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Research, part of a Special Feature on A Systems Approach for Sustainable Development in Coastal Zones

Mussel Production and Water Framework Directive Targets in the Limfjord, Denmark: an Integrated Assessment for Use in System-Based Management

Grete E. Dinesen [1], *Karen Timmermann* [2], *Eva Roth* [3], *Stiig Markager* [2], *Lars Ravn-Jonsen* [3], *Morten Hjorth* [2], *Marianne Holmer* [4], *and Josianne G. Støttrup* [1]

ABSTRACT. Growth of human activities often conflict with nature conservation requirements and integrated assessments are necessary to build reliable scenarios for management. In the Limfjord, Denmark's largest estuary, nutrient loading reductions are necessary to fulfill EU regulations criteria, such as the Water Framework Directive (WFD). Cuts in nutrient loadings do not necessarily result in corresponding reductions in eutrophication impacts or in improving primary and higher trophic-level production. Similarly, the socioeconomic consequences of a mussel fishery and aquaculture production are complex and hard to predict. This study focuses on the usefulness of a System Approach Framework (SAF) implementation for stakeholder understanding of complex systems and development of sustainable management. Ecological-social-economic (ESE) model simulations clearly demonstrated the potential problems of WFD implementation for mussel fishers and mussel farmers. Simulation of mussel fishery closures resulted in a tenfold increase in the hitherto fishable mussel biomass and a similar decrease in the biomass of shallow-water mussels and medium-sized ones in deep water. A total closure of the mussel fishery could result in an annual profit loss of ~€6.2 million. Scenario simulation of the introduction of one, two, three, and four mussel culture farms of ~19 ha showed that the introduction of line-mussels would decrease the biomass of wild mussels both in shallow and deep waters, affecting the catch and profit of fishers. The SAF, which included consultation with stakeholders at all stages, differs from the traditional public consultation process in that (1) communication was verbal and multilateral, (2) discussion among stakeholders was facilitated, and (3) stakeholder opinions and priorities formed the focus of the ESE assessment.

Key Words: *aquaculture; bioeconomical modeling; blue mussels; Danish estuary; eutrophication; fishery; integrated coastal system assessment; stakeholder involvement*

INTRODUCTION

Coastal systems throughout the world suffer from rapidly increasing anthropogenic pressures, and integrated management solutions are required to ensure sustainable use of resources (Moksness et al. 2009). In European coastal waters, eutrophication caused by nutrient leaching from arable and urban areas threatens both ecosystem health and opportunities for important economic development. Nitrogen (N) and phosphorous (P) loading in the largest Danish estuary, the Limfjord, increased sixfold since 1900, peaking in the mid 1980s. By the 1970s finfish fishery had declined dramatically. The concurrent increase in blue mussel (*Mytilus edulis*) biomass supported a thriving mussel fishery, which became the largest harvest yield from the fjord (Hoffmann 1994, 2005). In recent years mussel biomass and harvest have decreased with a decrease in nutrient loadings. With national implementation of the European Union's Water Framework Directive (WFD), further reductions in nutrient loadings are required, giving rise to more concern from mussel producers who anticipate continued diminishing resources. Dredging of wild mussel stocks causes temporary habitat disturbance (Hoffmann and Dolmer 2000, Dolmer et al. 2009), and alternative mussel production methods such as bed (Dolmer at al. 2008) and line cultures (Dolmer and Geitner 2004, Christensen et al. 2008) have been developed. However with further decreases in nutrient loading, there is concern for the future of this industry as well as for increasing conflicts between mussel fishers and mussel farmers.

The Limfjord coastal zone

Ecosystem description

With a coastline of 1000 km, a surface area of 1526 km² and a mean depth of 5.5 m, the Limfjord connects with the North Sea to the west and the Kattegat to the east (Fig. 1). The Limfjord's catchment area is 7528 km², of which 62% is arable land (Christiansen et al. 2006, Markager et al. 2006, 2010). The estuary has experienced a sixfold increase in total nitrogen (N) and phosphorous (P) loadings over the past ~100 years, peaking in the mid 1980s with annual loadings of 12 tons N/km² and 0.92 tons P/km² surface area (Christiansen et al. 2006). Since then, the loadings have decreased by 40% and 71%, respectively. Stratification occurs for about half the summer season. Water clarity has been reduced and anoxia and hypoxia occur regularly from July to September (Markager et al. 2006, Dolmer et al. 2008), particularly in the inner southeastern parts of the estuary, and harmful algal blooms (HABs) are common (E. Roth, G. E. Dinesen, K. Timmermann, L. Ravn-Jonsen,

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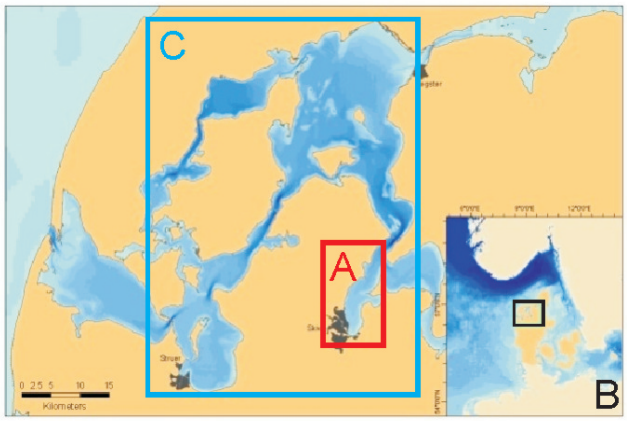
D. Ahsan, and J. Støttrup, *unpublished manuscript*; Fig. 2). Eelgrass (*Zostera marina*) covers < 5% of the 1900s extensive meadows and today phytoplankton dominates primary production (Krause-Jensen et al., *in press*). The fish fauna has changed from a cod (*Gadus morhua*) dominance in the early 1900s to flatfish (Flintegaard et al. 1982), which declined in the 1960s and was replaced by pelagic species, in particular sprat and herring (Hoffmann 1994, 2005, Mouritsen et al. 2005). New evidence supports the argument that a regime shift took place in the early 1990s, substituting periodic-equilibrium with opportunistic organisms and decreasing ecosystem resilience (T. T. Tomczak, G. E. Dinesen, E. Hoffmann, S. Markager, and J. Støttrup, *unpublished manuscript*).

