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SC-CAMLR-II/INF.4
31 August, 1983

MODELLING: THE APPLICATION OF A RESEARCH TOOL TO ANTARCTIC MARINE LIVING RESOURCES

Abstract

Modelling is an integral part of fisheries research throughout the world. The significant advances resulting from modelling studies directed at the North Sea and Georges Bank (North-West Atlantic) are considered. The North Sea model is a multi-species extension of the Beverton and Holt yield per recruit model. The Georges Bank model describes a static energy budget of this area. Several models have already been applied to marine living resources of the Antarctic. The pelagic ecosystem of the Ross Sea has been simulated. Behaviour of biological systems exploited simultaneously at two or more trophic levels (e.g. baleen whales and krill) has been studied by means of heuristic models. Numerous modelling investigations have been related to assessment and management of whale stocks. Several examples of specific research and management problems for the Antarctic which may be treated by modelling are provided. Modelling should be an integral part of research on Antarctic marine living resources.

UTILISATION DE MODELES: L'APPLICATION D'UN OUTIL DE RECHERCHE A LA FAUNE ET LA FLORE MARINES DE L'ANTARCTIQUE.

Résumé

L'utilisation de modèles constitue une partie intégrale des recherches halieutiques dans le monde entier. Les progrès importants qui résultent d'études mettant en jeu des modèles et portant sur la Mer du Nord et Le Banc Georges (Atlantique Nord-Ouest) sont examinés. Le modèle de la Mer du Nord est une extension à de multiples espèces du modèle représentant le taux de rendement par recrue de Beverton et Holt. Le modèle du Banc Georges rend compte de l'énergie statique dans cette zone. Plusieurs modèles ont déjà été appliqués à la faune et la flore de l'Antarctique. L'écosystème pélagique des mers de Ross a été simulé. Le comportement de systèmes biologiques exploités simultanément à deux niveaux trophiques ou plus (par exemple baleines mysticètes et krill) a été étudié au moyen de modèles heuristiques. De nombreuses études utilisant des modèles ont été associées à l'estimation et au contrôle des stocks de baleines. Plusieurs exemples sont donnés de problèmes spécifiques de recherche et de contrôle concernant l'Antarctique et qui pourraient être traités par l'utilisation de modèles. L'utilisation de modèles devrait constituer une partie intégrale de la recherche sur la faune et la flore marines de l'Antarctique.

МОДЕЛИРОВАНИЕ: ИСПОЛЬЗОВАНИЕ НАУЧНО-ИССЛЕДОВАТЕЛЬСКИХ МЕТОДОВ ПРИ ИЗУЧЕНИИ МОРСКИХ ЖИВЫХ РЕСУРСОВ АНТАРКТИКИ

Резюме

Моделирование используется повсеместно как составная часть научно-исследовательских работ в области рыбного промысла. Рассматривается значительный прогресс, достигнутый в результате изучения моделей, примененных для районов Северного моря и Банки Джордж (северо-западная Атлантика). Модель Северного моря является расширенной многовидовой моделью Бевертона и Хольта для улова на единицу пополнения. Модель Банки Джордж описывает расчет статической энергии для данного района. Уже применялись различные модели для изучения морских живых ресурсов Антарктики. Была симулирована пелагическая система моря Росса. При помощи эвристических моделей изучалось поведение биологических систем, подвергнутых промыслу одновременно на двух или более трофических уровнях (напр., гладких китов и криля). Многочисленные изучения с применением моделей относились к оценке запасов китов и их управлению. Даны различные примеры конкретных проблем, возникающих при изучении и управлении Антарктикой, которые могут быть разрешены при помощи моделирования. Моделирование должно быть составной частью исследовательских работ по морским живым ресурсам Антарктики.

PREPARACION DE MODELOS: APLICACION DE UN INSTRUMENTO DE INVESTIGACION A LOS RECURSOS VIVOS MARINOS ANTARTICOS

Resumen

La preparación de modelos es una parte integrql de la investigación pesquera mundial. Consideremos el importante progreso logrado con los estudios de preparación de

modelos relacionados con el Mar del Norte y Georges Bank (Atlántico Noroeste). El modelo del Mar del Norte es una extensión del modelo de rendimiento por cría de Beverton y Holt, tomando varias especies. El modelo de Georges Bank presenta un cálculo de energía estática en esta área. Se han aplicado ya varios modelos a los recursos vivos marinos del Océano Antártico. Se ha simulado el ecosistema pelágico del Mar de Ross. El comportamiento de sistemas biológicos explotados simultáneamente a dos o más niveles tróficos (por ej. ballenas mysticetas y krill) se han estudiado a través de modelos heurísticos. Muchas de las investigaciones sobre modelos han estado relacionadas con la evaluación y administración de las existencias de ballenas. Se proporcionan varios ejemplos de problemas específicos de investigación y administración con relación al Océano Antártico, que pueden tratarse con modelos. La preparación de modelos debería ser una parte integral de la investigación sobre los recursos vivos marinos antárticos.

