Economic impacts of changes in fish population dynamics: the role of the fishermen's harvesting strategies

Working Paper FNU-50

P. Michael Link [a,b,c], Uwe A. Schneider [b,d] & Richard S.J. Tol [e,f,g]

[a] Research Group Climate Change and Security, KlimaCampus Hamburg, Hamburg University, Hamburg, Germany
[b] Research Unit Sustainability and Global Change, Center for Marine and Atmospheric Sciences, Hamburg University, Hamburg, Germany
[c] International Max-Planck Research School on Earth System Modelling, Hamburg, Germany
[d] International Institute for Applied Systems Analysis, Laxenburg, Austria
[e] Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands
[f] Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA
[g] Economic and Social Research Institute, Dublin, Ireland

Correspondence to P.M. Link:
Tel. +49 (40) 42838-7719
Fax +49 (40) 42838-7721
eMail: michael.link@zmaw.de

Abstract

Using a bioeconomic model of the cod (*Gadus morhua*) and capelin (*Mallotus villosus*) fisheries of the Barents Sea, this study assesses the role of the fishermen's behavior in reducing or intensifying the effects on the stocks caused by altered population dynamics. The analysis focuses on the economic development of the fisheries employing a coupled stock size-hydrography based fishing strategy, which attempts to maximize returns from fishing over a given number of fishing periods. Results show that if the fishing strategy is based on a short optimization period of only two fishing periods, changes in population dynamics have a direct influence on the returns from fishing due to the strong pressure on the stocks applied by the fisheries. If the strategy is based on a longer optimization period, fishing activities may be deferred to allow for stock regrowth, which improves the economic performance of the fisheries. However, in that case the relationship between population dynamics and fishing activities becomes less clear, as even a reduction of the carrying capacities of the two species allows for an increase in the amount of fish landed without causing a stock collapse due to an increased efficiency of fleet utilization. The simulations indicate that management considerations and the time horizon of the fishing strategy dominate the influence of altered population dynamics on the development of the stocks considered in the model.

Key words

bioeconomic modeling, Barents Sea, cod, capelin, population dynamics, fishing strategy

1 Introduction

Changes in the population dynamics of fish can be brought about by altered environmental conditions that are a consequence of climate change. Shifts in temperature, salinity, or oxygen content have a direct influence on the reproductive success of fish species. A change in hydrographic conditions caused by global warming, together with a possible weakening of the thermohaline circulation (THC), will affect recruitment success and the overall development of the Arcto-Norwegian cod (*Gadus morhua*) and capelin (*Mallotus villosus*) stocks in the Barents Sea. This in turn will have an influence on the economic exploitation of these fish populations.

Unfortunately, fishing strategies are usually determined on the basis of short-term considerations of stock development and on bioeconomic models that cover only a few years. In such analyses, environmental conditions are constant and only economic aspects are allowed to vary. However, some long-term environmental effects on the stocks can be quite substantial and should be considered when fishing strategies are determined.

The model used in this assessment integrates long-term trends in population dynamics in a bioeconomic model covering the two most important fish species in the Barents Sea. Since environmental change influences the stocks on a much longer timescale than the economic exploitation, it is necessary to extend the overall simulation period of the model to appropriately capture any changes in hydrographic conditions. On the other hand, it does not make sense to consider the entire simulation period at once in the bioeconomic assessment. Thus, a dynamic recursive approach is applied. The best fishing strategy is determined for a limited period of time. This strategy is implemented for the first time step, after which the actual economic and environmental developments are considered and an updated fishing strategy based on the altered conditions is obtained.

The hydrographic conditions in the Barents Sea have an effect on the population dynamics of the two species covered in the model. Recruitment success of cod in cold waters such as the Barents Sea increases with warmer average water temperatures (Nilssen *et al*., 1994; Ottersen *et al*., 1994; Planque & Frédou, 1999; Eide & Heen, 2002; Hannesson, 2007), while there is no trend in the temperature-recruitment relationship in temperate waters (e.g. near Georges Bank off Canada) and a negative trend in warm waters such as the North Sea or the Irish Sea. The Russian fleet would be the prime beneficiary of an expansion of the Arcto-Norwegian cod stock in the Barents Sea (Stenevik & Sundby, 2007), but this may be beneficial to the Norwegian bargaining position (Hannesson, 2006), since less emphasis has to be placed on stock conservation.

While climate change induced warming has positive implications on fish stock development in the Barents Sea, the impact of reduction in the ocean circulation is negative (Eide & Heen, 2002). The effects of these two opposite influences on the major fish stocks in this region are addressed in Link and Tol (2009). In the current study, we assess whether changes in management or changes in the environment have a greater influence on the long-term development of the commercial fish stocks in this region. To this end, we extend the earlier model of Link and Tol (2006) with explicit fishing behavior, as recommended by Salas and Gaertner (2004).

Vellinga and Wood (2002) show that average temperatures over the North Atlantic drop considerably if the THC were to weaken or shut down completely. This has significant implications on marine and terrestrial ecosystems throughout Northern and Western Europe. The overall consequences of such substantial environmental changes are addressed by Kuhlbrodt and others (2009).

In the Norwegian Sea and the Barents Sea, a reduced THC results in a reduced availability of plankton, which is an important food source for many fish species (Skjoldal *et al.*, 1992). Furthermore, survival chances of cod larvae are likely to decline because of less favorable drift trajectories (Vikebø *et al.*, 2005). Lower biological productivity leads to smaller stocks and can even cause complete stock collapses, especially if the stocks are commercially exploited. For example, the Barents Sea capelin stock collapsed after a shift in temperature in the 1980s (Jennings & Kaiser, 1998). The cod stock was small in that period as well, but increased again after the surge in capelin availability in the late 1980s.

Besides the environmental conditions, the fishing strategies applied by the fishermen have a considerable influence on the development of the commercially exploited fish species. The choice of an appropriate fishing strategy by individual fishermen ultimately determines the success of large-scale management strategies. According to Lane (1988), short-term considerations of fishermen often focus on the improvement of their individual position within the fishing fleet, while in the long run the preservation of the stock plays a more important role. The objective of a profit maximizing stock size-hydrography based fishing strategy is more applicable in industrial than in small-scale fisheries (Robinson & Pascoe, 1997).

Steinshamn (1998) analyzes the influence of the fishing strategy on biomass levels and their variability for different durations of reproductive cycles and different degrees of stochastic fluctuations in stock size. Results indicate that for short recruitment cycles, the greatest biomass stability is attained with a constant catch strategy. For long recruitment cycles, constant escapement strategies yield the best results. A particularly unstable and highly variable development of a fish stock can cause fishermen to refrain from the objective of profit maximization and to turn to cost-covering instead (Chaboud, 1995). Johnston and Sutinen (1986) show that the risk of a stock collapse due to environmental change increases the speed of optimal exploitation of the stock, regardless of whether or not fishermen could turn to a replacement species if necessary.

Depending on the strategy chosen, anthropogenic fishing regimes can intensify or alleviate the consequences of the environmental change for the population dynamics. In Link & Tol (2006), we assessed the impacts of changes in population dynamics of the Barents Sea fish stocks if the fishermen follow adaptive fishing strategies, i.e. the fishermen determine the extent of the fishing effort based on the economic result of the previous fishing periods.

This study analyzes the economic development in situations of reduced reproductive success of the Barents Sea cod and capelin stocks for a combined stock size-hydrography based approach of the fishermen, i.e. effort levels are determined solely on the basis of reaching the maximum possible economic returns from fishing over a specified number of fishing periods. Fishing activities have to remain within the limits of fisheries management advice. This corresponds to the current management scheme of the Barents Sea fisheries: there is a total allowable catch (TAC) for both species, but within this limit the fleets compete for the resources.

2 The model

The consequences of changes in fish population dynamics described in the previous section can be observed using a long-term bioeconomic model. In the following, we apply a long-term age-structured model of Arcto-Norwegian cod and capelin in the Barents Sea and their fisheries and assess the economic impacts of altered population dynamics as they might occur in the wake of modifications in hydrographic conditions that are induced by global climate change. This model setup is used since it allows the inclusion of interactions between the two species in question as well as constraints on the fisheries imposed by management measures.

In general, bioeconomic models of fisheries assess the magnitude of returns from fishing in a variety of scenarios with different economic conditions. Environmental conditions are usually considered to be constant, a reasonable assumption if the simulation period covers only a few years or decades. The model used in this study covers a time period of one century to allow population dynamics of the fish species to change in response to environmental change.

At the midpoint of each simulation, a change of the biological productivity of both species and/or a reduction of the species' carrying capacities sets in, linearly adjusting to a new level of the respective variable over two decades. Such shifts may occur if there are large-scale changes in hydrographic conditions, e.g. after warming of the Barents Sea or a shutdown or considerable weakening of the THC. Since such shifts would take a long time to reverse, we assume that the fish population dynamics remain in the altered state for the remaining three decades of the simulation period.

The cod stock is exploited by two competing vessel types, trawlers and coastal vessels. Since the purse seine fishery is the dominating form of capelin fishery, only this vessel type is considered here. Both stocks are jointly managed by Norway and Russia, but we do not distinguish between fishermen.

A fishing period is one year. For reasons of comparability of the scenarios, inter-annual stochastic variability of recruitment success and of the survival rates of the individual age classes are disregarded. Variables concerning the development of the stock size and the economic exploitation of the two species are determined for each fishing period. The scenarios are compared to a reference case, in which the population dynamics remain unaltered. In addition, sensitivity analyses using the reference scenario are conducted to determine the influence of changes in key parameters on the simulation results. These quantities are the share of capelin devoted to human consumption, the discount rate, and the rate of technological progress.

A dynamic recursive approach is utilized to link the long-term scenarios of environmental change to the short-term economic planning horizons: The sets of fleet utilizations, which yield maximum profits for a given optimization period, are determined for all vessel types based on the given stock sizes, population dynamics, and management constraints. The optimal fleet utilization for the first fishing period is applied and the stock information is updated accordingly. The next optimization is then performed after the actual developments of the fish stocks and the environmental conditions have been accounted for.

2.1 Population dynamics of cod and capelin

The model distinguishes 15 age classes for cod and 5 for capelin. The number of individuals in each age class and the stock biomass at the beginning of a fishing period are known. In each fishing period, the number of fish is reduced by fishing. Due to the predator-prey relationship between the two species, the number of capelin (Eq. 2.1) is further reduced afterwards (cf. Moxnes, 1992).

$$B_{cap,t}^{pred} = \frac{\iota D_{cap}^{\max} B_{cod,t}^{harv}}{1 + \left(D_{cap}^{\max} - 1\right)\left(\frac{B_{cap,t}^{harv}}{B_{cap}^{std}}\right)^{-\gamma}} \qquad (2.1)$$

Predation depends on the maximum prey density of capelin D^{max} and the stock biomasses B of the two species after economic exploitation. Another consequence of predation is the weight increase of cod (Eq. 2.2, cf. Magnússon & Pálsson, 1991), which depends on the amount of capelin consumed. The larger the share of capelin in the cod diet, the larger the weight increase of the predators. The average capelin weight-at-age is assumed constant.

$$(2.2) \qquad w_{cod,a+1,t+1} = w_{cod,a,t} + \widehat{w}_{cod,a} \left(\frac{D_{cap}^{\max}}{1+\left(D_{cap}^{\max}-1\right)\left(\frac{B_{cap,t}^{harv}}{B_{cap}^{std}}\right)^{-\gamma}} \kappa + \left(1-\kappa\right) \right)$$

Recruitment adds to the lowest age class and depends on the spawning stock size SSB at the end of the fishing period. The number of recruits (Eq. 2.3) is determined by using a Beverton-Holt recruitment equation (Beverton & Holt, 1954), which is commonly used in age-structured models of the Barents Sea fish stocks.

$$(2.3) \qquad R_{s,t} = g_{s,t} \frac{\alpha_{s,t} SSB_{s,t}}{\left(1+\beta_{s,t} SSB_{s,t}\right)}$$

The parameters are set such that in the reference scenario the carrying capacities are 6 million tons for cod (Sumaila, 1997) and 10 million tons for capelin. They are updated after each fishing period based on a procedure by Clark (1990) that relates these parameters to the carrying capacity and reproductive potential. Thus, changes in these fundamental stock properties can be linked to recruitment success and therefore to the development of the stock over time. The age classes at the beginning of the next fishing period consist of the surviving individuals n of the next younger age classes in the previous year (Eq. 2.4). Cod older than 14 years accumulate in the 15+ age class.

$$(2.4) \qquad \begin{aligned} n_{s,1,t+1}^{init} &= R_{s,t} \\ n_{s,a+1,t+1}^{init} &= \chi_{s,a} n_{s,a,t}^{harv/pred} \\ n_{cod,A,t+1}^{init} &= \chi_{cod,A} n_{cod,A,t}^{harv} + \chi_{cod,A-1} n_{cod,A-1,t}^{harv} \end{aligned}$$

In each of the 100 year simulations, a change in biological productivity g or the environmental carrying capacity K sets in at year 50. Such changes can be triggered by altered environmental conditions in the ocean, like shifts in temperature regimes near the spawning grounds or in regional circulation patterns. During the next two decades, these quantities increase or decrease to a new level, at which they remain for the remainder of the simulation period. It is assumed that the change is of the same magnitude for both species. Changes in g reduce or increase the number of recruits of each species (Eq. 2.3) while changes in K influence the parameters α and β and thus have an impact on recruitment success and therefore on stock development as well.