Fig. 1. Map of the Limfjord area. The virtual system (ecological-social-economic or ESE-model) covers the ecology of Skive Fjord (A), mussel fishery activities in the entire fjord (B), and line mussel culture farms in the central area of the fjord (C).



Historical, cultural, and economic activities

The Limfjord is a rural area, traditionally supporting farming activities in summer and fishing in winter. Fishing was once a thriving industry, more important than agriculture as a local source of food (Møllgaard 1992). After World War II, industrialization took place in both fishing and agriculture, increasing the use of fertilizers and harvest yields, with associated requirements for capital and know-how.

Today's agriculture is dominated by large, specialized units mainly producing pigs based on imported fodder because of low fertile, sandy soils. In the 1960s, a blue mussel fishery replaced the finfish fishery providing harvest yields that peaked at > 100,000 tons in the 1990s (Hoffmann 1994, 2005, Mouritsen et al. 2005). In 2006-2008, the mussel fishery declined to ~30,000 tons (data available at http://fd.fvm.dk/landings-_og_fangststatistik.aspx?ID=24363).

Fig. 2. The Limfjord study site environment and selected stakeholders. From left, top row: a mussel bed after a hypoxia event, blue mussel (*Mytilus edulis*) predators, Common Eider (*Somateria mollissima*), and Common Starfish (*Asterias rubens*); bottom row: mussel dredging, line-mussel farm, and line-mussel husbandry (top row photographs by Peter Bondo Christensen, Carsten Siems, and Karsten Dahl).

Governance

In response to increasing concerns about eutrophication, a joint monitoring program of the Limfjord began in 1982 by the four counties surrounding the estuary. In January 2007, the counties were abolished and their responsibilities shared between municipalities and the national administration. In 2010, action plans to comply with the WFD to achieve good ecological status entered a public consultation process. In addition to the WFD, other EU directives, such as the NATURA 2000 Habitat Directive (HD) and Birds Directive (BD) also apply to the Limfjord, and mussel production activities now require an Environmental Impact Assessment (EIA) evaluation by the Directorate of Fishery.

Fisheries management is carried out at the national level outside the jurisdiction of local authorities. The Danish Fisheries act (LBK nr. 978 af 26/09/2008, §6 and §6a) stipulated the establishment of two advisory committees to aid the Minister of Food, Agriculture and Fishery in the implementation of fishing and mussel production management. Both committees have a broad representation from the industry, labor market partners, and NGOs, and provide advice on matters concerning regulation and implementation of fisheries and aquaculture management.

The mussel fishery is regulated through 51 individual, transferable licenses distributed between 39 vessels. No vessel can hold more than two licenses. Weekly quotas, minimum mussel size, and meat content, as well as food safety regulations are under the jurisdiction of the Fisheries Directorate (BEK nr. 155/03/2000, BEK nr. 372 af 15/05/2009). An agreement between fishers sets weekly quotas (≤ 45 tons/week) lower than official quotas set by management (85 tons/week). The first licenses for line-mussel

culture in the Limfjord were issued in 2003 (Christensen et al. 2008). At present, 18 mussel farms are in production. Each license covers 250 x 750 m² (~19 ha) but mussel farmers try to exploit economy of scale through cooperative solutions and the effective average farm size is 34 ha (Ahsan and Roth 2010).

Simulation analysis

The applicability of the System Approach Framework (SAF) to facilitate knowledge transfer between decision makers, the public, and scientists (including our team), was evaluated with the aim of enhancing sustainable integrated management solutions (Hopkins et al. 2011). In the ecological-social-economic (ESE) assessment, we aimed at integrating empirically-based process descriptions and activities related to specific policy issues, as identified by stakeholders. A major challenge was to incorporate spatial and temporal scale data approximations because of system knowledge constraints and lack of data. The establishment of a conceptual model was required to set system boundaries and select the ESE components and linkages important for the policy issues addressed.

Aims

The aims of this research were to describe two selected aspects of the SAF: (1) scenario simulations to assist stakeholders in understanding the complexity of ecosystem responses and economic consequences of potential management options and (2) usefulness of SAF implementation and stakeholder engagement for sustainable management.

MATERIAL AND METHODS

Policy-stakeholder involvement

The Limfjord stakeholder group (Fig. 3) comprised members of established forums concerned with environmental, fisheries, and aquaculture management and was broadened to encompass other sectors, such as tourism, agriculture, and recreational fishing.

Virtual system

Boundaries

The virtual system of the ecological component of the study covered Skive Fjord, an embayment of the Limfjord, whereas the socioeconomic components covered the entire Limfjord (Fig. 1). This reflects existing scale differences between monitoring strategies related to different legislative issues, such as fisheries, aquaculture, WFD, and NATURA 2000. Information from national environmental monitoring (Berg et al. 1988, Kronvang et al. 1993, Kaas and Markager 1998, Conley et al. 2002) provided external input into the ecological model component. The latter included a linkage between nutrient loadings and phytoplankton primary production based on an empirical model (Broadhurst et al. 1997, Markager et al. 2006, 2008) and data on hypoxia (E. Roth, G. E. Dinesen, K. Timmermann, L. Ravn-Jonsen, D. Ahsan, and J. Støttrup, *unpublished manuscript*). External input into the economic component for aquaculture included new data on labor optimization and profit maximization (Ahsan and Roth 2010). External input to the mussel fishery component included account statistics, temporary closures of the mussel fishery due to HAB events (summer) and a low meat content (winter), quotas, and numbers of licenses. External input to the aquaculture component included time of larval settlement (May) and harvest time (August-September, depending on market opportunities).

Fig. 3. Limfjord stakeholder meetings. From left: stakeholder discussions to prioritize policy issues during the design step, plenary presentation during the formulation step and hands-on experience with the ESE-model during the output step.

