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

Mussels and Yachts in Loch Fyne, Scotland: a Case Study of the Science-Policy Interface

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ABSTRACT. We report an application of the Science and Policy Integration for Coastal System Assessment (SPICOSA) Systems Approach Framework (SAF) to Loch Fyne, a fjord in western Scotland. The issue was the potential for conflict between shellfish aquaculture and recreational use for yachting. This was investigated by building an ecological-economic model to simulate: (1) release of modern anti-fouling compounds by recreational boats; (2) dilution of these in the upper layers of the loch by exchange with the sea; (3) their effects on photosynthesis by phytoplankton; (4) the role of phytoplankton (along with non-algal particulate matter) in providing food for mussels; (5) the growth of seeded mussels to harvest, determining (6) the cash input to farms, offset by their costs and allowing (7) the farm revenue to be compared with that from marinas used to berth the yachts. It was concluded from simulations that no noticeable effect on mussel harvest would occur (from this route) for any likely number of yachts berthed in the loch. The application took place in consultation with a local environmental forum and a small reference group of public officials; we reflect on it in the context of a 3-component schema for the science-policy interface and changes in the culture of UK science.

Key Words: *antifouling toxicity; Firth of Clyde, Scotland; governance Scotland; Loch Fyne Scotland; mussel aquaculture; science-policy interface; SPICOSA; Systems Approach Framework*

INTRODUCTION

We applied the Science and Policy Integration for Coastal System Assessment (SPICOSA) 'Systems Approach Framework', or SAF (Hopkins et al. 2011), to a fjord in the west of Scotland. A SAF application involves two tasks: (i) the construction and use of conceptual and numerical models of the social-ecological dysfunction that motivates that application; and (ii) the operation of a 'science-policy interface' (SPI) that brings scientists, civil society stakeholders, and public officials together for discussion of the dysfunction, scenarios for its solution, and the results of simulations. The purpose of the application was to test the SAF against a problem of scale and type appropriate to the SPICOSA project's resources at this study site. Thus, the application team initially saw its aim as being to identify a dysfunction, simulate it with a numerical model, and show that the SAF was practically useful for improving social-ecological sustainability. As the application and the team evolved, we came to see that the application process was as important as the end result (MacMynowski 2007), and have generalized our experience of this process as a 'schema' for the SPI (Fig. 1). The schema informs the application, and draws on *"the theory of communicative action"* developed by Habermas (1984, 1987).

Habermas (1987) distinguishes 'system' from 'lifeworld'. The system includes the institutions of the economy and governance, which provided some of the boundary conditions for our comparatively small-scale SAF application. A lifeworld is where actors communicate using a common language. The 'communications space' in Fig. 1 is the intersection amongst the lifeworlds of the groups of actors who are brought together by an agreement to take part in the application. Habermas (1984) identifies two categories of rational social action at the level of the lifeworld: 'strategic', oriented to success through influencing group decisions; and 'communicative', oriented to reaching understanding by way of *"discursively redeemable validity claims"* about the natural world, the human social world, and the actors' own states of mind and values. This theory provides us with a framework for discussion of some of the problems of stakeholder engagement, especially those relating to trust and legitimacy in model-building and problem-solving.

The Firth of Clyde and Loch Fyne

The Firth of Clyde is a large fjordic basin on the west coast of Scotland (Fig. 2a), opening into the North Channel of the Irish Sea (Edwards et al. 1986). The northern and western shores of the Firth lie in a mountainous region of old granitic rocks, poor soils, heavy rainfall, and comparatively low population densities. The mountains shelter several narrow fjords, locally called 'sea-lochs', that are connected to the Firth. East of the Firth are more fertile soils over sedimentary rocks including coal measures. There are large post-industrial populations in Glasgow and adjacent towns. Pollution of the Firth from this conurbation is decreasing (Haig 1986, Baxter et al. 2008), but exploitable fin-fish populations have been exhausted by overfishing (Thurstan and Roberts 2010).

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Fig. 1. The Science-Policy Interface as conceptualized for this Systems Approach Framework (SAF) application (Tett and Sandberg 2011). Institutions are shown as sharp-cornered rectangles, groups of actors as round-cornered rectangles. 'Knowledge', 'decision' and 'deliberation' refer to the characterizing features, for present purposes, of each group of actors. Three levels of governance (constitutional, collective, and operational) are shown. It is a key feature of this schema that only legal persons in civil society can have 'interests' in relation to the application 'Issue', i.e. can be 'stakeholders' in a strict sense. Actors from the institutions of Science and Governance are supposed to be neutral in relation to the differences between the scenarios comprised in the Issue package.

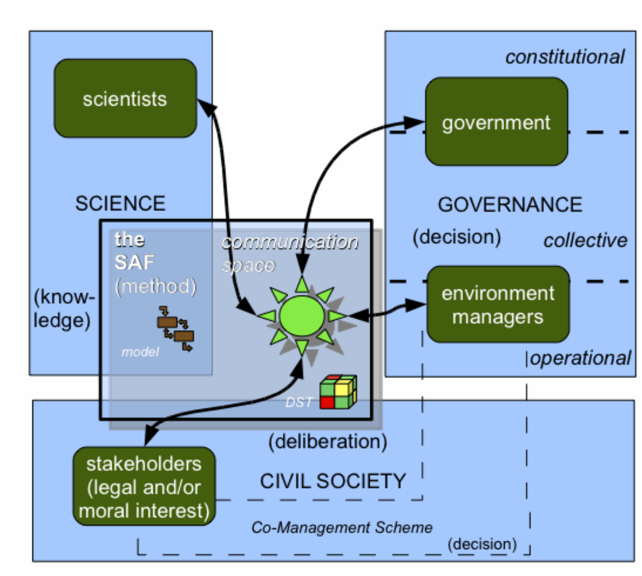
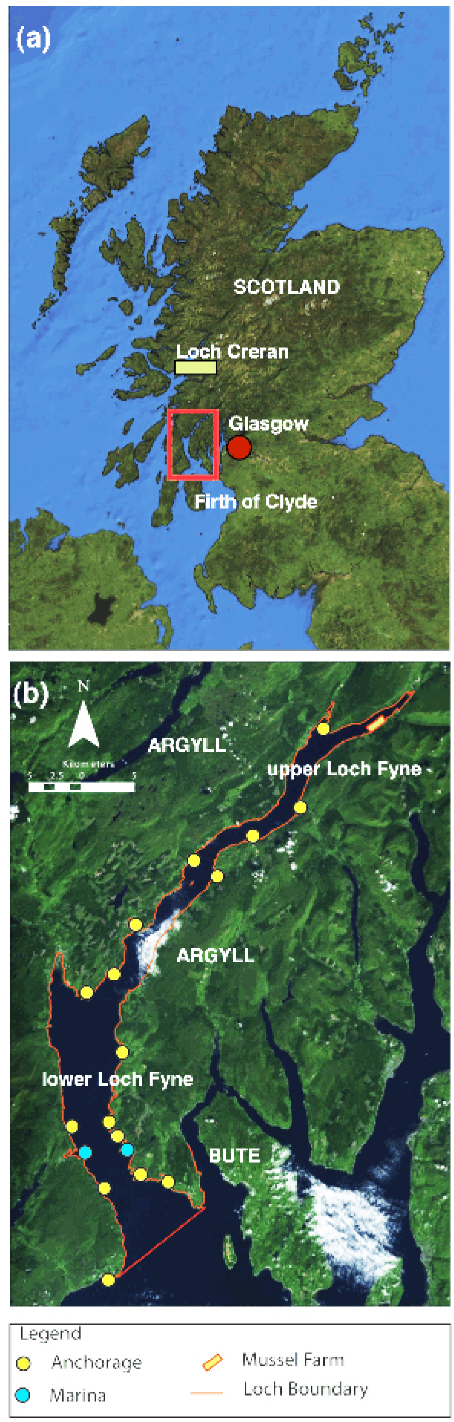


Fig. 2. Map of the study area. (a) location of the Firth of Clyde and the main study area (Loch Fyne, within the red box) within Scotland. The position of Loch Creran, used for testing the physical-biological model, is also shown. (b) Loch Fyne as defined for the purposes of modeling, and showing relevant features.



Sea-lochs, characteristic features of Scotland's northern and western coasts, are long and narrow arms of the sea. Many are fjords, glacially deepened basins with one or more sills that restrict exchange. Loch Fyne (fig. 2b) is amongst the longest and deepest of these Scottish fjords. Its inner part ('upper Loch Fyne') is separated by a sill from the outer part ('lower Loch Fyne') in which the deep water is contiguous with that in the Firth of Clyde. Whereas the deep water in both basins can remain isolated from the upper waters and atmosphere for months, the superficial waters comprise a circulation driven by freshwater inflow, tide and wind (Edwards et al. 1986, Tett et al. 1986, Simpson and Rippeth 1993).

