A Bioeconomic Perspective on the Norwegian Barents Sea Cod Fishery

Arne Eide

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UNIVERSITY OF TROMSØ
Norwegian College of Fishery Science
Department of Economics and Management/Centre for Marine Resource Management

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Content

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Tromsø, 5 May, 2008

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List of papers

Paper 1

Eide, Arne, Frode Skjold, Frank Olsen and Ola Flaaten (2003). Harvest Functions: The Norwegian Bottom Trawl Cod Fisheries. Marine Resource Economics, 18:81–93.

Paper 2

Eide, Arne and Knut Heen (2002). Economic impacts of global warming. A study of the fishing industry in North Norway. Fisheries Research 56:261–274.

Paper 3

Eide, Arne (2007). Economic impacts of global warming: The case of the Barents Sea fisheries. Natural Resource Modeling 20(2):199-221.

Paper 4

Eide, Arne (2008). An integrated study of economic effects of and vulnerabilities to global warming on the Barents Sea cod fisheries. Climatic Change 87:251–262.

Paper 5

Eide, Arne (2008). A bioeconomic MPA study based on cellular automata population growth and distribution. Forthcoming

Paper 6

Eide, Arne and Arild Wikan (2008). Optimal Selection and Effort in a Fishery on a Stock with Cannibalistic Behaviour – The Case of the Northeast Arctic Cod Fisheries. Submitted Open Fish Science Journal (Bentham Open) for reviewing.

Paper 7

Wikan, Arild and Arne Eide (2004). An Analysis of a Nonlinear Stage-Structured Cannibalism Model with Application to the Northeast Arctic Cod Stock. Bulletin of Mathematical Biology 66:1685–1704.

A Bioeconomic Perspective on the Norwegian Barents Sea Cod Fishery

The bioeconomic perspective

Fishing is an economic activity. The aim may be to get food for own consumption, to bring fish products to a market or to achieve recreational value. This economic activity interacts directly with natural resources, usually a common pool fish resource. Fishing could be unrestricted, but is now more often regulated. Modern fisheries regulation focuses resource conservation and sustaining exploitable fish stocks. Overfishing is regarded the major problem of the world's fisheries today. Basically the economic argument is to maintain the resource base of viable fisheries, but ethical reasoning of nature conserving seem to be more and more frequent, referring to the value of pristine nature as such. From an economic point of view economics also covers such values, namely the value of well-being produced by the existence of untouched, viable nature.

Old-established fisheries regulation systems aimed to solve social and economic problems caused by the unregulated fishing; as the Lofoten Act of 1816, targeting the problem of gear collisions caused by high fleet densities on local fishing grounds in the Norwegian cod fishery. Other regulations with a long-standing tradition focus market and trade issues, controlling landings and production facilities.

Development of modern fisheries economics is closely related of two seminal works in the mid fifties by the Canadian economists Anthony Scott and Scott Gordon (Gordon, 1954; Scott, 1955). They were both utilising recent achievements within the biological area of fisheries modelling, in particular the works of Schaefer (1954, 1957) who used mathematical modelling to express the relationship between fishing activities and biological growth on the basis of empirical studies. A dynamic approach was later introduced by Smith (1968) and a complete capital theoretic framework was established Clark and Munro (1975). A comprehensive theory presentation and several examples are given by Clark (1990).

It was no coincidence that these results were achieved in the multidisciplinary centre of fisheries science in Canada at the time. Fisheries science and modelling made great progress during this period within and between several disciplines. The concepts of fish population modelling and fishing mortality were introduced in economics, constituting a new interdisciplinary modelling tool which made it possible at the same time to evaluate biological and economic impacts from fishing, controlled or not by management decisions.

The biological models by which important breakthroughs were achieved, had however solid references back to the early period of modern economics more than hundred years before. During this period classical economists as Adam Smith, David Ricardo, John Stuart Mill, Thomas Malthus and others, gave important contributions to the study of human population growth and initiated the development of demographic models. In addition to making a great impact on the development of economic theories, Malthus' 'Principle of population' (Malthus, 1789) also inspired the mathematicians Benjamin Gompertz and Pierre-Francois Verhulst to construct mathematical demographic models incorporating and developing further Malthus' ideas. In fisheries biology the Gompertz curve (Gompertz, 1828) now more often is labelled the Fox model, while the logistic model (Verhulst, 1838) often is named Pearl (Pearl and Reed, 1920) or Schaeffer model, all referring to persons who redefined the demographic models to also cover biomass growth of fish and animal populations. The linkage back to classical economics and moral philosophy of the 18th century is evident and provides us with an interesting perspective on multidisciplinary research. Modern economics developed to become a discipline and inspired the initiation of others in a period of transition into a new time where also natural resources were regarded differently from before. The following quote from Adam Smith' 'Wealth of Nations' (Smith, 1904) is illuminating:

> "Hunting and fishing, the most important employments of mankind in the rude state of society, become in its advanced state their most agreeable amusements, and they pursue for pleasure what they once followed from necessity. In the advanced state of society, therefore, they are all very poor people who follow as a trade, what other people pursue as a pastime. Fishermen have been so since the time of Theocritus. A poacher is everywhere a very poor man in Great Britain. In countries where the rigour of the law suffers no poachers, the licensed hunter is not in a much better condition. The natural taste for those employments makes more people follow them than can live comfortably by them, and the produce of their labour, in proportion to its quantity, comes always too cheap to market to afford anything but the most scanty subsistence to the labourers."
>
> *Adam Smith (1776), An Inquiry into the Nature and Causes of the Wealth of Nations. Book I, Ch.10 (I.10.6): Of Wages and Profit in the Different Employments of Labour and Stock in paragraph.*

After the period of classical economics the value of nature and natural resources were for many years almost absent in economic research. This has however changed radically the last few decades. Environmental economics and natural resource economics are fast growing theory areas, receiving constantly new challenges from general societal development and political interests of our time. Environmental concern and consciousness of our vulnerability and dependence on natural resources become more evident every day. The current focus on global warming and climatic changes issues is only one example. Maybe the disaster theories of our time in the future will prove to be as influential and crude as the theories Malthus promoted 200 years ago.

This thesis includes seven papers which all deals with issues related to resource use, environmental change and management. Six of the papers refer to the Norwegian Barents Sea cod fishery. The papers include simulation models as well as analytical models. One paper represents population growth by cellular automata modelling. Most papers combine case studies with theoretical analyses. Four of the papers (1-IV) relate to the EconMult fleet model, a modelling effort initiated as a part of a Norwegian research programme on multispecies management models in the mid nineties (Eide and Flaaten, 1998). EconMult has later to some extent been rewritten and updated as described in paper III.

Hopefully the articles may contribute in creating more insight on management issues beyond the special case of the Norwegian cod fishery, which is the focused fishery throughout this work. The next sections present some elements in the history of this particular fishery, modelling in general and the Barents Sea ecosystem in particular, before arriving at management issues relevant in most industrialised fisheries.

