in four years rather than 10000 t annually). This might be more acceptable in practice, in allowing one year of large-scale fishing, followed–or preceded–by a period of complete closure.

In any case the present data are barely adequate to propose specific measures–other than a precautionary closure to all fishing while analysis proceeds, and there is some recovery of those stocks that seem clearly depleted. The need for comprehensive reporting of catch and effort statistics has already been stressed. Other approaches, less dependent on effort data, are also needed. The direct application of cohort or VPA analysis, which is the standard method used in providing management advice in the Northeast Atlantic, may be difficult because of difficulties in aging the fish. However the same principle can be applied directly to length-composition data (JONES, 1981). Length samples should therefore be collected in a comprehensive manner from all the major fisheries and emphasis given to analysing these data, either directly, or through the use of age-length keys.

Attention also needs giving to the stock-recruitment problem. The growth and mortality patterns seem to be such that the yield per recruit is not likely to be greatly reduced by heavy fishing. Therefore management is urgent to the extent that recruitment is being affected. This is a definite possibility because several species do not mature until they have been exposed to fishing for some time. While the resolution of the stock-recruitment problem is difficult for any species, it would be valuable to collect data on the abundance of pre-recruits, *e.g.*, through surveys with small-meshed trawls.

The need to act to manage krill is some way off, but it is not too early to consider how krill might be managed. Whatever controls are set it will be important that all interested parties are able to be assured that the controls are being followed. This may make limits on the catches possibly less attractive than direct limits on the fishing effort–the number and type of vessels that can be operated–with full reporting on what specific vessels are licensed to fish and when they enter and leave the fishing area. It would then be easy to see if a vessel was fishing legally, whereas with a catch quota system this is much less easy.

Determining when a limit should be set, and at what level, is difficult. Rough estimates of the sustainable yield are available from, for example, considerations of changes in whale consumption, and other analyses of the present (virtually unexploited) situation. Further such analyses would achieve some improvement, but it is unrealistic to expect that sufficiently good results can be obtained to determine precisely when management measures should be applied, and at what level catch quotas or effort limits should be set. These must be determined by seeing what happens when exploitation begins to have a significant effect on the stock. Since it will take time for the effect to be detectable and the detection to be acted on, management must include some scheme to keep the developments of the fishery within reasonable limits (*e.g.*, effort does not increase by more than $x\%$ per year, or catches by more than y t), so that controls are applied before the rate of fishery has overshot the optimum level. As has been pointed out *e.g.*, by MAY *et al.* (1979) while krill stocks will react quickly (at most one or two years) to heavy exploitation, it may take decades (but only one or two generations) for the full effects of krill exploitation to show up in the abundance of the stocks of whales and other long-lived animals. This suggests that development should be kept slow, *i.e.*, the values of $x\%$ and yt above should be low. It also suggests that more sensitive indices than total abundance, *e.g.*, pregnancy rate, should be used to monitor the "health" of these long-lived stocks. Attention should also be given to determining suitable indices of the krill stock to be monitored regularly as part of the management programme. Monitoring changes in abundance, either from commercial catches-per-unit-effort, or by acoustic or other surveys, may prove difficult, though should definitely be considered. Consideration should therefore be given to other measures, particularly examination of changes in length frequency data.

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