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Sustainable Mariculture in northern Irish Lough Ecosystems

J.G. FERREIRA, A.J.S. HAWKINS, P. MONTEIRO, M. SERVICE, H. MOORE, A. EDWARDS, R. GOWEN, P. LOURENCO, A. MELLOR, J.P. NUNES, P.L. PASCOE, L. RAMOS, A. SEQUEIRA, T. SIMAS, J. STRONG

J.G. Ferreira, A.J.S. Hawkins, P. Monteiro, M. Service, H. Moore, A. Edwards, R. Gowen,
P. Lourenco, A. Mellor, J.P. Nunes, P.L. Pascoe, L. Ramos, A. Sequeira, T. Simas, J. Strong, 2007.
SMILE – Sustainable Mariculture in northern Irish Lough Ecosystems – Assessment of Carrying
Capacity for Environmentally Sustainable Shellfish Culture in Carlingford Lough,
Strangford Lough, Belfast Lough, Larne Lough and Lough Foyle.
Ed. IMAR – Institute of Marine Research. 100 pp.

ISBN 978-972-99923-1-5

Design: Martin Rästa (www.mammut.baas.ee)
Layout: Lauri Järvlepp

Agri-Food and Biosciences Institute
Queen's University Belfast
INSTITUTE OF MARINE RESEARCH
WWW.IMAR.PT
Plymouth Marine Laboratory
CSIR

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FOREWORD

The assessment of environmentally sustainable carrying capacity for aquaculture in coastal areas poses a major challenge, given the range of issues that must be taken into account, the interactions between natural and social components, and the coupling between watershed and coastal zone.

In 2001, The Department of Agriculture and Rural Development published the Shellfish Aquaculture Management Plan for Northern Ireland. The Minister for Agriculture and Rural Development stated at the presentation: “There has been a significant growth in shellfish aquaculture in Northern Ireland over the past few years. It is important that this growth is structured and that the shellfish aquaculture industry develops in a sustainable manner and with minimal environmental impact.” Following this publication, Queen’s University Belfast and the Department for Agriculture and Rural Development (DARD) produced a Phase I study of Carrying Capacity in 2003.

In 2004, a consortium made up of the Institute of Marine Research – IMAR (Portugal), Plymouth Marine Laboratory – PML (U.K.) and CSIR (South Africa) was awarded a two-year contract for the Sustainable Mariculture in northern Irish Lough Ecosystems (SMILE) project, with a duration of two years, with the aim of “developing dynamic ecosystem level carrying capacity models for the five northern Irish sea loughs.

In order to provide medium-term guidelines, this work needed to be placed in the context of a set of European legislative instruments in the area of water policy, which include older generation directives such as Habitats, and new and emerging ones such as the Water Framework Directive and the proposed Marine Strategy Directive.

The SMILE contract was conceived as an application of know-how collected in many R&D projects, but the excellent collaboration with the Agri-Food and Biosciences Institute (AFBI), Queen’s University of Belfast (QUB) and the Loughs Agency, together with the interest and feedback of the Environment and Heritage Service (EHS) and other agencies on the Oversight Committee, provided several avenues for research. In SMILE, carrying capacity assessment can be summed up as a clear practical application of integrated coastal zone management, using water quality criteria, cultivated shellfish production and sustainability of native wild species as environmental metrics.

This book provides an overview of the approach taken in SMILE, and presents the key results for the five loughs. Data were drawn from many sources, and collected into databases that form the backbone of the modelling work. Our thanks go to all who provided data and information, and especially to the people on the ground, who watched this work develop and trusted us to get on with it. We are very grateful to Anne Dorbie for her support for this work, and her faith in the team, and to Jason Holt (POL) for Irish Sea boundary conditions. We additionally wish to thank all the producers and growers who helped with growth trials and provided the use of vessels, Tom Cowan, Greg Hood and Roy Griffin from Fisheries Division, Annika Mitchell from QUB and Nuala McQuaid from CMAR. We hope managers and shellfish farmers alike in Northern Ireland will find this and the other SMILE products both useful and profitable. Europe cannot hope to compete on quantity with the emerging shellfish export markets, the added value which is required to provide growth in jobs and profits at home must come from superior product quality, branding and environmental sustainability.

SMILE TEAM

J.G. Ferreira	IMAR – Institute of Marine Research, Centre for Ecological Modelling, New University of Lisbon, Portugal
A.J.S. Hawkins	PML – Plymouth Marine Laboratory, United Kingdom
P. Monteiro	CSIR – Council for Scientific and Industrial Research, South Africa
H. Moore	QUB – Queen's University of Belfast
M. Service	AFBI – Agri-Food and Biosciences Institute
A. Edwards	SEPA – Scottish Environmental Protection Agency, Scotland
R. Gowen	AFBI – Agri-Food and Biosciences Institute
P. Lourenco	IMAR – Institute of Marine Research, Centre for Ecological Modelling, New University of Lisbon, Portugal
A. Mellor	QUB – Queen's University of Belfast
J.P. Nunes	IMAR – Institute of Marine Research, Centre for Ecological Modelling, New University of Lisbon, Portugal
P.L. Pascoe	PML – Plymouth Marine Laboratory, United Kingdom
L. Ramos	Ministry of the Environment, Portugal
A. Sequeira	IMAR – Institute of Marine Research, Centre for Ecological Modelling, New University of Lisbon, Portugal
M.T. Simas	IMAR – Institute of Marine Research, Centre for Ecological Modelling, New University of Lisbon, Portugal
J. Strong	QUB – Queen's University of Belfast

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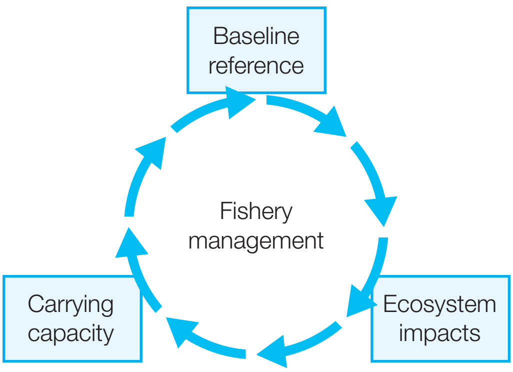
EXECUTIVE SUMMARY

The five sea lough systems addressed by the *Sustainable Mariculture in northern Irish sea Lough Ecosystems* (SMILE) project are Carlingford Lough, Strangford Lough, Belfast Lough, Larne Lough and Lough Foyle. The project began in September 2004, had a duration of two years, and addressed four key objectives.

SMILE OBJECTIVES

- To establish functional models at the lough scale, describing key environmental variables and processes, aquaculture activities and their interactions
- To evaluate the sustainable carrying capacity for aquaculture in the different loughs, considering interactions between cultivated species, targeting marketable cohorts, and fully integrating cultivation practices
- To examine the effects of overexploitation on key ecological variables
- To examine bay-scale environmental effects of different culture strategies



These four objectives together provided a foundation for sustainable fishery management. The baseline results supply reference conditions to manage against. Evaluation of both carrying capacity and ecosystem impacts included consultation with stakeholders, to ensure an integrated management approach.

The key outputs of SMILE are presented in this book, which begins with a brief introduction to carrying capacity assessment, and to the northern Ireland sea loughs, and follows with a further five chapters. Every effort has been made to make each chapter readable on its own, by including the basic components of the theme, from concepts to methods and results. The **Tools** chapter provides an overview of the techniques used for the different parts of the work. A summary of the key outputs and findings of SMILE are presented below.

- Problem definition and objectives
  Carrying capacity for shellfish culture
- Tools
  Summary of tools used in SMILE
- Spatial domain
  Spatial description of the five SMILE loughs
- Shellfish
  Outline of experimental work, development of individual growth models and validation
- Carrying capacity assessment
  Description of modelling work, together with results for the five loughs
- Management
  Analysis of model outputs, development scenarios and environmental sustainability

DATA

Over 185,000 records of data for the five loughs were archived in relational databases during the project. These are available online, and contain variables ranging from water and sediment quality to biological species lists, collected over the past 22 years. These data were the foundation for the work that has been developed, and are an important reference collection of historical information on which future monitoring and research activities may build.

SPATIAL DOMAIN

The bathymetry and morphological features of the systems were integrated into GIS projects, together with spatial information on shellfish aquaculture areas, species distribution, water quality and sediment sampling locations. GIS was used to superimpose various features such as morphology, system uses and water body limits to define boxes used in EcoWin2000 for carrying capacity modelling, as illustrated in the example opposite for Strangford Lough (Figure 2).

Together, the five loughs have an area of 522 km^2, of which about 20% is used for shellfish culture.

SHELLFISH MODELS

The majority of the revenue from shellfish culture in the SMILE loughs is derived from the blue mussel (*Mytilus edulis*) and the Pacific oyster (*Crassostrea gigas*). All Pacific oyster culture is intertidal, placing hatchery-reared juveniles within bags placed on trestles or placing half grown animals onto rubber mats to support them from sinking into soft sediments. Blue mussel seed is obtained by dredging natural beds in coastal waters, and the seed cultured either by seeding onto the bottom or by suspending from ropes, on submerged structures or rafts.

To model the complex feedbacks, both positive and negative, whereby mussels and oysters interact with ecosystem processes, measurements of physiological responses were undertaken in each species over experimental conditions that spanned the full normal ranges of food availability and composition in the SMILE loughs. Mathematical equations were then derived that define functional inter-relationships between the component processes of growth, integrating those interrelations within a dynamic model structure (ShellSIM) developed to simulate time-varying rates of individual feeding, metabolism and growth in these and other species (http://www.shellsim.com/index.html).

Figure 1. Data distribution for the SMILE loughs.

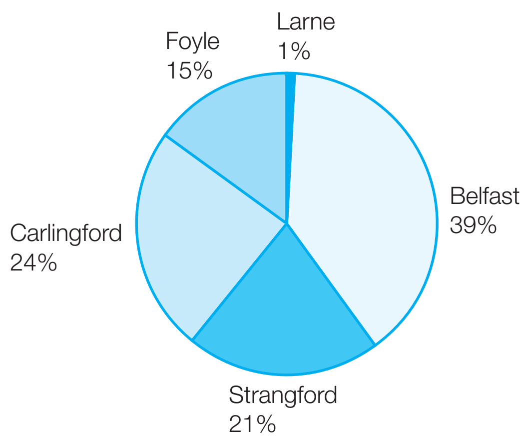
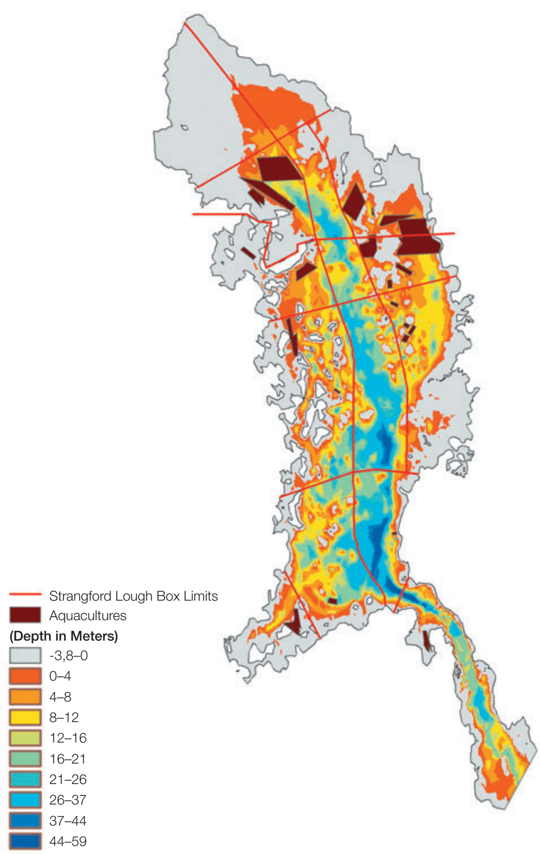


Figure 2. Box definition in Strangford Lough.



Simulations have been validated successfully using monthly field measures of environmental drivers and shellfish growth for both the blue mussel and Pacific oyster from the SMILE loughs. Model outputs confirm that ShellSIM, when run with a separate single standard set of parameters for each species, optimized upon the basis of calibrations at different sites, can effectively (± 20%) simulate dynamic responses in physiology and growth across the full range of natural environmental changes experienced within northern Irish sea loughs and elsewhere.

CARRYING CAPACITY

A short summary is given below of some of the key findings resulting from simulations carried out using the standard models developed in EcoWin2000.

Some of the aquaculture sites in the SMILE ecosystems are inactive at present, detail is required on the commercial and biological status of aquaculture sites in each lough, as well as the aquaculture type at each site (Figure 3). Areas of active aquaculture of each type were estimated and are presented in the **Shellfish** chapter.

Figure 3. Active aquaculture areas in each study site. Species cultured and type of aquaculture are also shown (NI – Northern Ireland; ROI – Republic of Ireland).

	Lough		Aquaculture		
System	**Area (ha)**	**Total active area (ha)**	**Species**	**Area (ha)**	**Type**
Carlingford Lough	4900	1063 (NI+ROI) 251 (NI)	Mussel	868 (NI+ROI) 168 (NI)	Bottom culture, rafts
			Pacific oyster	198 (NI+ROI) 83 (NI)	Trestles
Strangford Lough	14900	29	Mussel	6	Rafts
			Pacific oyster	24	Trestles
Belfast Lough	13000	953	Mussel	953	Bottom culture
Larne Lough	800	70	Mussel	10	Bottom culture
			Pacific oyster	60	Trestles
Lough Foyle	18600	1603	Mussel	1603	Bottom culture
			Pacific oyster	0.1	Trestles

The ShellSIM individual growth model (see the **Shellfish** chapter) was implemented and tested within the EcoWin2000 platform. Individual growth in weight and length were simulated for one mussel and one oyster in each model box where cultivation occurs (Figure 4).

With the addition of population dynamics to the individual model, changes in shellfish stock over several years can be estimated. As the shellfish culture cycle in all the SMILE loughs occurs over a three year period, the ecological model for each system needs to run for at least 6 years to produce stable simulations of harvestable biomass. Figure 5 shows the variation in (a) length and weight in mussels from box 34 in Carlingford Lough over a three year culture cycle and (b) population biomass for seeded and harvestable mussels over seven years.

An estimate of total production for both mussels and Pacific oysters in each system was carried out by running the standard models. Figure 6 illustrates the simulated production values in Carlingford Lough

Figure 4. Individual length and weight simulated in E2K for blue mussels and Pacific oysters cultured in Carlingford Lough.

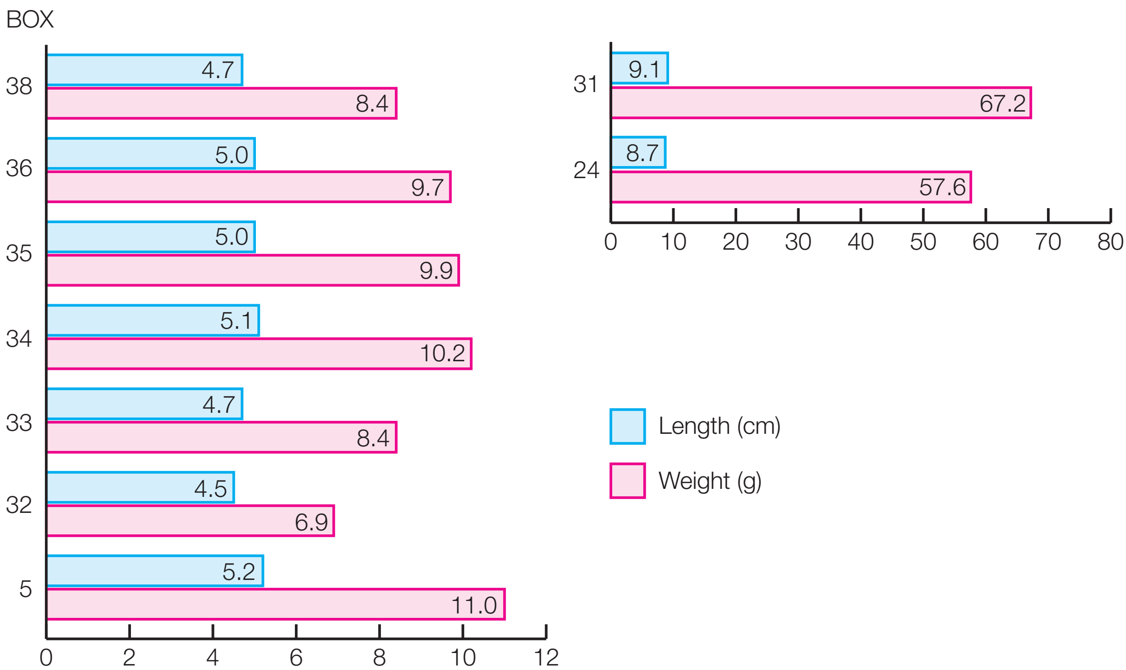
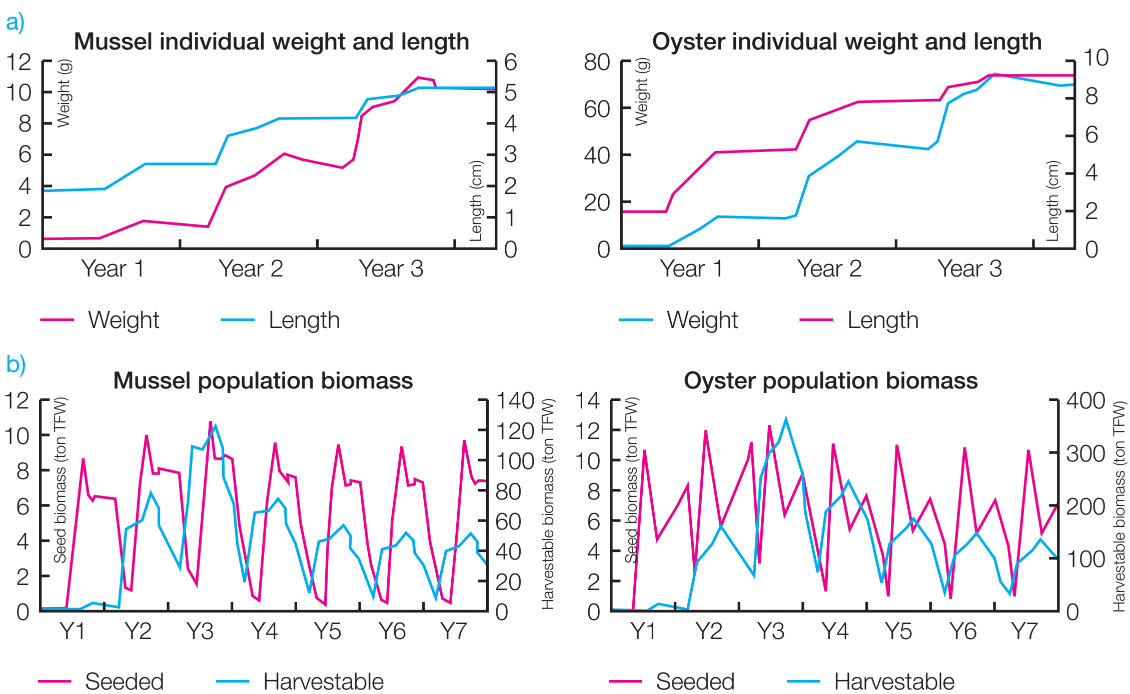


Figure 5. Results of simulations in Carlingford Lough: a) blue mussel and Pacific oyster growth in weight (g) and length (cm) during one culture cycle and b) mussel population biomass in total fresh weight (TFW) of seed and harvestable weights in boxes 31 and 34.



for a 10 year model run. The model shows production values ranging from about 2500 to 1300 tons for blue mussel, stabilising at a production of about 1300 tons, and from about 750 to 280 tons for Pacific oyster, stabilising at 280 tons.

The EcoWin2000 models were run for ten years to produce stable multi-year harvests for the five SMILE loughs, and the predictions compared with harvests recorded by Fisheries Division, Loughs Agency and Bord Iascaigh Mhara (BIM) (Figure 7).

The average physical product (APP) is defined as the ratio between harvested biomass (total physical product – TPP) and seed biomass, and is a measure of ecological and economic efficiency. In Figure 8, simulated TPP and APP are shown for Belfast Lough. Results presented correspond to year 10 of simulation, in order to show stable outputs.

Figure 6. Simulated production values for Carlingford Lough. Model was run for a 10 year period to show consistently stable harvesting results.

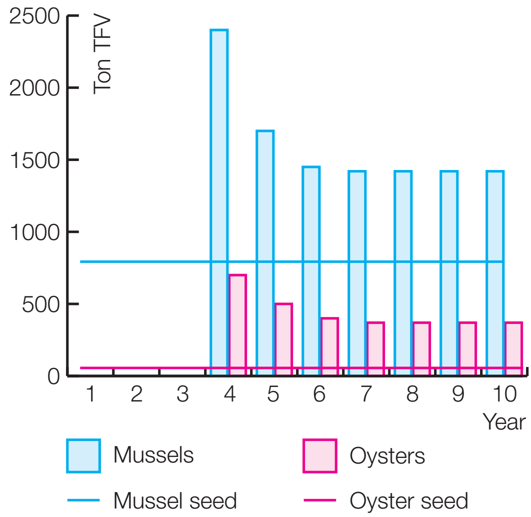
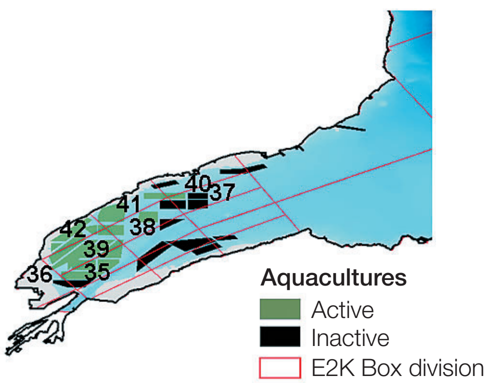
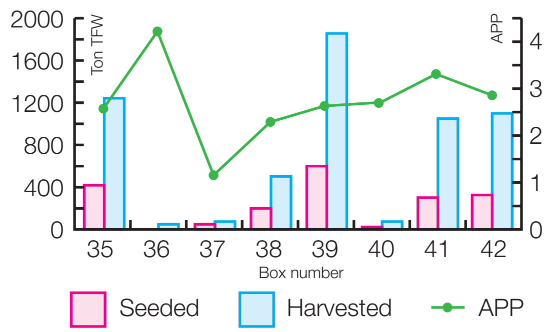


Figure 7. Production data (tons total fresh weight y^{-1}) for the five SMILE loughs and comparison with production simulations with EcoWin2000.[1]

System	Species	Carlingford Lough	Strangford Lough	Belfast Lough	Larne Lough	Lough Foyle[2]	Total
Production records	Blue mussel	1500 to 3000	2.4	10000	200	15318	27300
	Pacific oyster	365 to 868	260	-	10.4	50	820
Model simulation	Blue mussel	1300	9	6000	300	1325	8934
	Pacific oyster	280	223	-	9	12	524

Figure 8. Model results for mussel production in Belfast Lough.





[1] The production records shown were given by DARD Fisheries Division for Strangford, Belfast and Larne Loughs and by the Loughs Agency and BIM for the transboundary systems (Carlingford Lough and Lough Foyle).

[2] There are substantial uncertainties on culture practice in Lough Foyle, regarding areas, seed densities etc. SMILE model results are based on cultivation areas shown in Figure 3.

A summary of the model results for each system is shown in Figure 9. The total production per unit of area is also shown, and varies within each system depending on the location of the aquaculture.

Figure 9. Summary of model results for all SMILE systems.

Ecosystem and species		Aquaculture Area (ha)	TPP (tons)	APP	TPP per ha
Carlingford Lough	Blue mussel	868 (NI+ROI) 167.9 (NI)	1300 (NI+ROI) 320 (NI)	2.5 (NI)	1.5 (NI+ROI) 1.9 (NI)
	Pacific oyster	198 (NI+ROI) 83.2 (NI)	280 (NI+ROI) 110 (NI)	5.3 (NI)	1.4 (NI+ROI) 1.3 (NI)
Strangford Lough	Blue mussel	6	9	7	1.5
	Pacific oyster	24	223	8.4	9.5
Belfast Lough	Blue mussel	953	6000	2.8	6.3
Larne Lough	Blue mussel	10	300	3.3	28.8
	Pacific oyster	60	9	14	0.15
Lough Foyle	Blue mussel	1602	1325	2.5	0.83
	Pacific oyster	0.1	12	6.9	171

MANAGEMENT

SCENARIOS

Scenarios to exemplify the use of system-scale carrying capacity models

Three scenarios were tested on different SMILE loughs to illustrate potential applications

1. Increase in the area seeded within Belfast Lough
2. Increase in water temperature in Strangford Lough
3. Partitioning of the food resource by wild species in Carlingford Lough

The first scenario was tested for Belfast Lough, where aquaculture already occupies a significant proportion of the entire system. Since there are several licensed sites in this lough which are not active at present, the EcoWin2000 model was run assuming that some of the inactive aquaculture sites had become active. The previously inactive aquaculture areas inside box 29 (see the **Spatial Domain** chapter) were considered to be active in this first scenario, with seeding densities that were the same as for the rest of the lough.

The results obtained are compared with standard model outputs per box in Figure 10, showing that an increase in seeded area affected harvested biomass, APP and mussel individual weight in the remaining boxes.

The second scenario tested for potential climate change effects by considering an increase in water temperature for Strangford Lough.

The predicted effects on aquaculture in Strangford Lough, for an increase of 1 °C and 4 °C in the water temperature are shown in Figure 11.

An increase of 1 °C in water temperature would lead to a reduction of about 10% in mussel production and less than 2% in Pacific oyster production, and an increase of 4 °C would result in a reduction of 50%

Figure 10. Belfast model results for an increased seeding area. Results of the standard model are shown for comparison.

Box	Seeded		Harvested		APP		Individual weight	
	Standard	Scenario	Standard	Scenario	Standard	Scenario	Standard	Scenario
29	none	264	none	562	none	1.9	none	4.8
35	426	no change	1258	1222	2.7	2.6	9.3	8.8
36	6	no change	28	27	4.2	4.1	19.2	18.6
37	37	no change	57	56	1.4	1.4	3	2.9
38	193	no change	517	507	2.5	2.4	8.3	8
39	599	no change	1862	1841	2.7	2.7	9.7	9.5
40	19	no change	56	55	2.8	2.8	10.8	10.6
41	293	no change	1072	1062	3.4	3.3	14.3	14
42	313	no change	1114	1107	3	3.0	10.9	10.8
	1886	2150	5964	6441	3	3	11	9.8

in mussel production and less than 5% in oyster production. These results suggest that an increase in the water temperature would lead to a reduction in both the mean weight and mean length of individuals, although this reduction is more pronounced in mussels than in oysters for physiological reasons. As a consequence, there would be an overall decrease in aquaculture productivity.

The third scenario was simulated in Carlingford Lough where a GIS resource partitioning model was applied, taking into account the average abundances of wild species per unit area. The EcoWin2000 model predicts that by taking wild filter-feeding species into account, production of cultivated species would be reduced by 19% for mussels and 13% for Pacific oysters, together with associated reductions in individual length and weight (Figure 12). Carrying capacity assessment should take place at a first stage at the system level, as has been carried out in the SMILE project. However, after this system-scale planning approach is completed, it is appropriate to evaluate the sustainability of aquaculture activities at the local scale (farm, raft etc).

Figure 11. Model results for the Strangford standard model and two scenarios considering an increase in water temperature of 1 °C and 4 °C.

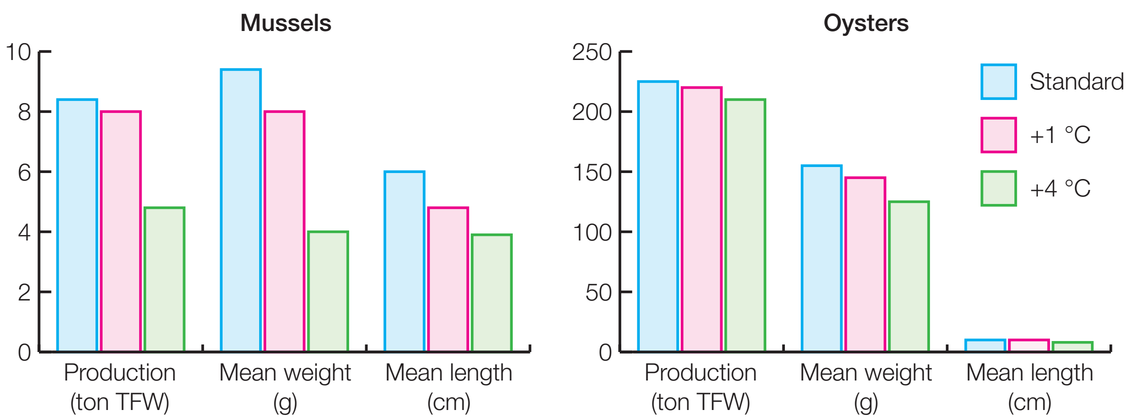
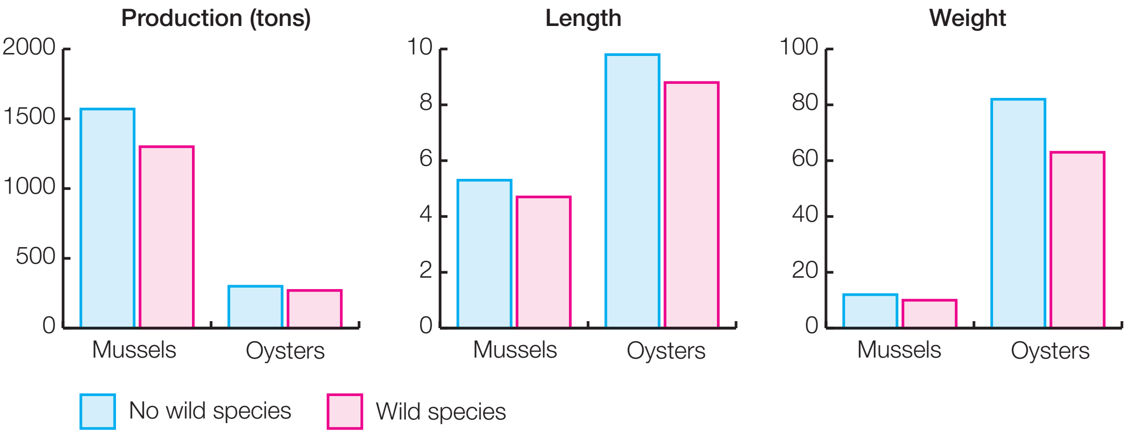


Figure 12. Scenario showing aquaculture production with and without taking into account resource partitioning in Carlingford Lough.