A brief history of the North Norwegian cod fishery

The Norwegian Barents Sea cod fishery is today a technologically advanced and highly commercialised fishery with an unbroken international trade history going back more than 1000 years. The cod stock and other fish stock resources have of course been exploited by coastal inhabitants much longer. It is no wonder the rich fish stock resource along the Norwegian coast and in the Barents Sea became a source of food and income for coastal communities in this arctic region. The long lasting fish trade tradition, transporting fish from some of Europe’s most remote areas to central cities in the southern Europe, reflects the uniqueness of the resource available in the high north. Unlike most other European fisheries, landing fresh fish products in the major cities, the products of the Barents Sea cod fishery used months or even years to reach their markets thousands of kilometres away. This was possible because of the early preservation method of drying cod on wooden racks (stockfish), a method still being of major importance in the cod trade. Later the salted and dried variant, a product uniquely produced for export, was introduced by import of salt. Modern freezing and cooling technologies add now frozen and fresh fish to the list of commercial products from the cod fishery.

How cod trade between two geographical extremes of Europe developed we don't know. According to the Norwegian King Eystein I Magnusson's saga the king built a church and sponsored the construction of fishermen cabins (rorbu) in the town Vágar located in the Lofoten Islands in 1120. A royal tax on fishermen in the area had already been introduced several years before. After 1250 Hanseatic merchants took over the fish trade, with local tradesmen in between the exporters and the fishermen (Christensen and Nielssen, 1996). The central area of this fishery was the Lofoten Islands where most of the land was owned by the king. Access to land areas along the coast was given by royal privileges for local guest houses which soon developed to become centres of trade with a strong position towards fishermen. By the end of the 19th century the guest house owners also were allowed to buy the land, which further strengthened their position as fish buyers.

The buyers preserved their strong position up to the introduction of the Norwegian Raw Fish act in 1938, from when the sale of raw fish was organised through bodies controlled by fishermen. These changes were initiated by economic crises in the fishery and fishermen unions established during the 1920s. Up to then the fishery had virtually only been an inshore fishery, capturing the migrating cod during the winter and spring season, while spawning cod approach the North-Norwegian coast. With the introduction of engines and new fishing technologies open sea fisheries became increasingly more important. Long line was introduced already during the 16th century and by the end of the 18th century both long line and gillnetting were commonly used, while hand line still was the most important fishing gear. Foreign trawlers started to visit Norwegian waters from 1905, causing conflicts between trawlers and Norwegian fishermen (Christensen and Nielssen, 1996). Norwegian attempts to introduce a Norwegian trawler fishery failed several times until a vertically integrated salt fish production line succeeded in the mid 1930ies. Worries put forward by small-scale fishermen resulted in the Trawler Acts of 1936 and 1939, limiting the number of trawlers and constraining their operations. This may be seen as the first type of modern fishery management in Norway, aiming to protect the resource base for the activities of other fishermen. The cod fishery was finally closed as a common-pool resource by the introduction of the Limited Entry Act in 1972 (Mikalsen and Jentoft, 2003).

Development of fisheries management

With reference to the description of the Norwegian cod fishery above, fisheries management as we know it today has a rather short history, in Norway as in most other countries. Open access to common-pool fish stock resources was until recently the normal. Marine biological resources around the world were practically regarded immense and almost impossible to deplete. Crises and collapses in fisheries were related to environmental fluctuations which could not be controlled by humans. High fishing pressure by new technology and increased fishing activities learnt however both fishers and governments the need of implementing management measures to protect fish stock resources in order to secure future resource utilisation.

Also in the case of the Barents Sea cod fishery the main concern now reflected in regulations, is to keep an exploitable stock and to avoid situations where the cod fishery has to stop in order for the stock to recover. The resource conservation perspective was first of all an economic concern, since economically efficient fisheries only are possible at efficient stock levels. Over a rather short period therefore the management approach changed from assuming no negative stock impact from fishing activities, to assuming the fish stocks to be determined by previous harvesting activities.

The short history of resource based fisheries management is a history of stepwise management development through crises. Management measures could not perfectly remove any market failures and their ability of doing so changes with varying stock, fleet and market situations. There are therefore good reasons to expect market imperfections to remain even in fully regulated fisheries.

The basic uncertainty every fisher face regarding present and future fish stock situation adds to the uncertainty related to future management decisions, market prices, costs, etc. The fluctuations and loosely understood dynamics ask for flexible and dynamic management rules and recently more emphasis has been placed on the development of transparent and robust management rules, with the ability also to cope with situations often referred to as *crisis*. At the same time as the overall system knowledge and assessment methodology is improved, management based on Harvest Control Rules (*HCR*) is supposed to provide the industry with a longer planning horizon and the government with a more flexible tool for managing the fisheries.

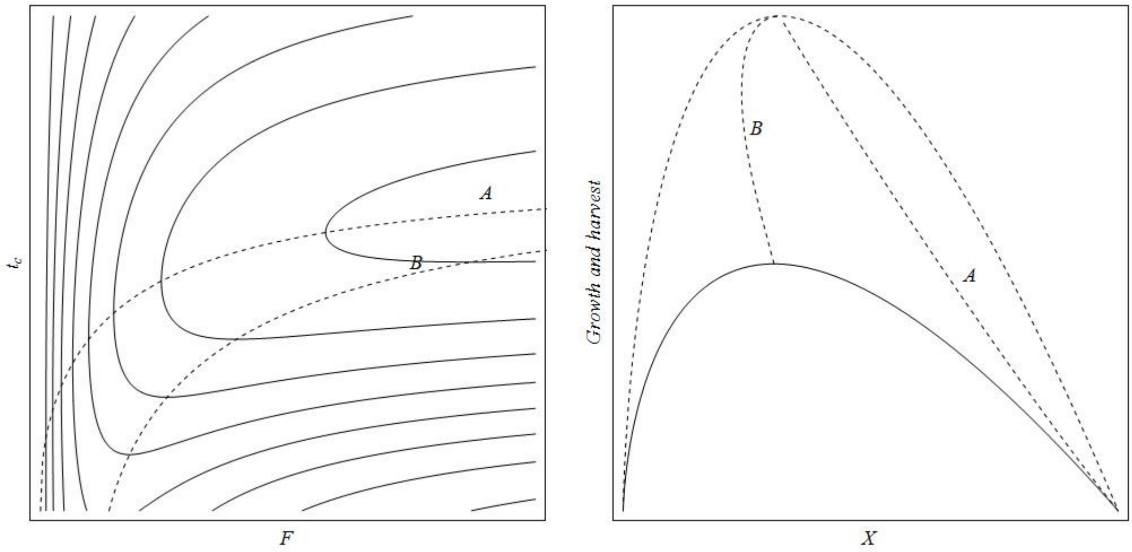

***Figure 1**. The left panel shows the well-known yield-contour map from Beverton and Holt (1957) as function of fishing mortality (F, horizontal axis) and age of fish at first catch (t_c vertical axis). The right panel shows the same range of yield between the two bell-shaped curves, presented as a surplus production model with equilibrium stock size (X) as the variable. Each point found in the area between the two curves is uniquely defined by a pair of (F, t_c)-values*

When the International Council for the Exploration of the Sea (*ICES*) was established in 1902 one of the two scientific committees of the council was the Overfishing Committee, reflecting the increasing concern related stock depletion, first of all by the introduction of new efficient steam trawlers in the North European fisheries. One of the results of the scientific work carried out within the Overfishing Committee was the groundbreaking work of Beverton and Holt (1957) after the Second World War. Their ideas and modelling approach were however not utilised in fisheries management until crises and collapses of huge fisheries asked for immediate actions in the late 60ies.