Although there is a diversity of settlement pattern along Loch Fyne's coastline of 173 km, including small towns, villages and scattered dwellings, there is little development along the shoreline, and semi-native woodland often extends down to the tidemark. The main trunk road follows the coast and gives spectacular views. These features, and the easy access from urban lowland Scotland, explain why the area comes under high pressure from tourism. In contrast to the under-developed nature of the coastal land, the loch itself is exploited commercially (shell-fisheries and aquaculture) and recreationally (diving, boating).

Governance

Table 1 shows the tiers of decision making that are relevant to the management of the coastal zone in the Firth of Clyde. Scotland has devolved powers within the United Kingdom (UK), itself a member state of the European Union (EU). The UK has a Government and Parliament in Westminster (London), responsible for most offshore and international, including EU, environmental issues and negotiations. In Scotland, many administrative and some legislative responsibilities have been devolved to the Scottish Government and Parliament at Holyrood (Edinburgh). In terms of marine policy, Scotland is mainly responsible for infrastructure, fisheries and environmental management and regulation within the inshore (12 nautical miles) region. Future responsibilities will extend further offshore.

For policy direction, marine planning, and licensing of activity, Marine Scotland is the key government department. The Scottish Environment Protection Agency is the main environmental regulator. It is a public body overseen by the Scottish Government and implements UK and Scottish transpositions of European Union legislation relating to pollution and coastal water management (e.g. the Water Framework Directive). Scottish Natural Heritage is the agency that is responsible for regulating and providing statutory advice on nature conservation, for example, in relation to the EU Habitats and Birds Directives. Local authorities such as the Argyll and Bute Council are the third tier of government. The elected Council and its appointed officers manage local services and planning in the former counties of Argyll (on the mainland, together with some islands) and Bute (a large island within the Firth of Clyde, Fig. 2b).

The Integrated Coastal Zone Management (ICZM) policy context and process was changing at the time of this study, culminating in the passing into law in 2010 of the Marine (Scotland) Act. This requires the Scottish Government to prepare marine plans, and local authorities to take account of them. Argyll and Bute Council is responsible for the western part of the Firth of Clyde, including Loch Fyne, and is required to publish policies and zoning plans, and to approve individual applications for development. The council released the first draft of an ICZM plan for Loch Fyne in 2008 (Argyll and Bute Council 2008), identifying the following issues: (1) coastal development and employment; (2) the scale and location of shellfish and fin-fish farms; (3) nature conservation and maintaining a healthy, clean, and productive marine environment; (4) proactive management, enhancement and diversification of recreational and tourism activities and aquaculture; and (5) management of scenic coastal areas.

For several decades, from 1975 until 1996, administrative counties surrounding the Firth of Clyde, or containing rivers draining into it, were part of the Strathclyde Region of local government. The dissolution of this tier of government did not remove the need for environmental management across the Firth, and the Clyde Forum (Box 1) now provides a place for discussing common interests in such management.

Box 1: The Clyde Forum is a voluntary partnership of local authorities, organizations, businesses and communities committed to working towards integrated, sustainable management of the Clyde's environmental, economic and community resources.

Its membership includes:

Local governments (which have planning duties and powers), e.g. Argyll and Bute Council

Scottish Government agencies, including: Scottish Environment Protection Agency (SEPA), and Scottish Natural Heritage (SNH)

Other public-sector bodies, such as the Crown Estate (which manages former royal lands), Highlands & Islands Enterprise (a regional development agency), and Glasgow and the Clyde Valley Strategic Development Planning Authority

Broader social actors and community groups such as COAST (Community of Arran Seabed Trust), recreational fishermens' and sailors' associations, and national charities such as the Royal Society for the Protection of Birds

Private-sector companies, such as Loch Fyne Oysters Ltd. (involved in aquaculture and its products) and Clydeport Operations Ltd (formerly the public-owned Clyde Port Authority, which was sold to a management buy-out in 1992, and became a subsidiary of Peel Holdings plc in 2003).

Institutions representing commercial users, such as the Association of Scottish Shellfish Growers and the Clyde Fishermen's Association

Academic institutions, such as the University Marine Biological Station, Millport and the Department of Geography & Topographical Sciences, University of Glasgow

It is funded by:
Scottish Natural Heritage; The Crown Estate; Clydeport; Marine Scotland (the Scottish Government's “lead marine management organization”); Glasgow and the Clyde Valley Strategic Development Planning Authority.

Source: clydeforum.com

Conflicts

Conflicts amongst human uses of a water-body such as Loch Fyne can be seen as sectoral (e.g., leisure industries versus aquaculture) or functional (e.g., the potential of the waste from finfish aquaculture to cause eutrophication; Tett 2008). Such

Table 1. Institutions of Governance relevant to matters described this paper

T-ier	Level (fig. 1)	Deliberative & legislative	Executive	relevant functions	example relevant instruments	external influences
1	constitutional	European Parliament & Council of Ministers	European Commission	issues Directives and monitors implementation	Directives: Dangerous Substances (1976/464/ EEC as amended); Shellfish Hygiene (1991/ 492/EEC); Habitats (R1992/32/EEC); Water Framework (2000/60/ EC); Shellfish Waters (2006/113/EC, replacing 79/923/EEC)	
2	constitutional / collective	UK Parliament ('Westminster')	UK Government	passes Acts, makes Regulations, monitors compliance	Control of Pollution Act 1974; Marine and Coastal Act 2009; Conservation (Natural Habitats, &c.) Regulations 1994 (as amended); Surface Waters (Shellfish) (Classification) (Scotland) Regulations 1997† (a); Surface Waters (Dangerous Substances) (Classification) (Scotland) Regulations 1997†; Fishery Products and Live Shellfish) (Hygiene) Regulations 1998 (b)	(1) international commitments, e.g. Agenda 21, CBD; (2) UK electorate, lobbies, media
	operational		Crown Estates (Board)	administers former UK royal estates including seabed to 12 nm	sea-bed leases (for aquaculture, moorings, etc.)	Monarch, Prime Minister, UK Treasury
2-/3	collective	Scottish Parliament (from 1999) ('Holyrood')	Scottish Government (SG; formerly Executive)	passes Acts, makes Regulations, monitors compliance	Water Environment and Water Services (Scotland) Act 2003(c); Marine (Scotland) Act 2010; Water Environment (Controlled Activities) (Scotland) Regulations 2011 (WECASR)(c)	electorate, lobbies, media
	operational		SG directorate: Marine Scotland (since 2009) and research sub-directorate Marine Scotland Science	strategic planning; develops policy; monitors complianance and marine status; carries out research & strategic planning		
	operational		agency: Scottish Environment Protection Agency (SEPA)	consenting of discharges and control of pollution; gives special protection to designated 'Shellfish Growing Waters'	general binding rules, registrations, or licenses under WECASR	
	operational		agency: Scottish Natural Heritage (SNH)	protection of species, habitats and biodiversity	implementation of Habitats regulations	
3	operational	Firth of Clyde Forum		deliberative harmonization of management of social, economic and ecological resources by component bodies	Firth of Clyde Sustainable Marine Environment Initiative (SMEI)	nongovernmental organizations, commercial companies, and other interest groups in Civil Society
	collective	Argyll & Bute Council	Argyll & Bute Council (ABC)	oversees local operation of national legislation		electorate
	operational		ABC department: Planning	local strategic planning including ICZM; consenting developments	Integrated Coastal Zone Management Plan Loch Fyne; development approvals	
	operational		SEPA: regional office	SEPA operational functions in the Firth of Clyde and Loch Fyne	discharge consents	

† denotes laws made at Westminster solely for its Scottish jurisdiction before the recreation of the Scottish parliament in 1999.
(a .. c) refer to transpositions of EC into UK or Scottish law. (a) transposes the Shellfish Waters; (b) transposes the Shellfish Hygiene Directive; (c) transpose the Water Framework Directive.

conflicts can be ameliorated by several means. Spatial planning, including the designation of conservation areas, separates conflicting uses. Harmful effects can be reduced by regulation of fisheries or prevention of pollution.

Tourists are attracted by good environmental conditions, but can impact on those conditions and on other users of ecosystem services. Likely interactions between shellfish farming and recreational boating in Loch Fyne exemplify some of the matters of concern if tourism increases as envisaged (Tourism Strategy Group 2006).