2.2 The fisheries

Both fish species are economically exploited throughout the simulation period. For each fleet engaged in fishing activities, the number of fish caught h (Eq. 2.5) is used to determine the weight of the entire catch in each fishing period.

$$h_{s,i,a,t} = q_{s,i,a,t} n^{init}_{s,a,t} v_{s,i} e_{s,i,t} \quad (2.5)$$

where q denotes the catchability coefficient, v the number of vessels, and e is the fleet utilization, which is measured as a percentage of the fishing period, in which the vessels are actually engaged in fishing activities.

$$P_{s,i,t} = \zeta_s + \eta_s \sum_{s,a} h_{s,i,a,t} w_{s,a,t} \quad (2.6)$$

Market prices P of both species are adjusted for purchasing power parity and depend linearly on the amount of fish landed (Eq. 2.6), with ζ denoting the unit price of each species and η the rate of price change with respect to catch size. A fixed portion of capelin is sold for human consumption at a higher price while most of the catch is used for the production of fish meal and oil: Here, we use a weighted average that is slightly above the capelin price for industrial use.

$$\pi_{i,t} = r_{i,t} - v_{i,t}\psi_{i,t} = \sum_{s,a} P_{s,i,t} h_{s,i,a,t} w_{s,a,t} - \left(\varphi_i + e_{i,t}\theta_i\right) \quad (2.7)$$

In each fishing period, profits of each fleet π reflect the difference between revenues from sales of landings r and the total cost of fleet operation Ψ (Eq. 2.7). Total costs consist of fixed costs for fleet maintenance φ, which are independent of fleet utilization, and variable costs θ directly related to the extent of fleet utilization. As the unit costs per vessel adjusted for purchasing power parity do not vary extensively, it is assumed that they remain constant during the simulations.

$$\Pi_i = \sum_{t=t_0}^{t_0+14} e^{-\delta(t-t_0)} \pi_{i,t} \quad (2.8)$$

While harvest activities occur in all fishing periods throughout the entire simulation, we specially focus on the profits from fishing in three different time periods of 15 years (the average lifetime of a vessel): the period 30-44 years (i.e. a time period before the change in population dynamics), 50-64 years (i.e. the time period revealing short-term impacts of the change in population dynamics), and 70-84 years (i.e. a time period in which long-term impacts of changes in population dynamics become evident). Within each period of interest, profits are discounted at a rate δ (Eq. 2.8) relative to the beginning of the particular time period. This is done because economic impacts in the immediate future are of greater concern to the fishermen than challenges in more distant years. Assuming the length of a generation to be approximately 20 years, the focus on the three different periods of interest resembles a comparison of different generations of fishermen that each has their own economic considerations. Therefore, it is necessary to consider all periods of interest separately (cf. Sumaila & Walters, 2005; Frederick, 2005). In each optimization period, the control variable is the fishing effort. The economic exploitation of the fish stocks is limited by stock size, population dynamics of the two species, and management constraints imposed on the fisheries.

2.3 The fishing strategies of the fishermen

The assessment in this study considers the situation, in which fishermen attempt to maximize profits over a given number of fishing periods. The length of the optimization periods is specified prior to the simulation. Two different durations are used in the simulations: two years and five years. An optimization period of two years is the situation, in which the fishermen are sure that their fishing license will be withdrawn in the near future, or that their vessel is depreciated and they have decided to retire. This strategy has an entirely short-term focus, in which long-term considerations such as sustainable stock development etc. play no role. With a five-year optimization period, there is a reasonable certainty that fishing will be allowed for some time, which makes the objective to obtain the highest possible returns over a period of several years into the future more appropriate.

In order to protect the stocks from overfishing, regulatory management measures are also considered: Based on catch data and TAC levels in recent decades (Statistisk Sentralbyrå, 1980-2004), harvest activities of the respective fisheries in the model cease if the cod and capelin stock biomasses fall below 500 000 tons or 1 million tons respectively. Above these thresholds, the TAC is assumed to be 35% of the stock biomass for cod and 50% for capelin. These limits are based on data of stock sizes and catch quotas in the past decades. Since the regulatory management measures of the cod stock affect both trawlers and coastal vessels, profits for these vessel types are maximized jointly. Profits from purse seiners used in the capelin fishery are considered separately.

We assume perfect information about the current state of the stocks, i.e. the stock sizes and age distributions of both species at the beginning of each fishing period are known to the fishermen. As the individual optimizations cover very short time periods compared to environmental change, environmental conditions and therefore population dynamics are assumed to remain stable within each individual optimization cycle.

Because of the long simulation period of a whole century, it is necessary to allow the number of vessels involved in fishing activities to vary depending on the economic success. Therefore, fleet size is included in the model as endogenous variable. If marginal profits are positive, economic exploitation of the stock is increased, and the number of vessels rises. The number of new vessels depends on the expected increase in profits from fishing and the investment costs for new ships. In contrast, if marginal profits are negative, vessels are decommissioned to cut costs and the fleet size is reduced accordingly. In addition, technological progress of fishing techniques also has to be considered. Data show that technological progress in fisheries is actually not continuous and hard to forecast (Hannesson, 2005). In the simulations, progress in fishing productivity is approximated by a steady increase of the catchability coefficient of 0.5 % per year while the cost per unit effort remains unaltered. This accounts for the fact that progress occurs, without necessitating a prediction of individual large leaps in fishing technology.

3 Results

Simulations with varying degrees of improving or deteriorating productivity and/or carrying capacities were conducted to assess the consequences of changes in fish population dynamics on the fish stocks and the resulting economic impacts. The initial stock sizes are based on the average number of individuals in each age class during the time period from 1983 to 2002 for cod (ICES, 2003a) and capelin (ICES, 2003b). The simulations use the same parameterizations as the analyses in Link & Tol (2006) and Link & Tol (2009).

The economic consequences of changes in population dynamics are assessed under the assumption that all fleets determine their respective fishing effort based on a maximization of economic returns over two or five years, applying a constant discount rate of 7%. This rate is generally used in modeling assessments of the Norwegian cod fishery. In each fishing period, a set of fishing efforts is determined that yields the best economic result for the whole optimization period within the given limits of fisheries management. Also, it is assessed whether new vessels should be added to the fleets or old vessels should be decommissioned. The optimal efforts are used to calculate the landings and returns from fishing. Afterwards, the actual development of the fish stocks, which is based on the given environmental conditions, is considered. This provides the updated information on the resources, so that the extent of harvest activities in the next fishing period can again be determined by optimization, this time with the optimization period shifted forward in time by one year.

3.1 Impacts of a change in biological productivity

A change in biological productivity of both species has a more pronounced long-term impact on the capelin stock than on cod. The average cod stock size before the change in population dynamics varies around one million tons of biomass for an optimization period of two years. Depending of the extent of change in productivity, the stock biomass is sometimes reduced to roughly 600 000 tons. However, even for a significant reduction in productivity, the stock size remains close to the reference scenario. For a longer optimization period, only a strong decline in productivity produces a long term downward deviation in stock size compared to the reference scenario. On the other hand, improved productivity may very well lead to a considerably higher standing stock biomass which is the basis for improved economic exploitation of the stock (Fig. 1).

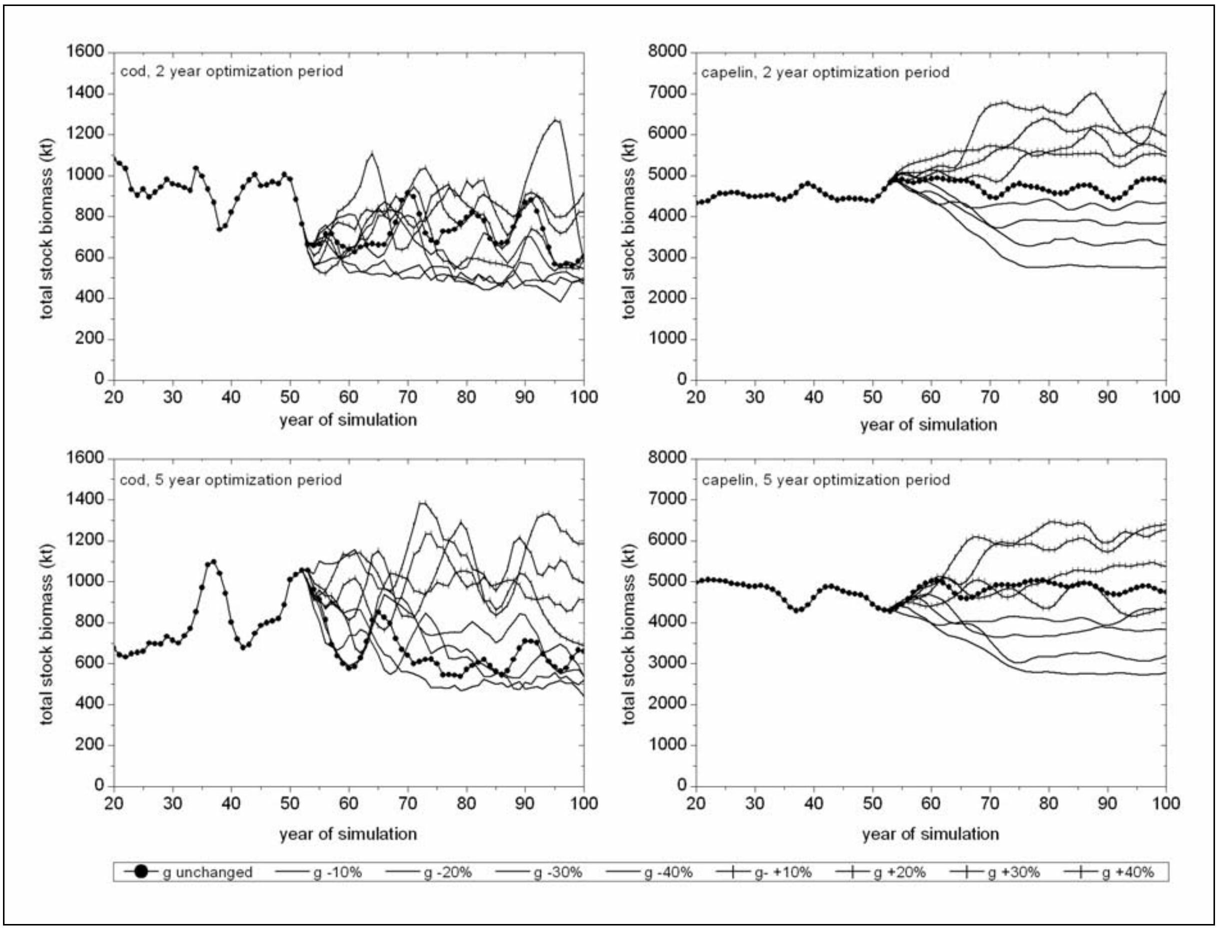

Figure 1. Development of the stock sizes with altered biological productivities.