A number of tools have been developed to carry out this kind of assessment, including the FARM™ model, developed by members of the SMILE team, and MUSMOD, a mussel model developed in the U.S. by Carter Newell and John Richardson. To illustrate some of the local-scale issues, this book includes two case studies:

- The first was contributed by Carter Newell, and focuses on some of the problems and approaches for farm-scale carrying capacity work, using examples from Maine, USA;
- The second applies the FARM™ screening model to illustrate how system-scale simulations carried out with EcoWin2000 can be used to analyse production at the farm scale. Suzanne Bricker, from the US National Oceanic and Atmospheric Administration, contributed to this example through the application of the ASSessment of Estuarine Trophic Status (ASSETS) Model.

CONCLUSIONS

System-scale assessments of sustainable mariculture in general and shellfish culture in particular are conditioned by different definitions of carrying capacity, which may be regarded as physical, production, ecological and social. The SMILE products were desiged to address the first three of these definitions (Figure 13).

These various products were delivered to the DARD Permanent Secretary in February 2007, and have been consolidated in a bespoke website (Figure 14).

Drawing upon the process developed for application of the SMILE models, including the fundamental interrelations identified by those models, simpler screening models have been developed for eutrophication assessment and other purposes, which will help environmental managers to evaluate the effects of aquaculture on Ecological Status, as defined by the Water Framework Directive.

The modelling work developed in the SMILE project has allowed a clear link to be established between environmental variables, social aspects such as cultivation practice and shellfish production. This has empowered managers, scientists and industry through the delivery of tools which allow different development scenarios to be analysed. However, although we now understand much more about the underlying processes than at the start of this work, there are a number of improvements which will over time

Figure 13. SMILE products and carrying capacity definitions.

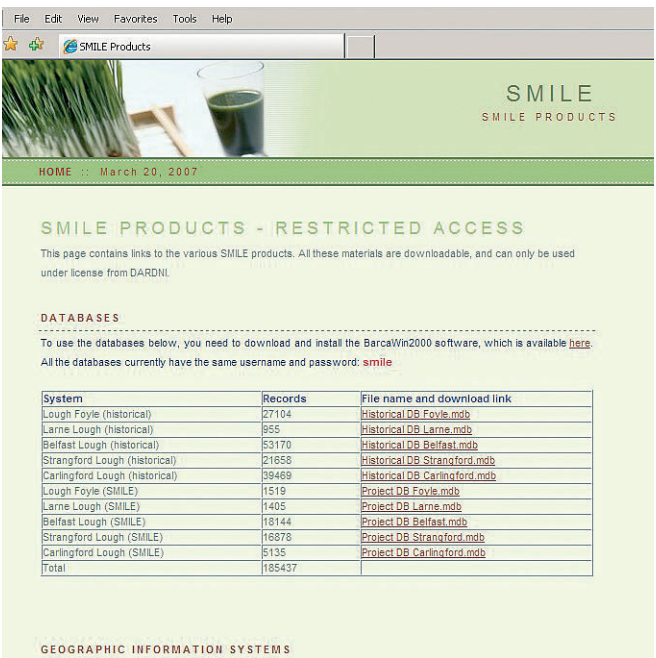
Carrying capacity definition	SMILE solution
Physical	Bathymetry, morphology: GIS models
	Current speed and direction: Delft3D Model
Production	Individual shellfish growth: ShellSIM model
	Population growth: D3D-ShellSIM-EcoWin2000 framework
Ecological	Ecosystem response – plankton, nutrients: E2K Model
	Wild species, reefs: E2K-GIS resource partitioning model
	Watershed management strategies: SWAT-E2K
Social	The SMILE team has addressed this in the EU SPEAR project (China) at the system scale, and in the EU ECASA project (Europe) at the local scale using the FARM™ model. Not explicitly considered in SMILE

increase the value of the SMILE models, GIS and databases for decision support. A better understanding of cultivation practice, shellfish mortality and its variation in time and space, issues related to seed deployment and more accurate production data will greatly improve the accuracy and usefulness of these models.

The progress which was made in SMILE illustrates the potential of this approach in implementing a national programme for sustainable aquaculture, drawing on the excellent collaboration of science, management and industry, and harmonising the concerns of fisheries and environmental decision-makers, the aquaculture industry and conservation agencies.

More information on the SMILE project is available at: http://www.ecowin.org/smile/

Figure 14. Web-based SMILE product delivery.



PROBLEM DEFINITION

INTRODUCTION

AQUACULTURE WORLDWIDE

Aquaculture is increasing in importance due to the overexploitation of marine resources, worsened by the progressive environmental degradation of many marine areas. As a result, recommendations have been made to encourage nations to produce marine and estuarine species through cultivation.

However, these cultivation activities can themselves provoke environmental changes, which may in some cases be quite severe. Additionally, in many countries aquaculture is a subject of controversy, particularly involving conservation agencies and non-governmental organizations. Consequently, there are licensing concerns in many nations and the respective regulators can place obstacles to licensing of aquaculture.

The acknowledgement of this paradox has led to discussions in different international fora, and to the presentation of documents to guide the exercise of these activities in order to minimise the negative impacts on the environment, and where appropriate to value aspects of aquaculture that may help to solve some environmental problems.

THE LEGAL FRAMEWORK RELATING TO AQUACULTURE

INTERNATIONAL LEGAL FRAMEWORK

There are several international conventions e.g. the Oslo-Paris Convention (OSPAR), Bern Convention, Helsingfors Convention (HELCOM) which include provisions in relation to aquaculture. In addition, the European Union is committed to the principles of the Precautionary Approach, the guidelines for aquaculture in the FAO Code of Conduct for Responsible Fisheries (Article 9 of which covers Aquaculture Development) and other international arrangements or guidelines such as the ICES Code of Practice on the Introductions and Transfers of Marine Organisms.

One of the more important documents related to the environment and biodiversity is the Convention on Biological Diversity (CBD).

CONVENTION ON BIOLOGICAL DIVERSITY

The objectives of the Convention on Biological Diversity are the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources.

Loss or alteration of habitats as a result of aquaculture operations can become a biodiversity concern when it changes the living conditions of other species:

- Seed collection for aquaculture purposes from habitats such as lagoon bottoms using destructive gear causes habitat destruction and/or alteration
- Aquaculture takes up space, often very large areas, not only in bays and oceans, but also on nearby foreshore areas as a result of development of aquaculture infrastructures
- Tidal marshes serve as important nursery grounds for populations of fish and shellfish and their destruction may cause species loss

However, in the work carried out within the framework of the CBD, it has also been recognized that aquaculture may have positive effects on biodiversity.

POTENTIAL POSITIVE IMPACTS OF AQUACULTURE

- Reduction of predation pressure on commonly harvested aquatic species can help preserve biodiversity
- Best site selection (including optimal flushing and dispersal of nutrients) may promote an increase of local and total productivity, especially in oligotrophic and mesotrophic systems, particularly when additional substrate heterogeneity, such as building of artificial reefs to soft bottom areas, is provided
- Increased nutrient inputs could provide extended food webs and possibly increase biodiversity, at least within a certain range
- Act as a mitigation process for biodiversity recovery – under controlled reprodutive activity
- Improve ecological status – e.g. macroalgal cultivation can remove significant amounts of nutrients from the surrounding waters and shellfish cultivation can extract both nutrients and contaminants from the water column
- Provide the market with high quality farmed shellfish

EUROPEAN UNION LEGAL FRAMEWORK

Specific European legislation relevant to limiting the effects of aquaculture on biodiversity is less well established than for capture fisheries. Relevant Community legislation includes that on aquatic animal health, and the Environmental Impact Assessment (EIA) legislation.

Most aquaculture concerns are regulated by national legislation which is influenced by a number of horizontal Community Directives governing water, habitat and bird life. Following from these directives it is required that developing projects, including new fish farms, should be subjected to prior assessment if they are likely to have significant effect on the environment.

In the framework of the reform of the Common Fisheries Policy, the European Commission recognised the importance of aquaculture and the necessity to develop a Strategy for the Sustainable Development of European Aquaculture. The Strategy sets out a wide range of policy principles on which the future development of aquaculture in the EU would be based, including the necessity to ensure that aquaculture becomes an environmentally sound activity. Additionally, an action plan was developed for biodiversity, which includes a chapter dedicated to aquaculture impacts on marine biodiversity.

AQUACULTURE IN NORTHERN IRELAND

The shellfish aquaculture industry in Northern Ireland has expanded over the past decade and with this expansion has come increasing pressure for environmental regulation and the need for sustainable development. It is therefore, vital for the industry and the environment that the industry operates within sustainable guidelines.

The development of aquaculture in Northern Ireland has largely centered around the five main sea Loughs although other smaller bays have been developed. These sea loughs are used for a variety of activities and one of them, Strangford Lough, is a Marine Nature Reserve, one of only three in the United Kingdom. All are subject to a range of conservation designations. Competing commercial activity comes from fishing, tourism, harbour developments, shipping and the use of the loughs as receiving bodies for wastewater discharges.

CARRYING CAPACITY AS MANAGEMENT TOOL

Assessments of sustainable shellfish culture are conditioned by different definitions of carrying capacity, which may be regarded as physical, production, ecological and social. These are themselves modulated by scaling, usually considered to be either system scale (bay, estuary or sub-units thereof), or local scale (farm).

To overexploit an area will have severe effects on the commercial productivity and potentially also on ecosystem health. A method to predict the ability of coastal environments to sustain bivalve culture is required for successful development of the industry through the determination of the carrying capacity.

The concept of carrying capacity of an ecosystem for natural populations is derived from the logistic growth curve in population ecology, and defined as the maximum standing stock that can be supported by a given ecosystem for a given time. Carrying capacity estimates in terms of aquaculture (production) may be defined as the stocking density at which production levels are maximised without having a negative impact on growth. Subsequently, carrying capacity for shellfish culture has been further defined as the standing stock at which the annual production of the marketable cohort is maximized. This will differ substantially from the ecological carrying capacity, and is termed the sustainable aquaculture carrying capacity.

It is important to assess the carrying capacity of an area prior to the establishment of large-scale shellfish cultivation, to ensure an adequate food supply for the anticipated production and to avoid or minimise any ecological impacts.

For bivalve suspension feeders, the dominant factors determining the sustainable carrying capacity at the ecosystem scale are primary production, detrital inputs and exchange with adjacent ecosystems. At the local scale, carrying capacity depends on physical constraints such as substrate, shelter and food transported by tidal currents, and density-dependent food depletion. Mortality is a critical factor, and high seed mortality due to sub-optimal seed deployment, particularly in bottom culture, is a key factor in reducing production yield and economic competitiveness.

Generic carrying capacity modelling should include both ecosystem-scale and local-scale approaches. Estimation of the carrying capacity should take into account the functional role of shellfish beds as components of an ecosystem. This may be achieved if carrying capacity modelling is applied within the broader framework of decision support systems, where exploitation and conservation are evaluated.

OBJECTIVES

Four key objectives were established for the Sustainable Mariculture in northern Irish Sea Lough Ecosystems (SMILE) project.

SMILE OBJECTIVES

- To establish functional models at the lough scale, describing key environmental variables and processes, aquaculture activities and their interactions
- To evaluate the sustainable carrying capacity for aquaculture in the different loughs, considering interactions between cultivated species, targeting marketable cohorts, and fully integrating cultivation practices
- To examine the effects of overexploitation on key ecological variables
- To examine bay-scale environmental effects of different culture strategies

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TOOLS

INTRODUCTION AND OBJECTIVES

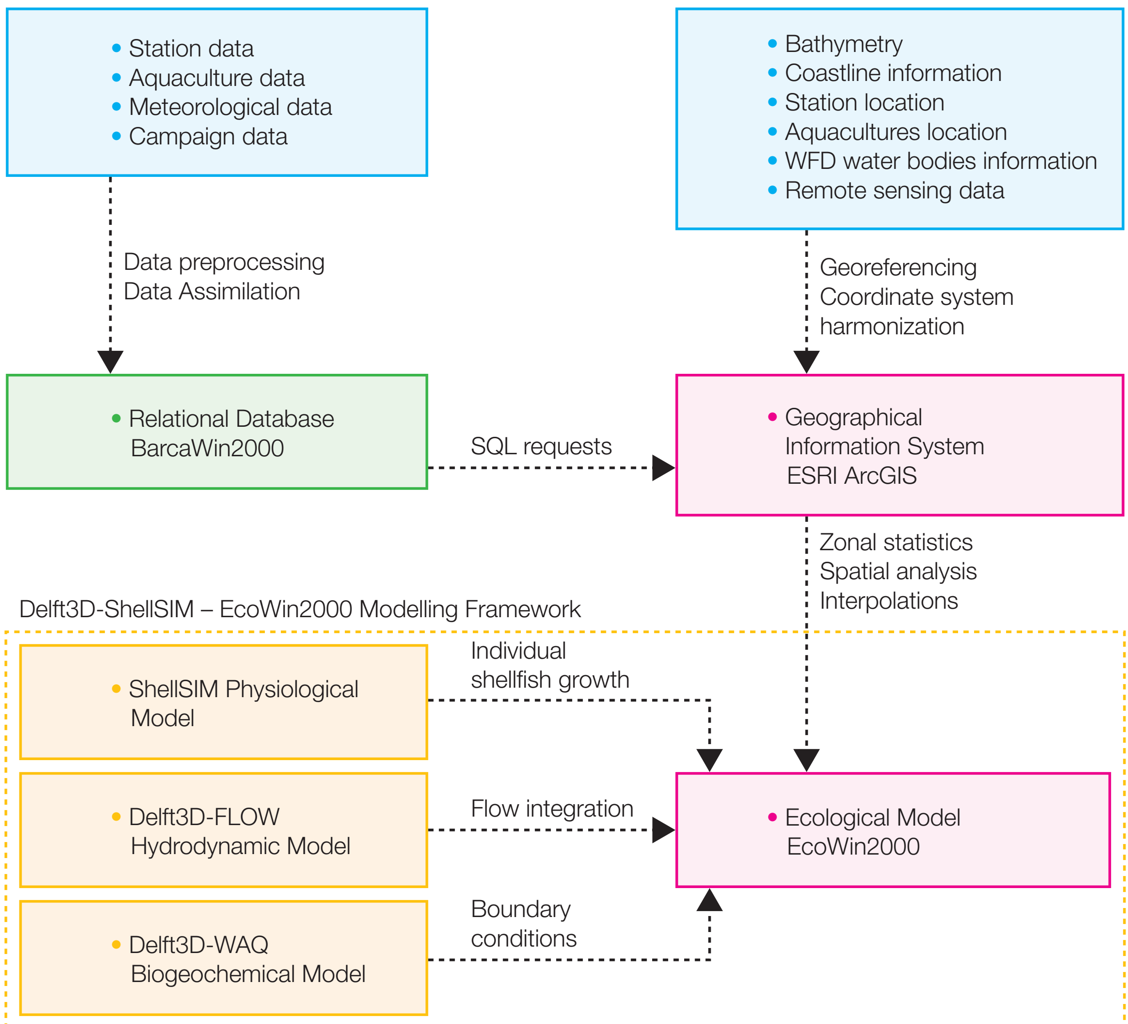
This chapter reviews the tools used and/or developed in SMILE.

Based on their role in the project, these tools may be divided into three categories.

SMILE TOOLS

- Data analysis tools
  Supply the framework for the project as a whole.
- Modelling tools
  Used for simulations at different scales.
- Management tools
  Provide instruments for managing the systems.

Figure 15. Relationships among tools in the SMILE toolset.



OVERVIEW OF TOOLS

BRIEF DESCRIPTION

Relational database

Relational databases were built for the five SMILE systems using the Barcawin2000™ software, for water quality data assimilation and management.

Geographic Information System (GIS)

A geographical information system (GIS) was implemented for each system, for the analysis and management of spatially distributed data.

Modelling tools

Bespoke tools were developed and implemented to simulate catchment discharge, fine-scale circulation in the loughs, individual shellfish growth and system-scale multi-year aquaculture activity.

Management tools

The aim of this toolset is to provide a user-friendly approach for testing management options using the integrated EcoWin2000 (E2K) model.

Figure 15 illustrates the relationships among the various tools applied in SMILE.

SUPPORTING TOOLS

WATER QUALITY DATABASES

Data assimilation was carried out using the Barcawin2000 software. For each system a relational database was built. The software in use has been developed since 1985 and has been used in multiple research projects with widely varying data storage requirements.

Figure 16. Number of records for SMILE system databases.

System	Stations	Parameters	Samples	Results
Carlingford Lough (historical)	113	273	4912	34171
Strangford Lough (historical)	22	92	3417	18127
Belfast Lough (historical)	63	79	7514	45514
Larne Lough (historical)	7	14	84	850
Lough Foyle (historical)	42	105	3284	23673
Carlingford Lough (SMILE)	13	19	884	4219
Strangford Lough (SMILE)	29	19	3530	13300
Belfast Lough (SMILE)	28	19	3135	14962
Larne Lough (SMILE)	10	20	178	1197
Lough Foyle (SMILE)	20	20	170	1309
Totals	**347**	**660**	**27108**	**157322**
Overall total				**185437**

The main advantages of this database can be summed up as follows:

- Organization of information in a state-of-the-art relational model
- Security for five levels of user access
- Easy input of data, by mapping MS-Excel spreadsheets to database fields, followed by automatic import and validation
- Robust data entry validation
- Numeric listings and search results are output to an Excel compatible spread sheet, or to graphs created directly in Excel
- Open architecture and easy export to Oracle, SQL server, etc

GEOGRAPHIC INFORMATION SYSTEMS

A geographic information system (GIS) is a system for capturing, storing, analyzing and managing data and associated attributes which are spatially referenced. Data for the SMILE project were collated and integrated in a GIS framework adding value and allowing the creation of a consolidated product for the northern Irish systems that provided the spatial support to the SMILE project.

The coordinate system used for all data was the Irish National Grid, which uses the OSGB1936 Modified Datum and the Transverse Mercator Projection. Data integration and analyses were performed using the same methodologies for all loughs, thus generating a similar and comparable geographical information data structure. The software used for all GIS operations was ESRI ArcGIS 9.2. The metadata produced for each lough are shown in Figure 17.

Relations between spatial data present in the BarcaWin2000 database and the EcoWin2000 ecological model were established through the use of the GIS framework created for the SMILE project. This proved to be a powerful and effective connection tool between the database and modelling structures increasing effectiveness of operations and decreasing model preparation and calibration times.

Figure 17. Different types of geographical information produced in the SMILE project.

Layer Type	Spatial Resolution (in meters)	Layer type	Data Type	Main GIS Operations
Bathymetry	25	Raster (Regular grid)	Real	Interpolation (IDW)
Sampling station data	-	Vectorial (Points)	Integer	Digitising
Box definition	-	Vectorial (Polygons)	Integer	Digitising / Analysis tools
Water bodies	-	Vectorial (Lines)	Integer	Digitising / Analysis tools
Aquaculture areas	-	Vectorial (Polygons)	Integer	Digitising / Analysis tools
Coastline	-	Vectorial (Line)	Integer	Digitising / Analysis tools
Sediments	25	Raster (regular grid)	Integer	Digitising / Georeferencing / Resampling
Shellfish sampling stations	-	Vector (points)	Integer	Digitising
Wild shellfish distibution	25	Raster (regular grid)	Real	Interpolation / Geo-statistical analysis

MODELS

SWAT

The Soil and Water Assessment Tool (SWAT) catchment model was used to simulate nutrient inputs from agricultural and urban sources. The model simulates processes such as vegetation growth (taking into account agricultural and grazing activities), river flow, soil erosion and nutrient transport from fields and wastewater discharge points into the lough. The physical equations which form the backbone of SWAT allow its application to investigate scenarios of climate, land use and agricultural management changes in order to predict consequences for water discharge, nutrient and sediment loadings to aquatic systems.

SHELLSIM

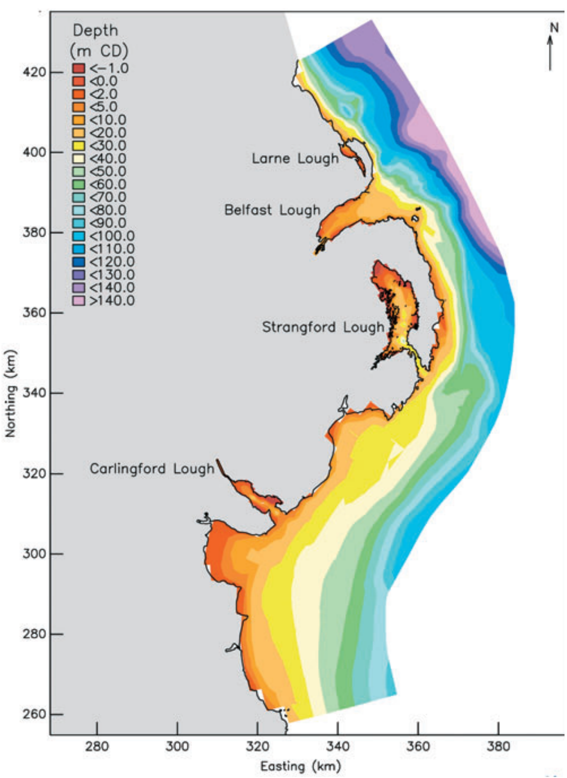
To model the complex feedbacks, whereby mussels and oysters interact with ecosystem processes, experimental measurements of physiological responses were undertaken in each species over conditions that spanned full normal ranges of food availability and composition in each SMILE lough.

Mathematical equations were then derived that define functional inter-relationships between the component processes of growth, integrating those interrelations within a dynamic model structure (ShellSIM) developed to simulate time-varying rates of individual feeding, metabolism and growth in these and other species.

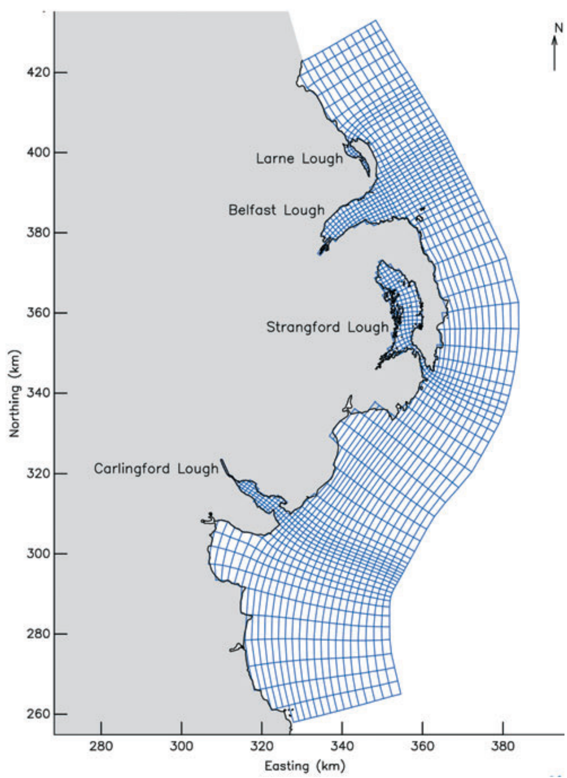
DELFT3D

The Delft3D-FLOW hydrodynamic model was used to simulate the tidal, wind and ocean currents in the study area.

Model bathymetry



Model grid

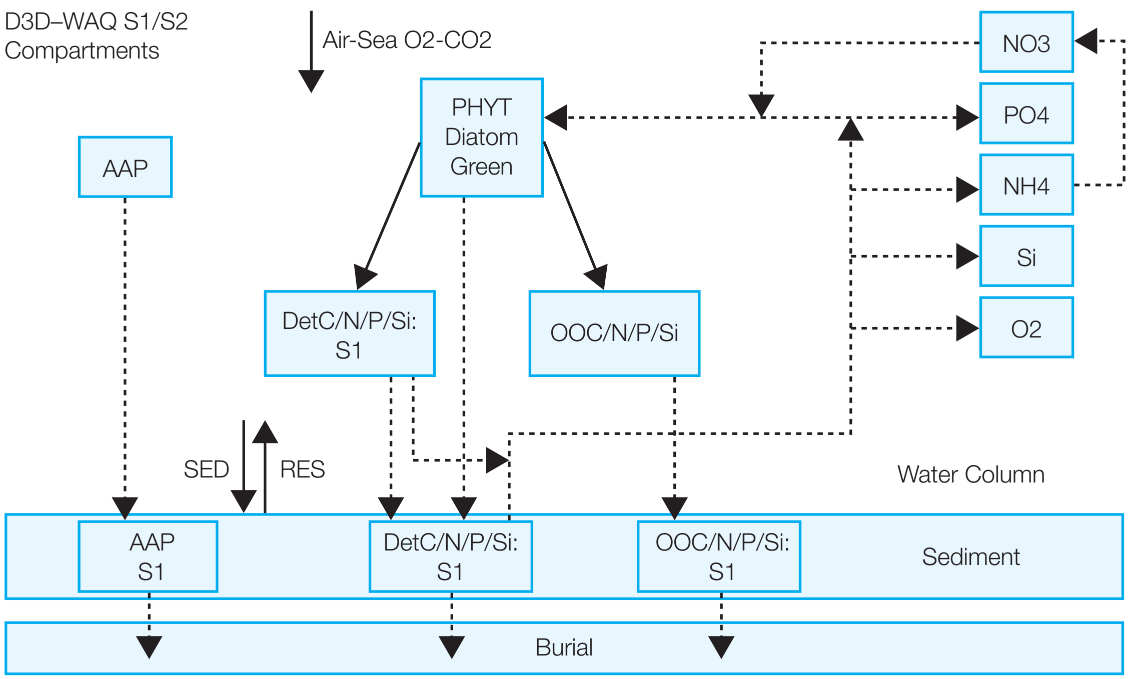


This fine-grid model provides a detailed description of the circulation, and is coupled with other models to provide an appropriate description of hydrodynamics for broader-scale models such as EcoWin2000.

DELFT3D-WAQ BIOGEOCHEMICAL MODEL

The biogeochemical model adopted for this study was the D3D-WAQ model, which is capable of integrating the complexity of dynamic variability linked to physics with the core processes that govern the biogeochemistry. It does not include higher levels of the marine ecosystem (e.g. zooplankton, shellfish, fish) that are explicitly addressed by the EcoWin2000 ecological model. The core structural features of the model are depicted in Figure 18, which shows the main model compartments and how they are linked. The model deals explicitly with primary production (new and regenerated) and remineralization.

Figure 18. The structural characteristics of the D3D-WAQ biogeochemical model.



The model parameterises heterotrophic activity in the water column and sediments. It deals with particle sedimentation and resuspension explicitly using user-defined critical shear stresses to define thresholds for deposition and resuspension. The air-sea gas exchange functionality was the Wanninkoff formulation which improves on gas exchange rates under high winds by parameterising momentum transfer.

ECOWIN2000

EcoWin2000 is an ecological model for aquatic systems, developed using an object-oriented approach. It resolves hydrodynamics, biogeochemistry and can incorporate population dynamics for target species. The various components consist of a series of self-contained objects, rather than multiple sub-models.

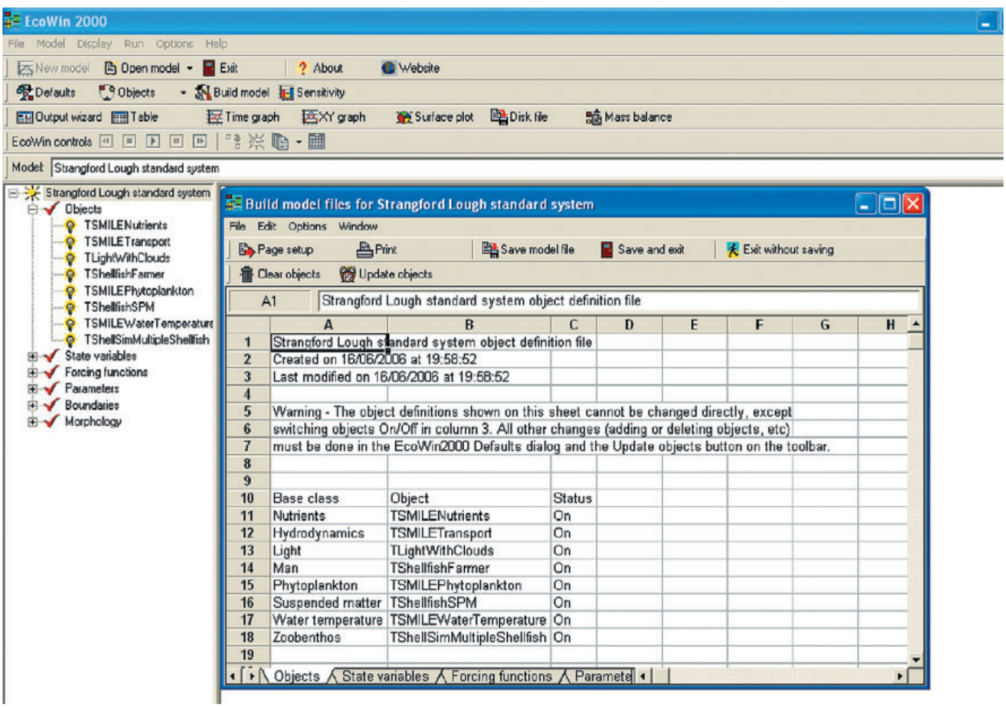
The EcoWin2000 model consists of two basic parts: a shell module and “ecological” objects. The shell is responsible for communication with the various objects, for interfacing with the user, supplying model outputs and general maintenance tasks.

Objects have “attributes” (variables) and “methods” (functions) – see Figure 19.

Figure 19. Attributes and methods (active and passive) for some objects of EcoWin2000 modelling platform.

Object	Sample attributes	Typical active methods	Typical passive methods
Transport	Salt	Advection-diffusion	-
Dissolved substances	Forms of DIN, $PO4^{3-}$, SiO_2, D.O.	Nitrification, formation of particulates	Mineralization of detritus, exsudation
Phytoplankton	Phytoplankton, toxic algae	Production, respiration, senescense, exsudation, production of toxins	Grazing by zooplankton, fish, benthic filter-feeders
Phytobenthos	Microalgae, macroalgae, salt marsh flora	Production, respiration, senescence	Grazing by zooplankton, fish, harvesting of seaweeds
Zooplankton	Zooplankton, copepods	Eat, grow reproduce, excrete, natural mortality, swim, settle (for benthic larvae)	Predation by other objects and within the object
Zoobenthos	Filter-feeders, deposit-feeders	Filter, grow, reproduce, excrete, natural mortality, swim, settle (for benthic larvae)	Fisheries, predation by several other objects
Nekton	Fish, large-invertebrates (e.g. Sepia)	Hunt (including select), grow, reproduce, excrete, natural mortality, swim, migrate	Fisheries, hunting by birds
Man	Various socio-economic attributes	Seed and harvest shellfish	-

Figure 20. Screenshot of the EcoWin2000 model, as applied to Strangford Lough.



Each object groups together related state variables, and may at any time be extended to contain a new state variable without affecting the code of any other part of EcoWin2000. Similarly, the methods which control interactions among state variables within objects may be easily changed, due to inheritance (which is a property of object-oriented programming languages).

EcoWin2000 uses a range of equations depending on the application requirements, and may be used as a research model to examine nutrient loading and aquaculture development scenarios. It has been extensively tested, and is a potentially useful tool for supporting an ecosystem approach to sustainable aquaculture development.

