Enhanced Application of the
SMILE Ecosystem Model to Lough Foyle

EASE

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EASE TEAM INFORMATION

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Foreword

The Enhanced Application of the SMILE Ecosystem Model to Lough Foyle (EASE) project was executed between 2014 and 2016, as a follow-on from work developed in SMILE **(https://longline.co.uk/smile).** The ecosystem modelling framework developed for carrying capacity assessment in Belfast Lough, Strangford Lough, Carlingford Lough, Lough Foyle, and Larne Lough had previously been applied to Lough Foyle in a simplified form, and it was therefore important to set up a more detailed simulation framework, similar to that applied in the first three systems listed.

By the second decade of this century, the River Basin Management Plans (RBMP) mandated by the EU Water Framework Directive (WFD, 2000/60/EC) were in their second cycle, and the need for explicit coupling of land-based loading to estuaries and coastal waters was extremely clear.

Although the SMILE application to Lough Foyle used a simplified approach to water circulation, it was the only one of the five systems where a hydrological model was applied to the catchment. This was the first use of the Soil and Water Assessment Tool (SWAT), developed by Texas A&M University, for carrying capacity assessment in Northern Ireland.

By the start of EASE, the project team had successfully applied this coupled modelling approach in various parts of the world and could demonstrate the benefits of including the SWAT model in a carrying capacity modelling framework. In particular, given the agricultural nature of the catchment, policy-makers and managers were provided with a key tool for relating drivers, pressure, and state.

The WFD context made this all the more important since participating nations were required to meet targets for Good Ecological Status based on a set of thresholds for Biological Quality Elements (BQE) and other parameters.

The EASE project was funded through Loughs Agency **(https://www.loughs-agency.org/)**, a transboundary organisation jointly managed by the UK and Ireland that has a specific purpose in the "conservation, management, promotion and development of the fisheries and marine resources of the Foyle and Carlingford areas."

As with SMILE, the project team was transdisciplinary and multi-institutional. The work was carried out by the Northern Ireland Agri-Food and Biosciences Institute (AFBI), Longline Environment Ltd, and Loughs Agency. This complementary team was engaged in data collection, both in the field and laboratory, experimental work on shellfish physiology, and calibration, validation, and deployment of a complex modelling framework.

Overall, the EASE project substantially advanced the state-of-the-art achieved in SMILE, both in the quality of the different models applied and in the overall framework within which they interact. As with SMILE, the fundamental goal was to provide the tools developed to the contracting agencies, enabling these to use the models to address practical management questions.

The approach used, results obtained, and policy-relevance of EASE are the object of this book, which is divided into six chapters, designed to be read separately if appropriate, and which include examples of scenario analysis, for instance of different land-based nutrient loading alternatives, aquaculture development strategies, and eutrophication control.

List of Abbreviations

AFBI	Agri-Food and Biosciences Institute
APP	Average Physical Product
ASSETS	Assessment of Estuarine Trophic Status
ASSI	Area of Special Scientific Interest
BIM	Bord Iascaigh Mhara (Ireland's Seafood Development Agency)
BQE	Water Framework Directive's Biological Quality Elements
DAERA	Department of Agriculture, Environment and Rural Affairs
DARD	Department of Agriculture and Rural Development
DCCAE	Department of Communications, Climate Action and Environment
DIN	Dissolved Inorganic Nitrogen
DRP	Dissolved Reactive Phosphorus
EASE	Enhanced Application of the SMILE Ecosystem Model to Lough Foyle
EHS	Environment and Heritage Service
FARM	Farm Aquaculture Resource Management model
FCILC	Foyle, Carlingford and Irish Lights Commission
IMP	Integrated Marine Plan for Ireland
LA	Loughs Agency
MinP	Mineral Phosphorus
NAP	Nitrates Action Programme
NPP	Net Primary Production
NSMC	North South Ministerial Council
NWP	Numerical Weather Prediction model
POM	Particulate Organic Matter
RDCP	Recording Doppler Current Profiler
RMS	Root Mean Square
SAC	Special Area of Conservation
SMILE	Sustainable Mariculture in northern Irish Sea Loughs
SPA	Special Protection Area
SRP	Soluble Reactive Phosphorus
SWAT	Soil and Water Assessment Tool
TPM	Total Particulate Matter
UKHO	UK Hydrographic Office
UWWTD	Urban Waste Water Treatment Directive
WFD	Water Framework Directive
WWTW	Waste Water Treatment Works

Executive Summary

Executive Summary

The EASE project was developed to determine the carrying capacity and sustainable expansion of shellfish aquaculture in Lough Foyle. The issue is complex because it deals with provisioning services (i.e., goods), as well as regulatory and support services (i.e. environmental services).

Moreover, as in any multi-use environment, important social aspects are at stake, including conservation of wild species, fisheries, and tourism.

The environmental services of mussel and oyster culture include provisioning of habitat for other species, enhancing biodiversity, but also the reduction of phytoplankton concentrations.

This reduction provides positive environmental externalities by: (i) increasing transparency, and therefore indirectly promoting oxygenation of bottom waters; and (ii) 'short-circuiting' the organic decomposition cycle—phytoplankton is removed before the cells can die naturally, thus curtailing the second stage of eutrophication.

The drawdown of chlorophyll contributes to the compliance with thresholds for the Water Framework Directive's Biological Quality Elements (BQE), particularly with respect to phytoplankton biomass and abundance, and increased transparency may also contribute to an improvement in composition and abundance of other aquatic flora such as seagrasses.

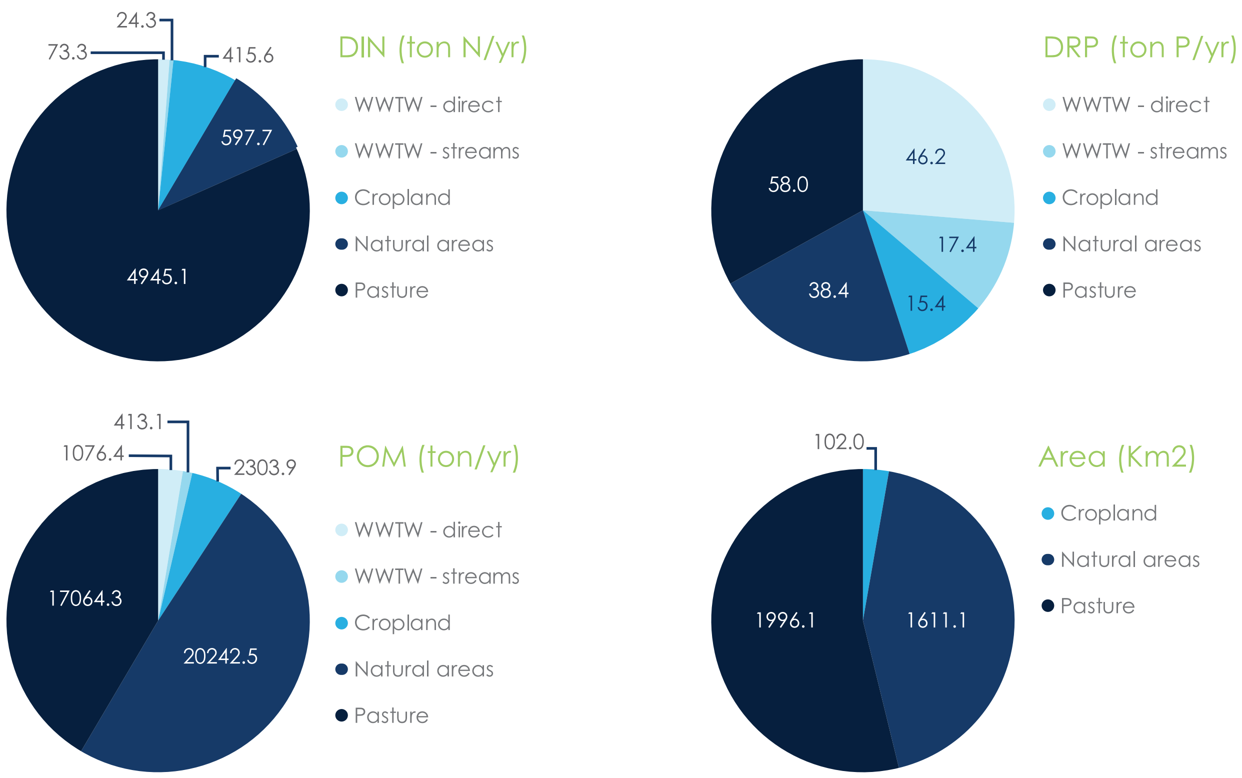


Fig. 1 SWAT estimates for sources of Dissolved Inorganic Nitrogen (DIN; upper left), Dissolved Reactive Phosphorus (DRP; upper right) and Particulate Organic Matter (POM; lower left) in 2014, for the sum of Lough Foyle and River Foyle; and land use in the Foyle catchment

The application of catchment models in EASE suggests that nutrient loading into Lough Foyle is mostly associated with agricultural activities such as pasture and natural areas (Fig. 1). As a consequence, the implementation of source control measures to deal with potential non-compliance of the Lough under the Water Framework Directive (WFD) would need to focus mainly on changes to land use, rather than discharge control e.g. through urban wastewater treatment.

Controls of diffuse inputs are difficult, expensive, and if they affect the established way of life of human populations, may have significant social consequences. The holistic management of potential eutrophication symptoms by including a burgeoning shellfish industry in the lough allows traditional catchment activities to flourish while taking advantage of the full range of ecosystem services supplied by bivalve filter-feeders.

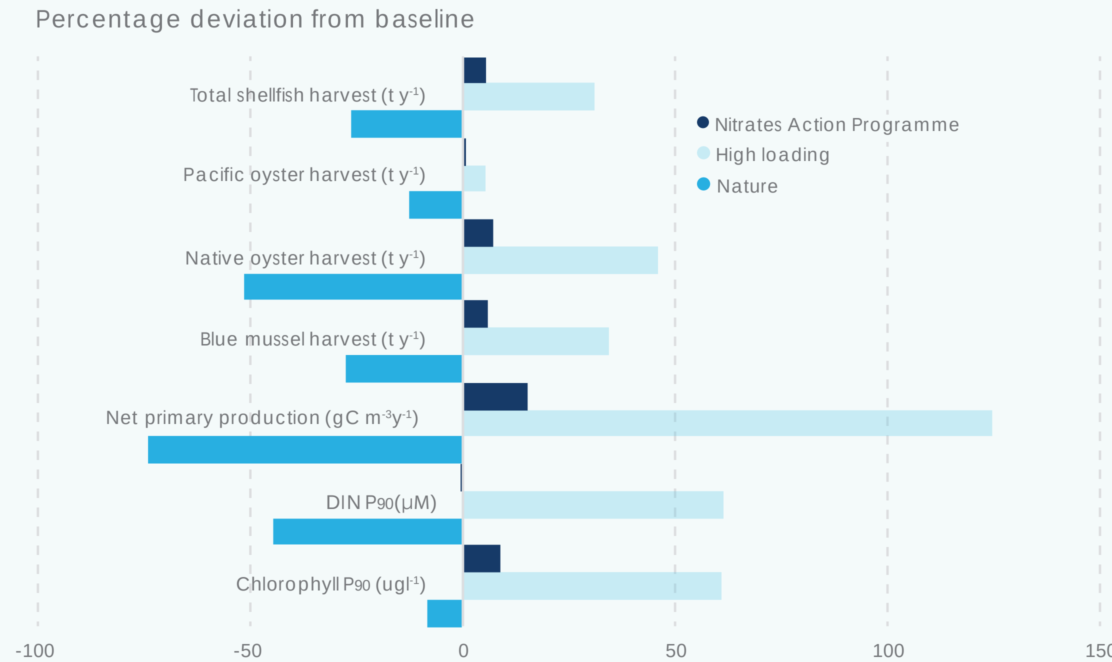


Fig. 2 Percentage change in indicators for eutrophication and shellfish performance for three different scenarios in Lough Foyle.

Two scenarios were examined in EASE, in order to exemplify how the modelling framework can be used in practice to support policy. Various alternatives for nutrient loading showed for instance that the application of the Nitrates Action Programme, which constrains the application of slurry in the early part of the year to avoid nutrient leakage to surface waters, actually results in higher net primary production (Fig. 2), possibly because the slurry release in later months provides a nutrient subsidy for plankton growth at a time when there is more sunlight and a longer diurnal cycle.

A second scenario examined the effects on chlorophyll concentration of bottom-up land-based nutrient control and top-down control by filter-feeding oysters and mussels cultivated in the lough. The use of an ecological model at the system scale showed the effects of changes in phytoplankton biomass (one of the WFD BQEs) with varying shellfish stocking densities, and allowed the calculation of the relative cost of unit reduction of chlorophyll (e.g. by 1 µg L^{-1}) using different management strategies (or combinations of both types of eutrophication control).

I. The EASE Project

Carrying Capacity and the Ecosystem Approach

At a national level, the UK/NI and Irish Governments view the marine environment as an important asset which offers significant potential for marine enterprises. There is an increasing emphasis from both jurisdictions on harnessing this blue growth and this has been recognised in a number of National Strategies, primarily the UK Marine Science Strategy and the Irish Government's Harnessing Our Ocean Wealth: An Integrated Marine Plan for Ireland (IMP). Both jurisdictions insist that growth must be achieved in an environmentally sustainable manner, as it is recognised that anything less will have severe effects on commercial productivity and potentially ecosystem health.
Loughs Agency's wider aims is "to provide sustainable social, economic and environmental benefits through the effective conservation, management, promotion and development of the fisheries and marine resources of the Foyle and Carlingford Areas" to support the development of the marine environment for environmentally sustainable marine enterprises.

The sustainable expansion of aquaculture and bivalve harvesting industries are widely acknowledged as important components in the development of marine enterprise in Ireland and Northern Ireland. In order to forecast the availability of resources in coastal ecosystems and their subsequent ability to sustain future aquaculture and bivalve harvesting, a methodology for predicting environmental capacity is required. The determination of the carrying capacity of the ecosystem is thus crucial to managing the growth of the sector. Assessment of carrying capacity prior to the establishment of large-scale shellfish cultivation will help to inform managers and ensure an adequate food supply for the anticipated production while avoiding or minimising any negative ecological impacts.

Development of the EASE project

In 2004, the SMILE (Sustainable Mariculture in northern Irish Sea Loughs) project was initiated by the Department of Agriculture and Rural Development (DARD) to "develop dynamic ecosystem-level carrying capacity models for the five northern Irish sea loughs". SMILE was completed in 2007 and provided a set of tools that could be used to assist in the management and development of the aquaculture sector and a methodology to examine the environmental effects of the aquaculture industry in the five Northern Ireland Sea Loughs.

Due to funding constraints and uncertainty over shellfish management at the time of the original SMILE project, the Lough Foyle model was not prioritised. Instead, a simple one-dimensional hydrodynamic model was developed for the lough based on salinity gradients as well as information gathered from industry and government sources. The SMILE Foyle model, therefore, lacked the detail of those developed for the other four sea loughs. The introduction of legislation for the management of the European flat oyster (*Ostrea edulis*) by Loughs Agency (LA) in 2008 and the availability of funds in 2014 offered an opportunity to finally complete the model and bring it into line with the Carlingford Carrying Capacity Model, which was developed as part of SMILE. A contract was offered by Loughs Agency to the Agri-Food and Biosciences Institute (AFBI) and Longline Environment Ltd. to undertake the delivery of this project.

1 The functions of the Department of Agriculture were transferred to the Department of Agriculture, Environment and Rural Affairs from 9th May 2016.

Loughs Agency

Loughs Agency is an agency of the Foyle, Carlingford and Irish Lights Commission (FCILC), established as one of the North South Implementation Bodies under the Good Friday/ Belfast Agreement, constituted under the North South Cooperation (Implementation Bodies) (Northern Ireland) Order 1999 and the British Irish Agreement Acts 1999 and 2002. The Board of Loughs Agency report to the North South Ministerial Council (NSMC) and Northern Ireland government Sponsor Departments – the Department of Agriculture, Environment and Rural Affairs (DAERA) in Northern Ireland and the Department of Environment, Climate and Communications (DECC) in Ireland.

Loughs Agency aims to provide sustainable social, economic and environmental benefits through the effective conservation, management, promotion and development of the fisheries and marine resources of the Foyle and Carlingford areas. Loughs Agency's statutory functions are as follows:

01 Promotion of development of Lough Foyle and Carlingford Lough for commercial and recreational purposes in respect of marine, fishery and aquaculture matters;

02 Management, conservation, protection, improvement and development of the inland fisheries of the Foyle and Carlingford areas; Development and licensing of aquaculture and shellfisheries;

03 Development of marine tourism.

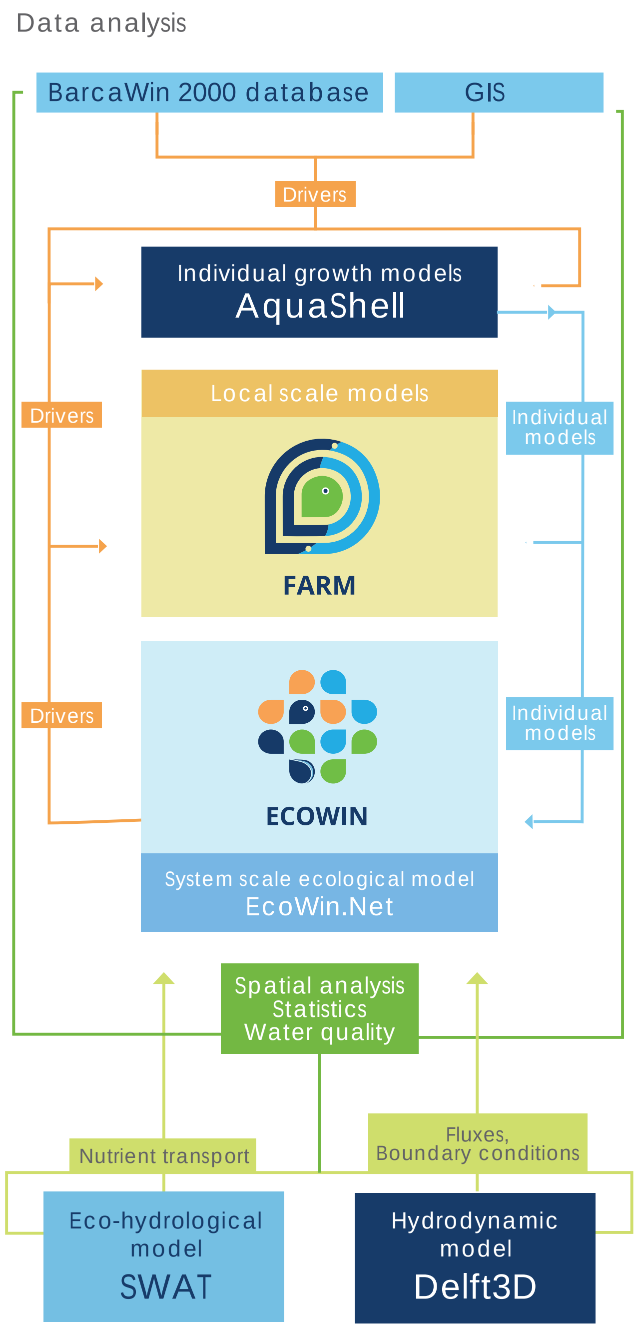
Scope and Objectives of EASE

In 2010, Loughs Agency developed the Aquaculture and Shellfisheries Management Strategy for Lough Foyle and Carlingford Lough. The overall objective of this strategy aims to achieve the sustainable development of aquaculture and shellfisheries activities for the social, economic and environmental benefit of the communities, who influence, enjoy and depend on these resources.

As part of the Management Strategy, Loughs Agency committed to the development of the Wild Shellfish and Aquaculture Management Plan for the Lough Foyle and Carlingford Lough catchments. The objectives of this management plan are to promote sustainable wild shellfish and aquaculture industries based on the best scientific information and ensure a balance between economic and environmental considerations. The Management Plan proposes mechanisms to bring forward an environmentally sustainable system of management for aquaculture and shellfisheries in the Foyle and Carlingford areas and encompasses several methodologies including the development of carrying capacity models.

The scope of the EASE project was to make improvements and additions to the SMILE model with the overall aim of providing a model to aid sustainable fishery management. The application of the EASE model will allow managers and policymakers the opportunity to investigate the potential impact of decisions in advance, thus providing a vital tool in ensuring that the development of shellfish and aquaculture is carried out in an environmentally sustainable manner. EASE builds on the SMILE project, with the inclusion of components such as integrated catchment management and local-scale simulation of shellfish culture.

Fig. 3 General modelling framework for the EASE project.



EASE Objectives

To enable Loughs Agency to have an integrated coastal zone management framework, bringing together catchment pressures, aquaculture activities in the loughs and offshore exchanges. This framework will enable managers to address relevant issues associated with the WFD and the Habitats Directive, and potentially also the Marine Strategy Framework Directive;

- To provide tools for aquaculture management both at the system-scale and at the farm-scale;
- To make improvements to the existing SMILE models for Foyle, with a focus on
  (i) improved simulation of water circulation; and
  (ii) more accurate representation of the role of wild species;
- To explicitly simulate the catchment processes through the use of detailed hydrological models.

EASE Application

- Enable managers to simulate the growth and environmental effects of culture of oysters and mussels in Lough Foyle;
- Provide indicators of performance for the shellfish industry with respect to yields, income, and impact;
- Allow decision-makers to analyse different development scenarios for the shellfish industry in the context of changes in cultivation areas, stocking densities, and multiple water uses;
- Examine the interactions between catchment-scale pressures such as nutrient discharge, which are linked to urban and agricultural drivers, and the performance of cultivated species in Lough Foyle.
- This is achieved through the framework shown in Fig. 3, which is discussed in detail in subsequent chapters of this book. The modelling elements of this framework were all delivered to EASE, but their use requires different levels of training. The successful application of EASE in the years to come very much depends on an effective legacy program.