The development of the capelin stock size is more directly affected by changes in population dynamics than cod. In case of deteriorating productivity, the stock size declines, while it expands if productivity improves (Fig. 1). Fluctuations in predation and catches by the fishermen have only a slight impact on the stock, at least if the fishermen follow a short-term fishing strategy. For a longer-term fishing strategy, the positive influence of an improved productivity on the stock size is offset by increased losses due to predation, so that a substantial improvement of population dynamics is necessary to have a notable influence on the stock size.

time period, change of biological productivity	**trawlers** (cod)		**coastal vessels** (cod)		**purse seiners** (capelin)	
	average annual catch (1000 t)	change from reference scenario	average annual catch (1000 t)	change from reference scenario	average annual catch (1000 t)	change from reference scenario
2-year opt.						
years 30-44	145.2		42.9		1443.4	
years 50-64						
g +40%	131.9	-8.0%	63.7	119.0%	1616.2	-0.7%
g +30%	140.7	-1.9%	16.9	-41.9%	1782.8	9.5%
g +20%	134.2	-6.4%	34.9	20.1%	1651.4	1.4%
g +10%	136.7	-4.7%	24.7	-15.0%	1642.9	0.9%
g	143.4		29.1		1628.1	
g -10%	118.1	-17.7%	27.9	-4.0%	1606.0	-1.4%
g -20%	133.3	-7.1%	31.9	9.8%	1506.1	-7.5%
g -30%	134.1	-6.5%	23.1	-20.5%	1559.4	-4.2%
g -40%	133.3	-7.0%	25.2	-13.5%	1523.7	-6.4%
years 70-84						
g +40%	174.6	70.9%	29.0	-40.1%	2147.8	42.4%
g +30%	169.9	66.3%	23.7	-51.2%	1955.8	29.7%
g +20%	146.1	43.1%	31.6	-34.7%	1825.0	21.0%
g +10%	152.9	49.7%	14.2	-70.6%	1817.9	20.5%
g	102.2		48.4		1508.5	
g -10%	91.8	-10.2%	41.0	-15.4%	1428.7	-5.3%
g -20%	106.3	4.1%	15.5	-67.9%	1302.9	-13.6%
g -30%	73.6	-27.9%	15.7	-67.7%	1138.5	-24.5%
g -40%	72.2	-29.3%	13.7	-71.7%	951.0	-37.0%
5-year opt.						
years 30-44	152.3		29.6		1512.5	
years 50-64						
g +40%	181.8	11.2%	30.2	21.4%	1494.1	-1.5%
g +30%	163.3	-0.1%	30.5	22.6%	1456.4	-4.0%
g +20%	154.8	-5.3%	42.0	68.8%	1335.0	-12.0%
g +10%	151.7	-7.2%	23.8	-4.3%	1487.7	-1.9%
g	163.5		24.9		1516.4	
g -10%	142.8	-12.6%	41.4	66.7%	1217.3	-19.7%
g -20%	146.8	-10.2%	21.2	-14.7%	1451.0	-4.3%
g -30%	162.7	-0.5%	30.8	24.1%	1405.7	-7.3%
g -40%	141.6	-13.4%	37.7	51.7%	1288.4	-15.0%
years 70-84						
g +40%	193.0	67.4%	14.0	68.1%	1902.2	12.9%
g +30%	173.7	50.6%	11.1	33.0%	1858.2	10.3%
g +20%	158.5	37.5%	23.4	181.7%	1431.8	-15.0%
g +10%	117.7	2.1%	42.7	413.2%	1390.1	-17.5%
g	115.3		8.3		1684.7	
g -10%	93.7	-18.7%	33.1	298.4%	1308.1	-22.4%
g -20%	107.9	-6.4%	18.9	127.4%	1195.9	-29.0%
g -30%	66.2	-42.5%	33.3	300.0%	1016.5	-39.7%
g -40%	63.3	-45.1%	13.2	59.0%	950.0	-43.6%

Table 1. Development of annual catches when biological productivity is altered as a consequence of changing environmental conditions.

In the long run, average annual catches of cod are generally negatively affected by a reduction in biological productivity if a short-term fishing strategy is applied (Tab. 1). The fishery is dominated by the trawlers; catches in coastal areas are less important. The development is not as clear if fishermen follow a longer term fishing strategy. While reductions in productivity are harmful for the trawl fishery, there are substantial increases in the importance of the coastal fisheries, even though their significance remains marginal. In general, the importance of coastal vessels is much higher with a longer term harvest strategy as deferments of catches, i.e. possible fishing periods without activity, lead to less extensive losses due to the lower operating costs of coastal vessels. Catches of capelin are much less influenced by changes in hydrographic conditions than cod catches. This is particularly the case for a longer term fishing strategy and has to do with the large impact of predation on the

time period, change of biological productivity	**trawlers** (cod) profit index	**coastal vessels** (cod) profit index	**purse seiners** (capelin) profit index
2-year opt.			
years 30-44	77.0	37.2	127.4
years 50-64			
g +40%	52.8	27.6	156.3
g +30%	56.3	34.2	187.3
g +20%	63.4	33.1	167.8
g +10%	68.7	32.5	147.6
g	63.4	32.4	161.1
g -10%	62.8	32.2	133.2
g -20%	45.8	36.7	128.0
g -30%	52.4	32.5	143.0
g -40%	47.0	34.6	147.5
years 70-84			
g +40%	111.6	36.9	239.3
g +30%	146.3	37.3	181.7
g +20%	128.9	31.8	183.8
g +10%	62.4	33.2	171.5
g	86.4	35.4	135.3
g -10%	67.7	35.9	103.2
g -20%	47.8	38.0	98.7
g -30%	20.0	39.1	83.9
g -40%	35.8	43.9	70.7
5-year opt.			
years 30-44	77.6	33.3	114.1
years 50-64			
g +40%	146.3	43.6	109.9
g +30%	134.8	43.4	92.6
g +20%	151.2	44.6	94.2
g +10%	105.4	35.8	102.0
g	87.4	39.6	107.2
g -10%	119.6	41.7	78.0
g -20%	66.8	36.8	93.4
g -30%	103.1	31.9	96.1
g -40%	104.6	41.8	82.2
years 70-84			
g +40%	191.7	42.8	150.6
g +30%	172.5	36.3	132.3
g +20%	236.5	51.1	98.4
g +10%	162.6	52.3	86.4
g	63.3	31.3	115.6
g -10%	107.1	41.4	77.9
g -20%	87.2	41.2	73.0
g -30%	67.1	41.4	60.1
g -40%	33.7	42.7	50.8
reference values (million Nkr):			
Index 100 =	10.0	5.0	20.0
Index 0 =	-10.0	-5.0	0.0

Table 2. Development of profits per vessel when biological productivity is altered as a consequence of changing environmental conditions.

capelin stock. A reduction of the predator stock via lower productivity offsets the decreasing productivity of the prey. The consequence is a less pronounced decline of remaining prey biomass so that more fish is available to economic exploitation. Vice versa, a higher biological productivity does not necessarily translate to more capelin to be caught.

The net present values of profits of the three fleet types develop quite differently over time depending on the length of the optimization period. With a short-term harvest strategy, trawlers are negatively affected in the long run if productivity declines but profits increase to some extent with a rising productivity (Tab. 2). Coastal vessels are only of secondary importance, as their profitability does not even increase with growing productivity. The pattern is different when profits are maximized over five fishing periods. The relative importance of the coastal vessels is considerably higher compared to the two-year optimization, but there is no clear trend in the development of profitability.

In the long run, an increase in productivity is beneficial to the cod fishery as a whole, with the trawl fleet benefiting noticeably from increases in biological productivity. The number of vessels employed in the cod fishery declines over time in all scenarios for a long-term fishing strategy. In contrast, the number of trawlers remains fairly stable and only decreases in some scenarios if cod productivity reduced. However, coastal vessels generally decline by one third to one half over the simulation period regardless of the length of the optimization period. The decline is particularly pronounced in the scenarios with increasing biological productivity, when there is a clear shift towards exploitation of the stock using trawlers.

Profits of the capelin fishery remain constantly positive regardless of the scenario. This leads to a slow but consistent increase of the number of purse seiners engaged in the capelin fishery by up to one third at the end of the simulation period. Overall, the profitability of the capelin fishery is higher the shorter the optimization period becomes, since the standing stock biomass of cod and thus the number of cod preying on capelin is higher in case of the longer-term harvest strategy (Tab. 2). This negatively affects the profitability of the purse seine fleet in the long run, as profits go down with reductions in biological productivity without being able to recover if productivity increases. Also, there is no clear trend in the development of profitability of the capelin fishery in the first few decades after the onset of the change in productivity, which suggests that the influence of predation is a more determining factor for the capelin stock size than limitations in population dynamics of capelin themselves.

3.2 Consequences of changes in the environmental carrying capacities

Changes in the environmental carrying capacities of both fish species have a similar effect on the stocks as a reduction in biological productivity, but here the effects are less pronounced. There is a generally declining trend in the cod stock biomass for decreased carrying capacities. However, the stock size remains within or close to its fluctuation range in the reference scenario irrespective of the length of the optimization period (Fig. 2). In contrast, it is well possible that the stock grows considerably if this stock size can be supported by the environment. The impact of an altered carrying capacity on the development of the capelin stock is weaker than of a change in productivity. Regardless of the length of the optimization period, the deviation from the original range of fluctuation in the reference scenario does not exceed 25%.

The development of cod catches depends to a great extent on the length of the optimization period if the environmental carrying capacity changes. With a short-term fishing strategy, the amount of fish landed follows the development of the carrying capacity: a lower cod carrying capacity leads to smaller annual catches while the long term trend of cod catches is positive if the carrying capacity increases (Tab. 3). However, practically all of the additional catch is landed by the trawlers. The situation is curiously different if the fishing strategy is based on a longer optimization period. Here, a reduction of the carrying capacity does not have a negative impact on the amount of fish landed while a higher carrying capacity is beneficial to the fishery only up to a certain extent. This suggests that in the long run a change in an abstract quantity such as the carrying capacity has a much lower influence on the actual development of the stock than a change in an environmental factor that is directly linked to reproductive success.

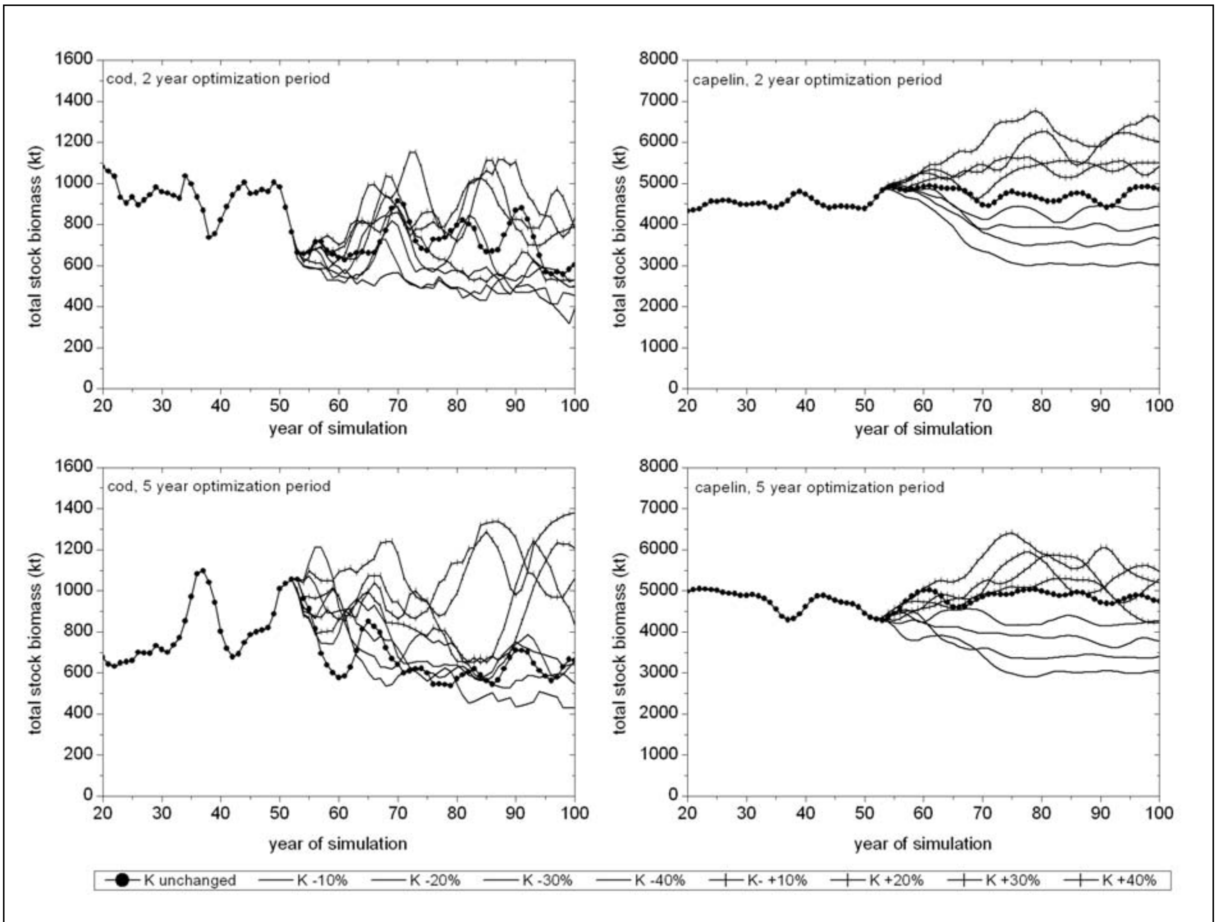

Figure 2. Development of the stock sizes with altered carrying capacities.

Capelin catches show relatively little variability regardless of the fishing strategy chosen. For a short-term fishing strategy, the amount of capelin landings corresponds to the development of the carrying capacity (Tab. 3). In contrast, the long-term development of capelin landings is generally negative with a longer optimization period. Even an increase in capelin carrying capacity does not pay off to the fishermen, as any additional capelin is consumed by cod instead of being caught.