INTRODUCTION

Modeling should be an integral part of research on Antarctic living marine resources. It is the process of formalizing thought. Mathematical models express ideas in the concise and universal language of mathematics. Like thinking, modeling is an ongoing process which is stimulated by observations (i.e., data). Models in turn stimulate additional data collection, usually followed by further modeling.

The process of modeling forces consistent thinking. This process is particularly important for multi-disciplinary, multi-national studies where observations are made and ideas evolve independently. A model is a synthesis of these observations and ideas. It is invalid if the ideas are contradictory or incompatible with the observations. Thus models are validated in the sense of statistical hypothesis testing. The null hypothesis or the model is never proven true, it is accepted when there is no basis for rejection. Research is conducted in order to reduce the number of acceptable models.

Modeling has been an integral part of research directed at exploited marine ecosystems throughout the world. This paper reviews some of the significant advances resulting from modeling studies directed at the North Sea and Georges Bank (off the northeastern USA). It then focuses on living marine resources of the Antarctic, including a review of previous modeling activity and some examples of problems amenable to modeling in the future.

APPLICATIONS OF MODELS TO EXPLOITED MARINE RESOURCES

North Sea: Fisheries of the North Sea are managed by various international bodies (North East Atlantic Fisheries Commission, International Baltic Sea Fishery Commission, European Economic Community). Management is based on scientific advice provided by the International Council for Exploration of the Sea (ICES). Traditionally, this advice has been based on single species yield assessments such as the Beverton and Holt (1957) yield per recruit analysis.

Anderson and Ursin (1977) developed a multispecies extension of the Beverton and Holt yield per recruit model. Their multispecies model takes predation by fish into account. They apply a prey suitability function which is based on the ratio of predator weight to prey weight.

The importance of the model is amply demonstrated by comparison of the results of traditional yield per recruit analysis with the results from the multispecies extension (Figure 1; Ursin 1982). Traditional yield per recruit analysis indicates that the fishing mortality rate for North Sea cod should be reduced to 30% of the value for 1977 in order to increase yield by 43% and increase biomass by a factor of 5.9. On the other hand, when predator-prey effects are taken into account, fishing mortality should be approximately cut in half in order to increase yield by 31% and increase biomass by a factor of 2.6.

Ursin (1982) also demonstrates the importance of the fishing strategy applied to cod with respect to other species (Figure 2). As fishing mortality on cod is reduced, the species composition of the North Sea finfish community changes, with small fish species (norway pout, dab, long rough dab, herring, sprat, sand eels) increasing relative to large species (saithe, haddock, whiting, plaice, mackerel).

There are other plausible formulations of multispecies ecosystem models of the North Sea, which might produce different results. Nevertheless, Anderson and Ursin's (1977) model has been validated in the sense that there is no basis for rejecting it. It does demonstrate the insight, with respect to management of exploited ecosystems, that can be achieved through modeling.

Georges Bank: Georges Bank is a highly productive fishing ground off the northeast coast of the USA. There is an intensive multispecies (e.g., cod, haddock, several species of hake, several species of flounder, squid, mackerel, herring, and others) fishery. The region has been heavily investigated.

Sissenwine et al. (1982) conducted an empirical examination of species interactions for the fish populations of Georges Bank and surrounding area. They found no statistically valid evidence of interactions. Yet, there is ample data to indicate tropho-dynamic relationships between species. They concluded that while species interactions probably exist, they were obscured by variability associated with abiotic factors. Therefore, an alternative modeling approach was adopted.

Sissenwine et al. (in press) compiled a static energy budget of Georges Bank (Figure 3). The most reliable data in the model describes production and abundance of phytoplankton and exploitable size (generally greater than 15 cm in length) fish. Since these are at the top and bottom of the food web, estimates of production at intermediate trophic levels are bounded. Thus the conclusions based on the model are robust.

One of the most important components of the Georges Bank ecosystem are pre-exploitable or young fish. Little is known about the early life history (i.e., their growth and mortality) of young fish. Nevertheless, it is possible to estimate their production and consumption by applying an exponential model which interpolates between their size at birth (size of an egg) and size at recruitment; and between the biomass of a cohort at birth (total biomass of female gonad spawned) and its biomass at recruitment.