Validation data

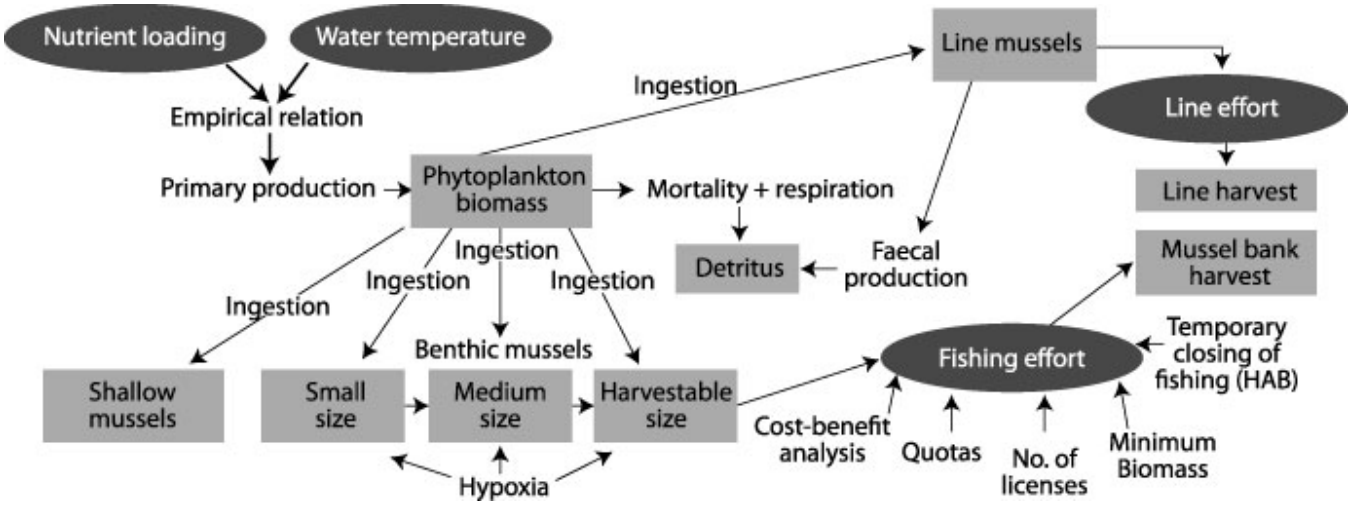
Measurements of chlorophyll *a* (Chl *a*), blue mussel biomass, and annual mussel landings were used to calibrate and validate the ecological model. Data on Chl *a* concentration and mussel biomass were obtained from the national environmental monitoring program (data available at www.dmu.dk/en/water/marinemonitoring/mads/). Yearly reports of mussel landings in Skive Fjord and culture harvests from the entire Limfjord were used for model calibration.

ESE-model

The bioeconomic model is a fully coupled model consisting of an ecological model, an agent-based mussel fishing model, and a line-mussel culture model (Fig. 4). This ESE-model was developed using basin model software (ExtendSim® v.7.1.5; model details in Støttrup et al. 2010; Dinesen et al., *in press*; E. Roth, G. E. Dinesen, K. Timmermann, L. Ravn-Jonsen, D. Ahsan, and J. Støttrup, *unpublished manuscript*; available at http://dataportals.pangaea.de/spicosa/SPICOSA_model_library.html).

The hydrographic and ecological conditions differ greatly between the Limfjord basins, and ecological models need to be basin specific for credibility (Kronvang and Bruhn 1996, Bøgestrand 2001, Markager et al. 2006). Because of limited resources we chose to include only one basin, Skive Fjord, in the ecological model component. It describes the conversion of N and P loadings to phytoplankton primary production and blue mussel biomasses, and consists of six state variables including phytoplankton and five groups of mussels (unit: mmol C/m²), i.e., mussels in shallow water < 2 m, three size classes of mussels in deep water (shell length, SL: < 2.0 cm,

Fig. 4. Conceptual flow diagram of the ecological-social-economic (ESE) model.



2.0-4.5 cm, and > 4.5 cm, depth, ≥ 2 m), and line-mussels (mmol C/line-meter[1]). Empirical relations were used to describe the link between nutrient loadings (total N and P), freshwater run-off, seawater temperature, surface radiation, NAO index, salinity, wind speed, and monthly averages of phytoplankton production in spring (January-June) and autumn (July-December) using forward selection multiple linear regression (Sokal and Rohlf 2000) applied to data for the years 1984-2003 (Markager et al. 2008; Dinesen et al., *in press*). Primary production values (mmol C m^{-2} day^{-1}) were calculated from 12-48 measurements annually (^{14}C method) obtained from the Skive Fjord station. Simultaneously obtained Chl *a* measurements by spectrophotometry (at two depths) and calibrated with in situ fluorescence measurements (10 cm depth resolution) were converted to monthly averages of phytoplankton biomass (mmol C/m^2) for ESE-model usage. Hypoxia was simulated as random events during July-September, with frequencies based on weekly measurements of oxygen concentrations in Skive Fjord over the last 26 years.

Biomass of each mussel group depends on recruitment, growth rate, and mortality rate. Growth rates were determined by food ingested, egestion, and respiration, and mortality rates by predation, hypoxia, and catch. Only deep-water mussels are affected by hypoxia. The dominant predator is the shore crab (*Carcinus maenas*; Frandsen and Dolmer 2002). Equations and parameter values used are provided in Støttrup et al. (2010). The model had monthly recruitment to the small size class from June to September, and a monthly transfer rate to medium and harvestable size classes. The model covers 19 years (1985-2003) with monthly time-steps, equal to 228 steps, and was calibrated to match observed annual mean values for the four state variables (Table 1).

Table 1. State variables used for calibration of the ecological-social-economic (ESE) model, equal to the average of the annual mean values over the modeled 19 year period from 1985-2003.

State variable	Unit	Target, mean observed value	Model estimate, after calibration
Phytoplankton biomass	mmol C/m²	200	198
Mussel biomass Z < 2m	mmol C/m²	969	943
Mussel biomass Z > 2m	mmol C/m²	296	296
Mussel, annual catch	Tons WW	7000	7073

The linkages between the ecological and socioeconomic model components are harvestable yields of benthic mussel biomass at depths > 2 m and of line-mussel biomass in Skive Fjord. A novel approach was the empirical inclusion of secondary data obtained from food safety monitoring, to establish frequency of mussel fishery closures due to occurrence of toxic algae (Støttrup et al. 2010; E. Roth, G. E. Dinesen, K. Timmermann, L. Ravn-Jonsen, D. Ahsan, and J. Støttrup, *unpublished manuscript*). The fishery component describes fishing efforts, associated costs, and potential earnings for fishers and their voluntary quota-system. A fishing effort submodel estimates the effort provided by mussel fishers. This submodel treats fishers as adaptive agents who make decisions concerning their effort based on mussel biomass, allowed quota, benefits and mussel catching costs, temporary closure of the fishery due to HAB events, and

mussel mortalities due to hypoxia. Limfjord mussel fisheries vessel data were provided by the Danish national account statistics of fishery production for the years 2000-2006 and included variable costs, fixed costs, and prices at first hand sales.