Scottish marine aquaculture is dominated, in both amount and value, by salmon farming (Ministry of the Environment, Scotland 2009). However in some inshore waters, such as Loch Fyne, shellfish farming is an important part of the local economy (Argyll and Bute Council 2008). In 2005, common (or blue) mussels (*Mytilus edulis*), king scallops (*Pecten maximus*), queen scallops (*Aequipecten opercularis*), and (pacific) oysters (*Crassostrea gigas*), were under cultivation in the loch, with about 20 people employed in farms and immediate processing. Annual production was about 100 tonnes each of mussels, oysters and scallops. Most of this production was marketed through a single large company, turning over about £10 million per year, employing 109 people in the study area, contributing £1.94 million in salaries and spending £2.37 million with suppliers in the west of Scotland (Argyll and Bute Council 2008). Much of the loch's coastal strip is a designated 'Shellfish Growing Water' (SEPA 2010) under UK transposition of the EU Shellfish Waters Directive. The strip is monitored by SEPA for water quality, and, by the Food Standards Agency, to ensure that the shellfish are fit for human consumption under the EU Shellfish Hygiene Directive (SEPA 2011).

It was estimated that the turnover from recreation and tourism in Loch Fyne totaled £35.8 million in 2005, with Gross Value Added of £11.5 million in 2005, and 630 people employed locally (Argyll and Bute Council 2008). Of the recreational industries, sailing was the biggest single generator of economic activity. Before 2007 there were in Loch Fyne around 100 boat moorings and berths available to visitors. Developments in two marinas has increased this number to over 300, suggesting an annual income of about £2.1 million from a mean spend per boat of £7,000 (Argyll and Bute Council 2008).

Aquaculture, especially shellfish farming, depends on good water quality both to maintain the health of the cultivated animals and to keep them safe to eat. Marinas can deteriorate water quality through sewage discharges, litter, and leaching of anti-foulants from boat hulls. Shellfish contaminated with sewage bacteria require costly depuration, although the contamination can be avoided by retaining sewage on ships and pumping ashore to treatment facilities. Pleasure craft, and mooring structures in marinas, are painted with chemicals to inhibit the growth of 'fouling', i.e., of seaweeds and encrusting animals, on their submerged parts. Since these compounds were designed to poison marine biota (Readman 2006), it is unsurprising that early types such as tributyltin (TBT) had widespread harmful effects, including a case of damage to farmed oysters by TBT leached from salmon cages (Balls 1987). Since 1997, TBT has been banned from use in UK coastal waters by regulations under the (UK) Control of Pollution Act 1974. Organo-tin compounds have been replaced by chemicals using copper and zinc, intended to be less damaging to non-target marine organisms. One of these chemicals is zinc pyrithione, which has, however, been shown to interfere with photosynthesis and growth in some planktonic microalgae (Devilla et al. 2005).

Thus, conflicts between aquaculture and recreational yachting might arise from the use of space: farms interfering with navigation, for example, or marinas or shore facilities occupying potential sites for farms. Or there might be clashes through water quality, as already mentioned. Conversely, there might be mutual benefit. Visitors provide a market for farmed fish and shellfish, and local people might profit from increased employment and infrastructural development.

METHODS

Issue Resolution and the 'Issue'

'Issue Resolution' is the task that starts the SAF's first step of 'System Design' (Hopkins et al. 2011). A stakeholder-policy mapping exercise (Vanderlinden et al. 2010) for the Firth of Clyde region was started in 2007, leading to discussions with stakeholder groups, directly and by way of the Clyde Forum, in order to gauge the decision-making environment and explore the policy issues in Table 2. The following Issue was jointly agreed with the Forum: *the implications of increased leisure and tourist use of the Firth of Clyde*.

In order to narrow the matter of concern, and align it with available skills, the scientific team proposed that the Issue should concern: *the interactions between yachting and shellfish mariculture on the scale of a sea-loch, specifically, Loch Fyne*.

As thus framed, this Issue was not the highest priority for the members of the Forum, for whom spatial planning (e.g. to achieve an optimum distribution of mussel farms and yacht marinas within the loch) was a dominant concern. Nevertheless, the identification of 'loch-scale' rather than 'loch-resolving' allowed us to draw on existing, comparatively simple, box-models of lochs (Laurent et al. 2006, Portillo et al. 2009). These models could be easily implemented in the ExtendSim software adopted as standard in SPICOSA, rather than requiring the expensive and time-consuming programming of a spatially-resolving biological-hydrodynamic model. So far as the application team was concerned, the Issue seemed appropriate for a test of the SAF because it combined

Table 2. Potential Policy Issues

Human Activity (in priority order)	Objective	Indicators of: Pressures	Indicators of: States / Conditions	Indicators of: Societal response
Tourism & leisure	Increase, e.g. 5% per year in moorings / berths in Firth of Clyde	- Number of moorings/ berths/ visiting boats - Number of wildlife operators - Tourism levels - Coastal recreation visitor days, overnights		
Activities reducing water quality in the Clyde system	Maintain & improve water quality to legislative standards - EU, UK	- Number of reported pollution incidents - Waste water points - Water quality testing failures	- Quality elements from the WFD and other water quality directives (e.g., N, P, coliforms etc.) - Status of monitored beaches	- Acreage of shellfish growing areas with harvest restrictions resulting from pollution - Beach closures
Competition and conflict for space and resources e.g. moorings, infrastructure	Minimize conflict for space and resources by integrated development and spatial planning within ecological carrying capacity	- Number of marinas/moorings - Land tenure	- Aquaculture productivity - Number of sectors and proportional representation - Area of coastal water off limits to fishing	- Presence of marine spatial planning and/or coastal zone partnerships - Opportunity costs
Disturbance to marine wildlife & ecosystems from leisure operations e.g. wildlife watching, strikes, anchors etc.	Minimize disturbance to wildlife and habitats through appropriate planning and management instruments	- Number of wildlife watching tours - Number of infringements / reported incidents	- Status of indicator species	- Presence of management instruments - Presence of monitoring/ reporting programs
Infrastructure development (e.g. marinas) causing habitat loss	Minimize habitat loss from existing and new leisure infrastructure	- Land use changes	- Status of designated areas - Percent change in extent of some marine and coastal habitats	- Protected areas as % of total area
Socio-economic development in rural communities	Maximize and diversify the socio-economic development in rural communities in the Clyde in a sustainable context		- Value of, employment in, tourism industry - Employment in other industries - Average wage - Proportion of seafood sold locally - Pop. age structure - Economic diversity - Unemployment / GDP - Income distribution	- Population within x km of the coast
Safety incidents and severity	Improve safety at sea within appropriate regulatory limits and guidelines		- Number and severity of accidents - Number of RNLI boat/ tourism/leisure related call-outs	
Carbon footprint of increased leisure activities and associated travel	Minimize the carbon footprint of leisure travel		- Tourist statistics + CO2 emissions - Mode of travel / location	

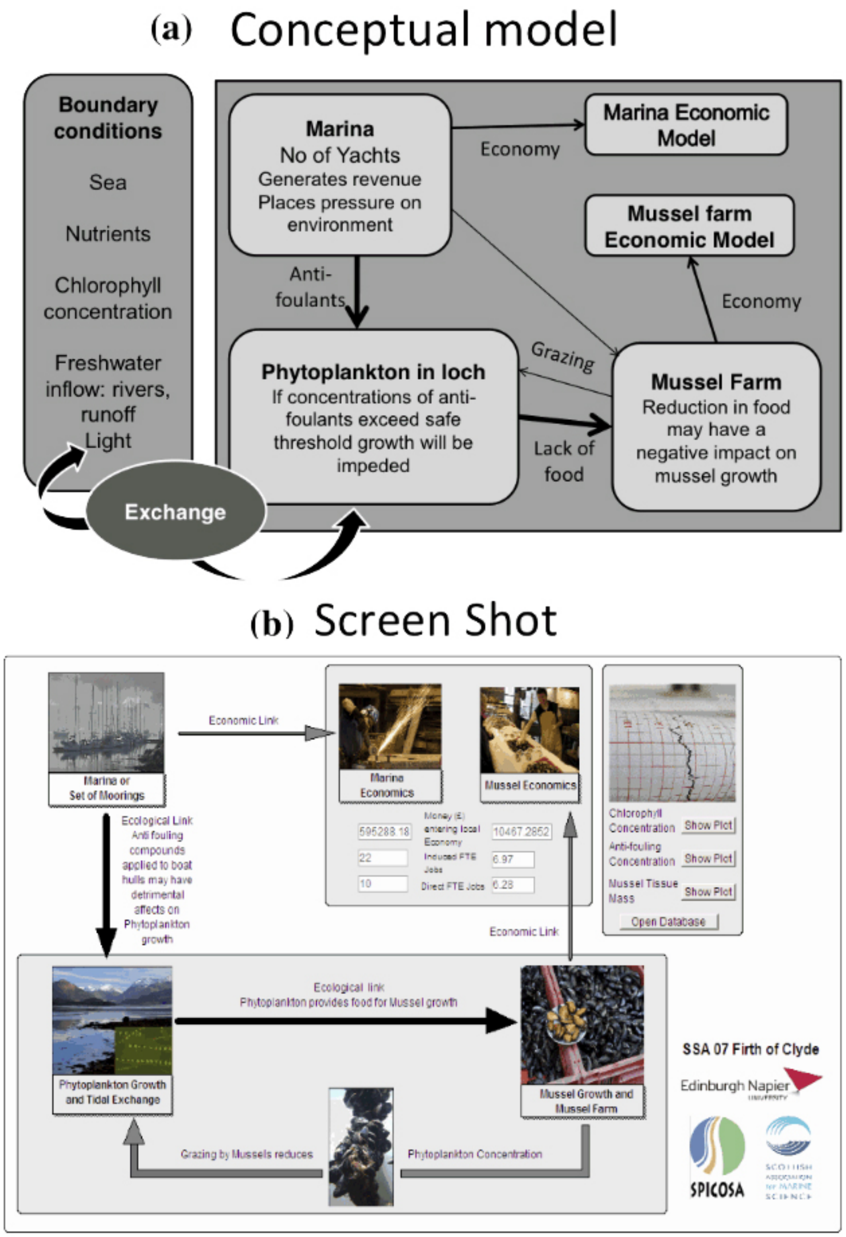
social and ecological components. The socio-economic component involved the interactions between the economic sectors of mussel farming and recreation. The ecological component related to the effects that increased leisure boating might have on mussel harvest. Given the local history involving aquaculture and anti-fouling compounds, it was decided to try to simulate *the effect of the new Anti-Fouling Compounds (AFCs) on phytoplankton production and thus on mussel harvest*.

