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A note on relating Antarctic krill catch-per-unit-effort measures to abundance trends

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*A crude mathematical framework is developed to describe krill abundance in terms of selected parameters of various aggregation behaviours exhibited by the Antarctic krill (*Euphausia superba *Dana). The relationship of combinations of these parameters to various possible measures of catch-per-unit-effort (CPUE) for the Antarctic krill fishery is considered. The combined index of catch-per-hour (CPH) of trawling multiplied by the inverse of the average inter-concentration search time (IST) is suggested as a possible measure of krill abundance; such an index should be stratified both spatially and by krill aggregation type - this has implications for routine data collection. Models should be constructed to investigate how substantial the non-linearities in the relationship between the index and krill abundance might be.*

*'n Onafgewerkte matematiese raamwerk is ontwikkel om die talrykheid van kril volgens gekose parameters te beskryf aan die hand van die Antarktiese kril (*Euphausia superba *Dana) se saamgroepingsgedrag. Die verband word bespreek wat bestaan tussen kombinasies van dié parameters en verskillende metodes om die vangs van Antarktiese kril per pogingseenheid te meet. Die gesamentlike indeks van vangs per uur treiltyd, vermenigvuldig met die omgekeerde gemiddelde soektyd tussen krilsaamgroepings, word as 'n maatstaf vir die talrykheid van kril voorgestel. So'n indeks moet ruimtelik en volgens die tipe krilsaamgroeping gestratifiseer word, aangesien dit implikasies vir die roetineversameling van data inhou. Modelle moet geskep word om vas te stel hoe wesenlik die nie-lineariteite in die verband tussen die indeks en die talrykheid van kril is.*

Introduction

Krill (*Euphausia superba* Dana) has long been recognized as a key component of the Antarctic marine ecosystem (*cf.* Marr 1962, Knox 1984). Increased interest in the species' exploitation and a concomitant need to conserve the ecosystem as a whole are two of the primary considerations implicit in the various Articles of the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR). It is in this context that a strong need to monitor krill fisheries activities has come to be recognized (Knox 1984, Anon. 1985).

An important method for monitoring marine stock trends is the fisheries dependent index of catch-per-unit-effort (CPUE) (Gulland 1983).(Note that in this paper CPUE is used in the general sense of a fishery-based index of abundance; thus it may relate to a combination of various statistics from the fishing operation, rather than only to a direct measure of catch rate *per se* such as catch-per-hour-trawled). A critical aspect requiring consideration in the relation of krill CPUE measures to krill abundance trends is the effect of the various aggregation behaviours displayed by krill at a variety of spatial scales.

Krill characteristically aggregate into **concentrations.** These in turn may be divided into a variety of aggregation types, depending on the manner in which they are formed and on their spatial conformation. For purposes of this (perhaps oversimplified) analysis, three types of krill aggregation behaviour (i.e. three types of concentration) have been selected, although the fundamental principles of the analysis are likely to pertain were a larger number of krill aggregation types to be taken into account. The aggregation modes chosen are **swarms, layers** and **super-patches.** These are defined in more detail in Appendix I and are illustrated schematically in Figure 1.

This note attempts to provide an initial and crude mathematical representation of these features and their implications for various possible CPUE measures to index krill abundance. It was orginally formulated as a discussion document for the *ad hoc* CCAMLR Workshop on Krill CPUE held in 1985. As such, the ideas pre-empted the initiation of the CCAMLR sponsored Krill CPUE Simulation Study (SC-CAMLR-IV 1985). The material presented is intended to be suggestive and is certainly not exhaustive.

Definitions and relationships

Areas:

A_t - total management area
A_{ci} - average concentration area
  (i = s/l/sp swarms/layers/superpatches)
A_s - average swarm area for the swarms comprising a concentration of swarms
(1)

A_t corresponds to the total area of extent of the stock being considered (termed "management area" in view of difficulties arising from imprecise boundary determination of separate krill stocks at this time). If there are trends in concentration density within a management area, this could be taken into account by spatial stratification in data analysis. [Note: The word "density" used in the following refers to a **surface** density, i.e. after integration over the vertical dimension.]