In the line-mussel culture component of the ESE-model, mussels are grown for 11-18 months and total biomass depends on food availability, temperature, and the numbers and sizes of farms. The range of possible prices conforms to the range in the accounting statistics, but showed no relationship between price and labor intensity.

Hind-cast simulation and sensitivity analyses

The ESE-model's performance was tested during a major policy change from 1985-2003, when several water action plans were implemented. Hind-cast simulation results were averaged over the entire period and compared with yearly averages of measured Chl *a* concentration, mussel biomasses at shallow ($z < 2$ m) and deep ($z > 2$ m) water depths, and mussel harvest. Good agreement between observed and estimated values indicated that this ESE-model represented the ecosystem adequately (Table 1). Validation could have been improved if rate measurements of grazing pressure, mortality, and mussel growth, for example, had been available.

Calibration of the ecological model component included adjustment of phytoplankton mortality (excluding mussel ingestion), mussel mortality (except from hypoxia and dredging), transfers between size classes, minimum biomass for voluntary closure of dredging, and depletion of phytoplankton concentration within mussel beds. Primary production rate measurements could not be used for validation purposes because they were used to establish the empirical relationship incorporated in the model.

The ESE-model represents actual fishery activity, regulated by common agreement on quotas, closed seasons, and licenses. One aspect not included was the opportunity for fishers to operate outside the Limfjord or to fish on species other than mussels, because required data on opportunity income are not available. In the virtual system, the mussel fisher may continue to dredge until the quota is reached even when the profit margin is small. In the real world, fishers may stop fishing before reaching their quotas. The economic benefit mirrored closely the modeled optimal solution with lower landings and higher biomasses compared with the consequences for quotas set by the ministry. The mussel culture production model builds on the assumption that capital and raw material costs per farmed area are constant and a mussel farmer's behavior is driven by the license restrictions on the area (E. Roth, G. E. Dinesen, K. Timmermann, L. Ravn-Jonsen, D. Ahsan, and J. Støttrup, *unpublished manuscript*).

Selected aspects

Scenario simulation

Stakeholder-prioritized concerns were 'increased nutrient loadings,' 'no fish,' and 'no oxygen.' The policy issues to be addressed were: (1) regulation of nutrient effluents to reduce eutrophication, (2) potential closure of the mussel fishery because of national implementation of international directives, and (3) potential resource conflicts between mussel fishers and mussel farmers. The simulation scenarios chosen were: (1) reductions of total N and P, (2) closure of the wild mussel stock fishery, and (3) introduction of line-mussel culture. These scenarios were compared with the present situation.

SAF implementation and stakeholder engagement

The conceptual model was constructed based on stakeholder prioritization and data availability. Model design was discussed with stakeholders before formulation. Similarly, during formulation and appraisal, details and scenarios of each model component were presented and discussed during meetings. After model component linkages were established, a user-friendly model layout was developed and used to disseminate the ESE-model to stakeholders (Støttrup et al. 2010). The model layout enabled stakeholders to run scenarios and examine results on their own initiative, and requiring a minimum of assistance.