The scenarios were to be those associated with 'increased leisure boating'. Each scenario involved a certain number of moored boats. The indicators would be *the socio-economic benefits and economic sustainability of recreational boating and mussel farming*.

Simulating the ecological-economic system

The cause-and-effect chain relevant to the Issue involves: (1) release of anti-fouling compounds (AFCs) by recreational boats, in proportion to their numbers; (2) dilution of these AFCs in the upper layers of a sea-loch in exchange with the sea; (3) AFCs' effects on photosynthesis by phytoplankton, whose growth is also dependent on seasonal fluctuations in light and nutrients; (4) the role of phytoplankton (along with non-algal particulate matter) in providing food; (5) the growth of seeded mussels to harvest, determining (6) the cash input

Fig. 3. The system model: (a) conceptual model, (b) the 'front page' of the ExtendSim model.



to farms, offset by spending on staff, equipment, etc. The resulting conceptual model is shown in Fig. 3, together with the 'front page' of the ExtendSim 7.05 implementation. Table 3 lists state variables and main components in this simulation model, and Fig. 4 gives key details of the physical-biological model.

This model was assembled from existing mathematical models, including a simple box model of sea-loch exchange and microplankton growth (Tett et al. 2003, Laurent et al. 2006) and a dynamic energy balance model of individual mussel growth (Grant and Bacher 1998). The microplankton model parameterizes the coupled dynamics of pelagic microalgae (phytoplankton) as a single entity that includes pelagic protozoa and bacteria (Tett and Wilson 2000). Its main state variable is chlorophyll, which is linked to N and P depletion through a yield coefficient q (Gowen et al. 1992).

The physical-microplankton model simulates a box that represents the superficial waters of Loch Fyne, over the region

Table 3. Model state variables and main terms (see also Fig. 4)

State variable(s) and units	subject to ex-change	external inputs & outputs	local gains	local losses	effects on	Reference
chlorophyll mg m^{-3}	yes		light and nutrient controlled growth	mesozoo-plankton and benthic grazing	itself(-), via transparency; nutrients (-); mussels (+)	dCSTT model (Tett et al. 2003, Laurent et al 2006)
nutrients (N, P, Si) mmol m^{-3}	yes		recycling from grazing	uptake by phytoplankton	chlorophyll (+)	dCSTT model, as above
POM mg m^{-3}	yes		mussel pseudo-faeces	feeding by mussels; sinking	mussels (+)	
AFC(s) g m^{-3} [as mg/L]	yes	from yachts in marinas	none	none	chlorophyll (-)	MAMPEC (van Hattum et al. 2002)
individual mussel biomass mg C	no	initial biomass at seeding	feeding on algal C (from chlorophyll) and POM C	respiration	chlorophyll (-); POM (-); farm revenue (+)	Grant & Bacher 1998
mussel numbers (*c* x *lines*)[‡]	no	seeding (+), harvest (-)		natural mortality	as above, mussel biomass (effect = *numbers* x *biomass*)	
mussel farm revenue	no		selling harvested mussels (unit price depends on biomass)	pay to employees[†]; taxation; replacing depreciated capital; cost of seed	*[employment in local community]*[§]	
marina revenue	no		renting moorings (to yachts)	pay to employees[†]; taxation; replacing depreciated capital	AFCs release (+) *[employment in local community]*[§]	

[†] In each sector the simulated number of employees was set by the size of the enterprise. Mussel farms had 1 full-time employee per 4 *lines*, and 12 lines were simulated in loch Fyne. Marinas had 10 full-time employees per 250 berths, plus seasonal employees up to 10 when the berths were full.
[‡] A *line* is a mussel farm unit, comprising a line of moored buoys, each supporting a rope containing *c* mussels when seeded at the start of year 1; simulated harvest took place in year 2.
[§]*Employment in the local community* by the enterprises: we used the annual total of wages paid to people directly employed as a proxy for social benefit;

shown outlined in red in figure 2b. The box contents were assumed homogenous, and the exchange term *E* (the proportion of box water replaced in a day) was a very simple parameterization, i.e., a Galilean idealization (Frigg and Hartman 2006), of the 24-hr averaged consequences of the numerous physical processes that move water or passive tracers around and in and out of the loch.

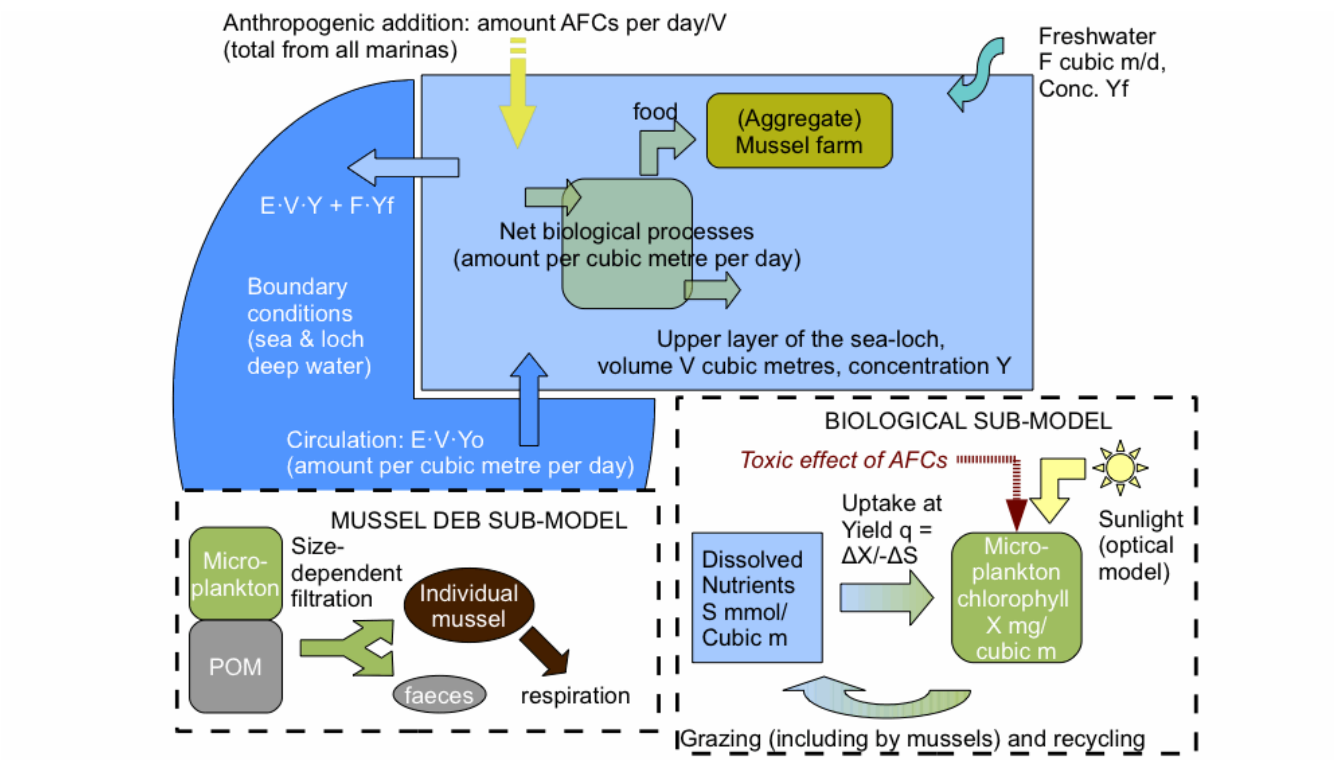
Amounts of AFCs for introduction into the box model were calculated by the MAM-PEC model (Van Hattum et al. 2002) for a single marina containing various numbers of berths, according to the different scenarios for test. Berths were assumed to be occupied on a seasonal schedule, giving low occupancy in winter and complete occupancy from July through September. The model was run for three compounds: zinc pyrithione, Dichlofluanid and Zineb, and the results (release of AFC per day) made available to the Extend model via a database and drop down-menus for scenarios and choice of AFCs.