Concentration densities:

D_s - density of concentrations of swarms
D_l - density of concentrations of layers
D_{sp} - density of concentrations of super-patches
In no. of concentrations per unit area
(2)

Swarm densities:

d_s - average density of swarms within a concentration (i.e. number of swarms per unit of the total area of the concentrations) (3)

Krill densities:

δ_{ks} - average density of krill in a swarm
δ_{kl} - average density of krill in a layer
δ_{ksp} - average density of krill in a super-patch

} In mass krill/surface area of swarm etc. (4)

Krill abundance:

$$K_s = A_t . D_c . A_{cs} . d_s . A_s . \delta_{ks} \quad (5)$$

$$K_l = A_t . D_l . A_{cl} . \delta_{kl} \quad (6)$$

$$K_{sp} = A_t . D_{sp} . A_{csp} . \delta_{ksp} \quad (7)$$

$$K_t = K_s + K_l + K_{sp} \quad (8)$$

where $K_s/K_l/K_{sp}$ denote the biomass of krill in concentrations comprised of swarms/a layer/a super-patch, and K_t is the total krill abundance[1].

Note that use of "average" areas and densities ((1), (3) and (4)) assumes that the variables concerned are uncorrelated (e.g. larger concentrations do not tend to have larger swarm densities etc.). Experiments/analysis could perhaps be carried out to check this.

