a three-Species Community: Interactions With fisheries

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Overview: *In this Lab we examine interactions with a commercial fishery that exploits the largest of the grey seals' main prey. We first construct a predator-prey model, in which a deterministic, age-structured sandeel population interacts with a stochastic, age-structured grey seal population. We then consider the implications of different management strategies for the sandeel fishery, specifically focusing on the probability of extinction from different levels of proportional harvesting.*

1. the Study System

The sandeel fishery started at a moderate level in the early 1950s and increased gradually to around 150 000 tonnes in the latter half of the1960s. In the 1970s, the fishery developed rapidly and after 1980 annual landings have fluctuated around 800 000 tonnes. In 2003 and 2004, landings dropped abruptly to around 350 000 tonnes and dropped even further in 2005 to merely 172 000 tonnes. In 2006, landings were still low (288 000 tonnes). The collapse of the fishery was particularly severe in the Norwegian economic zone with a 95% reduction in landings in 2005. By 2006 there was only a limited, monitoring fishery. Except for the closure of the fishery in 2006 restricted to the Norwegian zone, sandeel landings have never been limited by quotas. However, in 2007 a total allowable catch (TAC) of 170 000 tonnes was set for the whole of the North Sea. Because there is no agreement between EU and Norway on how to share the sandeel, the TAC was overfished by 21% resulting in total landings of 206 000 tonnes. Some sandeel grounds in the Norwegian economic zone that had been depleted for several years, showed signs of recovery in 2007. However, there are still several fishing grounds in the northern part of the North Sea that have low sandeel abundance.

The International Council for the Exploration of the Sea (ICES) recommends that local depletion of sandeel aggregations by fisheries should be prevented, particularly in areas where predators congregate. In the light of studies linking low sandeel availability to poor breeding success of kittiwake, ICES advised a closure of the sandeel fisheries east of Scotland for 2000-2003. All commercial fishing was excluded, except for a maximum of 10 boat days in each of May and June for stock monitoring purposes. The closed area was maintained for three years with an annual evaluation. Furthermore, there are a number of ongoing empirical and modelling investigations of sandeels and interactions between sandeels, predators and the fishery.

Stock management currently treats sandeels in the North Sea as a single population. However, research indicates that there are a number of stock components in the North Sea which, because of isolation of suitable habitat and limited larval movements, do not inter-mix. Given the potential for differences in growth, recruitment and mortality between these stock components, the present management of the stock by a single Total Allowable Catch (TAC) covering the whole North Sea makes sandeels vulnerable to regional over-exploitation. Scientists from the UK and Denmark are now trying to understand the dynamics of regional stock components in order to provide advice on regional management.

Scotland has led the way in the local management of sandeel fishing through its governance of inshore sandeel fisheries at Shetland and to the west of Scotland. In both cases three-yearly management agreements are in place, agreed by groups representing fishing and environmental concerns as well as national fisheries administrators. FRS provides scientific and management advice as input to the process, which some commentators have called the only real application of the Precautionary Approach to fisheries management in European waters.

We will consider a hypothetical Scottish fishery which has remained closed for the last three years. Currently, within the ICES square enclosing the fishery, the estimated densities of sandeels of both sexes for the three different age classes are respectively, 12×10^6, 12×10^5, 12×10^5. During the closure period, sandeels have shown a marked recovery maintaining a fine balance with the small, local population of grey seals. Currently, a total of only 69 female seals use the area and the local population's age structure is (12, 8, 7, 8, 8, 26).

The fishery only takes sandeels of class three. It is assumed that the annual estimates of sandeel density obtained by fisheries surveys are accurate. We would therefore like to set a proportional quota in the range 30-40% of class three sandeels. We will assume that demand for sandeels is high, fishers are honest and there are no discards (fish caught over the quota that are thrown overboard). These assumptions (rather conveniently) imply that the annual harvest is exactly the same as the quota set by the managers. The management objective for the next 3 years is to ensure a risk of less than 50% for the seal population. This is arbitrarily defined as the probability that the population goes extinct within a 100 years of the quota being continuously applied. That is not to say that the quota will be applied for 100 years, or that the predictions of population size 100 years from now are expected to bear any relevance to the true populations, however it is useful to take a longer-term view in estimating the vulnerability of the seal population to the consequences of fishing.

