Summery

Essays on integrated modelling
with applications to marine ecosystem management

Many natural systems are used for economic purposes. Often this decreases natural or environmental values of an ecosystem. Therefore, there is a demand for management of these natural systems that balances the interest of commercial exploitation and nature conservation. This thesis shows how mathematical modelling in various forms and from different perspectives, ecological and economical can aid a decision maker or manager to design and evaluate potential policies.

The thesis describes some case studies in which modelling is used to find a balance between exploitation and conservation of the ecosystem. It is shown that the question: “How to manage the environmental resource?” can be approached from different (modelling) perspectives. Depending on the specific question, approaches are chosen in which, for example economic optimisation is dominant. This explains pros and cons of particular economic measures such as taxes and quota and why and when one should favour one above the other. Other approaches focus more on gaining insight in the ecological system such as its sensitivities and feedbacks. That understanding may give rise to other potential management strategies such as nature reserves.

A large part of the thesis, chapters 3 to 6, is devoted to the shellfisheries in the Dutch Wadden Sea. The thesis is divided in four parts addressing dynamics, space, conflict and uncertainty. These reflect important aspects of modelling environmental problems. Each of these aspects is addressed in different chapters.

In chapters 3 and 4 a simple bioeconomic model is developed even though the simplified ecology is more complex than is usual in economic analysis. Apart from shellfish the model also incorporates a bird species. The two species interact as shellfish serves as the sole food for birds. The model is used to find an optimal harvest rate in the tradition of fishery economics. The social welfare function that is maximised consists of the profits from the fisheries and also a nature conservation value that is dependent on the size of the bird population. The model analysis shows that depending on parameter values many different types of optimal harvesting solutions are possible in a predator-prey system when conservation of the predator species is considered valuable. The type of solution depends on economic parameters such as the maximum harvest rate, the discount rate, and the cost of fishing, as well as on ecological parameters such as the birds’ search and handling time of shellfish. The final optimal state can be one of three possibilities: not fishing when the nature value is considered to high to be balanced by any fishing profits, fishing maximally when the nature value is considered too low to compensate any loss of fishing profits, or coexistence of fishers and birds. The most important general conclusion is that to ensure harvesting and conservation the following conditions must be met:

- the absolute marginal cost of harvesting at the pristine equilibrium shellfish density is large,
- the cost of harvesting at that shellfish density is small,
- the discount rate is small,
- the mortality rate of birds is dominated by food shortage,
the pristine state carries many predators,
- predators can quickly deplete prey in equilibrium, i.e. predators eat many prey,
- the marginal value for birds at either no birds or at the pristine equilibrium is small.

An example of a value function consistent with the latter condition is an S-shaped function with the sharp increase after $0$ or an asymptotic function that is close to its maximum in the pristine state.

In chapter 4 it is shown that with realistic parameter values based on the shellfisheries in the Dutch Wadden Sea, birds and fishers can coexist and that some form of regulation is needed. In the deterministic ecosystem, quotas are necessary to obtain coexistence between a profitable fishery and a sustainable bird population, whether the fishers are rational or boundedly rational. Nonetheless, most ecological systems are stochastic. The effect of taxes versus quota on fisheries in a stochastic ecosystem has been discussed extensively in the literature. As do other authors we show that taxes are the preferred instrument compared to quota to maximise social welfare. This is because taxes better control the surviving stock. Unfortunately the optimal tax is about 50% of the price of shellfish. Thus, most of the exploitation profits show up as tax revenues. This will undoubtedly make it difficult to obtain support from fishers to implement a tax as the preferred regulatory instrument.

The models developed in the chapters 3 and 4 offer predominantly an economic perspective. Most biologists would consider the ecology in these models rather simple if not naïve. Therefore in chapter 5 a multi-species, spatial temporal model of an ecosystem resembling the earlier mentioned Wadden Sea is developed. The model describes two bird species, common eiders and oystercatchers and two shellfish species, cockles and mussels divided over several age classes. Birds move to a different spot if they cannot find enough food. Fishers fish only at locations where the shellfish density is high enough so it can be profitably fished.