Changes in the environmental carrying capacities have a similar impact on profits than alterations of biological productivity. The trawlers' profits are somewhat less stable in all scenarios, as declines in profitability owing to lower carrying capacities are more pronounced for both fishing strategies than the declines caused by lower productivity (Tab. 4). Vice versa, increases due to higher carrying capacities are less substantial than for changes in productivity. With a short-term fishing strategy, the profitability of coastal vessels is always low, regardless of the development of the carrying capacity. However, the profit index of the coastal vessels can increase in the long run in some scenarios, when market shares can be taken up at the expense of the trawl fishery. The profitability of the purse seine vessels is stable throughout the simulation period and develops even slightly better than for changes in productivity. It has to be noted that the development of the fleet sizes is essentially the same as for the change in biological productivity: the number of trawlers slowly declines to a final size of approximately two thirds of its original size, coastal vessels decline by one third to one half, while the capelin fishery remains more or less unchanged, even though there may be smaller fluctuations in fleet size in the last decades of the simulation period.

time period	**trawlers** (cod)		**coastal vessels** (cod)		**purse seiners** (capelin)	
change of the carrying capacity	average annual catch (1000 t)	change from reference scenario	average annual catch (1000 t)	change from reference scenario	average annual catch (1000 t)	change from reference scenario
2-year opt.						
years 30-44	145.2		42.9		1443.4	
years 50-64						
K +40%	149.7	4.4%	25.8	-11.4%	1710.4	5.1%
K +30%	123.0	-14.3%	37.6	29.4%	1674.2	2.8%
K +20%	148.9	3.8%	27.7	-4.8%	1686.2	3.6%
K +10%	131.5	-8.3%	26.5	-8.8%	1663.5	2.2%
K	143.4		29.1		1628.1	
K -10%	133.2	-7.1%	26.1	-10.3%	1603.2	-1.5%
K -20%	132.5	-7.6%	20.0	-31.1%	1636.6	0.5%
K -30%	148.1	3.2%	15.7	-46.1%	1616.0	-0.7%
K -40%	123.2	-14.1%	24.6	-15.2%	1544.4	-5.1%
years 70-84						
K +40%	128.0	25.3%	48.3	-0.4%	2112.2	40.0%
K +30%	140.5	37.6%	33.5	-30.9%	1856.7	23.1%
K +20%	108.2	5.9%	54.9	13.2%	1747.3	15.8%
K +10%	124.9	22.3%	30.9	-36.2%	1816.2	20.4%
K	102.2		48.4		1508.5	
K -10%	96.7	-5.4%	38.0	-21.7%	1388.7	-7.9%
K -20%	80.4	-21.3%	26.6	-45.2%	1313.6	-12.9%
K -30%	74.0	-27.5%	13.4	-72.3%	1215.4	-19.4%
K -40%	55.5	-45.7%	16.9	-65.1%	1035.1	-31.4%
5-year opt.						
years 30-44	152.3		29.6		1512.5	
years 50-64						
K +40%	132.5	-9.4%	29.2	15.5%	1619.2	7.0%
K +30%	110.3	-24.6%	22.2	-12.2%	1559.8	3.1%
K +20%	101.7	-30.4%	16.7	-33.9%	1270.5	-16.0%
K +10%	123.6	-15.5%	24.5	-3.1%	1144.8	-24.3%
K	146.2		25.2		1513.1	
K -10%	140.3	-4.0%	26.1	3.5%	1489.7	-1.5%
K -20%	151.7	3.8%	28.6	13.3%	1524.8	0.8%
K -30%	174.0	19.0%	9.9	-60.9%	1688.0	11.6%
K -40%	214.3	46.6%	29.0	14.9%	1528.4	1.0%
years 70-84						
K +40%	125.1	1.0%	12.5	49.5%	1735.0	3.3%
K +30%	133.4	7.8%	19.7	136.1%	1341.6	-20.2%
K +20%	228.0	84.2%	30.1	260.7%	1514.6	-9.9%
K +10%	182.7	47.6%	12.3	47.6%	1676.9	-0.2%
K	123.8		8.3		1680.3	
K -10%	128.5	3.8%	18.6	123.0%	1447.4	-13.9%
K -20%	150.8	21.8%	27.7	231.8%	1311.9	-21.9%
K -30%	150.6	21.6%	27.4	228.2%	1486.3	-11.5%
K -40%	169.6	37.0%	28.5	241.9%	1521.0	-9.5%

Table 3. Development of annual catches when the environmental carrying capacity is altered as a consequence of changing environmental conditions.

time period change of the carrying capacity	**trawlers** (cod) profit index	**coastal vessels** (cod) profit index	**purse seiners** (capelin) profit index
2-year opt.			
years 30-44	77.0	37.2	127.4
years 50-64			
K +40%	60.6	31.2	167.6
K +30%	62.4	36.0	164.9
K +20%	53.8	30.8	161.3
K +10%	49.4	27.8	174.1
K	63.4	32.4	161.1
K -10%	57.6	34.5	160.1
K -20%	44.1	35.1	175.8
K -30%	38.2	35.7	167.9
K -40%	42.1	31.2	138.0
years 70-84			
K +40%	92.0	28.9	217.5
K +30%	103.7	39.9	199.1
K +20%	105.5	44.1	153.8
K +10%	53.2	34.9	165.2
K	86.4	35.4	135.3
K -10%	89.3	43.3	139.5
K -20%	24.1	35.1	127.1
K -30%	13.9	39.4	100.5
K -40%	13.8	44.9	87.3
5-year opt.			
years 30-44	77.6	33.3	114.1
years 50-64			
K +40%	115.3	42.0	105.3
K +30%	138.4	41.5	91.0
K +20%	108.8	42.9	95.8
K +10%	123.7	42.6	99.9
K	87.4	39.6	107.2
K -10%	124.9	38.8	85.9
K -20%	129.2	36.2	79.7
K -30%	103.5	38.0	88.5
K -40%	119.1	42.6	79.6
years 70-84			
K +40%	161.5	40.8	136.0
K +30%	174.2	41.0	116.5
K +20%	128.3	37.8	128.1
K +10%	101.1	36.8	112.4
K	63.3	31.3	115.6
K -10%	87.4	39.0	76.9
K -20%	95.3	35.3	73.5
K -30%	76.4	34.2	66.5
K -40%	31.6	38.5	55.9
reference values (million Nkr):			
Index 100 =	10.0	5.0	20.0
Index 0 =	-10.0	-5.0	0.0

Table 4. Development of profits per vessel when the environmental carrying capacity is altered as a consequence of changing environmental conditions.

4 Sensitivity analyses

In the sensitivity analyses, we explore the influence of changes in key economic parameters on the stocks and their respective fisheries. In contrast to the scenarios of changes in population dynamics, the nature of the stock-recruitment relationship does not change in the sensitivity analysis. Nonetheless, the economic development of the fisheries varies distinctly depending on the setting of these key economic parameters.

4.1 Influence of the share of capelin devoted to human consumption

Traditionally, most of the Norwegian capelin catch is used in the production of fish meal and oil. However, in recent years there has been an increase in the amount of capelin that is exported and used for human consumption. Close to 50% of the capelin landed by Norwegian fishermen was exported in 1999 (Statistisk Sentralbyrå, 2000) with the market price for capelin that is exported being up to seven times as high as the price for capelin that is used industrially (Fiskeridirektoratet, 2001).

share of capelin used for human consumption	*years 30-44* profit index	*years 50-64* profit index	*years 70-84* profit index
2-yr. optimization			
0%	106.3	127.2	108.9
10%	112.5	127.4	164.4
20%	203.1	164.4	154.2
30%	228.5	230.9	236.7
40%	273.3	336.3	335.3
50%	289.3	302.1	369.3
5-yr. optimization			
0%	105.6	71.9	100.5
10%	117.9	96.1	97.8
20%	148.0	155.2	134.4
30%	133.6	128.1	152.2
40%	168.3	169.2	138.6
50%	221.0	208.0	178.6
reference value (million Nkr):	Index 100 = 40.0		

Table 5. Influence of an increase in the amount of capelin used for human consumption on profits per vessel.

Simulations with different price levels of capelin show that the amount of capelin caught in each fishing period hardly varies despite the increased value of the resource. This can be explained by the fact that in each case the fleet utilization of the purse seine vessels is already quite high so there is only little room to expand the fishing effort. On the other hand, the net present values of profits of the capelin fishery change substantially (Tab. 5) for a higher average fish price. Profits generally increase if a larger share of the capelin catches is used for human consumption. However, profits per vessel decline over time as the profitability of the fishery leads to a distinct increase in the number of vessels engaged in the exploitation of the stock. This diminishes the profits of the individual vessels even though the fishery remains profitable as a whole. The overall profits from fishing are higher if the fishing strategy considers only a short period of time, since this causes fishermen to exploit the stock more aggressively. This leads to higher annual catches and therefore to higher returns from fishing. Without any environmental change negatively influencing the stock dynamics, the fishery is able to harvest such large amounts of fish without compromising the stability of the stock.

4.2 Influence of the discount rate

In order to determine the influence of the discount rate on the profits from fishing, simulations of the reference scenario are conducted with various discount rates ranging from 1% to 15%. For reasons of comparability, we focus only on the first period of interest (between years 30 and 44).

discount rate	**trawlers** (cod) profit index	**coastal vessels** (cod) profit index	**purse seiners** (capelin) profit index	**all fleets** (cod & capelin) profit index
2-yr. optimization				
1%	10.7	8.5	102.8	53.1
3%	7.9	0.0	169.2	114.6
5%	216.7	42.8	72.3	237.3
7%	10.6	31.5	96.5	52.5
9%	10.0	31.6	106.2	61.6
11%	38.7	13.5	106.4	85.9
13%	50.0	11.3	136.9	127.2
15%	74.4	14.8	100.1	115.7
5-yr. optimization				
1%	59.3	5.6	102.2	100.4
3%	79.2	31.4	99.1	123.6
5%	48.3	17.9	74.5	64.9
7%	133.0	31.9	81.3	159.8
9%	216.1	62.5	63.4	232.6
11%	143.3	41.7	100.8	192.0
13%	134.1	37.7	93.2	174.2
15%	30.1	37.9	91.6	68.7
reference values (million Nkr):				
Index 100 =	20.0	5.0	40.0	40.0
Index 0 =	-20.0	-5.0	0.0	0.0

Table 6. Influence of the discount rate on profits per vessel.

The results show that there is no simple relationship between the discount rate and the profitability of the different fleets. For an optimization period of two years, the returns from fishing of the fleets that are catching cod are by far highest for the interest rate of 5% (Tab. 6). However, this success is based on particularly profitable years at the beginning of the period of interest. In the long run, the economic success of the trawl fishery is much less pronounced in comparison with the other discount rates than suggested by these data. Because of the interannual variability of cod landings, the profits of the trawl fishery are otherwise generally larger for higher interest rates, when good years of fishing at the beginning of the period of interest cannot be offset by less successful years shortly afterwards. The overall low profitability of the coastal vessels confirms that the strategy of utilizing mostly trawlers to harvest cod and leaving the coastal vessels with constantly small landings is independent of the interest rate. In contrast, the profits from catching capelin are stable for practically all discount rates.

The situation is different if the optimization period is five years. Here, the profitability of the cod fishery is in general much better than for the shorter optimization period, particularly for high interest rates. The particularly bad economic performance for an interest rate of 5% is pure coincidence of some bad fishing periods at the beginning of the period of interest (Tab. 6). The profits of the capelin fishery remain positive and are more or less of the same magnitude as in the optimization over a short time horizon. However, the combined returns from fishing of all fleet types are higher for the longer optimization period in most cases, which has to do with the fact that the fleet sizes are smaller so that operation costs are lower.

4.3 Influence of the speed of technological progress

Because of the long term perspective of the model, it is important to consider technological progress of the fishing fleets, as it can be expected that an increase in catch efficiency has an influence on the economic results of the fisheries. Simulations of the reference scenario are conducted with various rates of annual technological progress ranging from 0.00% to 1.25% for both optimization periods considered. As in the assessment of the influence of the interest rate, the focus lies on the time period between years 30 and 44.

annual rate of technological progress	**trawlers** (cod) profit index	**coastal vessels** (cod) profit index	**purse seiners** (capelin) profit index	**all fleets** (cod & capelin) profit index
2-yr. optimization				
0.00%	10.3	7.7	106.3	56.1
0.25%	30.4	31.4	73.4	49.2
0.50%	65.1	4.5	61.8	65.6
0.75%	49.9	29.5	97.8	92.6
1.00%	34.1	25.9	120.1	98.1
1.25%	193.8	32.8	96.7	236.2
5-yr. optimization				
0.00%	58.2	4.7	105.6	102.5
0.25%	98.7	7.6	67.1	105.2
0.50%	94.7	14.6	86.3	122.1
0.75%	154.1	41.7	35.8	137.8
1.00%	181.7	13.2	100.1	222.6
1.25%	94.2	46.3	74.9	118.1
reference values (million Nkr):				
Index 100 =	20.0	5.0	40.0	40.0
Index 0 =	-20.0	-5.0	0.0	0.0

Table 7. Influence of technological progress on profits per vessel.

