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An overview of the Institute of Cetacean Research work on ecosystem modeling in the Antarctic and western North Pacific

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ABSTRACT

The development of ecosystem models has been an important research activity organized and promoted by the Institute of Cetacean Research (ICR). This paper presents an overview of the objectives and progress made in the research on ecosystem modeling in the Antarctic and western North Pacific. Whale abundance, prey composition and prey consumption of whales have been some of the input data to the models, which were obtained by ICR surveys. Several future research needs to progress the ecosystem modeling work have been identified.

INTRODUCTION

The development of ecosystem models has been an important research activity of the Institute of Cetacean Research (ICR) in its whale research programs in the Antarctic and western North Pacific. What is understood by 'ecosystem models'? An ecosystem model is an abstract, usually mathematical representation of an ecological system, which is studied to better understand the real system (Hall and Day, 1990). Ecological relationships, such as the relation between predators and preys, are derived using data gathered from the field, and these are combined to form ecosystem models. These model systems are studied in order to make predictions about the dynamics of the real system.

Ecosystem models have applications in a wide variety of disciplines including natural resource management. Morishita (2008) provided a good summary of the various interpretations of the ecosystem approach for fisheries management, one of them being the evolution from single-species management to multi-species management. According to the FAO home page (Fisheries and Aquaculture Department), ecosystem models for fisheries management purposes have ranged in complexity from enhanced single-species models to fully articulated food web models including physiological, spatial and environmental processes.

Objectives of ecosystem modeling studies are different according to the kind of model used. They could be, for example, 1) understanding structure, features and interactions of an ecosystem, 2) identifying major causes of changes in an ecosystem, 3) prediction of population dynamics for specific species, 4) assessment of the impact of fisheries and predation on an ecosystem, 5) providing some scientific advice on management of a stock or stocks.

Plagányi (2007) reviewed ecosystem modeling studies and grouped the models into two groups: 1) whole ecosystem models, which are models taking into account all trophic levels. This includes Ecopath with Ecosim (EwE) (Christensen *et al.*, 2005); and 2) Minimum Realistic Models (MRM), which are models restricted to represent a limited number of species most likely to have important interactions with a target species of interest. This includes MULTSPEC (Bogstad *et al.*, 1997; Tjelmeland and Bogstad, 1998) and BORMICON (Stefansson and Palsson, 1998).

This paper summarizes the studies on ecosystem modeling organized and promoted by the ICR in the Antarctic and western North Pacific Ocean.

ECOSYSTEM MODELING IN THE ANTARCTIC

Background

The ecological background for the ecosystem modeling in the Antarctic is provided by Fujise and Pastene (this issue). There are some hypotheses related to ecosystem changes in the Antarctic. The first is referred to as the 'krill surplus' hypothesis. After the depletion of Antarctic blue (*Balaenoptera musculus intermedia*), fin (*B. physalus*) and humpback (*Megaptera novaeangliae*) whales at the middle of the past century there was some 150 million tons of krill surplus. This surplus became available for other krill-eater species of penguins, seals and smaller whales (*e.g*. Antarctic minke whale, *B. bonaerensis*) (Laws, 1977). The krill surplus implied better nutritional conditions in those species, which was reflected in changes in some demographic parameters. For example from 1940 to 1970, recruitment had been increasing for Antarctic minke whales (Punt *et al.*, 2014) reflecting better nutritional conditions for the species at the middle of the past century.

The second hypothesis is that the population dynamics of Antarctic species is affected by environmental changes. A decrease in sea-ice cover by the middle of the twenty-first century due to global warming has been predicted by several studies (Levitus *et al.*, 2000; de la Mare, 1997). Warming of the Southern Ocean appears to be occurring faster than the warming of other oceans of the world (Gille, 2002).

It was therefore necessary to investigate and quantify the interactions among krill predators such as some baleen whale species, and to examine the dynamics of the Antarctic marine ecosystem. This would enable investigation of what has happened in the past and to predict what is going to happen in the future in the context of ecosystems in the Antarctic (GOJ, 2015). For this aim, ecosystem modeling has been used.

One of the main objective of the ecosystem modeling study in the Antarctic was to determine whether predator-prey interactions alone can broadly explain observed population trends without the need for recourse to environmental change hypotheses (Mori and Butterworth, 2006).

MRM Models in the Antarctic

Objectives

The objective of the study by Mori and Butterworth (2006) was to determine whether predator–prey interactions alone can broadly explain the observed population trends of four large baleen whale species, Antarctic blue, fin, humpback and Antarctic minke whales; two seal species, Antarctic fur seal (*Arctocephalus gazelle*) and crabeater seal (*Lobodon carcinophagus*); and Antarctic krill (*Euphausia superba*), without the need for recourse to environmental change hypotheses.