Devilla et al. (2005) and Macedo et al. (2008) found that AFCs acted on planktonic algae by impairing their photosynthetic efficiency. In the model, the effects were related to a risk quotient, $RQ = PEC * UF / PNEC$. *PEC* was the environmental concentration (mg m^{-3}) predicted by the model, and *PNEC* is the Predicted No Effect Concentration. The *PNEC* (Table 4) was calculated by dividing values obtained in laboratory tests on cultivated freshwater microalgae, by factors between 1 and 1000, as required by the Water Framework Directive (van Leeuwen 2007). UF is an Uncertainty Factor. It allowed extra precaution to be introduced on the grounds that the biocide test algae may be less sensitive than marine organisms and also, that there may be synergies amongst different antifouling compounds that were not taken into account when toxicities were tested individually (Bao et al. 2008). For $RQ > 1$, algal photosynthetic rate was reduced (to 0.5 for $RQ > 2$, and to 0 for $RQ > 4$). AFCs were assumed not to be consumed in their interactions with algae.

Individual mussel growth was simulated by a dynamic energy balance (DEB) model (Grant and Bacher 1998, Grant et al. 2007), in which biomass growth resulted from organic carbon obtained by filtering water for phytoplankton and particulate organic matter (POM), less losses to basal and activity respiration. Mussels were supposed to be cultivated according to standard Scottish practice, i.e., seeded onto buoy-suspended ropes and grown for 2 years, with harvesting in year 2. A line is a set of buoys and ropes sufficient, in the absence of AFCs, to yield 25 tonnes (wet weight) of mussels on harvest.

The economic model used for aquaculture or marinas was similar to the mussel DEB model. Net revenue resulted from

Fig. 4. The physical-biological components of the system model.



sales of mussels or rental of berths and services, less pay to employees, taxes, and costs of replacing depreciated capital.

The model simulated one mussel farm and one marina, each aggregating all relevant activity in the loch. Two indicators were taken for each enterprise: the annual total of wages paid to employees, which was proportional to monies entering the local economy; and the net revenue at the end of a year, with positive values indicating an economically sustainable business.

Data

Data were needed for model parameter values and for boundary conditions in simulations. In-loch observations were needed to validate models. In most cases, parameter values were taken from the publications describing the component sub-models; values used uniquely in the present work are listed in Table 5, along with sources of boundary and forcing data. Many of those data, especially those needed to simulate exchange in the single 'upper layer' box of Fig. 4 were obtained from simulations with the 3-layer ACExR-LESV model (Portilla et al. 2009, Tett et al. 2011). The physical ACExR model takes account of the gravitational driven estuarine circulation, tidal exchange, and wind-driven surface-generated or shear-driven intermediate-layer turbulence, opposed by buoyancy maintained by fluxes of heat and freshwater. It has been validated against observations in several sea-lochs (P. Gillibrand and M. Inall, SAMS, *unpublished data*) The biological LESV model is similar to that programmed into the ExtendSim implementation of Fig. 4, except that LESV includes two microplankton compartments, one with silicate limitation. Time-series of simulated concentrations from ACExR-LESV layer 2 (the main layer receiving marine inflow) were used as boundary conditions for the ExtendSim model, and the time-series of exchange rates between layers 1 and 2, and layer 1 thickness, averaged to provide single values for the ExtendSim model.

A total of 12 mussel lines was assumed: of these lines, it was supposed that one-third was harvested in a given year. Employee number was set by the number of mussel lines deployed. In the case of marinas, employee number was set on the basis of blocks of 250 berths, which were supposed to be completely occupied during summer, and partly occupied at other times of year. Occupation of a visitor berth for a night was supposed to result in spending of £130 pounds, including berth rental, purchases of meals, fuel and local maintenance (Tourism Resources Co. 2010).

Model validation

Only the ExtendSim implementation of the physical-microplankton model was explicitly validated. This was done

Table 4. Derivation of predicted no-effect concentration (PNEC) values for anti-fouling compounds (AFC). The value used in the Loch Fyne simulation are shown in bold.

AFC	Test organisms	Quantity measured	Value (μg L^{-1})	Factor	PNEC (μg L^{-1})	Reference
ZPT (zinc pyrithione)	*Selenastrum capricornutum* (1)	PNEC	0.03	1	0.03	Yamada (2007)
ZPT	*Selenastrum capricornutum* (1)	NOEC	7.8	1	7.8	Ward et al. (1994) cited in Madsen et al. (2000)
ZPT	*Thalassiosira pseudonana* (2)	96 hr EC50	1.9 1.6 – 2.3: (95% CI)	1000	**0.0019**	Bao et al. (2008)
Dichlo-fluanid	*Selenastrum capricornutum* (1)	72 hr LOEC	50 +/- 0.87	100	0.50	Fernández-Alba et al. (2002)
Zineb	*Chlorella pyrenoidosa* (3)	96 hr EC50	180	1000[†]	0.180[†]	Pesticide Action Network, URL: www.pesticideinfo.org

Test organisms: (1) a freshwater desmid; (2) a marine diatom; (3) a freshwater green alga
Acronyms:
NOEC: AFC concentration at which there is no observed effect;
LOEC: lowest concentration of the AFC at which there is an observed effect;
EC50: concentration of the AFC at which the observed effect (typically, death) is 50%;
Times are duration of experiments.
[†] Values calculated by authors.

by comparing (Fig. 5) simulations for Loch Creran (about 40 km north-west of the head of Loch Fyne; see Fig. 2(a)), forced with 1975 boundary conditions, with two sets of data from that loch. The first set comprised observations made in 1975 (Jones 1979), analyzed by Laurent et al. (2006). The second set was 1970s climatological envelopes for chlorophyll (Tett and Wallis 1978, Tett and Grantham 1980) and dissolved nutrients (from Jones 1979).

RESULTS

The output of the economic model is shown in Figure 6 and by estimates of wage inputs to the local community. Each scenario (identified by numbers of berths and the values of the scientific uncertainty factor, UF) was used in a 2-year simulation, from which were taken values of the indicators for mussel-farms and marinas. The graphs for net revenues show that both mussel farm and marina operators remain viable under almost all scenarios, i.e., they show that the net revenue was positive, in the case of the marina for more than 30 berths. They also show that, even taking account of scientific uncertainty, boat-derived AFCs are predicted to have little effect on mussel-farming profitability up to at least 10,000 berths. Calculations of wages showed that both sets of enterprises provided a sustainable income to the community. For example, in the scenario with 500 boat moorings (20 permanent and some seasonal employees) and 12 mussel lines (3 employees), the marinas paid 275 k£/year in wages and made a profit (excess of revenue over expenditure) of 128 k£/year, while the mussel farm paid 33 k£/year in wages and made a small profit (1 k£).

Stakeholders and System Output

The 'communications space' of our Fig. 1 schema was initially that of the Clyde Forum, which was formally consulted in September 2007. During the discussions that led to the Issue it was found difficult to engage with the members of civil society who are in Fig. 1 categorized as 'stakeholders' because they have an interest in, i.e., might be affected by, environmental problems in the study area. One reason for this might have been the dominance of the Clyde Forum by institutional interests, so that 'civil society' saw it as part of government, to be complained about rather than participated in. Another possibility is that the application team's research-driven approach was seen as too academic for the immediate practical concerns of, say, mussel farmers.

Fortunately, there were public officials who were willing to participate in the application: in particular, officers in the planning department of the Argyll and Bute local authority and in the nearest regional office of the Scottish Environmental Protection Agency (SEPA). They identified themselves as working largely at the 'operational' level of governance, implementing policies decided at higher levels in Scottish government, and we call them 'policy-stakeholders' hereafter.