The results show no clear trend in the profitability of the fleets regardless of the length of the optimization period (Tab. 7). No technological progress leads to the worst economic results but it needs a considerable increase in catch efficiency of 0.75% p.a. or more to substantially increase the long-term economic performance of the fisheries. However, even for a large annual increase in catch efficiency the profitability of the fisheries does not necessarily have to increase proportionally for two reasons: positive economic results due to larger catches per unit effort can lead to an expansion of the fleets, causing subsequent reductions in profits per vessel. Furthermore, the fisheries are regulated with TACs that have to be divided between the fleets. Since this strictly limits the amount of fish each vessel is allowed to harvest, any positive effects of increased catch efficiencies are hidden behind the limitations brought about by the management measures.

5 Discussion and conclusion

Changing environmental conditions in marine ecosystems are likely to have a profound impact on the population dynamics of commercially important fish species, influencing their survival rates and reproductive capacities. In conjunction with the economic exploitation of the stocks, these affect the development of the standing stock biomasses in a complex way, particularly if the species also interact via predation. This simulation model considers both the ecological and economic factors when it comes to determining an optimal fishing strategy of the fishermen. Since economic and ecological changes occur on substantially different time scales, it is necessary to apply long-term simulations and use a dynamic-recursive approach to make use of economic considerations in a meaningful way. While it may appear qualitatively obvious that improved population dynamics are beneficial to the stocks and worse recruitment has detrimental effects, the economic consequences that arise from such developments do not follow such simple rules. This model setup can be used to quantitatively estimate the economic impacts of environmentally induced changes in stock dynamics.

The simulations show that the extent of the change in stock size is approximately the same for the change in the carrying capacity and the altered biological productivity. This holds true for both species. The close link between both species that exists via predation becomes particularly obvious when stock sizes increase due to improved population dynamics. This effect becomes less important in comparison to the economic influence on the stocks if the populations decrease in size due to adverse developments in stock dynamics.

For a fishing strategy with only a short optimization period, smaller stock sizes generally lead to decreased landings while improved population dynamics have little positive impact on the stock and therefore leave little room for increases in landings. This has to do with strict management measures applied in the model. If a TAC is set and the fish species are exploited aggressively within the given limit, the importance of the management measures dwarves all possible impacts improved population dynamics could have on the stocks.

The situation is different if a fishing strategy that plans ahead over a longer time horizon. Here, it depends on whether the change in population dynamics directly influences the number of new recruits or affects a quantity that only indirectly affects recruitment success. For changes in the environmental carrying capacity, the cod fishery can expand despite a reduction in this factor influencing population dynamics. On the other hand, the largest expansions of the carrying capacity do not lead to the largest standing stock biomasses and thus to the highest landings. This shows that the state of the cod stock is much more influenced by economic activities than by intrinsic reproductive characteristics. A complementary development can be observed for the capelin fishery, which suffers a mostly negative development in the long run if the carrying capacities of the fish species change.

The results highlight the fact that not only the length of the optimization period has a distinct impact on the economic success of the fisheries but also the kind of change in population dynamics. The shorter optimization period, the more aggressive the fishing strategy becomes. This pressure on the stock causes any change in population dynamics to subsequently become apparent in the success of the economic exploitation of the stocks: improved population dynamics increase economic profits in the long run while negative developments in stock dynamics hurt also hurt the fisheries. However, if the fishing strategy is more relaxed and the change in population dynamics influences the number of recruits to the stocks only indirectly, the development of the stocks depends much more on management decisions than on the changes in fish biology. In these simulations, an increase in fleet efficiency and a slight reduction in fleet sizes improve the profitability of the cod fishery despite an adverse development in the carrying capacity. But since the economic exploitation of the stocks in the Barents Sea has caused the standing stock biomasses to be far below their carrying capacities to start with, any change in this quantity has a smaller influence on the stocks and the fisheries than a direct change in the number of recruits.

The returns from fishing are higher for the fishing strategy with the longer optimization period, but the longer term strategy does have its drawbacks. The strategy of an only periodic exploitation of the stock when conditions are best suited for fishing may yield particularly large catches in some years, but in several ways it can hardly be considered as optimal: if the stocks are exploited very heavily in some fishing periods, this has negative impacts on the spawning stock biomasses and thus on the capabilities to replace the losses from fishing. Furthermore, the frequent occurrence of fishing periods in which there is no fishing activity of a given fleet makes it necessary to use labor punctually instead of continuously. In reality, this would mean hiring a large number of fishermen for a short period of time and then laying them off again if it is optimal to cease fishing again soon afterwards. This is by no means a practical way to deal with the variability in the exploitation of commercial fish species.

Despite the simplifications embodied in our simulation model, it is possible to obtain some insights about the possible consequences of a reduction in biological productivity or the environmental carrying capacities on the cod and capelin stocks in the Barents Sea and the catches of their fisheries for a coupled stock size-hydrography based fishing strategy. The model applied in this study considers the behavior of fishermen, fisheries policy and scenarios of possible environmental change at the same time. This allows for assessments of economic impacts on the fisheries caused by long-term alterations in hydrographic conditions that may occur as a consequence of climate change. Assessments of concrete scenarios of a weakening of the Atlantic thermohaline circulation are subject of a separate analysis (Link & Tol, 2009).

Furthermore, the long-term scope of the model makes it possible to identify potential non-linear thresholds, such as critical stock biomasses that lead to stock collapse if exceeded. These thresholds are usually dependent on the state of the surrounding environment. And their shifts can generally not be discovered in bioeconomic analyses that cover only short time periods and consider constant environmental conditions.

Due to the inclusion of measures of fisheries policy and technological progress in the model, the long-term implications of policy instruments can be tested. Changes in population dynamics necessitate rather quick adjustments of management measures, which define the pressure imposed on the stocks by economic exploitation, if stock collapses are to be avoided. Short-term profits of the fisheries are much lower in the simulations conducted in this study as in unregulated fisheries. However, without the inclusion of policy instruments, the stocks would have collapsed under the immense pressure of the fisheries in many scenarios of altered population dynamics, highlighting the necessity of actively managing the anthropogenic exploitation of important marine resources such as the Barents Sea fish stocks. Further development of the model will be conducted in order get a more differentiated view of the economic consequences for marine fisheries in the Nordic Seas caused by changes in climatic or hydrographic conditions.

Acknowledgements

This study is part of the research project INTEGRATION to assess the impacts of a possible shutdown of the thermohaline circulation which is funded by the German Ministry of Education and Research (project no. 01 LD 0016).

References

Beverton, R.J. & Holt, S.J. (1954). *On the dynamics of exploited fish populations*. (London: Chapman & Hall)

Chaboud, C. (1995). Risques et incertitudes dans les pêches: le point de vue de l'économiste. (In F. Laloé, H. Rey & J.L. Durand (Eds.), *Questions sur la dynamique de l'exploitation halieutique* (pp. 263-295). Paris: ORSTOM)

Clark, C.W. (1990). *Mathematical bioeconomics: the optimal management of renewable resources*, 2nd ed. (New York: Wiley)

Commission of the European Communities (CEC) (2005). *Report of the Scientific, Technical and Economic Committee for Fisheries: Review of Scientific Advice for 2005*. (Brussels, European Union Report SEC 266)

Eide, A. & Heen, K. (2002). Economic impacts of global warming – A study of the fishing industry in North Norway. *Fisheries Research*, 56, 261-274.

Fiskeridirektoratet (Eds.) (2001). *Regulering av fisket etter lodde i Barentshavet i 2002*. (Oslo: Fiskeridirektoratet SAK 22/01) (in Norwegian)

Frederick, S. (2005). Valuing future life and future lives: A framework for understanding discounting. *Journal of Economic Psychology*, 27, 667-680.

Gjøsæter, H., & Bogstad, B. (1998). Effects of the presence of herring (*Clupea harengus*) on the stock-recruitment relationship of Barents Sea capelin (*Mallotus villosus*). *Fisheries Research*, 38, 57-71

Gjøsæter, H., Dommasnes, A. & Røttingen, B. (1998). The Barents Sea Capelin Stock 1972-1997. A Synthesis of Results from Acoustic Surveys. *Sarsia*, 83, 497-510

Hannesson, R. (1996). *Fisheries Mismanagement: The Case of the North Atlantic Cod*. (Oxford: Fishing News Books)

Hannesson, R. (2005). *The Development of Productivity in the Norwegian Fisheries*. (Bergen: Institute for Research in Economics and Business Administration, Working Paper No. 24/05)

Hannesson, R. (2006). Sharing the Northeast Arctic Cod: possible effects of climate change. *Natural Resource Modeling*, 19, 633-654.

Hannesson, R. (2007). Geographical distribution of fish catches and temperature variations in the northeast Atlantic since 1945. *Marine Policy*, 31, 32-39.

Hjermann, D.Ø., Stenseth, N.C. & Ottersen, G. (2004). The population dynamics of Northeast Arctic cod (*Gadus morhua*) through two decades: an analysis based on survey data. *Canadian Journal of Fisheries and Aquatic Sciences*, 61, 1747-1755

International Council for the Exploration of the Sea (ICES) (2003a). *Report of the Arctic Fisheries Working Group, San Sebastian, 2003*. (Copenhagen: ICES Report CM 2003/ACFM:22)

International Council for the Exploration of the Sea (ICES) (2003b). *Report of the Northern Pelagic and Blue Whiting Fisheries Working Group, Copenhagen, 2003*. (Copenhagen: ICES Report CM 2003/ACFM:23)

Jennings, S. & Kaiser, M.J. (1998). The Effects of Fishing on Marine Ecosystems. (In J.H.S. Blaxter, A.J. Southward & P.A. Tyler (Eds.), *Advances in Marine Biology*, vol. 34 (pp. 201-352). San Diego: Academic Press)

Kuhlbrodt, T., Rahmstorf, S., Zickfeld, K., Vikebø, F.B., Sundby, S., Hofmann, M., Link, P.M., Bondeau, A., Cramer, W. & Jaeger, C. (2009). An Integrated Assessment of changes in the thermohaline circulation. *Climatic Change*, 96, 489-537

Lane, D.E. (1988). Investment decision making by fishermen. *Canadian Journal of Fisheries and Aquatic Science*, 45, 782-796

Link, P.M. & Tol, R.S.J. (2006). Economic impacts of changes in population dynamics of fish on the fisheries in the Barents Sea. *ICES Journal of Marine Science*, 63, 611-625

Link, P.M. & Tol, R.S.J. (2009). Economic impacts on key Barents Sea fisheries arising from changes in the strength of the Atlantic thermohaline circulation. *Global Environmental Change*, 19, 422-433

Magnússon, K.G. & Pálsson, Ó.K. (1991). Predator-prey interactions of cod and capelin in Icelandic waters. *ICES Marine Science Symposia*, 193, 153-170

Mehl, S. & Sunnanå, K., (1991). Changes in growth of Northeast Arctic cod in relation to food consumption 1984-1988. *ICES Marine Science Symposia*, 193, 109-112.

Michalsen, K. (Ed.) (2004). *Havets ressurser 2004. Fisken og havet, 1-2004*. (Bergen: Institute of Marine Research) (in Norwegian)

Moxnes, E. (1992). *Multispecies Management under Uncertainty*. (Bergen: Stiftelsen for samfunns- og nærlingslivsforskning)

Planque, B. & Frédou, T. (1999). Temperature and the recruitment of Atlantic cod (*Gadus morhua*). *Canadian Journal of Fisheries and Aquatic Sciences*, 56, 2069-2077

Robinson, C. & Pascoe, S. (1997). *Fisher behaviour: exploring the validity of the profit maximizing assumption*. (Portsmouth: CEMARE Research paper R110)

Salas, S. & Gaertner, D. (2004). The behavioural dynamics of fishers: management implications. *Fish and Fisheries*, 5, 153-167

Schaefer, M.B. (1957). Some considerations of population dynamics and economics in relation to the management of commercial marine fisheries. *Journal of the Fisheries Research Board of Canada*, 14, 669-681

Statistisk Sentralbyrå (Eds.) (1980-2004). *Norges Offisielle Statistikk, Fiskeristatistikk*. (Oslo: Statistisk Sentralbyrå), multiple volumes.

Steinshamn, S.I. (1998). Implications of Harvesting Strategies on Population and Profitability in Fisheries. *Marine Resource Economics*, 13, 23-36.