Ecosystem model

Population dynamics models were developed to describe predator–prey interactions among the four large baleen whale species, the two seals species and krill (Figure 1). Functional responses are generally classified into three types, which are called Type I, II, and III (Holling, 1959). In the model, two types of functional responses were considered, Type II, which assumes that consumption rate decreases as prey abundance increases and that prey consumption is limited, and Type III, which assumes that consumption rate increases as prey abundance increases when prey abundance is lower than a threshold of prey abundance, and it decreases as prey abundance increases when prey abundance is higher than the threshold (Holling, 1959). Mori and Butterworth (2006) fitted the abundance estimates of these species to estimate parameters/coefficients in the models by maximum likelihood method.

Research area and data used

The predator-prey model was constructed in two sectors of the Antarctic. One in the Atlantic/Indian sector (east of 60°W and west of 130°E) and the other in the Pacific sector (east of 130°E and west of 60°W). Historical catch data for all species considered in the model were used. Abundance estimates of krill predators for the whole sectors were also used. Abundance trend estimates for blue, humpback, Antarctic minke whales and crabeater seal were made for a part of each sector, and were based on independent data sources.

Results

The main results of Mori and Butterworth (2006) were the following:

(i) species interaction effects alone can explain observed predator abundance trends;

(ii) it is necessary to consider species other than baleen whales and krill, to explain observed trends—

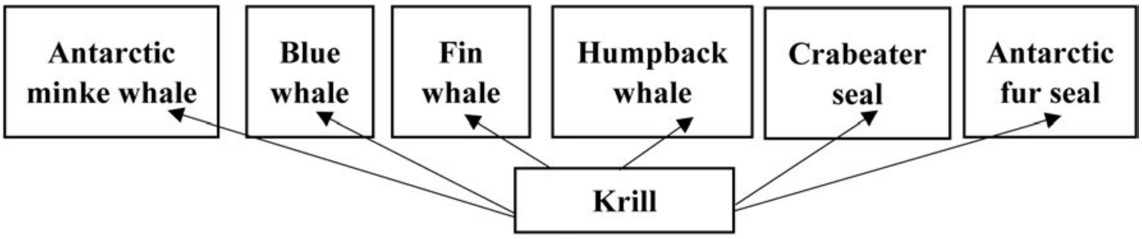

Figure 1. Food web in the Antarctic modeled in Mori and Butterworth (2006) and Moosa (2017).

crabeater seals seemingly play an important role and constitute a particular priority for improved abundance and trend information;

(iii) the Atlantic/Indian Ocean sector shows major changes in species abundances, in contrast to the Pacific Ocean sector, which is much more stable;

(iv) baleen whales have to be able to achieve relatively high growth rates to explain observed trends; and

(v) Laws (1977) estimate of some 150 million tons for the krill surplus may be too high because his calculations omitted consideration of density-dependent effects in feeding rates.

Moosa (2017) refined the ecosystem modeling work by Mori and Butterworth (2006), mainly by incorporating/updating catch history and abundance estimates of species considered in the model, and by making some technical improvement to the model. Preliminary results supported the main findings of Mori and Butterworth (2006).

Moosa (2017) identified the following future work required: i) inclusion of a space limitation term for the fur seals in the model so as not to increase their population to unrealistically high values; ii) consideration of a set of differently defined regions as this might possibly better represent the Antarctic minke whale abundance trends and population trajectories; iii) further consideration of the variation of the effective annual natural mortality rate of krill, because this is likely causing the oscillations in the krill dynamics; iv) further consideration of the variation of the bounds imposed on carrying capacity of krill; and v) further consideration of the variation in the proportion of fin whales assumed to feed south of 60°S.

This work is ongoing.

ECOSYSTEM MODELING IN THE WESTERN NORTH PACIFIC

Background

There were two main motivations for building ecosystem models in the western North Pacific. The first one was the rapid decrease of Japan′s fisheries catch from 12,785 thousand tons in 1988 to 4,690 thousand tons in 2015 (GOJ, 2000; 2017). Ecosystem models including fishery resources can provide some insight to the reasons for changes in stock status considering interaction among species.

The second one was the possibility of competition between marine mammals and fisheries on prey species of economic importance. For example, common minke whales (*Balaenoptera acutorostrata*) sightings occurred close to the fishing grounds of Pacific saury (*Cololabis saira*) off Kushiro. In fact, they fed mainly on Pacific saury near the fishing ground of the Pacific saury. This observation suggested a relationship between common minke whales and Pacific saury from summer to autumn in the western North Pacific (Tamura and Fujise, 2002). Ecosystem models can be used to investigate whether competition exists, for example by comparing ecosystem models with and without the assumption of competition.