The energy budget model indicates that demersal fish consume 57.2 Kcal/m^{2}yr. Ancillary data indicates that about half their consumption is of young (postlarval) fish. Thus, most of the production of young fish (29.0 Kcal/m^2yr) must be consumed by older fish. The implication is that fish predation is a significant cause of early life stage mortality and that mortality rates remain high into the postlarval stage. Thus, year-class strength is not established during the larval stage as has usually been assumed. Analysis of ichthyoplankton data verified these conclusions.

The energy budget is an integral part of fisheries research on Georges Bank. The model has resulted in a re-direction of some research aimed at understanding the factors that determine recruitment.

ANTARCTIC LIVING RESOURCES

The Antarctic ecosystem is relatively simple (Figure 4; Beddington and May, 1983). The food chain is short. Krill are the dominant herbivore. They are the prey of baleen whales, sea birds, fish, and squid.

Whaling in the Antarctic began in the 1930's. Several species of whales were quickly depleted. In addition, seals and groundfish have also been exploited. Some Antarctic groundfish may already be overexploited (Everson 1977). Experimental harvesting of krill began in the 1970's.

As a result of harvesting, the overexploited baleen whale stocks have been reduced to about one-sixth of their pristine abundance level. This dramatic reduction must have had a significant indirect effect on other components of the ecosystem. One implication of the decline in baleen whale abundance is that there must be more krill available for the whales that remain, and for other species. One estimate is that the reduction in baleen whale stocks resulted in a "surplus production" of krill of 150 million tons per year. In fact, the decline in abundance of most baleen whale stocks has been partially offset by increases in abundance of minke whales and seals (particularly crabeater) and other species. Nevertheless, krill abundance has probably also increased since some of the overexploited baleen whales exhibit an increase in birthrate, indicative of an increase in per capita prey abundance.

Management of Antarctic living marine resources began in 1935 under the auspices of the International Whaling Commission and its predecessor. All of the baleen whales, with the exception of minke whales, are now protected from further harvesting.

In 1982, the Convention on Conservation of Antarctic Marine Living Resources was ratified. The Convention applied to all living marine resources of the waters south of the Antarctic convergence. Although management authority under the Convention has not yet been exercised, Article II calls for the prevention of decreases in abundance of harvested populations below the level of greatest net annual increment; maintenance of ecological relationships among harvested, dependent and related populations; restoration of depleted populations; and avoidance of changes not reversible in two or three decades (Green Hammond 1981). A Scientific Committee has been established to design and implement research and advise the Commission on fulfillment of Article II.

Modeling is one of the research tools available to the Scientific Committee. Several models have already been applied to living marine resources of the Antarctic.

Green (1975) simulated the pelagic ecosystem of the Ross Sea, Antarctica. Green (1977) estimated the total production of krill, which is shared by natural predators and man, as about 330 million tons.

May et al. (1979) used heuristic models to investigate behavior of biological systems exploited simultaneously at two or more trophic levels (e.g., baleen whales and krill). Figure 5 indicates the trade-off between harvesting krill and whales. May et al. (1979) concluded that the concept of MSY is a useful point of departure for management of top predators like baleen whales; for lower trophic levels (e.g., krill), stocks should not be depleted to levels which reduce productivity of dependent populations; it is important to consider the difference in time scales between trophic levels; natural stochasticity would indicate that harvesting levels should be set conservatively; and there are economic considerations of multispecies systems that do not arise in single species systems.

Of course there have been numerous modeling investigations associated with assessment and management of whale stocks. For example, Beddington and Cooke (1981) and Cooke and Beddington (1982) developed a model for assessing sperm whale abundance based on length composition. There are also models investigating the relationship between whale catch per unit effort data and true abundance (Kirkwood, 1981). A nonlinear relationship, which has important management implications, is indicated.

It is clear that modeling is an important tool for application to research and management of living marine resources. There are numerous specific research and management problems associated with

Antarctic living marine resources amenable to future modeling studies. For example:

1. Article II of the Convention requires conservation of the multispecies resource and maintenance of ecological relationships. An operational definition of these concepts is still lacking. May et al. (1979) addressed them with heuristic models, but their approach lacked enough specificity. Further modeling of multispecies systems, with parameters applicable to the Antarctic, is necessary. The difference in the temporal scale of events at different trophic levels is of particular importance. It is noteworthy that herbivore production is dominated by a species that is relatively slow growing for herbivorous plankton.

2. Krill production has been estimated as 330 million tons per year based on calculated consumption by its predators. Yet, questions of krill biology (e.g., growth, life span, age of sexual maturity) make it difficult to calculate production directly from krill data. Data on the size distribution of krill may be interpreted in several ways. A more rigorous modeling study may provide better interpretation of the available data. Sensitivity analysis should be useful to identify priorities for further data collection.