In the SMILE project, the EcoWin2000 modelling platform was used to implement an ecological model for each northern Irish lough to estimate carrying capacity using appropriate biogeochemistry and population dynamics. The main features modelled for these systems were the hydrodynamics, suspended matter transport, nitrogen cycle, phytoplankton and detrital dynamics, shellfish growth and human interaction.

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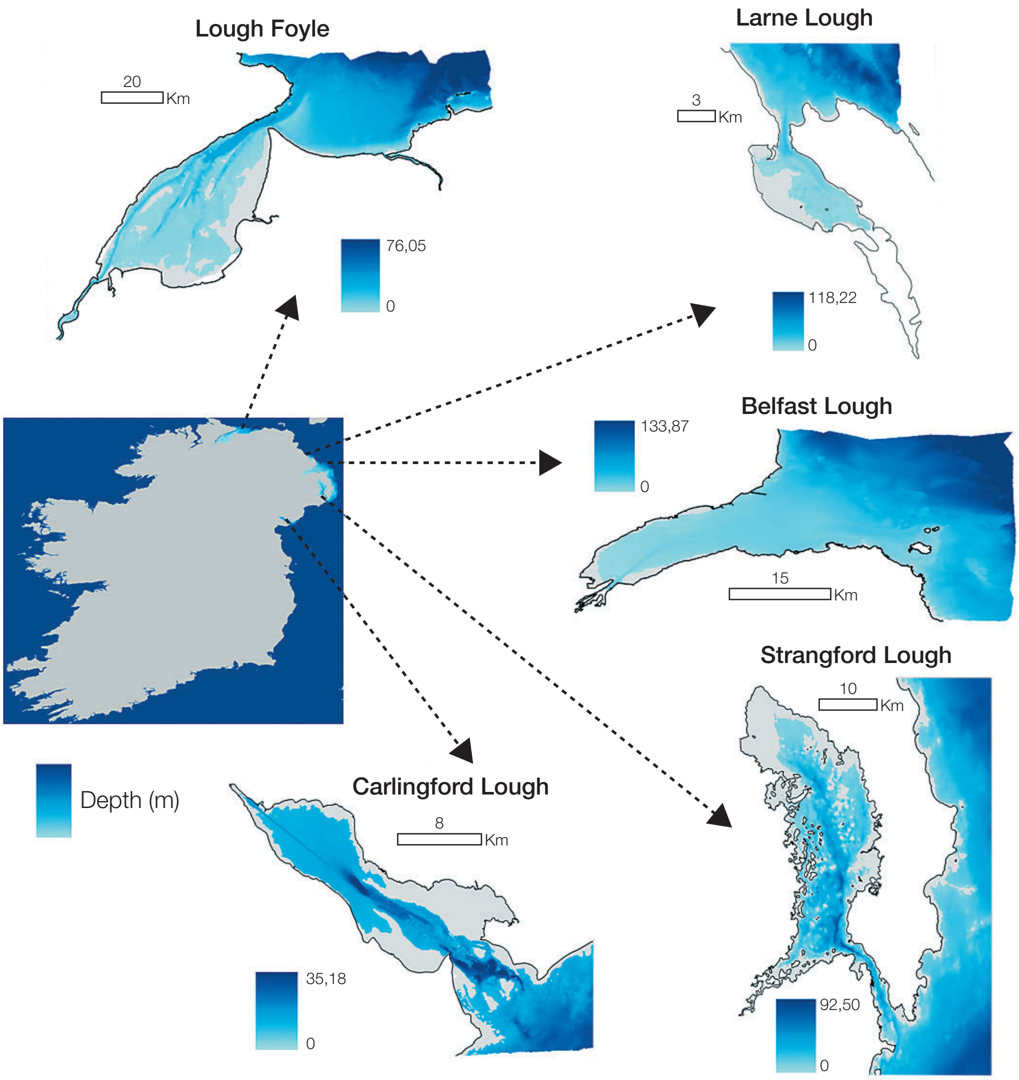
SPATIAL DOMAIN

DESCRIPTION OF SYSTEMS

The five sea loughs addressed by the SMILE project are situated in northern Ireland (Figure 21). Carlingford Lough and Lough Foyle are transboundary systems, and form an international border with the Irish Republic.

Figure 21. Location of the five northern Irish sea lough ecosystems studied in the SMILE project.



Together, the five loughs have an area of 522 km^2 and drain a combined catchment of about 6000 km^2.

Lough Foyle is the largest of all the loughs and forms the NW border between Northern Ireland and the Republic of Ireland, with 75% of the catchment in Northern Ireland. *Larne Lough* is a shallow marine embayment enclosed to the east by the peninsula of Islandmagee. Major freshwater sources are the Glynn and Larne rivers.

Belfast Lough is a shallow semi- enclosed bay, almost 96% of the area is subtidal. The main freshwater source is the River Lagan, which has a mean flow of 32 $m^3 s^{-1}$.

Strangford Lough is a large marine lough with an area of approximately 150 km^2, and is connected to the Irish Sea by the Strangford narrows. It has a maximum depth of 59 m, and a volume of 1537 x 10^6 m^3.

The main freshwater sources to Strangford Lough are the Comber River in the North West and the Quoile River in the south west.

Carlingford Lough is the most southerly of the five sea loughs. It is a shallow, well-mixed system with an average depth between 2 and 5 m and a deeper narrow channel along the centre of the lough. It is a cross-border system with an area of about 50 km^2 (15 km in length from the mouth to Warrenpoint and 4 km at its widest point), and a volume of 460 x 10^6 m^3.

The Newry River is its major freshwater source with a small flow rate that can vary from 1 $m^3 s^{-1}$ in summer to 9 $m^3 s^{-1}$ in winter. The residence time varies between 14 and 26 days. The main physical properties of these systems are shown in Figure 22.

A wide range of activities take place in these sea loughs, ranging from leisure and recreation to fishing and aquaculture.

Figure 22. Main physical properties of the five sea loughs in the SMILE project.

System	Carlingford Lough	Strangford Lough	Belfast Lough	Larne Lough	Lough Foyle	Total
Volume (x10^6 m^3) [3]	460	1537	1548	27	752	4324
Area (km^2) [3]	49	149	130	8	186	522
Maximum depth (m) [3]	35	59	22	13	19	-
Catchment (km^2)	474	772	900	115	3700	5961
Temperature (°C)	3–20	2-19	2-21	4–18	2–20	-
Mean salinity	32.5	33	28	33	21	-
River flow ($m^3 s^{-1}$)	1–9	3.5	32	3.2	105	-
Water residence time (d) [4]	14–26	4–28	10–20	7–19	4–30	-

[3] Volumes, areas and depths calculated at High Water using GIS.

[4] All residence times except Lough Foyle calculated using Delft3D. Lough Foyle from “Nutrient inputs and trophic status of the Foyle estuary and lough”.

ECOSYSTEM DATASETS AVAILABLE

The BarcaWin2000 relational database (see the **Tools** chapter) was loaded with data collected from sampling campaigns carried out in the five systems from 1984 to 2006.

Figure 23. Summary statistics for key parameters in the five SMILE loughs.

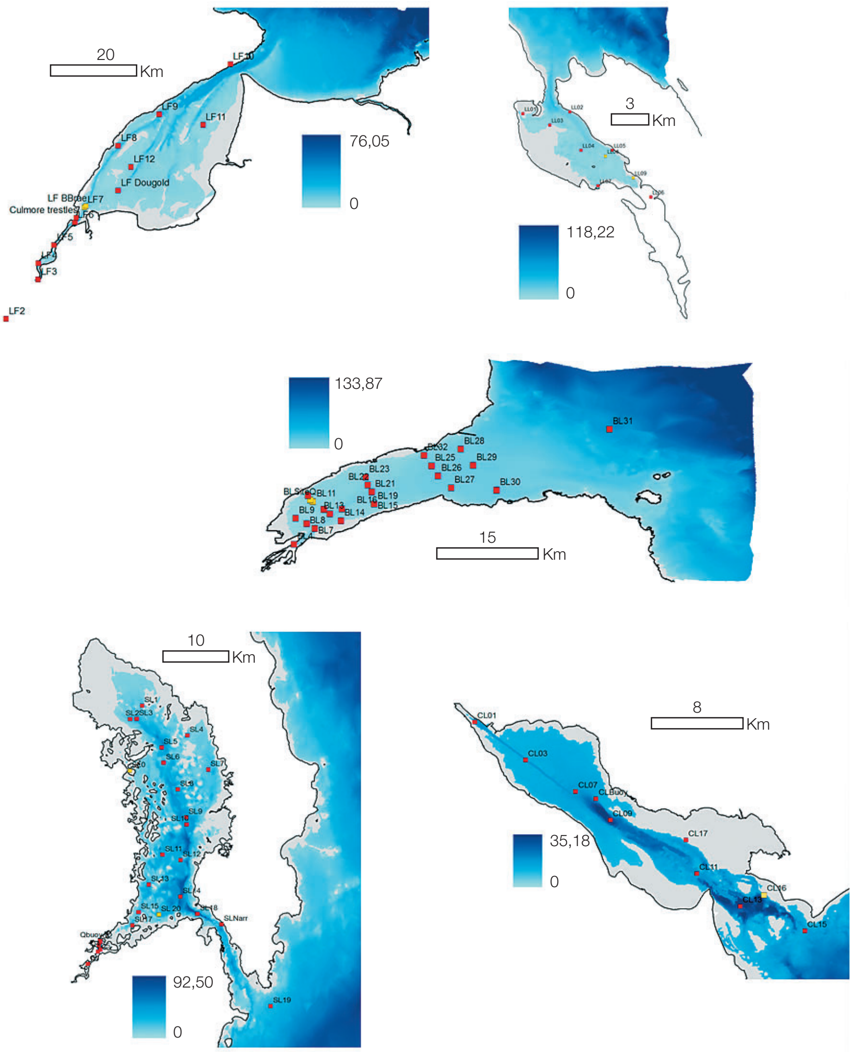
Lough	Parameter	Percentile 5		Mean		Median		Percentile 95		Sampling campaigns	
		Historical	Project	Historical	Project	Historical	Project	Historical	Project	Historical	Project
Carlingford	DIN (µmol L^{-1})	0.96	1.26	18.32	8.11	8.15	4.80	55.60	23.71		
	Phosphate (µmol L^{-1})	0.30	0.33	1.31	0.61	1.07	0.53	3.23	1.11	1994	2004
	Chlorophyll *a* (µg L^{-1})	0.26	0.35	2.34	2.25	1.57	1.55	7.16	5.70	2000	2006
	TPM (mg L^{-1})	9.38	4.22	20.84	7.61	21.86	6.57	25.98	13.82		
	POM (mg L^{-1})	9.47	1.50	9.82	2.53	9.82	2.28	10.18	4.43		
	Dissolved oxygen (mg L^{-1})	6.30	8.34	10.40	8.44	10.50	8.42	13.30	8.63		
	Oxygen saturation (%)	-	100.56	-	103.43	-	103.62	-	106.90		
Strangford	DIN (µmol L^{-1})	0.04	1.05	5.79	6.90	2.93	5.16	18.22	15.31		
	Phosphate (µmol L^{-1})	0.29	0.15	0.87	0.49	0.81	0.48	1.52	0.85	1993	2004
	Chlorophyll *a* (µg L^{-1})	0.29	0.33	1.65	1.94	1.12	1.48	4.62	4.79	1995	2006
	TPM (mg L^{-1})	-	2.74	-	5.19	-	4.76	-	9.65		
	POM (mg L^{-1})	-	1.08	-	1.93	-	1.96	-	2.97		
	Dissolved oxygen (mg L^{-1})	-	-	-	-	-	-	-	-		
	Oxygen saturation (%)	90.00	54.39	106.71	92.25	107.00	101.21	120.00	109.12		
Belfast	DIN (µmol L^{-1})	0.00	1.11	28.23	11.07	14.73	8.90	99.95	28.93		
	Phosphate (µmol L^{-1})	0.18	0.22	1.38	1.04	0.97	0.91	4.05	2.11	1984	2002
	Chlorophyll *a* (µg L^{-1})	1.01	0.22	14.23	2.53	9.76	1.59	39.72	8.53	1998	2006
	TPM (mg L^{-1})	-	4.04	-	6.81	-	6.50	-	11.50		
	POM (mg L^{-1})	-	1.64	-	2.54	-	2.28	-	4.44		
	Dissolved oxygen (mg L^{-1})	-	7.02	-	8.20	-	8.44	-	8.75		
	Oxygen saturation (%)	-	86.37	-	95.22	-	94.45	-	107.08		
Larne	DIN (µmol L^{-1})	3.08	1.32	11.03	6.36	9.88	4.73	24.42	15.71		
	Phosphate (µmol L^{-1})	0.34	0.15	0.63	0.41	0.62	0.37	0.89	0.71	1999	2005
	Chlorophyll *a* (µg L^{-1})	0.24	0.21	2.11	1.83	0.75	1.42	7.16	4.87		2006
	TPM (mg L^{-1})	-	4.32	-	7.33	-	6.19	-	12.59		
	POM (mg L^{-1})	-	1.38	-	2.48	-	2.21	-	4.70		
	Dissolved oxygen (mg L^{-1})	-	-	-	-	-	-	-	-		
	Oxygen saturation (%)	-	-	-	-	-	-	-	-		
Foyle	DIN (µmol L^{-1})	2.54	1.27	55.75	35.11	46.07	30.13	138.87	91.47		
	Phosphate (µmol L^{-1})	-	0.13	-	1.14	-	0.73	-	1.69	1994	2004
	Chlorophyll *a* (µg L^{-1})	0.42	0.30	3.74	3.19	2.51	1.85	10.14	11.21	1998	2005
	TPM (mg L^{-1})	7.67	4.35	31.84	15.53	29.08	10.57	69.75	26.27		
	POM (mg L^{-1})	16.34	2.46	32.37	5.43	26.47	4.23	73.46	10.71		
	Dissolved oxygen (mg L^{-1})	-	-	-	-	-	-	-	-		
	Oxygen saturation (%)	76.80	-	96.56	-	89.00	-	124.75	-		

Summary statistics extracted from the SMILE databases for dissolved inorganic nitrogen (DIN), phosphate, chlorophyll *a*, total particulate matter (TPM), particulate organic matter (POM), dissolved oxygen and oxygen saturation are shown in Figure 23.

Data were collected through a series of surveys, carried out by DARD/QUB and other institutes. Figure 24 shows the distribution of sampling stations surveyed in each system for the SMILE project. These included spatial surveys, in situ moorings and shellfish growth trials.

Two databases were built for each lough, the first to archive historical data and the second to store data collected during the SMILE project. Ten databases and respective software were delivered in SMILE, containing 185,000 records of data spanning 22 years.

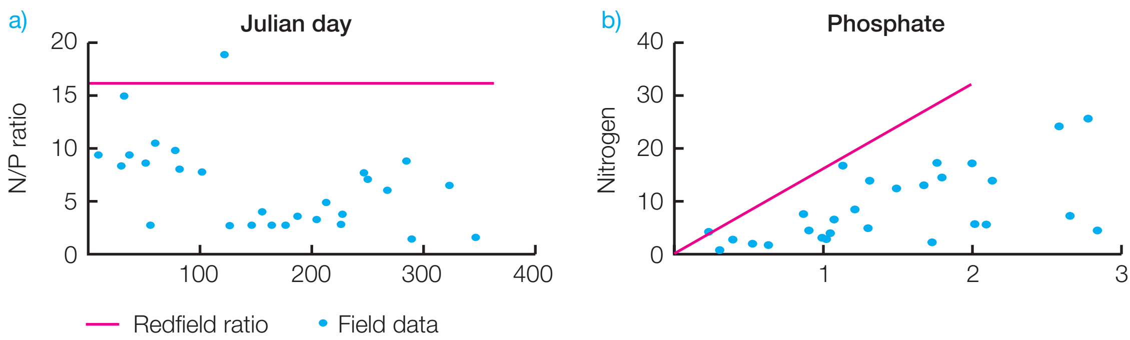
Figure 24. Location of sampling stations surveyed during the SMILE project; (clockwise from top: Foyle, Larne, Belfast, Carlingford, Strangford).



The DIN and phosphate data were used to determine the limiting nutrient for phytoplankton production in each lough. Figure 25 shows the Redfield (N:P) ratio for Belfast Lough. All the field data points are below 16 (in atoms), so this system is considered to be nitrogen limited. This type of information is critical to the modelling process.

Belfast Lough and Strangford Lough appear to be nitrogen limited, but the other three loughs show some phosphate limitation. In Carlingford Lough and Larne Lough the nitrogen to phosphate ratio only falls below the Redfield ratio in summer, whilst for Lough Foyle, the ratio was almost always above 16, suggesting a consistent phosphorus limitation.

Figure 25. Belfast Lough a) Annual variation in DIN to Phosphate ratio (N/P); and b) DIN versus phosphate. The red line represents the Redfield N:P ratio of 16 (in atoms).



DEFINITION OF BOXES – FROM DELFT3D TO ECOWIN2000

Hydrodynamic models use a fine grid to simulate the water circulation patterns at the coast-lough level for periods of up to one year. To simulate processes at the ecosystem scale a coarser grid of boxes needs to be defined, since these models are usually run for multi-year periods and simulate multiple variables such as nutrients, phytoplankton, detritus, and cultivated shellfish.

Boxes were defined according to homogenous physical conditions, evaluating morphology, currents and vertical stratification. The morphology was analysed through bathymetry data, currents through hydrodynamic modelling and the vertical stratification assessment by comparing surface and bottom densities, calculated using salinity and temperature data available for each system in the BarcaWin2000 database.

CRITERIA FOR UPSCALING THE HYDRODYNAMIC MODEL GRID TO ECOWIN2000

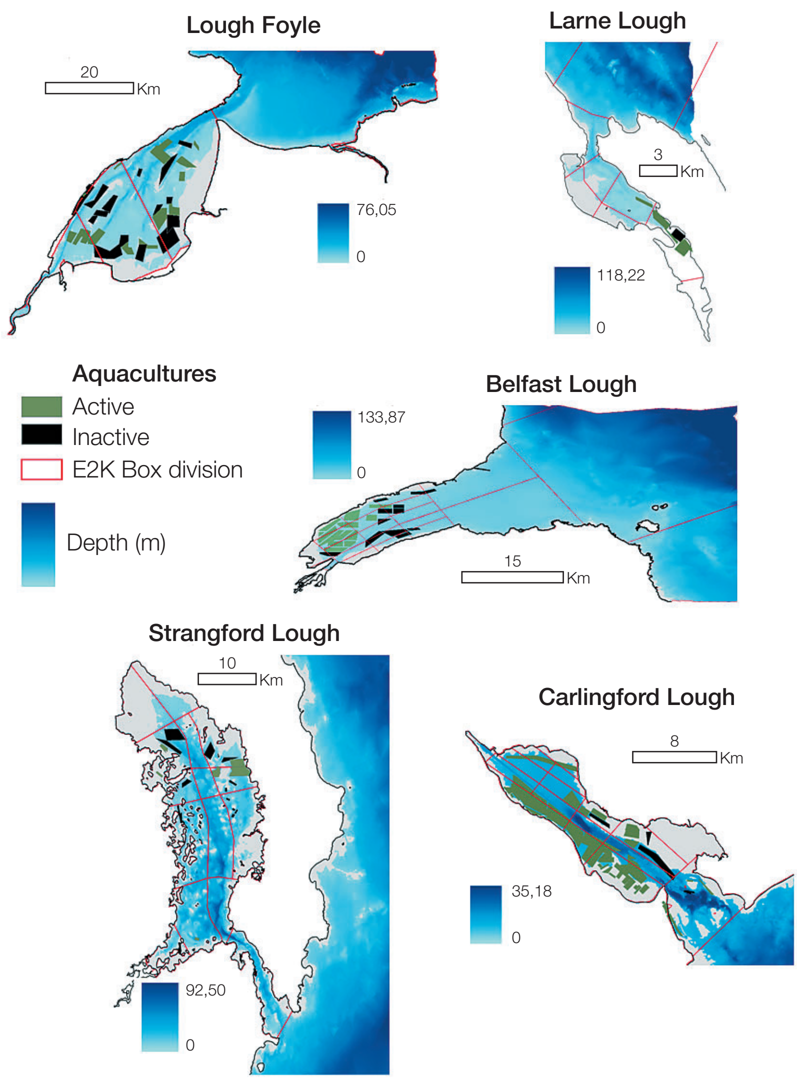
- Morphology, analysed by GIS
- Water circulation patterns, simulated by the Delft3D model
- Distribution of water quality parameters, including nutrients and chlorophyll, obtained from the databases
- Aquaculture farm locations and other human uses
- Policy divisions such as the boundaries of water bodies from the WFD

Although there does not appear to be significant vertical stratification, the systems were nevertheless modelled using two vertical layers, to reflect differences in food supply to shellfish in the upper and lower water column. Insofar as possible, the aquaculture areas were grouped into boxes rather than cutting across box limits.

For Lough Foyle, the same criteria for box division were considered, but no upscaling was applied and only one vertical layer was considered, since a different modelling approach was used.

Carlingford Lough was divided into 38 boxes, Strangford Lough into 34 boxes, Belfast Lough into 42 boxes, Larne Lough into 20 boxes and Lough Foyle into 4 boxes. The final grid for each system is shown in Figure 26.

Figure 26. Coarser grid used for ecological modelling of the SMILE loughs, showing active and inactive culture sites.



CONSERVATION STATUS FOR THE FIVE LOUGHS

Northern Ireland has different levels of nature conservation and protection, described as follows:

- Areas of Special Scientific Interest (ASSI)
- Special Protection Areas (SPA)
- Special Areas of Conservation (SAC)

Northern Ireland has designated 53 sites, all of them already declared SPA or ASSI. There are 47 designated nature reserves, as well as Ramsar sites.

The five sea loughs addressed by SMILE are classified as ASSI, SPA and RAMSAR sites (Figure 27). Strangford lough is the only system designated as a SAC and as a Marine Nature Reserve. This means that they all have interest for nature conservation, with special emphasis on Strangford Lough, and consequently need additional precautions in their use for the development of economic activities.

Figure 27. Classification of SMILE loughs in ASSIs, SPAs, SACs, Nature Reserves and RAMSAR sites.

Lough	Carlingford	Strangford	Belfast	Larne	Foyle
Areas of Special Scientific Interest (ASSIs)	Declared date: 03/10/1996 Area (ha): 1105	Declared date: Part 1 – 24/02/1988 Part 2 – 22/09/1988 Part 3 – 21/04/1989 Area (ha): Part 1 – 1549 Part 2 – 699 Part 3 – 1859.5	Declared date: Inner – 17/11/1987 Outer – 20/11/1996 Area (ha): Inner – 240 Outer – 228.57	Declared date: 25/03/1996 Area (ha): 398	Declared date: 20/07/1998 Area (ha): 2004.97
Special Protection Areas (SPAs)	Date classified: 09/03/1998 Area (ha): 830.51	Date classified: 09/03/1998 Area (ha): 15,580	Date classified: 05/08/1998 Area (ha): 432.14	Date classified: 04/03/1997 Area (ha): 395.94	Date classified: 02/02/1999 Area (ha): 2204.36
Special Areas of Conservation (SACs)	-	Date classified: June 1999 Area (ha): 15,398.54	-	-	-
Nature Reserves	-	All waters, seabed and shore (up to high water mark mean tide)	-	-	-
RAMSAR Sites	Date classified: 09/03/1998 Area (ha): 830.12	Date classified: 09/03/1998 Area (ha): 15,580.79	Date classified: 05/08/1998 Area (ha): 432.14	Date classified: 04/03/1998 Area (ha): 396	Date classified: 02/02/1999 Area (ha): 2204

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Environment and Heritage Service Northern Ireland. http://www.ehsni.gov.uk/

Loughs Agency. http://www.loughs-agency.org/

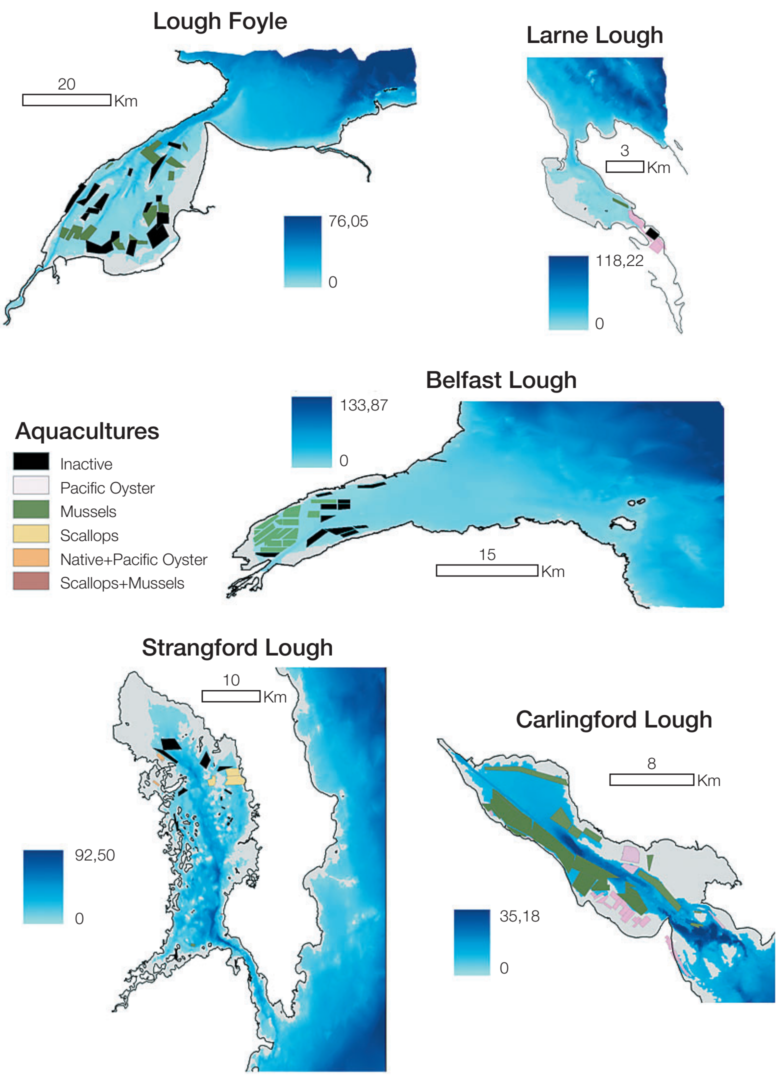
Joint Nature Conservation Committee. http://www.jncc.gov.uk/

SHELLFISH

INTRODUCTION

Aquaculture of suspension-feeding shellfish is among the fastest-growing of all food-producing sectors.

Figure 28. Current shellfish aquaculture sites in the SMILE loughs.



As a consequence, there is increasing pressure to develop management strategies which will allow sustainable development. Such modelling is complicated by observations that filter-feeding and metabolism in shellfish are highly responsive to fluctuations in temperature, salinity, food availability and food composition, as frequently occur in near-shore environments where most such aquaculture takes place.

These physiological adjustments affect growth of individual animals. By influencing the relative biogeochemical fluxes of different particles and nutrients, they also affect ecosystem processes. Only by modelling the complex set of feedbacks, both positive and negative, whereby suspension-feeding shellfish interact with ecosystem processes, such as may include stimulation of primary production by nitrogen excreted from shellfish, can environmental impacts of and capacities for culture be realistically assessed.

REVIEW OF CULTURE DISTRIBUTIONS, PRACTICES AND PRODUCTION

CULTURE DISTRIBUTIONS

Most revenue sources (Figure 31) from shellfish culture in the SMILE loughs are derived from blue mussels (*Mytilus edulis*) and Pacific oysters (*Crassostrea gigas*), with contributions from European oysters (*Ostrea edulis*) and King scallops (*Pecten maximus*). Figure 28 depicts current sites of shellfish culture throughout the SMILE loughs, with widest distributions in Carlingford Lough, Belfast Lough and Lough Foyle.

Figure 29 summarises the areas occupied by aquaculture, together with the total areas of each lough, and the proportions of those total areas that are comprised of shellfish culture. Carlingford Lough has the greatest proportion of licensed culture, representing about 22% of the total area. In Lough Foyle, there is no licensing for aquaculture, and although the declared area is only about 1600 ha, shellfish cultivation is thought to occupy about 50% of the seabed.

Figure 29. Areas within each SMILE lough that are occupied by active mussel and/or Pacific oyster cultures, and percentage of each lough used for shellfish culture.

Area (ha)	Carlingford	Strangford	Belfast	Larne	Foyle
Total lough	4900	14900	13000	800	18600
Mussel culture	867.5 (total) 167.9 (only NI)	5.9	952.6	10.4	1602.9
Oyster culture	197.8 (total) 83.2 (only NI)	23.5	-	59.9	0.07
Total shellfish culture	1065.3 (total) 251.1 (only NI)	29.4	952.6	70.3	1603
Percentage occupied by shellfish culture	21.7 (total) 5.12 (only NI)	0.2	7.3	8.9	8.6

CULTURE PRACTICE, PRODUCTION AND VALUE

Within the SMILE loughs, most Pacific oyster cultivation is intertidal, placing hatchery-reared juveniles into pouches placed on trestles (Figure 30A).

Blue mussel seed are obtained by dredging natural beds in coastal waters elsewhere (e.g. Skullmartin and Arklow), and cultured either by deploying onto the bottom and dredging again to harvest, or by attaching to ropes suspended from submerged structures or rafts (Figure 30B and Figure 30C).

Figure 30. Cultivation practices. From left to right: A – Intertidal culture of the Pacific oyster *Crassostrea gigas* within bags placed on trestles, B – Mussel dredger for the bottom culture of the blue mussel *Mytilus edulis*, C – Suspended rope culture of mussels.

Figure 31 summarises the details of culture practice in the SMILE loughs. In general, one third of the cultivation areas are seeded every year, and culture periods from seeding to harvestable size vary between 18 and 33 months. Total value of aquaculture production is around 8 million pounds (about 12 million euro) per annum, with the largest contributions from blue mussels (*Mytilus edulis*) and Pacific oysters (*Crassostrea gigas*).

In addition, about 25 and 50 ton of Native oysters (*Ostrea edulis*) are produced per year in Loughs Foyle and Strangford, respectively. Wild mussel dredging is an important source of shellfish products in Carlingford Lough, corresponding to about 1000 ton per year.

MODELLING OF FEEDING, METABOLISM AND GROWTH IN CULTURED SPECIES

BACKGROUND

To account for the complexity of both positive and negative feedbacks between shellfish and variable environments, there is a need for dynamic simulations that use mathematical equations to define functional inter-relationships between the component processes.

There are two main challenges in modelling these interactions. Firstly, to identify the environmental variables, and in particular the components of available food, with significant effects on shellfish physiology.

Secondly, to resolve the main interrelations, not only between environmental variables and physiology, but also between separate physiological processes, towards a common model structure that may be calibrated with a different standard set of parameters according to species and/or location.