Loughs Agency

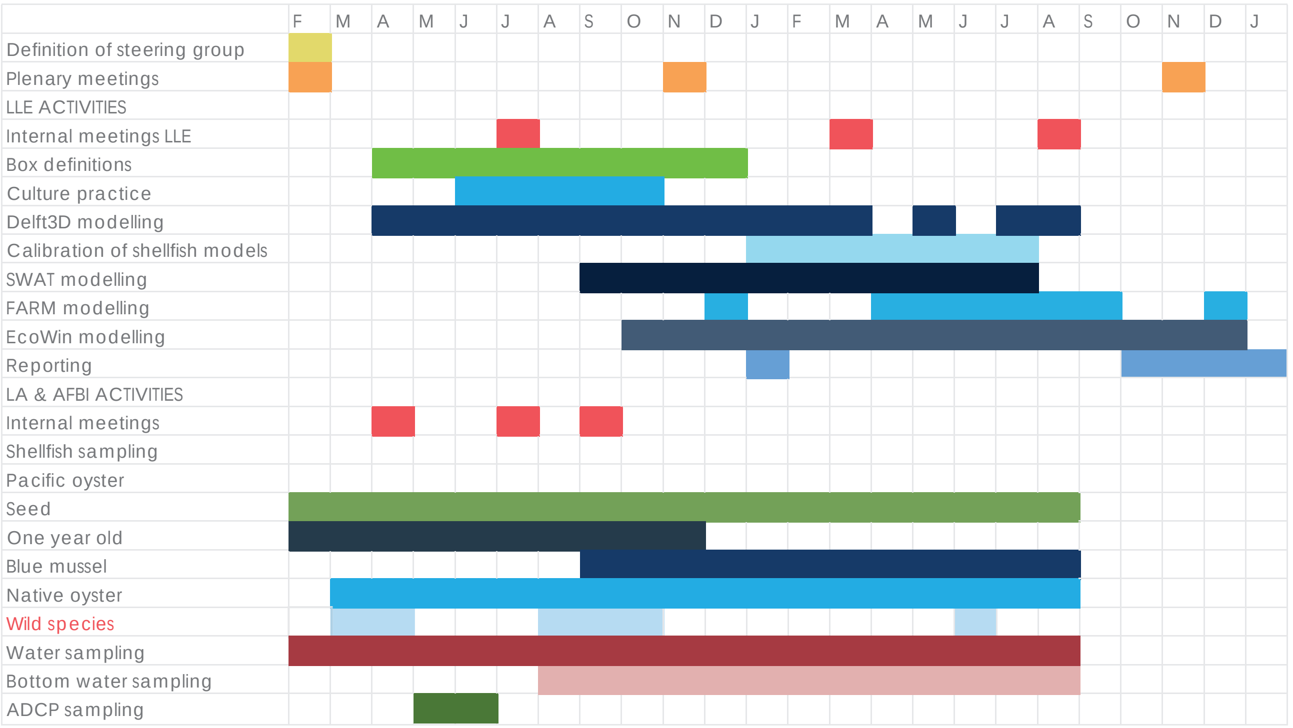


Table 1 Chronogram of activities in EASE.

In order to build, calibrate, and validate these models, a number of tasks were executed (Table 1) over a two-year period. These included field data acquisition, in situ and laboratory experiments, and software development and application, and were performed by the transdisciplinary EASE team.

Key References

Charlesworth, M., Service, M., Taylor, J.E., 1999. Nutrient Inputs and Trophic Status of the Foyle Estuary and Lough. Report to the Environment and Heritage Service (NI). 96 pp

Service, M., Durrant, A.E., Faughey, D., Millis, J.A., Taylor, J.E., 1998. Sources of nutrient inputs to the coastal waters of Northern Ireland. In: Wilson, James G. (Ed.), Eutrophication in Irish Waters. Royal Irish Academy, Dublin Chapter.

II. Tools

General Framework

EASE was developed as a multi-model framework (Fig. 3): each model has a number of intrinsic uses and addresses different management challenges; the coupling of these models allows the whole set to be leveraged as an improved holistic decision-support tool (Table 2).

Table 2 Models, scope of application, and deliverables.

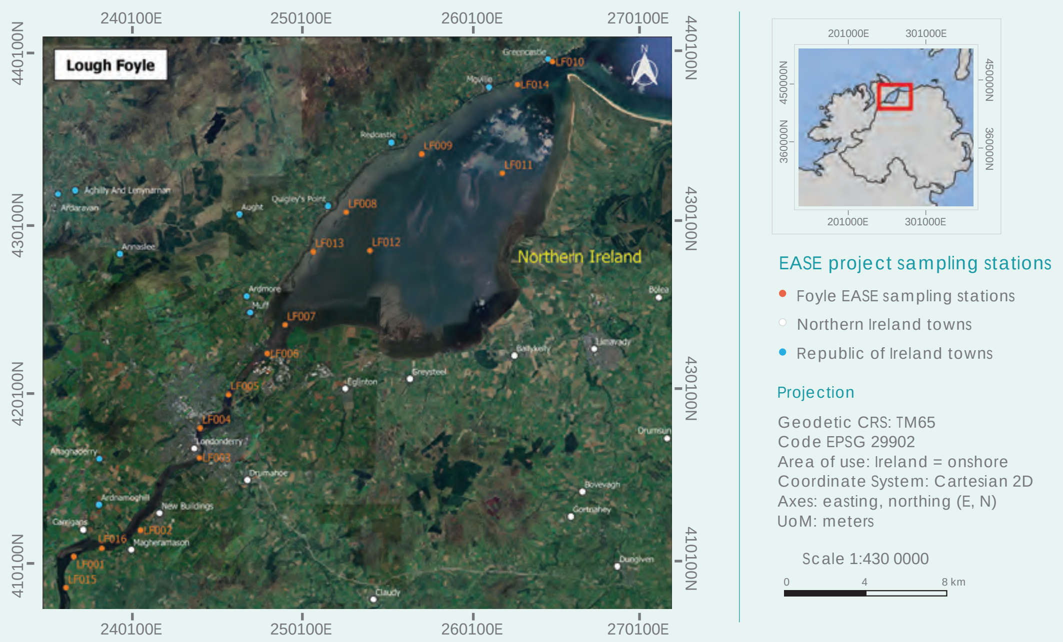
Name	Scope
Soil and Water Assessment Tool – SWAT	Catchment loading of water, nutrients, organic matter, and solids
Delft3D-Flow - 3D hydrodynamic model	3D detailed circulation within the Lough
AquaShell - Shellfish individual growth model	Individual growth and environmental effects of native oyster, Pacific oyster, and blue mussel
Ecosystem carrying capacity model – EcoWin.NET	System-scale carrying capacity for the Lough, including relevant biogeochemistry
Farm Aquaculture Resource Management model – FARM	Local-scale population growth and environmental effects, economic optimization

Supporting Tools

Field and laboratory work

An eighteen-month field sampling programme was established to collect the data required to drive the multi-model framework. Details of the programme are described below. Updated environmental driver data was required for water chemistry, shellfish growth patterns, and husbandry.

Fig. 4 Location of sampling stations.



Water chemistry

Monthly water chemistry samples were collected during spring and neap tides at 11 sites located in Lough Foyle—sampling took place from January 2014 to August 2015 (Fig. 4).

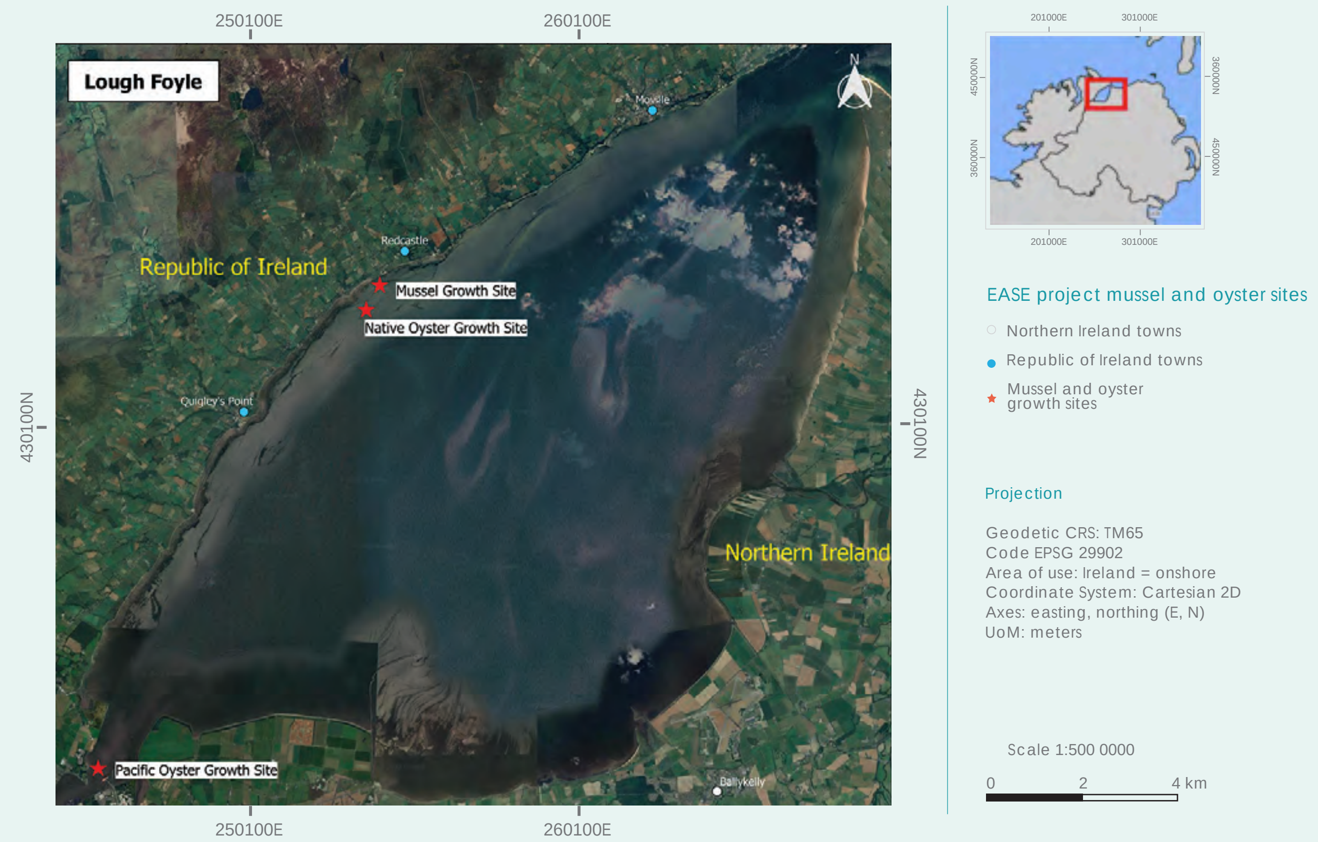
The sampling stations selected have been used as sentinel water sampling sites, first identified in the Foyle trophic status report (1999) and subsequently sampled during the SMILE project (2005 – 2007). Samples from January 2014 to August 2014 were surface samples only. From August 2014 to August 2015, the sampling regime was expanded to include surface samples taken at 1 m below the surface and samples from the bottom collected 1m above the seabed.

All samples were processed for chlorophyll, dissolved nutrients (ammonia, nitrite, nitrate, phosphate, and silica), C:N ratio and suspended particulate matter (SPM). A Seabird 19plus CTD was used synoptically to measure salinity and temperature; CTD profiles were binned at 0.5 m intervals. In addition to the monthly sampling regime, two 12-hour sampling regimes were carried out (tidal cycles at spring and neap tide) with samples collected every two hours.

Shellfish growth trials

Growth trials were undertaken for the three main commercial shellfish species produced in Lough Foyle. This growth data was used used to develop individual shellfish models, which provide the physiological component of the ecological models.

Fig. 5 Location of sampling stations for shellfish growth trials.



Target species

In Lough Foyle three shellfish species are harvested on a commercial scale:

- N Native (or European) oyster (*Ostrea edulis*)
- B Blue mussel (*Mytilus edulis*)
- P Pacific oyster (*Magallana gigas*)

Sample sites

Shellfish growth trials were conducted at three locations within Lough Foyle and growth data were used to validate the shellfish ecophysiological models (Fig. 5). The growth trial sites were selected based on site accessibility, historical cultivation, and the best fit representation of the growing areas for each of the three species.

N Native oyster growth trials

The native oyster seed was sourced in February 2014 from Viking Fish Farms' Ardtoe Hatchery in Scotland—the mean weight was 0.19 g and the mean length was 15.2 mm. The native oyster seed was grown in Ortac™ cages purchased from Jersey Sea Farms. The cages were mounted on purpose-built steel frames and deployed sub-tidally, suspended half a meter above the seabed.
The cages were allowed to swing on the frame with the tide, which created an upwelling effect within the c.

The cages were designed to minimise biofouling, permitting consistent water flow. Although the Ortac™ system may not be an exact representation of the commercial growout on the seabed, it was deemed the best available method to maintain experimental continuity. In Lough Foyle, commercial harvesting of native oysters is carried out by dredging from naturally occurring wild lays on the seabed. The growth trials were set up using the subtidal Ortac™ cages to allow for replication of sampling during the growth trials, to reduce predator interactions, and to protect the sample stock from fishing pressure.

Ortac™ cages were deployed in March 2014, 200 g of seed were placed in each cage and a monthly sample of shellfish (n=30) was collected Between April 2014 and September 2015. Length, width, depth, total wet weight, wet flesh weight, dry flesh weight, and total dry mass were recorded. Water chemistry samples were taken synoptically from the adjacent sentinel water chemistry site LF9. The initial batch of native oysters from Ardtoe Hatchery was fully depleted by April 2015. A second batch of native oysters was collected from the wild fishery in Lough Foyle and deployed in the Ortac™ cages. The second batch of native oysters had a similar mean weight and length to the April 2015 stock in the cages and the growth trial was continued with this wild stock.

[2]Pacific oyster, *Magallana gigas*, underwent a recent taxonomic change to a genus which was introduced subsequently to the research (Salvi et al., 2014). The species was formerly placed in the genus Crassostrea and denominated Crassostrea gigas. This taxonomic name is still accepted as an alternate representation.

B Blue mussel growth trials

Blue mussels were sampled from an actively maintained, commercial bottom-grown aquaculture site within Lough Foyle. The mussel stock on this culture plot was imported from the Irish Sea in September 2014 and the stock was subjected to standard cultivation and husbandry practices by the aquaculture site owner. Approximately 60 tonnes of mussel seed had been relayed on the aquaculture site and growth trial samples were collected from a commercial mussel dredge deployed at random locations across the site.

The blue mussel growth started in September 2014, an initial sample of the relayed seed (n=300) was collected to examine the variability and range in individual lengths (5 to 35 mm, with a mean length of 25 mm). Monthly samples of 30 mussels were collected for the duration of the growth trial, with a final sample collected in November 2015. Length, width, depth, total wet weight, wet flesh weight, dry flesh weight, and total dry mass were recorded. Corresponding water chemistry samples were taken from neighbouring water chemistry site LF9.

P Pacific oyster growth trials

Monthly samples were collected from a commercial oyster trestle site in Lough Foyle for the Pacific oyster growth trial. The oyster spat originated from a hatchery in France, the juvenile oysters were placed in labelled plastic oyster bags (pouches) with a mesh size between 4-20 mm depending on the size of the oysters. Pacific oysters were sampled from two age cohorts, the oysters were maintained as commercial stock and were subjected to standard cultivation practices and pressures.

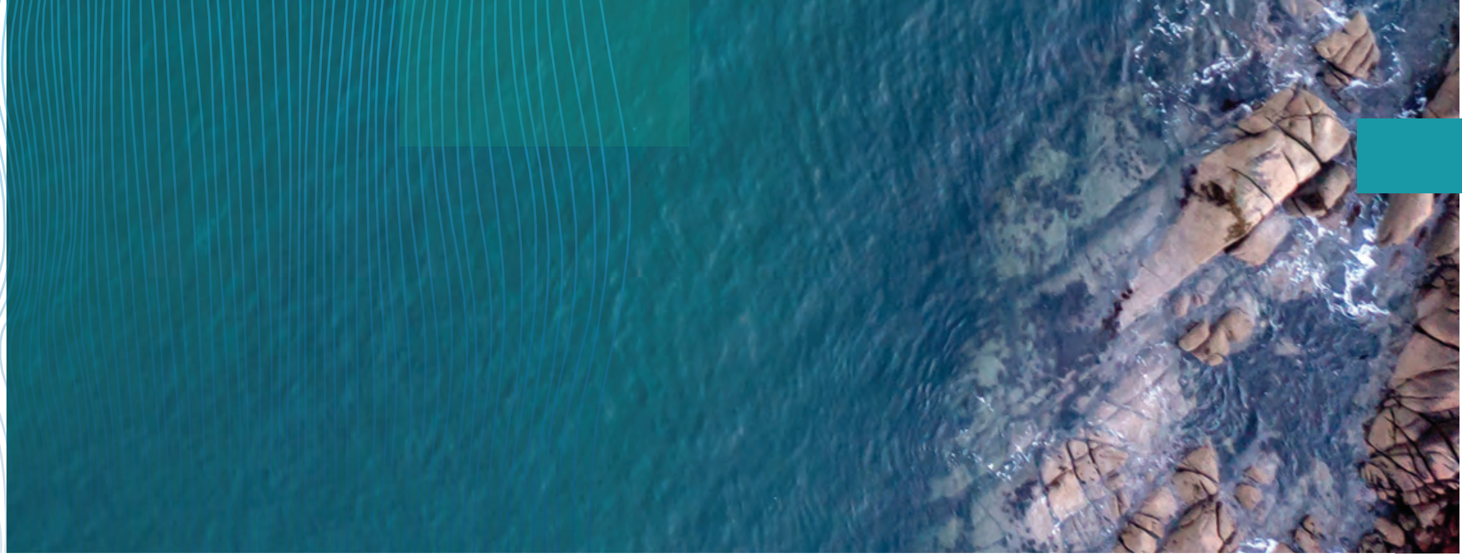
Once the cohorts reached the market size they were harvested and sampling ceased.

A sample of 30 Pacific oysters was collected each month for the duration of the growth trial. Length, width, depth, total wet weight, wet flesh weight, dry flesh weight, and total dry mass were recorded. Synoptic water chemistry samples were collected from the adjacent water chemistry site LF6.

Shellfish culture practice

Information on local shellfish cultivation practices was required to populate the EcoWin model and local-scale model (FARM) with site-specific data. Collation of data was achieved through stakeholder engagement, i.e. consultation with the local shellfish producers and licensed fishermen and dealers. The information was amalgamated for the three main commercial shellfish species in the Lough. The culture practice shown in Fig.6 presents a generalized view of the cultivation of these species; at an individual level there will be variation in seed and harvest weights within the cultivation area and between producers.

Seed size for blue mussel and Pacific oyster is dependent on multiple factors. Seed size for blue mussel varies depending on the seed source, the official opening of the seed mussel fishing season as prescribed by the department and local productivity, while seed size for Pacific oysters is determined by the production strategy and can therefore be affected by site productivity, predicted mortality levels, and seed costs.



The native oyster fishery is a wild fishery. As such it is self-propagating and there is no 'seed' stocking size. Harvest size is controlled, with a minimum landing size of ≥ 80mm for the native oyster. Harvest size for the other cultivated species is determined by market demands—for example, mussels for the Bouchot are being sold at the market at a smaller size.

Harvest price for all species is variable and depends on market demand. Market demand can be affected greatly by production levels for all species in other countries importing Irish and UK products to make up for any shortfall in their national supply.

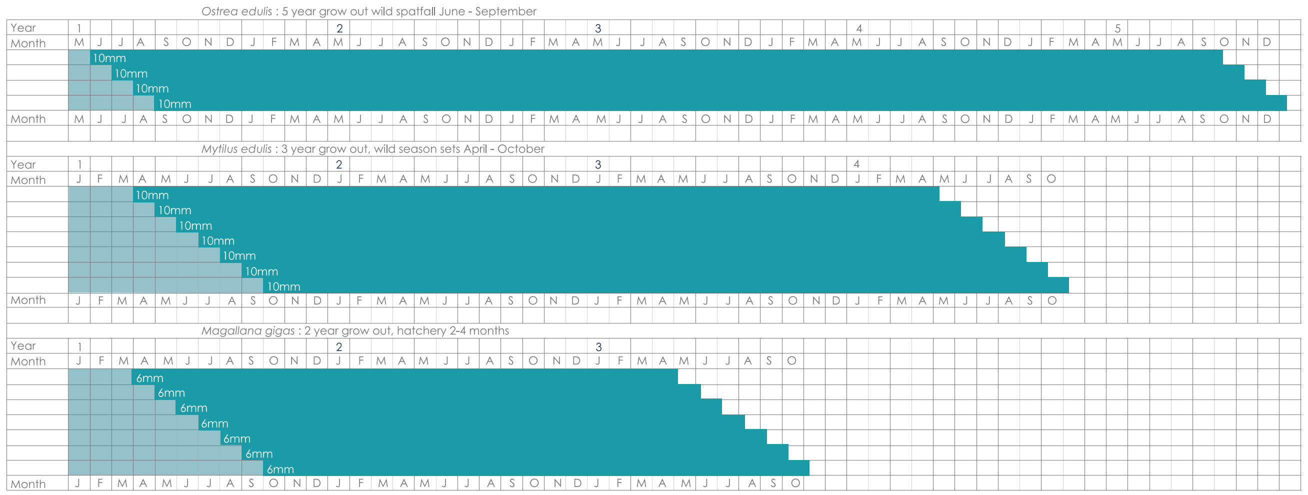


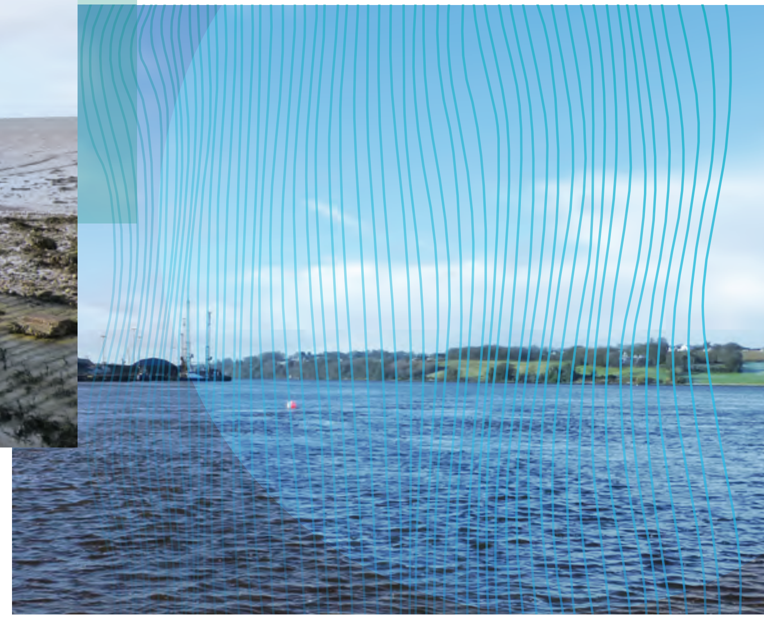
Fig. 6 Generalised view of cultivation practice for (i) *Ostrea edulis*, (ii) *Mytilus edulis* and (iii) *Magallana gigas*.

Database

Water quality data and results from shellfish growth trials were organised and formatted into a common structure and stored in a relational database framework (Table 3). The database serves as a permanent repository, ensuring that the data and associated metadata are safely preserved. The BarcaWin™ software used to build the database delivers a number of search operations to facilitate full dataset interrogation: these include synoptic variable listing, identification of trends and hotspots, and calculations of derived variables such as the Redfield ratio, using built-in algorithms.