3. Krill form dense swarms. These swarms are targets of both baleen whales and man.

This swarming behavior of krill and the behavioral response of its predators raised two problems which are amenable to modeling. Firstly, non-random fishing behavior may effect the spatial distribution of the krill. Thus the effect of krill harvesting on the baleen whales may be greater than would be expected, since the energetic cost of feeding by the whales may increase as man crops the largest swarms.

Secondly, since harvesting of krill is directed at the swarms, the relationship between catch per unit effort and actual abundance is almost certainly nonlinear. Therefore, modeling studies (analogous to Kirkwood's 1981 study of sperm whale CPUE) are necessary if fisheries data are to be used to monitor krill. These modeling studies will help to refine data collection schemes.

4. Changes in demographic parameters of several exploited species (e.g., pregnancy rate of blue, fin, and minke whales have increased) have been observed. The abundance of other species has increased (e.g., crabeater seals). The implication is that krill abundance has increased although some stocks are consuming more krill (for the total stock and/or per capita). Further energetic modeling is necessary to verify that these observations are compatible.

These energetic models are also necessary to confirm the validity of proposed indicator populations or demographic parameters. For example, we now interpret an increase in pregnancy rate of baleen whales as indicating an increase in krill abundance. But how large an increase in krill abundance is indicated?

5. Decisions concerning the management of living marine resources are always made in an environment of uncertainty. This is particularly true of the Antarctic because scientific investigation is relatively recent and because of the logistic problems unique to Antarctic research. Thus it has been suggested that management decisions should be conservative in order to leave a margin of safety. But how large a margin of safety is necessary? Questions of this nature should be addressed within the modeling context of risk analysis (Starr and Whipple, 1980).

CONCLUSIONS

The Scientific Committee of the Convention on Conservation of Antarctic Marine Living Resources should utilize modeling as a research tool. One approach would be to convene an inter-sessional ad hoc working group meeting to (1) review relevant applications of models to marine ecosystems (the Antarctic and elsewhere), (2) review the Antarctic data base available for modeling, (3) identify specific problems that should have a high priority for modeling, and (4) recommend terms of reference for a permanent modeling working group. These recommendations should be made to the third session of the Scientific Committee of the Commission.

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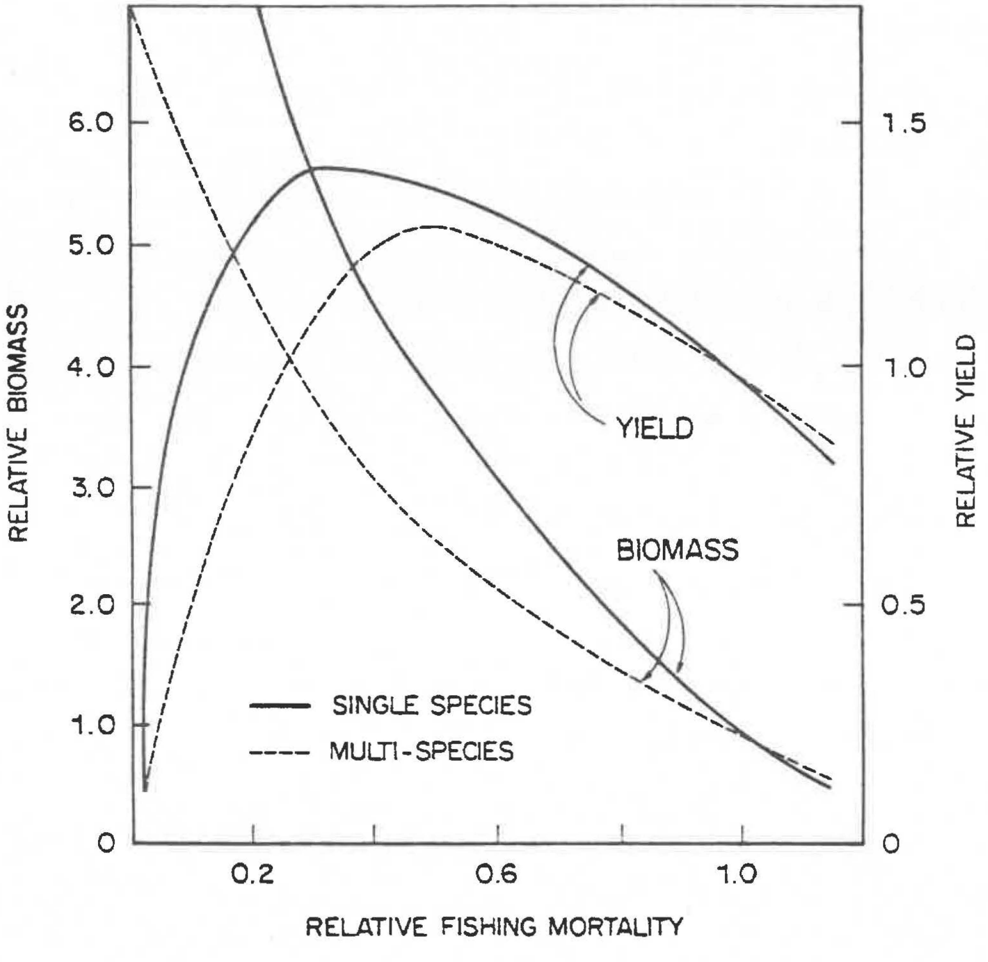

Figure 1. Multispecies and single species yield per recruit analysis for North Sea cod. Fishing mortality, biomass and yield are relative to 1977. After Ursin (1982).