The difficulty with complicated models like these is that their behaviour is hard to understand because of the many feedbacks. A different set of parameters may change the behaviour drastically. In order to analyse management policies, one needs to understand the behaviour and sensitivities of the underlying ecosystem model. Therefore, we examine the behaviour of the ecosystem model without fishing and undertake a sensitivity analysis according to a Plackett-Burman design. A Plackett-Burman design is not often used in the sensitivity analysis of integrated ecological-economical models. It is however, much more efficient than the traditional one-at-a-time approach, especially if many parameters are involved.

The sensitivity analysis shows that average population levels of birds are most sensitive to parameters that directly govern the amount of shellfish in the ecosystem in relation to what they need to survive. These are parameters such as the mass of shellfish and the amount of food birds need to survive. Another important parameter controls the decision of a bird to leave a certain spot to forage elsewhere. Unfortunately this is a parameter that is difficult to measure in the field. But it shows that for a bird population it is more important to find the best feeding places than it is to be able to deplete a spot efficiently. Finally, when this model is used to analyse management options for the fisheries recruitment of this shellfish should be modelled as a stochastic process. Recruitment of shellfish varies greatly over the years. The sensitivity analysis showed that bird populations are very sensitive to the presence of shellfish in the ecosystem. Therefore, a great deal of variability in fishery profits and population size of birds is not accounted for when one uses constant average recruitment.
Chapter 6 describes the results of simulating policy scenarios with the ecological model of the previous chapter. The scenario analysis shows that quota and food reservation are measures that hardly bring about conservation of birds. Until recently food reservation was a key instrument for the regulation of the cockle and mussel fisheries in the Dutch Waddensea. Bird preservation is most successful through closure of the mechanised cockle fisheries and by creating nature reserves, i.e. areas closed for fishing. This happens to be the current policy in the Dutch Waddensea. Furthermore, because the dredges of fishing boats scrape the top layer of the sea bottom which hampers shellfish recruitment, average catches could increase if catch restrictions are implemented.

The last two chapters are not devoted to balancing shellfishery profits and bird conservation. Chapter 7 is concerned with a theoretical analysis of conflict and cooperation, namely optimal strategy in a single-shot Prisoner’s Dilemma tournament. The Prisoner’s Dilemma is a standard game-theoretical problem that deals with conflict and cooperation. It is an often-used paradigm in the social sciences to describe the conflict between optimising one’s own (short-term) profits and gaining more (in the long term) through mutually beneficial restrictions. The analysis in chapter 7 follows the tradition set by the seminal work of Axelrod in which strategies are examined in a tournament setting of the Prisoner’s Dilemma. The tournament in chapter 7 differs from the Axelrod tournament in that strategies do not meet each other many times but instead only meet each other once. However, each strategy has full knowledge of the result of every games that has been played. Hence, strategies have the opportunity of establishing and detecting a reputation. It is shown that reputations can play a role in the Prisoner’s Dilemma. A role that makes cooperation possible even when there is only one interaction between a pair of players. As in Axelrod’s tournament, conditional cooperation is successful. But in addition fairness is a characteristic of successful strategies. A fair strategy upholds a norm by punishing strategies that do not obey the norm, and plays according to that norm itself.

Chapter 8 is devoted to uncertainty in climate change projections. It describes a model, or actually a series of models that simulate climatic change due to emissions of greenhouse gases. The series of models computes the chain from greenhouse gas emissions to atmospheric concentrations of greenhouse gases to radiative forcing to climatic change to sealevel rise. Every simulation step in the chain is performed by multiple models, each of which is described in the peer-reviewed literature. Therefore, it is possible to compute an uncertainty band for each simulation step and to establish which process contributes most to the final uncertainty. As it happens, the largest part of the final uncertainty is due to the radiative forcing models, notably those for the effect of aerosols. Furthermore, there is a strong positive relationship between maximum uncertainty in the year 2100 on the one hand and cumulative emissions of CO₂ over the period 1990–2100 on the other hand. Thus, a more certain future can be established by choosing low emission paths.