Figure 31. Culture practice, production and value for mussels *Mytilus edulis* and oysters *Crassostrea gigas* in the SMILE loughs.

Lough	**Carlingford Lough**[5]		**Strangford Lough**[6]		**Belfast Lough**[7]	**Larne Lough**[7]		**Lough Foyle**[5]		**Total**	
Species cultured	Mussels	Oysters	Mussels	Oysters	Mussels	Mussels	Oysters	Mussels	Oysters	Mussels	Oysters
Seeding											
Weight (g)	0.5	0.8	0.1	0.8	0.6	0.6	0.8	0.5	0.8	-	-
Length (mm)	10–15	12–16	2	13	20	20	12–16	10–15	12–16	-	-
Period	May–Sep	May–Jun	Mar–May	Apr–Jun	Jun–Aug	Jun–Jul	May–Apr	Jun–Nov	May–Aug	-	-
Harvesting											
Weight (g)	12	60–70	13	115	13	13	60–70	12–15	60–85	-	-
Length (mm)	60–65	75	53	114	55–65	70–75	90–95	55–65	90	-	-
Period	Jan–Feb	Jan–Mar	Dec–Feb	Jan–Feb	Oct–Jan	Nov–Dec	Aug	Nov–Feb	Oct–Dec	-	-
Growing time (months)	18–24	33	24	26	30	30	33	26	33–36	-	-
Mortality (% of individuals)	>70	<2	<20	10–15	70	>70	<2	>70	<2	-	-
Crop rotation	1/3	1/3	1/3	1/3	1/3	3	1	1/3	1	-	-
Aquaculture type	Bottom culture Submerged rafts	Trestles	Submerged rafts	Trestles	Bottom culture	Bottom culture	Trestles	Bottom culture	Trestles	-	-
Production (ton)[8]	2,500	320	2	272 *50*	10,000	200	10	15,318	50 *25*	28,020	602.9 *75*
Value (GBP)[8]	1,617,331	217,697	Unknown	601,596 102,800	Unknown	Unknown	Unknown	7,070,934	Unknown	8,688,265	819,293 *102,800*

[5] Production values for Lough Foyle and Carlingford Lough (NI + ROI) are for 2003 and 2004, respectively (source Loughs Agency).

[6] Oyster production and revenue values for 2002 are from the SLECI report. Mussel production values are for year 2003 (source Fisheries Division).

[7] Production values for Larne Lough and Belfast Lough are for year 2003 (source Fisheries Division).

[8] For oyster columns, where applicable – upper number: Pacific oyster *Crassostrea gigas*, lower number (in italics): native oyster *Ostrea edulis*.

MODEL STRUCTURE

Towards addressing these challenges, we have based our simulations upon the functional dependencies whereby environmental drivers influence shellfish physiology, including functional interrelations between the component processes of growth, drawing upon established physiological principles of energy balance (Figure 32).

Those various functional interrelations have been integrated within a dynamic model structure (ShellSIM), developed to simulate time-varying rates of feeding, metabolism and growth in the blue mussel *Mytilus edulis*, Pacific oyster *Crassostrea gigas* and other species (http://www.shellsim.com/index.html).

The environmental drivers used by ShellSIM, known as “forcing functions”, are summarised together with simulated responses in Figure 33. Compared with previous simulations of shellfish physiology, notable novel elements of ShellSIM include correcting for a significant and variable error in the measurement of TPM and POM, based upon water that is bound to minerals, and which has historically been mistaken for POM following ashing at high temperatures.

Figure 32. Physiological components of net energy balance.

C = Energy ingested (feeding rate)

F = Energy egested (as faeces)

E = Energy excreted (as ammonium)

R = Energy expenditure (heat loss)

NEB = Net energy balance (tissue gain or wasting)

Net energy balance = (Energy gains) - (Energy losses)

$$NEB = C - (F + R + E)$$

Figure 33. Generic model structure (ShellSIM) simulates how feeding, metabolism and growth in bivalve shellfish respond to changes in key environmental variables.

Forcing functions
- Date
- Food availability
- Food composition
- Temperature
- Salinity
- Aerial exposure

→ **ShellSIM** →

Simulated responses
- Particle clearance
- Ammonia excretion
- Oxygen uptake
- Faecal deposition
- Reproduction
- Growth

Advantages include:
- Common structure, easily calibrated
- Optimised and cost-effective requirement for drivers
- Corrects for historic errors in the measurement of food availability
- Differentiates between relative abundances, selection and energy contents of phytoplankton and detrial organics

Affording generic value over wide environmental ranges

In addition, ShellSIM resolves rapid regulatory adjustments in the relative processing of living chlorophyll-rich phytoplankton organics, non-phytoplankton organics and the remaining inorganic matter during both differential retention on the gill and selective pre-ingestive rejection within pseudofaeces.

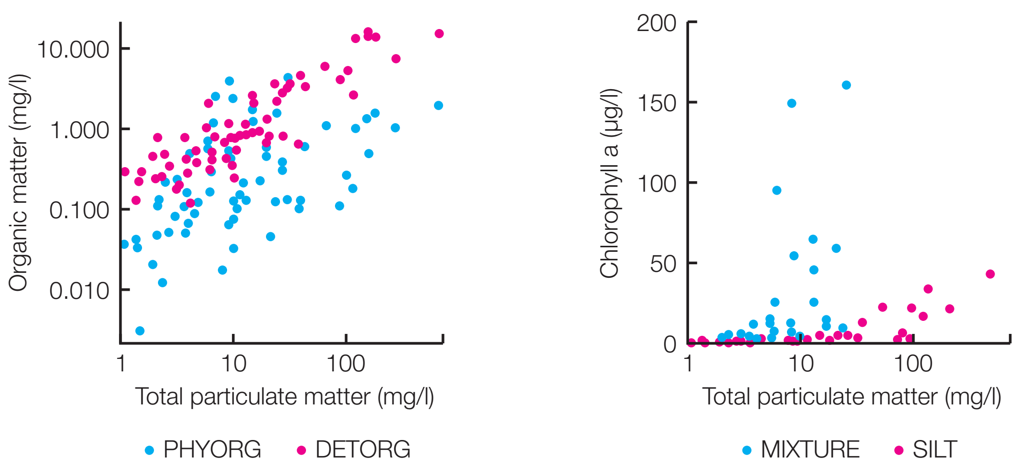
SHELLSIM CALIBRATION

Experimental measures of dynamic physiological responses were undertaken using local field facilities in blue mussel and Pacific oyster from the SMILE loughs.

Measures included clearance rate, particle retention efficiency, filtration rate, rejection rate, ingestion rate, absorption efficiency, absorption rate and total deposition rate over feeding conditions that spanned full normal ranges of food quantities and qualities.

To create those feeding conditions, cultured microalgae were mixed with natural resuspended sediments to varying degrees, when shellfish were exposed to maxima of up to about 400 mg total particulate matter and 160 µg chlorophyll per litre, including many measures at lower levels of food availability as are commonly experienced in the natural environment (Figure 34).

Figure 34. Experimental conditions of food availability under which feeding responses have been measured in blue mussel and Pacific oyster from SMILE loughs.



SHELLSIM VALIDATION

Figure 35 illustrates growth and environmental impacts predicted by ShellSIM for the Pacific Oyster during a typical culture cycle in Carlingford Lough, having been deployed as seed of 24 mm shell length in April (Julian Day 96) and harvested at 57 mm shell length in January the following year (Day 375).

Simulations illustrate the significant cumulative environmental impacts resulting from each individual oyster, and which included about 9 m^3 of water cleared of particles > 2 µm diameter, 50 g of dry biodeposits, 0.5 litres of dissolved oxygen consumed and 30 mg of nitrogen excreted. These simulations have been successfully validated using monthly field measures of environmental drivers and shellfish growth for both *M. edulis* and *C. gigas* in each SMILE lough where these species are currently cultured.

Comparisons of simulated and observed growth in SMILE and other projects indicate that ShellSIM is an effective common model structure that may be calibrated according to species and/or location, successfully simulating growth across a broad range of shellfish types cultured in a diverse range of locations under varying culture scenarios and/or practices (http://www.shellsim.com/index.html). Model outputs confirm that ShellSIM, when run with a separate single standard set of parameters for each species, optimized upon the basis of all calibrations undertaken to date, can effectively (± 20%) simulate dynamic responses in physiology and growth to natural environmental changes experienced by *C. gigas* and *M. edulis* at contrasting sites and under different culture practices throughout Europe and Asia.

In addition, ShellSIM has been validated for other species, with potential for greater accuracy (± 10%) upon site-specific calibration, as has been achieved to date in the Chinese scallop *Chlamys farreri*, short-necked clam *Tapes philippinarum*, blood clam *Tegillarca granosa*, Chinese oyster *Ostrea plicatula* and razor clam *Sinonvacula constricta*, all during culture in China (http://www.shellsim.com/index.html). Figure 36 illustrates results from the SMILE Project, confirming that growth measured in *C. gigas* and *M. edulis* matches growth predicted by ShellSIM during culture in Strangford and Belfast Loughs, respectively.

Figure 35. Growth and environmental impacts predicted by ShellSIM for Pacific oysters during a typical culture cycle in Carlingford Lough.

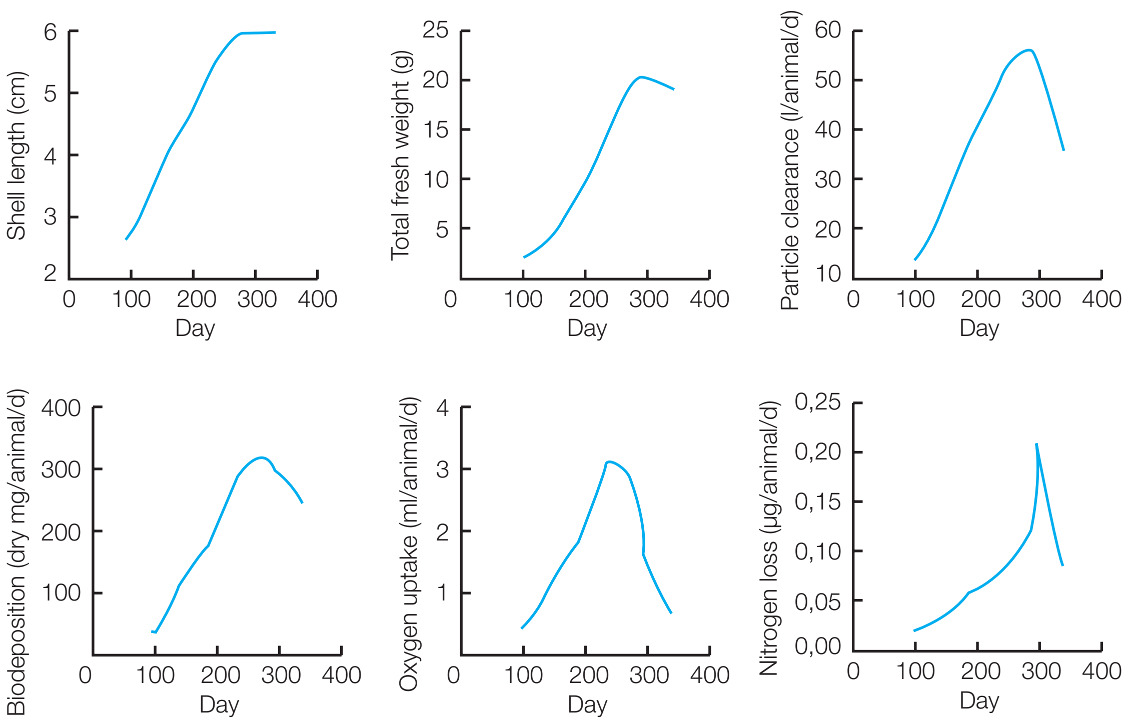
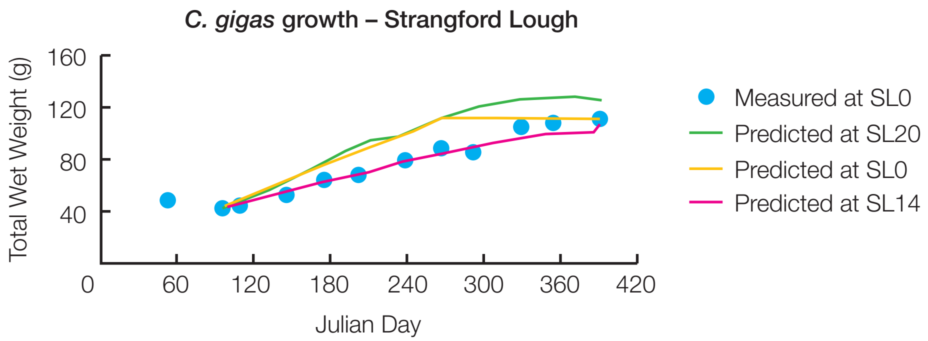
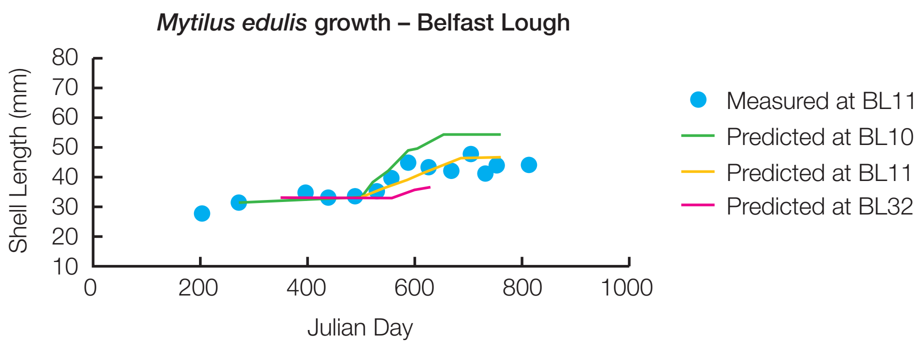


Figure 36. Comparisons of growth measured in *Crassostrea gigas* and *Mytilus edulis* during culture in Belfast and Strangford Loughs, respectively, with growth predicted by ShellSIM on the basis of temperature, aerial exposure, salinity, food availability and food composition.





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CARRYING CAPACITY

INTRODUCTION AND DEFINITIONS

Assessments of sustainable mariculture in general and shellfish culture in particular are conditioned by different definitions of carrying capacity, which may be regarded as physical, production, ecological and social.

These are themselves modulated by scaling, usually considered to be either system scale (bay, estuary or sub-units thereof), or local scale (farm). McKindsey and co-workers provide a critical review of methods, including models, used for evaluating these various types of carrying capacity.

System-scale management of shellfish aquaculture requires a top-down assessment of carrying capacity, and has many similarities to any other large-scale plan for optimising the multiple uses of goods and services. A number of models of varying complexity have been developed to address system-scale issues over the past 15 years.

ASSESSMENT APPROACH

The approach used in SMILE combines field data acquisition, experimental work on shellfish feeding behaviour, database and geographical information systems (GIS), and the implementation and coupling of various types of dynamic models. In this chapter the focus is on the development and coupling of dynamic models, drawing on the spatial divisions described in the **Spatial Domain** chapter, and on models of individual growth described in the **Shellfish** chapter.

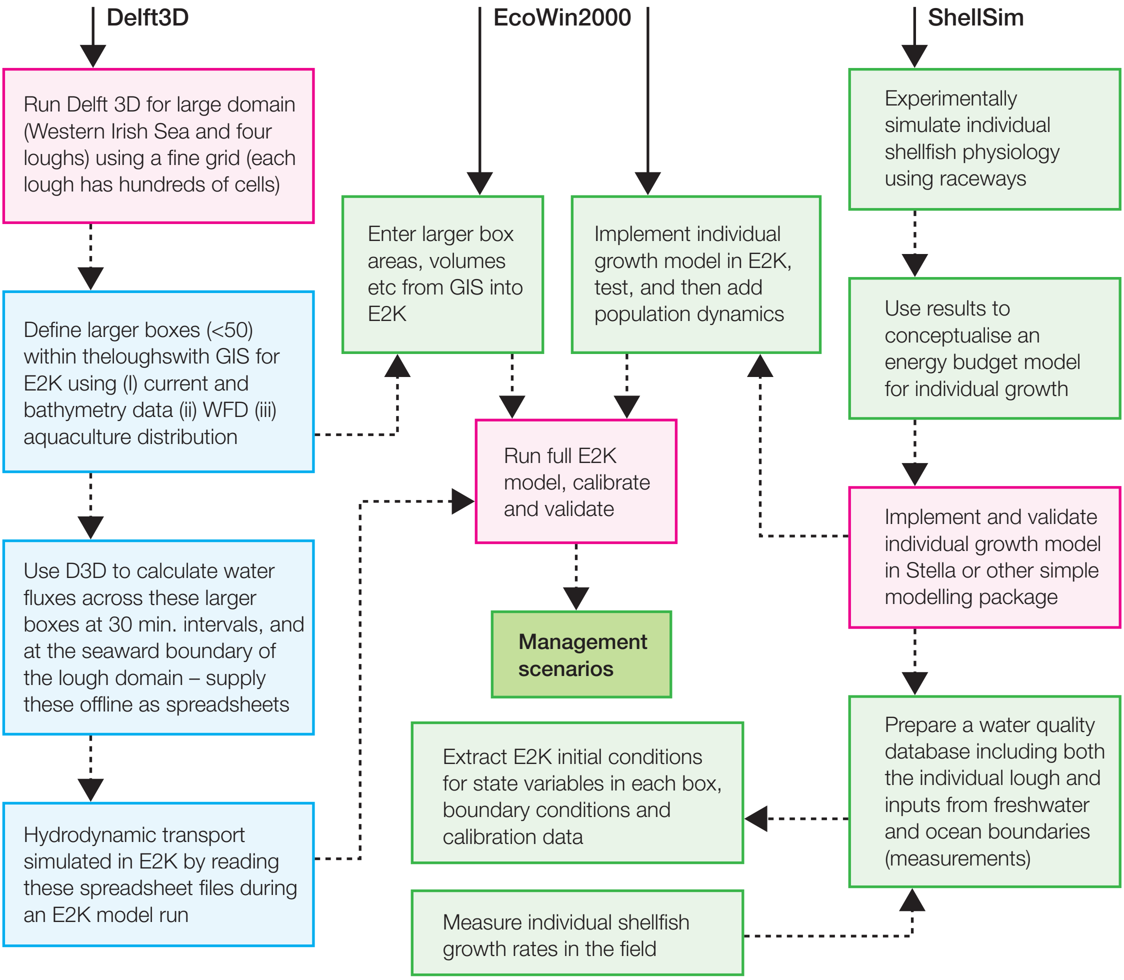
MODELS

The general modelling approach is shown in Figure 37.

This framework may be interpreted as a series of steps.

- Development of fine-scale circulation models for the loughs and adjoining shelf waters
- Use of such models to provide a detailed description of the coastal-lough circulation, and to upscale processes in space and time for the development of ecological models
- Application of GIS and databases for the definition of larger boxes, where detailed ecological processes and shellfish growth will be simulated
- Development of models for individual growth of shellfish, capable of resolving different aspects of feeding behaviour, such as the use of phytoplankton and organic detritus
- Combination of the various components into ecological models which simulate processes over long periods, and thus allow predictions of multi-year system carrying capacity for sustainable shellfish aquaculture, in equilibrium with other ecosystem uses

Figure 37. General modelling framework used in SMILE.



The fine-scale Delft3D model shown in Figure 38 runs for a part of the Irish Sea and four of the loughs, and represents both the local conditions in each lough and the processes that exchange water among the different loughs and with the Irish Sea as a whole.

This model simulates the circulation and phytoplankton productivity for periods of up to a year, and is used to generate water exchange and boundary conditions for each of the loughs, to implement ecological models which run for multi-year periods. These ecological models use a coarser grid of boxes, performing simulations of variables such as nutrients, phytoplankton, and cultivated shellfish.

To evaluate the role of wild populations, a combination of benthic grab-sample data, GIS and specific filtration rates is used.

Some results are shown in Figure 39 for Carlingford Lough, showing high densities of wild populations per square metre. These calculations are used for each box in the ecological model, allowing the simulation of both wild and cultivated animals. The addition of these populations to the EcoWin2000 ecological model will permit:

Figure 38. Delft3D model of 4 sea loughs.

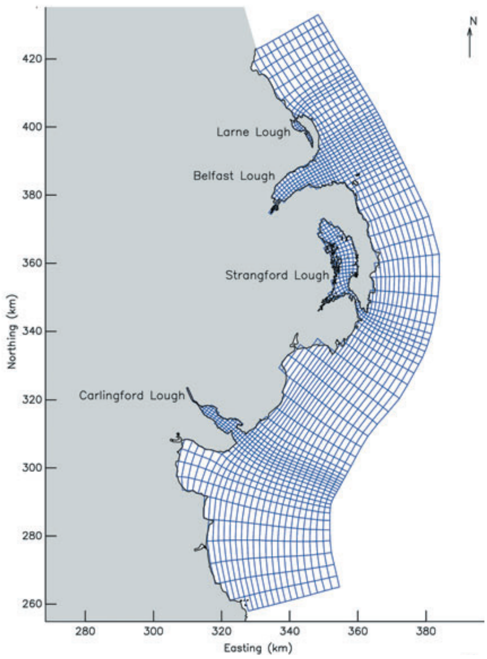
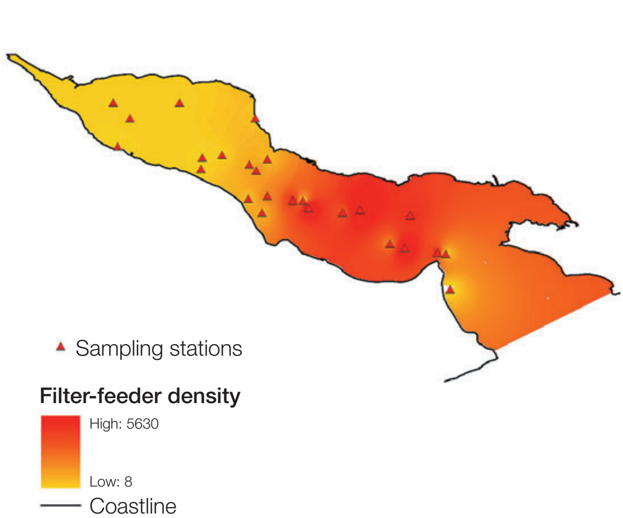


Figure 39. Wild populations in Carlingford Lough.



(i) a more realistic estimate of carrying capacity for cultivated species, accounting for resource partitioning with wild species; and (ii) a clear "conservation threshold" to be set for management scenarios in order to restrict aquaculture expansion to levels which will not exceed the calculated food requirement for the wild populations.

Growth predicted by ShellSIM for individual shellfish species is used in the EcoWin2000 ecological model to simulate the population dynamics of cultivated Pacific oysters and mussels. These models are able to determine not only the overall production for a certain stock, but the standing stock at which the production of the marketable cohort is maximized.

CATCHMENT MODELLING WITH SWAT

The Soil and Water Assessment Tool (SWAT) is a catchment model developed by the US Department of Agriculture to assess water resources, soil erosion and agricultural pollution in watersheds. As an example of its potential use in SMILE, SWAT was applied to the Lough Foyle catchment area to estimate nutrient inputs for localized (urban wastewater) and diffuse sources (agricultural fertilization and cattle grazing).

The model was selected for application in SMILE due to the following characteristics:

1. It can predict the impacts of human intervention on water flow, soil erosion, especially in agricultural and human pollution
2. It is able to simulate large watersheds with complex soil and land use patterns, fitting the large drainage area associated with Lough Foyle
3. It provides continual results for long time periods – one or more years – making it able to identify annual nutrient loads and their seasonal distribution

Two of SWAT's characteristics make the model particularly useful for SMILE. Firstly, the model is based on physical equations rather than empirical relations, thus increasing the confidence of model results when applied to watersheds without continuous monitoring of water runoff or water quality data. Secondly, the model was designed to use readily-available input data, especially geographical and climate data. Most of the datasets used in this application are freely available on the internet (Figure 40).

Figure 40. SWAT main input data sources for the Lough Foyle watershed.

Dataset	Source	Details
Altimetry map	NASA – Shuttle Radar Topography Mission	90 x 90 m grid Dataset freely available
Land use map	Supervised classification of land use types using a LANDSAT satellite image*	25 x 25 m grid Dataset prepared by the SMILE team
Soil map	FAO – 1978 world soil map	1:1,000,000 map Dataset freely available
Climate data	WMO – Daily Global Historical Climatology Network	Daily rainfall and temperature data for 4 climate stations Dataset freely available for 1990–1999

* this dataset can be replaced by the CORINE Land-Cover map for Europe, which is freely available.

The SWAT model was applied to the drainage area of Lough Foyle, including the rivers Foyle, Faughan and Roe, as well as other smaller rivers, for the period running from 1990 to 1999. The watershed area is shown in Figure 41; the red dots represent the location for model outputs. For each of these locations, SWAT provides daily time-series of river flow, suspended particulate matter, nitrogen loads divided into nitrate, nitrite and organic nitrogen, and phosphorus loads divided into phosphate and organic phosphorus. These datasets can be used by the Lough Foyle ecological model directly as water, nutrient and sediment inputs to the system.

DETAILED HYDRODYNAMIC MODELLING WITH DELFT3D

DELFT3D – FLOW HYDRODYNAMIC MODEL

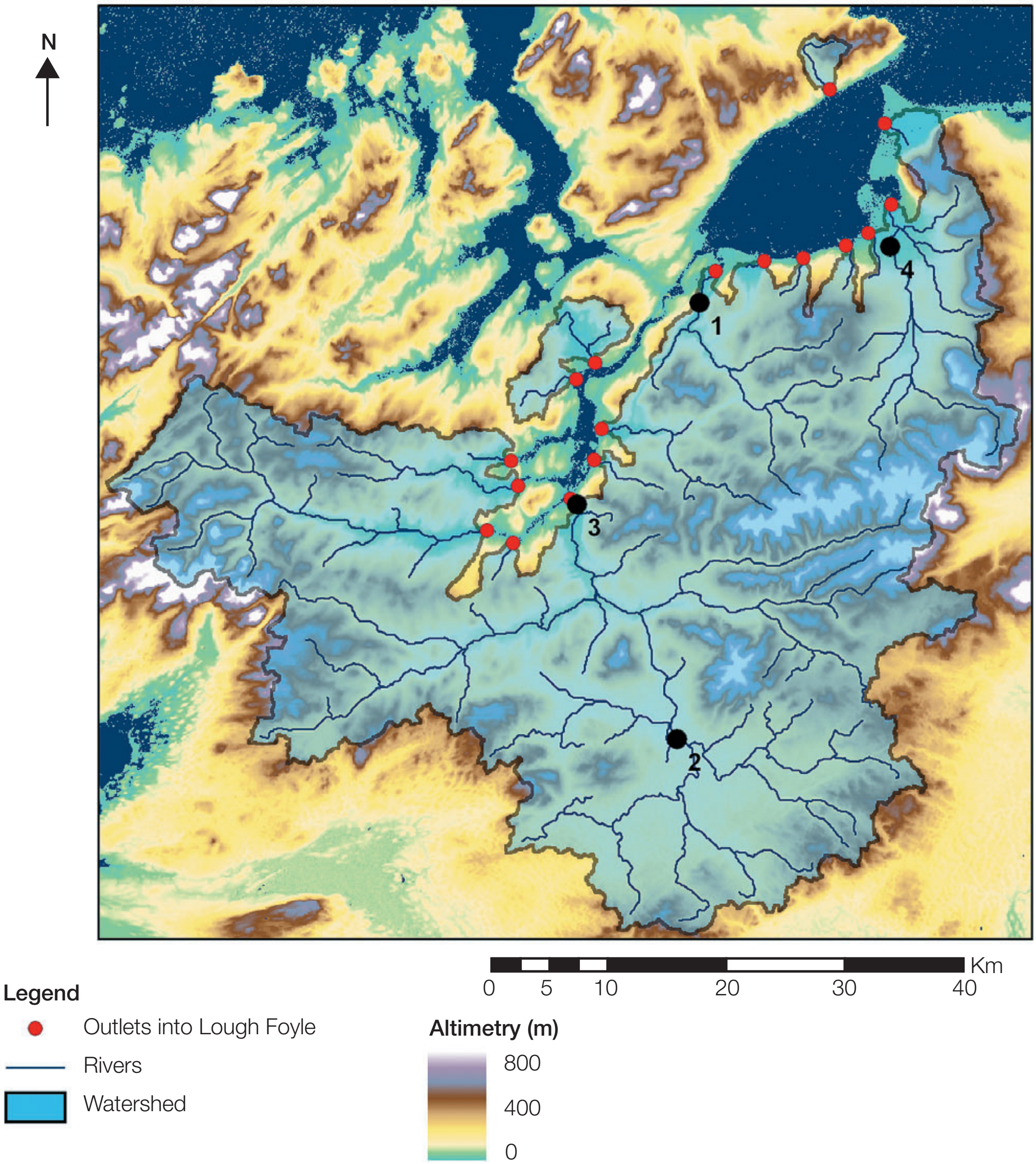
The D3D model solves the horizontal momentum equations and the continuity equation in three dimensions using the Alternating Direct Implicit scheme. The computation grid is an irregularly-spaced, orthogonal, curvilinear grid in the horizontal and a sigma-coordinate grid in the vertical (8 layers). Tidal forcing, temperature, salinity and water flows were applied by specification of appropriate open boundaries from the Proudman Oceanographic Laboratory (POL) model for the Irish Sea. The magnitude of the wind shear stress on the water surface is modelled as a quadratic function of the wind speed obtained from the European Centre for Medium-Range Weather Forecasting (ECMWF). Vertical turbulence is modelled by a k-ε turbulence model. Baroclinic effects due to temperature and salinity variations were also modelled. Bottom friction is modelled with a Chézy coefficient obtained from the White-Colebrook formulation defined by the Nikuradse roughness length, which was set to 0.03 m. Coriolis effects due to the earth's rotation are included, as are drying and flooding on tidal flats. The model formulation is more fully described in publications from WL|Delft Hydraulics.

NORTHERN IRELAND COASTAL ECOSYSTEM MODEL

OBJECTIVES AND APPROACH

The main objective of the high resolution coastal ecosystem model was to downscale the regional physics and the biogeochemical variability to the lough scale. In this way the Lough models, implemented in EcoWin2000, could accommodate increased ecological complexity by reducing spatial resolution without losing the underlying critical scales of forcing. The high resolution ecosystem model provided aggregated flows and biogeochemical boundary conditions to the EcoWin2000 model. An important part of the need

Figure 41. Altimetry of the area draining into Lough Foyle, with the SWAT model area superimposed.