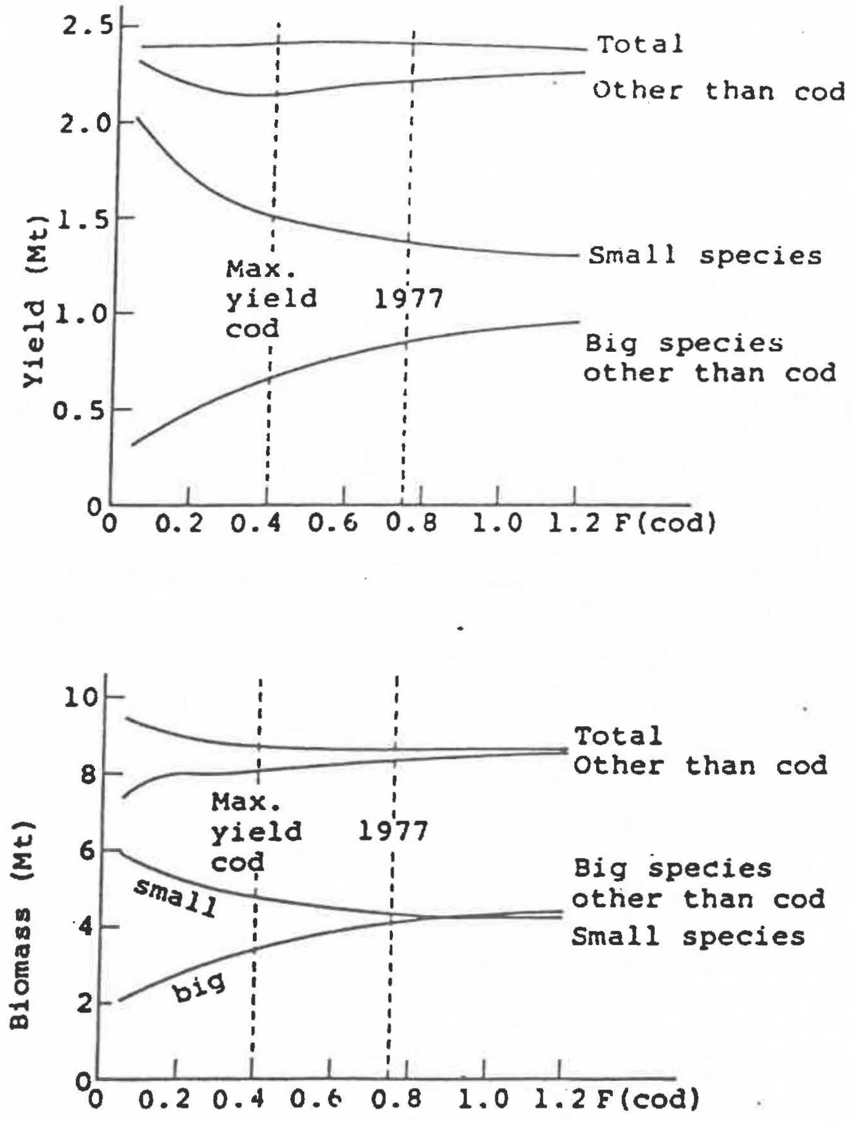

FIG. 2. Multispecies assessment of the response of yields and biomasses to changes in fishing effort upon cod. From Ursin (1982).