Table 3 Data tables and volumes stored in the EASE relational database

Table	Number of records
Sampling stations	16
Samples	1882
Parameters	39
Results	7506
Total (includes records for other ancillary tables)	9522



Management Tools

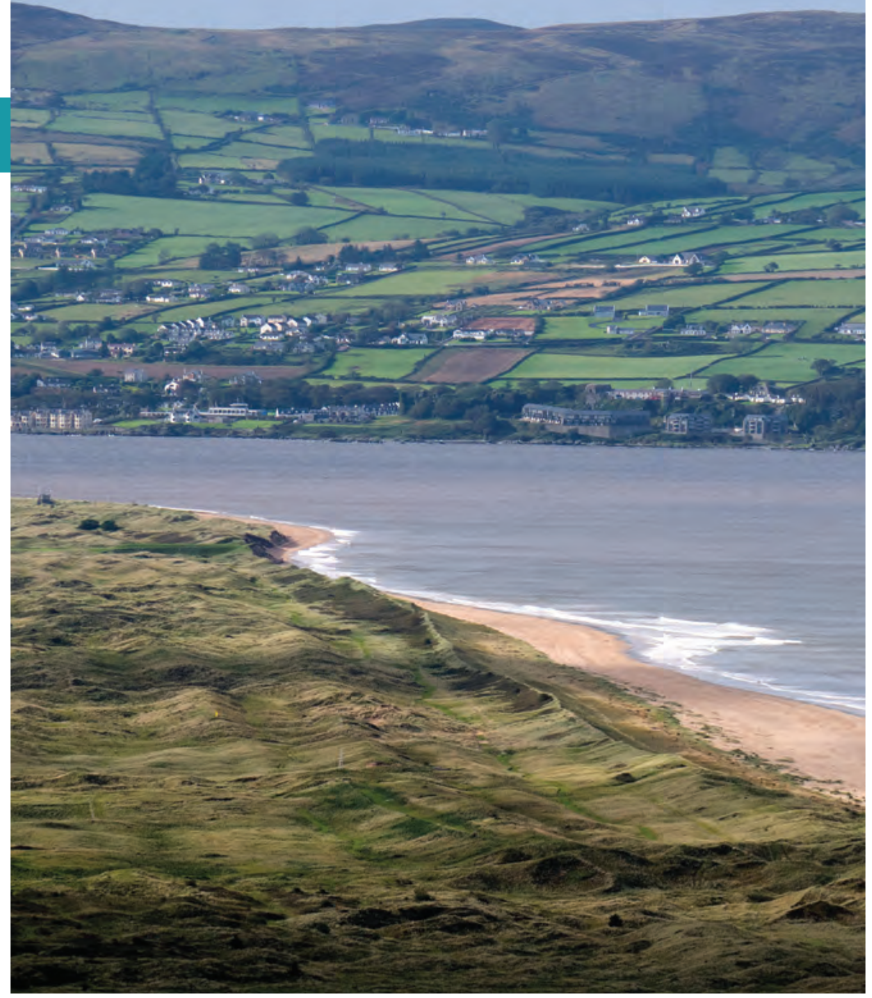
Geographic Information Systems

A Geographical Information System was built for Lough Foyle based on information supplied by LA, including:

- Mussel lay areas (2004, 2007 and 2014);
- Wild oyster beds (2014);
- Oyster density in beds based on survey points (2014);
- Bryozoan density in oyster beds based on survey points (2014 and 2015);
- Intertidal mussel beds (2014);
- Pacific oyster farms (2014);
- Bathymetry;
- Current velocity based on numerical simulations;
- Location of water quality sampling stations.

Water quality data for DIN, SRP, and chlorophyll *a* were assessed for two sampling campaigns: 1997-1998 and 2004-2005. The data for both periods show similar spatial and temporal patterns; since the dataset for 1997-1998 is more complete in terms of frequency and number of bottom samples, this was selected to assess the coastal system in EASE.

Mathematical models



Catchment model

Nutrient inputs from agricultural and urban sources were simulated using the SWAT model: the main processes associated with this catchment model are shown in Fig. 5. It is capable of simulating agricultural land use and management, vegetation growth, and grazing, estimating the consequences for sediment and nutrient exports from fields to streams and routing these through the stream network into the coastal systems. The daily time-step allows the simulation of peak nutrient inflows capable of presenting acute contamination problems, while the process-based nature of the SWAT equations allows the investigation of the consequences of different climate, land use and agricultural management scenarios.

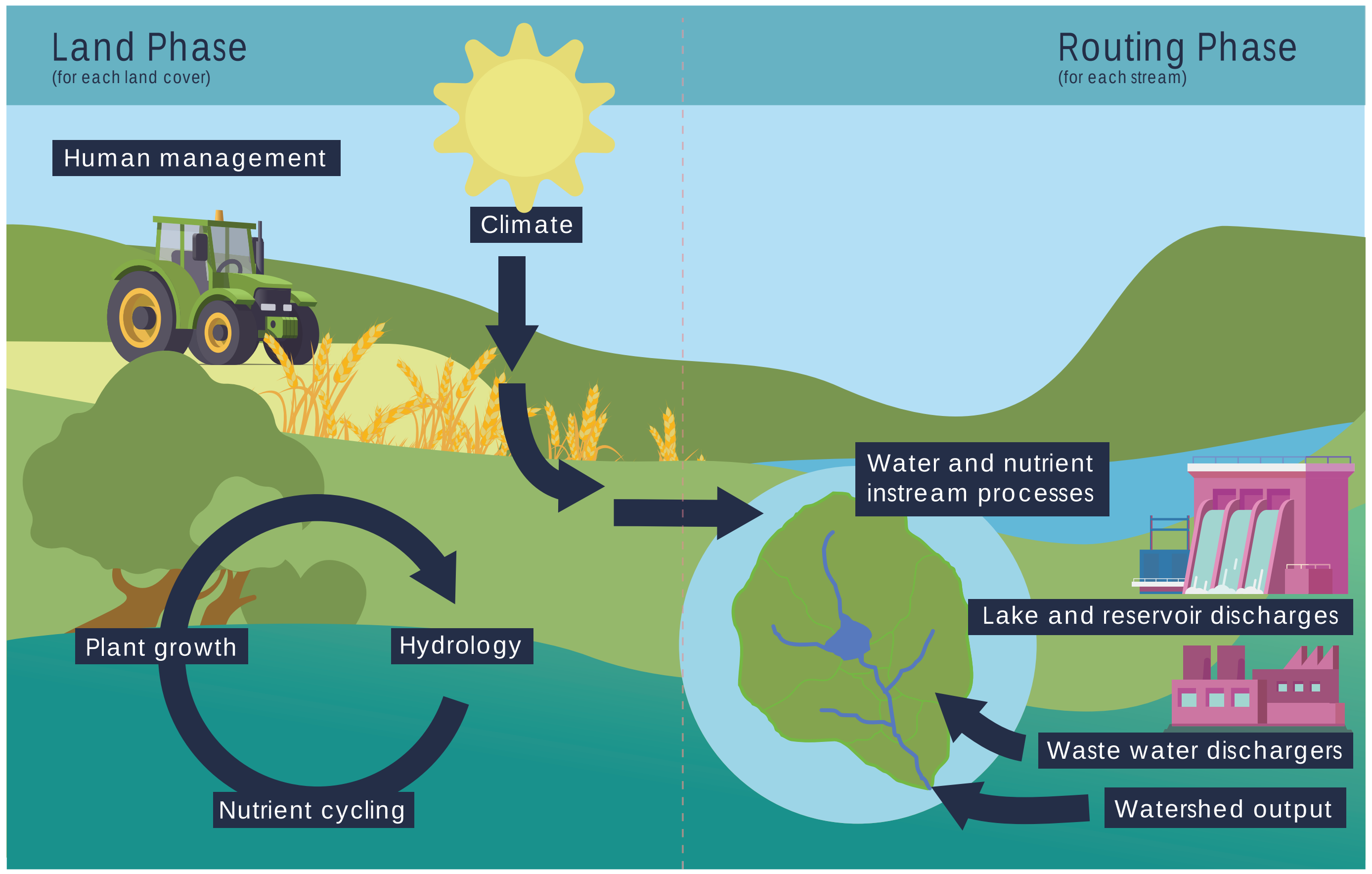


Fig. 7 Main processes and components simulated with the SWAT model.

Hydrodynamic model

In order to solve the movement of water and its properties within the Lough and how the water is exchanged with the adjacent shelf, a numerical model of the hydrodynamics was applied to Lough Foyle.

In order to represent how the water movement interacts with the bathymetry at the spatial and time scales required, the modelling of hydrodynamic quantities is finer than the ones used in the ecological model. Thus, there was a need for an independent detailed hydrodynamic model and for a procedure to translate the hydrodynamic quantities from the physical to the ecological modelling scales.

The platform chosen for hydrodynamic and transport modelling was Delft3D-Flow, a three-dimensional, finite difference, hydrodynamic and transport model which simulates flow and transport resulting from tidal and meteorological forcing. In this application, the hydrodynamic model solved the Navier-Stokes shallow water equations with hydrostatic and Boussinesq approximations. Delft3D-Flow uses a limited area, horizontal Arakawa-C grid with control volumes and for most applications an Alternating Direction Implicit integration method.

In addition to the SMILE project, the Delft3D-Flow platform has been used previously in estuarine conditions under mesotidal forcing in, e.g., Xianshang Gang, China, Ria Formosa, Portugal, Tomales Bay, California, and Maputo Bay, Mozambique.

Oceanic and atmospheric conditions in the region of interest prompted for an accurate depiction of the evolution of oceanography of the shelf as well as fine resolution of the weather variables. We chose to use data from operational weather and ocean models in order to provide the state-of-the-art in the prediction of local weather and regional ocean circulation at the boundary of our limited area model (Fig.6).

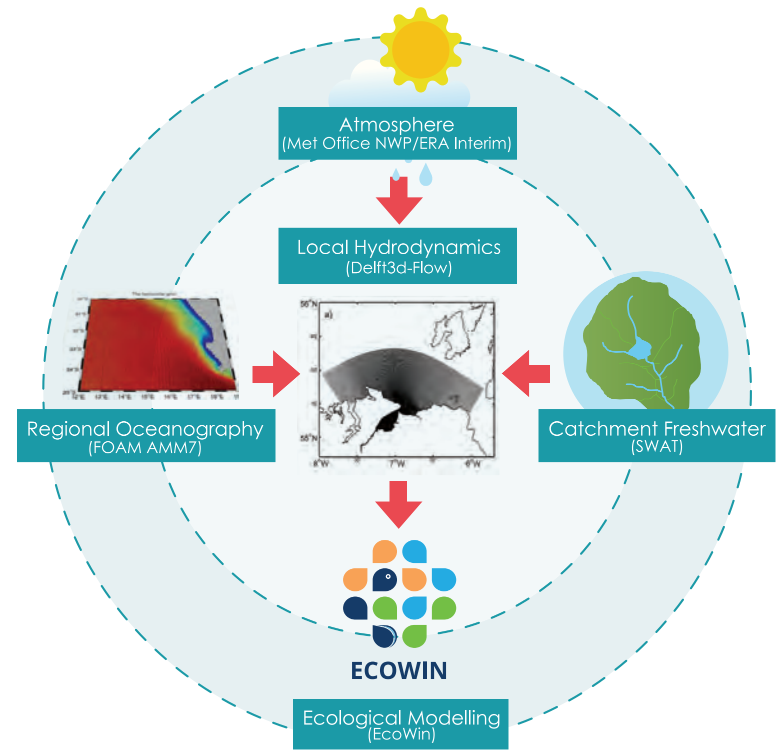


Fig. 8 Delft3d-Flow interactions with external models.

The source of regional circulation data was the FOAM AMM7, an operational model with 7 km horizontal resolution and vertical hybrid coordinates maintained by the MyOcean consortium and built with the NEMO platform. This choice was made due to the ready availability of archived data since April 2011 and the reliability of the infrastructure for future applications, given its institutional acceptance. The atmospheric variables were sourced from the Unified Numerical Weather Prediction model (NWP) developed and supplied by the UK's Met Office.

Shellfish growth models

Individual shellfish models were developed to provide the physiological component to ecological models such as EcoWin.NET and FARM, with the aim of simulating potential harvest, sustainable carrying capacity, economic optimization, key financial data, and positive (e.g., eutrophication abatement) and negative (e.g., biodeposition) externalities at the farm scale. The AquaShell individual growth model is used at several stages of EASE for simulation of growth.

The key features of the model are:

- Simulation of change in individual weight, expressed as tissue dry weight, scaled to total fresh weight and shell length;
- Integration of relevant physical and biogeochemical components such as temperature, salinity, and chlorophyll, and partitioning of phytoplankton and detrital food resources;
- Provision of environmental feedbacks for the production of particulate organic waste (faeces and pseudofaeces), excretion of dissolved nitrogen, and oxygen consumption.

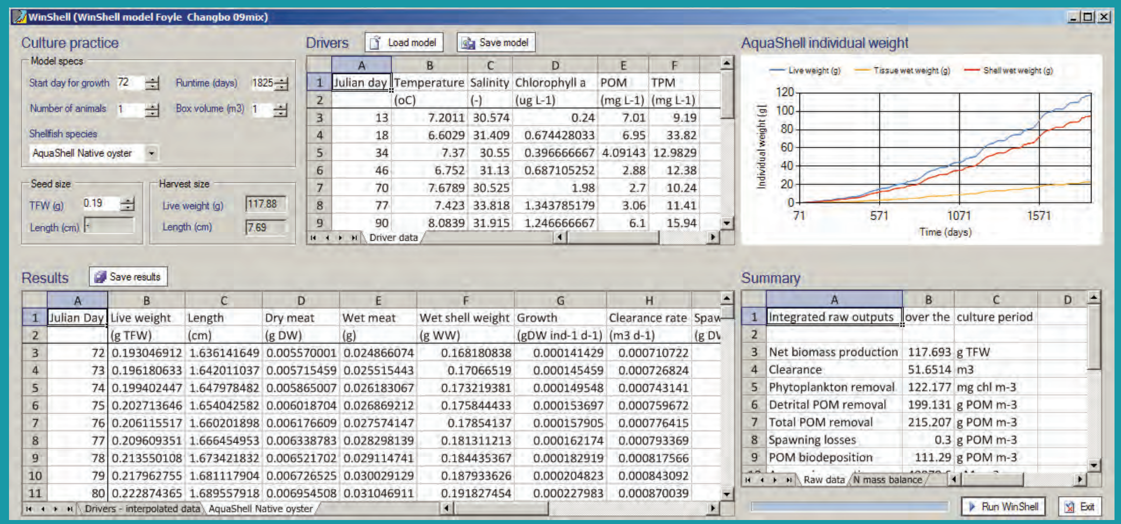


Fig. 9 Screenshot of WinShell – example model run for the native oyster *Ostrea edulis*.

WinShell (Fig. 9) is a workbench application that handles pre- and post-processing for AquaShell. It is not designed to analyse the overall cultivation of multiple (thousands or millions of) animals, but provides a user-friendly interface to handle input and output from AquaShell and allows the farmer to look at the environmental and growth performance of an animal for a particular set of environmental drivers.

The individual growth models are then used at the ecosystem-scale in EcoWin.NET, and at the farm-scale in the FARM model to determine both production and environmental effects, using the same code that is used for individual growth—this means that any improvement to the individual model is automatically transmitted to the higher-level models.

Ecological models

Ecosystem-scale model

EcoWin.NET is an ecosystem-scale model developed to address carrying capacity for aquaculture. In EASE, it includes 154 state variables, 20 forcing functions and runs for a period of at least ten years, with a timestep of 30 minutes. Decadal periods are important to simulate multiple aquaculture cycles for all the relevant species.

EcoWin is built using an object-oriented approach; it incorporates the relevant physics to simulate water circulation, a full representation of catchment loading, including both point and diffuse sources of water and nutrients, and simulates a comprehensive set of biogeochemical processes. Growth and environmental effects of cultivation of the three key shellfish species—blue mussels, native oysters, and Pacific oysters—are the main simulation outcomes. The model analyses the partitioning of food resources between cultivated species and other naturally occurring filter-feeding species (wild species) such as bryozoans.

Fig. 10 EcoWin.NET interface, showing model information for Lough Foyle.

A screenshot of the model interface is shown in Fig. 10. The version used for EASE runs on both 64- and 32-bit Windows operating systems and a full simulation for a ten-year period takes about 15 minutes to run.

Farm-scale model

FARM

The FARM model (Fig. 11) simulates aquaculture at the local scale for offshore, coastal, or onshore sites. The model can be applied to finfish, shellfish, macroalgae, and deposit-feeders, and combines physical and biogeochemical models, individual growth models, and cost-benefit models.

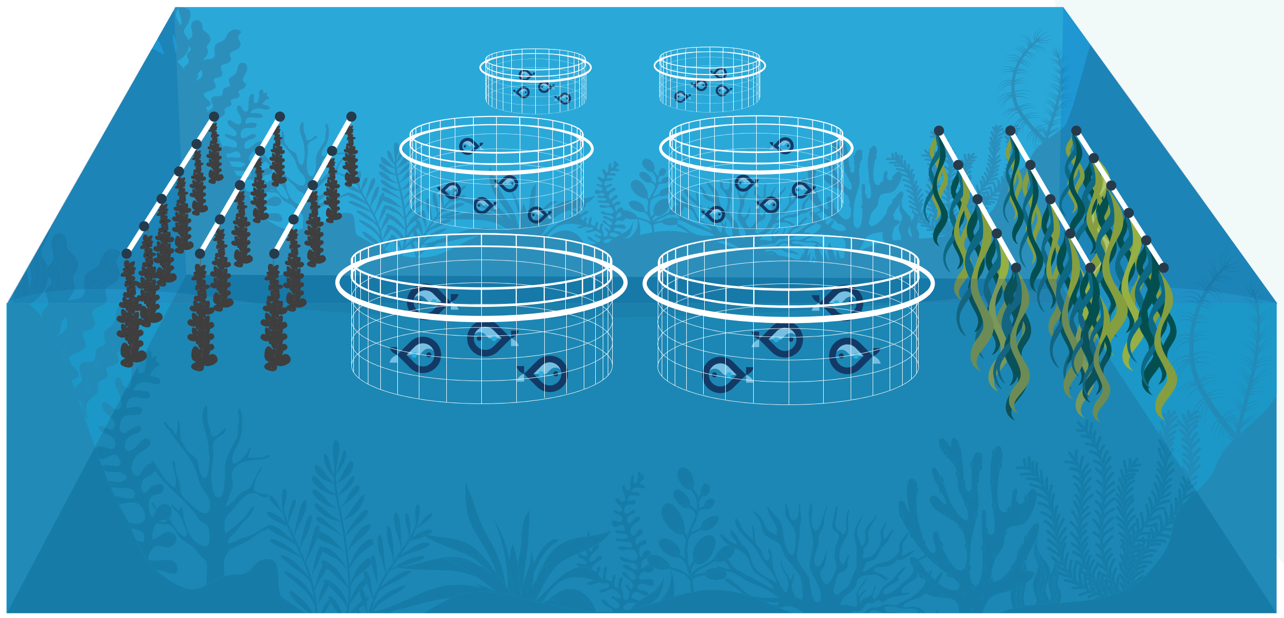


Fig. 11

Environmental effects are calculated both at the level of sediments and with regard to eutrophication of the water column. This type of model is targeted at both the producer and manager and is categorised as a screening model, requiring a minimal dataset, and is fast and easy to use.

FARM

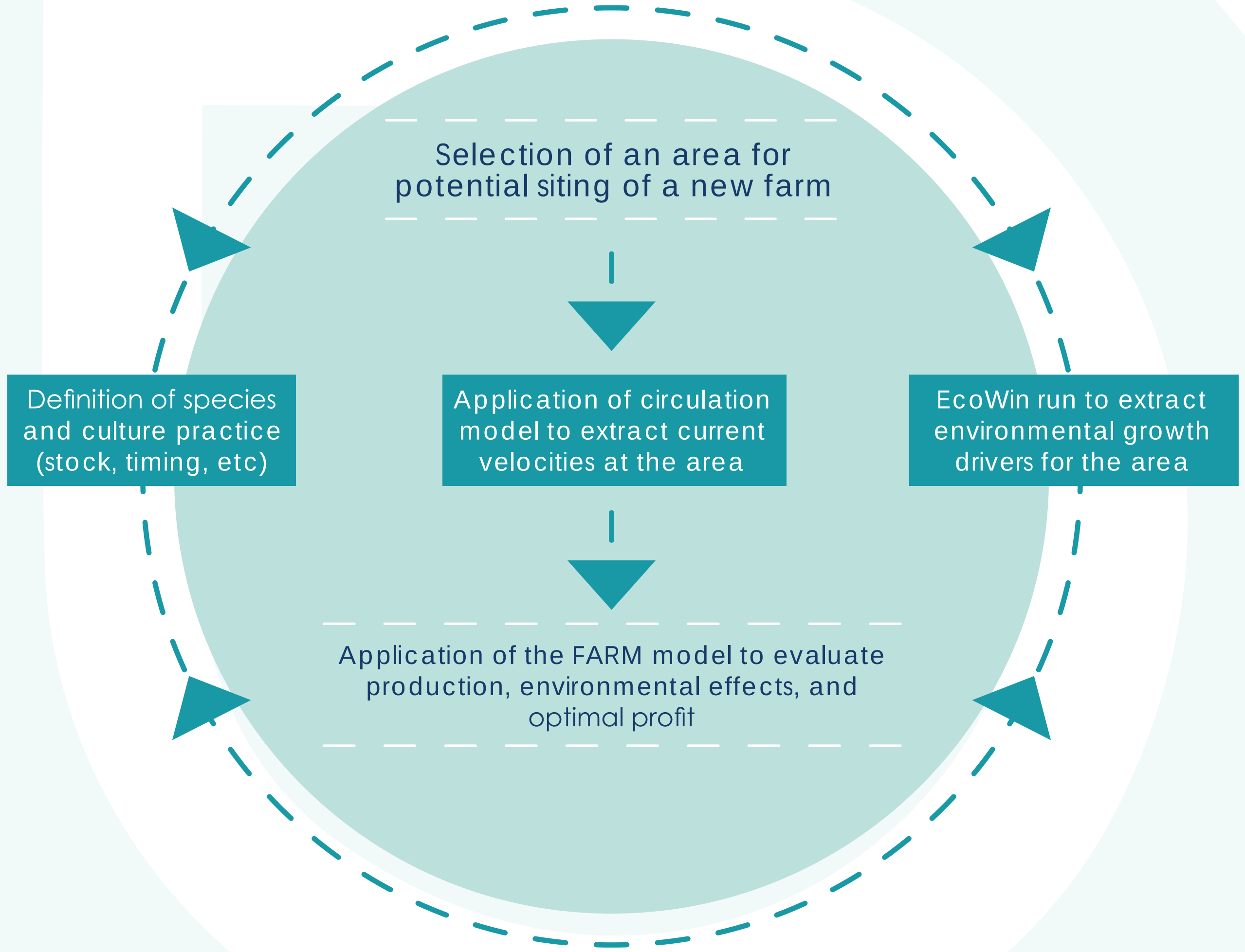


Fig. 12

The FARM model can be driven by data or by the results of more complex models such as EcoWin (Fig. 12). The only data requirement is for culture practice, but current velocities and environmental drivers can equally be measured. However, if a manager is considering a broader development scenario, it can be simulated in EcoWin, and the outputs used as drivers to run FARM. Moreover, even in the standard situation, outputs from validated circulation and ecosystem models will save time and money in evaluating site selection.