Based on pioneer works by Baranov (1917) and von Bertalanffy (1934), Beverton and Holt constructed a comprehensive single species model and applied it on commercial fisheries in the North Sea. Density dependent recruitment was studied and several models proposed during the 50ies by Beverton and Holt (1957), Ricker (1954) and others. Ricker (2006) gives in a recent contribution a fascinating picture of this innovative period of several groundbreaking works, also including the works of Scott and Gordon previously mentioned.

The relation between cohort-models and surplus production models often used in bioeconomics is indicated in Figure 1. Simplifying assumptions often seen, for example in the Beverton and Holt cohort model mentioned above, make it rather straight forward to express a cohort model within the framework of surplus biomass production models. Assuming constant natural mortality and recruitment the equilibrium biomass in the Beverton and Holt cohort model is expressed by

$$X(f) = -\frac{R\,w_\infty}{k} e^{-i\,\pi\,b+m\,k\,tr} \quad B(m+f, 1+b),$$

when R is the number of recruits at time tr, w_∞ the maximum individual weight, b the length weight relationship (normally expected to be close to 3) and k the individual growth rate. Z is the sum of natural mortality (M) and fishing mortality (F), $m = \frac{M}{k}$ and$f = \frac{F}{k}$. $B(.)$ is the Euler Beta function. The yield function is obtained similarly, also including the additional parameter t_∞[1] (oldest age in stock) and the one additional variable, t_c (fish age when first targeted by fishing), assuming knife edge sharp selecting at age t_c:

$$Y(tc, f) = fR\,w_\infty e^{-i\,\pi\,b+f\,k\,tc+m\,k\,tr} \quad (B_{e^{k\,t\infty}}(-b-f-m, 1+b) - B_{e^{k\,t_c}}(-b-f-m, 1+b))$$

Basic calculations and assumptions of the equations are explained in more details in Eide (2000).

Common for most of the works referred to above was focusing the fish stock rather than the fishery. The impact from fishing on the stock was reflected in the fishing mortality rate (F), but less effort was put in investigating how fishing activity converts into fishing mortality. This is reflected in the equation above, where the control variables are the t_c-value, reflecting the age by which fish is recruited to the exploitable stock, and the fishing mortality rate (F).

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[1] A slightly more complicated expression covers the case $t_\infty = \infty$: $Y(f, tc) = -fR\,w_\infty e^{-i\,\pi\,b+f\,k\,tc+m\,k\,tr} \left(B_{e^{k\,t_c}}(-b-f-m, 1+b) + \frac{(-1)^{b+f+m}}{b+f+m} \frac{\Gamma(1-b-f-m)\Gamma(f+m)}{\Gamma(-b)}\right)$, including three gamma functions ($\Gamma(.)$).

t_c-regulation could in principle be introduced by gear regulation (mesh-size regulation) and minimum size regulation. Regulating the fishing mortality rate may soon prove to be more complicated. By the invention of a simple accounting system based on previous catches (Virtual Population Analyses, *VPA*; referred to in several of the included papers) a method of converting the desired fishing mortality combined with a given t_c-value into allowable catch quota of the next year (Total Allowable Quota, *TAC*) emerged.

The complicated relation between fishing effort and fish mortality could only be investigated by including both fleet dynamics and fish biology. Hilborn (1985) suggested that the lacking interest from fisheries economists in studying this dynamic area was their attraction towards equilibrium models. Even though this statement may be disputed it is still true that the dynamic area in the intersection between fleet dynamics and biological dynamics where several coexisting fleet segments exploit mutual dependent fish stocks, even today is surprisingly unexplored. Impressing case studies (e.g. Holland and Sutinen, 1999) and remarkable theoretic studies (e.g. Hannesson, 1975) have been carried out; but pulse fishing, diverse fleet structures and varying stock-output elasticities, to mention only a few substantial topics, are still absent from discussions regarding management de cisions as well as from the common understanding on how the two dynamic systems interact.

In addition to *TAC* regulation the other standard method of regulating a fishery on the basis of desired fishing mortality, is to assume linearity between the fishing mortality rate and standard units of fishing effort (input regulation). The assumed linearity simply converts the ratio between estimated F-value of last year and desired *F*-value of next year to a similar ratio between fishing efforts (e.g. fishing fleet) of the two years. According to the few studies done on the relationship between fishing mortality and fishing effort (of which paper I of this thesis is one), linear relationships are rarely found. Since the exponential error of assuming linear relationship may be substantial, erroneously assuming proportionality when making management decisions has severe consequences.

Recent efforts on developing feedback-based management systems may be more promising. In many regards modern fisheries management tools in principle assume perfect knowledge to be accessible or achievable, on the biological and economic dynamics in the fishery. Truly determinism is usually assumed and the challenge then is to identify still hidden functionalities of the system. A quite different approach is to acknowledge the basic uncertainties and to accept that full knowledge could never be obtained. Rather than expect it to be possible to perfectly unmask the system, the management challenge is to find ways to cope with uncertainties. The precautionary approach to fisheries management represents a way to deal with such uncertainties.

The precautionary principle was introduced to international agreements and treaties in the 1980ies and confirmed by the *UN* Rio Declaration on Environment and Development in 1992. The precautionary approach is also included in the *FAO* Code of Conduct for Responsible Fisheries. The aim is to reduce the probability of unwanted events, acknowledging that decisions have to be taken on the basis of poor knowledge. The idea is to create a buffer zone where the probability of harmful decisions is acceptably low. One practical implementation is to use confidence intervals to frame the probability space and use the borders of this rather than expected values for management decisions.

The state of a fish stock resource (e.g. in terms of total biomass) could only be measured indirectly. The importance of choosing good and relevant measuring methods is crucial, but so are the decisions on which stock properties to measure. Chosen properties are referred to as indicators. Precautionary approach management is often implemented in fisheries by the use of two basic indicators: Spawning biomass and fishing mortality rate, utilising the lower and upper confidence interval at a certain level of significance of the two respectively. If the current measure tells the spawning biomass to be below the lower, let us say 95%, confidence interval of the minimum acceptable level and/or the fishing mortality rate is higher that the upper 95% confidence interval of the maximum acceptable, the fishery is outside the precautionary area. In case of quota regulation, the total quota needs to be reduced or the fishery should be closed, according to the principle of precautionary approach.

This reasoning introduces some quite new ideas to fisheries management. The example above shows how quota setting becomes automated on the basis of some predefined rules of action; if this, then that. Such rules in fisheries management are now commonly referred to as Harvest Control Rules (*HCR*) in fisheries. *HCR* may operationalise precautionary approach, but also other considerations, including economic objectives. A set of relevant indicators is needed and control system involving a set of rules based on combinations of indicator values, could be implemented as fuzzy logic control (Zadeh, 1973). Evaluation of the effects of previous decisions could be utilised in refining the predefined rules, adding a dimension of adaptive management to the rule based control system.

In many ways this ideas represent a paradigm shift in fisheries management, as the focus shifts from the direct stock-catch relations based on crude assumptions on how the two dynamic systems interrelates, to a indicator based system where current level of understanding is implemented in a set of rules defining precautionary actions. The first is based on the assumption of perfect knowledge on system functionalities; the latter is a way to operationalise the best knowledge available, uncertainty and possibly learning the system from previously experienced effects.