1. For simplicity, this formulation has assumed that each layer or super-patch concentration is not already segmented.

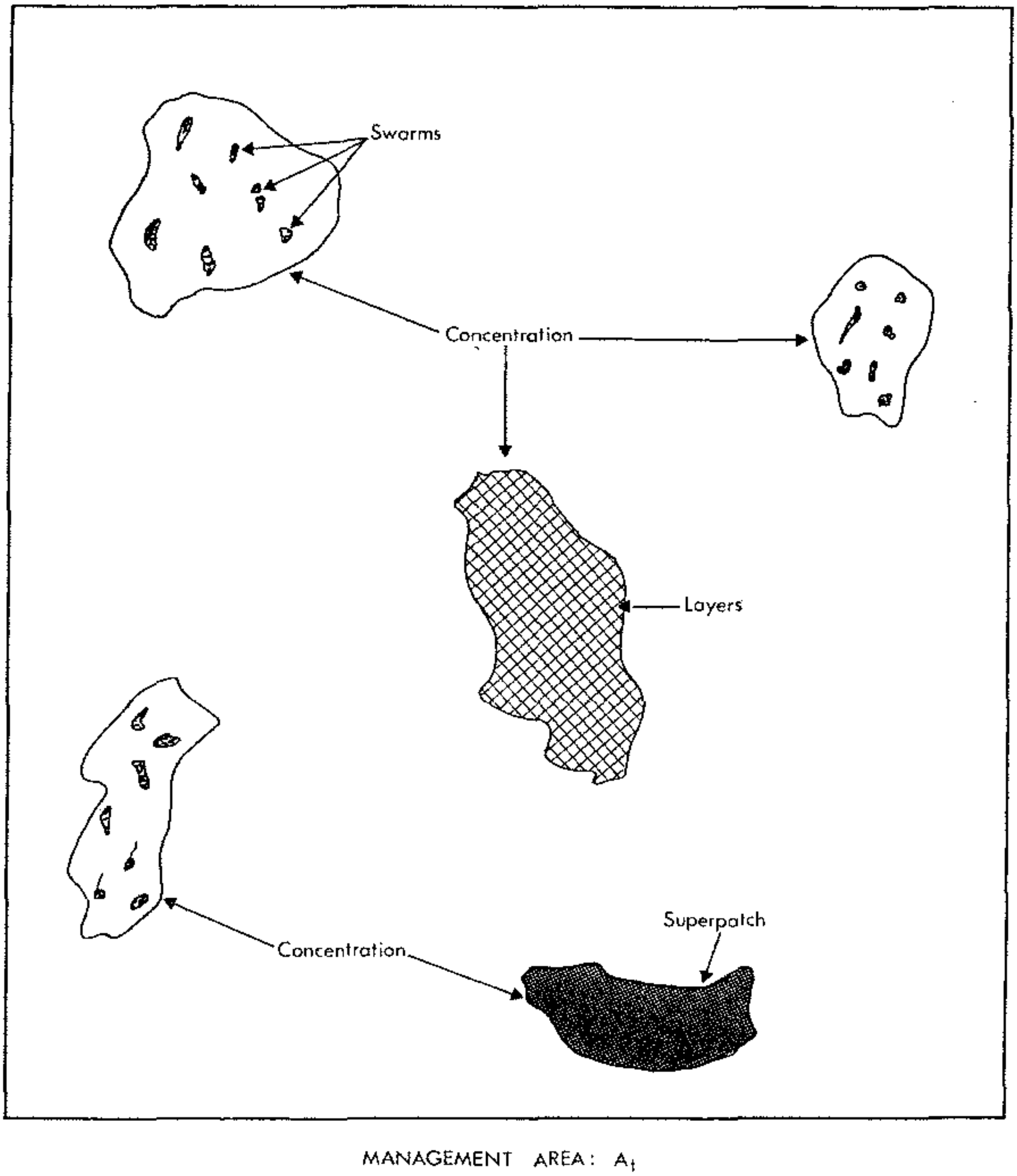

Fig. 1. Schematic representation of different krill aggregation types and associated terminology.

Detection of trends

From equations (5)-(8) it is clear that a temporal trend in the total krill abundance could be reflected by a change in any one or more of a number of factors. It is important to consider to which combination of factors a particular CPUE index may relate, and to ensure as far as possible that every factor that could undergo change is being monitored in some way[2].

i). Within-concentration krill density

Such densities are represented by $d_s A_s \delta_{ks}/\delta_{kl}/\delta_{ksp}$ for concentrations of swarms/layered concentrations/super-patches.

For each case it seems that catch-per-hour-trawled (CPH) would provide a reasonable index linearly[3] proportional to the density. Comments made by Gulland (1985) suggest that Japanese trawlers do not target on specific swarms within a concentration, so that CPH would measure the product of $d_s A_s \delta_{ks}$[4] rather than δ_{ks} alone, and hence monitor the relevant changes in any one or more of these parameters.

ii). Concentration densities

A problem here is that it is not only the concentration density ($D_s/D_l/D_{sp}$) that requires monitoring, but rather its product with average concentration area ($A_{cs}/A_{cl}/A_{csp}$).

An appropriate index might be inverse-average-search-time (IST), where only the time spent finding the first concentration and the time between finishing fishing on one concentration and starting on another, but not the time spent fishing on the same concentration, is taken into account. Operational definition of such time for objective data extraction may be difficult.

Some consideration needs to be given to the likely functional relationship of IST to abundance parameters – whether it would be linearly related to D_i alone, or to some function of $D_i A_{ci}$? This would depend on the typical size of A_{ci}, and the nature of the cue used to find a patch – whether short-range (e.g. hydroacoustics), medium-range (e.g. visual swarm sighting), or long-range (e.g. predator sighting).

An extreme form of "long-range-cue" is inter vessel cooperation through radio contact. Care needs to be taken to exclude vessels not themselves making initial concentration detection from calculations of IST.

iii). Area "shrinkage"

For a number of shoaling pelagic fish species, it has been suggested that stock collapses were reflected not by local density decreases, but rather by a shrinkage of the total area over which the stock extended (*cf.* discussion in Gulland 1983a).