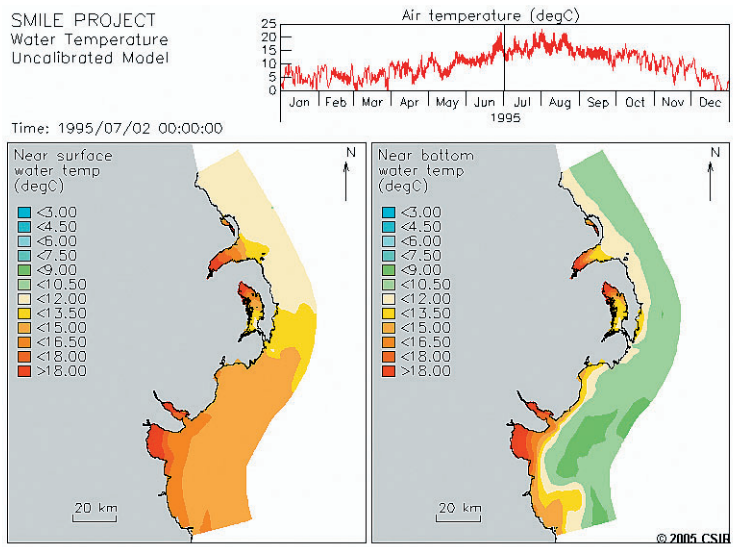
for upscaling was to accurately reflect the temporal and spatial characteristics of Lough–Shelf biogeochemical boundary conditions. The system scale approach also provided an understanding that the individual loughs are not isolated ecosystems but part of an interconnected Lough-Coastal-Shelf ecosystem.

PHYSICS

The hydrodynamic model was run for 1995 using atmospheric forcing inputs obtained from ECMWF and boundary condition from the POL model. The model outputs were used to provide aggregated flows to the EcoWin2000 ecosystem model and to provide the advection dispersion inputs for the WAQ – D3D biogeochemical model which supplies the boundary conditions to the EcoWin2000 lough models.

Figure 42 shows the spatial characteristics of stratification in the western Irish Sea shelf during mid-summer (2/7/1995), with a meridional gradient of stratification strongest in the south and weakest in the north. This explains the seasonal phasing of the spring bloom from south to north. The loughs have a horizontal temperature gradient between the head and the mouth but remain largely vertically well mixed.

Figure 42. Mid-Summer stratification in the western Irish Sea shelf.



RESIDENCE TIMES

Residence times (Figure 43) are important because of the way they govern productivity rates as well as the vulnerability to water quality degradation. The summer period residence time gradients for the surface and near bottom model layers in the three largest loughs in northern Ireland are shown below. These show that both Carlingford and Strangford loughs can be divided into three zones of long (> 20 days), mid (8–20 days) and short (< 8 days) residence times. Belfast Lough is largely characterised by the intermediate periods in the surface layers and short – intermediate in the bottom layers.

These residence time gradients have important ecological implications because they modulate the dynamical relationship between nutrient dispersion/transport and its utilization by phytoplankton. Domains with long residence times are vulnerable to both nutrient depletion and low production if the main supply flux is from the coast and to eutrophication if the land based flux is much larger than the advection/dispersion rates. Ecologically the upper reaches are likely to be predominantly regeneration production driven in contrast to the short residence time areas near the mouth which will be largely new production driven.

LOUGH – COASTAL ADVECTION LINKAGES

Coastal advection linkages are important because they characterise the degree of connectivity between the loughs with potential relevance to transport and dispersion between spawning, nursery or settlement areas, including the transfer of pathogens and pollutants. The model runs indicate that although these linkages are sporadic at the event scale they can deliver large volumes of water containing up to 5% of the original lough source water.

Figure 44 shows a linkage event between a release of a passive tracer in Belfast Lough and its presence in Strangford Lough. The ecological significance is that loughs along this coast should not be seen as isolated units but as an integrated interconnected coastal – lough system.

Figure 43. Water residence times in Belfast, Strangford and Carlingford loughs.

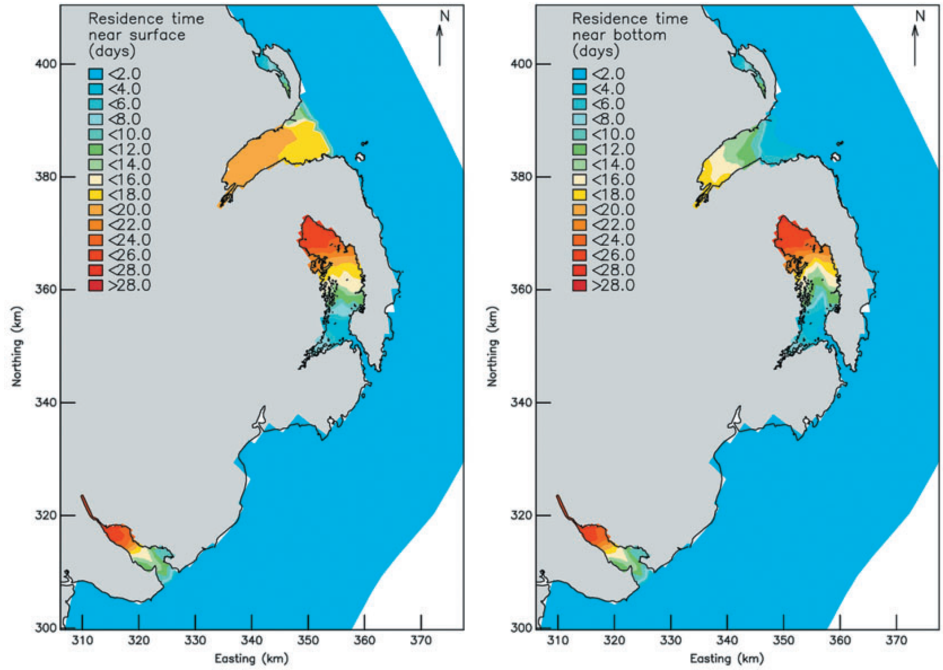
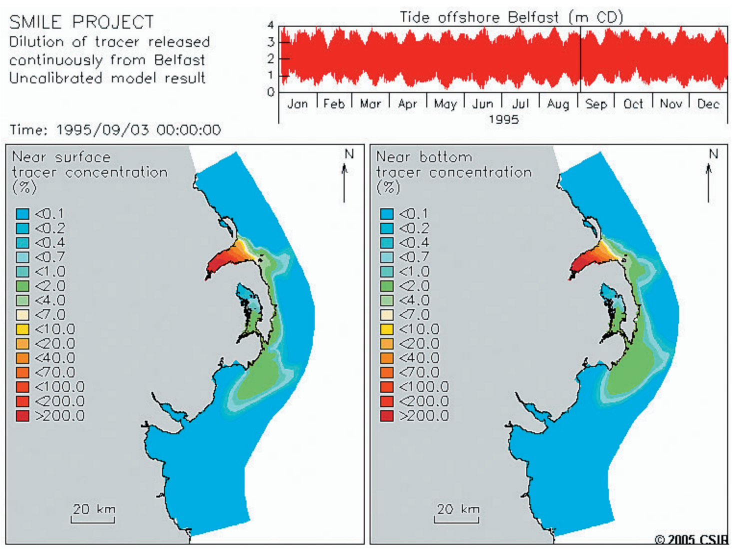


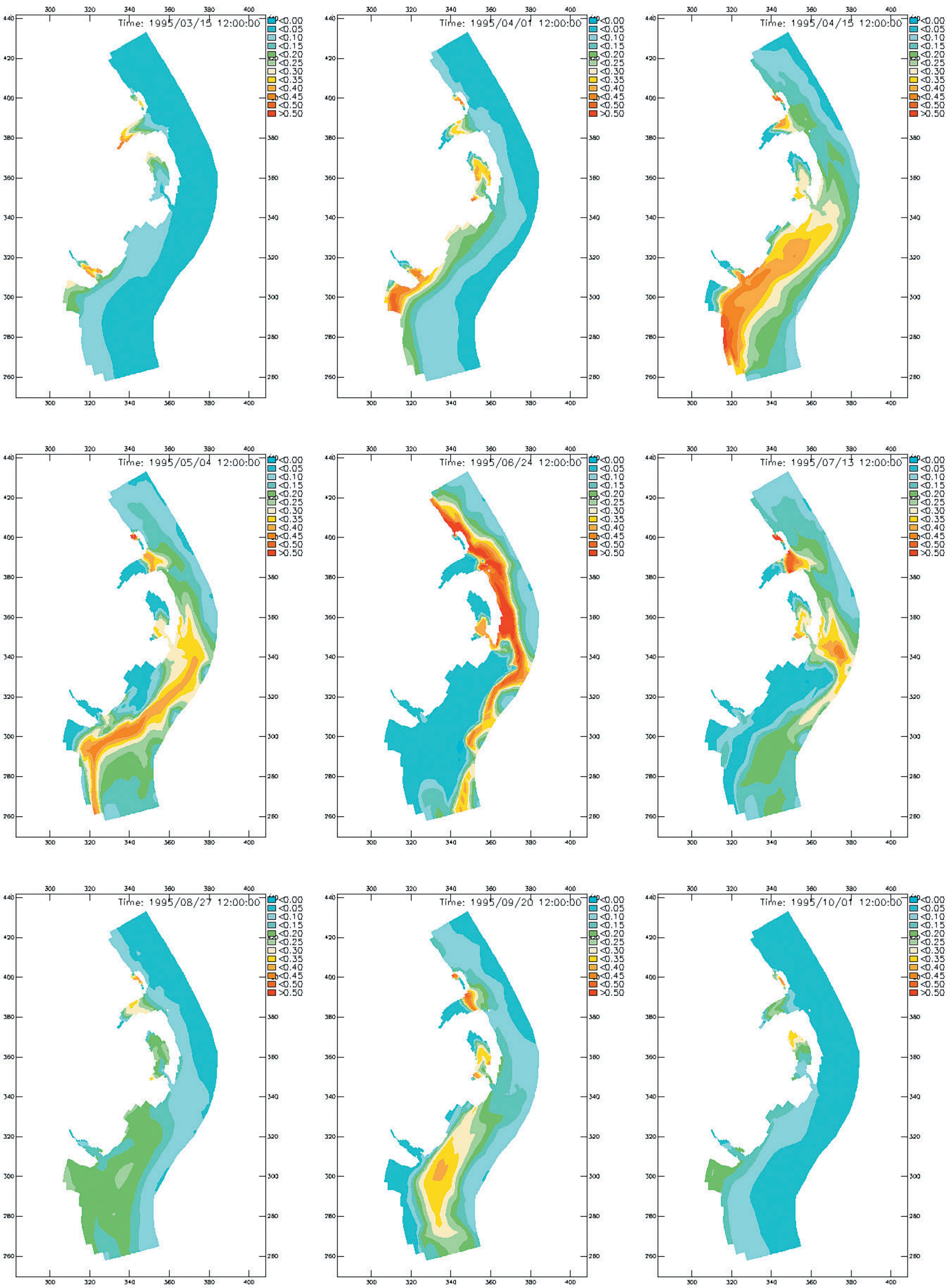
Figure 44. Lough-coastal advection linkages.



SEASONAL CHARACTERISTICS OF PRODUCTION

The temporal and spatial scales of the seasonal cycle of production are depicted in Figure 45, which highlights the phased progression of production from early spring to late autumn. It shows that production begins initially in the shallow lough waters when solar irradiance exceeds the critical threshold for shallow depths. As light intensities increase the production zone progresses into deeper water areas in the outer loughs and inshore coastal areas. The long residence times in the upper loughs limit the supply of coastal nutrients, which rapidly reduces productivity rates in those areas. The ecological implication is

Figure 45. Phased progression of production from early spring to late autumn.



that, in the absence of significant land inputs, the upper lough zone may shift to a regenerated production mode. Surface warming and the relatively sluggish circulation in the shallow southern shelf stabilize the surface layer leading to the onset of the early spring bloom by mid-April. Further warming, partly linked to the development of the summer-stratified region, is required to stabilise the surface layer in the deeper central shelf zone.

This progressively phases the spring/summer bloom to the central region in May and the northern shelf in June. The spring/summer phasing is inverted during the summer/autumn period as the production peak shifts southwards, moves into shallower regions and finally into the upper lough zones.

The ecological importance of this phasing is that it results in a longer production season in the south than in the northern zone. This increases the importance of shallow water production in the lower reaches of the northern loughs. The spatial and temporal phasing of the seasonal production highlights the importance and need to take the system approach adopted in SMILE for the boundary conditions of the loughs. These boundary conditions vary at the advective event and seasonal scales, such that the system scale approach ensures sensitivity to this cross scalar variability.

LARGE-SCALE MODELLING WITH ECOWIN2000

EcoWin2000 (E2K) is an ecological model that provides a platform for integration of the various other models, and adds functionality of its own. This model has been developed over the last 15 years, and although it can be used to run short-term simulations, in the past five years it has mainly been used to run multi-year models.

EcoWin2000 typically divides coastal systems into (less than one hundred) boxes, which may be structured in one, two or three dimensions, and performs simulations at the system scale. It is not an appropriate tool for looking at effects at the farm scale. Other tools such as the Farm Aquaculture Resource Management (FARM™ – http://www.farmscale.org) are tailored to smaller scale processes, and may be driven by measured data or by outputs of models such as Delft3D or EcoWin2000 (see Case Study 2 in the **Management Recommendations** chapter).

Figure 46 shows an abridged list of state variables used in the SMILE models. The full model runs with eight different objects, containing a total of 20 forcing functions and 82 state variables. EcoWin2000 simulates one year in about one minute.

Two different approaches were used:

1. Lough Foyle was simulated by means of a combined approach using SWAT and E2K, where river flows, nutrient loads and solid discharge were obtained as described previously, and a one-dimensional application of E2K was made to the lough. Lough Foyle was divided longitudinally into four boxes (see Figure 26 in the **Spatial Domain** chapter). The hydrodynamics of the lough were simulated using an advection-dispersion model calibrated on salinity.
2. The other four systems were simulated as 3-D models, using offline coupling between the D3D model and E2K, as detailed previously.

A simpler approach was chosen for Lough Foyle and Larne Lough, partly due to project timing and budget constraints, partly due to a reduced information base for these systems, but equally to optimise the cost-benefit of testing the methodology on three systems in order to establish its merits. The simpler hydrodynamic modelling approach used in the Foyle was initially also to be applied to Larne Lough, but the use of the D3D model for part of the Irish Sea shelf enabled the 3D approach to be used for Larne, albeit as a demonstration of the potential of this work, visible in the implementation for Belfast, Strangford and Carlingford.

Figure 46. Variables simulated in the application of EcoWin2000 to SMILE (abridged).

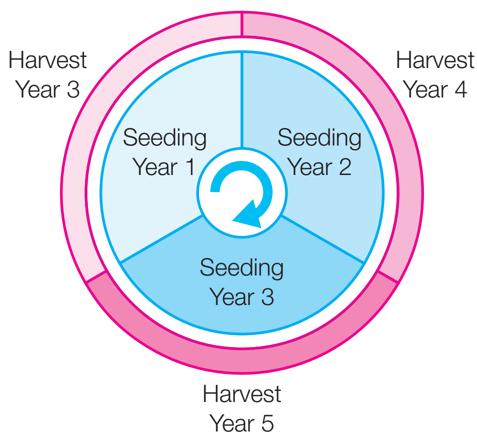
Variable	Source/details	Comments
Water exchange	Water fluxes from the Delft3D model, provided every 30m for 1 year	Coupled offline, read by E2K at each timestep
Physical	Water temperature and salinity	
Nutrients	Dissolved available inorganic nitrogen, phosphate, silica	Nitrification and denitrification
Suspended particulate matter	Total particulate matter, particulate organic matter	Simulated separately based on transport, erosion/deposition and biological sinks and sources. Five grain sizes are simulated, accounting for flocculation effects
Phytoplankton		
Cultivated bivalves	Blue mussel and Pacific oyster, see the **Shellfish** chapter	Dynamic energy budget models for individual growth, upscaled to cultivated populations
Benthic wild species		
Human interaction	Developed within E2K, to fully accommodate shellfish culture practice	Simulates licensed cultivation areas, seeding and harvesting periods, multi-year crop rotation and economic variables such as Average Physical Product (APP)
Forcing functions	Includes nutrients, incident light, light climate in the water column, air temperature, etc	Imposed at the boundaries from measured data, Delft3D model results, or simulated within E2K

The work on the Foyle was enhanced by the application of SWAT for catchment modelling; this was not included in the initial SMILE blueprint, and has the added value of allowing for catchment management scenarios to be easily tested. Although Foyle is termed a lough, it is the most estuarine of all five systems, with significant freshwater discharge and a clear longitudinal salinity gradient.

It is now accepted, and reinforced by the WFD, that management of water bodies should take place at the basin scale, and combine both natural and social sciences. This defines a major challenge to modelling, with respect to combining processes which occur at widely differing scales, ranging from minutes to decades.

The EcoWin2000 large-scale ecosystem models are designed to run for multiple years, necessarily simplifying some of the finer-scale system behaviour, whilst permitting the capture of event-scale phenomena such as tidal and seasonal variability. The commercial production of shellfish in northern Ireland generally occurs over a three year period, and for bottom culture, "crop rotation" is widely practised, with only some parts of the licensed areas seeded annually.

An E2K model run will produce the first harvest (of the part of the overall area seeded in the first year) over the third year, and begin to yield results for the overall culture only after the fifth year.



Over that period, some animals will remain unharvested. Consequently, the model needs to be run for a relatively long period of about 10 years in order to give consistently stable harvesting results.

This 5 year “spin-up” period reflects the dynamics of cultivation practice, and means that the scaling approach used in SMILE is essential in order to provide appropriate outputs for system management.

ASSESSMENT OF THE ECOLOGICAL SIGNIFICANCE OF WILD SPECIES

Carrying capacity for aquaculture should take into account food for wild populations of grazers and filter feeders, including wild bivalve stocks.

Therefore, an ecosystem modelling approach based on the application of Geographical Information Systems (GIS) was developed and tested in Carlingford Lough in order to:

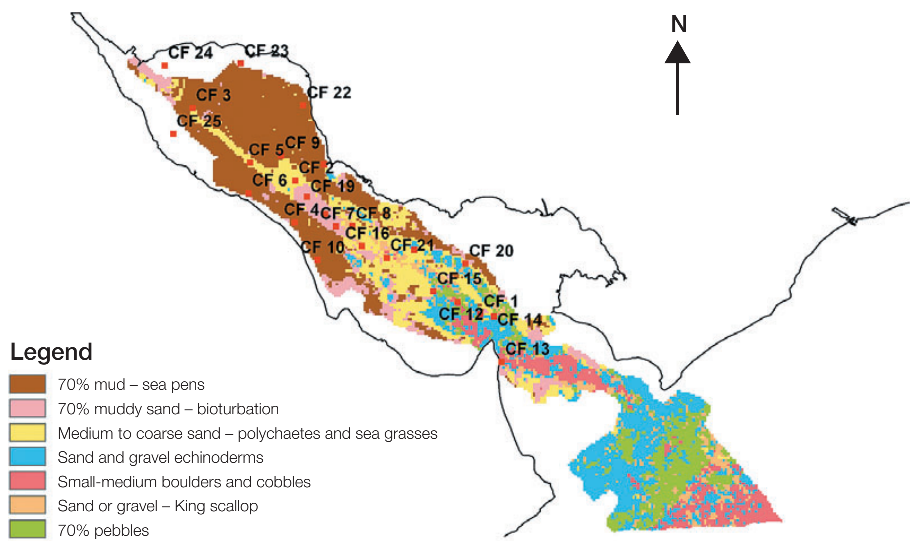
1. Determine baseline food requirements for maintaining benthic biodiversity;
2. Improve accuracy of carrying capacity modelling by appropriately partitioning the food resource comprised of phytoplankton and other particulate organic matter between wild and cultured species;
3. Establish an upper threshold for shellfish aquaculture development scenarios in order to assure the sustainability of wild populations.

DISTRIBUTION AND ABUNDANCE

The GIS resource model was applied to Carlingford Lough to estimate the number of individuals representing wild species in the ecosystem. The distribution and abundance of wild species in Carlingford Lough were estimated making use of an existing habitat map, wild shellfish species density data from the lough and by generating interpolation surfaces in GIS, where several ecosystem features were taken into account.

Wild species are distributed within the system according to their typical habitat conditions as defined by sediment type and biotope. A habitat map for Carlingford Lough is shown in Figure 47, which also depicts the 25 stations sampled for species abundance, and which illustrates how sediments vary gradually from coarse sand to mud from the mouth of the lough towards the Newry river at the head.

Figure 47. Habitat mapping for Carlingford Lough (courtesy A. Mitchell).



RESULTS

OVERVIEW

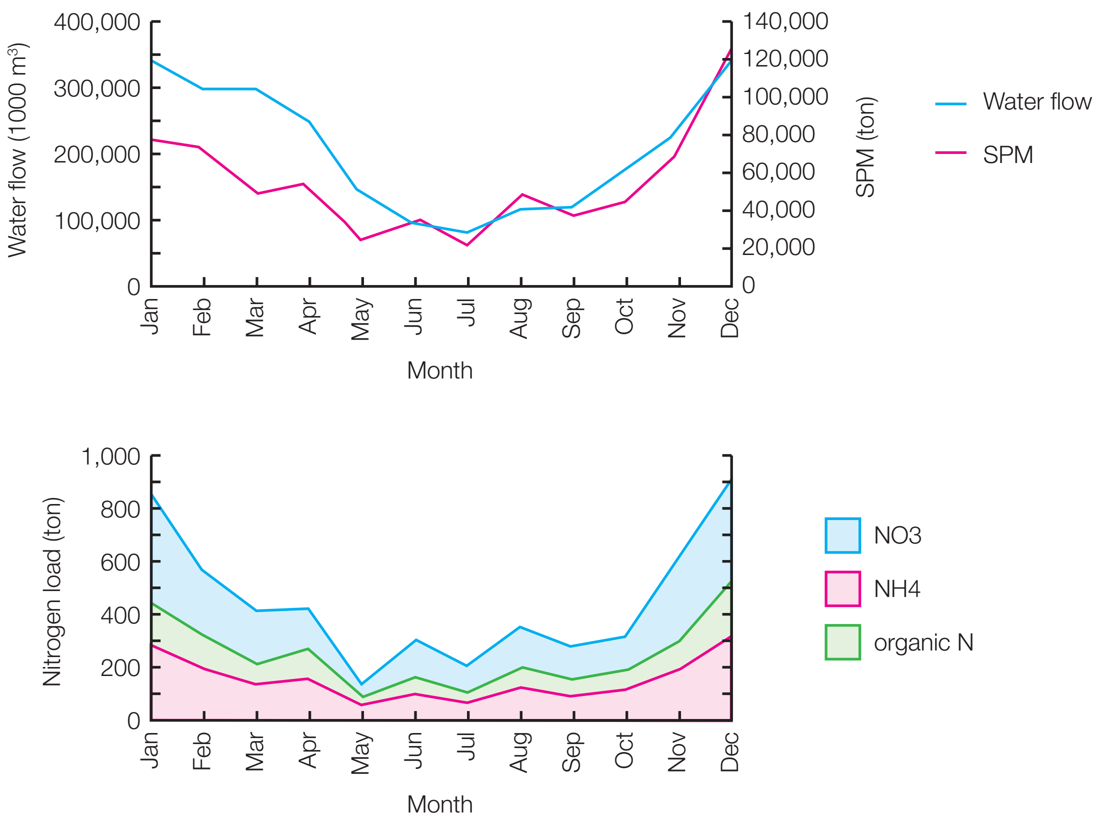
SWAT-E2K-SHELLSIM FRAMEWORK

LOUGH FOYLE

Some model results can be seen in Figure 48, representing average monthly catchment exports of water, sediment and nitrogen into lough Foyle. Note the winter peak of nutrient loadings, caused by a combination of higher rainfall and river flow rates with the fertilization of winter crops (i.e. ryegrass) and pastures. Note also the different forms of nitrogen loads. Dissolved Inorganic Nitrogen (DIN: NO_3 and NH_4) comprises about 65% of the total nitrogen input, but its importance grows in the autumn and winter due to the export of fertilizer NO_3 through surface runoff.

Figure 49 shows the simulated values for inputs of water, SPM, nitrogen and phosphorus into lough Foyle during an average year. The loads are apportioned according to the EcoWin2000 box divisions described in the **Spatial Domain** chapter.

Figure 48. SWAT simulation of monthly river flow and Suspended Particulate Matter (left) and nitrogen loads (right) into Lough Foyle during 1995.



Differences between those boxes result from associated inflow catchments (see Figure 41). Box 1 receives water from the Foyle catchment and also from the smaller, but still important, Faughan catchment, as well as urban wastewater from Omagh, Londonderry and Strabane, whilst Box 3 receives inputs from the river Roe and a few minor streams, as well as the urban input from Limavady.

Figure 49. Estimated average annual loads into Lough Foyle from the catchment, split by EcoWin2000 box divisions.

Parameter	Units	Box 1	Box 2	Box 3	Total
Water flow	10^6 m^3 y^{-1}	2064	36	360	2460
SPM	10^3 ton y^{-1}	402	72	182	656
DIN	Ton y^{-1}	2979	28	406	3413
Total N	Ton y^{-1}	4443	74	757	5274
DIP	Ton y^{-1}	559	4	77	641
Total P	Ton y^{-1}	750	12	125	887

This explains the high loads when compared with Box 2, which receives catchment loads from only a few minor streams. Model results are in general agreement with observed values for annual river flow: 75 versus 105 m^3 s^{-1} respectively, and with estimates for annual nitrogen loads: 5274 versus 5872 ton N y^{-1} respectively. The model was also able to satisfactorily simulate the observed monthly pattern of DIN concentrations in the rivers discharging into Lough Foyle.

DELFT3D-ECOWIN2000-SHELLSIM FRAMEWORK

After upscaling the hydrodynamic model (see the **Spatial Domain** chapter), the larger boxes were applied in the ecological model. Tests were carried out to check for stability in the ecological model for each system, and residence times compared with those obtained with the hydrodynamic models.

The water residence time was calculated using the e-folding time, defined as the time required for the concentration in a grid cell to be reduced to factor of 1/e, i.e. from an initial concentration of 100% to a concentration of about 36%.

Residence times were estimated to vary between 7 and 19 days in Larne Lough, 8 to 21 days in Belfast Lough, 4 to 18 days in Strangford Lough and 4 to 12 days in Carlingford Lough. Figure 50 shows the residence time estimation for Larne Lough. Due to the different approach followed for Lough Foyle, this type of comparative calculation was not required.

With the objective of simulating individual shellfish growth and total production at the population scale in the SMILE loughs, the models were initialised with nutrient and growth driver inputs specific for each system, drawing on data archived in the BarcaWin2000 databases or on other models. Boundary conditions for the river and ocean end-members were set following the results from the WAQ – D3D model and river sampling stations where appropriate. The ecological model outputs for each box were validated against field data to check if conditions for shellfish growth were being properly simulated. Example results from a few boxes from the Strangford Lough model are shown in Figure 51.

Some of the aquaculture sites in the SMILE ecosystems are inactive at present. Consequently, a further analysis of the commercial and biological status of each aquaculture area in each lough as well as the aquaculture type in each site was performed. Areas of active aquaculture of each type were estimated and are presented in the **Shellfish** chapter (Figure 29).

Figure 50. Larne Lough residence time estimation using the e-folding time. The residence time graphs are shown for the boxes showing longest and shortest residence times.

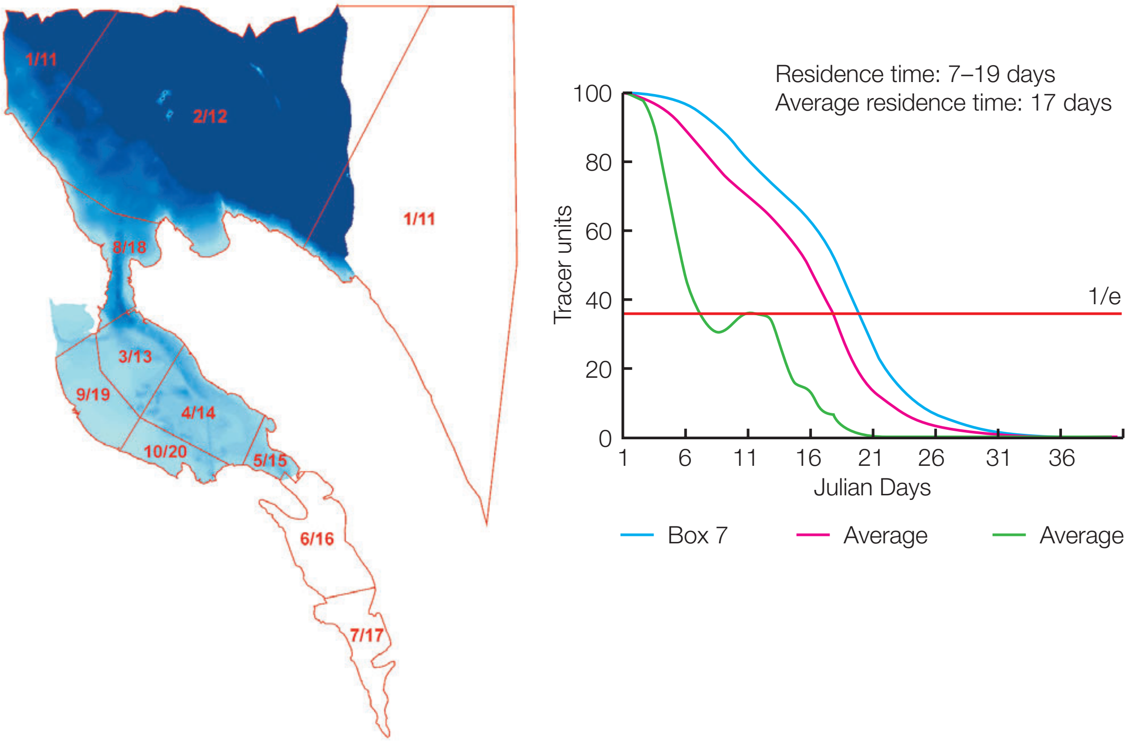
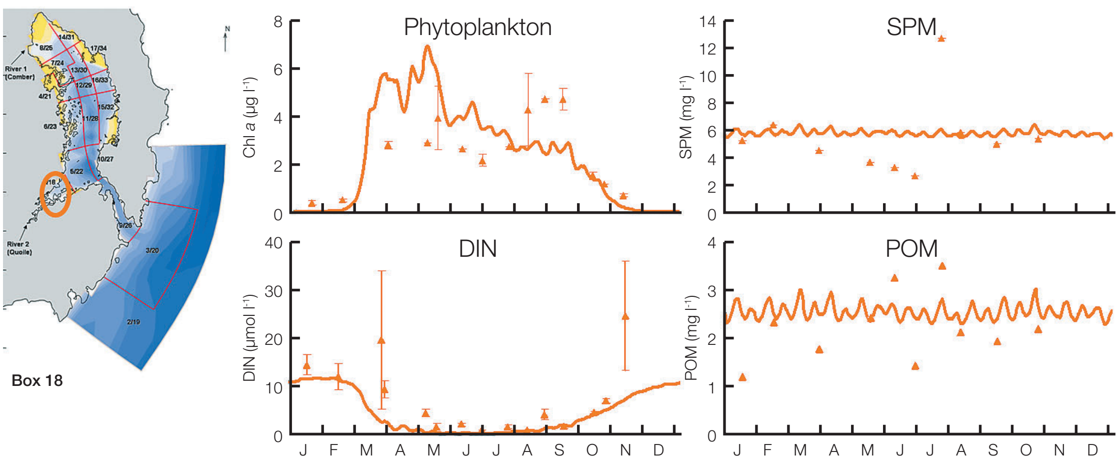
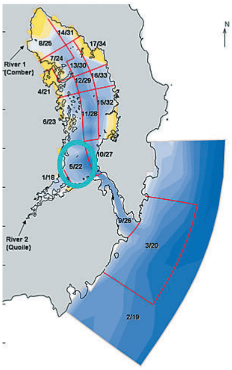


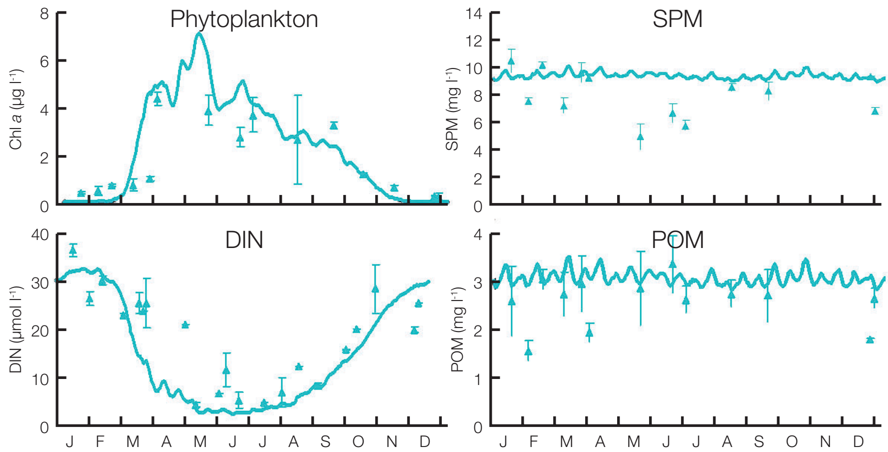
Figure 51. Validation of shellfish growth drivers simulated by EcoWin2000 for the Strangford Lough model.[9]

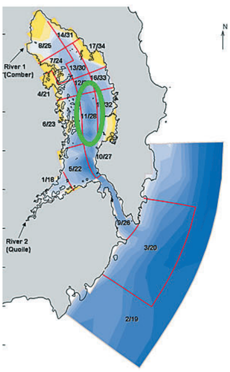


[9] Model results are shown for one year (January – J to December – D). Lines represent model simulation and points represent field data with standard deviation bars.