A formal report was made in March 2010, during the 'System Output' step of the SAF, to a meeting of policy-stakeholders and the application team. The meeting's composition determined how the modeling output was presented and discussed, because there was no tension such as might have

Table 5. Model boundary conditions and forcing

Variable (and units)	Loch Fyne	Loch Creran
Volume of box (10^6 m^3)	[2132]†	[83]†
Depth of box (m)	[13]	[7]
box Exchange Rate (d^{-1})	[0.021]	[0.22]
Solar irradiance (W m^{-2})	solar radiation climatology for N-W Scotland	daily values for 1978 from Dunstaffnage meteorological station (Tyler 1983)
River discharge (m^3 d^{-1})	daily values for 2003 from Loch Fyne catchment and rainfall	daily values for 1978 from scaled-up flow guage in river Creran (Tyler 1983)
Nutrients in river (mmol m^{-3})	typical value for each nutrient in highland run-off (Portilla et al. 2009)	typical value for each nutrient in highland run-off (Portilla et al. 2009)
Nutrients at sea-boundary (mmol m^{-3})	[daily values in layer 2 of ACExR-LESV simulation for loch Fyne, 2003]	[daily values in layer 2 of ACExR-LESV simulation for loch Creran, 1975]
chlorophyll at sea- boundary (mg m^{-3})	[daily values in layer 2 of ACExR-LESV simulation for loch Fyne, 2003]	[daily values in layer 2 of ACExR-LESV simulation for loch Creran, 1975]
POC§ in river (mg m^{-3})	0	0
POC at sea-boundary (mg m^{-3})	seasonal climatology from loch Creran (Jones 1989)	seasonal climatology from loch Creran (Jones 1989)
heterotroph fraction, η ‡	0.125	0.125
autotroph chlorophyll yield from nitrogen, ${}^{X}q^{N}_{a}$ in $q = {}^{X}q^{N}_{a}.(1-\eta)$ ‡	2.2 mg chl (mg-at N)$^{-1}$	2.2 mg chl (mg-at N)$^{-1}$
light attenuation coefficient at 0 chlorophyll	0.2 m^{-1}	0.2 m^{-1}
employees	0.25/mussel line 10 FTE + seasonal/250 berths	n.a.
wages	16,667/FTE.year	n.a.
revenues	2.4/wet kg mussels 130/yacht.night	n.a.

† values in square brackets were those taken from simulations with the ACExR-LESV model of Portilla et al. (2009) and Tett et al. (2010). The model used forcings for years 2003 (Loch Fyne) or 1975 (Loch Creran) where possible, otherwise Clyde Sea climatologies (Slesser and Turrell 2005) for Loch Fyne and Firth of Lorne climatologies (Portilla et al. 2009) for Loch Creran.
‡ all other microplankton parameters were calculated from the two adjustable parameters:the 'heterotroph fraction', η (Tett and Wilson 2000), and the chlorophyll yield *q* (Gowen et al. 1992), and the equations and constants given by Portilla et al. (2009).
§POC = Particulate Organic Carbon.

arisen amongst stakeholders involved in conflicting use of resources, and because all those present drew on common educational backgrounds, even if differing in discipline and professional application. The outcome was that the presentation of results developed into a true conversation which yielded unexpected questions and creativity during the meeting. Discussions about uncertainty took place that could be focused by means of the UF term in the model and which led to real-time exploration of the simulation model.

Despite stakeholder awareness of the limitations in the models, which included the lack of spatial resolution, feedback was extremely positive. This may have been in part because the model, and its outputs from the worst-case scenario, gave something concrete on which discussion could focus. It may also have been because the policy-stakeholders were already familiar with the use of models in policy- and decision-making. For example, an environment manager commented:

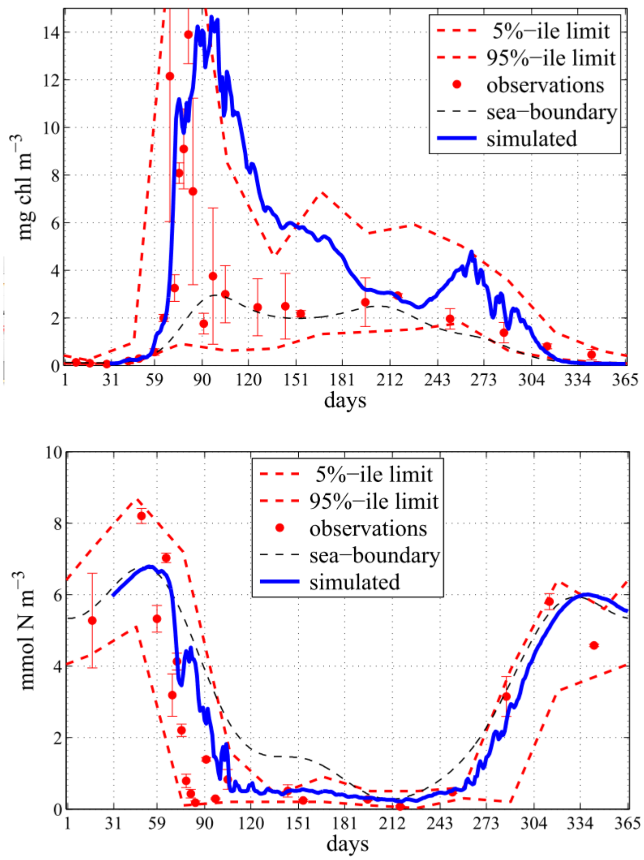
> *Modeling is our main tool for certain licenses.... It is what industry accepts... We absolutely rely on it for consenting.*

> *A model brings consistency and transparency to this level of decision-making.*

The policy-stakeholders' experience was of the use rather than the development of numerical models. Thus, although interested in the model's assumptions and about how the model works, they were willing to accept the model and its contents as legitimate, implying a trust in the expertise of the modelers in the application team. One of these commented:

> *I found Extend intuitive to use particularly if mathematics isn't your strong point. It is able to carry out a range of fairly complicated tasks allowing good predictive models to be constructed. However I found it particularly good when it was used as a tool to help communicate ideas to our stakeholders. The software allows easily accessible graphical user interfaces to be created enabling stakeholders to get hands on experience of the model which invariably generated lively and useful discussion.*

Fig. 5. Test of the physical-biological model against data for Loch Creran. The simulation does not satisfy the strong test of fitting well to the 1975 observations (c.f. Portilla et al. 2009) but does satisfy the weaker tests of falling (mostly) within the climatological envelopes and matching expectations of the seasonal cycle.

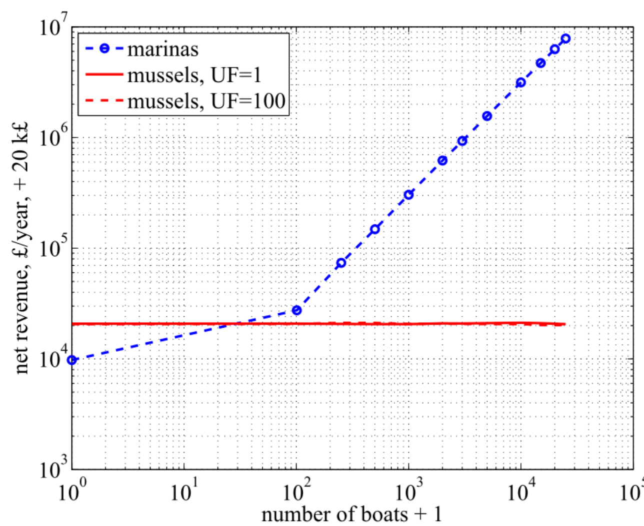


DISCUSSION

In this scientist-driven SAF application, the team successfully identified an Issue in collaboration with a stakeholder forum, and made a model of one cause-and-effect chain relevant to this Issue. The model was used to simulate the biological and economic effect on mussel farms of scenarios of increasing recreational boating whilst taking account of scientific uncertainty. Although the application partners proved not to think of themselves as stakeholders (narrowly defined), and are better located in 'governance' in our schema (Fig. 1) of the Science-Policy Interface (SPI), the SAF application functioned as a learning process for both them and us.

The model played a key role in this, not so much in the results of simulations but as an exhibit placed in the 'communications space' where it could be examined and discussed. That is one of the main lessons learnt from this application. Furthermore, the team had seen model conceptualization and formulation as purely technical steps, to be carried out by experts. Now, were we to repeat the application, we would seek to involve partners in the conceptualization of the model as well as in deliberating its results.

Fig. 6. Model results: Performance of mussel farm and marinas under different scenarios (of numbers of berths in marinas, corresponding to maximum number of visiting boats) and 2 values of the anit-fouling compounds (AFC) uncertainty factor (UF). The indicator values are annual total revenues net of costs.



This raises a point about the modeling procedures and the software tools used for simulation. One the one hand, both need to allow good communication with stakeholders. On the other hand, they have to produce reliable results, both as assessed by standard methods (Alexandrov et al. 2011, Oreskes et al. 1994, Portilla et al. 2009) and in terms of engendering the trust of participants. Standard validation methods were only weakly applied in this application, but the model results appeared sufficiently realistic to be accepted by the scientific team and the policy-stakeholders. Although ExtendSim lacks, in particular, the robust and accurate numerical integration routines available to users of Matlab^{TM}, or in Fortan libraries, it had two key features for the SAF application: (i) it allowed inexperienced programmers to assemble models from parts (some already in Extend, some made in other software) and to use, as forcing, numerical outputs from other models; and (ii) its provisions for building user-friendly interfaces, and making explicit the conceptual models, engaged the interest of the modelers' application partners.