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III. The System

The Catchment

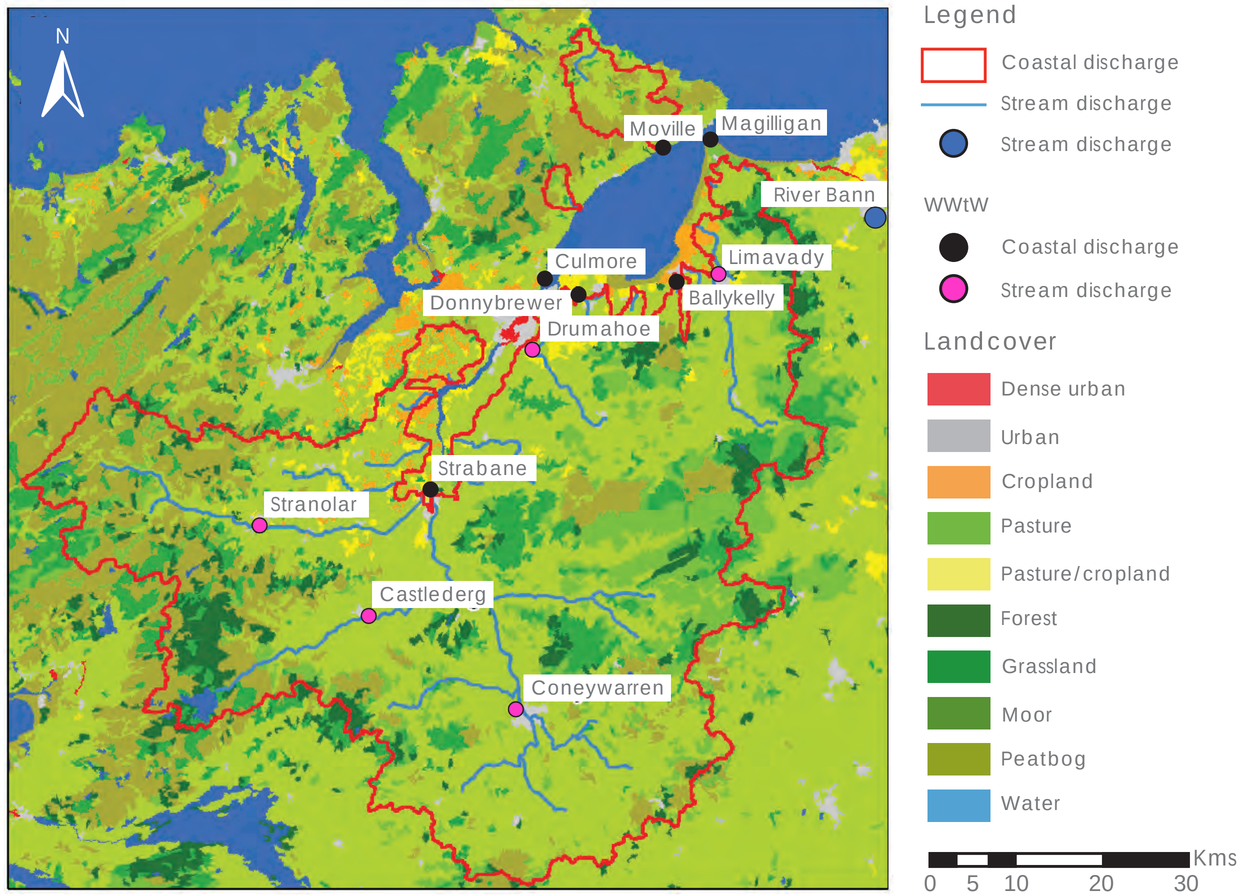


Fig. 13 Map of the Foyle catchment considered in EASE, including land use and location of major wastewater treatment works.

The Foyle catchment area considered in EASE (Fig. 13) occupies an area of 3709 Km^2, including the major rivers draining into the River Foyle from both Northern Ireland and the Republic of Ireland, as well as those discharging directly into Lough Foyle. The area is mostly occupied by pasturelands, which are fertilised and receive manure from grazing, but also with important natural grasslands, forests, moors and peat bogs. Other sources of nutrients include areas of croplands closer to the river, and 11 WWTWs discharging either directly into Lough Foyle and the River Foyle, or into the stream network.

Finally, the outlet of the River Bann discharges to the ocean but close to Lough Foyle, therefore nutrient discharges from the River Bann might also influence the Foyle system.

The Coastal Area

The marine area adjacent to Lough Foyle is characterized by strong tidal flows in the east and west directions with the outputs of the Irish Sea meeting the Atlantic Ocean.
This area is impacted by a complex ocean front, the Islay Front, which drives productivity within this coastal area. The estuaries of the Foyle, Bann, and Swilly discharge nutrient loads from the catchment into this coastal area, further contributing to marine primary production. There are no indications of eutrophication in the marine area.

Lough Foyle is situated in a complex oceanographic context with the Malin shelf edge at the North, and the influence of the Irish Sea coming through the North Chanel at the East. The circulation here is dominated by the tide and to a lesser extent by westerly winds. The residual currents are driven by a combination of non-linear tidal rectification, density gradients, as well as the prevailing meteorological forcing. These work to change the stratification conditions imposed by the seasonal cooling-heating cycle and the freshwater runoff from the Clyde Sea and large Irish Sea estuaries.

Semidiurnal tides dominate with marked spatial variations due to the region's topography, which lead to complex amphidromic systems. One such system has its node to the east of the study area. Tidal currents can reach 1-2 $m.s^{-1}$ at the shelf offshore of Lough Foyle.

The seasonal heating between March and September leads to the onset of thermal stratification by April. Thermal mixing fronts are established where the stabilizing effect of surface heating prevails over the turbulent mixing by wind at the top and tide at the bottom. The Islay Front is one of these structures and its location can be predicted using the Simpson-Hunter criterion. The onset, migration and destruction of this front conditions the temperature, salinity and circulation at the mouth of Lough Foyle. From late summer to early spring, thermal vertical stratification erodes and haline fronts may form between the less saline Irish Sea water and the Malin shelf ambient water.

Lough Foyle

Lough Foyle is a shallow estuarine sea lough, geographically straddling the border of the Inishowen peninsula in County Donegal, Republic of Ireland and County Londonderry in Northern Ireland.
The Lough contains extensive intertidal sand flats, mudflats, and salt marsh. Areas within the Lough have been designated as protected sites. These include:

- RAMSAR (Wetlands of International Importance). The site qualifies under Criterion 1b, being a particularly good representative example of a wetland complex including intertidal sand and mudflats with extensive seagrass beds, saltmarsh, estuaries, and associated brackish ditches. The site also qualifies under Criterion 1c by being a particularly good representative example of a wetland, which plays a substantial hydrological, biological, and ecological system role in the natural functioning of a major river basin which is located in a trans-border position;

- Area of Special Scientific Interest (ASSI). The physiographical interest relates to various active coastal processes which occur on both the intertidal and upper beach areas of the shore, in the river and in the saltmarsh environments. These processes include the development of shell and gravel ridges, saltmarsh pans, drainage creeks and sand spits;

- Special Protection Area (SPA). Selected as an SPA under the E.U. Birds Directive, since it is part of an internationally important wetland site that regularly supports in excess of 20,000 wintering waterbirds. The assemblage of birds that utilise Lough Foyle includes internationally important populations of Whooper Swan, Light-bellied Brent Goose and Bar-tailed Godwit, and nationally important populations of a further 18 species: Great Crested Grebe, Bewick's Swan, Greylag Goose, Shellduck, Wigeon, Teal, Mallard, Red-breasted Merganser, Oystercatcher, Golden Plover, Lapwing, Knot, Dunlin, Curlew, Redshank, Black-headed Gull, Common Gull and Herring Gull;

- Special Area of Conservation (SAC). River Foyle and Tributaries, River Roe and Tributaries and River Faughan and Tributaries. The diversity of coastal habitats within the Lough Area has made it of international importance.

The diversity of coastal habitats within the Lough Area has made it of international importance.

Physical aspects

Lough Foyle is a drowned valley estuarine system. Mesotidal (1 - 3 m range) forcing results in fast tidal currents in the main and side channels and strong sediment transport at the mouth of the lough. Most of the flow occurs in the fast deeper channels of the left bank where non-cohesive sediments are predominant. In the opposite bank, shallow intertidal mud flats condition the velocity. A sand bar at the mouth of the estuary reduces the effect of wave action at the shelf—the 50-year maximum wave height is about 25 m. Depth averages five meters in large sections of the Lough and the reported maximum depth is 15 m. In the navigational shipping channel, the chart datum depth is eight meters, allowing a maximum tidal draft of 9.3 m through to the port of Londonderry.

A clear horizontal haline stratification is present throughout the year with salinities between 0–30 at the head of the lough increasing to 20–34.5 at the mouth. A clear seasonal temperature cycle is caused by local atmospheric heat exchange and also affected by the migration of the Islay Front, thus modulating the temperature of the ambient shelf water. The estuary is usually well mixed in the vertical due to the intense tidal action but can stratify when high river runoff events occur around the neap tide.

Nutrients and primary production

The trophic status of the Foyle Estuary and Lough was first examined in the late 1990s, with an addendum report in 2003 entitled 'Nutrient Inputs and Trophic Status of Foyle Estuary and Lough, 1999', which considered all available data at the time using the newly agreed UK-wide criteria for assessing trophic status.

During 2005, the Environment and Heritage Service (EHS) reviewed the trophic status of waters across Northern Ireland under the Urban Waste Water Treatment Directive (UWWTD, 91/271/EEC) and made recommendations for new sensitive areas, where higher standards of wastewater treatment may be required in future. This report highlighted the need for a further assessment of the Foyle Estuary and Lough data and indicated that this area may need to be reconsidered as a sensitive area. The freshwater systems in the Foyle, Roe, and Faughan catchments were designated as sensitive in 2006, following a review in 2005.

The reason for this changing view was improved scientific knowledge. In 2004, an *in situ* monitoring buoy was installed in Lough Foyle through a collaborative project between EHS, Loughs Agency, and DARD/Queen's University Belfast. The in-situ monitoring buoy detected high fluorescence events (a proxy for chlorophyll), accompanied by the depletion of dissolved oxygen and nutrients, which can be indicative of eutrophication.

This report investigated all the available evidence and on the basis of the nutrients, algal biomass, and dissolved oxygen concentrations concluded that the Foyle Estuary and Lough are showing some signs of eutrophication and could become eutrophic if protective action is not taken.

It was recommended that the Foyle Estuary and Lough are designated as Sensitive Areas (Eutrophic) under the Urban Waste Water Treatment Directive and a Potential Problem Area under OSPAR[3] .

[3]The UK is one of the 15 signatory members of the OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic since the convention entered into force on 25 March 1998.

It was recommended that the Foyle Estuary and Lough are designated as Sensitive Areas (Eutrophic) under the Urban Waste Water Treatment Directive and a Potential Problem Area under OSPAR . This designation complements the total territory designation already made under the Nitrates Directive and ensures that all sectors are treated equitably in reducing nutrient discharges to the waterways of Northern Ireland.

The designation as a Sensitive Area implies that qualifying discharges within the Foyle Estuary and Lough catchments must be considered for the removal of phosphorus (P) and/or nitrogen (N) unless it can be demonstrated that the removal will not affect the level of eutrophication. There are three qualifying discharges from the catchment: Omagh, Strabane, and Culmore (Londonderry), of which the latter two discharge to the Foyle Estuary.

The Foyle Estuary and Lough were not considered enriched with phosphorus and therefore P removal was not recommended for works discharging directly to this area. However, P removal is already required within the freshwater Foyle system as phosphorus is the main limiting nutrient in the freshwater environment. N removal is now recommended at Culmore WWTW, which discharges over 5% of the total N loading to the Foyle Estuary. A new WWTW has been built at Strabane and further N removal is not required from this plant, which already meets UWWTD nitrogen removal standards.

Aquaculture

The modern aquaculture industry on the island of Ireland began in the 1970s. The sector is an important contributor to the economy of rural coastal communities. The sector was at its peak in the mid-2000-2010 decade.

In 2006, total aquaculture production on the Island of Ireland stood at over 68,000 tonnes and was valued in excess of €136 million—at this time, the industry supported 2,275 jobs. Since then, the industry declined due to major challenges associated with microbusinesses and small and medium-sized enterprises. Increasing overheads attributed to the economic climate coupled with high distribution costs and supply-chain inefficiencies made market access to high-value markets difficult. Around this time, significant competition from other countries, capable of aquaculture practices on a large scale/low budget, began to impinge on traditional European markets.

Despite this, the aquaculture sector in Ireland was relatively stable in 2018, with over 1,800 people employed either part-time or full-time in aquaculture in 2014. Total aquaculture production for 2014 stood at 30,882 tonnes. The overall value of the industry in 2014 was also stable, amounting to €115 million.

In 2015, there were 28 active aquaculture producers in Northern Ireland (NI), employing some 130 people. The main shellfish species cultivated are subtidal mussels and intertidal oysters on trestles (smaller amounts of scallops and native oysters are also produced, the latter, not true aquaculture); and finfish species: marine salmon, freshwater rainbow trout and brown trout. The combined aquaculture industry is valued at approximately £11.6 million. In 2018, the salmon sector was worth £4.86m (42% of total sector), oyster sector £2.97m (26%), trout sector £1.9m (17% of total sector), and mussel sector £1.84m (16%) .

The aquaculture sector in the border counties provides employment in peripheral coastal areas where few alternative opportunities exist. The industry complements employment in inshore fishing, tourism, and small-scale agriculture. By providing additional income opportunities to these other areas, aquaculture creates social cohesion and maintains rural communities, removing the necessity for translocation to find work. In 2006, aquaculture production in the border counties stood at 26,613 tonnes, valued at €50,912,463 and accounting for 55% of the total production of the island of Ireland.

Native oyster

Historical records show that the native oyster *Ostrea edulis* has been harvested from Lough Foyle since the 18th Century. The fishery has always been a self-propagating wild fishery and therefore reliant on spat production and settlement onto natural oyster beds. There was one notable exception to this in 1970, when 250,000 oyster spat were introduced into the lough to replenish depleted stocks.

Since September 2008, Loughs Agency has licensed and regulated the native oyster fishery in Lough Foyle. The Agency licences approximately 50-60 fishers in Lough Foyle annually. The fishery catches approximately 100-150 tonnes of oysters annually, is valued at £400,000 per annum, and operates a closed season yearly between the 1st April and the 18th September. Fishing is permitted under licence between 06:00 Monday to 18:00 Friday weekly from the 19th September to the 31st March. Licence holders are required to adhere to the following licence conditions and regulations:

- Foyle Area (Licensing of Oyster Fishing) Regulations 2008 as amended (The Foyle Area (Licensing of Oyster Fishing) (Amendment) Regulations 2010);
- Foyle Area (Control of Oyster Fishing) Regulations 2008 as amended (The Foyle Area (Control of Oyster Fishing) (Amendment) Regulations 2010);
- Foyle Area (Oyster Logbook and Identification Tagging) Regulations 2008;
- Foyle Area (Landing Areas for Oysters) Regulations 2008.

A traditional dredge fishery is operated for native oysters. Production is variable and driven by trends in seed settlement success affected by environmental conditions during the spawning period. The majority of the native oysters produced are exported to Spain.

The oyster beds in Lough Foyle have been subject to infestation by bryozoans (*Alcyonidium* sp.). Field campaigns during the EASE project estimated a density range of 2-20 g fresh weight m^{-2} which translates into an estimated water filtration rate of 28 L m^{-2} h^{-1}. Given that the filtration rate of oysters is estimated at 1 L m^{-2} h^{-1}, bryozoans could provide strong competition for food, although they could filter smaller particles than those used by oysters. This and other potential interactions between bryozoans and oysters are still unknown, limiting an assessment of the impacts of bryozoans on food availability for shellfish until further information is available.

[4] A shift in the main species cultivated has been noted over the last 5 years, from mussels to pacific oysters. Mussel production has dropped from 3324 t in 2013 to 2060 t in 2018. Price per tonne also dropped from £1730/t to £891/t, while Pacific oyster production has grown from 138 t in 2013 to 909 t in 2018. Price per tonne increased from £2503/t to £3278/t.

Blue mussel

Wild mussel seed beds in the Irish Sea form the basis of the bottom-culture mussel aquaculture industry in Lough Foyle. The seed mussels are gathered by dredging and taken to the farms where they are grown to a marketable size. The majority of the mussels produced were exported to the Netherlands. During the peak of the bottom grown mussel industry in Lough Foyle, production accounted for around 20% of the total bottom grown mussel production on the Island of Ireland. The majority of mussels were landed into Moville, Lisahally and Greencastle, mussel landings for 2003 to 2008 are as reported by Sea Fisheries Protection Authority (Fig. 14).

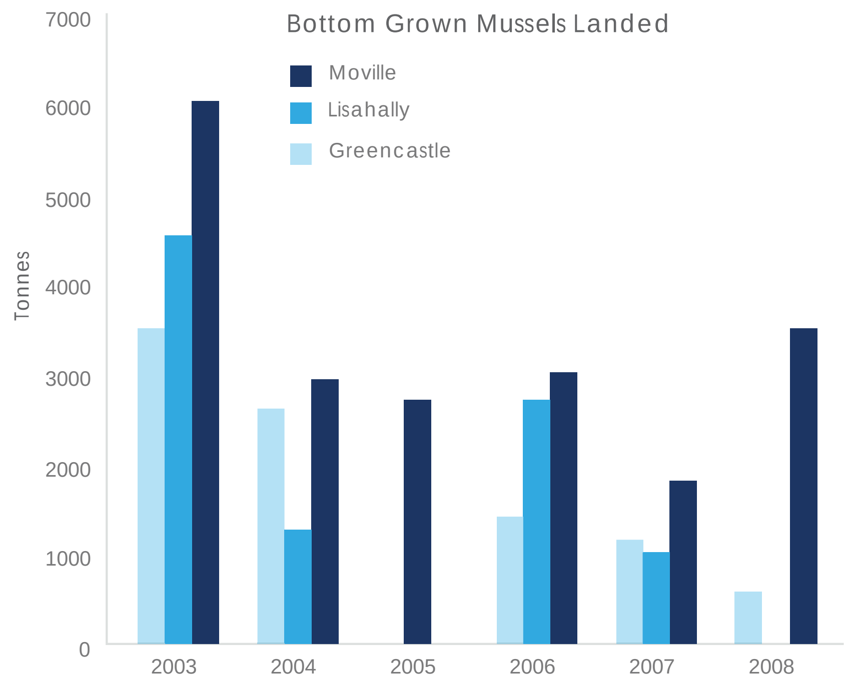
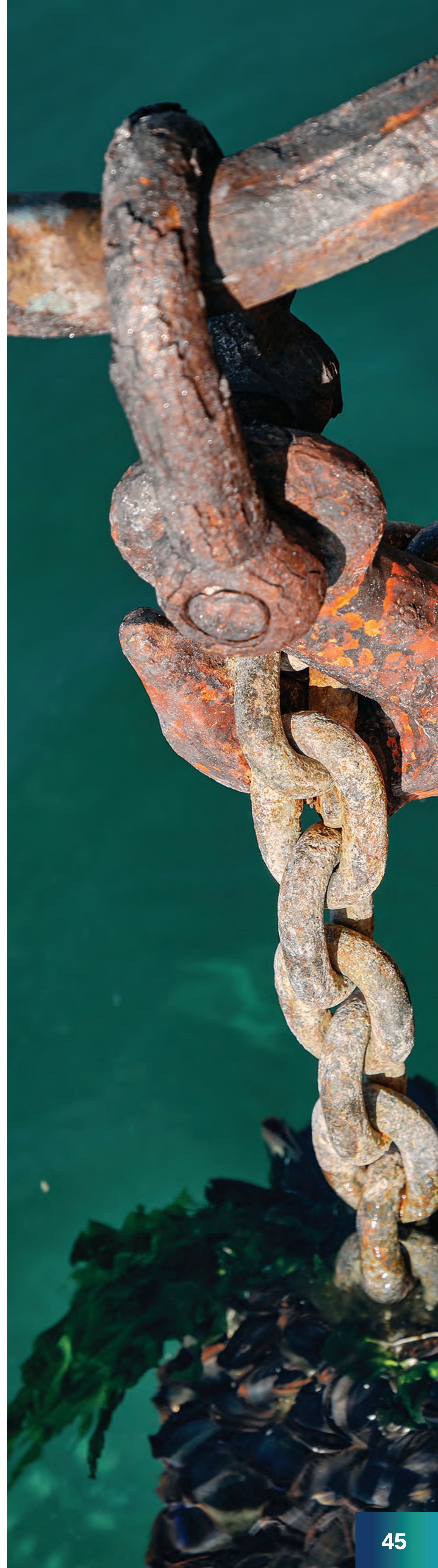


Fig. 14 Bottom-grown mussels landed into Moville, Lisahally and Greencastle 2003-2008.

Peak production occurred in 2003 when a total of 14,000 tonnes was landed in Lough Foyle (discounting small quantities landed at smaller ports). Values per tonne ranged from €400/tonne in 2003 to €826/tonne in 2007.

Since 2008, the bottom grown mussel industry in Lough Foyle has been largely dormant. Figures from 2009 show landings of just 400 tonnes in total. Mussel farming started again in 2015 although accurate production figures are not Available; anecdotal reports suggest that 2015 landings were valued at approximately €1500/tonne.