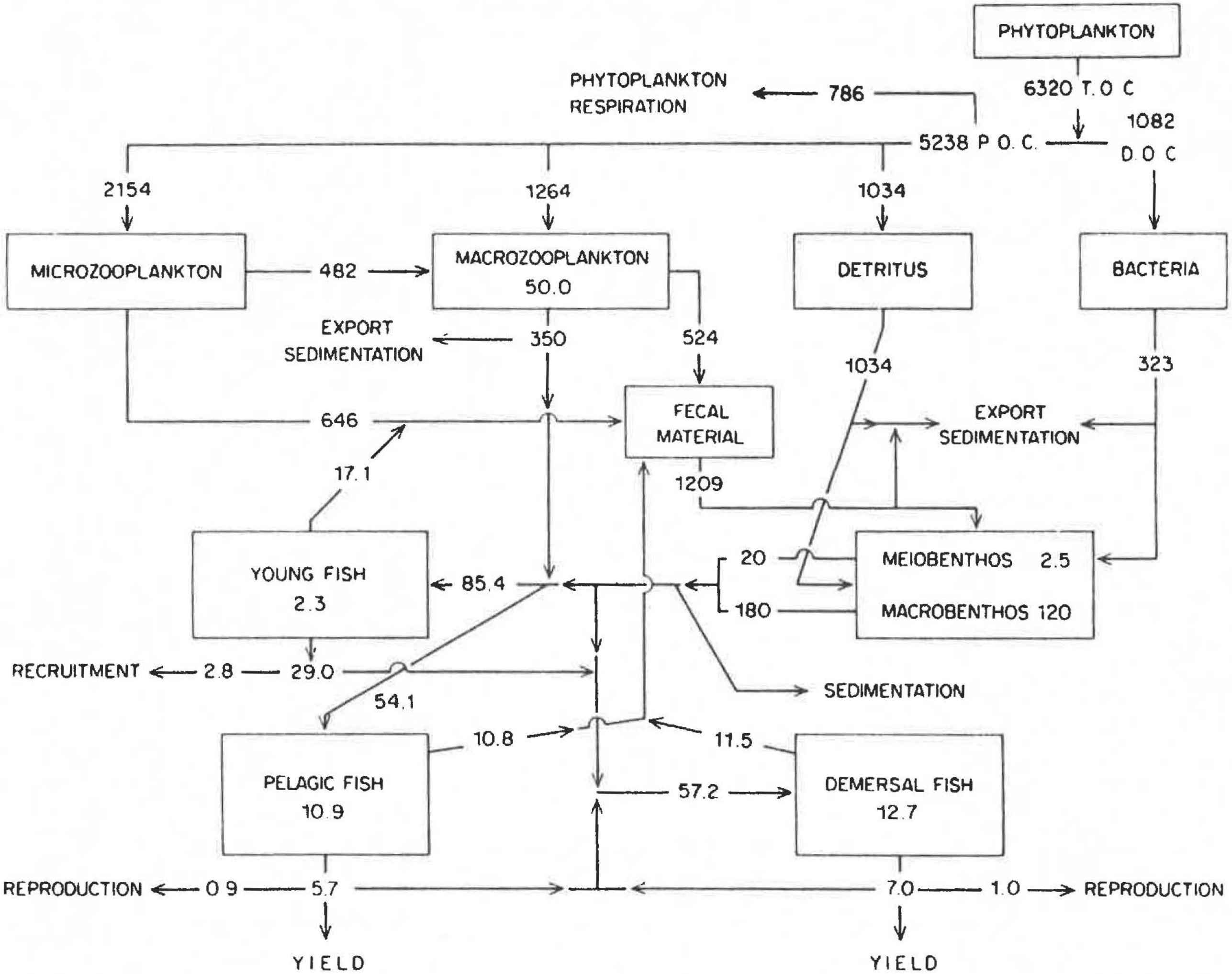

Figure 3. Energy budget (in kcal/m^2 yr and kcal/m^2) for Georges Bank. Fish production and consumption estimates apply to 1973-1975, a period of reduced abundance due to heavy fishing. After Sissenwine et al (in press).