The new concept of *HCR* also opens for new ways to include other ecosystem effects which are not necessarily fully understood today. Examples are the within and between year fluctuations, multispecies relations, ecosystem dynamics, but also economic dynamics as fisher's behaviour, fleet dynamics, effects of skills, technological differences, etc. In addition the rates by which different participants adapt to changing conditions, natural fluctuations in age structures and other properties of stocks, cost compositions, stock output elasticises, differences in future evaluation, etc., may contribute in understanding phenomena as the diverse fleet structures and other observations which are not easily explained by currently available analytical tools.

The need of fisheries management

This work concentrates on sustainable exploitation of renewable natural stock resources for wealth creation through commercial markets. Biological stock properties, environmental conditions political objectives and economic framework set the constraints for the exploitation. Within this multidimensional and multidisciplinary setting the different works included in this thesis aim to identify fishing activities as economic rational behaviour, given the above constraints and the specified simplifications of each paper. Management decisions expressing different political goals play essential roles in most articles, as management is the constraint by which the system could be directly controlled. Following an established tradition in bioeconomic research, most articles investigate effects of different management regimes, as time paths (simulations) or static analyses (equilibriums).

From an economic point of view management is motivated from a political wish of imposing market failures where it before was a more or less perfect market situation (e.g. the state-owned liquor stores in Norway) or to resolve existing market failures (e.g. public goods).

Therefore political reasons may exist for both introducing and eliminating market failures. Exploitation of common-pool resources normally includes market failures which need management measures if it should be corrected. In short the market failures in fishing origin both from the discrepancy between real value (reflecting relative scarcity) and zero payment from the resource users, in case of free access to the resource, and from the long-term interrelation between the two essential input factors in the production of fish harvest; Fishing effort and stock biomass. According to standard textbook production theory efficient production is obtained by substituting fishing effort by fish stock biomass; since access to stock biomass is free while effort production is costly. But since the size of the stock biomass in the short run is given and in the long run determined by the growth properties of the stock and previous fishing efforts, the basic conditions for normal substitution are not met and the presence of the free factor (stock biomass) leads to increasing the use of the other factor (fishing effort), while the opposite should be expected if the factors were independent of each other. Together the two problems constitute the situation referred to as the market failure of open access fishery; the first of them origins from a value not reflected in the market (the economic problem) and the other origins from the stock response on harvest, simply the fact that the natural equilibrium of the stock declines as mortality increases (the biological problem).

Above the presence of these two types of market failure is labelled as problems. They certainly are the causes for the need of management, but they are at the same time the reasons of why it is possible to obtain resource rent. The potential rent creation is the reverse of the existence of market failures. If these market failures are not corrected for, rent is wasted, which really means that the rent value vanishes by being placed elsewhere, namely in financing excess capacity of fishing effort production. The resource value increases as the resource becomes scarcer, making the potential gain by proper management even greater. Fisheries management is therefore not equally relevant in all fisheries to all time. When briefly addressing the history of fisheries management above, the absence of resource based management until recently is not necessarily reflecting inadequate economic policy, but merely different markets, relative scarcity of fish harvest products, and also less interaction between the two essential input factors in harvest production, fishing effort and stock biomass.

Hardin titled his famous Science paper in 1968 "*The tragedy of the commons*", referring to how open access to common-pool resources leads to over-exploitation (Hardin, 1968).

Fisheries are often used as a case illustrating Hardin's point. Similar reasoning was presented in the seminal works of Gordon (1954) and Scott (1955). Hardin also refers to much older works expressing the same ideas regarding open access to the common-pool resources in ancient literature (e.g. Aristotle). The new metaphor Hardin created proved to be a powerful rhetoric phrase. The phrase was catchy, putting together two terms which at the time of the paper was a surprising composition; the negative (tragedy) by a something most people regarded as beneficial, the common. The former so powerful expression put together by the positive word 'common' and the negative 'tragedy' is now moreover understood as two equally negatives. Maybe it is about time to restore some of the positive aspects of a common property resource and shared (open) access to the common?

Common property resources are essential for the survival of poor fishers and their families in many developing countries; as described in the quote by Adam Smith in the introduction. From a food supply perspective the market failures do not reduce fish harvests as long as total fishing effort is at levels below what corresponds to the maximum sustainable yield (*MSY*). A resource rent which in principle could have fed even more people may vanish. This rent could only be obtained if the fish harvests meet markets, and if that happen the chance for the poor community of getting some of the returning resource rent in return may be small. Such fisheries, with poor technology and lack of markets, are often seen in coastal communities of developing countries. In such cases the market failures by open access to a common-pool resource are not causing the food supply to decrease, food supply increases at a diminishing rate and the value of the resource is utilised by fishing being the employer of last resort.

Cost efficiency and fleet diversity

Several of the papers included utilise EconSimp (Eide and Flaaten, 1998), covering several categories of vessels operating in the cod fishery. The Norwegian cod fishing fleet is quite diverse, covering vessel lengths from less than 6 up to more than 30 meters. The types of fishing gears used show a corresponding diversity; a wide range of gears, from hand line to bottom trawls. The range of vessel sizes and different gears included in EconSimp2000 are shown in Table 1 of paper IV, where groups 1-14 cover the cod fishery.

Table 1. *Cod stock estimates distributed on year classes 1946-2004, from Anon. (2005).*