Stenevik, E.K. & Sundby, S. (2007). Impacts of Climate Change on Commercial Fish Stocks in Norwegian Waters. *Marine Policy*, 31, 19-31.

Sumaila, U.R. (1995). Irreversible Capital Investment in a Two-Stage Bimatrix Fishery Game Model. *Marine Resource Economics*, 10, 263-283

Sumaila, U.R. (1997). Strategic Dynamic Interaction: The Case of Barents Sea Fisheries. *Marine Resource Economics*, 12, 77-94

Sumaila, U.R. & Walters, C. (2005). Intergenerational discounting: a new intuitive approach. *Ecological Economics*, 52, 135-142.

Vellinga, M. & Wood, R.A. (2002). Global climatic impacts of a collapse of the Atlantic thermohaline circulation. *Climatic Change*, 54, 251-267.

Vikebø, F.B., Sundby, S., Ådlandsvik, B., & Fiksen, Ø. (2005). The combined effect of transport and temperature on distribution and growth of larvae and pelagic juveniles of Arcto-Norwegian cod. *ICES Journal of Marine Science*, 62, 1375-1386.

Appendix A. List of symbols used in the model.

Symbol	meaning
a	index denoting the age class
A	highest age class of a species
B	biomass
cap	index referring to capelin
cod	index referring to cod
D	prey density
d	discount rate
e	fleet utilization
g	biological productivity
h	harvest
harv	index denoting the stock size after fishing activities have been considered
hum	index referring to human consumption
i	index denoting the fleet type
ind	index referring to industrial use
init	index referring to the beginning of a fishing period
K	carrying capacity
n	number of individuals in an age class
P	fish price
pred	index denoting the stock size after fishing activities and predation have been considered
q	catchability coefficient
r	revenue
R	recruitment
s	index denoting the species
SSB	spawning stock biomass
sw	spawning weight
t	index denoting the fishing period
v	number of vessels
w	weight
α	parameter used in recruitment function
β	parameter used in recruitment function
δ	discount factor
ζ	base price of fish
η	fish price change depending on amount landed
θ	variable costs
ι	rate of predation
κ	parameter used in calculation of predated biomass
μ	share of mature individuals
π	profit per fishing period
Π	net present value of profits over a 15-year period
φ	fixed costs
χ	natural survival rate
ψ	total costs
ω	cost per unit effort

Working Papers

Research Unit Sustainability and Global Change

Hamburg University and Centre for Marine and Atmospheric Science

Tol, R.S.J. (2009), *International Equity Aversion and the Social Cost of Carbon*, **FNU-178** (submitted)

Koleva, N.G., U.A. Schneider and B.A. McCarl (2009), *Pesticide externalities from the US agricultural sector - The impact of internalization, reduced pesticide application rates, and climate change*, **FNU-177** (submitted)

Osmani, D. (2009), *A Note on Optimal Transfer Schemes, Stable Coalition for Environmental Protection and Joint Welfare Maximisation Assumption*, **FNU-176** (submitted)

Anthoff, D. R.J. Nicholls and R.S.J Tol (2009), *The Economic Impact of Substantial Sea Level Rise*, **FNU-175** (submitted)

Leahy, E., S. Lyons, E.L.W. Morgenroth and R.S.J. Tol (2009), *The Spatial Incidence of a Carbon Tax in Ireland*, **FNU-174** (submitted)

Genova Koleva, N. and U.A. Schneider (2009), *The impact of climate change on aquatic risk from agricultural pesticides in the US*, **FNU-173** (submitted)

Osmani, D. (2009), *Burden Sharing Emissions and Climate Change: A Theoretic Welfare Approach*, **FNU-172** (submitted)

Genova Koleva, N., U.A. Schneider, and R.S.J. Tol (2009), *The impact of weather variability and climate change on pesticide applications in the US - An empirical investigation*, **FNU-171** (submitted)

Calzadilla, A., T. Zhu, K. Rehdanz, R.S.J. Tol and C. Ringler (2009), *Economy-Wide Impacts of Climate Change on Agriculture in Sub-Saharan Africa*, **FNU-170** (submitted)

Calzadilla, A., K. Rehdanz and R.S.J. Tol (2008), *The Economic Impact of More Sustainable Water Use in Agriculture: A Computable General Equilibrium Analysis*, **FNU-169** (submitted)

Schleupner, C. and P.M. Link (2008), *Eiderstedt im Spannungsfeld zwischen Naturschutz- und Agrarpolitik - Entwicklung eines methodischen Ansatzes für ein nachhaltiges Ressourcenmanagement in ökologisch sensiblen Regionen*, **FNU-168** (*Marburger Geographische Schriften*, **145**, 33-49)

Sauer, T., P.M. Link and U.A. Schneider (2008), *The role of water resources in agricultural land use modeling: an extension of the land use model KLUM*, **FNU-167** (submitted)

Meier, H.A. and K. Rehdanz (2008), *Determinants of Residential Space Heating Expenditures in Great Britain*, **FNU-166** (forthcoming, *Energy Economics*)

Link, P.M., C.I. Ramos, U.A. Schneider, E. Schmid, J. Balkovic and R. Skalsky (2008), *The interdependencies between food and biofuel production in European agriculture - an application of EUFASOM*, **FNU-165** (submitted to *Biomass & Bioenergy*)

Schneider, U.A. and P. Smith (2008), *Greenhouse Gas Emission Mitigation and Energy Intensities in Agriculture*, **FNU-164** (submitted)

Maddison, D. and K. Rehdanz (2008), *Carbon Emissions and Economic Growth: Homogeneous Causality in Heterogeneous Panels*, **FNU-163** (submitted)

Osmani, D. and R.S.J. Tol (2008), Evolution in time of Farsightedly Stable Coalitions: An Application of FUND, **FNU-162** (submitted)

Schneider U.A., P. Havlik, E. Schmid, I. Huck, M. Obersteiner, T. Sauer, C. Llull, R. Skalsky, J. Balkovic, S. Fritz, B. Dorin, and S. Leduc (2008), *Global interdependencies between population, water, food, and environmental policies*, **FNU-161** (submitted)

Calzadilla, A, K. Rehdanz and R.S.J. Tol (2008), *Water Scarcity and the Impact of Improved Irrigation Management: A CGE Analysis*, **FNU-160** (submitted)

Schleupner, C. and U.A. Schneider (2008), *A cost-effective spatial wetland site-selection model for European biotope restoration*, **FNU-159** (submitted)

Schleupner, C. and U.A. Schneider (2008), *Evaluation of European wetland restoration potentials by considering economic costs under different policy options*, **FNU-158** (submitted)

Bigano, A., J.M. Hamilton and R.S.J. Tol (2008), Climate Change and Tourism in the Mediterranean, **FNU-157** (submitted).

Schneider U.A., J. Balkovic, S. De Cara, O. Franklin, S. Fritz, P. Havlik, I. Huck, K. Jantke, A.M.I. Kallio, F. Kraxner, A. Moiseyev, M. Obersteiner, C.I. Ramos, C. Schleupner, E. Schmid, D. Schwab, R. Skalsky (2008), *The European Forest and Agricultural Sector Optimization Model – EUFASOM*, **FNU-156**.

Schneider, U.A. and P. Kumar (2008), *Greenhouse Gas Emission Mitigation through Agriculture*, **FNU-155**.

Tol, R.S.J. and S. Wagner (2008), *Climate Change and Violent Conflict in Europe over the Last Millennium*. **FNU-154** (forthcoming, *Climatic Change*).

Schleupner, C. (2007), *Regional Spatial Planning Assessments for Adaptation to accelerated sea level rise – an application to Martinique's coastal zone*. **FNU-153** (submitted).

Schleupner, C. (2007). *Evaluating the Regional Coastal Impact Potential to Erosion and Inundation caused by Extreme Weather Events and Tsunamis*. **FNU-152** (submitted).

Rehdanz, K. (2007), *Species diversity and human well-being: A spatial econometric approach*, **FNU-151** (submitted).

Osmani, D. and R.S.J. Tol (2007), *A short note on joint welfare maximization assumption*, **FNU-150** (submitted).

Osmani, D. and R.S.J. Tol (2007), *Towards Farsightedly Stable International Environmental Agreements: Part Two*, **FNU-149** (submitted).

Ruane, F.P. and R.S.J. Tol (2007), *Academic Quality, Power and Stability: An Application to Economics in the Republic of Ireland*, **FNU-148** (submitted).

Tol, R.S.J. (2007), *A Rational, Successive g-Index Applied to Economics Departments in Ireland*, **FNU-147** (*Journal of Informetrics*, **2**, 149-155).

Tol, R.S.J. (2007), *Of the h-Index and its Alternatives: An Application to the 100 Most Prolific Economists*, **FNU-146** (forthcoming, *Scientometrics*).

Yohe, G.W. and R.S.J. Tol (2007), *Precaution and a Dismal Theorem: Implications for Climate Policy and Climate Research*, **FNU-145** (submitted).

Tol, R.S.J. (2007), *The Social Cost of Carbon: Trends, Outliers and Catastrophes*, **FNU-144** (E*conomics the Open-Access, Open-Assessment E-Journal*, **2** (25), 1-24).

Tol, R.S.J. (2007), *The Matthew Effect Defined and Tested for the 100 Most Prolific Economists*, **FNU-143** (*Journal of the American Society for Information Science and Technology*, **60** (2), 420-426).

Berrittella, M., K. Rehdanz, R.S.J. Tol and J. Zhang (2007), *The Impact of Trade Liberalisation on Water Use: A Computable General Equilibrium Analysis*, **FNU-142** (*Journal of Economic Integration*, **23** (3), 631-655).

Lyons, S., K. Mayor and R.S.J. Tol (2007), *Convergence of Consumption Patterns during Macroeconomic Transition: A Model of Demand in Ireland and the OECD*, **FNU-141** (*Economic Modelling*, **26**, 702-714).

Osmani, D. and R.S.J. Tol (2007), *Towards Farsightedly Stable International Environmental Agreements*, **FNU-140** (*Journal of Public Economic Theory*, **11** (3), 455-492).

Rehdanz, K. and S. Stöwhase (2007), *Cost Liability and Residential Space Heating Expenditures of Welfare Recipients in Germany*, **FNU-139** (submitted).

Schleupner, C. and P.M. Link (2007), *Potential impacts on bird habitats in Eiderstedt (Schleswig-Holstein) caused by agricultural land use changes*, **FNU-138** (*Applied Geography*, **28** (4), 237-247).

Link, P.M. and C. Schleupner (2007), *Agricultural land use changes in Eiderstedt: historic developments and future plans*, **FNU-137** (*Coastline Reports*, **9**, 197-206).

Anthoff, D., R.J. Nicholls and R.S.J. Tol (2007), *Global Sea Level Rise and Equity Weighting*, **FNU-136** (submitted).

Schleupner, C. (2007), *Wetland Distribution Modelling for Optimal Land Use Options in Europe*, **FNU-135** (submitted).

Mayor, K. and R.S.J. Tol (2007), *The Impact of the EU-US Open Skies Agreement on International Travel and Carbon Dioxide Emissions*, **FNU-134** (*Journal of Air Transport Management*, **14**, 1-7).

Schneider, U.A., M. Obersteiner, and E. Schmid (2007), *Agricultural adaptation to climate policies and technical change*, **FNU-133** (submitted).

Lychnaras, V. and U.A. Schneider (2007), *Dynamic Economic Analysis of Perennial Energy Crops - Effects of the CAP Reform on Biomass Supply in Greece*, **FNU-132** (submitted).

Mayor, K. and R.S.J. Tol (2007), The Impact of the UK Aviation Tax on Carbon Dioxide Emissions and Visitor Numbers, **FNU-131** (*Transport Policy*, **14** (6), 407-513).

Ruane, F. and R.S.J. Tol (2007), *Refined (Successive) h-indices: An Application to Economics in the Republic of Ireland*, **FNU-130** (*Scientometrics*, **75** (2), 395-405).

Yohe, G.W., R.S.J. Tol and D. Murphy (2007), *On Setting Near-Term Climate Policy as the Dust Begins the Settle: The Legacy of the Stern Review*, **FNU-129** (*Energy & Environment*, **18** (5), 621-633).

Maddison, D.J. and K. Rehdanz (2007), *Happiness over Space and Time*, **FNU-128** (submitted).

Anthoff, D. and R.S.J. Tol (2007), *On International Equity Weights and National Decision Making on Climate Change*, **FNU-127** (submitted).

de Bruin, K.C., R.B. Dellink and R.S.J. Tol (2007), *AD-DICE: An Implementation of Adaptation in the DICE Model*, **FNU-126** (forthcoming, *Climatic Change*).