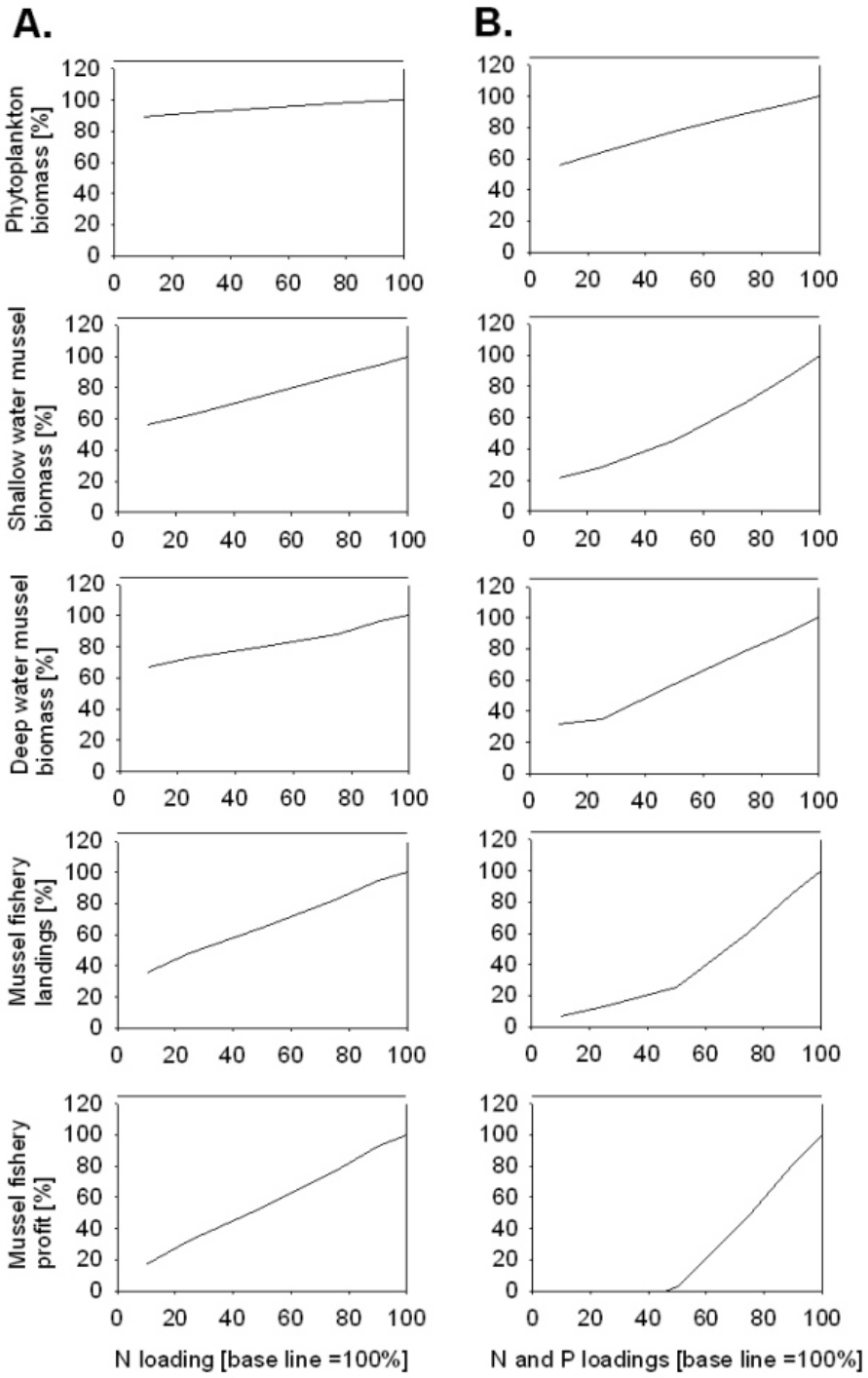
RESULTS

ESE-model scenarios

Scenario 1: Reductions in total N and P loadings

Figure 5 shows the relative difference (in %) between baseline loadings (hind-cast averages from 1985-2003) and reductions in N alone (Fig. 5A) and in N and P simultaneously (Fig. 5B). Reducing nitrogen loadings to the expected target for WFD implementation (Table 2, 54%) demonstrated a negligible decrease in phytoplankton biomass (< 5%), some biomass decrease in shallow (~25%) and deep-water mussels (~20%), and a near halving of the mussel fishery profit (Fig. 5A). An N reduction to ~69% (Table 2) would result in ~25% reduction of fishery profit. Simultaneous reduction in both N and P to ~50% level demonstrated a minor decrease in phytoplankton biomass (~20%), considerable biomass decrease in both shallow and deep-water mussels (~50%), and a near-collapse of the mussel fishery (Fig. 5B). Simultaneous reduction in both N and P had more impact than a reduction in N alone. Simulation of nutrient reductions showing bottom-up propagation of impacts in the food chain was a surprising result for mussel producers. They had not anticipated this scale of negative impact, their focus being on competition between mussels and other filter-feeders in the ecosystem. The WFD targeted level for P loading (60%) has nearly been reached (64%), which may partly explain the mussel fishery decline from ~100,000 to ~30,000 tons/year. The latest WFD only targets N reduction. This would allow the mussel fishery to continue, although at a lower level. In contrast, if both N and

Fig. 5. Results of model simulation of Scenario 1. Impact of percentage reduction of total nitrogen (A) and total nitrogen and phosphor (B) relative to the annual averages from 1985-2003 of (from top to bottom) phytoplankton concentration, mussel biomass in shallow and deep waters, mussel landings, and mussel fishery profit. The baseline is 100% loading, corresponding to the average from 1985-2003 (Table 2).



P were reduced to a similar level, the mussel fishery would cease.

Table 2. Total nutrient loadings in the Limfjord. Mean values (tons km^{-2} $year^{-1}$) and proportions relative to the mean values used for the ecological-social-economic (ESE) model calibration period from 1985-2003[†].

	Nitrogen		Phosphorous	
	T km^{-2} $year^{-1}$	%	T km^{-2} $year^{-1}$	%
1985-2003 mean obs. values	10.3	100	0.44	100
1984-1986 mean obs. values	12.3	120	0.91	207
2010 estimated values[‡]	6.8	66	0.28	64
Markager et al. 2006	*4.1*	*40*	*0.23*	*52*
Water action plan targets[§]	**5.6**	**54**	**0.24**	**60**
Water action plan targets[|]	**7.1**	**69**	**0.24**	**60**

[‡]Scaled to normal precipitation.
[†]Values in italics have been suggested by Markager et al. (2006) as the loadings that would be required to achieve 'good environmental status' as defined for the WFD.
[†]Values in bold are from the official Danish water action plan targets ([§]initial proposal from January 2010 and [|] modified proposal from May 2010, the latter of which is now under public consultation).

The empirical model for phytoplankton growth would require regular updating, particularly if nutrient loadings fall below the range of that of the hind-cast simulation period. Seasonality in phytoplankton diversity and production was included through differentiation between half yearly spring and autumn phytoplankton biomasses. The relationship established from the empirical model enhanced the ESE-model performance by allowing rapid simulations over a long time span. On the other hand, we did not have information on the nitrogen budget, including effluxes, regenerated production, and sediment remineralization. The latter is important to quantify because of decadal levels of accumulation and an unknown duration of remineralization.

Scenario 2: Closure of mussel fishery on wild stocks
Simulation of mussel fishery closures resulted in a more than tenfold increase in hitherto fishable mussel biomass and a similar decrease in shallow-water and medium-sized deep-water mussel biomass (Fig. 6). These are mainly controlled by phytoplankton availability, and increased competition for food from large-sized deep-water mussels. The smallest mussel group in deep-waters was less affected because this group is controlled by a fixed recruitment. The average total landings from 2000-2006 in the Limfjord was ~50,000 tons $year^{-1}$. A total closure of the mussel fishery could result in an annual profit loss of ~€6.2 million. This value was estimated from average profit recorded in national account statistics.

Linking the ecological and economic components was a major challenge because of spatial and temporal scale inequalities. Our decision to scale down to Skive Fjord, rather than scaling up to the whole Limfjord, was because of high sub-basin heterogeneity. However, the highly eutrophic Skive Fjord may support a proportionally larger mussel fishery than the $^1/_7$ area used for down-scaling. Thus, model simulation results provided conservative estimates for fishery and line culture.

The ESE-model considers the adaptive behavior of fishers due to changes in mussel biomass, prices, and mussel fishery regulations in the Limfjord. Frost et al. (2009) estimated the consequences of fewer vessels participating in this fishery on resource rent, i.e., economic surplus, in the industry under different exogenously set catch regimes (total landings of 73,000 tons and 30,000 tons/year, respectively). The present resource rent for 51 vessels at landings of 73,000 tons/year was estimated to be ~€2,133,333 (equivalent to 16 million DKK). A reduction to the most efficient 23 vessels would increase the resource rent to €6 million, which is a higher return compared with other Danish fisheries ventures. A reduction to seven vessels would earn a resource rent of €3.2 million and increase the income of these vessel owners to a level far above normal profit. At today's level of Limfjord mussel landings (30,000 tons/year) the estimated economic surplus for the original 51 licensed vessels is a loss of €3.2 million.