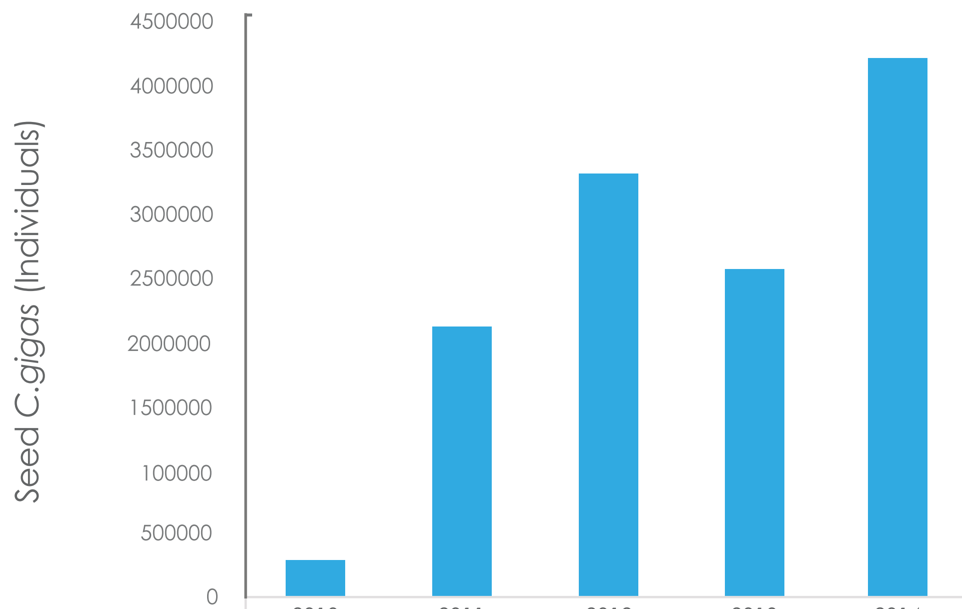


Pacific oyster

Pacific oysters are grown in traditional bag and trestle farms with the seed originating in hatcheries in the UK or France. Lough Foyle is fast gaining a reputation for its high-quality oysters, with many farmers producing the ‘speciales’ grade for the French market.

Production of Pacific Oyster (*Magallana gigas*) has increased significantly across the island of Ireland in recent years. The *M. gigas* production figures for the island of Ireland in 2014 represented a 7% increase relative to 2013. Production for the Island of Ireland in 2014 stood at 9,000 tonnes. County Donegal accounted for 24% (2150 t) of the Island of Ireland total production for 2014.

The industry has expanded significantly over the past 10 years. In 2018, the production of Pacific oysters in Lough Foyle by aquaculture was an unregulated activity. As a result, accurate figures on inputs and production are difficult to obtain.



	2010	2011	2012	2013	2014
Seed Input (Individuals)	265000	2115000	3280000	2550000	4200000

Fig. 15 Reported Pacific oyster seed imports to Lough Foyle for the period 2010-2014.

In 2010 and 2011, the seed was imported from Guernsey and from 2012 to 2014 the seed was imported from France.

Other uses

Foyle Port is at Lisahally on the east shore of the River Foyle at the southern end of Lough Foyle. The Port attracts imports from bulk carriers bringing coal from South America and small coastal cargo vessels importing agricultural fertiliser, silica and grain as well as a small number of cruise ships annually. The navigation channel in Lough Foyle is maintained to a depth of seven meters through licensed maintenance dredging by the Ports vessels.

Greencastle has a large commercial harbour and is the base for Foyle Pilot, National Fisheries College, Inishowen Maritime Museum and Planetarium and an Irish Coastguard Station. The Lough Foyle Ferry which operates from March to October provides a link from Greencastle to Magilligan.

Commercial fishing takes place within Lough Foyle for whelks, green crabs, lobsters, herring, and mackerel. The harbour, owned and managed by Donegal County Council, has a commercial fishing fleet, although this is significantly smaller than in the past. Traditional static pots are used for crustaceans and towed nets are employed for pelagic species.

There is an industrial hub on the shores of the estuary close to the City of Londonderry with a major textile factory close to the shoreline. Coolkeeragh ESB Power Station, the most efficient large-scale electricity power plant in Northern Ireland, is located at Maydown on the Lough Foyle Estuary. The station abstracts cooling water from the estuary with an associated cooling water discharge.

Recreation

The Foyle river is well-known for recreational fishing of Atlantic Salmon. The river has the largest population of Atlantic Salmon in Northern Ireland and it is a top producing river in the country. Salmon stocks have been declining since the mid-1970s with a brief recovery in 1980s following another decrease in stock. A management project using an audit point management system was put in place to monitor the population and, since 2009, no commercial fishing of the species has been allowed. Recreational fishing of Atlantic salmon is solely permitted with a license on the basis of catch and release angling.

Recreational boating and angling take place throughout Lough Foyle mainly during the summer period. Shore fishing is popular for mackerel, sea trout, dogfish, flounder, bass, silver eels, and dab along the length of Downhill, Benone, and Magilligan Beaches.

Within the Lough itself, there are no specific bathing waters; however, close to Inishowen Head, an area with many coves includes a beach known as 'Big White Bay' which is an EU designated Blue Flag Beach. It is also an access point for the East Inishowen Sea Kayak Trail. The area has been designated as a Discovery Point along the Wild Atlantic Way by Fáilte Ireland. On the Eastern side, Benone Beach (an EU Designated Bathing Water with Blue Flag Award) stretches for over seven miles from Downhill westwards to where it meets Magilligan Point at the mouth of Lough Foyle and forms part of one of Ireland's longest beaches. Benone Beach is popular throughout the year for a variety of outdoor activities.

Model box definitions

For ecological modelling with EcoWin, Lough Foyle was divided into simulation areas, called model boxes (Fig. 16). Ideally, the system should be subdivided into enough boxes to take into account spatial heterogeneity, but without making the model excessively complex, which might limit its subsequent utility. In practice, achieving a balance between these goals requires a detailed analysis of the spatial variability of the system.

Table 4. Criteria for division of Lough Foyle into model boxes

Criteria	Details
Physical	Bathymetry, current speed and direction (simulated data supplied by AFBI) and salinity gradients
Administrative	Boundaries of Water Framework Directive water bodies
Water quality	Concentrations of nitrogen, phosphorus and chlorophyll *a*
Aquaculture	Location of blue mussel, native oyster, and Pacific oyster cultivation areas

The methodology used to achieve this relied on assessing several spatial heterogeneity criteria. Inside Lough Foyle itself, four criteria were applied (Table 4). A first approach for defining homogenous regions using these criteria was then assessed and modified by Loughs Agency experts.

Model boxes were also defined for the Foyle River and the nearby coastal region. Due to the low availability of information, the former was defined based mostly on the salinity gradient in the river, while the latter was based on crossing the boundaries of the WFD coastal water bodies with Loughs Agency remit area and the simulation area for the Delft3D-Flow hydrodynamic model. This division was also assessed by local experts.

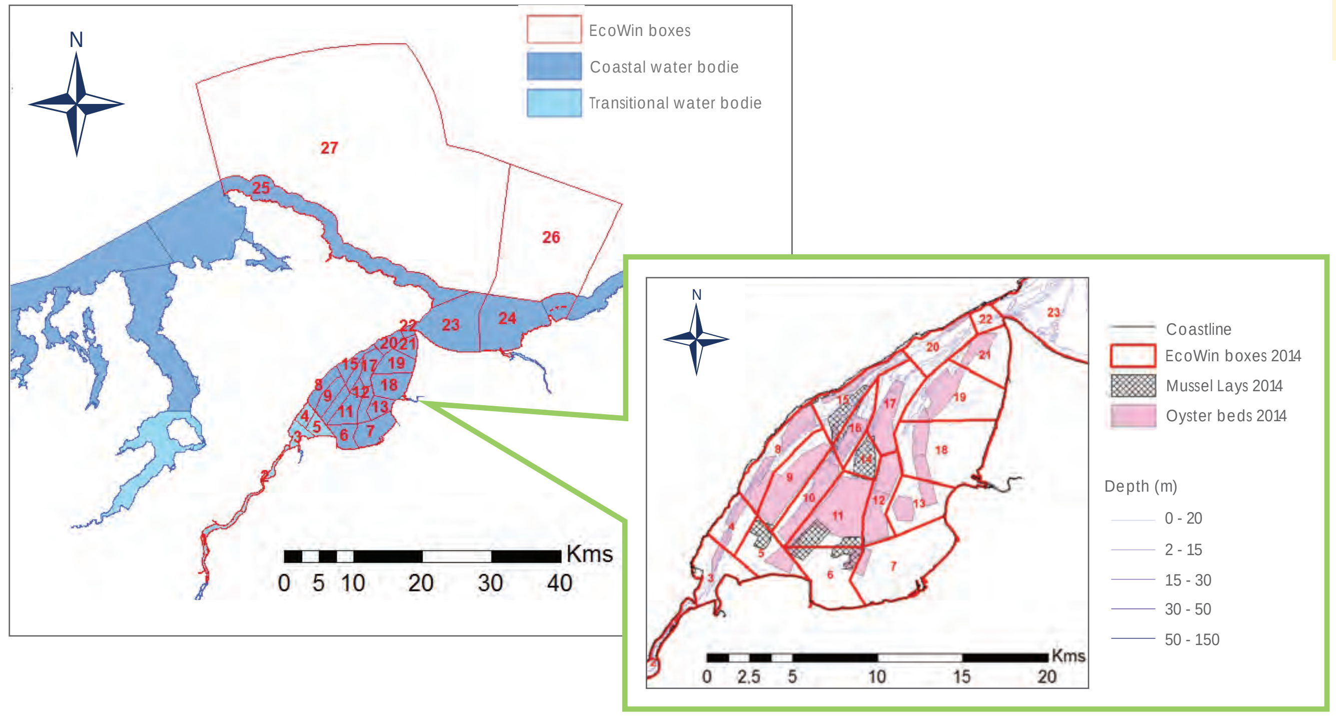


Fig. 16 Left: map of the subdivision of the Foyle River, Lough Foyle and nearby coastal area into model boxes; right: detailed map of the subdivision for Lough Foyle overlaid with mussel lays and oyster beds in 2014.

The final box division is shown in Fig. 16. These boxes were also subdivided into a lower and an upper layer, due to the observed vertical stratification of salinity and currents depending on tides and streamflow. The subdivision was achieved using a sigma layer approach, where the boundary between upper and lower boxes was set at mid-depth. This resulted in 54 boxes, 27 for surface waters and 27 for bottom waters; Of these boxes, four represent the Foyle River, ten represent the coastal areas, and forty represent Lough Foyle itself.

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IV. Carrying Capacity

Catchment Model

Terrestrial nutrient loads from the Foyle catchment (Fig. 13) were calculated using three methods:

- Loads from WWTWs were taken from measured values or, for smaller WWTWs with missing measurements, calculated from population equivalents;
- Loads from River Bann were calculated from measured concentrations and streamflow since the river's artificial flow regime (controlled by sluices) both prevents the application of the SWAT model and facilitates an estimate using available monthly measurements;
- Loads from the agricultural part of the catchment were calculated using the SWAT model. SWAT was applied to the Foyle catchment (Fig. 13). WWTWs with stream discharge were included in the model. The catchment was subdivided into 29 sub-basins and 330 Hydrological Response Units, i.e. homogenous combinations of land use, soil and slope inside a given sub-basin; these units serve the same role as EcoWin model boxes. The model was applied to the period between 1981 and 2014 [5].

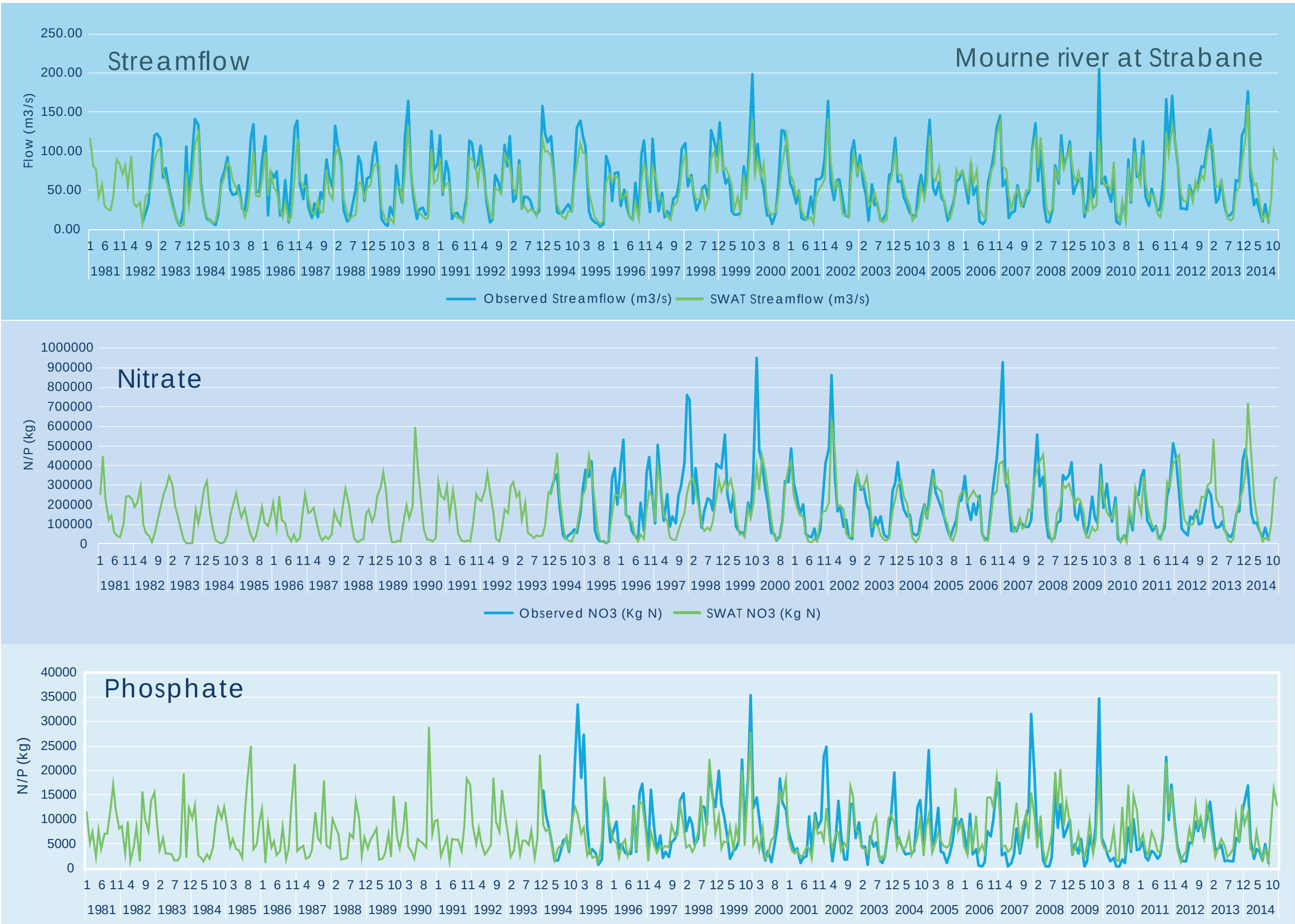


Fig. 17 Monthly observations and SWAT results for streamflow, nitrate and phosphate for the Mourne river near Strabane.

[5] Streamflow results should be valid for the entire period, but nutrient loads should only be valid for the period after the mid-2000s, since before this period WWTWs treatment methods were less thorough in nutrient removal, and fertiliser application rules were less strict than in the present-day.

SWAT was calibrated and validated with data from eight hydrometric stations at the main rivers, many with data going back to the 1980s; and with water quality data measured simultaneously at six of these stations, going back to 1995. Agricultural exports were also compared with those estimated by Foy and Girvan (2004). Fig. 17 shows model results for the Mourne river, the major source of streamflow in the catchment (comparison for Strabane, for the point shown in Fig. 13). SWAT performs very well for streamflow, and satisfactorily for nitrates and phosphates. The worst performance is for nutrient winter peaks before 2010, probably indicating the effect of changes to fertiliser application practices. The model performs very well for all parameters for the EASE study year of 2014.

SWAT load estimates of DIN, DRP and POM for 2014 are shown in Table 5. In general terms, lough Foyle receives the greater loads of DIN, mostly from the Mourne river, followed by the coastal region, mostly from River Bann. For DRP and POM the relation is inverted, with greater loads coming from the coastal region. Direct loads to Lough Foyle represent a smaller but still important component of nutrient and POM loads. These estimates are higher than those for the SMILE project but lower than those from Foy and Girvan (2004). This is partly due to inter-annual variations of nutrient loads, but also (for the latter) to the decrease of WWTWs contributions since the 1990s thanks to improved nutrient removal.

Table 5. SWAT estimates for loads of Dissolved Inorganic Nitrogen (DIN), Dissolved Reactive Phosphorus (DRP) and Particulate Organic Matter (POM) in 2014, for Lough Foyle, River Foyle and the nearby coastal region.

Load	Region				
	Lough Foyle	River Foyle	Total Foyle	Coastal	Overall total
DIN (ton N)	1 468	4 588	6 056	3 405	9 461
DRP (ton P)	60	115	175	266	442
POM (ton)	7 382	33 718	41 100	51 320	92 420

The daily timing of these loads is shown in Fig. 18. DIN loads for Lough Foyle and River Foyle follow streamflow inputs, occurring mostly from mid-autumn to mid-spring, with higher peaks in February associated with fertiliser application. For the same regions, DRP loads have a more irregular pattern, linked to heavier rainfall events and soil erosion, given the strong link between sediment and phosphate exports. For the coastal region, DIN and DRP loads are much more constant although still concentrated between mid-Autumn and mid-Spring; this is due to the heavily controlled streamflow in River Bann.

The sources for DIN, DRP and POM loads are shown in Fig. 19, together with the land-use distribution in the Foyle catchment area (shown in Fig. 13). The dominant DIN source is diffuse, from pasture; this is due to the dominance of pasture land uses, fertiliser application in pasture, and the humid nature of the climate which facilitates nitrate mobilisation in water and its transport to the stream network. In contrast, DRP sources are more evenly divided between point-source (about one third) and diffuse (about two thirds), and the latter roughly follows land-use distribution. This is due to the already mentioned link between erosion and phosphorus exports; relatively low erosion rates in pasture and croplands lead to exports close to background values, i.e., those expected from natural areas.

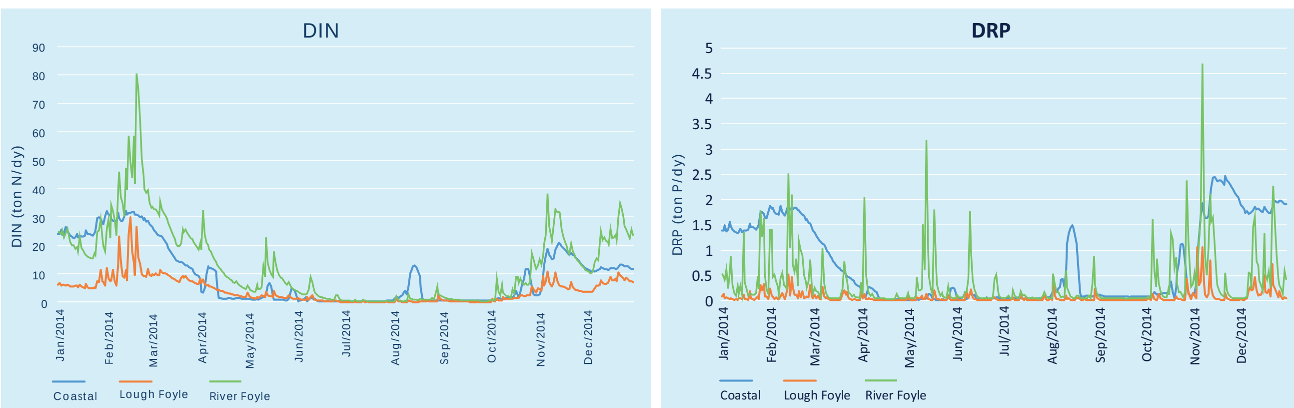


Fig. 18 SWAT estimates for daily loads of Dissolved Inorganic Nitrogen (DIN), Dissolved Reactive Phosphorus (DRP) and Particulate Organic Matter (POM) in 2014, for Lough Foyle, River Foyle and the nearby coastal region.

Source apportioning for DIN and DRP roughly follows the conclusions of Foy and Girvan (2004) but reflects the increased nutrient removal from wastewater, and therefore a decreasing importance of WWTW loads when compared with agricultural loads. Sources for POM are also mostly diffuse, due to the effective POM removal rates by WWTWs when compared with those of nutrients. However, diffuse POM sources follow land-use distribution as, again, low erosion rates in all land uses lead to exports close to background values.