In our schema (Fig. 1) of the SPI, stakeholders are persons in civil society who have a moral claim or legal right in the Issue. Their interests are fundamental to their involvement in the identification of the Issue and their deliberation of the results of simulations. Stakeholders, thus defined, contrast with scientists and public officers, who should be neutral in respect of the Issue and in choosing amongst potential solutions. But although stakeholders, thus narrowly defined, did not take part in deliberations, it can be argued that both scientists and public officers had, or developed, an interest in the SAF process, and so became stakeholders in it. The evidence suggests that, amongst those willing to engage in the 'communications space', there was sufficient common ground and trust for fruitful discussion, which, if sustained, could lead to improved outcomes within the restricted framework chosen for the Issue in this study. This fruitful interaction can be assessed from two theoretical perspectives.

(1) Boden et al. (2006) discuss the extent to which, following the Rothschild Report of 1971 and the introduction of 'new public management', UK research moved from self-managed 'professional science', funded by but independent of government, to an activity ruled by the 'customer-contractor principle', under which, *"the customer says what he wants, the contractor does it (if he can), and the customer pays."*

Boden et al. argued that the neo-liberal theories of state failure that provided the motor for these changes assumed that, given adequate information, *"markets alone provide for socially optimal decision making"* . But for reasons that included institutional inertia as well as the inappropriateness of a fully-marketized research economy, the result was less revolutionary than intended. On the one hand, Boden et al. found that laboratory staff and civil servants agreed that the customer-contractor principle and the conversion of government laboratories into agencies had improved the laboratories' focus on the problems defined by their customers. On the other hand, they cited the Leven-Stewart report of 1993, which found that

> *the relationships between the departmental customers and their laboratory agencies [still] put a premium on: ...'working co-operatively to ensure intelligent contractor-educated status for the departmental customer' ....*

Such a mixed economy, in which scientists work with public officials rather than deliver impersonally commissioned research, is in our opinion still characteristic of much UK applied science, and may have contributed to the good working relationships with our policy-stakeholders in this SAF application. In addition, the application's stakeholders were not its customers: the funder for the application was ultimately the European Commission and proximately the management of the SPICOSA project. The policy-stakeholders were self-selected on the basis of their perception of the relevance of the application and were not required to distance themselves as managers of the study.

2) Habermas (1984) distinguishes 'communicative action', allowing the possibility of *"discursive redemption of validity claims"* and leading to improved understanding of the matter in hand and each person's interests and role requirements in relation to it, from 'strategic action', in which individuals aim directly to achieve their own interests, or those of the institutions that they represent. The 'communications space' in Fig. 1 is supposed to enable communicative action, leading to communicative rationality and an optimally sustainable outcome for the social-ecological system concerned (Mette 2011). Our conclusion is that we did, to some extent, achieve such a space, but it could be argued that this was helped by both (a) lack of strong direct or institutional interests in the Issue, and (b) lack of direct customer-contractor relationship. These lacks seemed likely to have weakened pressures on participants for strategic action. And this in turn led to trust-building and 'redemption of validity claims' through questions and answers about models that allowed the models and their results to be seen as legitimate.

Brennan and Valcic (2012) compare the social dynamics of the Loch Fyne application with those of a consultation concerning the establishment of a marine Special Area of Conservation in the Western Isles of Scotland. They use the comparison to discuss the roles available to, and chosen by, scientists in particular cases. In the Western Isles case, local stakeholders clashed with the institutional interests of governance, with scientific information used strategically rather than for increasing understanding of the issue under discussion. There would seem to have been no intersection of life-worlds. In the Loch Fyne case, Brennan and Valcic argue, there was divergence from social relevance because scientists were driven by the need to carry out a research project, in order to satisfy project funders and to be able to write publishable papers or theses. Perhaps then, it was lack of clashing interests that led to the fruitful if limited social outcome we have described above.

This discussion leads to some important questions. How can stakeholders with relevant interests best be involved in similar applications in future? If they become engaged, i.e., if the schema of Fig. 1 fully applies, how is the 'communications space' to be maintained as a place for communicative rather than strategic action? How might SAF applications, or similar, be funded, given the increasing grip in the UK (and elsewhere) of the 'new public management' on the support of applied science? These specific questions can perhaps be seen as aspects of a general problem: how best to organize a SPI that brings together institutions (science, governance) with different codes and programs (Luhmann 1989) and time-scales of operation, as well as stakeholders with a range of interests and world-views.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol17/iss3/art16/responses/

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LITERATURE CITED

Alexandrov, G. A., D. Ames, G. Bellocchi, M. Bruen, N. Crout, M. Erechtchoukova, A. Hildebrandt, F. Hoffman, C. Jackisch, P. Khaiter, G. Mannina, T. Matsunaga, S. T. Purucker, M. Rivington, and L. Samaniego. 2011. Technical assessment and evaluation of environmental models and software: Letter to the Editor. *Environmental Modelling & Software* 26: 328-336. http://dx.doi.org/10.1016/j.envsoft.2010.08.004

Argyll and Bute Council. 2008. *Integrated coastal zone management plan Loch Fyne*. 1st draft. Marine & Coastal Development Unit, Planning Services, Argyll & Bute Council, Lochgilphead, Scotland. [online] URL: http://www.argyll-bute.gov.uk/planning-and-environment/loch-fyne-integrated-coastal-zone-management-plan.

Balls, P. W. 1987. Tributyltin (TBT) in the waters of a Scottish sea loch arising from the use of antifoulant treated netting by salmon farms. *Aquaculture* 65: 227-237. http://dx.doi.org/10.1016/0044-8486(87)90235-3

Bao, V. W. W., K. M. Y. Leung, K. W. H. Kwok, A. Q. Zhang, and G. C. S. Lui. 2008. Synergistic toxic effects of zinc pyrithione and copper to three marine species: implications on setting appropriate water quality criteria. *Marine Pollution Bulletin* 57: 616-623. http://dx.doi.org/10.1016/j.marpolbul.2008.03.041

Baxter, J. M., I. L. Boyd, M. Cox, L. Cunningham, P. Holmes, and C. F. Moffat, editors. 2008. *Scotland's seas: towards understanding their state*. Fisheries Research Services, Aberdeen. [online] URL: http://www.scotland.gov.uk/Publications/2008/04/03093608/0.

Boden, R., D. Cox, and M. Nedeva. 2006. The appliance of science? New public management and strategic change. *Technology Analysis and Strategic Management* 18: 125-141. http://dx.doi.org/10.1080/09537320600623941

Brennan, R. and B. Valcic. 2012. Shifting perspectives - how the masks we wear can facilitate and inhibit channels of communication in the social-environmental policy context. Ocean & Coastal Management 62: 1-8. http://dx.doi.org/10.1016/j.ocecoaman.2012.02.004

Devilla, R. A., M. T. Brown, M. Donkin, G. A. Tarran, J. Aiken, and J. W. Readman. 2005. Impact of antifouling booster biocides on single microalgal species and on a natural marine phytoplankton community. *Marine Ecology - Progress Series* 286: 1-12. http://dx.doi.org/10.3354/meps286001

Edwards, A., M. S. Baxter, D. J. Ellett, J. H. A. Martin, D. T. Meldrum, and C. R. Griffiths. 1986. Clyde Sea hydrography. *Proceedings of the Royal Society of Edinburgh* 90B: 67-83.

Fernández-Alba, A. R., M. D. Hernando, L. Piedra, and Y. Chisti. 2002. Toxicity evaluation of single and mixed antifouling biocides measured with acute toxicity bioassays. *Analytica Chimica Acta* 456: 303-312. http://dx.doi.org/10.1016/S0003-2670(02)00037-5

Frigg, R. and S. Hartmann. 2006. Models in Science. [online] URL: http://plato.stanford.edu/entries/models-science/ (accessed: 6 May 2010).

Gowen, R. J., P. Tett, and K. J. Jones. 1992. Predicting marine eutrophication: the yield of chlorophyll from nitrogen in Scottish coastal phytoplankton. *Marine Ecology - Progress Series* 85: 153-161. http://dx.doi.org/10.3354/meps085153

Grant, J. and C. Bacher. 1998. Comparative models of mussel bioenergetics and their validation at field culture sites. *Journal of Experimental Marine Biology and Ecology* 219: 21-44. http://dx.doi.org/10.1016/S0022-0981(97)00173-1

Grant, J., K. J. Curran, T. L. Guyondet, G. Tita, C. Bacher, V. Koutitonsky, and M. Dowd. 2007. A box model of carrying capacity for suspended mussel aquaculture in Lagune de la Grande-Entrée, Iles-de-la-Madeleine, Québec. *Ecological Modelling* 200: 193-206. http://dx.doi.org/10.1016/j.ecolmodel.2006.07.026

Habermas, J. 1984. The theory of communicative action. Volume 1: Reason and the rationalization of society. Translated by McCarthy, T. Boston, MA/Cambridge, England: Beacon Press/Polity Press.