Scenario 3: Increase in mussel culture
Scenario simulation of the introduction of one, two, three, and four line-mussel culture farms of ~19 ha showed a decrease in wild mussel biomass both in shallow and deep waters (Fig. 7), adversely affecting the catch and profit of fishers. The small decrease in catch and profit indicated low potential for conflict with the wild mussel fishery in terms of harvestable biomass (Fig. 7). The increase in line-mussel production had little impact on shallow-water mussel biomass (Fig. 7). Model results indicated that the introduction of line culture would increase the total harvestable mussel biomass, e.g., the introduction of two farms would produce > 400 tons/year but decrease the catch of wild stocks by < 200 tons/year.

The mussel fisher's corporate view found the model highly credible because results from the fisheries model supported their own solution to reduce quotas. Although model simulated fishable mussel biomass decreased because of competition for food among mussel groups, the simulation results showed a lower impact than expected by the stakeholders (Fig. 7). Line-mussel culture, in addition to fishery, would increase total

Fig. 6. Results of model simulation for Scenario 2. Impact of mussel fishery activity as recorded from 1985-2003 (A), and total closure of mussel fishery (B), on (from top to bottom) shallow-water (< 2 m) mussel biomass, and biomasses of deep-water (> 2 m) small, medium, and large-sized mussels.

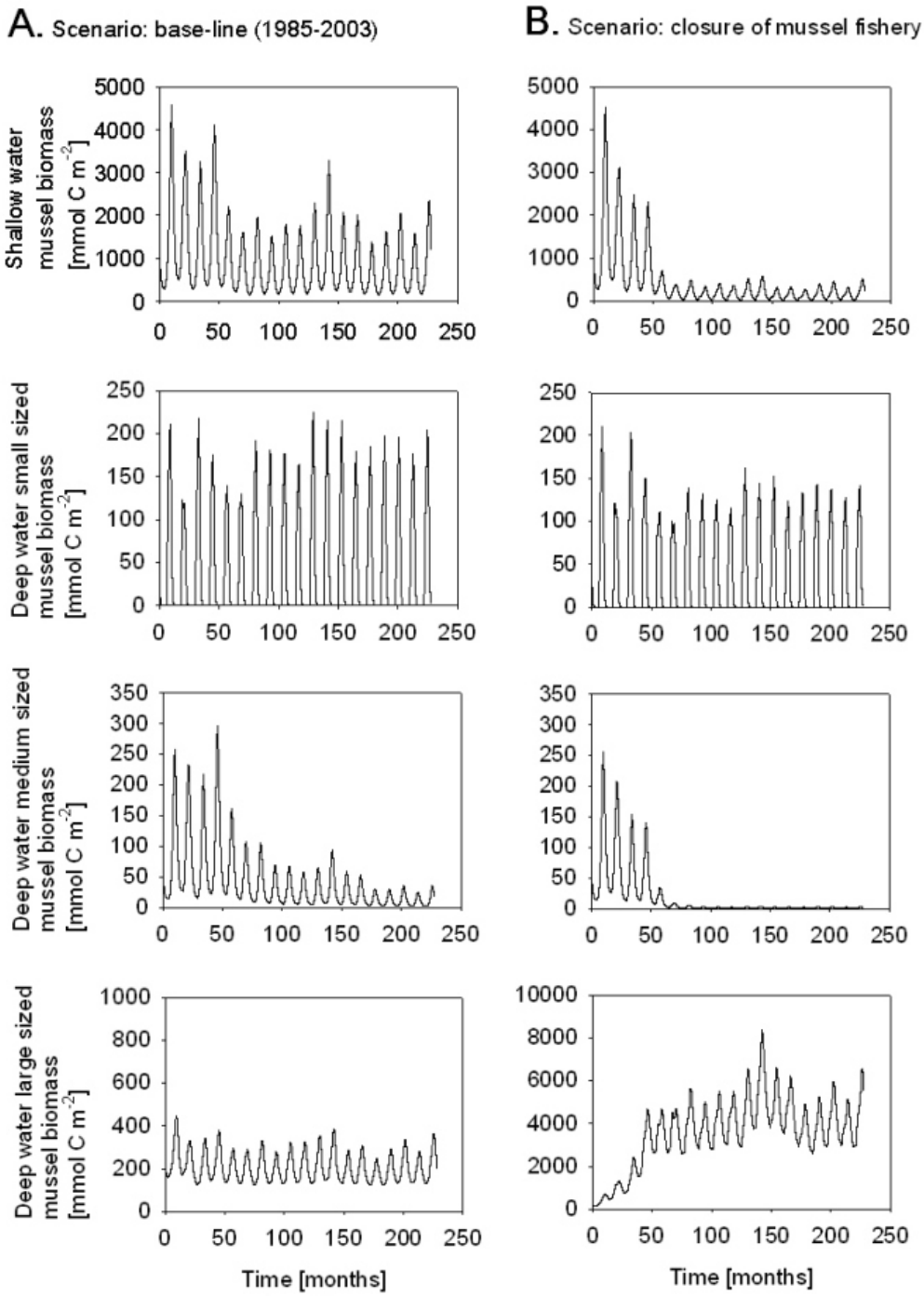
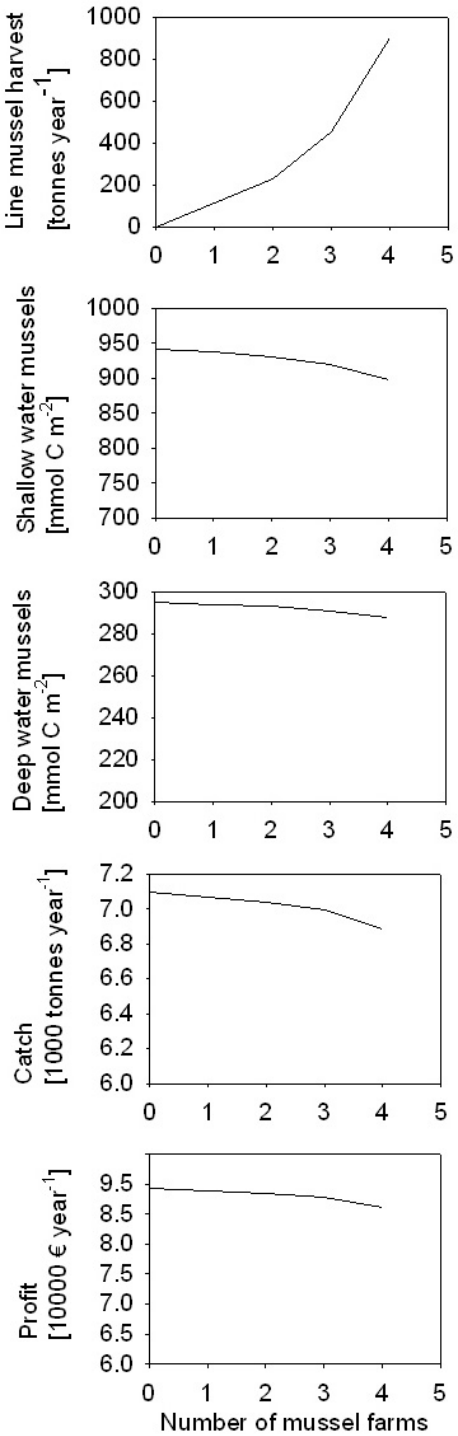