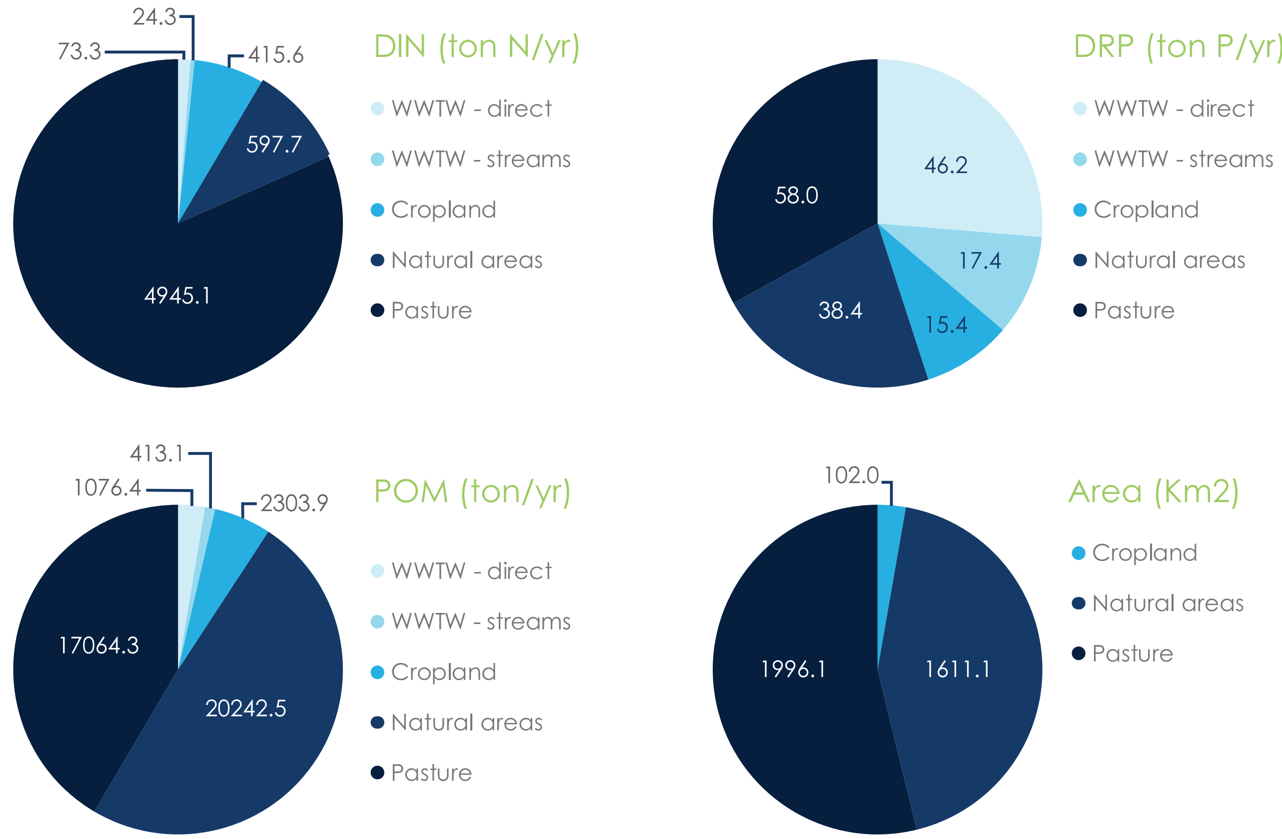
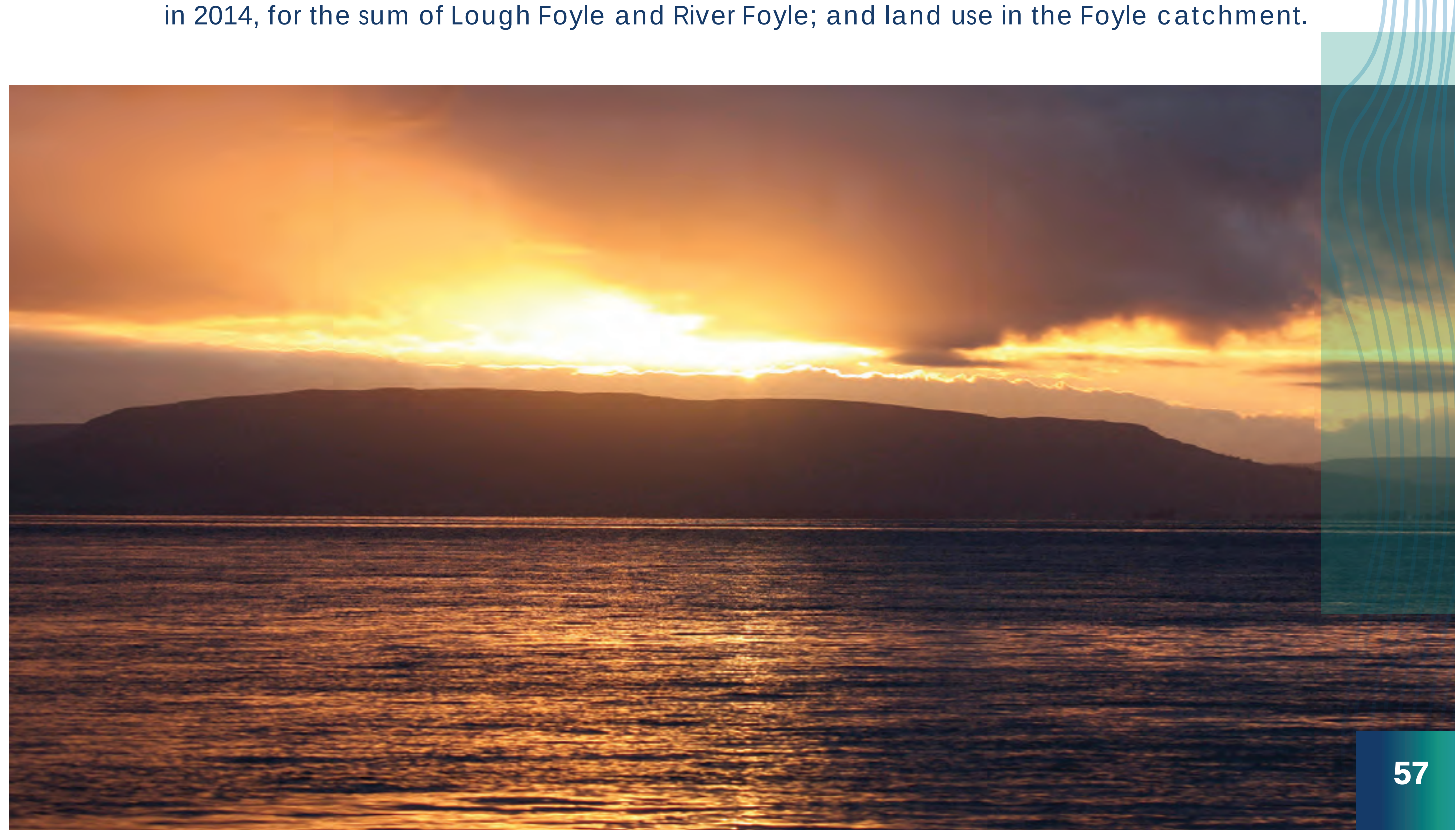


Fig. 19 SWAT estimates for sources of Dissolved Inorganic Nitrogen (DIN; upper left), Dissolved Reactive Phosphorus (DRP; upper right) and Particulate Organic Matter (POM; lower left) in 2014, for the sum of Lough Foyle and River Foyle; and land use in the Foyle catchment.



Hydrodynamic Model

A detailed hydrodynamic model of Lough Foyle was required in order to supply water exchanges between the spatial compartments of the EcoWin ecological model. The choice of the type of hydrodynamic model, its design and calibration had to provide the capability of reproducing both tidal and estuarine circulation at the 1 required to represent the bottom features capable of affecting the hydrodynamics at the scale of the lough. At this scale, heat and mass fluxes with the catchment were included using outputs from the SWAT model. Fine resolution energy and momentum exchanges with the atmosphere were represented throughout the domain using the Met Office's NWP and ERA-Interim reanalysis data.

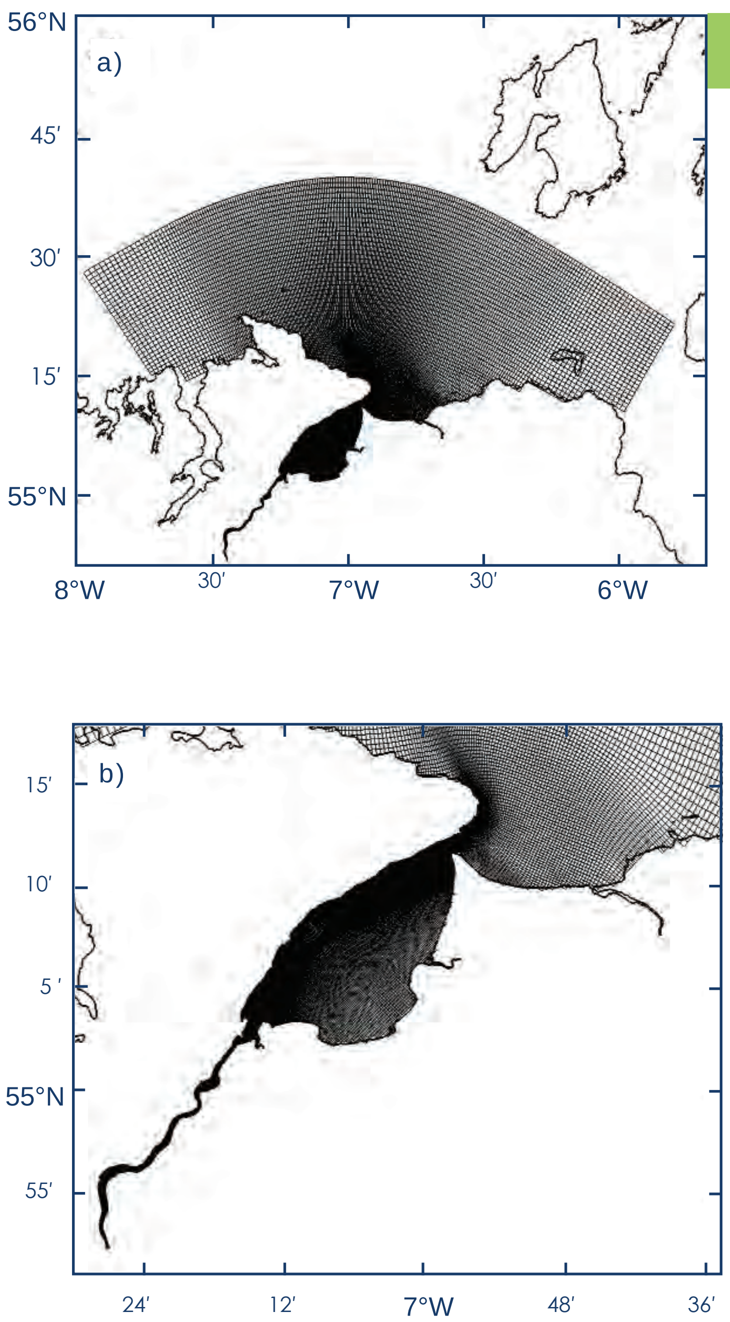
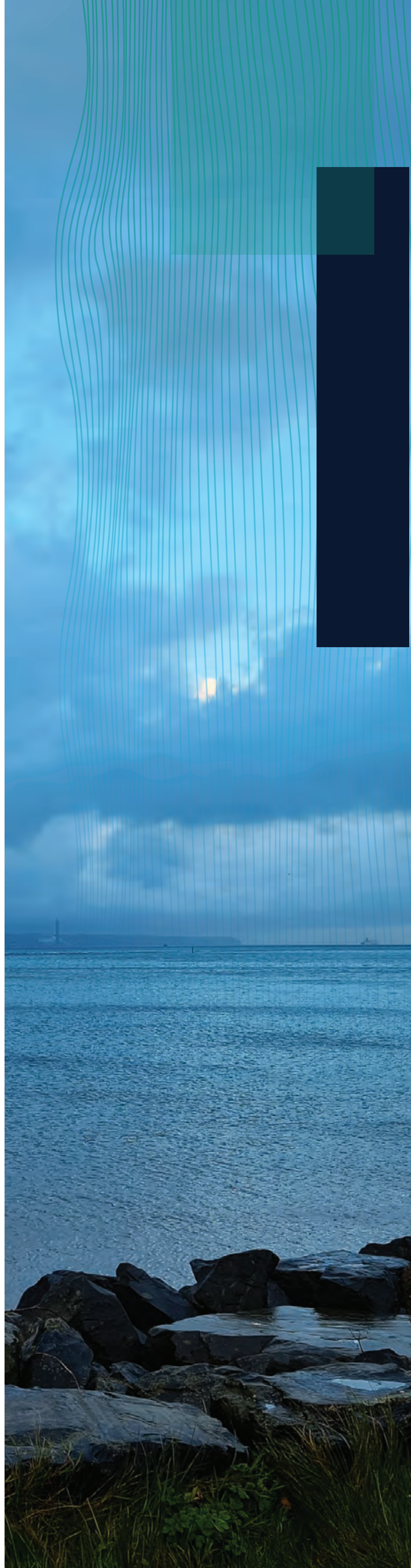


Fig. 20 Computational grid (a) and zoomed area for Lough Foyle (b).

The oceanography of the adjacent shelf had to be included in the hydrodynamic modelling domain due to its complexity and expected influence over Lough Foyle. Several factors occurring outside the mouth of the lough were candidates to affect the local hydrodynamics. Freshwater inflow from the Bann justified the extension of the modelling domain to its limit of influence. With this extension, the spatially heterogeneous forcing of the tide and frontal systems such as the Islay Front were included using results from the FOAM AMM7 regional oceanographic model. The large resolution difference between the FOAM AMM7 (7 km) and our local domain (between 50–100 m) prompted for further offshore extension of the calculation grid to allow a smoother coupling between the Delft3D-Flow setup and the regional model results. At the end of the design phase, we reached a final curvilinear grid of 119856 (528 X 227) cells, with a mean resolution of 50 m in the tidal channels, 100 m in the tidal flats and 500 m at the offshore open boundary (Fig. 20), covering an area of about 5500 km^2.



As boundary conditions, the model uses currents, water level, salinity, and temperature results obtained from FOAM AMM7 imposed at the boundaries using a Riemann condition. This is a weakly radiative boundary condition allowing the flux of salt and heat across the oceanic open boundary.

In addition to salinity and temperature, velocity and sea surface elevation are forced at the open boundary, including both the tidal component and the slow-varying component resulting from atmospheric and baroclinic forcing. The heat budget formulation used in the model takes into account air temperature, relative humidity and net solar radiation to calculate heat losses from convection, evaporation and back radiation which were obtained from ERA-Interim. For variables such as wind and surface atmospheric pressure, we chose the Unified Numerical Weather Prediction model (NWP) developed and supplied by the UK's Met Office. This atmospheric model has a high-resolution inner domain (1.5 km grid boxes) over the area of interest, separated from a coarser grid (4 km) near the boundaries by a variable resolution transition zone.

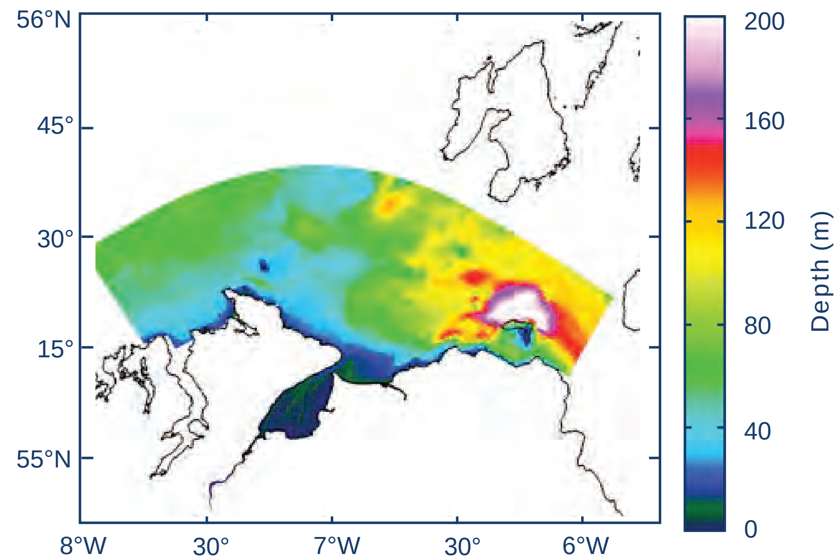


Fig. 21 Lough Foyle and adjacent shelf bathymetry

To establish the depth at these computational points we used topo-hydrographic data from the UKHO digital elevation model with 1–30 m resolution (Fig. 21). In the vertical, the model is divided into 15 terrain-following sigma layers. These are unevenly spaced to provide finer resolution near the surface and improve the model's ability to reproduce vertical mixing and stratification processes.

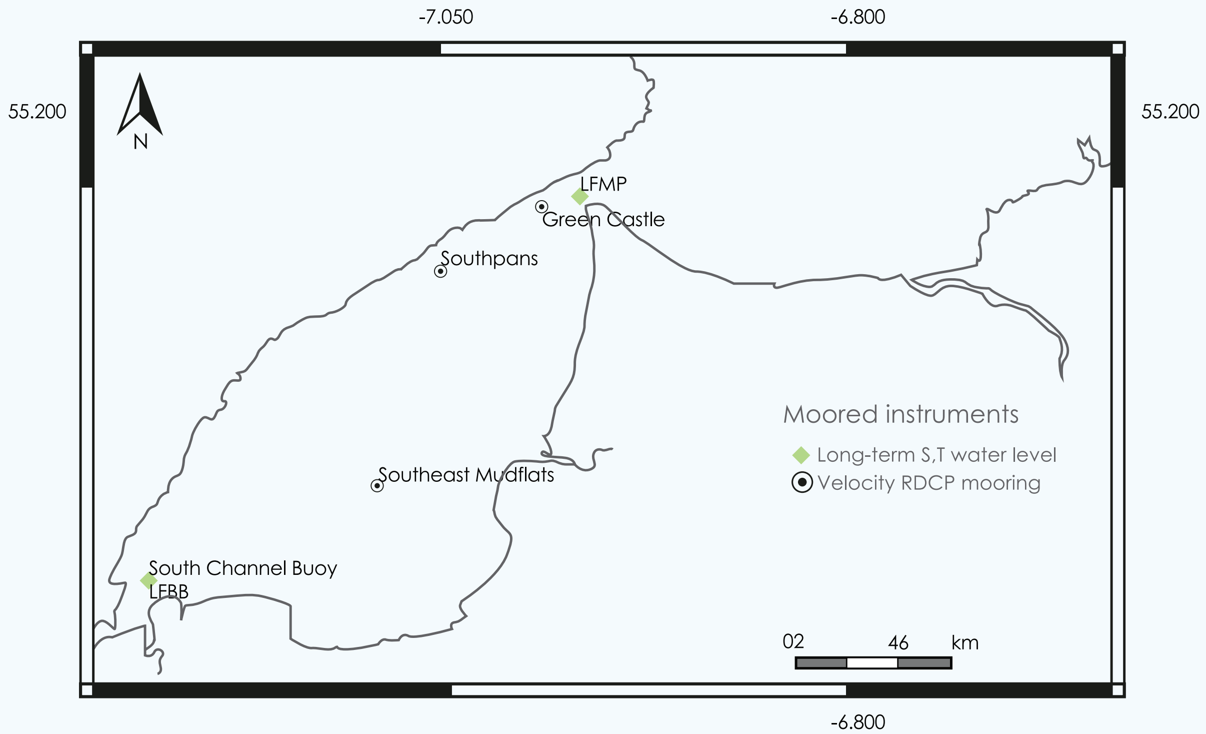
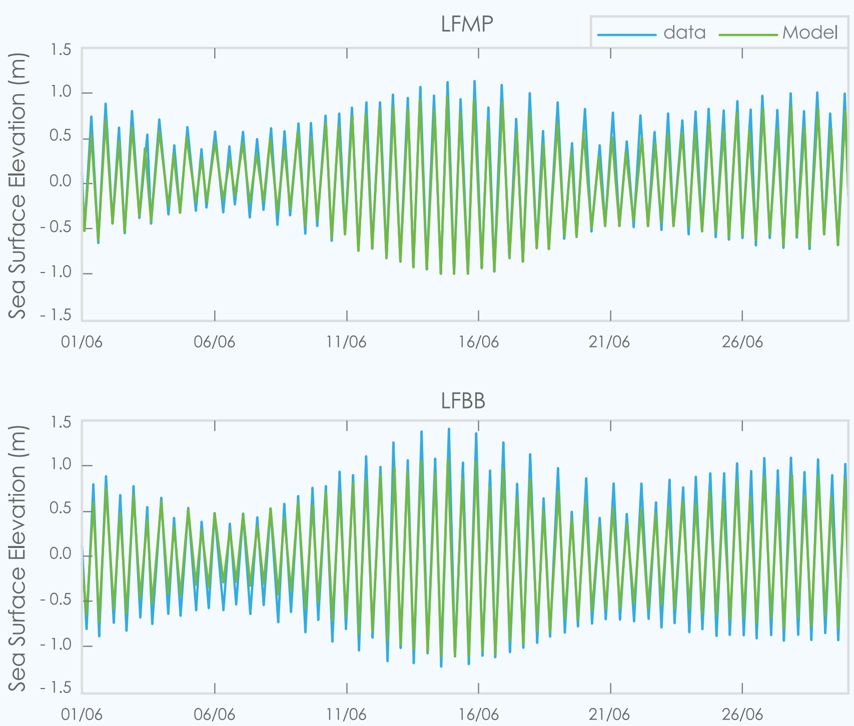


Fig. 22 Positions of the long-term moorings (salinity, temperature, and water level) and short-term RDCP current meter deployments.

Lough Foyle's complex bathymetry with a network of channels, intertidal areas, and mud and sand flats posed a challenge for the calibration of the propagation of the tidal and estuarine circulation. Thus, the model uses a space-variable friction in the formulation of bottom boundary condition, represented by the Manning-Chézy formulation.



This parameter allows for the variation of bottom drag as the tide changes the depth of the water column and was the main adjustment performed during model calibration process.

Model predictions were compared against observed water levels measured at permanent moorings located at the mouth of lough (LFMP) and near the mouth of Foyle River (LFBB).

Fig. 23 Observed and predicted sea surface elevation time series at LFMP and LFBB stations.

The calibration runs of the model were performed using measured freshwater inputs from the catchment for the Mourne, Roe, and Bann River discharges, supplied by the Centre for Ecology & Hydrology.

After the calibration and during the simulation phase, the model used freshwater calculated by the SWAT model (see *Catchment Model*). The detailed results of the SWAT model were aggregated in 16 interfaces between the catchment and the estuary for the rivers Mourne, Roe and Faughan. Measured data was used for the Bann River.

Table 6. Comparison of harmonic analysis results of observed and predicted sea surface elevation data for LFMP and LFBB (M_2, S_2, O_1 and K_1 constituents).

	Tide gauge	Amplitude (m)			Phase (o)		Lag (minutes)
		Data	Model	Difference	Data	Model	Difference
M_2	LFMP	0.61	0.54	0.07	202.66	195.70	14
	LFBB	0.77	0.61	0.16	231.15	220.05	22
S_2	LFMP	0.19	0.20	0.01	218.20	217.61	1
	LFBB	0.24	0.21	0.03	253.13	249.96	6
O_1	LFMP	0.06	0.06	0.00	22.47	34.41	51
	LFBB	0.08	0.06	0.02	45.71	42.46	14
K_1	LFMP	0.11	0.09	0.02	171.42	165.57	23
	LFBB	0.12	0.09	0.03	174.36	175.45	-4

The predicted tidal elevations closely follow the observed records, showing that the numerical model proficiently reproduces the tidal propagation inside the estuary. The RMS error between the predicted and observed time series reaches a maximum of 0.17 m at LFBB and is partially attributable to the propagation of the error already incorporated by the regional model placed at approximately 0.1 m.

The predictive skill is close to 1 for both stations. This estimator incorporates not only the point-to-point comparison but also the correlation between observed and predicted datasets, confirming the excellent agreement between both. The time lag and elevation difference between model results and observations is considered negligible as shown by comparison of amplitude and phase for main harmonic constituents M_2, S_2, O_1 and K_1 in Table 6.

Tidally varying velocities were compared with the observations measured by the three RDCP current meters containing valid data for the four units deployed (Fig. 22).

Fig. 24 shows the model's RMS error and skill at several depths in the water column above the instruments. Apart from the unit deployed in the Saltpans which showed poor data at quality control, there is good agreement between the measured and the modelled velocity data.

The skill of the model's representation of water temperature and salinity is a value in itself but also indicates how well the exchanges between the lough and its boundaries are being represented (Table 7).

Fig. 24. Velocity RMS error (a) and Skill (b) at South Channel Buoy (red), Saltpans (green) and Greencastle (blue).