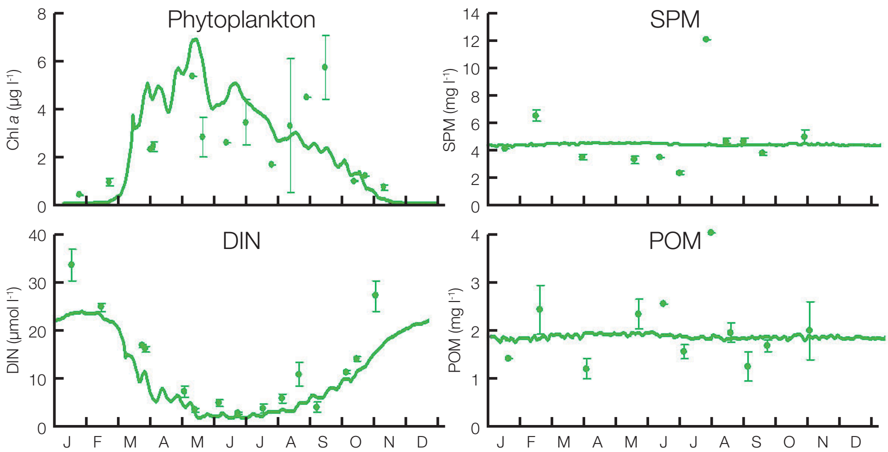


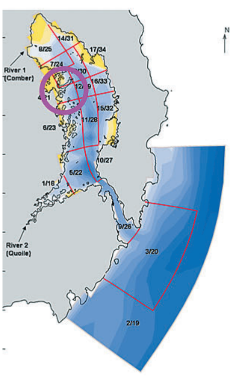
Box 22





Box 28





Box 21

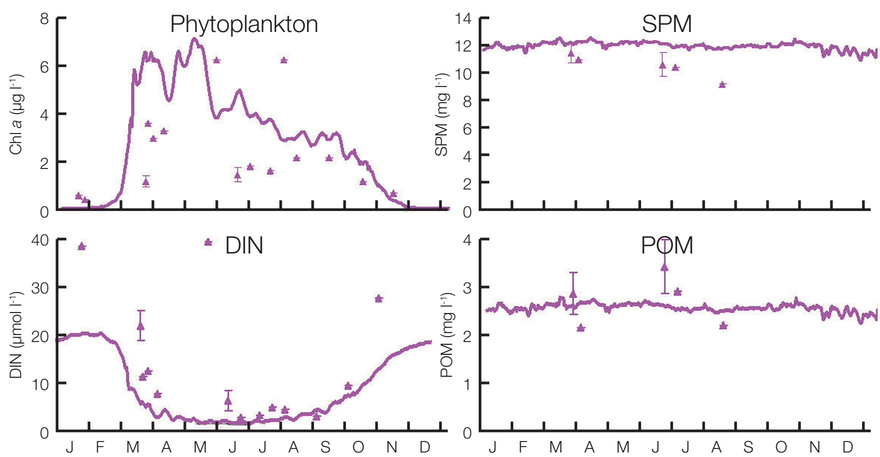


Figure 52. Individual length and weight simulated in E2K for blue mussels and Pacific oysters cultured in Carlingford Lough.

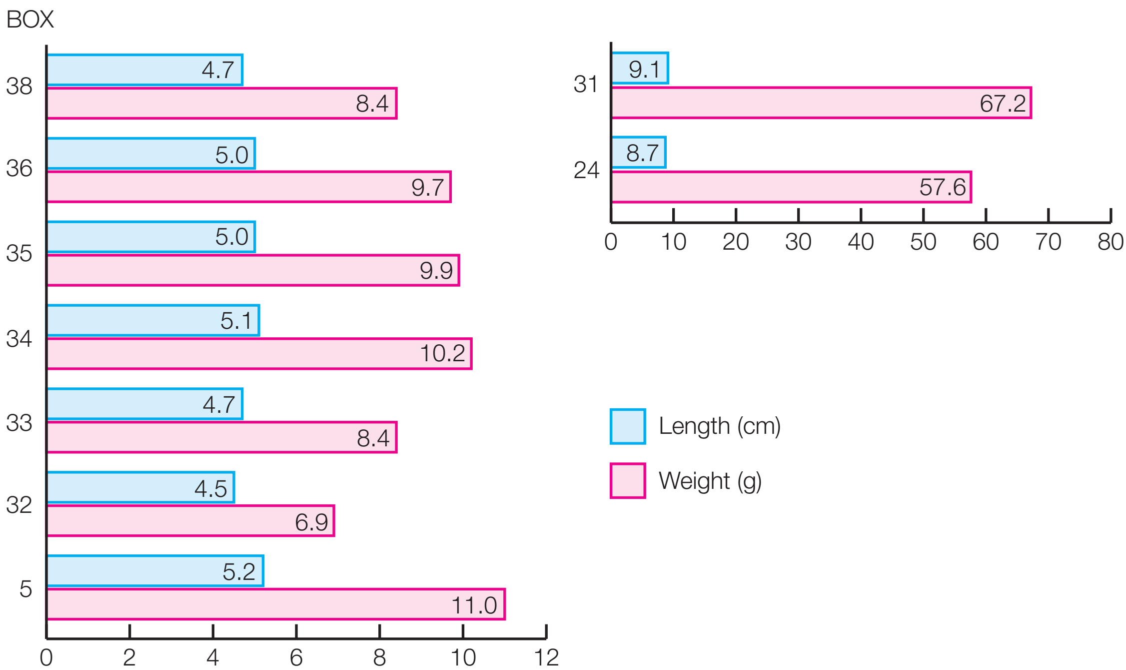
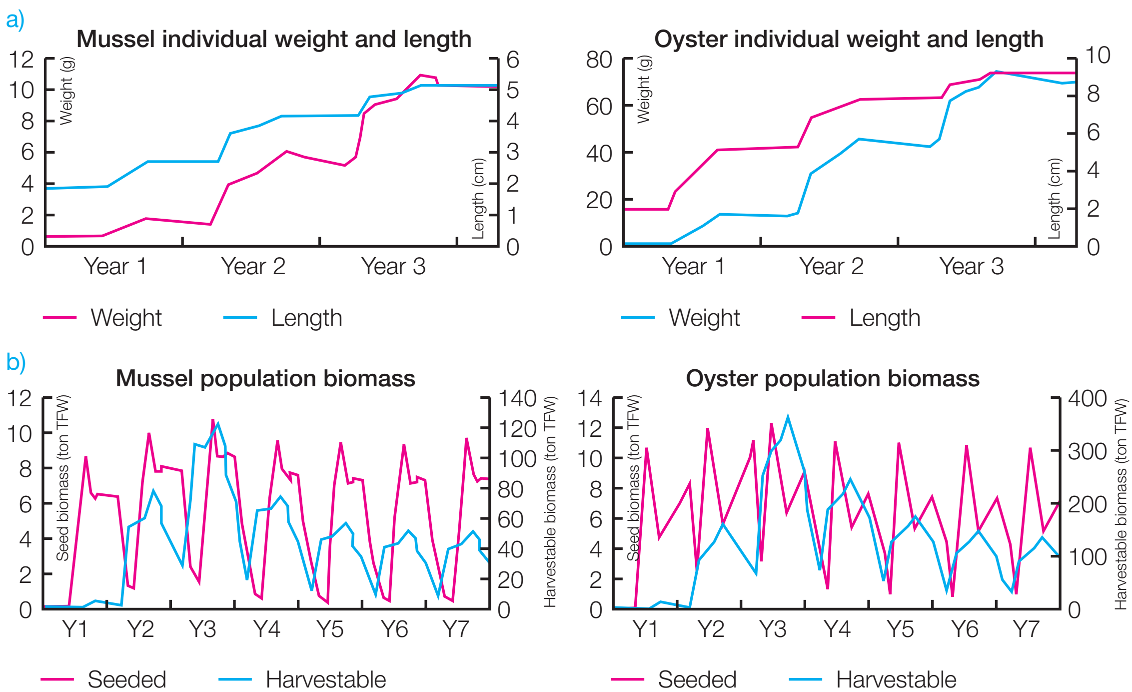


Figure 53. Results of simulations in Carlingford Lough: a) blue mussel and Pacific oyster growth in weight (g) and length (cm) during one culture cycle and b) mussel population biomass as total fresh weight (TFW) of seed and harvestable weights in Boxes 31 and 34.



The ShellSIM individual growth model (see the **Shellfish** chapter) was implemented and tested within the EcoWin2000 platform. Individual growth in weight and length were simulated for one mussel and one oyster in each model box where cultivation occurs (Figure 26).

With the addition of population dynamics to the individual model, shellfish stocks over multi-year periods can be estimated. As the shellfish culture cycle in all the SMILE loughs occurs over a three year period, the ecological model for each system needs to run for at least 6 years to produce stable results.

Figure 53 shows variations in (a) length and weight of mussels from box 34 in Carlingford Lough over a three year culture cycle and (b) population biomasses of seeded and harvestable mussels.

An estimate of total production for both mussels and oysters in each system was achieved by running the standard models. Figure 54 shows the simulated production values in Carlingford Lough for a 10 year model run. The model shows production values ranging from about 2500 to 1300 tons for mussels, stabilising at production values of about 1300 tons, compared with production values from about 750 to 280 ton for Pacific oysters, stabilising at 280 tons.

The EcoWin2000 models were run for 10 years to produce stable multi-year harvests for the five SMILE loughs, and the predictions compared with harvests recorded (by Fisheries Division, Loughs Agency and BIM) (Figure 55).

Figure 54. Simulated production values for Carlingford Lough. Model was run for a 10 year period to show consistently stable harvesting results.

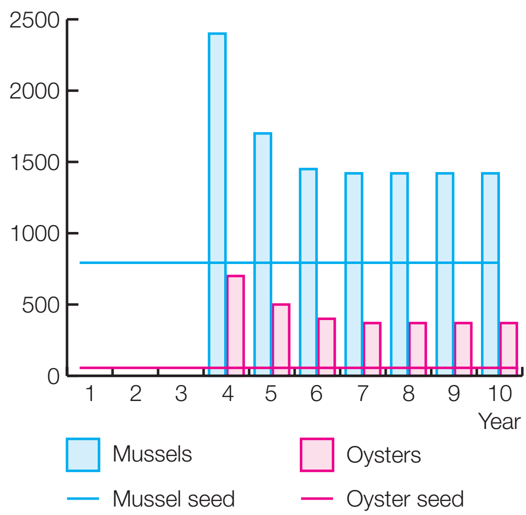


Figure 55. Production data for the five SMILE loughs and comparison with production simulations from EcoWin2000.[10]

System	Species	Carlingford Lough	Strangford Lough	Belfast Lough	Larne Lough	Lough Foyle[11]	Total
Production records	Blue mussel	1500 to 3000	2.4	10000	200	15318	27300
	Pacific oyster	365 to 868	260	-	10.4	50	820
Model simulation	Blue mussel	1300	9	6000	300	1325	8934
	Pacific oyster	280	223	-	9	12	524

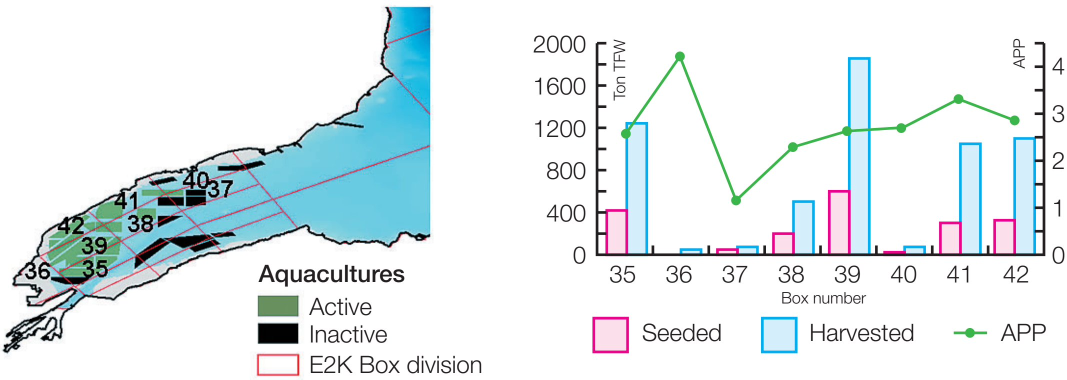
[10] The production records shown were given by DARD Fisheries Division for Strangford, Belfast and Larne Loughs and by the Loughs Agency and BIM for the transboundary systems (Carlingford Lough and Lough Foyle).

[11] There are substantial uncertainties on culture practice in Lough Foyle, regarding areas, seed densities etc. SMILE model results are based on cultivation areas shown in Figure 3.

The average physical product (APP) is defined as the ratio between harvested biomass (total physical product – TPP) and seed biomass, and is a measure of ecological and economic efficiency. In Figure 56, TPP and APP results are shown for Belfast Lough.

The results show stable model outputs, corresponding to year 10 of simulation.

Figure 56. EcoWin2000 model results for mussel production in Belfast Lough.



A synthesis of the model results for each system is shown in Figure 57. The total production per unit of area is also shown, and varies depending on the location of the aquaculture.

Figure 57. Synthesis of model results for each system.

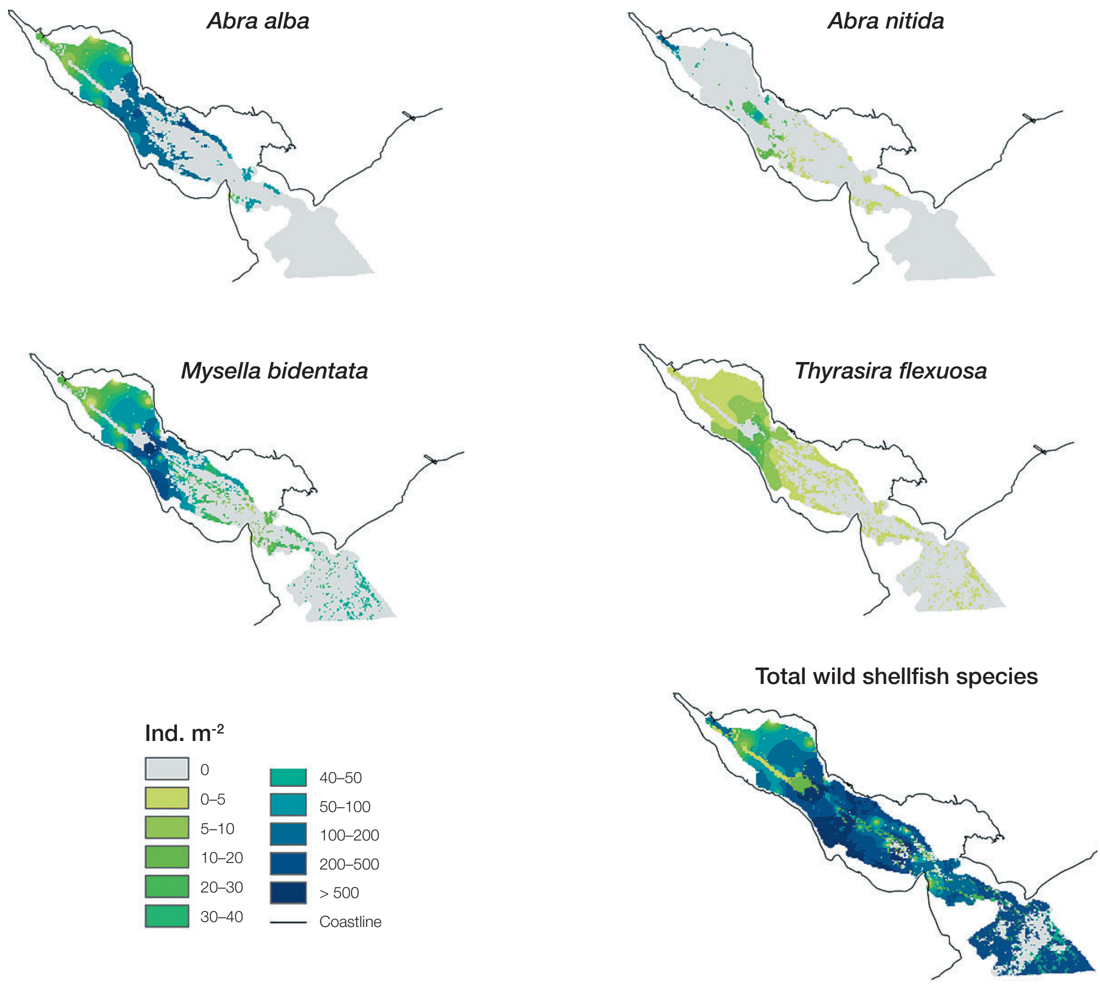
Ecosystem and species	Aquaculture Area (ha)	TPP (tons)	APP	TPP per ha	
Carlingford Lough	Blue mussel	865.2 (NI+ROI) 165.6 (NI)	1300 (NI+ROI) 320 (NI)	2.5 (NI)	0.03–2.1(NI)
	Pacific oyster	197.8 (NI+ROI) 83.2 (NI)	280 (NI+ROII) 110 (NI)	5.25 (NI)	0.7–1.15(NI)
Strangford Lough	Blue mussel	5.9	9	7	0.66–0.81
	Pacific oyster	23.5	223	8.4	9.5
Belfast Lough	Blue mussel	953.7	6000	2.8	3–8.75
Larne Lough	Blue mussel	47.4	282	3.32	2.7
	Pacific oyster	22.9	8.7	14	0.14–0.15
Lough Foyle	Blue mussel	2000	3650	-	-
	Pacific oyster	0.07	24	-	-

WILD SPECIES – GIS RESOURCE PARTITIONING MODEL

Interspecific differences in spatial distribution are recognised, resulting from the types of sediment, water depths and the biotopes present. The differential distribution of species in Carlingford Lough is shown in Figure 58.

Although aquaculture occupies a large proportion of the lough seabed, the diversity of wild suspension-feeding shellfish is high, for 18 species are present with average densities of 94.5 ind m^{-2}. A total number of 4632 million wild individuals were estimated to be present in Carlingford Lough, spatially distributed as shown in Figure 58 (bottom right).

Figure 58. Wild shellfish species in Carlingford Lough. Spatial distribution of four different species found (*Abra alba, Abra nitida, Mysella bidentata* and *Thyasira flexuosa*) and overall distribution of all wild shellfish species.



ECOLOGICAL SIGNIFICANCE

The population of non-commercial benthic species present in Carlingford Lough has an impact on food consumption, and the level of competition for resources between wild and cultured species needs to be quantified in order to appropriately partition resources.

Based upon the estimated total number of wild shellfish species present in Carlingford Lough, this system can be cleared in 2–4 days by the wild populations alone. Baseline food requirements for maintaining these species, estimated using the average chlorophyll *a* and POM concentrations (2.3 µg l^{-1} and 5.4 mg l^{-1}, respectively), are approximately 140–200 ton chl *a* y^{-1} and 315-500 ton POM y^{-1}.

The different spatial distributions obtained suggest that baseline food requirements are in fact variable, not only at different times of the year (e.g. in spring blooms or winter periods) as expected, but also in different areas of the ecosystem depending on how many wild shellfish are present. This means that where wild species are present in large numbers more phytoplankton and POM are required in the water column, and less competition for food should be imposed through aquaculture.

The high number of at least 18 suspension-feeding shellfish species within Carlingford Lough suggests that competition for food is not currently an issue at the aquaculture production levels being practised in this ecosystem. Since the wild species data is based on a study carried out in 1994, it is recommended that new surveys be conducted to validate findings.

Information on the distributions of wild species will assist in the licensing of new aquaculture areas. In addition, the establishment of upper thresholds for shellfish aquaculture development in an ecosystem or in certain areas of that ecosystem can be estimated to assure the sustainability of wild populations.

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MANAGEMENT RECOMMENDATIONS

INTRODUCTION

The management of shellfish aquaculture in Northern Ireland should take into consideration the sustainability of the various activities, and be framed by the major guidelines that currently constitute best practice in Europe. The first part of this chapter provides an overview, often quoted verbatim, of the EU vision as relevant to shellfish aquaculture. A number of scenarios are then presented, designed to illustrate the potential applications of the EcoWin2000 model to address management questions. Finally, two case studies are presented. The first one focuses on some of the problems and approaches for farm-scale carrying capacity work, using examples from Maine, USA; the second applies the FARM^{TM} screening model to illustrate how system-scale simulations carried out with the EcoWin2000 can be used to analyse production at the farm scale.

STRATEGY FOR THE SUSTAINABLE DEVELOPMENT OF EUROPEAN AQUACULTURE

The Commission's Strategy for the sustainable development of the European Aquaculture industry aims to:

- Create long term secure employment, in particular in fishing-dependent areas
- Assure the availability to consumers of products that are healthy, safe and of good quality, as well as promoting high animal health and welfare standards
- Ensure an environmentally sound industry

Some extracts from the document are given below.

ENVIRONMENTAL OBJECTIVES

ENSURING AN ENVIRONMENTALLY SOUND INDUSTRY

It is important to reduce the negative environmental impacts of aquaculture by developing a set of norms and/or voluntary agreements which prevent environment degradation. Conversely, the positive contribution of certain aquaculture developments to the environment must be recognised and encouraged, including by public financial incentives.The Commission's Demonstration Programme on integrated coastal zone management has shown that the best response to such complex situations is an integrated territorial approach that addresses concurrently the many different problems an area faces and involves all the stakeholders. Aquaculture is included in activities that shall be considered in the aim of Integrated Coastal Zone Management (ICZM) process.

CHALLENGES

COMPETITION FOR SPACE

Many complaints against aquaculture development reflect competition for space; the recent growth of aquaculture, particularly on the coastline where there is already a high concentration of activities, put it in the place of the newcomer disrupting the long-established status quo between existing users. Land and water for aquaculture will be more and more expensive in future. Aquaculture establishments may be forced to move offshore, but this is a possibility for some species only.

IMPLICATIONS OF THE WATER FRAMEWORK DIRECTIVE FOR MARICULTURE

DEFINITION OF WATER BODIES AND REFERENCE CONDITIONS

At the moment, most countries have defined their water bodies. These tend to be large, on the scale of kilometres to low tens of kilometres, and therefore the majority of mariculture activities will be considered as one of the pressures acting on the overall quality of the water body.

Whilst it is somewhat clearer what implications the WFD may have for intensive aquaculture activities that are confined to small spatial areas, there are certain activities e.g. bottom culture of mussels and intertidal culture of oysters, that may be impacted as a consequence of the Directive. Given that these activities may constitute large proportions of a water body, the areas may be representative of the water body. These activities have defined impacts on the benthos over wide spatial scales, of the order of km^2, and consequently may put the water body at risk of failing to meet good ecological status. Initial risk assessment efforts carried out by England and Wales have determined that the shellfisheries (even if comprising up to 50% of a water body) may not be considered of having high pressure on a water body. However, this exercise considered managed wild-fisheries only and not true aquaculture operations. As yet, the implications on broad-scale aquaculture activities have not been fully assessed and discussed.

MEASURES TO IMPROVE ECOLOGICAL QUALITY (MITIGATION MEASURES)

The overall aim of the Water Framework Directive is the achievement of good water status in all waters by 2015. It is probable that the initial classification will result in some water bodies being classified as a having an ecological status below the target level. In such cases, Member States will then be required to take steps to improve the status of these water bodies.

“Member states should adopt measures to eliminate pollution of surface waters by the priority substances and progressively to reduce pollution by other substances which would otherwise prevent Member States from achieving the objectives for the bodies of surface water.”

At this time it is not clear what measures/actions Member States may choose to take. It is apparent that rather little consideration has so far been given to this aspect of the Directive, with most attention being given to prior activities with more pressing deadlines, such as may include the development of reference conditions, monitoring, and subsequent classification. However, it can be anticipated that additional management and mitigative actions may be required of aquaculture operations in some areas where good ecological status has not been achieved.

It is clear that the promotion of sustainable European aquaculture does not conflict with the requirements of the WFD. Aquaculture should therefore not seek “special treatment”. Rather, aquaculture is to be viewed as a coastal zone activity in the same manner as other activities that can influence, and have requirements for, good coastal water quality, such as domestic waste disposal, agriculture, tourism and forestry. The contribution of aquaculture to ecological conditions assessed as less than good should be considered in the same manner as the contributions from other activities.

In developing mitigation schemes, however, it should be noted that aquaculture can also contribute to improving ecological status of surface water bodies. Such activities could include:

- Macroalgal cultivation which can remove significant amounts of nutrients from the surrounding waters
- Bivalve mollusc cultivation which can extract both nutrients and contaminants from the water column through their filtering activity
- Polyculture, e.g., finfish and macroalgae in which the inorganic nutrients from the finfish farms are taken up by the macroalgae and in which both products can have an economic value

GUIDELINES FOR ENVIRONMENTALLY ACCEPTABLE COASTAL AQUACULTURE

The ecological and socio-economic benefits and costs of aquaculture activity are potentially so significant that action-oriented policies are necessary. In order to ensure that financial gain is not at the expense of the ecosystem or the rest of society, aquaculture developments must follow established principles.

The formulation of strategies will provide the focus for an equitable balance between those seeking a simple livelihood, those wanting to make a profit, the quality of the environment and the interests of local people, the wider community and, where appropriate, the international community.

GENERAL PRINCIPLES

- Coastal aquaculture has the potential to produce food and to generate income contributing to social and economic well-being
- Planned and properly managed aquaculture development is a productive use of the coastal zone if undertaken within the broader framework of integrated coastal zone management plans, according to national goals for sustainable development and in harmony with international obligations
- The likely consequences of coastal aquaculture developments on the social and ecological environment must be predicted and evaluated, and measures formulated in order to contain them within acceptable, pre-determined limits
- Coastal aquaculture activity must be regulated and monitored to ensure that impacts remain within pre-determined limits and to signal when contingency and other plans need to be brought into effect to reverse any trends leading towards unacceptable environmental consequences
- Carrying capacity for aquaculture shall take into account food for wild populations of grazers and filter feeders, including wild bivalve stocks

STRATEGIES

Strategy 1. The sound utilization of the ecological capacity of the coastal zone to produce aquatic products and generate income.

Strategy 2. The development of policy and management mechanisms to reduce conflict with other coastal activities.

Strategy 3. The prevention or reduction of the adverse environmental impacts of coastal aquaculture.

Strategy 4. The management and control of aquaculture activities to ensure that their impacts remain within acceptable limits.

Strategy 5. The reduction of health risks from the consumption of aquaculture products.

SCENARIOS

The scenarios developed below are intended as illustrations of the potential of this modelling framework for informing managers and industry alike. All were proposed by the Northern Ireland management community.

SCENARIOS TO EXEMPLIFY THE USE OF SYSTEM-SCALE CARRYING CAPACITY MODELS

THREE SCENARIOS WERE TESTED ON DIFFERENT SMILE LOUGHS

1. Increase of the seeded area;
2. Increase in water temperature;
3. Partitioning of the food resource by wild species.

The first scenario was tested for Belfast Lough, where aquaculture already occupies a significant percentage of the entire system. Since there are several licensed sites in this lough which are not active at present, the EcoWin2000 model was run considering that some of the inactive aquaculture sites had become active.

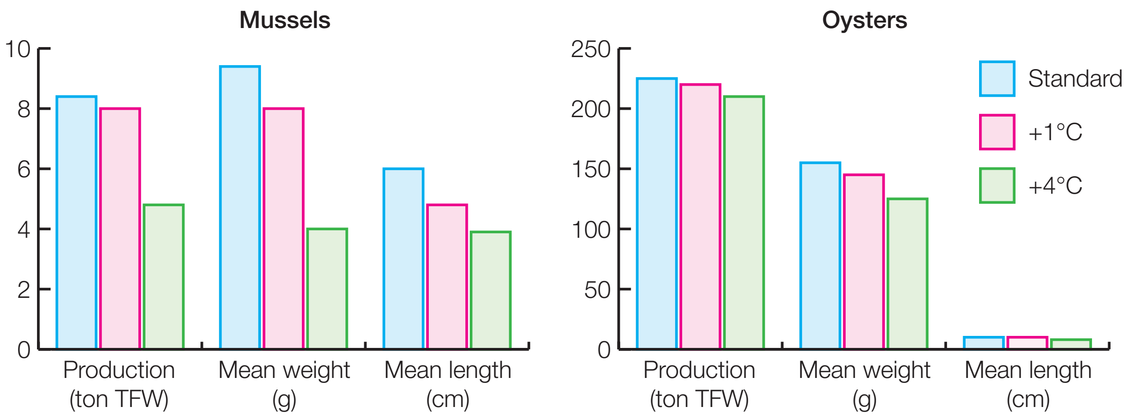
Figure 59. Belfast model results for an increased seeding area. Results of the standard model are shown for comparison.