Habermas, J. 1987. The theory of communicative action. Volume 2: Lifeworld and system: a critique of fundamentalist reason. Translated by McCarthy, T. Boston, MA/Cambridge, England: Beacon Press/Polity Press.

Haig, A. J. N. 1986. Use of the Clyde estuary and Firth for the disposal of effluents. *Proceedings of the Royal Society of Edinburgh* 90B: 393-405.

Hopkins, T. S., D. Bailly, and J. G. Støttrup. 2011. A systems approach framework for coastal zones. *Ecology and Society* 16(4):25. http://dx.doi.org/10.5751/ES-04553-160425

Jones, K. J. 1979. Studies on nutrient levels and phytoplankton growth in a Scottish sea loch. PhD thesis. University of Strathclyde, Glasgow.

Laurent, C., P. Tett, T. Fernandes, L. Gilpin, and K. J. Jones. 2006. A dynamic CSTT model for the effects of added nutrients in Loch Creran, a shallow fjord. *Journal of Marine Systems* 61: 149-164. http://dx.doi.org/10.1016/j.jmarsys.2005.05.007

Luhmann, N. 1989. *Ecological communication* (translated by Bednarz, John). Polity Press/University of Chicago Press, Cambridge (UK)/Chicago.

Macedo, R. S. and A. T. Lombardi. 2008. Effects of the herbicide bentazon on growth and photosystem II maximum quantum yield of the marine diatom *Skeletonema costatum*. *Toxicology in Vitro* 23: 716-722. http://dx.doi.org/10.1016/j.tiv.2007.11.012

Madsen, T., L. Samsøe-Petersen, K. Gustavson, and D. Rasmussen. 2000. *Ecotoxicological assessment of antifouling biocides and nonbiocidal antifouling paints*. Danish Environmental Protection Agency, Copenhagen.

Marine Scotland. 2009. *A fresh start: the renewed strategic framework for Scottish aquaculture*. Scottish Government, Edinburgh. [online] URL: http://www.scotland.gov.uk/Publications/2009/05/14160104/0

Marine (Scotland) Act 2010. [online] URL: http://www.scotland.gov.uk/Topics/marine/seamanagement/marineact.

MacMynowski, D. P. (2007). Pausing at the brink of interdisciplinarity: power and knowledge at the meeting of social and biophysical science. *Ecology and Society* 12(1):20. [online] URL: http://www.ecologyandsociety.org/vol12/iss1/art20/.

Mette, A. 2011. Bridging the gap between science and society. Pages 103-149 in Tett, P., A. Sandberg and A. Mette, editors. *Sustaining coastal zone systems*, Dunedin Academic Press, Edinburgh.

Oreskes, N., K. Shrader-Frechette, and K. Belitz. 1994. Verification, validation, and confirmation of numerical models in the earth sciences. *Science* 263: 641-646. http://dx.doi.org/10.1126/science.263.5147.641

Portilla, E., P. Tett, P. A. Gillibrand, and M. Inall. 2009. Description and sensitivity analysis for the LESV model: water quality variables and the balance of organisms in a fjordic region of restricted exchange. *Ecological Modelling* 220: 2187-2205. http://dx.doi.org/10.1016/j.ecolmodel.2009.05.004

Readman, J. W. 2006. Development, occurrence and regulation of antifouling paint biocides: historical review and future trends. Pages 1-15 in Konstantinou, I. K., editor. *Handbook of environmental chemistry*, Springer-Verlag, Berlin & Heidelberg.

SEPA. 2010. *Designated shellfish waters in Scotland: Site data: Loch Fyne coastal strip*. [online] URL: http://www.sepa.org.uk/water/protected_areas/shellfish_waters/site_reports.aspx (accessed: 21 Oct 2010).

SEPA. 2011. *Regulation of designated shellfish waters*. [online] URL: http://www.sepa.org.uk/water/protected_areas/shellfish_waters/regulation.aspx (accessed: 17 November 2011).

Simpson, J. H. and T. P. Rippeth. 1993. The Clyde Sea: a model of the seasonal cycle of stratification and mixing. *Estuarine, Coastal and Shelf Science* 37: 129-144. http://dx.doi.org/10.1006/ecss.1993.1047

Slesser, G. and W. R. Turrell. 2005. *Annual cycles of physical, chemical and biological parameters in Scottish waters* (2005 update). Fisheries Research Service, Aberdeen.

Tett, P. 2008. Fishfarm wastes in the ecosystem. Pages 1-46 in Holmer, M., K. Black, C. M. Duarte, N. Marbà and I. Karakassis, editors. *Aquaculture in the Ecosystem*, Springer, Netherlands. http://dx.doi.org/10.1007/978-1-4020-6810-2_1

Tett, P., L. Gilpin, H. Svendsen, C. P. Erlandsson, U. Larsson, S. Kratzer, E. Fouilland, C. Janzen, J.-Y. Lee, C. Grenz, A. Newton, J. G. Ferreira, T. Fernandes, and S. Scory. 2003. Eutrophication and some European waters of restricted exchange. *Continental Shelf Research* 23: 1635-1671. http://dx.doi.org/10.1016/j.csr.2003.06.013

Tett, P., R. Gowen, B. Grantham, K. Jones, and B. S. Miller. 1986. The phytoplankton ecology of the Firth of Clyde sea-lochs Striven and Fyne. *Proceedings of the Royal Society of Edinburgh* 90B: 223-238.

Tett, P. and B. Grantham. 1980. Variability in sea-loch phytoplankton. Pages 435-438 in Freeland, D. H., D. M. Farmer and C. D. Levings, editors. *Fjord Oceanography*. Plenum, New York.

Tett, P. and A. Sandberg. 2011. Introduction. Pages 1-28 in Tett, P., A. Sandberg and A. Mette, editors. *Sustaining coastal zone systems*, Dunedin Academic Press, Edinburgh.

Tett, P., E. Portilla, P. A. Gillibrand, and M. Inall. 2011. Carrying and assimilative capacities: the ACExR-LESV model for sea-loch aquaculture. *Aquaculture Research* 42: 51-67. http://dx.doi.org/10.1111/j.1365-2109.2010.02729.x

Tett, P. and A. Wallis. 1978. The general annual cycle of chlorophyll standing crop in Loch Creran. *Journal of Ecology* 66: 227-239. http://dx.doi.org/10.2307/2259190

Tett, P. and H. Wilson. 2000. From biogeochemical to ecological models of marine microplankton. *Journal of Marine Systems* 25: 431-446. http://dx.doi.org/10.1016/S0924-7963(00)00032-4

Thurstan, R. H. and C. M. Roberts. 2010. Ecological meltdown in the Firth of Clyde, Scotland: two centuries of change in a coastal marine ecosystem. *PLoS ONE* 5: e11767. http://dx.doi.org/10.1371/journal.pone.0011767

Tourism Resources Company Ltd. 2010. *Sailing Tourism in Scotland*. Scottish Enterprise, Glasgow. [online] URL: http://www.researchonline.org.uk/sds/search/go.do?action=document&ref=B15606.

Tourism Strategy Group. 2006. *Scottish tourism: the next decade - a tourism framework for change*. Scottish Executive, Edinburgh, Scotland [online] URL: http://scotland.gov.uk/Publications/2006/03/03145848/0.

Vanderlinden, J.-P., T. Stojanovic, D. Schmuëli, S. Bremer, C. Kostrzewa, and L. McFadden. 2010. *The SPICOSA stakeholder-policy mapping users' manual, complete version with worked examples*. Université de Versailles Saint-Quentin en Yvelines, Guyancourt. [online] URL: http://www.coastal-saf.eu/issue-identification/refs.shtml.

Van Leeuwen, C. J. 2007. Introduction. Pages 1-36 in Van Leeuwen, C. J. and T. G. Vermeire, editors. *Risk assessment of chemicals. An introduction (2nd edition)*. Springer, Dordrecht.

Van Hattum, B., A. C. Baart, and J. G. Boon. 2002. *Computer model to generate predicted environmental concentrations (PECs) for antifouling products in the marine environment*. IVM, Vrijje Universiteit and Delft Hydraulics, Delft, Amsterdam. [see also: online] URL: http://www.deltares.nl/en/software/1039844/mampec/ [accessed 15 November 2011]

Ward, T. J., J. P. Magazu, and R. L. Boeri. 1994. *Growth and reproduction test with zinc omadine (zinc bis-1-oxide-2(1H)-pyridinethionate) and the freshwater alga, Selenastrum capricornutum.* Arch Chemicals, Atlanta, Georgia.

Yamada, H. 2007. Behavior, occurrence and aquatic toxicity of new antifouling biocides and preliminary assessment of risk to aquatic ecosystems. *Bulletin of Fisheries Research Agency* 21: 31-45.