Presentation and comparison of comparable CPUE trends in different spatial strata of A_t may provide a basis for detecting such an effect.

iv). Improvement in fishing efficiency

The detection of temporal trends in krill abundance from CPUE data may be confounded by changes in overall fishing efficiency. The krill fishery is in a developmental stage, during which substantial improvements in fishing technology and searching efficiency (as experience accumulates relating to the hydrographic features usually associated with concentrations of krill) would be expected. These factors could mask any downward trend in krill abundance if a CPUE-based monitoring index is used.

The effects of technology changes (e.g. different gear) should be quantifiable using standard methods for fishing power-factor analysis (*cf.* Robson 1966). Accounting for improvements in searching efficiency may prove a more difficult problem. Spatial stratification of A_t will counter the difficulty to some extent. However it may not be possible to stratify on a sufficiently small scale that random search constitutes an adequate assumption in the face of increasingly intelligent fishing tactics. This would introduce bias into both indices of concentration density (such as IST), and the estimation of temporal abundance trends from such indices.

Stratification based on aggregation behaviour

A priori it seems desirable that krill CPUE trends be presented and considered separately on the basis of aggregation behaviour. The foregoing has suggested three such behavioural strata: concentrations of swarms, layered concentrations and super-patches.

The reason for this is that catchability q, where q is defined by:

$$\text{CPUE} = q \times \text{krill density} \qquad (9)$$

may well differ for different aggregation types. This could arise because of different density profiles with depth for different aggregation types. Furthermore, research vessel midwater trawling for anchovy (*Engraulis capensis*) off the South African coast has indicated that these fish tend to avoid nets more effectively when in tight shoals (*cf.* "swarms") than when dispersed in layers (I. Hampton *pers. comm.*) – krill may well behave similarly.

Accordingly $q = q_i$ (i = s/l/sp), so that for example CPH indices may not be comparable for different aggregation types (even given correction of effort measures for fishing power differences between vessels – see Gulland 1985).

Until such time as data are available to allow statistical tests to check the justification of possible pooling of catch rate data by aggregation-type (i.e. whether in fact some q_i's may not be substantially different), CPUE trends should be extracted and stratified in this manner. Otherwise there is the very real danger of an abundance decline being masked by fishing patterns changing towards aggregations with larger q_i, so that a pooled CPH index might appear stable or even indicate the reverse trend to the abundance. There may even be a case for a more detailed behavioural stratification than suggested here.

A further problem is that the response of krill to exploitation (including decreased abundance) may affect

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2 The following analysis assumes that the average depth profile for any krill aggregation type remains invariant in terms of change in total krill abundance - in principle the formalism could be extended to incorporate this factor.

3 See also Conclusions section

4. Further CPH would measure the average of the product of these factors, rather than the product of their averages, so avoiding the possible problem of correlation effects mentioned earlier.

krill behaviour patterns. If P_i is the probability that one krill manifests aggregation behaviour i[5], where

$$P_s + P_l + P_{sp} = 1 \qquad (10)$$

then

$$K_t \propto P_s(CPUE)_s/q_s + P_l(CPUE)_l/q_l + P_{sp}(CPUE)_{sp}/q_{sp} \qquad (11)$$

That is the right hand side of equation (11) provides an index of total krill abundance. However apart from the practical difficulties in determining the P_i and q_i/q_j (relative catchability) ratios[6], the P_i's may change as a result of harvesting. Furthermore fishing fleets may not sample the different behaviour patterns in proportion to their probability of actual occurrence (as assumed by (11)). The degree of such deviation may also alter as exploitation rates, krill abundance and (so) fishing patterns change.

All in all there could be considerable problems and dangers inherent in considering an aggregation-behaviour-pooled CPUE index. The most suitable first step would seem to be to analyse behaviour-stratified indices for possible trends.

Conclusions

A change in krill abundance could be associated with changes in any one (or any combination) of the large number of parameters required to specify the krill distribution in a specific management area. CPUE indices should be chosen to reflect as many of these parameters as possible.