Year	**Percentage distribution of stock biomass on age groups**							**Total biomass (mill. tonnes)**
	3	4	5	6	7	8	9+	
1946	6.11	8.18	10.71	7.99	5.31	7.32	54.39	4.169
1947	3.69	8.99	11.93	12.68	8.49	5.06	49.18	3.693
1948	4.10	5.03	16.26	17.91	14.01	7.25	35.44	3.666
1949	5.65	7.92	10.18	19.47	18.60	10.70	27.48	3.065
1950	9.71	8.65	13.24	11.92	17.01	13.79	25.68	2.830
1951	13.80	15.22	13.42	12.66	9.85	12.22	22.83	3.141
1952	15.41	20.31	15.67	10.75	10.16	7.19	20.53	3.408
1953	17.88	20.40	21.57	12.31	7.12	6.60	14.11	3.557
1954	6.99	24.01	21.37	19.02	10.20	5.72	12.70	4.039
1955	2.50	8.41	28.87	21.28	18.04	8.45	12.45	3.488
1956	4.55	4.00	13.00	31.45	18.74	14.93	13.33	3.190
1957	10.64	8.28	6.46	14.66	26.07	15.73	18.16	2.496
1958	7.81	15.46	11.25	9.32	13.75	20.70	21.73	2.164
1959	9.91	11.28	24.74	16.20	7.36	8.67	21.85	2.416
1960	13.09	13.20	12.75	20.77	11.80	5.70	22.69	2.051
1961	13.30	15.76	17.02	14.28	15.61	9.06	14.97	2.137
1962	11.91	19.94	18.15	15.02	10.49	12.82	11.66	1.957
1963	8.64	19.48	23.49	16.17	10.76	8.56	12.9	1.748
1964	8.13	14.99	24.92	22.56	11.55	6.90	10.94	1.375
1965	20.49	12.86	18.97	21.44	14.05	5.48	6.71	1.441
1966	31.67	20.93	10.72	11.90	12.12	7.99	4.68	2.198
1967	13.17	35.36	21.73	9.46	8.09	6.75	5.44	2.852
1968	1.61	21.27	38.24	19.62	8.20	5.43	5.64	3.387
1969	1.76	3.71	30.06	34.45	16.61	6.58	6.83	2.806
1970	3.54	3.96	5.58	33.79	33.18	12.25	7.68	2.058
1971	11.31	8.46	5.45	6.31	30.74	26.23	11.50	1.611
1972	23.79	15.40	10.09	5.42	5.96	21.33	18.00	1.621
1973	28.78	30.28	14.40	6.55	3.17	3.34	13.49	2.402
1974	7.50	36.13	28.04	12.82	5.53	2.44	7.55	2.236
1975	12.51	10.88	33.26	23.91	9.21	4.33	5.90	2.037
1976	11.13	17.69	14.15	30.89	14.86	5.63	5.65	1.931
1977	8.74	19.64	20.56	12.23	23.21	9.91	5.70	1.951
1978	19.84	12.81	18.18	14.73	9.25	16.16	9.02	1.577
1979	6.23	28.38	18.16	15.90	10.69	6.41	14.23	1.114
1980	4.30	10.03	35.43	18.80	13.70	7.74	9.98	0.864
1981	7.52	10.88	16.29	36.56	12.57	8.04	8.14	0.984
1982	7.48	10.59	14.54	19.19	32.80	8.22	7.18	0.751
1983	8.36	14.48	17.28	16.14	17.65	19.94	6.16	0.739
1984	20.44	18.98	17.16	16.01	11.18	7.15	9.09	0.818
1985	22.44	29.36	16.17	13.68	8.68	3.88	5.80	0.957
1986	24.87	27.66	25.04	10.36	6.30	2.98	2.79	1.293
1987	4.85	33.47	30.71	19.01	6.40	3.04	2.52	1.120
1988	4.70	9.16	41.39	27.47	11.49	2.76	3.01	0.913
1989	5.81	9.17	14.71	44.88	17.95	5.29	2.19	0.892
1990	10.08	10.09	13.85	16.87	37.78	8.83	2.51	0.964
1991	13.67	14.34	11.75	12.58	12.63	27.37	7.66	1.561
1992	16.61	16.13	14.36	10.14	9.78	8.87	24.12	1.911
1993	13.08	28.18	18.42	11.88	6.40	5.32	16.72	2.357
1994	8.85	23.72	27.79	15.45	9.09	4.37	10.73	2.152
1995	7.29	14.35	28.42	28.54	11.25	3.54	6.60	1.819
1996	5.03	8.87	19.67	31.88	23.27	6.39	4.89	1.702
1997	9.49	7.65	12.57	21.57	27.58	14.88	6.26	1.531
1998	14.88	18.19	12.86	13.02	16.68	16.37	8.00	1.230
1999	10.44	22.29	25.65	12.17	8.52	10.59	10.34	1.106
2000	10.87	17.18	34.11	20.33	7.25	4.18	6.09	1.113
2001	11.07	17.60	25.02	27.05	12.17	3.72	3.36	1.405
2002	6.75	15.97	25.88	24.67	17.35	6.58	2.81	1.592
2003	7.62	10.15	24.71	26.12	17.65	9.13	4.60	1.648
2004	4.49	12.71	16.59	25.50	20.96	11.72	8.01	1.583

According to standard economic theory open access to common-pool fish stock resources causes resource rent to be wasted by building up overcapacity of fishing effort. If bioeconomic equilibrium is established, only the most cost efficient vessels could cover their costs and a normal profit. Less efficient vessels would earn less than a normal profit; hence they would leave the fishery in the long run. There are however many open access fisheries which rather than being dominated a homogenous group of vessels are characterised by a rich diversity of vessels and gears.

The Norwegian cod fishery (before 1972 when the open common was closed) is such a fishery. Obviously a truly bioeconomic equilibrium therefore could never have been established in this fishery. The reasons may be many, including both the specific properties of the ecosystem, the cod stock dynamics and the fleet characteristics. The EconMult fleet model represents a tool also to evaluate the economic performance of the different vessel groups under varying conditions, first of all when stock size and age composition in stock is changing.

Table 2. *Fleet sizes in vessel number, fishing days and catch per year and cost and price numbers calculated on the basis of statistics from the Norwegian Fisheries Directorate (Anon., 2000). The fishing days per year refers to the number of fishing days allocated the targeted species, cod and capelin.*

Stat. group	Gear	Number of vessels (N)	Average employees per vessel (S)	Fishing days per year $\left(\sum E\right)$	Annual target catch per vessel (tonnes) (h)	Variable cost in NOK per tonne harvest (vc_h)	Variable cost in NOK per fishing day (vc_E)	Fixed cost in NOK per fishing day $\left(\frac{fc}{E}\right)$	Average price per kg catch in NOK $(\overline{p})$
001	Gill nets/hand lines	513	1.2	137	21.96	178.64	460.94	268.69	12.77
002	Gill nets/hand lines	158	3.5	107	75.78	218.61	1,902.58	1,296.07	13.81
003	Danish seine	7	2.0	141	36.29	153.84	733.14	382.30	14.30
004	Danish seine	86	3.8	119	98.69	205.02	2,714.81	3,168.80	13.08
005	Long line	163	1.3	129	26.23	284.18	479.28	367.36	12.49
006	Long line	86	3.3	117	74.20	348.82	1,762.92	925.00	13.30
007	Sundry gears	409	1.2	57	10.14	170.97	216.47	729.58	13.05
008	Sundry gears	95	2.4	98	45.81	166.01	969.08	1,509.39	13.97
009	Danish seine	22	5.3	101	148.59	170.23	3,756.64	5,990.30	12.92
010	Sundry gears	43	6.6	84	153.33	279.92	4,529.11	13,160.91	14.84
011	Long line	52	12.5	100	334.37	333.28	6,478.96	26,395.85	15.43
012	Sundry gears	5	20.0	88	205.60	224.37	1,600.32	278,716.64	16.34
013	Wet fish/freezers trawlers	31	13.7	91	716.71	247.25	26,472.53	20,617.13	11.58
014	Industrial trawlers	19	28.2	110	1,202.53	255.11	46,591.03	46,889.58	15.04

Assuming a catch equation of each group given by equations (4) and (5) in paper I, parameterised by Tables 1 and 2 of paper III, the fleet performance of the 14 vessel groups in the cod fishery could be analysed. Year class biomass estimates of the cod stock for the period 1946-2004 are obtained from the Arctic fisheries Working Group (Table 1). Data reflecting economic performance and technical efficiency of year 2000 (Anon., 2000) is summarised in Table 2.