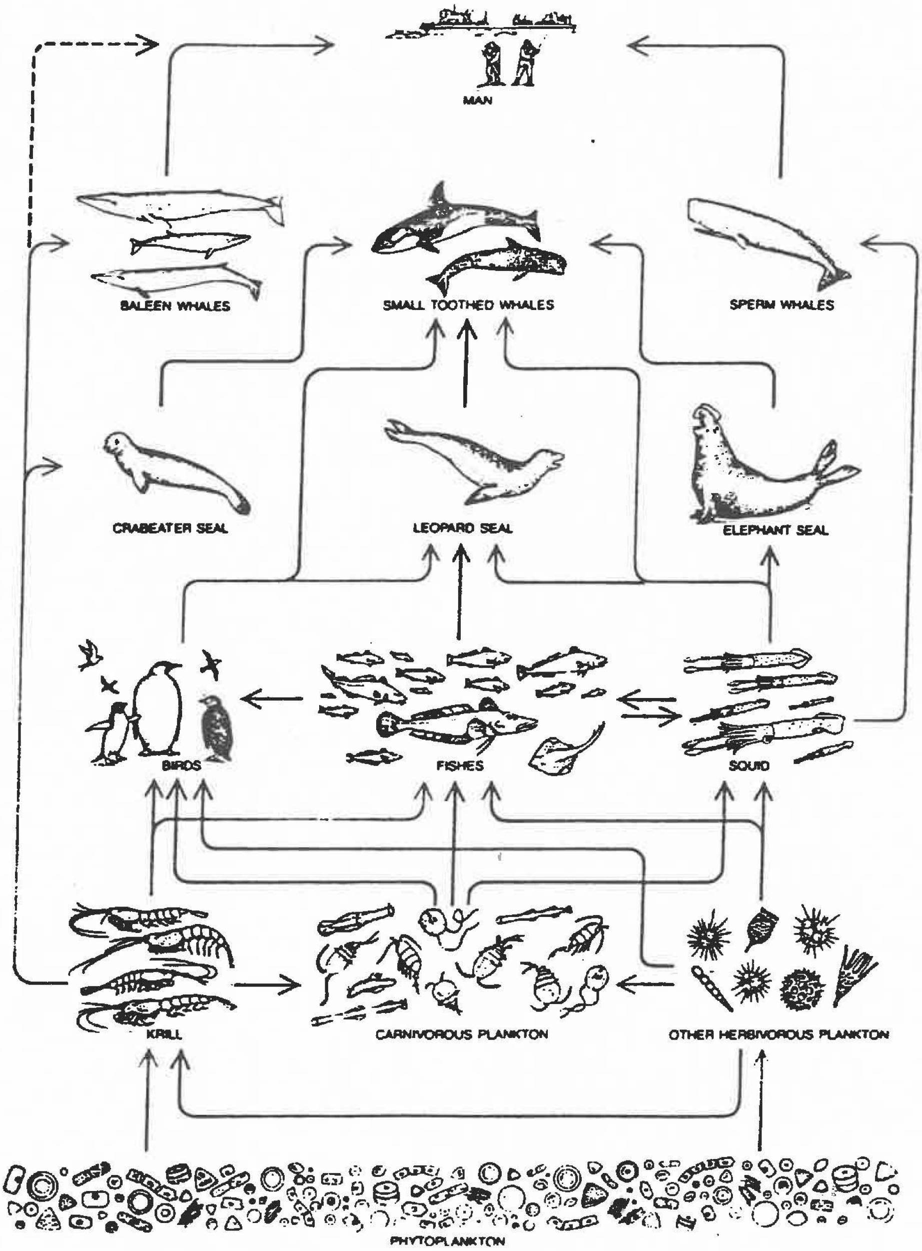

Figure 4. Diagram of the Antarctic ecosystem. From Beddington and May (1982).