2. Ecological theory

Body condition, or its proxies, can be used to determine the predator's performance (fitness), in terms of survival, individual growth and reproduction. The same formulations used to describe density dependence, can be used to describe performance as a function of condition. For example, the Beverton-Holt function can give an expression for survival

$$s(E) = s_{\max} \frac{E}{E_s + E} \qquad (1)$$

In which E is a measure of energy stores. Note that as E becomes very large, survival tends to the maximum value $s_{\max}$. E_s is the energy at which the predator's survival is half of its possible maximum value of $s_{\max}$ (you can verify that by setting $E = E_s$ in eq. (3) - can you think of any reasons why $s_{\max} < 1$?). Similarly, fecundity can be modelled as follows

$$b(E) = b_{\max} \frac{E}{E_b + E} \qquad (2)$$

Most of the remaining fundamental ecological concepts have already been covered in previous handouts. It may, however, be worth remembering that a quota, only defines the maximum take. A very generous quota may even exceed the fish that are available to be caught. Any model that is not protected against this eventuality may result in negative population sizes which mathematically is acceptable but ecologically nonsensical. This caveat would also apply to functional responses. Functional responses are often applied at discrete time intervals (e.g. to calculate consumption of prey each year). This means that they don't always take account of short-term depletion and may predict consumption exceeding the availability of prey. This is something that needs to be checked, especially in models that deal with questions of extinction.

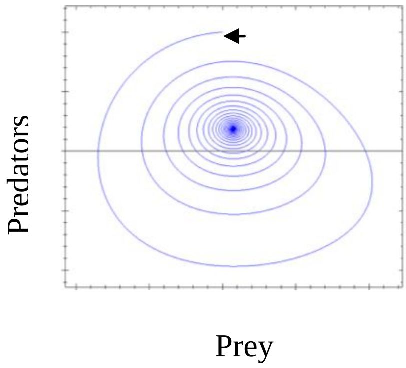
3. Mathematical theory

A quick refresher on unstructured predator prey models. The main three components are the prey growth model, the predators' functional response and the predators' numerical response. The generalised Lotka Voltera model is as follows:

$$
\begin{aligned}
\frac{dP}{dt} &= \text{Prey growth-Prey consumption} \\
\frac{dN}{dt} &= \text{Predator growth-Predator mortality}
\end{aligned}
\qquad (3)
$$

Our case study is different from this basic model because it is formulated in discrete time and both prey and predator populations are stage structured. Nevertheless, the evolution of the system through time can still be visualised with the aid of a phase-space plot.

Phase-space plots, introduced by Willard Gibbs in 1901, occupy a space in which all possible states of a system are represented, with each possible state of the system corresponding to one unique point in the phase space. In a phase space, every degree of freedom or parameter of the system is represented as an axis of a multidimensional space. In predator prey models the two axes usually correspond to prey and predator density. For every possible state of the system, or allowed combination of values of the system's parameters, a point is plotted in phase-space. Although time is not explicit in this plots the succession of plotted points is analogous to the system's state evolving through time. The shape of trajectories in the phase-space can elucidate qualities of the system that might not be obvious otherwise. For example, here is the phase space of a system which is oscillating towards an equilibrium – a point at which neither predator nor prey numbers change any more.



4. R ingredients

■ *Setting hard numerical limits to a variable*: In simulations of population dynamics, it is generally preferable if population size is modulated by smooth functions (such as the Beverton Holt that we saw in the two previous practicals). However, sometimes, it is necessary to set hard numerical limits (for example, when the harvest term in the simulation exceeds the available yield to be harvested). This can be done by using the `max` and `min` functions. Here are two examples: The first makes sure that the variable `x` does not take a negative value. The second keeps `x` within a range [a,b]. See if they make sense to you (try them out in R).

```
x<-max(0,x)
x<-min(max(a,x),b)
```

Comparison of vectors, element-by-element can be done by using the commands `pmax` and `pmin`. So, for example `pmax(c(0,1),c(-1,2))` will return the vector `c(0,2)`.