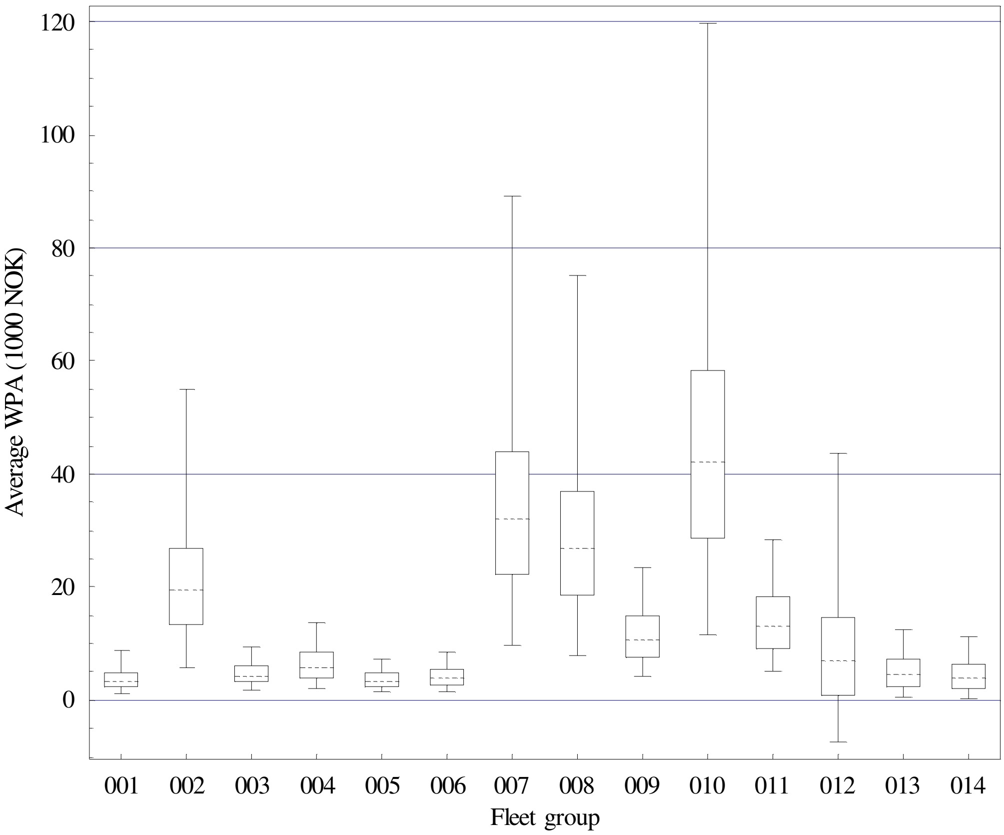

***Figure 2**. Box-whisker plot of calculated quarterly WPA per day per employee of each fleet group over the period 1946-2004 based on EconSimp2000 production equations and year 2000 prices and costs (from Anon., 2000). The WPA values are in 1000 NOK. The fleet numbers refers to Table 2.*

Quarterly economic performance of each vessel could be expressed by wage paying ability (*WPA*), in the *EconMult* model described by

$$WPA(X,E,N) = -fc - vc_E E + \sum_y (p_y - vc_h)\, h_y\,(X_y, E, N),$$

summing up revenue and cost of the fishing activity. The first term (*fc*) is the quarterly fixed cost, while the second term represents the unit cost of fishing effort (fishing days, *E*). The third and last term sums up net revenues from the catches of all cod year classes when including the size (age) specific price *p* and unit costs of harvest. The term *wage paying ability* refers to the definition made in Anon. (2000); not including cost of labour, as labour cost is covered by the share of *WPA* allocated fishers (Turvey, 1964).The equation above represents vessel *WPA*. Total *WPA* of a fleet is the vessel *WPA* multiplied by the number of vessels, *N*, assuming homogenous vessel within each group. Average *WPA* (*R*) at time *t* is in this study defined by

$$R_t = \frac{WPA(X_t, E, N)}{S\,E},$$

S being the average number of employees of one vessel in the group (see Table 2). *R* is considered being a proxy of economic performance.

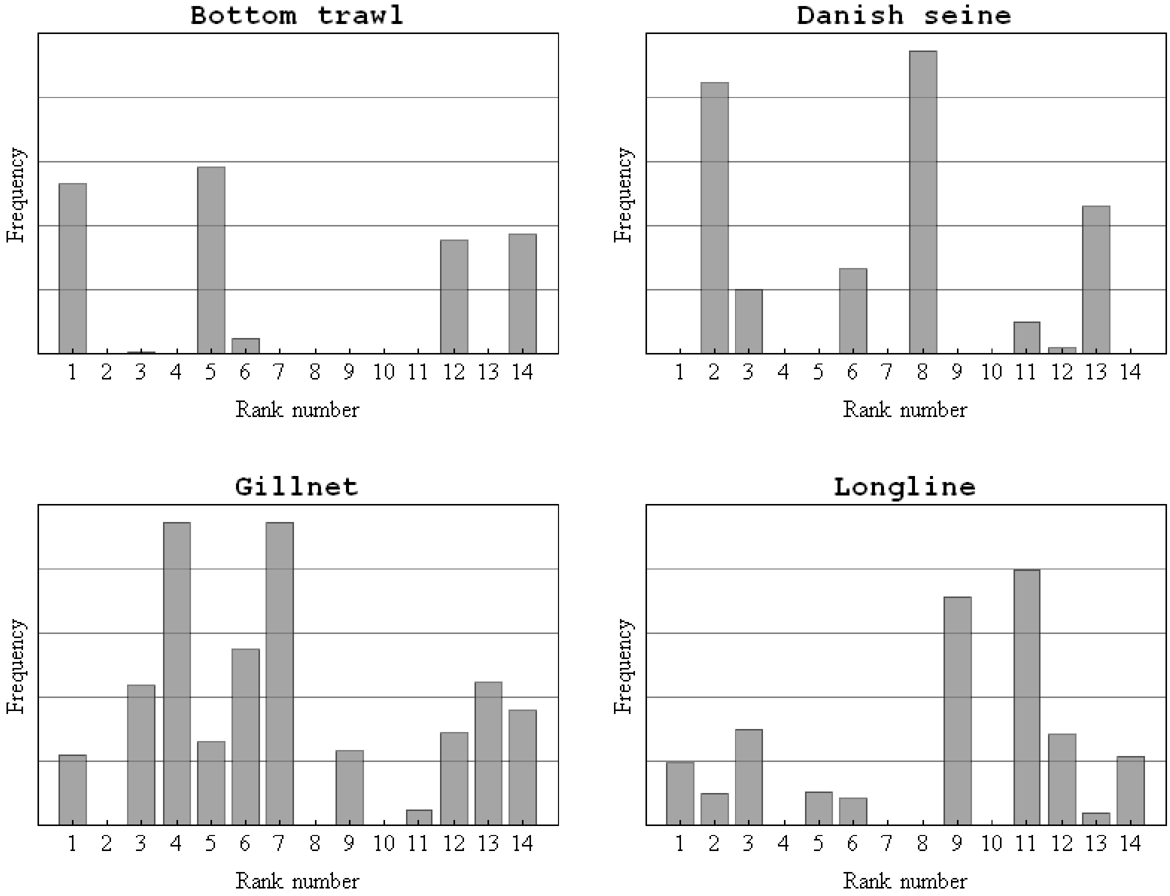

Figure 3. *Frequencies of ranking in calculated WPA performance in 14 vessel groups (Table 2) ordered by type of fishing gear, for the period 1946-2004.*

Seasonal profiles caused by spawning and feeding migration also cause similar seasonal profiles in the fleet activities. The seasonal profile of cod stock abundance estimated in Paper I is used in the *WPA* calculations presented here.

Per vessel *WPA* per fisher (*R*) is presented in Figure 2, while Figure 3 shows the frequency of how different vessel within four gear groups is ranked in terms of economic performance (*R*) over 236 quarters (during the period 1946-2004) between the 14 vessel groups. As seen from Figure 3 there is no type of fishing gear with significantly better performance than others in this period. In fact bottom trawl, long line and gill net all have been in both ends of the scale several times during the period.