Fig. 7. Results of model simulation for Scenario 3. Impact of line-mussel culture deployment on (from top to bottom) harvested line-mussel biomass, biomass of shallow and deep-water mussels, mussel fishery landings and mussel fishery profits. The baseline is zero line-mussel cultures.



mussel production, indicating improved use of phytoplankton resources and higher system productivity. Because of higher market prices obtained for line-mussels than for fished mussels, the profit from introducing line-mussel culture would surpass economic losses from decreased fisheries by 200%. However, during stakeholder meetings it became clear that substituting mussel fisheries with farming is not viable as few stakeholders are involved in both production types. Furthermore, economies of scale are restricted by the size of plots licensing system and an expressed reluctance by both farmers and investors to raise sufficient capital under the present risk conditions (Ahsan and Roth 2010). The economic contribution to the formal economy from this sector is therefore at present negative.

SAF implementation and stakeholder engagement

The main concerns and opinions of the stakeholders were mapped during the first meeting (Table 3). The meeting format with plenary sessions and smaller group workshops proved popular among stakeholders, giving them a strong sense of engagement and ownership. Over a four-year period, the project's scientific team met six times with the stakeholders. The meetings were instrumental in providing information for setting the boundaries of the virtual system, for model adjustments relative to the real world, identifying scenarios for model simulation, and facilitating discussion of simulation results under different management scenarios.

Table 3. The participating Limfjord stakeholders and their main concerns prior to System Approach Framework (SAF) implementation.

Stakeholders	Main concerns and opinions prior to SAF implementation
Agriculture farmers[†]	Concern related to potential restriction on use of fertilizers.
Commercial fishers	Concern about eutrophication and loss of profitable finfish fisheries.
Environmental managers	National implementation of EU Directives.
Fisheries managers	Management and development of mussel and finfish fishery according to regulations and negatively affected yield by decreasing catchable stocks.
Mussel farmers	Development of profitable mussel farms, wish to reduce hypoxia and harmful algal blooms (HAB) events, avoid mussel predators and filter-feeding competitors.
Mussel fishers	Maintaining mussel fishery profitability, wish to reduce hypoxia events, avoid mussel predators/competitors, and secure natural mussel recruitment.

(con'd)

Nature conservation NGOs	Wish to decrease Total N and P loadings to reduce hypoxia events, secure shallow-water mussels as food for foraging birds, maintain high biodiversity, and secure recreational use of the Limfjord.
Recreational fishers	Restoration of a recreational finfish fishery in the Limfjord.
Municipals (Tourisms, Harbors)	Management of the Limfjord environment and use of goods and services.

[†]Some stakeholders were only present at the initial meeting and have not seen and discussed the simulation results.

Scenario simulation results provided both recognizable and unexpected results, which stimulated discussion among stakeholders. At the same time, scenario results provided cognition of a higher ecosystem complexity than hitherto understood. Stakeholders, who participated in the output meetings, expressed a positive reaction to the user-friendliness of the model and its ability to provide a credible overview of the ecosystem with which they were familiar. Nature conservation representatives radically changed their opinions with regard to management solutions from a complete mussel fishery ban to a more holistic approach because of a better understanding of the potential competition between harvestable mussels and those available to foraging birds. The changes in stakeholder perceptions initiated an open dialogue between conflicting stakeholders, in which a better understanding of each other's opinions and needs was expressed. Further, it led to new collaboration on other policy issues of common interest.

The regional environmental managers agreed with the model system component details from design to output. They felt the model gave a transparent and credible view of what is a complex system. In particular, the inclusion of economic components was found to be novel and useful for evaluating possible management solutions. The managers supported the SAF approach and suggested the model be developed as a tool for municipal manager's responsibilities with regard to WFD implementation.

DISCUSSION

The ESE-model simulation clearly demonstrated the potential problems of WFD implementation for mussel fishers and mussel farmers. Although mussel production is negatively impacted by frequent and prolonged hypoxia events due to nutrient overloading, model simulations demonstrated that nutrient reduction increases competition between mussel groups thereby reducing harvestable biomass. Extensive hypoxia events are among the most devastating effects of eutrophication in coastal systems (Ærtebjerg et al. 1998, Hansen et al. 1999, Thomsen et al. 2002) and cause high mortalities that impact mussel yields. An expected relationship between increased hypoxia and nutrient loadings could not be established empirically (Markager et al. 2006, 2008). The most likely reason for this is the large pool of nutrients and organic matter in the sediment that, when degraded, directly consumes oxygen and results in a continuous endogenous nutrient replenishment of the water column. Results for the Limfjord have shown a time lag of 8-12 years from a reduction in external loadings to a new equilibrium for total N and P concentrations (Markager et al. 2006). Because the time lag duration is not known, the exact threshold where reduced mussel growth due to nutrient related reduced phytoplankton production would outweigh expected increases in mussel survival is difficult to predict. Thus, with implementation of WFD, it is hard to predict when mussel biomass would increase because of improved oxygen conditions.