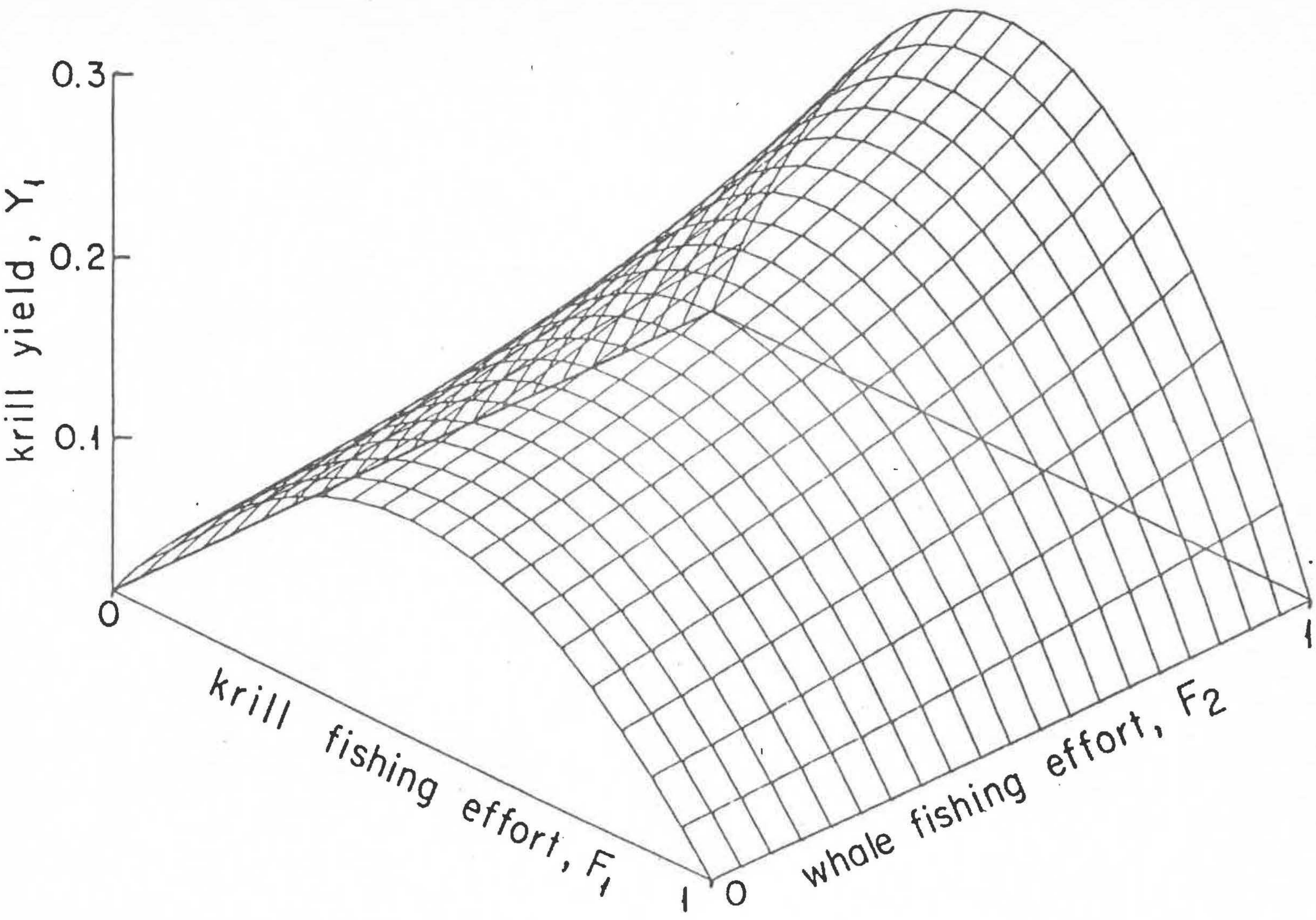

Figure 5. Hypothetical relationship between fishing effort applied to krill and their whale predators. From May et al (1979).

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Figure 1. Analyse du rendement-par-recrue (espèces multiples et espèces simples) pour la morue de la Mer du Nord. La mortalité par pêche, la biomasse et le rendement concernent l'année 1977. D'après Ursin (1982).

Figure 2. Estimation à espèces multiples de la réaction des rendements et biomasses aux changements concernant l'effort de pêche sur la morue. D'après Ursin (1982).

Figure 3. Budget de l'énergie (en kcal/m^2 année et kcal/m^2) pour le Banc Georges. Les estimations de la production et de la consommation des poissons s'appliquent aux années 1973-1975, qui est une période d'abondance réduite en raison de l'intensité des opérations de pêche. D'après Sissenwine et autres (sous presse).

Figure 4. Diagramme de l'écosystème antarctique. D'après Beddington et May (1982).

Figure 5. Relations hypothétiques entre l'effort de pêche au krill et celui s'appliquant aux baleines qui s'en nourrissent. D'après May et autres (1979).

Рисунок 1. Многовидовой и одновидовой анализ вылова на единицу пополнения для североморской трески. Промысловая смертность, биомасса и вылов соотнесены с данными 1977 г. По Урсину (1982 г.)

Рисунок 2. Многовидовая оценка влияния изменений в промысловых усилиях на вылов и биомассу по отношению к тресковым. По урсину (1982 г.)

Рисунок 3. Распределение энергии (Ккал./кв.м. в год и Ккал./кв.м.) в банке Джорджа. Оценки воспроизводства и потребления рыбы относятся к 1973 - 1975 гг. - периоду пониженной численности в результате интенсивного промысла. По Сиссенвайну и др. (Публикуется).

Рисунок 4. Диаграмма экосистемы Антарктики. По Беддингтону и Мэю (1982 г.)

Рисунок 5. Гипотетическое соотношение промысловых усилий при промысле криля и китов, питающихся крилем. По Мэю и др. (1979 г.)

Ilustración 1. Análisis de rendimiento por cría de varias especies y de especies únicas con respecto al "North Sea Cod" (Bacalao del Mar del Norte). La mortalidad pesquera, biomasa y rendimiento corresponden a 1977. Según Ursin (1982).

Ilustración 2. Evaluación tomando varias especies de la respuesta de los rendimientos y biomasas a los cambios en el esfuerzo pesquero con respecto al bacalao. Según Ursin (1982).

Ilustración 3. Presupuesto de energía (en kcal/m^2 yr y kcal/m^2) para Georges Bank. Las estimaciones de producción pesquera y consumo corresponden a 1973 - 1975, un período de abundancia reducida debido a la pesca excesiva. Según Sissenwine et al (publicado).

Ilustración 4. Diagrama del ecosistema antártico. Según Beddington y May (1982).

Ilustración 5. Relación hipotética entre el esfuerzo pesquero aplicado al krill y sus depredadores, las ballenas. Según May et al (1979).