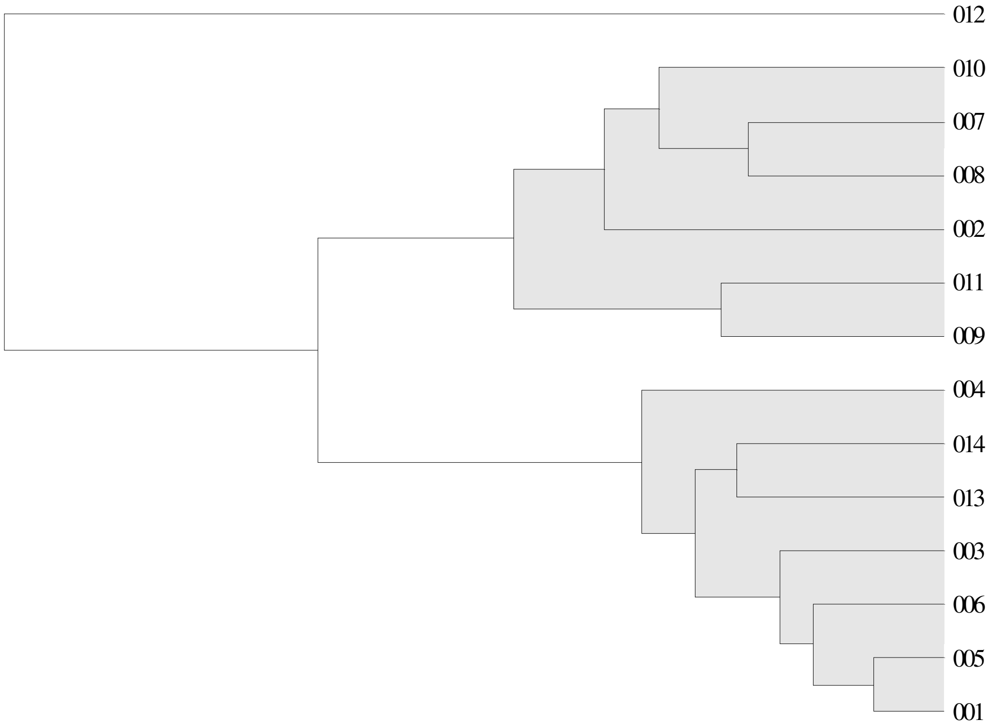

Figure 4*. Dendrogram clustering the fleet groups with the closest calculated WPA profiles over the period 1946-2004. The shaded clusters indicate two 3-level relations. The fleet numbers refers to Table 2.*

Group clustering over the period (1946-2004) is displayed as a dendrogram showing two strong clusters of several groups and one unique fleet group (group 012) in Figure 4. The bottom multi-group cluster contains groups with less variation in *R*, while the other shows higher variability (see figure 2). The unique group 012 is a group participating in the cod fishery, but specialised for other fisheries, and occurrences of negative *R* in this group may indicate a weaker dependency of income from the cod fishery.

A recurring discussion regarding the Norwegian cod fishery is whether trawlers or the conventional fleet is the most efficient. Based on the calculations presented above (Figure 3) the answer depends on the situation. Table 3 shows the most cost efficient each quarter over the period, in terms of highest *WPA* per fisher per fishing day, the shaded cells representing trawlers and the other conventional vessel groups.

Table 3. *The table shows the most cost efficient fleet group in terms of average WPA each quarter over the period 1946-2004. The fleet numbers refers to Table 2.*

Year	**Quarter**				**Year**	**Quarter**			
	1	**2**	**3**	**4**		**1**	**2**	**3**	**4**
1946	013	013	013	013	1976	011	012	013	013
1947	013	013	013	013	1977	012	012	013	013
1948	013	013	013	013	1978	011	012	014	014
1949	013	013	013	013	1979	011	011	014	013
1950	013	013	013	013	1980	011	011	014	013
1951	013	013	013	013	1981	011	011	014	014
1952	012	013	013	013	1982	011	011	014	014
1953	011	011	013	013	1983	011	011	014	013
1954	011	012	012	012	1984	011	011	013	013
1955	012	012	012	012	1985	011	011	013	012
1956	013	013	013	013	1986	011	011	012	012
1957	014	014	014	014	1987	011	011	012	012
1958	014	014	014	014	1988	011	011	013	013
1959	012	012	013	013	1989	011	011	014	014
1960	011	012	013	013	1990	011	012	014	014
1961	012	013	013	013	1991	012	013	014	014
1962	011	011	013	013	1992	011	012	014	014
1963	010	011	013	013	1993	010	010	013	013
1964	011	011	014	014	1994	010	010	013	013
1965	011	011	014	014	1995	010	011	013	013
1966	010	011	014	014	1996	012	012	013	013
1967	010	010	013	013	1997	013	014	014	014
1968	010	011	012	012	1998	011	012	014	014
1969	012	012	013	013	1999	011	011	014	013
1970	013	013	013	013	2000	011	011	013	013
1971	014	014	014	014	2001	010	010	013	013
1972	011	011	014	014	2002	010	011	013	013
1973	010	010	013	012	2003	011	012	013	013
1974	010	010	012	012	2004	012	014	014	014
1975	010	010	013	013					

The results reflect the economic importance of taking into consideration diverse fleet structures covering vessels with different properties, when the overall efficiency in fishing activities is investigated. It also demonstrates the potential problem of management means reducing this diversity towards a more homogenous fleet structure, as the overall profitability in the long run may suffer even though the homogenous fleet during a specific period happened to be the most cost efficient.

Modelling the Barents Sea ecosystem and fisheries

The Barents Sea ecosystem is described in some details in several of the papers included. At the first look the system seems comprehensible, being dominated by a few fish species. The species and year classes within each species relate to each others in complex and dynamic relationships as prey, predators and competitors; within and between species. Seasonal and annual fluctuations add yet another significant challenge for those attempting to a model the ecosystem. Within and between year fluctuations in sea currents, temperature, primary production, recruitment, migration pattern and other important factors, including intricate time lag effects, place the modeller into an environment of extreme complexity combined with significant uncertainties. The current precautionary approach management system represents one way to address such problems, defining core indicators in terms of confidence intervals representing overall uncertainty. But also the choice of indicators may be distorted in relation to the management objectives and the usefulness of indicators may be a function of the system dynamics.

Nevertheless there is a need for good models to provide the managers with useful tools. The only criterion of a '*good*' model is that it is '*useful*' in enlightening or solving a specific '*problem*'. Simple models of complex matters are considered being good models if they are useful for answering specific research or management questions. At the same time these models could be less useful (less good) for other purposes. In that sense the important first step of constructing a *good* model is to identify and clearly express the *problem* to be investigates. The papers constituting this thesis therefore make use of different models as the research problems are different in the different papers; different modelling perspectives and techniques are adapted due to the different research questions presented.

The combined AggMult/EconMult model (EconSimp) in particular demonstrates this view, as both the ecosystem model (AggMult) and the fleet model (EconMult) really are meta-models, covering infinite numbers of model resolutions, controlled by structural variables (time step, fleet number, number of species, number of age groups within each species). A more detailed description of the structural variables is found in Eide and Flaaten (1998). The concept of structural variable represents an attempt to facilitate different types of model setups to investigations various problems by applying the same meta-model.