It was not anticipated that the shallow-water mussel biomass would decrease in response to closure of the mussel fishery, in particular, because the model simulated a highly eutrophic ecosystem. This indicated a potential competition for food between harvestable mussel biomass and unexploited shallow-water mussel populations. However, a 3D ecological model exploring the mixing of water and Chl *a* is needed to determine the extent of food competition between spatially separated groups of mussels, e.g., mussels on shallow and deep water, and more explicit information on nutrient dynamics, such as carbon budget and N regeneration is needed to address this specific question. Also, to simulate the entire Limfjord system, each embayment must be modeled as separate subcompartments. The potential negative and positive consequences of the above simulations were understood easily by stakeholders. The simulated reduction of mussel biomass in shallow water was a particular concern for one stakeholder, whose focus was on food availability for foraging birds. Mussels are important food resources for birds, such as common goldeneye (*Bucephala clangula*) and eider ducks (*Somateria mollissima*; Madsen 1954, Pehrsson 1976, Clausen et al. 2008; see also www.jaegerforbundet.dk). However, it was important to explain where model limitation would not provide credible results for particular management options. A reduction in shallow-water mussels could potentially result in replacement of mussel beds with other emergent habitats, such as eel grass meadows, or bare sea bed, which are important habitats for other protected bird species (Laursen et al. 2010) and potentially beneficial for increasing biodiversity. Thus, a reduction of mussel dredging is likely to be beneficial for the biodiversity and environmental status of the estuary. However, with the present model, it is not possible to assess impacts on protected birds and biodiversity, i.e., NATURA 2000 targets, but the model could be developed to include these aspects.

Implementation of WFD focuses on an upstream solution to reduce nutrient loadings by enforcing limitations on fertilizer

usage in agriculture. From the model simulation, reducing only nitrogen loadings was shown to reduce shallow-water mussel biomass by ~25%. This reduction would be doubled with a simultaneous P reduction. Similarly, a decrease in deep-water mussel biomass doubled when P reduction would have been included. Because of bottom-up propagation of impacts demonstrated by the model, mussel fishery would cease if both N and P were reduced. With the present WFD target of reducing N loadings, mussel fishery is predicted to continue, although at half its present level.

Negative impacts of traditional mussel dredging, such as mechanical sediment disturbance, benthic faunal, and macro-algal changes and reductions in eelgrass distribution (Riemann and Hoffmann 1991, Dolmer and Frandsen 2002) were not included in the ESE-model because such data were not available. Mussel dredging on the edge of eelgrass meadows could hinder vegetative expansion (Dolmer et al. 2009), which is the indicator used for good ecological status in the WFD. The ESE-model could be developed to include spatial habitat distribution and relationships to habitat structure and function.

A mussel fishery maintains a growing population with high filtration rates because of regular removal of adults (Jørgensen 1990). The mussel fishery removes 7000 tons/year in Skive Fjord, equivalent to 19 tons of N and 1.2 tons of P, respectively equivalent to 2% and 3.7% of the present loadings. Negative public perception of mussel dredging combined with the need to maintain production has recently encouraged development of alternative culture methods. Line-mussel production does not disturb the benthic communities to the extent of traditional dredging (Lindahl et al. 2005) and utilizes phytoplankton in the whole water column, resulting in faster mussel growth and higher flesh quality (Christensen et al. 2008). E. Roth, G. E. Dinesen, K. Timmermann, L. Ravn-Jonsen, D. Ahsan, and J. Støttrup (*unpublished manuscript*) showed that nutrient removal through line-mussel harvest accounted for a < 1% reduction in present day loadings. Thus, the present downstream removal of nutrients by mussel production is insignificant but in a future, less eutrophicated system, this may be a feasible management option.

Mussel fishery is, as shown by Frost et al. (2009), potentially able to create substantial resource rent even under conditions of low productivity (30,000 tons/year) by switching to unrestricted individual transferable quota licenses. A similar resource rent cannot be expected through line-mussel production with present technological know-how (E. Roth, G. E. Dinesen, K. Timmermann, L. Ravn-Jonsen, D. Ahsan, and J. Støttrup, *unpublished manuscript*). Incentives to start new enterprises are low, because the industry is not yet economically viable. Mussel fishers hinted at animosity toward their businesses from fishers because of competition for space and nutrient availability for mussel growth. Downstream removal of nutrients through mussel culture may be an economically more feasible option in the future and could be an argument for subsidized mussel culture in the future. However, with the present level of nutrient loadings removal by line mussel culture only amount to a few percent of the present loadings and is thus not a viable option.

The stakeholder meetings became a forum for constructive dialogue among stakeholders who previously had not been engaged. During the study, it became evident that stakeholders who perceived an interest in a healthy Limfjord marine ecosystem, and had participated in management-related meetings over the last 10-20 years, were easily engaged and retained within the dialogues. Although all stakeholders were invited to all meetings, an important one, agriculture, only attended the second meeting because farmers felt the issues had no relevance to their activities. A reason for this could be their long-standing tradition as a food provider at the national level with already established close networks with and within the political system. The Danish legal framework makes provision for a broader participation in the management process, including advisory committees and public consultation to discuss proposals forwarded by authorities. Unfortunately, the outcome is typically predictable as individual interest groups argue their personal case bilaterally without prior consultation among stakeholders. Specific stakeholders with good networks and strong political influence may benefit from this. This is especially the case for stakeholders who benefit from an activity but are not directly impacted by the activity. Without substantiated scientific information, the consequences of different trade-offs cannot be estimated and included in the consultation process. However, if public preferences and trade-offs are to be included in setting the target level, a SAF can take on broader survey methods. In this study, the SAF facilitated this first attempt to form a multilateral network for discussion of policy issues and management options in relation to marine coastal systems. The ESE-model simulation and scenario results led to unexpected new insights into the complexity of the Limfjord system with potential implications for management related to WFD, NATURA 2000, and mussel production. The ESE-model could be developed further to consider potential spatial conflicts between mussel farmers, mussel fishers, and other stakeholders. The SAF seems well qualified for developing a common understanding of the needs and consequences of change as part of the public consultation process and the merging of public and scientific information.

CONCLUSION

The SAF approach with multidisciplinary and cross-sectorial dialogue was valuable in identifying prioritized policy issues and establishing an ESE-model for system assessment. The SAF approach, which included consultation with stakeholders at all stages, differs from the traditional public consultation process in that: (1) communication was verbal and

multilateral, (2) discussion among stakeholders was facilitated, and (3) stakeholder opinions and priorities formed the focus of the ESE assessment. Furthermore, during development of the ESE-model, stakeholder-suggested management options formed the basis for the simulations.

The ESE model simulation results explored and discussed among stakeholders inspired new perceptions of policy options and potential solutions. Stakeholder perceptions included: (1) a high degree of transparency at all levels of the model, including inputs, equations, and results of scenario simulations, (2) first time experiences of being able to follow all details of a model simulation and understanding it, (3) a high degree of recognition between the virtual system (model simulation) and the real world, and (4) first time understanding of ecosystem complexity. Thus, the ESE assessment made it easier to disseminate results at a higher level of complexity than formerly possible.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol16/iss4/art26/responses/

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