Salinity and water temperature data sampled near surface and near bottom in LFMP and LFBB stations (Fig. 4) was available for comparison with model predictions (Fig. 24).Both temperature and salinity showed a consistent representation of the annual cycle and showed proficient sensitivity to event-scale changes. However, the model showed consistently lower values of bottom salinity when comparing with the moored salinity sensor at LFMP and LFBB. Apart from the traditional bio-fouling problems associated with long-term salinity measurements, these instruments showed salinity values at the mouth of the lough (LFMP) higher than what is reported in the literature for the salinity at the shelf, pointing to a consistent error in their measurements.

The extensive tests conducted on the model's formulation showed no major flaw in its setup. Testing of the inputs at the boundaries and the internal mixing and stratification processes indicated a robust configuration that is reflected in the excellent results obtained for temperature. The model showed consistent horizontal stratification inside Lough Foyle characteristic of a well-mixed estuary. The maximum salinity zone moved inland between Redcastle and Quigley's Point during summer. During winter and spring, in episodes of high runoff and during neap tides there was some vertical stratification induced by freshwater input with evidence of estuarine circulation.

This moved the maximum salinity zone to the mouth of the lough, influencing the neighbouring coastal area with reduced salinity values. In late spring and early summer, vertical stratification was caused by temperature. The model clearly showed the influence of the shelf's oceanography in Lough Foyle's temperature and vertical stratification.

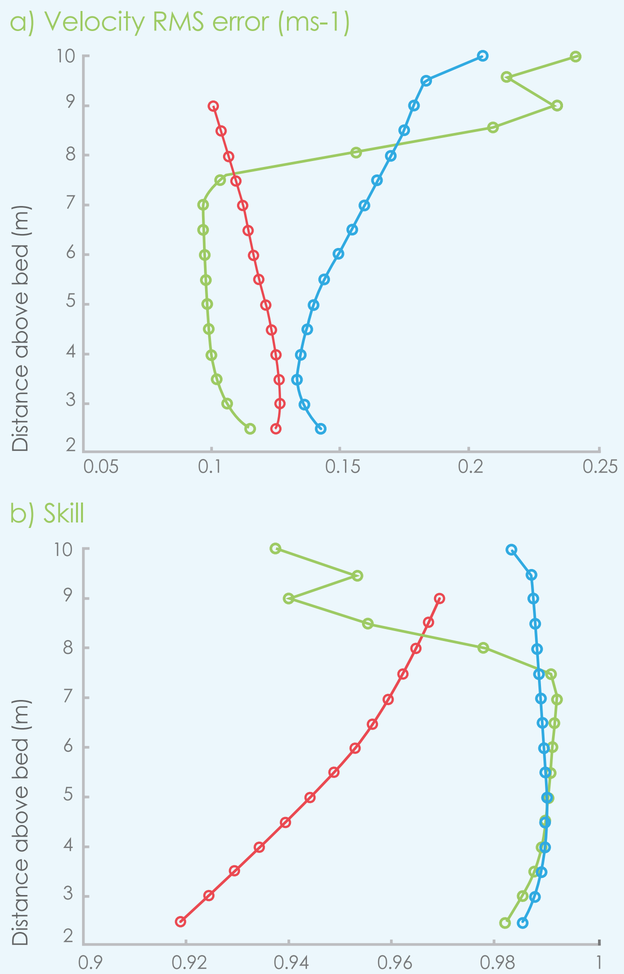


Fig. 24 Velocity RMS error (a) and Skill (b) at South Channel Buoy (red), Saltpans (green) and Greencastle (blue).

In late spring and early summer, a plume of thermally stratified water was observed rounding Malin Head, spreading to the mouth of the Lough and entering the estuary with the aid of the local hydrodynamics.

Table 7. Comparisons of data and model predictions for salinity and temperature.

LFMP						
	Salinity			Temperature		
	RMS	Bias	Skill	RMS (ºC)	Bias (ºC)	Skill
Surface	3.33	0.54	0.70	1.62	0.70	0.96
Bottom	4.02	1.08	0.61	1.30	-0.46	0.96

LFBB						
	Salinity			Temperature		
	RMS	Bias	Skill	RMS (ºC)	Bias (ºC)	Skill
Surface	3.71	2.00	0.88	1.44	-0.61	0.97
Bottom	4.78	1.75	0.81	1.51	-0.53	0.98

This water originates beyond the shelf edge and is moved into the Malin Shelf when conditions allow for the southeast migration of the Islay Front. This contrasts with the conditions in winter where the vertically mixed shelf water outside the lough originates in the Irish Sea.

Shellfish Growth Models

Individual growth models were tested with WinShell and calibrated for Lough Foyle based on growth curves and measured environmental drivers. A bespoke model was developed for the European oyster, *Ostrea edulis*.

The growth model of *O. edulis* was tested and validated using CTD data collected in the Foyle from April 2014 to August 2015. The observed data for native oyster growth trials with Ortac™ cages were taken from Jersey Sea Farms. The Ortac™ cages were sampled monthly from April 2014 with corresponding water chemistry samples being taken at the nearest station (LF9).

The model validation curve is driven by observed data from station LF9. Both the oyster fresh weight (upper pane) and shell length (lower pane) showed a good match to measured values (Fig. 25).

This individual model, together with AquaShell models for the blue mussel and Pacific oyster, was then integrated into EcoWin and developed as a population dynamics model, operating at the system scale.

These individual models are also available in the FARM model, providing consistency in tools within the modelling framework.

WinShell is not appropriate for scaling individual growth to populations, but it does provide extended information on the growth and environmental performance of an individual animal.

In particular, the rates of different processes such as the waste streams (pseudofaeces, faeces, and excretion) can be examined, and a comprehensive overview of the bivalve's performance over a culture cycle is presented in the form of a mass balance (Fig. 26).

The workbench application provides confidence to the user by comparing growth and environmental performance.

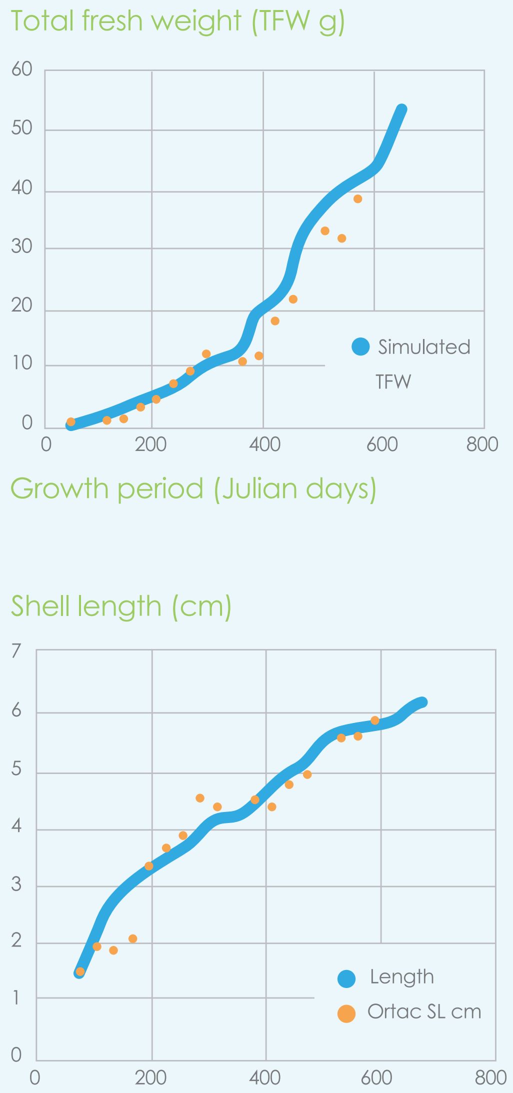


Fig. 25 Validation of growth for European oyster.

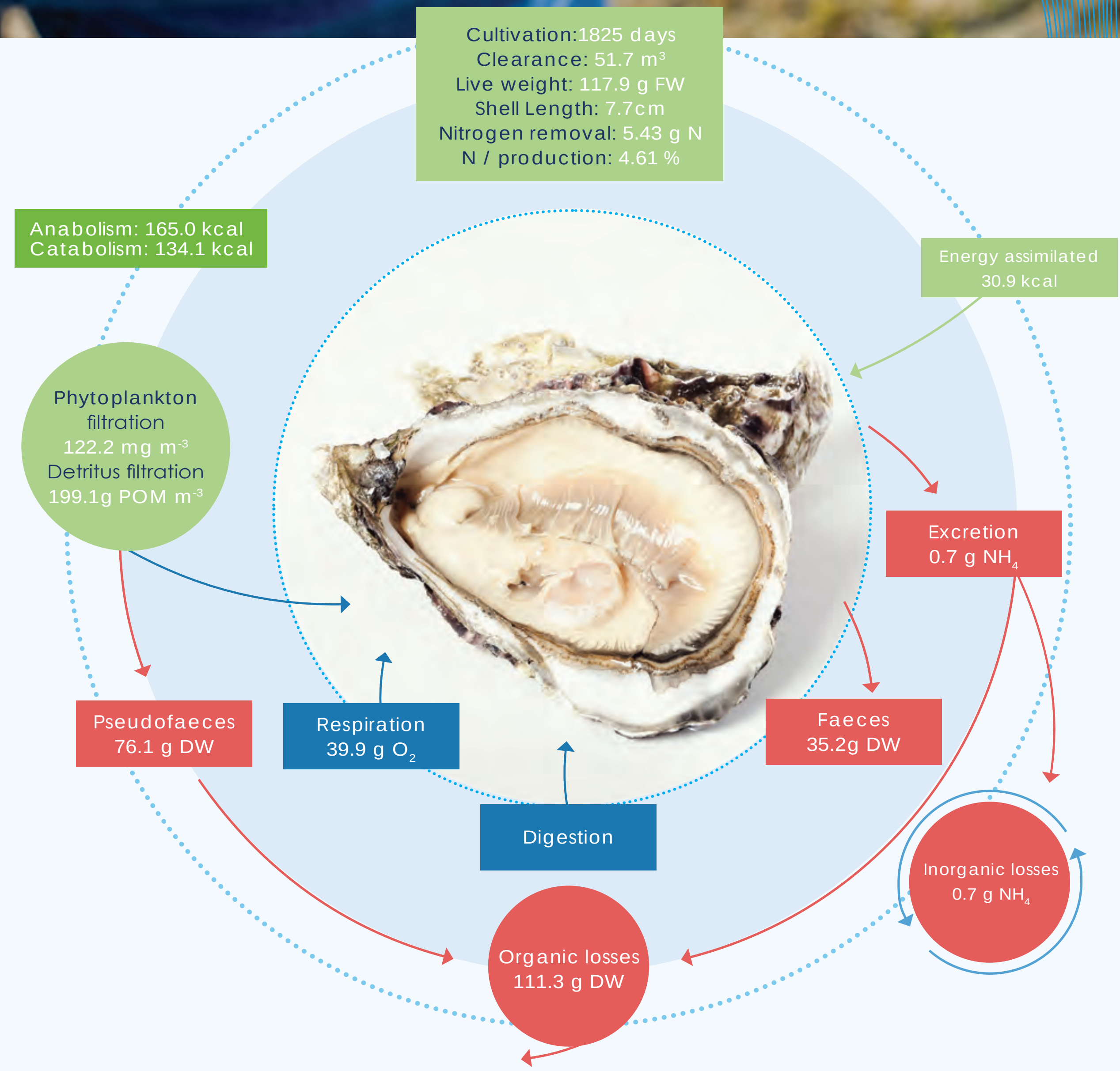


Fig. 26 Mass balance for the European (native) oyster *Ostrea edulis* over a culture cycle.

ECOWIN

The EcoWin.NET model was developed for Lough Foyle using a three-stage approach.

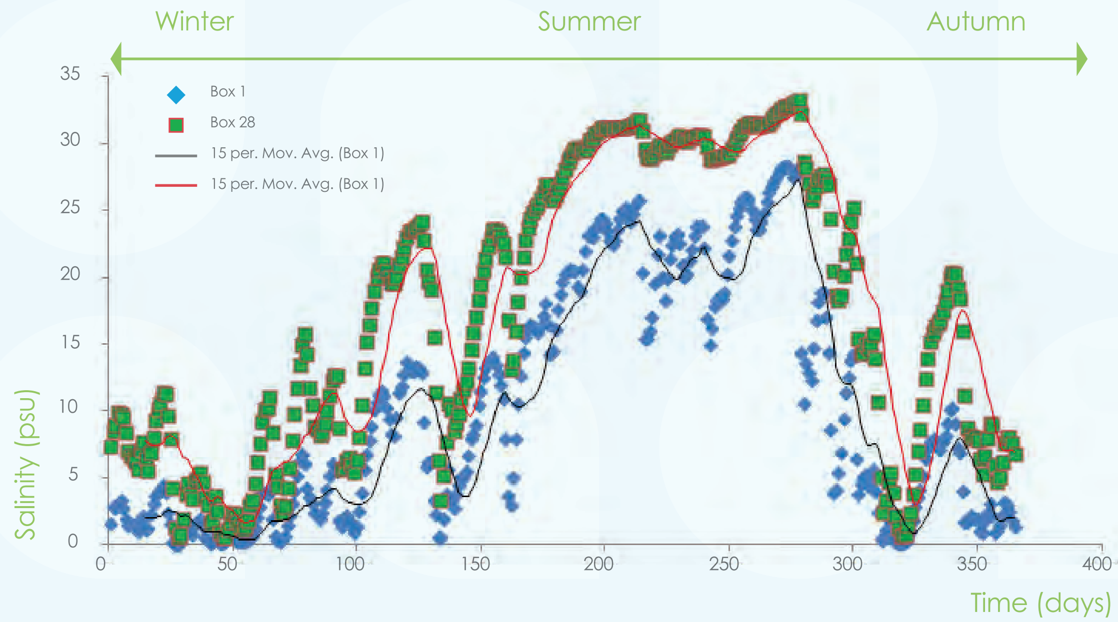


Fig. 27 Analysis of EcoWin salinity outputs (discrete values and moving averages) for the upstream boxes of the model (Box 1 = upper vertical layer, Box 28 = lower vertical layer).

System-Scale carrying capacity

Stage I implemented the physical framework, i.e., the definition of the morphology, boundaries, all the boxes and boundary water exchange (fluxes) results from SWAT and Delft3D- Flow. This was verified through the analysis of volume conservation over an extended (decadal) period, and the comparison of water residence times output by the more detailed circulation model and EcoWin.

In addition, EcoWin outputs for conservative variables such as salinity were matched against measured data and/or analysed for consistency with observed patterns.

Fig. 27 shows an example of this analysis for the most upstream segments of the Lough, illustrating the vertical stratification observed and the typical seasonal variation in salinity.

Stage II introduced all the relevant biogeochemistry, both for the water column and the sediment, together with the nutrient loading from all the contact points between SWAT and EcoWin. Nutrient discharges were provided as daily inputs to EcoWin, thus allowing the ecosystem model to respond to fluctuations in both agricultural and point-source discharges.

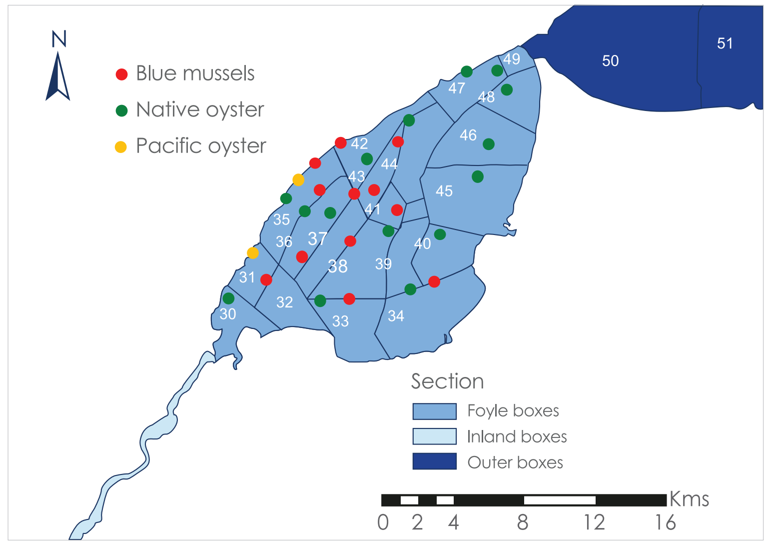


Fig. 28 Bottom boxes used for shellfish culture.

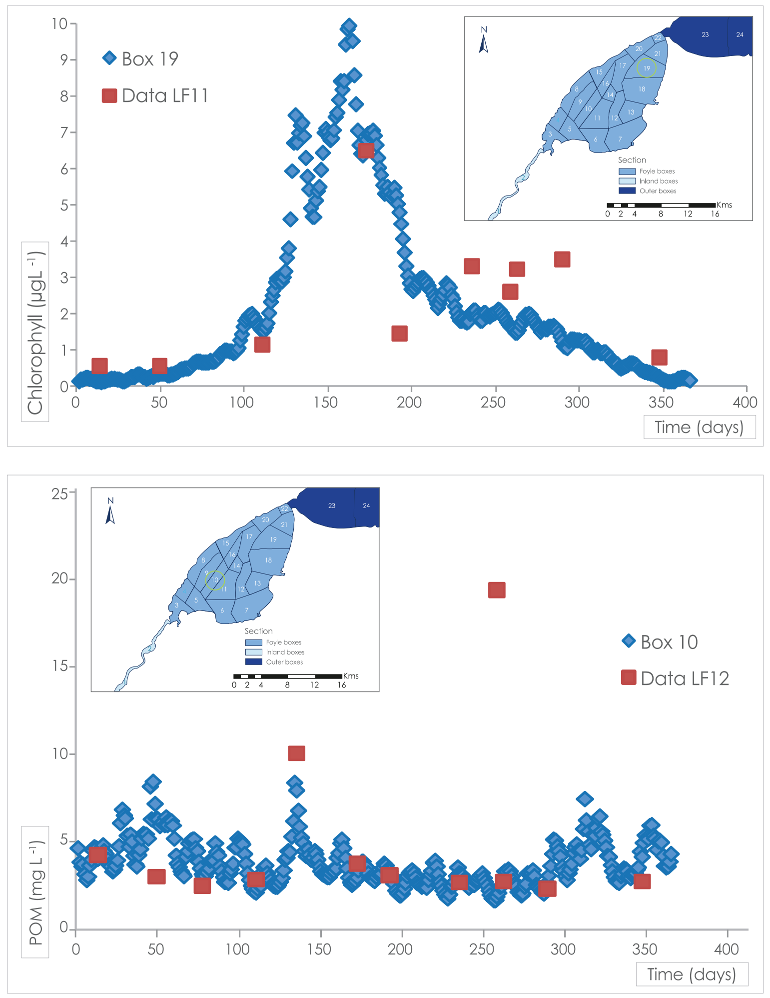


Fig. 29 Validation of chlorophyll *a* (upper pane) and POM (lower pane) in different model boxes.

At this stage the model was calibrated against measured data for key state variables such as dissolved inorganic nitrogen and chlorophyll (as a proxy for phytoplankton concentration).

Stage III added the cultivation component to the model. This included a full description of culture practice, including seeding and harvest periods and sizes, grow out duration, stocking density and natural mortality. A 'man' object, responsible for seeding and harvesting multiple species completed the model setup. Bryozoans were also added as wild species, to better represent the partitioning of food resources between the shellfish and *Alcyonidium* sp.

After the inclusion of all components in this final stage, the model was recalibrated and validated against measured data, because the Stage II validation would now result in an excessive drawdown of phytoplankton and detrital organic matter.

This model was defined as the standard EASE model and was then used to analyse the system-scale carrying capacity of Lough Foyle. Fig. 28 shows the EcoWin boxes where shellfish culture takes place. A subset of these boxes were used to extract the carrying capacity results for Lough Foyle. The boxes shown correspond to the lower layer of the model, since all culture takes place on the bottom.

The standard EASE model is run for a period of ten years, i.e., for multiple culture cycles of all three shellfish species (Fig. 29).

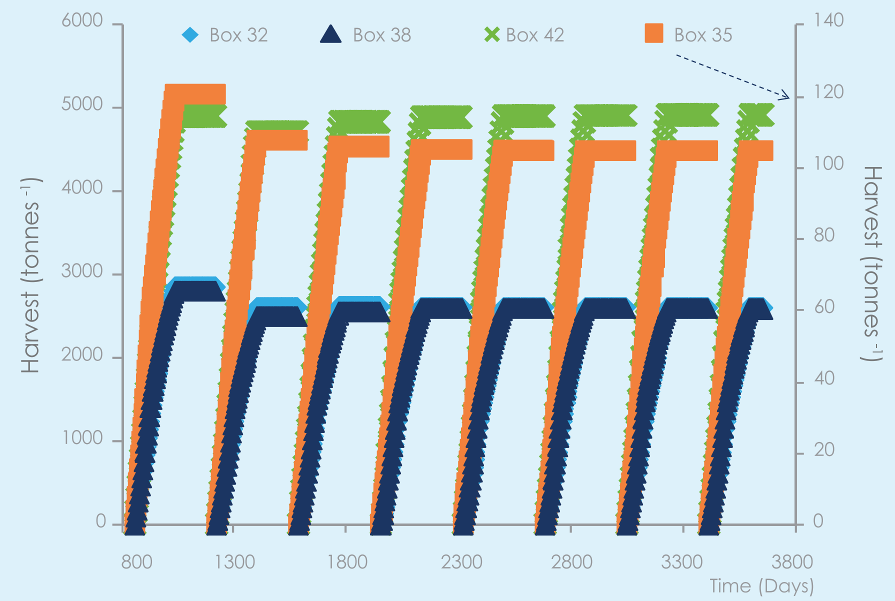
Table 8. Annual harvest for each shellfish species in Year 9 of a decadal run (tonnes y^{-1}).

Box	Blue mussel	Native oyster	Pacific oyster
30	-	1.87	-
31	-	3.96	1009.53
32	2742.9	2.5	-
33	101.29	-	-
34	99.72	1.52	-
35	108.93	13.31	936.42
36	291.73	14.28	-
37	58.83	4.97	-
38	2777.59	-	-
39	97.06	6.78	-
40	-	4.24	-
41	3003.21	-	-
42	5053.06	0.22	-
43	1364.02	0.62	-
44	160.54	0.1	-
45	-	0.36	-
46	-	0.95	-
48	-	0.03	-
49	-	-	-
Total	15859	56	1946

Table 8 shows the annual production in Year 9 of the model run. The native, or European, oyster is the most widely cultivated species, but with a relatively low overall harvest. Pacific oysters are cultivated intertidally on the north shore of the upper lough.

The results for blue mussels are based on the historical areas and densities for cultivation and reflect yields at the peak of the industry, in the 1990s. Currently, harvest is much reduced due to lack of seed availability—this can be simulated in the model as a scenario.

Fig. 30 Fig. 30. Blue mussel harvest over time for a ten-year period, four selected boxes.