Tol, R.S.J. and G.W. Yohe (2007), *The Stern Review: A Deconstruction*, **FNU-125** (*Energy Policy*, **37** (3), 1032-1040).

Keller, K., L.I. Miltich, A. Robinson and R.S.J. Tol (2007), *How Overconfident Are Current Projections of Anthropogenic Carbon Dioxide Emissions?*, **FNU-124** (submitted, *Energy Journal*).

Cowie, A., U.A. Schneider and L. Montanarella (2006), *Potential synergies between existing multilateral environmental agreements in the implementation of Land Use, Land Use Change and Forestry activities*, **FNU-123** (submitted)

Kuik, O.J., B. Buchner, M. Catenacci, A. Goria, E. Karakaya and R.S.J. Tol (2006), *Methodological Aspects of Recent Climate Change Damage Cost Studies*, **FNU-122** (*Integrated Assessment Journal*, **8** (1), 19-40)

Anthoff, D., C. Hepburn and R.S.J. Tol (2006), *Equity Weighting and the Marginal Damage Costs of Climate Change*, **FNU-121** (*Ecological Economics*, **68**, 836-849)

Tol, R.S.J. (2006), *The Impact of a Carbon Tax on International Tourism*, **FNU-120** (*Transportation Research D: Transport and the Environment*, **12** (2), 129-142).

Rehdanz, K. and D.J. Maddison (2006), *Local Environmental Quality and Life Satisfaction in Germany*, **FNU-119** (forthcoming, *Ecological Economics*)

Tanaka, K., R.S.J. Tol, D. Rokityanskiy, B.C. O'Neill and M. Obersteiner (2006), *Evaluating Global Warming Potentials as Historical Temperature Proxies: An Application of ACC2 Inverse Calculation*, **FNU-118** (forthcoming, *Climatic Change*)

Berrittella, M., K. Rehdanz and R.S.J. Tol (2006), *The Economic Impact of the South-North Water Transfer Project in China: A Computable General Equilibrium Analysis*, **FNU-117** (submitted, *China Economic Review*)

Tol, R.S.J. (2006), *Why Worry about Climate Change? A Research Agenda*, **FNU-116** (*Environmental Values*, **17** (4), 437-470)

Hamilton, J.M. and R.S.J. Tol (2006), *The Impact of Climate Change on Tourism in Germany, the UK and Ireland: A Simulation Study*, **FNU-115** (*Regional Environmental Change*, **7** (3), 161-172)

Schwoon, M., F. Alkemade, K. Frenken and M.P. Hekkert (2006), *Flexible transition strategies towards future well-to-wheel chains: an evolutionary modelling approach*, **FNU-114** (submitted).

Ronneberger, K., L. Criscuolo, W. Knorr and R.S.J. Tol (2006), *KLUM@LPJ: Integrating dynamic land-use decisions into a dynamic global vegetation and crop growth model to assess the impacts of a changing climate. A feasibility study for Europe*, **FNU-113** (submitted)

Schwoon, M. (2006), *Learning-by-doing, Learning Spillovers and the Diffusion of Fuel Cell Vehicles*, **FNU-112** (submitted).

Strzepek, K.M., G.W. Yohe, R.S.J. Tol and M. Rosegrant (2006), *The Value of the High Aswan Dam to the Egyptian Economy*, **FNU-111** (*Ecological Economics*, **66** (1), 117-126).

Schwoon, M. (2006), *A Tool to Optimize the Initial Distribution of Hydrogen Filling Stations*, **FNU-110** (*Transportation Research D: Transport and the Environment*, **12** (2), 70-82).

Tol, R.S.J., K.L. Ebi and G.W. Yohe (2006), *Infectious Disease, Development, and Climate Change: A Scenario Analysis*, **FNU-109** (*Environment and Development Economics*, **12**, 687-706).

Lau, M.A. (2006), *An analysis of the travel motivation of tourists from the People's Republic of China*, **FNU-108** (submitted).

Lau, M.A. and R.S.J. Tol (2006), *The Chinese are coming – An analysis of the preferences of Chinese holiday makers at home and abroad*, **FNU-107** (submitted).

Röckmann, C., R.S.J. Tol, U.A. Schneider, and M.A. St.John (2006), *Rebuilding the Eastern Baltic cod stock under environmental change - Part II: The economic viability of a marine protected area.* **FNU-106** (*Natural Resources Modelling*, **22** (1), 1-25)

Ronneberger, K., M. Berrittella, F. Bosello and R.S.J. Tol (2006), *KLUM@GTAP: Introducing biophysical aspects of land-use decisions into a general equilibrium model. A coupling experiment*, **FNU-105** (*Environmental Modelling and Assessment*, **14**, 149-169).

Link, P.M. and Tol, R.S.J. (2006), *Economic impacts on key Barents Sea fisheries arising from changes in the strength of the Atlantic thermohaline circulation*, **FNU-104** (*Global Environmental Change*, **19**, 422-433).

Link, P.M. and Tol, R.S.J. (2006), *Estimation of the economic impact of temperature changes induced by a shutdown of the thermohaline circulation: an application of FUND*, **FNU-103** (*Climatic Change*, doi: 10.1007/s10584-009-9796-7).

Tol, R.S.J. (2006), *Integrated Assessment Modelling*, **FNU-102** (submitted).

Tol, R.S.J. (2006), *Carbon Dioxide Emission Scenarios for the USA*, **FNU-101** (*Energy Policy*, **35**, 5310-5326).

Tol, R.S.J., S.W. Pacala and R.H. Socolow (2006), *Understanding Long-Term Energy Use and Carbon Dioxide Emissions in the USA*, **FNU-100** (*Journal of Policy Modelling*, **31**, 425-445).

Sesabo, J.K, H. Lang and R.S.J. Tol (2006), *Perceived Attitude and Marine Protected Areas (MPAs) establishment: Why households' characteristics matters in Coastal resources conservation initiatives in Tanzania*, **FNU-99** (submitted).

Tol, R.S.J. (2006), *The Polluter Pays Principle and Cost-Benefit Analysis of Climate Change: An Application of* FUND, **FNU-98** (submitted)

Tol, R.S.J. and G.W. Yohe (2006), *The Weakest Link Hypothesis for Adaptive Capacity: An Empirical Test*, **FNU-97** (*Global Environmental Change*, **17**, 218-227)

Berrittella, M., K. Rehdanz, R.Roson and R.S.J. Tol (2005), *The Economic Impact of Water Pricing: A Computable General Equilibrium Analysis*, **FNU-96** (*Water Policy*, **10** (3), 259-271)

Sesabo, J.K. and R. S. J. Tol (2005), *Technical Efficiency and Small-scale Fishing Households in Tanzanian coastal Villages: An Empirical Analysis*, **FNU-95** (submitted)

Lau, M.A. (2005), *Adaptation to Sea-level Rise in the People's Republic of China – Assessing the Institutional Dimension of Alternative Organisational Frameworks*, **FNU-94** (submitted)

Berrittella, M., A.Y. Hoekstra, K. Rehdanz, R. Roson and R.S.J. Tol (2005), *The Economic Impact of Restricted Water Supply: A Computable General Equilibrium Analysis*, **FNU-93** (*Water Research*, **42**, 1799-1813)

Tol, R.S.J. (2005), *Europe's Long Term Climate Target: A Critical Evaluation*, **FNU-92** (*Energy Policy*, **35** (1), 424-434)

Hamilton, J.M. (2005), *Coastal Landscape and the Hedonic Price of Accommodation*, **FNU-91** (Ecological Economics, **62** (3-4), 594-602)

Hamilton, J.M., D.J. Maddison and R.S.J. Tol (2005), *Climate Preferences and Destination Choice: A Segmentation Approach*, **FNU-90** (submitted)

Zhou, Y. and R.S.J. Tol (2005), *Valuing the Health Impacts from Particulate Air Pollution in Tianjin*, **FNU-89** (submitted)

Röckmann, C. (2005), *International Cooperation for Sustainable Fisheries in the Baltic Sea*, **FNU-88** (forthcoming, in Ehlers,P./Lagoni,R. (Eds.): *International Maritime Organisations and their Contribution towards a Sustainable Marine Development*.)

Ceronsky, M., D. Anthoff, C. Hepburn and R.S.J. Tol (2005), *Checking the price tag on catastrophe: The social cost of carbon under non-linear climate response* **FNU-87** (submitted, *Climatic Change*)

Zandersen, M. and R.S.J. Tol (2005), *A Meta-analysis of Forest Recreation Values in Europe*, **FNU-86** (*Journal of Forest Economics*, **15** (9), 109-130)

Heinzow, T., R.S.J. Tol and B. Brümmer (2005), Offshore-Windstromerzeugung in der Nordsee -eine ökonomische und ökologische Sackgasse? **FNU-85** (*Energiewirtschaftliche Tagesfragen*, **56** (3), 68-73)

Röckmann, C., U.A. Schneider, M.A. St.John, and R.S.J. Tol (2005), *Rebuilding the Eastern Baltic cod stock under environmental change - a preliminary approach using stock, environmental, and management constraints*, **FNU-84** (*Natural Resources Modelling*, **20** (2), 223-262)

Tol, R.S.J. and G.W. Yohe (2005), *Infinite uncertainty, forgotten feedbacks, and cost-benefit analysis of climate policy*, **FNU-83** (*Climatic Change*, **83**, 429-442)

Osmani, D. and R.S.J. Tol (2005), *The case of two self-enforcing international agreements for environmental protection*, **FNU-82** (submitted)

Schneider, U.A. and B.A. McCarl, (2005), *Appraising Agricultural Greenhouse Gas Mitigation Potentials: Effects of Alternative Assumptions*, **FNU-81** (submitted)

Zandersen, M., M. Termansen, and F.S. Jensen, (2005), *Valuing new forest sites over time: the case of afforestation and recreation in Denmark*, **FNU-80** (submitted)

Guillerminet, M.-L. and R.S.J. Tol (2005), *Decision making under catastrophic risk and learning: the case of the possible collapse of the West Antarctic Ice Sheet*, **FNU-79** (*Climatic Change*, **91** (1-2), 193-209)

Nicholls, R.J., R.S.J. Tol and A.T. Vafeidis (2005), *Global estimates of the impact of a collapse of the West Antarctic Ice Sheet: An application of FUND*, **FNU-78** (forthcoming, *Climatic Change*, **91** (1-2), 171-191)

Lonsdale, K., T.E. Downing, R.J. Nicholls, D. Parker, A.T. Vafeidis, R. Dawson and J.W. Hall (2005), *Plausible responses to the threat of rapid sea-level rise for the Thames Estuary*, **FNU-77** (submitted, *Climatic Change*)

Poumadère, M., C. Mays, G. Pfeifle with A.T. Vafeidis (2005), *Worst Case Scenario and Stakeholder Group Decision: A 5-6 Meter Sea Level Rise in the Rhone Delta, France*, **FNU-76** (submitted, *Climatic Change*)

Olsthoorn, A.A., P.E. van der Werff, L.M. Bouwer and D. Huitema (2005), *Neo-Atlantis: Dutch Responses to Five Meter Sea Level Rise,* **FNU-75** (forthcoming, *Climatic Change*)

Toth, F.L. and E. Hizsnyik (2005), *Managing the inconceivable: Participatory assessments of impacts and responses to extreme climate change*, **FNU-74** (submitted, *Climatic Change*)

Kasperson, R.E. M.T. Bohn and R. Goble (2005), *Assessing the risks of a future rapid large sea level rise: A review,* **FNU-73** (submitted, *Climatic Change*)

Schleupner, C. (2005), *Evaluation of coastal squeeze and beach reduction and its consequences for the Caribbean island Martinique,* **FNU-72** (submitted)

Schleupner, C. (2005), *Spatial Analysis As Tool for Sensitivity Assessment of Sea Level Rise Impacts on Martinique,* **FNU-71** (submitted)

Sesabo, J.K. and R.S.J. Tol (2005), *Factors affecting Income Strategies among households in Tanzanian Coastal Villages: Implication for Development-Conservation Initiatives,* **FNU-70** (submitted)

Fisher, B.S., G. Jakeman, H.M. Pant, M. Schwoon. and R.S.J. Tol (2005), *CHIMP: A Simple Population Model for Use in Integrated Assessment of Global Environmental Change*, **FNU-69** (*Integrated Assessment Journal*, **6** (3), 1-33)

Rehdanz, K. and R.S.J. Tol (2005), *A No Cap But Trade Proposal for Greenhouse Gas Emission Reduction Targets for Brazil, China and India*, **FNU-68** (*Climate Policy,* **18** (3), 293-304)

Zhou, Y. and R.S.J. Tol (2005), *Water Use in China's Domestic, Industrial and Agricultural Sectors: An Empirical Analysis*, **FNU-67** (*Water Science and Technoloy: Water Supply*, **5** (6), 85-93)