Paper I is a study aiming to parameterise one of the production functions of EconMult. A unique data set was prepared and the results are largely in line with other similar, though few, studies. The seasonal pattern and parameter values of the trawler production function are implemented in the three next studies, paper II-IV. All the three papers utilise EconSimp to study climatic change issues. The papers relate to each other and apply more or less the same model resolution (see Table 4 for details). Two of the papers (II and III) investigate simulation result over a certain period from different environmental scenarios combined with a number of management regimes. Paper II only covers standard input and output regulation (fishing effort and *TAC*) in addition to open access (absence of management), while paper III also includes *HCR* facilitating precautionary approach management.

While the applied models in paper III and IV are updated versions of AggMult and EconMult, the model used in paper II, EconSimp2, is an older version of the combined model. The new version among other things includes a temperature variable in the biological growth model (AggMult), not available at the time paper II was written. Biological growth effects caused by global warming in paper II therefore are calculated on the basis of single-species studies, implemented directly through growth parameters in AggMult. The use of a temperature variable in the newer papers reveals unexpected growth consequences by climatic change. These differences are discussed further in paper III and contradict to some extent some growth assumptions used in paper II. The interaction between the different species could not be adjusted for in the single-species studies, which probably is the reason of the seemingly inconsistence between modelled growth in the newer papers and pre-calculated growth rates of the earlier.

Open access to a common-pool cod stock resource serves in most of the papers as a standard reference to different types of management regimes. Climatic conditions naturally affect growth patterns in the fish stock, but significant within and between years fluctuations are normal in the Barents Sea area, having impact on all fish species included. Natural stock biomass fluctuation in the cod stock seems to increase by higher temperatures. The reasons may be found both in changes of growth pattern in the capelin stock as well as in cod stock recruitment dynamics and cannibalism. Combined with fleet entry/exit dynamics which is controlled by economic factors, the fluctuations are amplified by varying fishing effort, reaching quite high fishing pressure levels in the peaks. Stock biomass fluctuations which are strengthened by open access dynamics cause not only critical low biomass levels, but also create extreme peak biomass levels. Given that the possibility for the fleet to exit the fishery at a certain rate based on opportunity cost considerations, the economic gain during the peak periods outreach loss during the poor periods according to what is found in paper III, also confirmed by the findings of paper IV. There is however costs related to the risk of frequent critical biomass levels which are not counted for in these calculations. Still it is an intriguing observation to see that the management regime which comes out with the highest present value and also profits (in average) over the simulation period actually is no management at all (open access). This being caused by slowness in economic fleet dynamics combined with rather quick changes in stock biomass, as if the fleet is running after the stock, reflecting previous stock levels rather than being able to immediately correct according to current biomass situation. The fleet then is not able to fully take advantage of the peaks, as well as it is not completely managing to exit at the same rate as the stock is collapsing either. In average still it seems to perform better that rather sophisticated sets of dynamic management rules. The idea of really aiming to take advantage of rich periods by pulse fishing as indicated by Hannesson (1975) seems to fit very well with this observation.

Table 4. *Key model elements of the seven papers, referring to the biological and fleet properties of the models.*

Paper	Modelling approach	Stochastic component	Physical Environment	Biomass distribution	Space/area distribution	# of fish species	# of cohorts	# of fleets
I	Statistical	None	Constant	Observed	Yes (data) No (model)	1	13 (in data)	1
II	Numeric simulations	Herring recruitment	3 scenarios defined by biological growth rates	Seasonal variation in abundance	No	3	18 (10+3+5)	28
III	Numeric simulations	Herring recruitment	3 scenarios defined by average temperatures	Seasonal variation in abundance	No	3	18 (10+3+5)	18
IV	Monte Carlo simulations	Herring recruitment	Remo 5.1/SinMod physical environment and primary production	Seasonal variation in abundance	No	3	18 (10+3+5)	18
V	Cellular automata modelling	None	Pseudo-random	Spatial diffusion	Yes	1	1	1
VI	System of differential equations	None	Constant	None/ Observed	No	1	2	1
VII	System of difference equations	None	Constant	None/ Observed	No	1	2	1

Paper V presents a simulation model of a quite different kind. Cellular automata (*CA*) models now cover most all areas of modelling and the expansion since the first publications arrived in the 1980s has been tremendous. An informal study presented in Table 5, where simple search strings have been evaluated through two types of search engines, illustrates this. A general search on the term '*Cellular automata*' gives more than 70% of the number of hits found by the term '*Fisheries management*' and more than twelve times as much as the term ‘*bioeconomics’*. Google scholar hits reflect more or less the same pattern, illustrating that cellular automata modelling already is a well-established modelling approach, covering a wide range of different topics. CA modelling represents a method of constructing global models determined by micro dynamics, here represented by simple rules describing how a cell develops. The rules include simple interactions between neighbouring cells which in the long run may construct complicated patterns of state variables in the cells. There is no method to uncover the simple rules behind the complex pattern from studying the resulting pattern.

Table 5. *Results of an arbitrary web search performed on May 4 2008.”New kind of Science” is the title of Stephen Wolfram’s monumental work in 2002 (cited in paper V), where cellular automata motels are discussed excessively and described in details. The other three terms search for are well known terms and expressions from fisheries modelling. Two search engines have been used: Google web search and Google scholar search, the latter targeting academic publications.*

Search string	**Google search hits**	**Google scholar hits**
“bioeconomics”	57,500	4,920
“natural resource economics”	272,000	37,300
“fisheries management”	1 020,000	93,800
“New kind of Science”	133,000	2,520
“Cellular automata”	730,000	43,100

The motivation of including *CA* modelling here is however not to search for hidden rules. The *CA* models of paper V serve as simple 2D models in order to study the micro level impact from *MPA* regulations without the cost of a large scale modelling effort and still being able to cover area distribution, not only two biomass components as proxies for this. The simple *CA* models presented could easily be developed to 3D models covering several species and fleet diversity. The fleet distribution is of particular interest, as different rules of fleet distribution proves to cover a large probability area of stock biomass development and fleet performance, even when utilising the same total fishing effort. This is discussed in further details in paper V.

Areas closed for fishing appears under many different labels: Marine reserves, marine parks, closed areas, marine sanctuaries and marine protected areas. The latter represents a group of different levels of protecting, from the marine sanctuaries to only minor restrictions on fishing. An early contribution by Crutchfield (1961) closed areas are discussed briefly as an alternative method of regulating fisheries. It is stated that “area closures would have little or no effect unless they reduce efficiency by forcing the fleet to incur higher costs in reaching open areas”, given the basic assumption that fish migrate freely over the entire area. The model presented in paper V does not necessarily make use of this assumption, as migration only is defined between neighbouring cells. Over many cell evaluations, given that the live span of individuals, range of neighbouring cells and total number of cells allow it, in principle fish migrate freely over the whole area.

Paper VI and VII are related to each other, as paper VII is a discrete time version of the problem investigated by a continuous time cannibalism model in paper VI. The stage-structured cannibalism model (paper VII) does not include economics apart from what is indirectly reflected in the dataset (representing cod catch history) used in the case study. The economic analysis of the data set is placed in paper VI, where stability properties and reference equilibriums are identified.

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