Box	Seeded		Harvested		APP		Individual weight	
	Standard	Scenario	Standard	Scenario	Standard	Scenario	Standard	Scenario
29	none	264	none	562	none	1.9	none	4.8
35	426	no change	1258	1222	2.7	2.6	9.3	8.8
36	6	no change	28	27	4.2	4.1	19.2	18.6
37	37	no change	57	56	1.4	1.4	3	2.9
38	193	no change	517	507	2.5	2.4	8.3	8
39	599	no change	1862	1841	2.7	2.7	9.7	9.5
40	19	no change	56	55	2.8	2.8	10.8	10.6
41	293	no change	1072	1062	3.4	3.3	14.3	14
42	313	no change	1114	1107	3	3.0	10.9	10.8
	1886	2150	5964	6441	3	3	11	9.8

The aquaculture areas within box 29 (see the **Spatial Domain** chapter) were considered to be exploited in this scenario and seeding densities were considered to be same as for the rest of the lough. The results obtained per box can be seen in Figure 59, and a comparison between the standard model and the scenario can be made for seeded and harvested biomass, APP and mussel individual weight.

The second scenario tested for potential climate change effects by considering an increase in water temperature for Strangford Lough. The effects on aquaculture in Strangford Lough, for an increase of 1 °C and 4 °C in the water temperature are shown in Figure 60. The one degree increase scenario was proposed by DARD Fisheries; the higher increase of 4 °C is the maximum increase, by the year 2100, predicted by the UN Intergovernmental Panel on Climate Change, in its February 2007 report. From these results it can be seen that an increase in the water temperature would lead to reduction in aquaculture productivity and both the mean weight and mean length of individuals would decrease, though these decreases would have a greater effect on the mussel than on the Pacific oyster population.

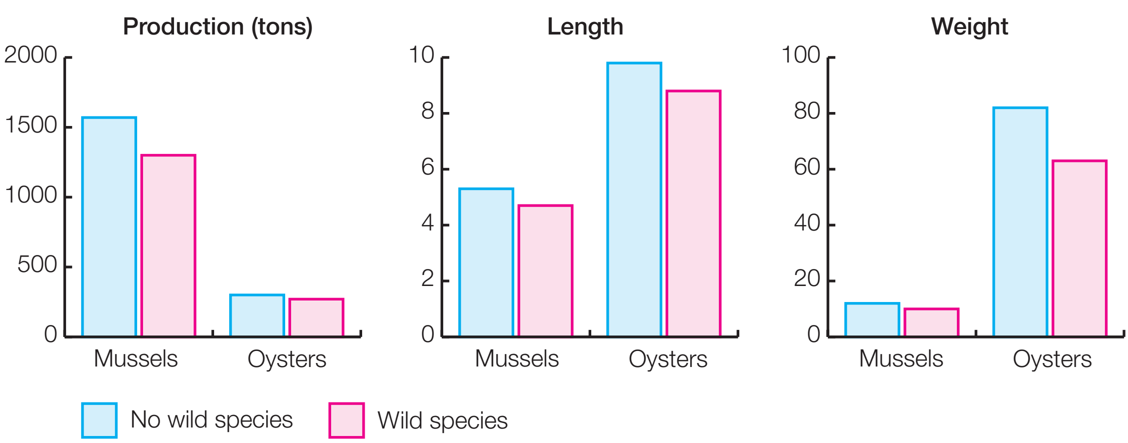
Figure 60. Model results for the Strangford standard model and two scenarios considering an increase in the water temperature of 1 °C and 4 °C.



According to the results obtained, an increase of 1 °C in the water temperature would lead to a reduction of about 10% in mussel production and less than 2% in Pacific oyster production, and an increase of 4 °C would result in a reduction of 50% in mussel production and less than 5% in Pacific oyster production.

The third scenario was simulated in Carlingford Lough where the GIS resource partitioning model was applied. Considering the average of wild species individuals existing per unit area, the EcoWin2000 model predicts that production values for cultivated species would be reduced, together with individual length and weight (Figure 61).

Figure 61. Scenario showing aquaculture production in Carlingford Lough with and without resource partitioning.



CASE STUDIES FOR LOCAL-SCALE CARRYING CAPACITY

The first stage of carrying capacity assessment should take place at the system level, as has been carried out in the SMILE project. However, after this system-scale planning approach is completed, it is appropriate to evaluate the sustainability of aquaculture activities at the local scale (farm, raft etc). A number of tools have been developed to carry out this kind of assessment, including the FARM™ model, developed by members of the SMILE team, and MUSMOD, a mussel model developed in the U.S. by Carter Newell and John Richardson. In order to illustrate some of the local-scale issues, two case studies are presented below. The first was prepared by Carter Newell, and illustrates some of the problems and approaches for farm-scale carrying capacity work, using examples from Maine, USA. The second was prepared by members of the SMILE team, together with Suzanne Bricker from NOAA, and focuses on the integration of system-scale and farm-scale approaches, using the FARM™ screening model.

CASE STUDY 1 – FACTORS WHICH INFLUENCE MUSSEL PRODUCTION ON BOTTOM LEASES

By: Carter Newell, Great Eastern Mussel Farms, Maine, USA

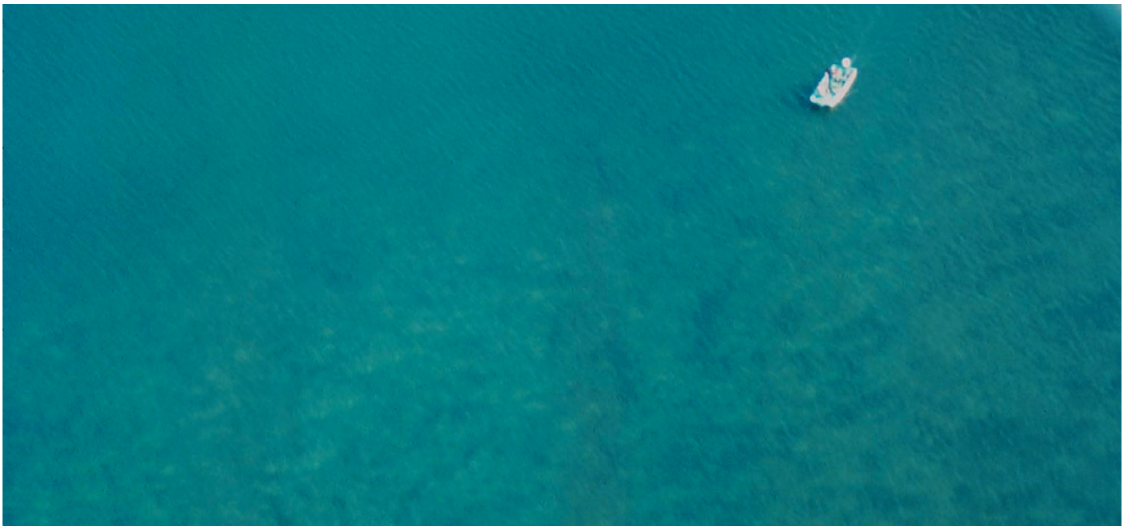
The management of shellfish aquaculture in bottom or suspended systems for maximum productivity is often based on field experience (trial and error) but not necessarily on a detailed quantitative knowledge of the hydrodynamics of the sites and factors which affect food supply and demand. Furthermore, husbandry practices which control shellfish density (number per square meter), biomass (tissue weight per square meter) and density distribution (patch size) affect the growth rates of shellfish due to competition for food two levels: the localized (culture unit) scale and farm scale (i.e. 100 meters). Shellfish mortality is also a function of size of seed, time of year seeded, handling, sedimentation, and activity of predators. Investigations on factors affecting survival, growth, and seed to harvest yield in bottom cultures of mussels in Maine, USA have resulted in the development of a productive capacity model MUSMOD which predicts the growth rates and yields of seed mussels based on key parameters which include:

1. The size and condition of the mussel seed;
2. Seeding mortality;
3. Mortality during grow-out;
4. The concentration and flux of live phytoplankton and organic detritus particles;
5. Water temperature: more important for rapid shell growth of seed;
6. Mussel density and biomass;
7. Mussel biomass distribution (i.e. patches or small clumps);
8. Time of year seeded.

MUSSEL SEED DISTRIBUTION

Mussel seed obtained from seed mussel beds and harvested by dredge, or mussel seed obtained from a plot of half-grown mussels, is spread by the vessel, and growth and survival is a function of both the quality (percent weight 100% live mussels), the physiological condition (mechanical damage, time and temperature from harvest to spreading, wet or dry storage) and the spreading rates (discharge rate of the vessel, water depth, vessel speed and seed dispersion) of the mussel seed. Mussels spread in numerous small patches are illustrated in Figure 62. The density distribution of the mussel seed either results in the production of mussel patches or a more uniformly distributed small clumps of mussels on the bottom. If seed is not evenly distributed, intense competition for food and space on a localized (mussel patch) level limits mussel growth in addition to larger (farm) scale patterns of food availability. Growth samples and a simulation model of depletion of chl *a* over mussel patches demonstrated severe competition for food for mussels within 0.5 m of the edges of thick mussel patches.

Figure 62. Aerial view of well-distributed mussel seed.



THE SPATIAL DISTRIBUTION OF BIOMASS

Ultimately, the maximum production obtained from a site will be determined by the asymptotic maximum biomass (weight of mussel tissue per square meter) a site can support. An example of asymptotic biomass developed on mussel rafts in Belfast Bay, Maine is presented in Figure 63. Due to the limitations on food supply (food concentration and flow), the biomass at a farm site cannot exceed these levels. There is a trade-off between mussel quality (size, meat yield) and total tonnage which may be sustained by any individual site.

In Maine, USA, we investigated three mussel farm sites which varied in food supply and demand. There was a three-fold difference in recommended seeding densities to produce a mussel with a 6 gram steamed meat weight after one year at the farm, ranging from 300-900 mussels per square meter (Figure 64). At the Deer Isle site, vessel seeding densities of 1000 mussels m^{-2} previous to the study were reduced to 300 m^{-2} in subsequent years.

This resulted in a reduction of grow-out time from 2 years to 1 year, higher harvest to seed yields (from 1:1 to 2:1) and higher mussel meat yields. At the Sullivan site, seeding densities could be increased to 900 individuals m^{-2} without a sacrifice in quality or elongation of the grow-out period.

Figure 63. Asymptotic biomass (about 1200 g m^{-1}) on a mussel raft.

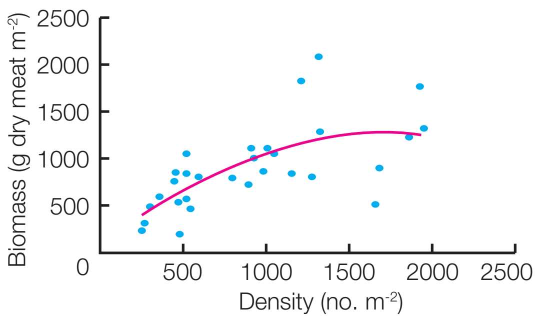
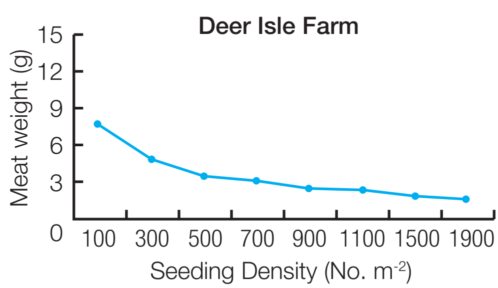
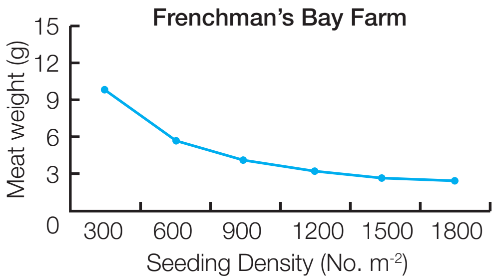
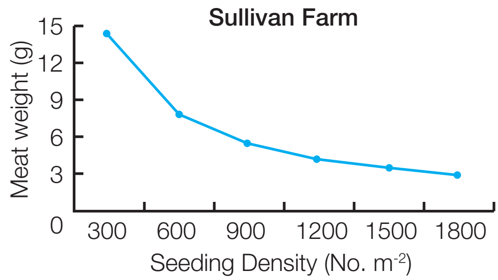


Figure 64. Effects of mussel density on steamed meat weight after 1 year of growth on three mussel farm locations in Maine, USA. Note that densities to obtain a 6 gram meat range from 300–900 m^{-2}. The Sullivan farm had both higher currents and higher food concentrations than the two other sites.





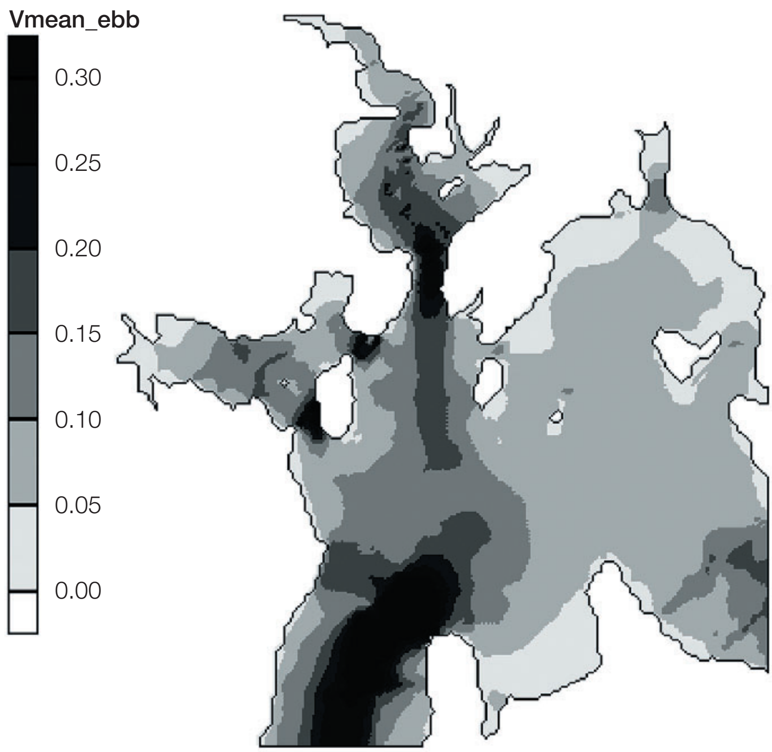


THE USE OF FLOW MODELS AT A HIGH SPATIAL RESOLUTION

While conditions may vary between farms, they also may differ within a single farm. We developed a simple 2-dimensional flow model for the Deer Isle farm, and discovered that half of the farm had twice the currents than the other half.

By adjusting seeding densities to the mean flow values, we were able to increase yields by seeding the higher flow area (western side of the lease) at higher densities than the lower flow, eastern side (i.e. 600 m^{-2} vs 300 m^{-2}) and still have even growth and meat yields throughout the farm. Flow models on the bay scale are useful in site selection and management (Figure 65).

Figure 65. Mean depth-averaged ebb velocity (m s^{-1}) modelled for a mussel farm region in eastern Maine.

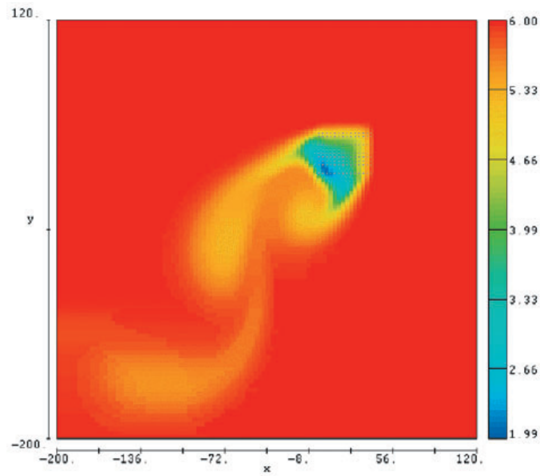


THE DEPLETION OF SUSPENDED PARTICLES AT AQUACULTURE SITES

Because food depletion by bottom cultures is more severe near the bottom, there may be adequate supplies of food particles in the surface waters. If a fallow zone is placed in the middle of a farm, it can allow for the downward mixing of these particles, providing more food for the next seeded area downstream.

Using information about the flow through a culture system and the distribution of biomass, it is possible to model the depletion of food particles (Figure 66) and optimize the production[12]. Field investigations of food supply and demand, performed at the site, can provide valuable information on how to improve cultivation practices (Figure 67).

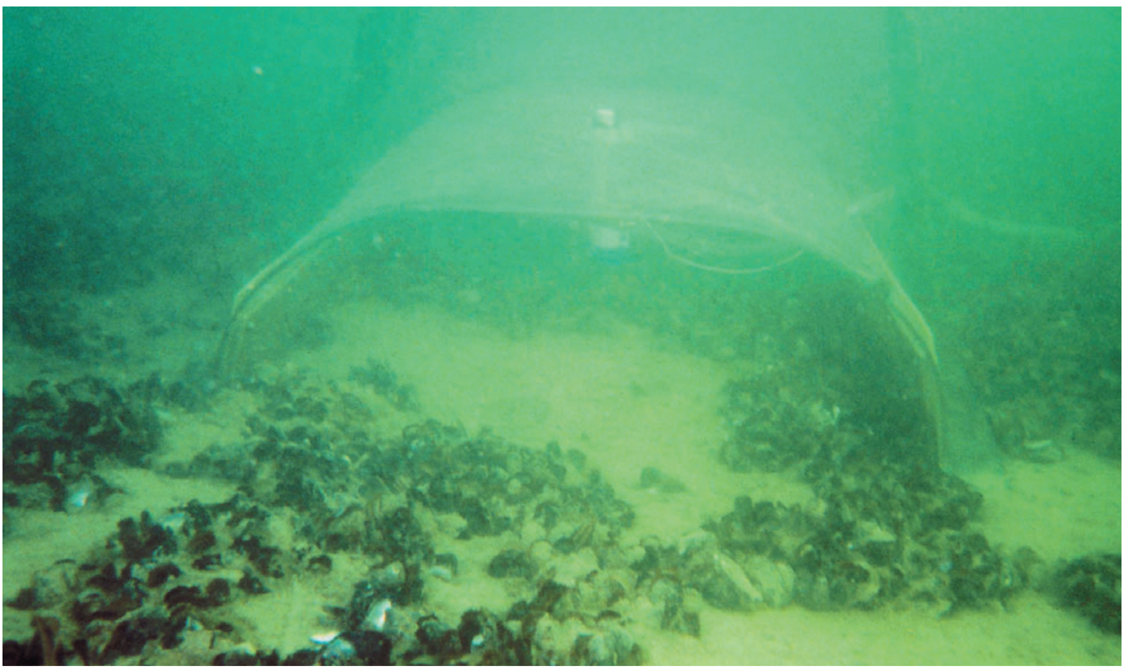
Figure 66. Chl *a* concentration (μg l^{-1}) around and inside a mussel raft.



THE IMPORTANCE OF MORTALITY

When mussel seed are transplanted to a bottom lease site, if counts are made of the number of seed mussels per kg (i.e. 500), and compared with the number of harvested mussels per kg (i.e. 50), it is possible that the bottom cultures could achieve a 10 to 1 harvest to seed yield. Since the industry standard harvest to seed yield is often 5–10 times lower than that, mussel mortality must be a major factor in affecting lease site productivity. Mortality can be reduced by reducing density-dependent mortality of the mussels by spreading them better. In addition, mussels which are larger and have a thicker shell stand a better chance of surviving benthic predators such as crabs. Experiments on dropping mussels more than 1 meter onto a hard surface, and observations on the decrease in survival in relation to time, temperature, and type of storage (wet or dry) have demonstrated that careful harvesting and storage, prompt reseeding and careful seed spreading at appropriate densities in farms result in big gains in mussel survival, quality, and production yields.

Figure 67. Measuring the feeding rates of mussels using a benthic ecosystem tunnel.



[12] Mussel raft with a 15 cm s^{-1} flow velocity, a 45 degree approach angle to the rafts and mussel dropper diameter of 30 cm.

CONCLUSIONS

Mussels reach their full growth potential when they are feeding at their maximum rates with adequate food. Through careful site selection, biomass management and seed spreading, mussel farmers may improve harvest yields and product quality through a more detailed understanding of their site's oceanography, by matching food supply with demand.

CASE STUDY 2 – APPLICATION OF THE FARM™ SCREENING MODEL TO CARLINGFORD LOUGH

By: J.G. Ferreira, A.J.S. Hawkins (SMILE team) and Suzanne Bricker, National Oceanic and Atmospheric Administration, USA

INTRODUCTION

The Farm Aquaculture Resource Management (FARM™) model is directed both at the farmer and the regulator, and has three main uses: (i) prospective analyses of culture location and species selection; (ii) Ecological and economic optimization of culture practise, such as timing and sizes for seeding and harvesting, densities and spatial distributions (iii) environmental assessment of farm-related eutrophication effects (including mitigation).

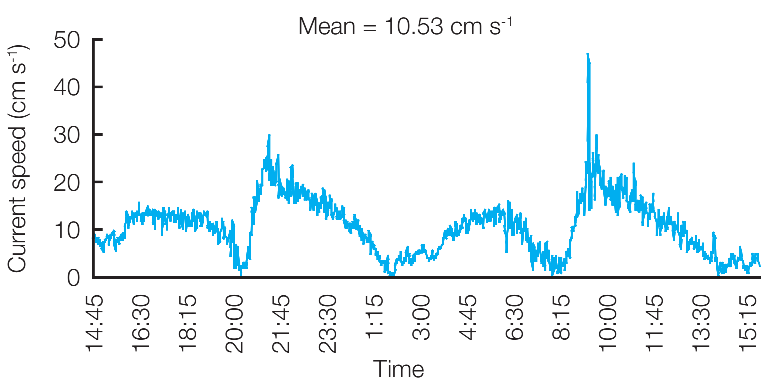
The modelling framework applies a combination of physical and biogeochemical models, bivalve growth models and screening models for determining shellfish production and for eutrophication assessment. FARM™ currently simulates the above interrelations for nine bivalve species: the oysters *Crassostrea gigas* and *Ostrea plicatula*, the mussels *Mytilus edulis* and *Mytilus galloprovincialis*, the Manila clam *Tapes philippinarum*, the ark shell *Tegillarca granosa*, the razor clam *Sinonvacula constricta*, the cockle *Cerastoderma edule* and the Chinese scallop *Chlamys farreri*. Shellfish species combinations (i.e. polyculture) may also be modelled.

The model has been implemented as a web-based client-server application and is available at http://www.farmscale.org/

APPLICATION TO CARLINGFORD LOUGH

The FARM™ screening model was applied to a mussel farm area in the upper reaches of Carlingford Lough, drawing on data and simulation outputs from the SMILE project, and on current velocities (Figure 68), kindly supplied by C. Newell. The publicly available version of FARM™ uses only average values for shellfish growth drivers. In this case study a bespoke version was applied, which incorporates drivers varying monthly over the annual cycle.

Figure 68. Current speed measured over a tidal cycle in the upper reaches of Carlingford Lough (courtesy C. Newell).



These drivers were extracted from Year Seven of a simulation performed in EcoWin2000 using the Carlingford Lough standard model, and correspond to the monthly averages for a mussel cultivation area in the upper reaches[13] of the system (Figure 69). Salinity was considered to be constant at 34.3 (annual coefficient of variation from EcoWin2000 model simulations = 1.5%). These data were used to initialise and force the FARM™ model, together with dissolved oxygen data collected at a mooring station, and extracted from the SMILE BarcaWin2000 database. The data for cultivation practice were taken from the EcoWin2000 standard model file for Carlingford Lough. A standard seed density of 500 animals m^{-2} and 70% annual mortality were considered. The model was run for a cultivation period of 1200 days, and the drivers and outputs are shown in Figure 70.

Figure 69. Growth drivers simulated in EcoWin2000 for the upper reaches of Carlingford Lough.

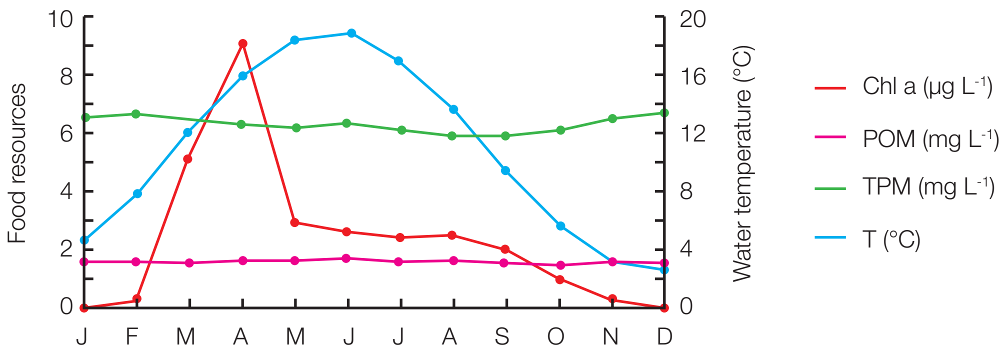


Figure 70. Drivers (above the dotted line) and outputs (below the dotted line) for the FARM™ screening model applied to blue mussel culture in Carlingford Lough.

Farm	Dimensions (m)	Species	Cultivation (d)
	300(L)x20(W)x5(D)	*M. edulis*	1200
Food	Chl *a* (µg L^{-1})	POM (mg L^{-1})	TPM (mg L^{-1})
	Time series	Time series	Time series
Environment	Current speed (m s^{-1})	T (°C)	O2 (mg L^{-1})
	0.105	Time series	8.6
Cultivation scenario	Low	Medium	High
Density (ind m^{-3})	25	100	300
Sections 1, 2, 3			
Total seed (x10^3 ind)	750	3000	9000
Total harvest (ton TFW)	1.2	3.8	7.6
Average Physical Product	0.64	0.51	0.34
Final mean Chl *a* (µg L^{-1})	8.85	8.7	8.4
Final minimum O_2 (mg L^{-1})	8.6	8.6	8.6
ASSETS score	Good	Good	Good
Income (kGBP)[14]	6	19	38
Annualised income m^{-2} (GBP)[13]	0.3	1	1.9

[13] Exact location not indicated to protect business interests.

[14] An example price of 5 GBP per kg of adult mussels was considered.

FARM™ was run for three different densities, 25, 100 (standard) and 300 seed individuals m^{-2}. The total harvest and income increases with increasing seed density, but the farm becomes progressively less profitable, as evidenced by the change in APP, which falls from 0.64 to 0.34. The low APPs are largely due to the high mortality.

Changes to culture practice in order to reduce mortality are paramount in order to improve industry profitability. As an example, the screening model was run for the standard density with an annual mortality of 20%, with the result that the total harvest increases to 14.5 tonnes and the APP is now 1.93, making the business significantly more competitive.

Figure 70 additionally shows that higher seed densities result in a lower chlorophyll concentration, i.e. act to reduce eutrophication, however in these simulations all the final chlorophyll values fall in the ASSETS *Medium* category, and there is no change detected in dissolved oxygen or in the final ASSETS grade of *Good*.

The individual growth of mussels was also simulated in ShellSIM, using the same set of drivers from EcoWin2000 as used in FARM™. Here only one animal is considered, growing in 1 m^3 of water, and there is no feedback from the animal on driver concentrations (this effect would in any case be irrelevant for one animal).

Figure 71. Growth of one animal simulated in ShellSIM, using drivers from EcoWin2000.

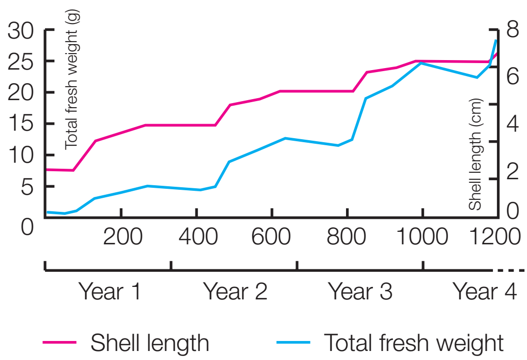
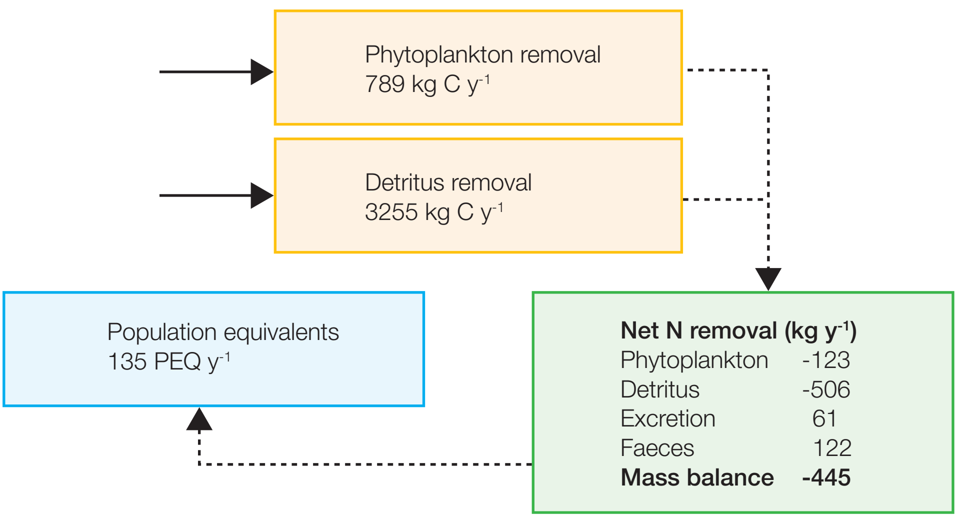


Figure 72. Mass balance for a 6000 m^2 mussel bottom lease in Carlingford Lough.



Assets

Chl *a*
O_2
Score

Annual income

Shellfish farming: 5.8 k£ y^{-1}
Sewage treatment: 27 k£ y^{-1}
Total income: 32.8 k£ y^{-1}

Parameters

Density of 100 mussels m^{-3}
1200 day cultivation period
70% mortality
3.3 kg N y^{-1} PEQ

Finally, Figure 72 shows an annualised mass balance carried out with FARM™ for the standard simulation. The mussels are responsible for a annual net removal of 445 kg of nitrogen, equivalent to the sewage discharge of 135 population equivalents (PEQ). The substitution costs of land-based nitrogen treatment (i.e. the reduction of emissions) are of the order of 25,000 pounds sterling per year, which may be considered an environmental contribution by the 6000 m^2 mussel farm. Such contributions may in the future form part of a trading system of nitrogen credits, to manage nutrient emissions at the watershed scale, thereby constituting a significant additional source of revenue to shellfish aquaculture farmers.