Rehdanz, K. (2005), *Determinants of Residential Space Heating Expenditures in Germany*, **FNU-66** (*Energy Economics* **29**)

Ronneberger, K., R.S.J. Tol and U.A. Schneider (2005), *KLUM: A Simple Model of Global Agricultural Land Use as a Coupling Tool of Economy and Vegetation,* **FNU-65** (submitted, *Climatic Change*)

Tol, R.S.J. (2005), *The Benefits of Greenhouse Gas Emission Reduction: An Application of* FUND, **FNU-64** (submitted, *Global Environmental Change*)

Röckmann, C., M.A. St.John, U.A. Schneider, F.W. Köster, F.W. and R.S.J. Tol (2006), *Testing the implications of a permanent or seasonal marine reserve on the population dynamics of Eastern Baltic cod under varying environmental conditions,* **FNU-63-revised** (*Fisheries Research*, **85**, 1-13)

Letsoalo, A., J. Blignaut, T. de Wet, M. de Wit, S. Hess, R.S.J. Tol and J. van Heerden (2005), *Triple Dividends of Water Consumption Charges in South Africa,* **FNU-62** (*Water Resources Research*, **43**, W05412)

Zandersen, M., Termansen, M., Jensen,F.S. (2005), *Benefit Transfer over Time of Ecosystem Values: the Case of Forest Recreation,* **FNU-61** (submitted)

Rehdanz, K., Jung, M., Tol, R.S.J. and Wetzel, P. (2005), *Ocean Carbon Sinks and International Climate Policy*, **FNU-60** (*Energy Policy*, **34**, 3516-3526)

Schwoon, M. (2005), *Simulating the Adoption of Fuel Cell Vehicles*, **FNU-59** (submitted)

Bigano, A., J.M. Hamilton and R.S.J. Tol (2005), *The Impact of Climate Change on Domestic and International Tourism: A Simulation Study*, **FNU-58** (submitted, *Integrated Assessment Journal*)

Bosello, F., R. Roson and R.S.J. Tol (2004), *Economy-wide estimates of the implications of climate change: Human health*, **FNU-57** (*Ecological Economics*, **58**, 579-591)

Hamilton, J.M. and M.A. Lau (2004) *The role of climate information in tourist destination choice decision-making,* **FNU-56** (forthcoming, Gössling, S. and C.M. Hall (eds.), Tourism and Global Environmental Change. London: Routledge)

Bigano, A., J.M. Hamilton and R.S.J. Tol (2004), *The impact of climate on holiday destination choice*, **FNU-55** (*Climatic Change*, **76** (3-4), 389-406)

Bigano, A., J.M. Hamilton, M. Lau, R.S.J. Tol and Y. Zhou (2004), *A global database of domestic and international tourist numbers at national and subnational level,* **FNU-54** (*International Journal of Tourism Research,* **9**, 147-174)

Susandi, A. and R.S.J. Tol (2004), *Impact of international emission reduction on energy and forestry sector of Indonesia*, **FNU-53** (submitted)

Hamilton, J.M. and R.S.J. Tol (2004), *The Impact of Climate Change on Tourism and Recreation*, **FNU-52** (forthcoming, Schlesinger et al. (eds.), Cambridge University Press)

Schneider, U.A. (2004), *Land Use Decision Modelling with Soil Status Dependent Emission Rates*, **FNU-51** (submitted)

Link, P.M., U.A. Schneider and R.S.J. Tol (2004), *Economic impacts of changes in fish population dynamics: the role of the fishermen's harvesting strategies,* **FNU-50** (submitted)

Berritella, M., A. Bigano, R. Roson and R.S.J. Tol (2004), *A General Equilibrium Analysis of Climate Change Impacts on Tourism*, **FNU-49** (*Tourism Management*, **27** (5), 913-924)

Tol, R.S.J. (2004), *The Double Trade-Off between Adaptation and Mitigation for Sea Level Rise: An Application of* FUND, **FNU-48** (*Mitigation and Adaptation Strategies for Global Change*, **12** (5), 741-753)

Erdil, E. and Yetkiner, I.H. (2004), *A Panel Data Approach for Income-Health Causality,* **FNU-47**

Tol, R.S.J. (2004), *Multi-Gas Emission Reduction for Climate Change Policy: An Application of* FUND, **FNU-46** (*Energy Journal* (Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue), 235-250)

Tol, R.S.J. (2004), *Exchange Rates and Climate Change: An Application of* FUND, **FNU-45** (*Climatic Change*, **75**, 59-80)

Gaitan, B., Tol, R.S.J, and Yetkiner, I. Hakan (2004), *The Hotelling's Rule Revisited in a Dynamic General Equilibrium Model*, **FNU-44** (submitted)

Rehdanz, K. and Tol, R.S.J (2004), *On Multi-Period Allocation of Tradable Emission Permits*, **FNU-43** (submitted)

Link, P.M. and Tol, R.S.J. (2004), *Possible Economic Impacts of a Shutdown of the Thermohaline Circulation: An Application of* FUND, **FNU-42** (*Portuguese Economic Journal*, **3**, 99-114)

Zhou, Y. and Tol, R.S.J. (2004), *Evaluating the costs of desalination and water transport,* **FNU-41** (*Water Resources Research,* **41** (3), W03003)

Lau, M. (2004), *Küstenzonenmanagement in der Volksrepublik China und Anpassungsstrategien an den Meeresspiegelanstieg*,**FNU-40** (*Coastline Reports* (1), 213-224.)

Rehdanz, K. and D.J. Maddison (2004), *The Amenity Value of Climate to German Households*, **FNU-39** (submitted)

Bosello, F., Lazzarin, M., Roson, R. and Tol, R.S.J. (2004), *Economy-wide Estimates of the Implications of Climate Change: Sea Level Rise*, **FNU-38** (*Environmental and Resource Economics*, **37**, 549-571)

Schwoon, M. and Tol, R.S.J. (2004), *Optimal CO_2-abatement with socio-economic inertia and induced technological change*, **FNU-37** (*Energy Journal*, **27** (4), 25-60)

Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2004), *The Effects of Climate Change on International Tourism*, **FNU-36** (*Climate Research*, **29**, 255-268)

Hansen, O. and R.S.J. Tol (2003), *A Refined Inglehart Index of Materialism and Postmaterialism*, **FNU-35** (submitted)

Heinzow, T. and R.S.J. Tol (2003), *Prediction of Crop Yields across four Climate Zones in Germany: An Artificial Neural Network Approach*, **FNU-34** (submitted, *Climate Research*)

Tol, R.S.J. (2003), *Adaptation and Mitigation: Trade-offs in Substance and Methods*, **FNU-33** (*Environmental Science and Policy*, **8** (6), 572-578)

Tol, R.S.J. and T. Heinzow (2003), *Estimates of the External and Sustainability Costs of Climate Change*, **FNU-32** (submitted)

Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2003), *Climate change and international tourism: a simulation study*, **FNU-31** (*Global Environmental Change*, **15** (3), 253-266)

Link, P.M. and R.S.J. Tol (2003), *Economic impacts of changes in population dynamics of fish on the fisheries in the Barents Sea*, **FNU-30** (*ICES Journal of Marine Science*, **63** (4), 611-625)

Link, P.M. (2003), *Auswirkungen populationsdynamischer Veränderungen in Fischbeständen auf die Fischereiwirtschaft in der Barentssee*, **FNU-29** (*Essener Geographische Arbeiten*, **35**, 179-202)

Lau, M. (2003), *Coastal Zone Management in the People's Republic of China – An Assessment of Structural Impacts on Decision-making Processes*, **FNU-28** (*Ocean & Coastal Management*, No. 48 (2005), pp. 115-159.)

Lau, M. (2003), *Coastal Zone Management in the People's Republic of China – A Unique Approach?*, **FNU-27** (*China Environment Series*, Issue 6, pp. 120-124; http://www.wilsoncenter.org/topics/pubs/7-commentaries.pdf)

Roson, R. and R.S.J. Tol (2003), *An Integrated Assessment Model of Economy-Energy-Climate – The Model Wiagem: A Comment*, **FNU-26** (*Integrated Assessment*, **6** (1), 75-82)

Yetkiner, I.H. (2003), *Is There An Indispensable Role For Government During Recovery From An Earthquake? A Theoretical Elaboration*, **FNU-25**

Yetkiner, I.H. (2003), *A Short Note On The Solution Procedure Of Barro And Sala-i-Martin for Restoring Constancy Conditions*, **FNU-24**

Schneider, U.A. and B.A. McCarl (2003), *Measuring Abatement Potentials When Multiple Change is Present: The Case of Greenhouse Gas Mitigation in U.S. Agriculture and Forestry*, **FNU-23** (submitted)

Zhou, Y. and Tol, R.S.J. (2003), *The Implications of Desalination to Water Resources in China - an Economic Perspective*, **FNU-22** (*Desalination*, **163** (4), 225-240)

Yetkiner, I.H., de Vaal, A., and van Zon, A. (2003), *The Cyclical Advancement of Drastic Technologies*, **FNU-21**

Rehdanz, K. and Maddison, D. (2003) *Climate and Happiness*, **FNU-20** (*Ecological Economics*, **52** 111-125)

Tol, R.S.J., (2003), *The Marginal Costs of Carbon Dioxide Emissions: An Assessment of the Uncertainties*, **FNU-19** (*Energy Policy*, **33** (16), 2064-2074).

Lee, H.C., B.A. McCarl, U.A. Schneider, and C.C. Chen (2003), *Leakage and Comparative Advantage Implications of Agricultural Participation in Greenhouse Gas Emission Mitigation*, **FNU-18** (submitted).

Schneider, U.A. and B.A. McCarl (2003), *Implications of a Carbon Based Energy Tax for U.S. Agriculture*, **FNU-17** (submitted).

Tol, R.S.J. (2002), *Climate, Development, and Malaria: An Application of* FUND, **FNU-16** (forthcoming, *Climatic Change*).

Hamilton, J.M. (2003), *Climate and the Destination Choice of German Tourists*, **FNU-15** (revised and submitted).

Tol, R.S.J. (2002), *Technology Protocols for Climate Change: An Application of* FUND, **FNU-14** (*Climate Policy*, **4**, 269-287).

Rehdanz, K (2002), *Hedonic Pricing of Climate Change Impacts to Households in Great Britain*, **FNU-13** (*Climatic Change* **74**).

Tol, R.S.J. (2002), *Emission Abatement Versus Development As Strategies To Reduce Vulnerability To Climate Change: An Application Of* FUND, **FNU-12** (*Environment and Development Economics*, **10**, 615-629).

Rehdanz, K. and Tol, R.S.J. (2002), *On National and International Trade in Greenhouse Gas Emission Permits*, **FNU-11** (*Ecological Economics*, **54**, 397-416).

Fankhauser, S. and Tol, R.S.J. (2001), *On Climate Change and Growth*, **FNU-10** (*Resource and Energy Economics*, **27**, 1-17).

Tol, R.S.J.and Verheyen, R. (2001), *Liability and Compensation for Climate Change Damages – A Legal and Economic Assessment*, **FNU-9** (*Energy Policy*, **32** (9), 1109-1130).

Yohe, G. and R.S.J. Tol (2001), *Indicators for Social and Economic Coping Capacity – Moving Toward a Working Definition of Adaptive Capacity*, **FNU-8** (*Global Environmental Change*, **12** (1), 25-40).

Kemfert, C., W. Lise and R.S.J. Tol (2001), *Games of Climate Change with International Trade*, **FNU-7** (*Environmental and Resource Economics*, **28**, 209-232).

Tol, R.S.J., W. Lise, B. Morel and B.C.C. van der Zwaan (2001), *Technology Development and Diffusion and Incentives to Abate Greenhouse Gas Emissions*, **FNU-6** (submitted).

Kemfert, C. and R.S.J. Tol (2001), *Equity, International Trade and Climate Policy*, **FNU-5** (*International Environmental Agreements*, **2**, 23-48).

Tol, R.S.J., Downing T.E., Fankhauser S., Richels R.G. and Smith J.B. (2001), *Progress in Estimating the Marginal Costs of Greenhouse Gas Emissions*, **FNU-4**. (*Pollution Atmosphérique – Numéro Spécial: Combien Vaut l'Air Propre?*, 155-179).

Tol, R.S.J. (2000), *How Large is the Uncertainty about Climate Change?*, **FNU-3** (*Climatic Change*, **56** (3), 265-289).

Tol, R.S.J., S. Fankhauser, R.G. Richels and J.B. Smith (2000), *How Much Damage Will Climate Change Do? Recent Estimates*, **FNU-2** (*World Economics,* **1** (4), 179-206)

Lise, W. and R.S.J. Tol (2000), *Impact of Climate on Tourism Demand*, **FNU-1** (*Climatic Change*, **55** (4), 429-449).