EwE model in the western North Pacific

Objectives

Mori *et al.* (2009) applied the EwE model to investigate the possible impact of whaling on the catch of other species in the western North Pacific ecosystem. They also compared single-species MSY and multi-species MSY. If there were substantial differences between the two MSYs, the stock status derived from the two models could be quite different. In such a situation, multi-species model should be used rather than single-species model for assessment of the stocks.

Ecosystem model used

Ecopath is a static, mass-balanced snapshot of the system and Ecosim is a time dynamic simulation module for policy exploration (Christensen *et al.*, 2005). The model consist of the species from detritus to top predators. Ecopath is used to model tropic flow within a food chain of an ecosystem. Ecosim can be used to simulate temporal change from the steady state described by the Ecopath model under some harvesting scenarios.

The scenarios examined in Mori *et al.* (2009) were: i) harvesting 4% of the common minke whale population; ii) harvesting 4% of the sei whale (*B. borealis*) population; iii) harvesting 4% of Bryde′s whale (*B. edeni*) population; iv) harvesting 4% of the common minke, sei and Bryde′s whale populations; v) harvesting 4% of the sperm whale (*Physeter macrocephalus*) population; and vi) harvesting 4% of the four whale species.

For an initial test run, the impact of no harvesting and harvesting 4% of the whales for the coming 50 years on catch of the fishes, was made. Uncertainty of the data input to Ecopath, functional response and trophic flow (top-down or bottom-up) were considered. Type I functional response, which assumes that prey consumption is in proportion to prey abundance up to the maximum (Holling, 1959) was assumed as the reference case, and the Types II and III functional responses were used for sensitivity analyses.

Research area and data used

Mori *et al.* (2009) developed the EwE in the western

Table 1
List of the species/groups used in the EwE model and Trophic Level (TL) estimated by Ecopath (Mori *et al.*, 2009).

Species/Group	TL	Species/Group	TL	Species/Group	TL
Minke whale	3.99	Albacore	4.08	Pacific pomfret	4.20
Bryde′s whale	3.83	Sword fish	4.81	Sardine	2.30
Sei whale	3.73	Skipjack tuna	3.97	Anchovy (<8 cm)	3.04
Other baleen whales	3.23	Blue shark	4.27	Anchovy (≧8 cm)	3.04
Sperm whale	4.17	Salmon shark	4.35	Pacific saury	3.12
Baird′s beaked whale	4.15	Lanternfish	3.06	Phytoplankton	1.00
Short-finned pilot whale	4.40	Neon flying squid	4.12	Euphausiids	2.18
Ziphiidae	4.24	Large surface squid	3.41	Copepods eaten by whales	2.00
Other toothed whales	4.46	Small surface squid	3.01	Other Copepods	2.00
Northern fur seal	4.08	Mid-deep water sea squid	3.11	Detritus	1.00
Marine birds	4.24	Mackerels	3.30		

North Pacific (north of 35°N and west of 170°E), where JARPNII surveys were conducted. The model consists of 32 species/groups ranging from detritus to whales (Table 1). Estimated trophic level (TL) for each species is shown in Table 1. Higher TL represents the species playing a role closer to top predator in the ecosystem. Input data required for the model were biomass, production, prey consumption, diet composition and total fishery catch of each predator in the target area. When production is not available, total mortality was used in the Ecopath instead of production per biomass (Christensen *et al.*, 2005).

Biomass, prey consumption and diet compositions for common minke, Bryde′s, sei and sperm whales were based on JARPNII surveys. Details of the input data were provided in Mori *et al.* (2009). Once the mass-balance model was constructed, possible effect on fisheries of the species in the model were simulated by using Ecosim under the harvesting scenarios examined.

Results

Results of Mori *et al.* (2009) suggested the following:

i) when minke whales are the only species that are harvested by 4% of its biomass (catch of other species are kept constant at current catch rate), depending on the functional response form assumed for the species, it is not certain whether catch of some Japanese fisheries resources (*e.g.* anchovy (*Engraulis japonicus*), Pacific saury, skipjack tuna (*Katsuwonus pelamis*), mackerels (*Scomber japonicus, S. australasicus*) will increase or not;

ii) when sei and Bryde′s whales are each the only species that are harvested by 4% of their biomass, regardless of the functional response form assumed for the species, catch of anchovy, skipjack tuna, and mackerels may increase;

iii) when minke, sei and Bryde′s whales are all harvested by 4% of their biomass, an increase in catch is expected for most of the fish resources (i.e. anchovy, skipjack tuna and mackerels), indicating the effectiveness of harvesting several whale species simultaneously; and

iv) when sperm whales are the only species that are harvested by 4% of its biomass, depending on the functional response form assumed for the species, catch of anchovy, Pacific saury, mackerels and skipjack tuna may decrease, but in contrast, catch of neon-flying squid may increase.