A possible candidate is the product

CPH x IST

(i.e. catch-per-hour of trawling multiplied by the inverse of the average inter concentration search time), stratified both spatially and by aggregation type. However, a problem with this suggestion is that this index may not adequately reflect alterations in krill abundance occasioned by changing average concentration size (A_c). Further, care must be taken that when using such an index to assess temporal trends in krill abundance, adequate allowance has been made for technological improvements by use of power-factors. Attention must also be given to the possible effects of improved fishing tactics as experience accumulates. The latter could result in substantial bias in IST as a measure of concentration density, because of the non-random nature of the searching operation.

Should consideration of existing data prove unable to exclude the possibility of the effects hypothesized above, routine data collection should allow for the extraction of search time (particularly inter-concentration-search-time as described earlier), the cue used to locate a krill concentration, and the type of aggregation fished upon. While such a recommendation is easily stated, the practicality of commercial vessels recording additional data of the type suggested also needs consideration. It would seem fairly straightforward to note the aggregation type fished so as to allow for stratification on this basis. However it is less obvious that the primary activity of a vessel at any time is sufficiently clear-cut, that the data required to evaluate IST can be simply and unambiguously recorded. Such aspects will clearly need to be addressed in more detail by the CCAMLR sponsored Krill CPUE Simulation Study (SC-CAMLR-IV 1985).

It is important that the possibilities of non-linearities in the relationship between the CPUE index (or indices) chosen and krill abundance be investigated. Saturation effects leading to such non-linearities could arise, for example, from fluctuations in catchability (Cooke 1985). Conceivably, either or both of the CPH and IST indices suggested above could be affected by this process. Models similar to that of Cooke & Christensen (1983) should be developed, and the appropriate parameters at least crudely estimated, in order to determine whether or not such non-linear effects are likely to be substantial in the case of krill.

5. Acoustic data from previous research vessel surveys (e.g. First and Second International BIOMASS Experiments [FIBEX and SIBEX]) may provide a basis to establish the P_i's

6. It may be possible to determine the relative catchability ratios by having research vessels undertaking localized hydroacoustic abundance estimation in conjunction with commercial vessels making catches on different krill aggregation types

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Appendix I

Krill aggregation terminology

The krill aggregation-type terminology used in this analysis forms part of a much more detailed hierarchical classification proposed by Kalinowski & Witek (1982, 1985), and derived from some twenty thousand acoustic records.

Concentrations

Concentrations are macro-scale features which extend over a distance of 1 to 100 km, and within which krill (surface) density is at least 10 g m^{-2} (range 10-10^{2} g m^{-2}). In this presentation and for simplicity, the distinction between concentrations and patches has been ignored although it is made by Kalinowski & Witek (*op. cit.*).

Swarms

Swarms are considered synonymous with Kalinowski & Witek's generic definition of the "cohesive form" of a concentration. They are generally the most common kind of krill aggregation and are characterized by their relatively small dimensions, clear definition, simple shape (usually) and their uniform, relatively high density. Typically, swarms are several tens of metres long, a few are as much as 20 m thick, and they have (volume) densities which generally lie between 10 and several hundred g m^{-3}. Densities may exceed 1000 g m^{-3} on occasion.

Swarms usually occur during daylight, tend to disperse at night, and undertake vertical diurnal migrations. In general, the swarm is a cohesive unit, and unlike a "school" does not exhibit parallel orientation of individual animals within it.

Layers

These are unique conformations comprising a layer of animals which may exceed 1000 m in length (sometimes by a considerable amount). Layers are usually several tens of metres thick, and their (volume) densities attain several tens of g m^{-3}. They are found both by day and at night, but according to Kalinowski & Witek (*op. cit.*) are encountered rather infrequently. However, results from FIBEX suggest that they may occur more frequently than previously thought (Anon. 1986).

Super-patches

Super-patches are rare aggregation forms some two to three orders of magnitude larger than a typical swarm of krill. They are often more than several hundreds of metres thick, and may extend over several km. Their (volume) densities are of the order of several hundred g's of krill m^{-3}.