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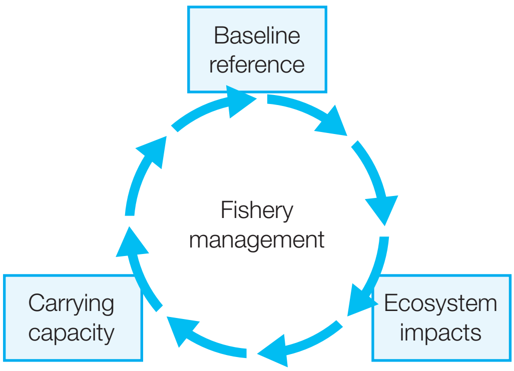
CONCLUSIONS

The five sea lough systems addressed by the Sustainable Mariculture in northern Irish sea Lough Ecosystems (SMILE) project are Carlingford Lough, Strangford Lough, Belfast Lough, Larne Lough and Lough Foyle. The project began in September 2004, had a duration of two years, and addressed four key objectives.

SMILE OBJECTIVES

- To establish functional models at the lough scale, describing key environmental variables and processes, aquaculture activities and their interactions
- To evaluate the sustainable carrying capacity for aquaculture in the different loughs, considering interactions between cultivated species, targeting marketable cohorts, and fully integrating cultivation practices
- To examine the effects of overexploitation on key ecological variables
- To examine bay-scale environmental effects of different culture strategies



These four objectives together provided a foundation for sustainable fishery management. The baseline results supply reference conditions to manage against. Evaluation of both carrying capacity and ecosystem impacts included consultation with stakeholders, to ensure an integrated management approach.

The key outputs of SMILE are presented in this book, which begins with a brief introduction to carrying capacity assessment, and to the northern Ireland sea loughs, and follows with a further five chapters. Every effort has been made to make each chapter readable on its own, by including the basic components of the theme, from concepts to methods and results. The Tools chapter provides an overview of the techniques used for the different parts of the work. A summary of the key outputs and findings of SMILE are presented below.

- Problem definition and objectives
  Carrying capacity for shellfish culture
- Tools
  Summary of tools used in SMILE
- Spatial domain
  Spatial description of the five SMILE loughs
- Shellfish
  Outline of experimental work, development of individual growth models and validation
- Carrying capacity assessment
  Description of modelling work, together with results for the five loughs
- Management
  Analysis of model outputs, development scenarios and environmental sustainability

DATA

Over 185,000 records of data for the five loughs were archived in relational databases during the project. These are available online, and contain variables ranging from water and sediment quality to biological species lists, collected over the past 22 years. These data were the foundation for the work that has been developed, and are an important reference collection of historical information on which future monitoring and research activities may build.

SPATIAL DOMAIN

The bathymetry and morphological features of the systems were integrated into GIS projects, together with spatial information on shellfish aquaculture areas, species distribution, water quality and sediment sampling locations. GIS was used to superimpose various features such as morphology, system uses and water body limits to define boxes used in EcoWin2000 for carrying capacity modelling, as illustrated in the example opposite for Strangford Lough (Figure 74).

Together, the five loughs have an area of 522 km^2, of which about 20% is used for shellfish culture.

SHELLFISH MODELS

The majority of the revenue from shellfish culture in the SMILE loughs is derived from the blue mussel (*Mytilus edulis*) and the Pacific oyster (*Crassostrea gigas*). All Pacific oyster culture is intertidal, placing hatchery-reared juveniles within bags placed on trestles or placing half grown animals onto rubber mats to support them from sinking into soft sediments. Blue mussel seed is obtained by dredging natural beds in coastal waters, and the seed cultured either by seeding onto the bottom or by suspending from ropes, on submerged structures or rafts.

To model the complex feedbacks, both positive and negative, whereby mussels and oysters interact with ecosystem processes, measurements of physiological responses were undertaken in each species over experimental conditions that spanned the full normal ranges of food availability and composition in the SMILE loughs. Mathematical equations were then derived that define functional inter-relationships between the component processes of growth, integrating those interrelations within a dynamic model structure (ShellSIM) developed to simulate time-varying rates of individual feeding, metabolism and growth in these and other species (http://www.shellsim.com/index.html).

Figure 73. Data distribution for the SMILE loughs.

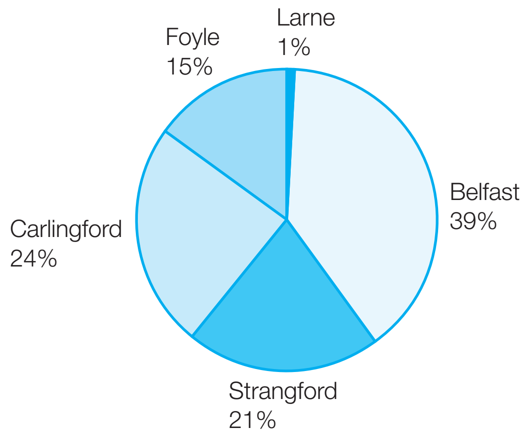
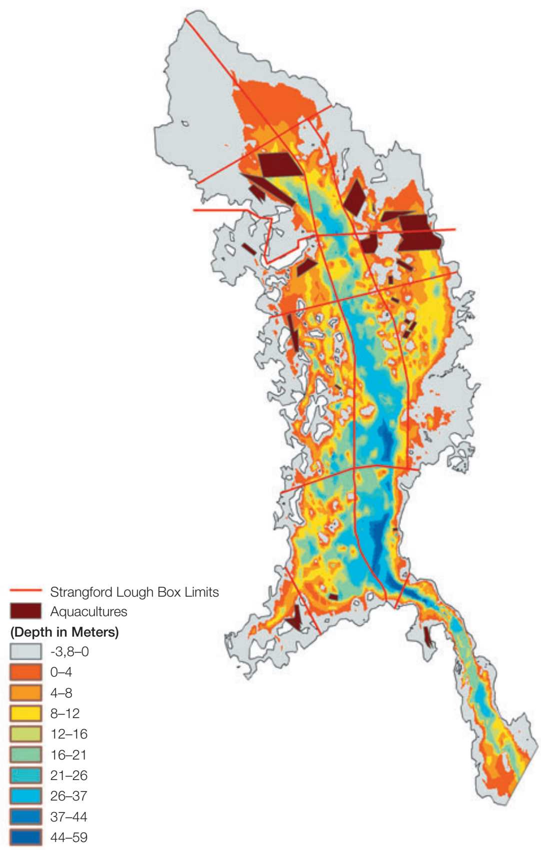


Figure 74. Box definition in Strangford Lough.



Simulations have been validated successfully using monthly field measures of environmental drivers and shellfish growth for both the blue mussel and Pacific oyster from the SMILE loughs. Model outputs confirm that ShellSIM, when run with a separate single standard set of parameters for each species, optimized upon the basis of calibrations at different sites, can effectively (± 20%) simulate dynamic responses in physiology and growth across the full range of natural environmental changes experienced within northern Irish sea loughs and elsewhere.

CARRYING CAPACITY

A short summary is given below of some of the key findings resulting from simulations carried out using the standard models developed in EcoWin2000.

Some of the aquaculture sites in the SMILE ecosystems are inactive at present, detail is required on the commercial and biological status of aquaculture sites in each lough, as well as the aquaculture type at each site (Figure 75). Areas of active aquaculture of each type were estimated and are presented in the **Shellfish** chapter.

Figure 75. Active aquaculture areas in each study site. Species cultured and type of aquaculture are also shown (NI – Northern Ireland; ROI – Republic of Ireland).

	Lough		Aquaculture		
System	**Area (ha)**	**Total active area (ha)**	**Species**	**Area (ha)**	**Type**
Carlingford Lough	4900	1063 (NI+ROI) 251 (NI)	Blue mussel	868 (NI+ROI) 168 (NI)	Bottom culture, rafts
			Pacific oyster	198 (NI+ROI) 83 (NI)	Trestles
Strangford Lough	14900	29	Blue mussel	6	Rafts
			Pacific oyster	24	Trestles
Belfast Lough	13000	953	Blue mussel	953	Bottom culture
Larne Lough	800	70	Blue mussel	10	Bottom culture
			Pacific oyster	60	Trestles
Lough Foyle	18600	1603	Blue mussel	1603	Bottom culture
			Pacific oyster	0.1	Trestles

The ShellSIM individual growth model (see the **Shellfish** chapter) was implemented and tested within the EcoWin2000 platform. Individual growth in weight and length were simulated for one mussel and one oyster in each model box where cultivation occurs (Figure 76).

With the addition of population dynamics to the individual model, changes in shellfish stock over several years can be estimated. As the shellfish culture cycle in all the SMILE loughs occurs over a three year period, the ecological model for each system needs to run for at least 6 years to produce stable simulations of harvestable biomass. Figure 77 shows the variation in (a) length and weight in mussels from box 34 in Carlingford Lough over a three year culture cycle and (b) population biomass for seeded and harvestable mussels over seven years.

An estimate of total production for both mussels and Pacific oysters in each system was carried out by running the standard models. Figure 78 illustrates the simulated production values in Carlingford Lough

Figure 76. Individual length and weight simulated in E2K for blue mussels and Pacific oysters cultured in Carlingford Lough.

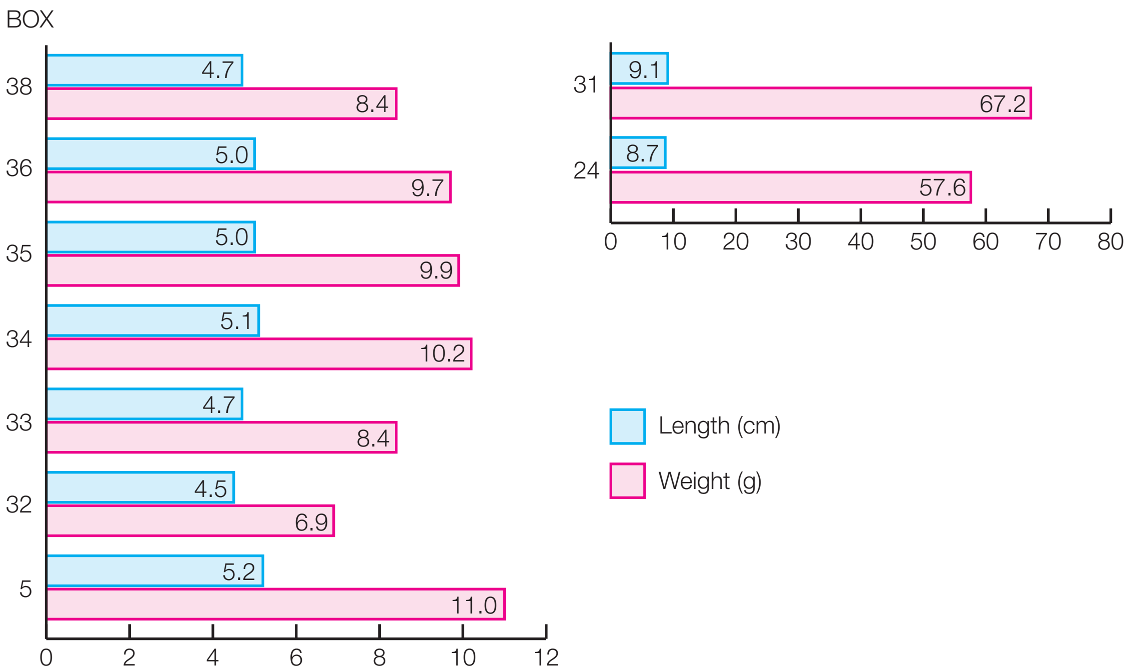
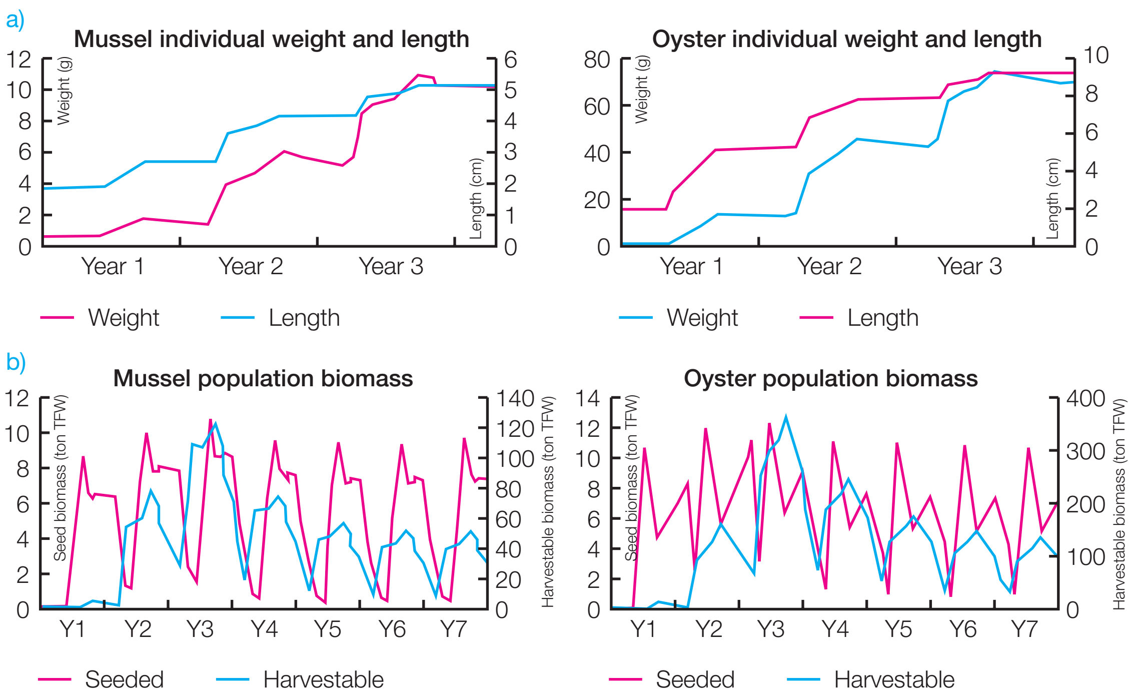


Figure 77. Results of simulations in Carlingford Lough: a) blue mussel and Pacific oyster growth in weight (g) and length (cm) during one culture cycle and b) mussel population biomass in total fresh weight (TFW) of seed and harvestable weights in boxes 31 and 34.



for a 10 year model run. The model shows production values ranging from about 2500 to 1300 tons for blue mussel, stabilising at a production of about 1300 tons, and from about 750 to 280 tons for Pacific oyster, stabilising at 280 tons.

The EcoWin2000 models were run for ten years to produce stable multi-year harvests for the five SMILE loughs, and the predictions compared with harvests recorded by Fisheries Division, Loughs Agency and Bord Iascaigh Mhara (BIM) (Figure 79).

The average physical product (APP) is defined as the ratio between harvested biomass (total physical product – TPP) and seed biomass, and is a measure of ecological and economic efficiency. In Figure 80, simulated TPP and APP are shown for Belfast Lough. Results presented correspond to year 10 of simulation, in order to show stable outputs.

Figure 78. Simulated production values for Carlingford Lough. Model was run for a 10 year period to show consistently stable harvesting results.

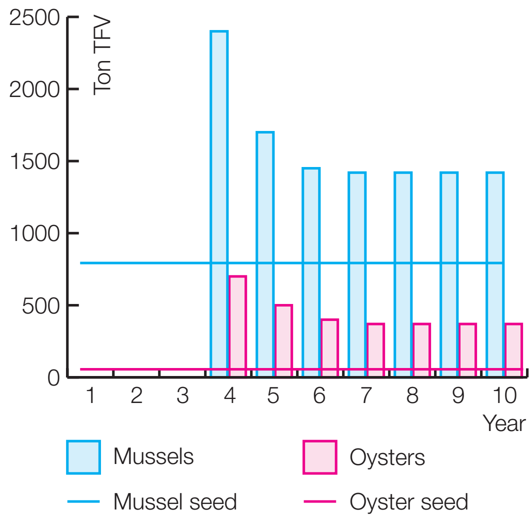
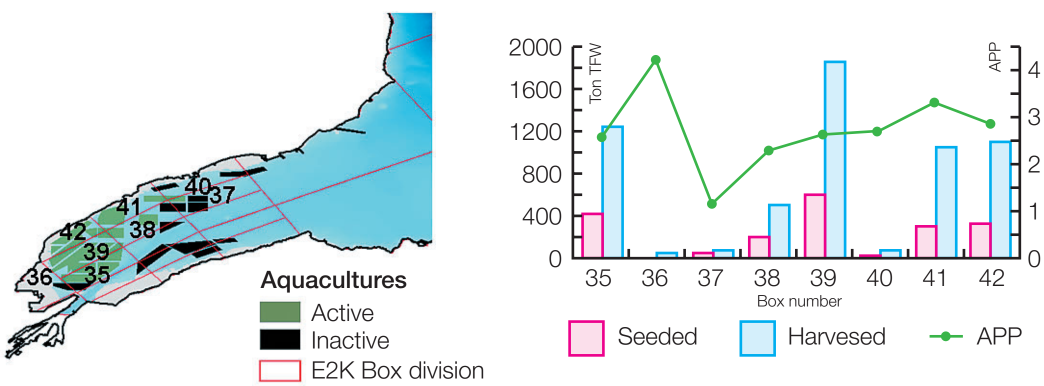


Figure 79. Production data (tons total fresh weight y^{-1}) for the five SMILE loughs and comparison with production simulations with EcoWin2000.[15]

System	Species	Carlingford Lough	Strangford Lough	Belfast Lough	Larne Lough	Lough Foyle[16]	Total
Production records	Blue mussel	1500 to 3000	2.4	10000	200	15318	27300
	Pacific oyster	365 to 868	260	-	10.4	50	820
Model simulation	Blue mussel	1300	9	6000	300	1325	8934
	Pacific oyster	280	223	-	9	12	524

Figure 80. Model results for mussel production in Belfast Lough.



[15] The production records shown were given by DARD Fisheries Division for Strangford, Belfast and Larne Loughs and by the Loughs Agency and BIM for the transboundary systems (Carlingford Lough and Lough Foyle).

[16] There are substantial uncertainties on culture practice in Lough Foyle, regarding areas, seed densities etc. SMILE model results are based on cultivation areas shown in Figure 3.

A summary of the model results for each system is shown in Figure 81. The total production per unit of area is also shown, and varies within each system depending on the location of the aquaculture.

Figure 81. Summary of model results for all SMILE systems.

Ecosystem and species		Aquaculture Area (ha)	TPP (tons)	APP	TPP per ha
Carlingford Lough	Blue mussel	868 (NI+ROI) 167.9 (NI)	1300 (NI+ROI) 320 (NI)	2.5 (NI)	1.5 (NI+ROI) 1.9 (NI)
	Pacific oyster	198 (NI+ROI) 83.2 (NI)	280 (NI+ROI) 110 (NI)	5.3 (NI)	1.4 (NI+ROI) 1.3 (NI)
Strangford Lough	Blue mussel	6	9	7	1.5
	Pacific oyster	24	223	8.4	9.5
Belfast Lough	Blue mussel	953	6000	2.8	6.3
Larne Lough	Blue mussel	10	300	3.3	28.8
	Pacific oyster	60	9	14	0.15
Lough Foyle	Blue mussel	1602	1325	2.5	0.83
	Pacific oyster	0.1	12	6.9	171

MANAGEMENT

SCENARIOS

Scenarios to exemplify the use of system-scale carrying capacity models

Three scenarios were tested on different SMILE loughs to illustrate potential applications

1. Increase in the area seeded within Belfast Lough
2. Increase in water temperature in Strangford Lough
3. Partitioning of the food resource by wild species in Carlingford Lough

The first scenario was tested for Belfast Lough, where aquaculture already occupies a significant proportion of the entire system. Since there are several licensed sites in this lough which are not active at present, the EcoWin2000 model was run assuming that some of the inactive aquaculture sites had become active. The previously inactive aquaculture areas inside box 29 (see the **Spatial Domain** chapter) were considered to be active in this first scenario, with seeding densities that were the same as for the rest of the lough.

The results obtained are compared with standard model outputs per box in Figure 82, showing that an increase in seeded area affected harvested biomass, APP and mussel individual weight in the remaining boxes.

The predicted effects on aquaculture in Strangford Lough, for an increase of 1 °C and 4 °C in the water temperature are shown in Figure 83.

An increase of 1 °C in water temperature would lead to a reduction of about 10% in mussel production and less than 2% in Pacific oyster production, and an increase of 4 °C would result in a reduction of 50% in mussel production and less than 5% in oyster production. These results suggest that an increase in the water temperature would lead to a reduction in both the mean weight and mean length of individuals, although this reduction is more pronounced in mussels than in oysters for physiological reasons. As a consequence, there would be an overall decrease in aquaculture productivity.

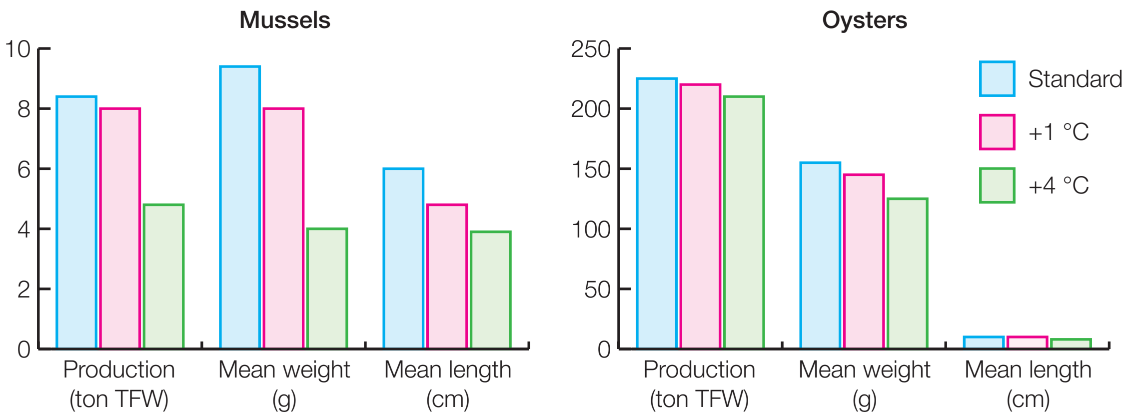
The third scenario was simulated in Carlingford Lough where a GIS resource partitioning model was applied, taking into account the average abundances of wild species per unit area. The EcoWin2000 model predicts that by taking wild filter-feeding species into account, production of cultivated species would be reduced by 19% for mussels and 13% for Pacific oysters, together with associated reductions in individual length and weight (Figure 84). Carrying capacity assessment should take place at a first stage at the system level, as has been carried out in the SMILE project. However, after this system-scale planning approach is completed, it is appropriate to evaluate the sustainability of aquaculture activities at the local scale (farm, raft etc).

A number of tools have been developed to carry out this kind of assessment, including the FARM™ model, developed by members of the SMILE team, and MUSMOD, a mussel model developed in the

Figure 82. Belfast model results for an increased seeding area. Results of the standard model are shown for comparison.

Box	Seeded		Harvested		APP		Individual weight	
	Standard	Scenario	Standard	Scenario	Standard	Scenario	Standard	Scenario
29	none	264	none	562	none	1.9	none	4.8
35	426	no change	1258	1222	2.7	2.6	9.3	8.8
36	6	no change	28	27	4.2	4.1	19.2	18.6
37	37	no change	57	56	1.4	1.4	3	2.9
38	193	no change	517	507	2.5	2.4	8.3	8
39	599	no change	1862	1841	2.7	2.7	9.7	9.5
40	19	no change	56	55	2.8	2.8	10.8	10.6
41	293	no change	1072	1062	3.4	3.3	14.3	14
42	313	no change	1114	1107	3	3.0	10.9	10.8
	1886	2150	5964	6441	3	3	11	9.8

Figure 83. Model results for the Strangford standard model and two scenarios considering an increase in the water temperature of 1 °C and 4 °C.



U.S. by Carter Newell and John Richardson. To illustrate some of the local-scale issues, this book includes two case studies:

- The first was contributed by Carter Newell, and focuses on some of the problems and approaches for farm-scale carrying capacity work, using examples from Maine, USA;
- The second applies the FARM™ screening model to illustrate how system-scale simulations carried out with EcoWin2000 can be used to analyse production at the farm scale. Suzanne Bricker, from the US National Oceanic and Atmospheric Administration, contributed to this example through the application of the AS Sessment of Estuarine Trophic Status (ASSETS) Model.

Figure 84. Scenario showing aquaculture production with and without taking into account resource partitioning in Carlingford Lough.

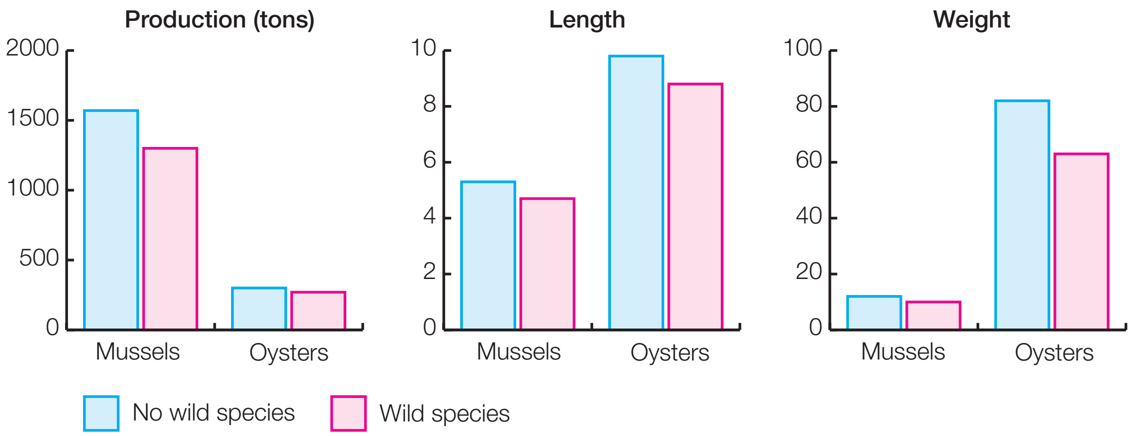


Figure 85. SMILE products and carrying capacity definitions.

Carrying capacity definition	SMILE solution
Physical	Bathymetry, morphology: GIS models
	Current speed and direction: Delft3D Model
Production	Individual shellfish growth: ShellSIM model
	Population growth: D3D-ShellSIM-EcoWin2000 framework
Ecological	Ecosystem response – plankton, nutrients: E2K Model
	Wild species, reefs: E2K-GIS resource partitioning model
	Watershed management strategies: SWAT-E2K
Social	The SMILE team has addressed this in the EU SPEAR project (China) at the system scale, and in the EU ECASA project (Europe) at the local scale using the FARM™ model. Not explicitly considered in SMILE

CONCLUSIONS

System-scale assessments of sustainable mariculture in general and shellfish culture in particular are conditioned by different definitions of carrying capacity, which may be regarded as physical, production, ecological and social. The SMILE products were desiged to address the first three of these definitions (Figure 85).

These various products were delivered to the DARD Permanent Secretary in February 2007, and have been consolidated in a bespoke website (Figure 86).

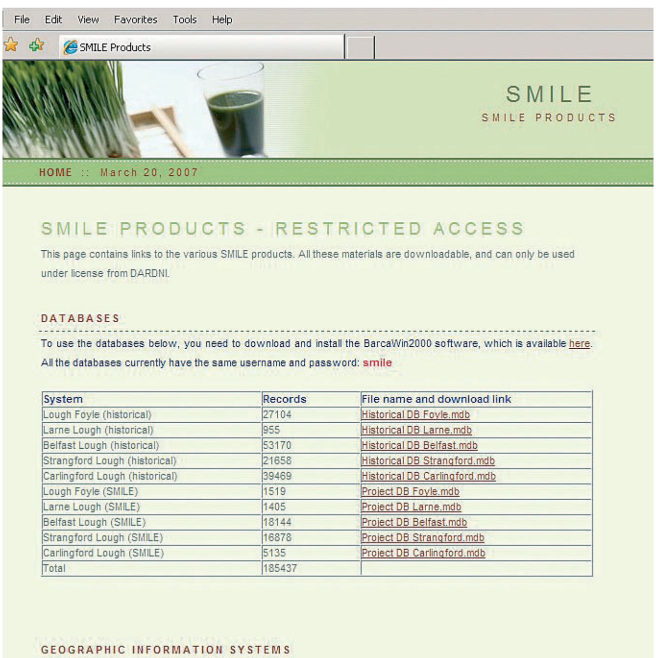
Drawing upon the process developed for application of the SMILE models, including the fundamental interrelations identified by those models, simpler screening models have been developed for eutrophication assessment and other purposes, which will help environmental managers to evaluate the effects of aquaculture on Ecological Status, as defined by the Water Framework Directive.

The modelling work developed in the SMILE project has allowed a clear link to be established between environmental variables, social aspects such as cultivation practice and shellfish production. This has empowered managers, scientists and industry through the delivery of tools which allow different development scenarios to be analysed. However, although we now understand much more about the underlying processes than at the start of this work, there are a number of improvements which will over time increase the value of the SMILE models, GIS and databases for decision support. A better understanding of cultivation practice, shellfish mortality and its variation in time and space, issues related to seed deployment and more accurate production data will greatly improve the accuracy and usefulness of these models.

The progress which was made in SMILE illustrates the potential of this approach in implementing a national programme for sustainable aquaculture, drawing on the excellent collaboration of science, management and industry, and harmonising the concerns of fisheries and environmental decision-makers, the aquaculture industry and conservation agencies.

More information on the SMILE project is available at: http://www.ecowin.org/smile/

Figure 86. Web-based SMILE product delivery.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SMILE Products

SMILE

SMILE PRODUCTS

HOME :: March 20, 2007

SMILE PRODUCTS - RESTRICTED ACCESS

This page contains links to the various SMILE products. All these materials are downloadable, and can only be used under license from DARDNI.

DATABASES

To use the databases below, you need to download and install the BarcaWin2000 software, which is available here.

All the databases currently have the same username and password: smile

System	Records	File name and download link
Lough Foyle (historical)	27104	Historical DB Foyle.mdb
Larne Lough (historical)	955	Historical DB Larne.mdb
Belfast Lough (historical)	53170	Historical DB Belfast.mdb
Strangford Lough (historical)	21658	Historical DB Strangford.mdb
Carlingford Lough (historical)	39469	Historical DB Carlingford.mdb
Lough Foyle (SMILE)	1519	Project DB Foyle.mdb
Larne Lough (SMILE)	1405	Project DB Larne.mdb
Belfast Lough (SMILE)	18144	Project DB Belfast.mdb
Strangford Lough (SMILE)	16878	Project DB Strangford.mdb
Carlingford Lough (SMILE)	5135	Project DB Carlingford.mdb
Total	185437	

GEOGRAPHIC INFORMATION SYSTEMS