The work by Mori *et al.* (2009) is being updated in the studies by Murase *et al.* (2016) and Watari *et al.* (2018). Murase *et al.* (2016) have focused on the interactions between forage fish and their predators including target species of JARPNII (common minke, sei, Bryde′s and sperm whales). They have updated the input data to the models by considering the data available in the period 1994–2013 and made several technical improvements following recommendations from the International Whaling Commission Scientific Committee (IWC SC). Watari *et al.* (2018) have improved Ecopath model focusing on the small pelagic fishes to investigate their role in the ecosystem by using two ecological indices.

Murase *et al.* (2016) and Watari *et al.* (2018) have identified several future data and work required to progress the development of ecosystem modeling in the western North Pacific. Some suggestions to improve input of EwE were the following: (i) consistency of spatial resolution of input data is required, (ii) regional models are to be developed within the EwE area, (iii) collection of diet composition data at regular interval is required because some of the diet composition data were old or obtained outside the research area, (iv) resolution (the numbers of species/group) and quality of data on non-commercial and lower trophic level species should be improved and (v) evaluation of the sensitivity of Ecopath models to input data is required.

This work is ongoing.

MRM in coastal areas

Objectives

Okamura *et al.* (2009) examined the effects of predation of common minke whales on sandlance (*Ammodytes* spp.) stock off Sanriku region to investigate the effect of predation by the common minke whales in terms of MSY of the sandlance population.

Model used

A Bayesian delay-difference approach (Hilborn and Walters, 1992; Meyer and Miller, 1999) was used to develop a MRM-type ecosystem model. They focused on interaction between sandlance and common minke whales (Figure 2), and constructed a population dynamics model of sandlance taking into account predation by the common minke whales. In the analysis, functional response Types I, II and III (Holling, 1959) were considered.

Research area and data used

The research area was the coastal area off Sanriku. Data used in this modeling were CPUE series of juvenile and adult sandlance fisheries, abundance estimate for adult sandlance, age, length and weight time series of sandlance during 1999–2005, catch series of sandlance by lift net with light fishery, dip nets, and trawl-net fishery from 1901 to 2006 and stomach contents of the common minke whales off Sanriku in 2003 obtained from JARPNII surveys (Tamura *et al.*, 2004).

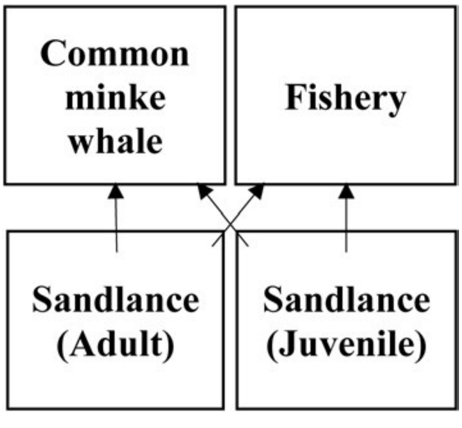

Figure 2. Ecosystem model off Sanriku modeled in Okamura *et al.* (2009) and Kitakado *et al.* (2016).

Results

Under the scenarios of the linear functional response curve (Type I), the resultant impact was so great that the median value of MSY was increased by 154%. Whereas using the constant functional response scenario (most extreme functional form), the impact was much smaller, where there was only a 17% increase of the median value of MSY. This suggested that estimating functional response is important to assess the impact of predation by the common minke whales.

Kitakado *et al.* (2016) updated the model work by Okamura *et al.* (2009) by using new data as follows: i) catch and CPUE series of juvenile sandlances by lift nets with light fishery (1994–2015); ii) catch and CPUE series of adult sandlances by dip nets fishery (1994–2015); iii) time series of age composition data of sandlances taken from summer sampling survey (2002–2014); iv) time series of density estimate of sandlances (in number) during summer sampling survey (2002–2014); v) consumption of sandlances by common minke whales in 2005, 2006 and 2012 (JARPNII surveys); and vi) time series of abundance estimates in Sanriku region for the common minke whales in 2004, 2005, 2006 and 2012.

Further analyses should be conducted to examine sensitivities of the results to the assumption of prior distributions. Because only the Type II functional response was assumed in Kitakado *et al.* (2016), other forms of functional response and multiple-prey functional response with krill and anchovy are worthy to investigate. The weight allocated among the components of the likelihood (likelihood relevant to abundance of juvenile sandlance, likelihood relevant to abundance of adult sandlance, and likelihood relevant to age composition of sandlance) should be carefully considered in future analyses (Kitakado *et al.*, 2016).

This work is ongoing.

CONCLUDING REMARKS

Progress has been made in the development of ecosystem modeling for some particular objectives related to fisheries management and ecosystem structure and dynamics, in both the Antarctic and western North Pacific. Biological and abundance data of the species considered in the models are important. In the case of whale species such data came from ICR surveys. Several research needs were identified which should be addressed to progress the work on ecosystem modeling work and potentially contribute to resources management taking into account multi-species considerations.

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