5. Practical tasks

■1■ Read carefully the material in sections 1-3 above.
■2■ Read through the tasks in this section
■3■ Decide on the important and useful facts from sections 1-3 that you will need in dealing with the tasks

Model 1: Predator-prey model

■4■ In this section you will need to combine the prey model and functional response developed in practical II, with the stochastic predator model developed in practical I.

■5■ Specify fecundity in the prey population as a Beverton-Holt function of density in exactly the same way as in practical II. Use the following parameter values: number of female sandeels produced by each female: 25, 1st year survival: 0.1, sub-adult and adult survival: 0.5, half-saturation density for Beverton Holt: 10×10^6 (Note that this last one, is different to the value used in practical II).

■6■ Bring into the new code the functional response routine that you created in practical II. Use the same parameter values, $\mathbf{a} = \{10, 30, 40\}, \mathbf{t} = \{0.01, 0.01, 0.01\}, \mathbf{m} = \{1, 2, 2\}$. You may assume that all seals have exactly the same functional response, independent of their age or sex.

■7■ Mortality in each class of sandeels must be determined from the appropriate output of the functional response scaled up by the total population of predators (both male and female).

■8■ It is essential to make sure that seals eat only up to the available amount of fish in each category. This check must apply to the fish removed but also, to the energy gained by the seals.

■9■ Total energy acquired by foraging can be calculated by adding up the energy acquired from each class of fish. You may assume that the energetic values (in kcal per fish) of sandeels in the three different classes are $\varepsilon = \{10, 45, 90\}$. So, if the consumption of class 1 sandeels by a population of 5 seals is 200000, the energy acquired by each seal will be $200000 \text{x} 10 / 5 = 400000$.

■10■ Specify survival and fecundity of all seals as a function of energy acquired through foraging (see eqs (3) & (4) in the notes of Practical II). This will give three energy-dependent functions (fecundity, juvenile survival and adult survival). Use the half-saturation value of 400 for all these functions (so, $E_S = E_b = 400$). The maximum values for the demographic rates are as in practical I (i.e. max number of female seals born to each female is 0.45, pup-survival is 0.7 and adult/sub-adult survival is 0.9).

■11■ Model the number of seal births and deaths as Binomial variables using the probabilities estimated from the previous step. Remember that these need to be re-estimated each year because prey density, prey consumption and energy acquisition will change as a result of past predation.

■12■ Run this model for 100 years

■13■ Generate a combined time series plot showing total prey and total predator numbers

■14■ Use the same data to generate a phase-space plot

Model 2: Management strategies

■15■ Keep the simulation run-time to 100 years

■16■ Add fishing to this model by removing a constant proportion of class-three sandeels before the end of the year (after the seals have taken their share). So, if your class-3 sandeel population for the next year would be 132×10^6 without fishing, a 20% quota would make it $(1-0.2) \times 132 \times 10^6 = 105.6 \times 10^6$

■17■ Use harvesting values in the range 30-40% in increments of 1%. Run each scenario several times (>10), each time recording whether the population of seals went extinct or not.

■18■ Hence, for each harvesting scenario estimate the empirical probability of extinction.

■19■ Create a plot of extinction probability against the proportion taken.

5. Practical tasks

6. Assessment

Write a report no longer than 3 pages of A4 (single-spaced, Times Roman, 12pt) containing the following:

Model 1: Predator prey model:

■1■ Time series plots of a single run of the predator prey model

■2■ A phase-space plot from the same simulation run

■3■ Comment on the differences in appearance between your phase space plot and the example shown in section 3, of this handout.

Model 2: Management strategies:

■4■ Attach your plot of extinction probability against the proportional quota.

■5■ Using the results in this plot, write a short recommendation for the management strategy that should be followed in the next three years.

■6■ Attach your code at the end of the 3 pages as an Appendix.