The harvest pattern for blue mussels is shown in Fig. 30 over a complete model run period of ten years. The first crop is harvested by the third year, so seven complete and one incomplete (the last) periods are shown. The higher harvests in the first three years are typical outputs for this kind of model and correspond to a spin-up period where smaller mussels accumulate on the bottom. From Year 6 (Day 1825) onward, a standard pattern is repeated for all the boxes, with a steady removal of mussels over the harvest period, and then no further harvest until the next period begins. The same kind of output can be seen for Pacific oyster and native oyster, although in the latter case only five complete harvests are simulated in a decade, because the growth cycle is much longer, a full five years.

In some model boxes, the harvestable biomass of native oysters is very low if blue mussels and wild species (bryozoans) are enabled. The effect of bryozoans on the end-point weight of the different species is shown in Table 9. There is a marked difference in the average weight of blue mussels (-26%) and native oysters (-24%) due to competition for food, but Pacific oyster growth appears to be much less affected.

Table 9. Effect of wild species on the growth of cultivated shellfish in the Foyle.

Live weight (g)	Blue mussel	Native oyster	Pacific oyster
Average without wild species	35.2	52.4	115.3
Average with wild species	25.9	39.7	108.6
Maximum without wild species	47.5	231.4	142.5
Maximum with wild species	40.5	209.2	134.1

The model tends to overestimate blue mussel individual growth, but because the emphasis is on the cultivated stock, and the population dynamics model is based on a weight-class approach, the harvestable biomass outputs are realistic since the highest-class ranges from 19-22 g live weight.

Fig. 31 shows the spatial distribution of the Average Physical Product (APP) for blue mussels and native oysters. The APP is the ratio of harvest: seed, and thus a proxy for return on investment. Mussel culture appears to be more profitable in the central area of the lough, whereas native oysters grow better in the upper part of the system.

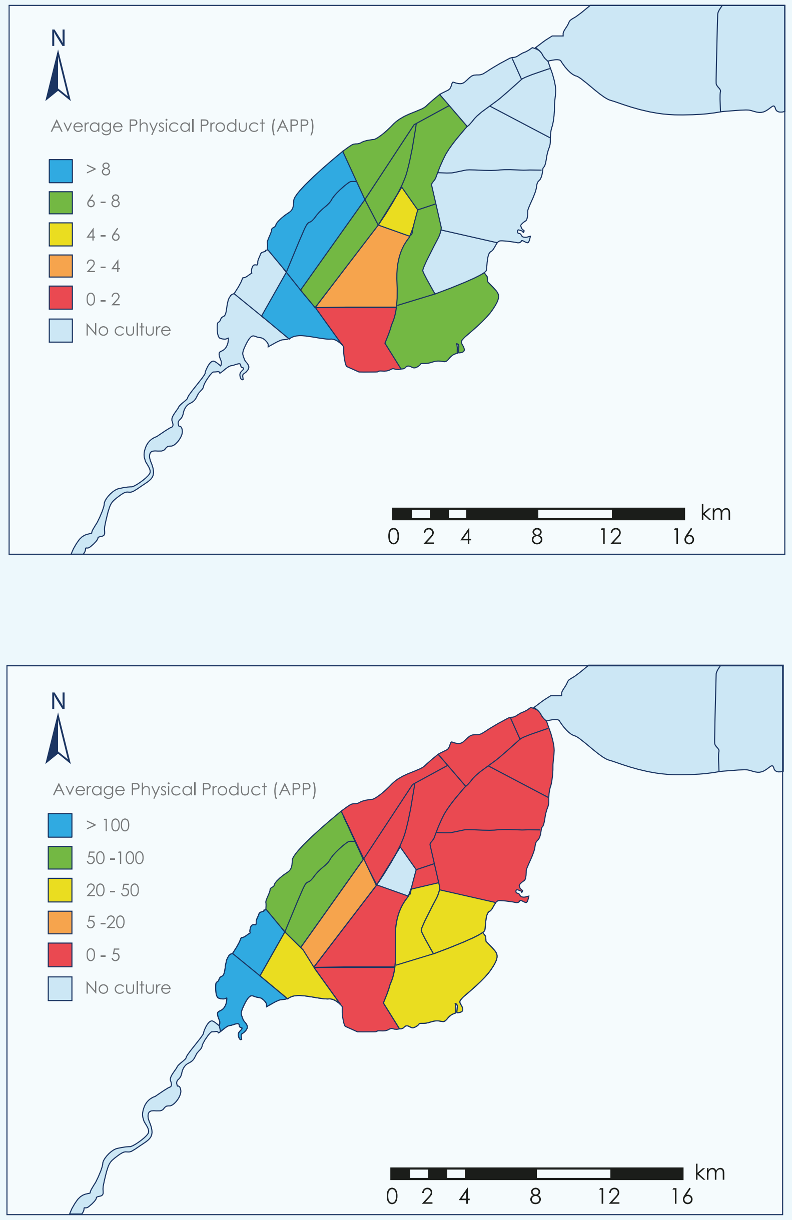


Fig. 31 Average Physical Product (APP) for blue mussels (upper pane) and native oysters (lower pane).

The poorer growth performance of native oysters in boxes where blue mussels are grown, and where Alcyonidium also competes for food, is reflected in the lower APP values, sometimes nearing zero. In general terms, oysters tend to have a much greater APP than blue mussels, where a multiple of 10 for a 1 -1.5 g seed weight mussel already corresponds to a harvestable animal.

The emphasis of the SMILE project was on production and ecological carrying capacity, but since then a substantial amount of research has been carried out on the quantification of shellfish ecosystem services, particularly with respect to nutrient regulation.

In parallel, the EU Water Framework Directive (WFD - 2000/60/EC) mandated that European surface waters achieve (at least) Good Status by December 2015. The abundance, biomass, and composition of phytoplankton are biological quality elements of the WFD. Chlorophyll *a* is an appropriate indicator for both abundance and biomass.

In instances where the concentration of chlorophyll *a* exceeds the threshold for a Good Status, measures must be implemented to improve water quality. In Lough Foyle, phytoplankton growth depends largely on nutrients derived from the catchment, and much less so on those from urban sources (see Catchment Model section).

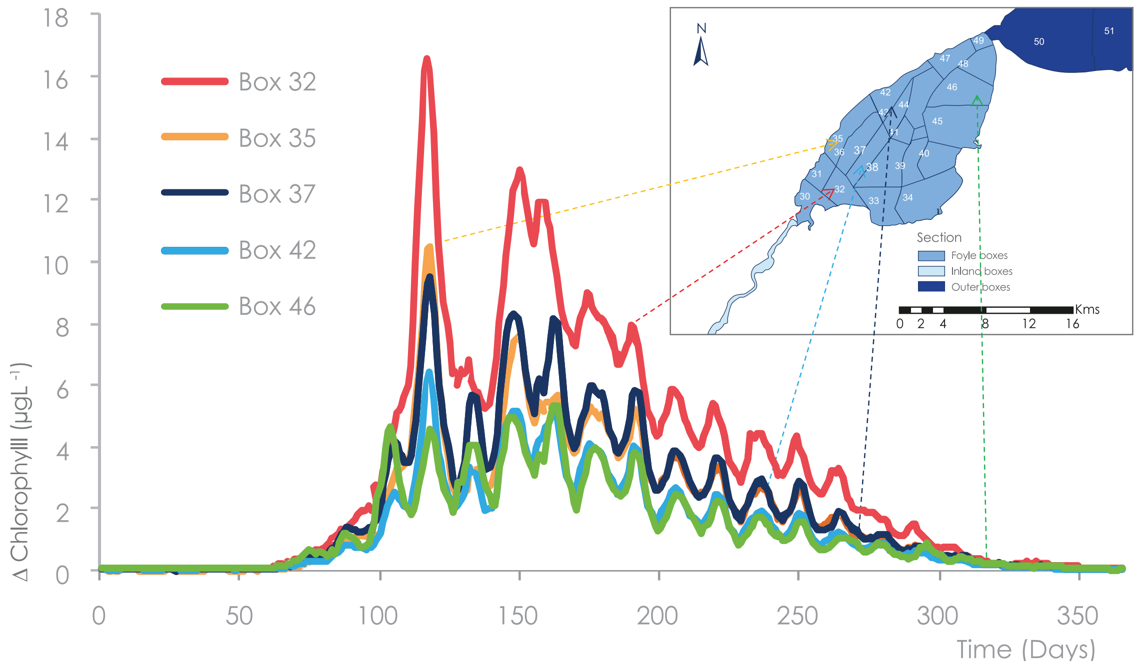


Fig. 32 Top-down control of eutrophication by shellfish at five model boxes in Lough Foyle (dotted lines).

This means that excessive algal growth cannot easily be controlled at source by nutrient removal, because that requires substantial changes to agricultural practices such as fertiliser application.

Bottom-up control measures are an option in such cases, but in addition, managers may analyse the potential benefits of top-down control. Shellfish cultivation is organically extractive, and therefore a complementary measure in limiting chlorophyll concentrations in Lough Foyle.

The analysis of chlorophyll concentrations with and without shellfish in the Lough was carried out using the EcoWin model (Fig. 32). The graph shows the difference in chlorophyll depending on whether the shellfish are active or not and suggests that filtration of algae and organic detritus makes a significant contribution to eutrophication control, particularly in the upper reaches of Lough Foyle.

Shellfish cultivation, therefore, takes on an important role in nutrient management and legal compliance. The removal of algae (primary symptoms of eutrophication) before the organic decomposition stage (secondary symptoms) acts to reduce hypoxia since it greatly reduces the organic substrate availability.

Local-scale carrying capacity

Local-scale carrying capacity was addressed through the application of the well-tested Farm Aquaculture Resource Management (FARM) model.
The model is used for evaluating production, environmental sustainability, and economic performance. System-scale carrying capacity is the appropriate metric for supporting policy options in terms of Lough Foyle as a whole, but a local-scale model can then provide a more accurate assessment for detailed licensing decisions.

The FARM model can use measured environmental drivers, but scenarios can also be analysed by extracting these drivers from the EcoWin model. As an example of this approach, FARM was run for Box 42, the most productive area of Lough Foyle. In this box, blue mussel and native oyster are cultivated; however, the yield of the latter is affected negatively by resource competition with blue mussels.

EcoWin model results for Year 9 were used, and the FARM setup used the standard culture practice of native oyster with a culture period of 5 years and seeding at Day 72, with a seed weight of 0.2 g per individual and included the presence of wild species to simulate resource partitioning by Alcyonidium.

Table 10. FARM results for native oyster in EcoWin Box 42

FARM section	Seed (ton)	TPP (ton)	APP (-)	Revenue (TVP k€)	Cost (k€)	Profit (k€)	Individual Weight (g TFW)	Length (cm)
1	0.1	6.1	65.2	30	0.093	30	164.26	8.31
2	0.1	6.1	65.2	30	0.093	30	158.19	8.26
3	0.1	6.1	65.2	30	0.093	30	158.24	8.26
Total	0.3	18.2	65.3	91	0.279	91	160.23	8.28

Table 10 shows a summary of FARM outputs. The model suggests that native oyster farming is profitable in this part of the Foyle, with a yield (TPP) of 18.2 t for this example farm, and an average physical product (APP = harvest/seed)—a proxy for return on investment—of about 65.

The FARM model provides a mass balance of the culture cycle, including phytoplankton and detritus removal from the water. Regulatory ecosystem services from shellfish cultivation include the net removal of nitrogen due to filtration, and the model therefore helps quantify top-down control of eutrophication.

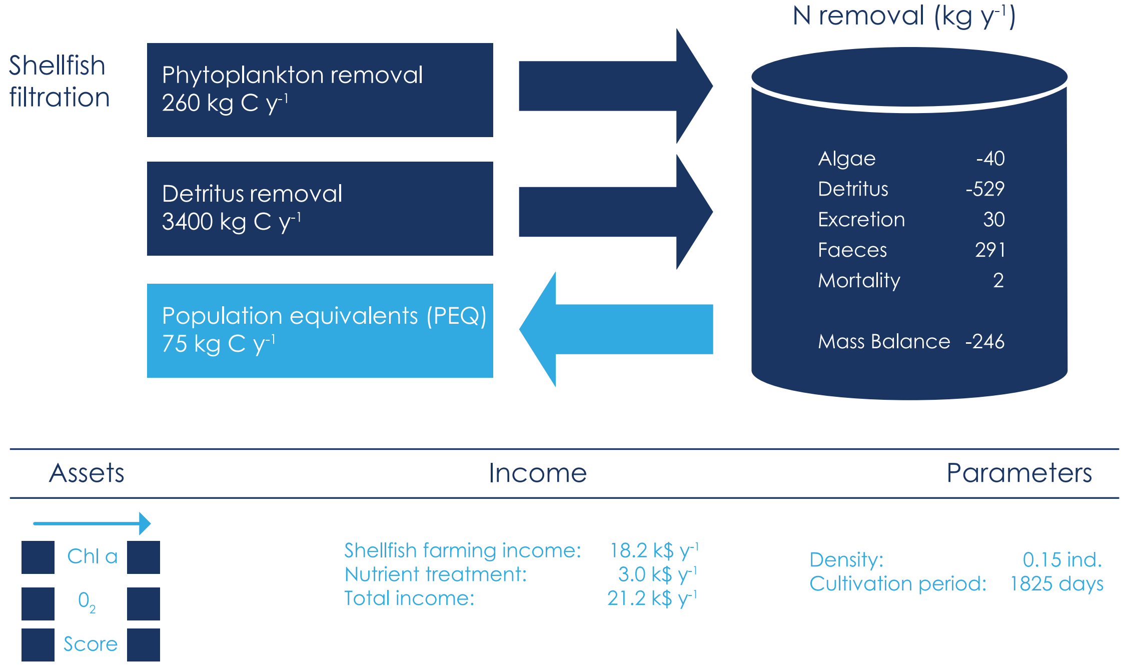


Fig. 33 Mass balance for shellfish cultivation in Box 42.

The removal of 246 kg y^{-1} of nitrogen by native oyster in Box 42 (Fig. 33) contributes to the compliance with WFD thresholds and equates to the removal of loading from 75 population equivalents (PEQ). If there were complementary measures in place for valuation and trading of regulatory services supplied by native oysters, the shellfish farmer would be able to obtain about £2,250 as compensation for nutrient control.

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V. Management Recommendations

Catchment Loading Scenarios

The SWAT model was applied for Lough Foyle with different sediment, nutrient, and POM loads. The lower and upper limits for loads were taken from realistic scenarios, reproducing catchment conditions that existed at some point in time. The changes made to baseline conditions in each scenario are shown in Table 11. The four scenarios were:

- **Baseline:** the standard model developed for the EASE project, reproducing conditions since the mid-2000s.
- **Nature:** the scenario with the lowest nutrient loads. Reproduces what would happen without human occupation, i.e., without agricultural and WWTP loads.
- **High:** the scenario with the highest nutrient loads. It reproduces the situation in the late 1990's as described by Foy and Girvan (2004), with less wastewater treatment and more fertiliser use.
- **Nitrates Action Programme (NAP):** a slight change to nitrogen loads due to changes in fertilisation and management practices. Reproduces the changes to present-day conditions from 2011 onwards, caused by the implementation of the Nitrates Action Programme 2011-2014 and 2015-2018.

The changes from the baseline conditions are shown in Table 12, and the results and source apportionments are shown in Fig. 34.

Table 11. Changes to the EASE baseline conditions made in each scenario.

Parameter	Nature	High	NAP
Land management	No land management; all agriculture and grazing converted to natural areas	Same as baseline	Fertiliser application in February. Better soil conservation measures during winter
Livestock	None	Increased: 10% over baseline	Same as baseline
N fertiliser limits	N/A	None	Pasture: same as baseline Cereals: lower
P fertiliser limits	N/A	None	Pasture: lower Cereals: same as baseline
WWTP loads	None	Increased: values by Foy and Girvan (2004)	Same as baseline
River Bann loads	No streamflow controls; assumed natural flow	Increased: values by Foy and Girvan (2004)	Decreased: lower loads estimated from changes in the Foyle catchment

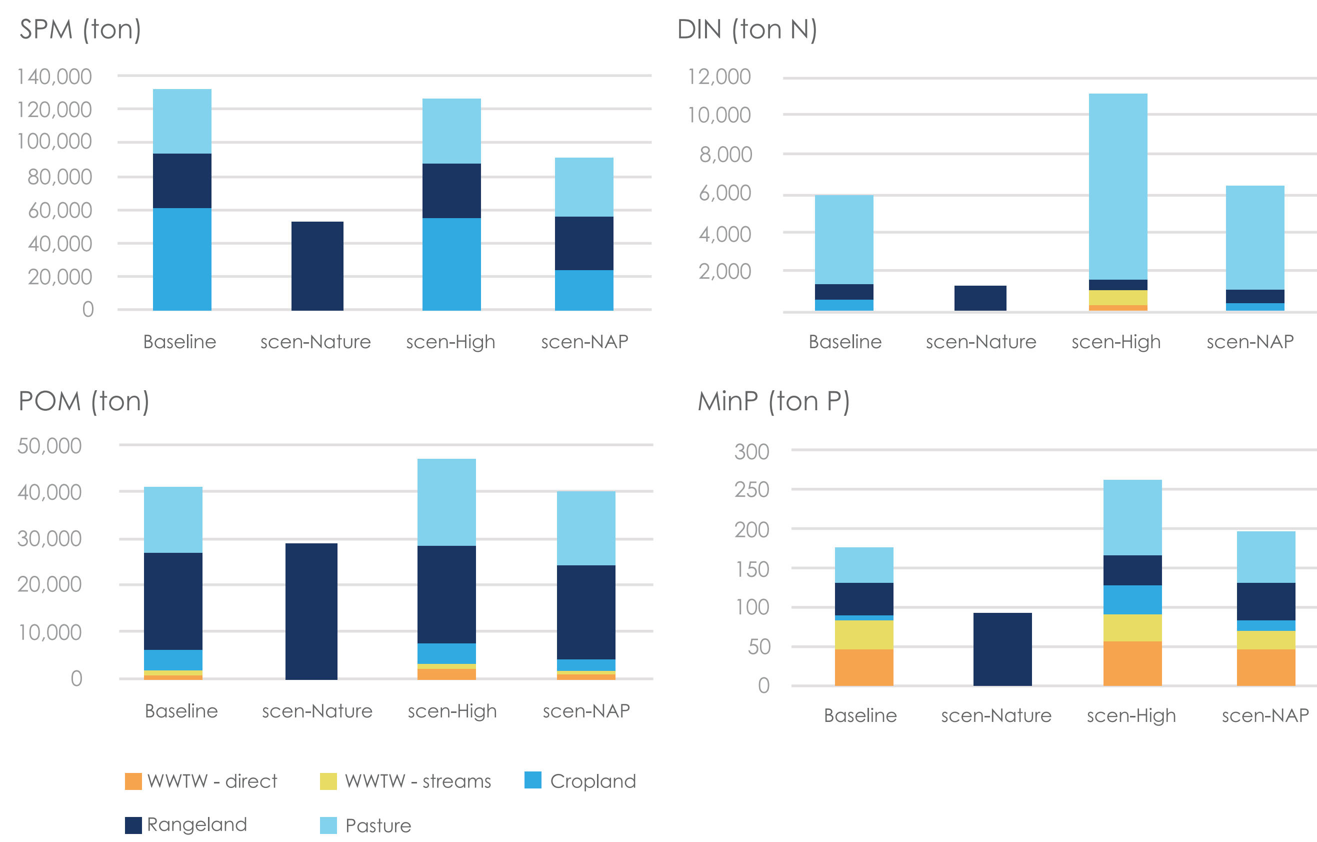
All scenarios had little impact on streamflow. The Nature scenario shows a large decrease in and DIN, due to the higher vegetation cover and lack of grazing; the decrease in MinP and POM were smaller but still important.

Table 12. Percentage change in SWAT estimates for loads into Lough Foyle compared with the baseline scenario (average annual values).

Variable	Nature	High	NAP
Streamflow	1.8%	-0.5%	-0.2%
SPM	-60.2%	3.3%	-31.2%
DIN	-79.2%	65.1%	3.1%
MinP	-42.0%	31.7%	4.2%
POM	-29.8%	20.8%	-2.8%

The High scenario led to large increases in DIN and important increases in MinP and POM; these changes were due to higher loads from WWTPs, and in the case of DIN, also from higher fertilisation rates in pastures. The NAP scenario led to important decreases in SPM due to the use of soil conservation measures during winter. It also led to a slight increase in DIN and MinP, despite similar fertilisation rates; here, the delay in fertilisation led to a slight delay in vegetation growth, leaving more nutrients available for mobilization.

Fig. 34 Source apportionment for loads into Lough Foyle (excluding coastal loads) for the baseline and the different scenarios (average annual values) according to the SWAT model.



The SWAT outputs for the four scenarios were used to generate new driver files for the Lough Foyle ecosystem model (EcoWin.NET). EcoWin was not recalibrated for the scenario model runs, since the key objective was to examine the differences in selected indicators when the loading from the catchment was altered. The indicators chosen, together with the rationale for these choices, are shown in Table 13.

Table 13. Indicators and rationale for analysing different loading scenarios.

Variable	Proxy for	Rationale
Chlorophyll	Phytoplankton biomass	Primary symptom of eutrophication
Dissolved inorganic Nitrogen (DIN)	Nitrogen in the lough	Causative factor of eutrophication
Net primary production (NPP)	Lough productivity	Eutrophication and shellfish yield
Bivalve shellfish harvest	-	Model objective function (human use)

The results for the four scenarios are presented in Table 14. Although phytoplankton biomass does not change significantly from the baseline situation to either the Nature or High scenarios, there are significant differences for DIN, NPP, and harvestable biomass of shellfish. Among the different shellfish species, the European (or native) oyster, *Ostrea edulis*, appears to be the most responsive to the increased nutrient loading.

Table 14. Results for Lough Foyle indicators with different loading scenarios.

Indicator	Baseline	Nature	High	NAP
Chlorophyll P90 (µg L^{-1}) *1	4.1	3.8	6.6	4.5
DIN P90 (µM) *1	25.5	14.2	41.2	25.5
Net primary production (gC m^{-3} y^{-1}) *2	22.1	5.7	49.8	25.5
Blue mussel harvest (t y^{-1}) *3	15858.9	11465.4	21309.1	16792.8
Native oyster harvest (t y^{-1}) *3	55.7	27.1	81.4	59.7
Pacific oyster harvest (t y^{-1}) *3	1945.9	1701.4	2046.9	1960.6
Total shellfish harvest (t y^{-1}) *3	17860.5	13193.9	23437.5	18813.1

*1 - Average for bottom boxes
*2 - P90 for surface boxes (daytime NPP only)
*3 - Model Year 9

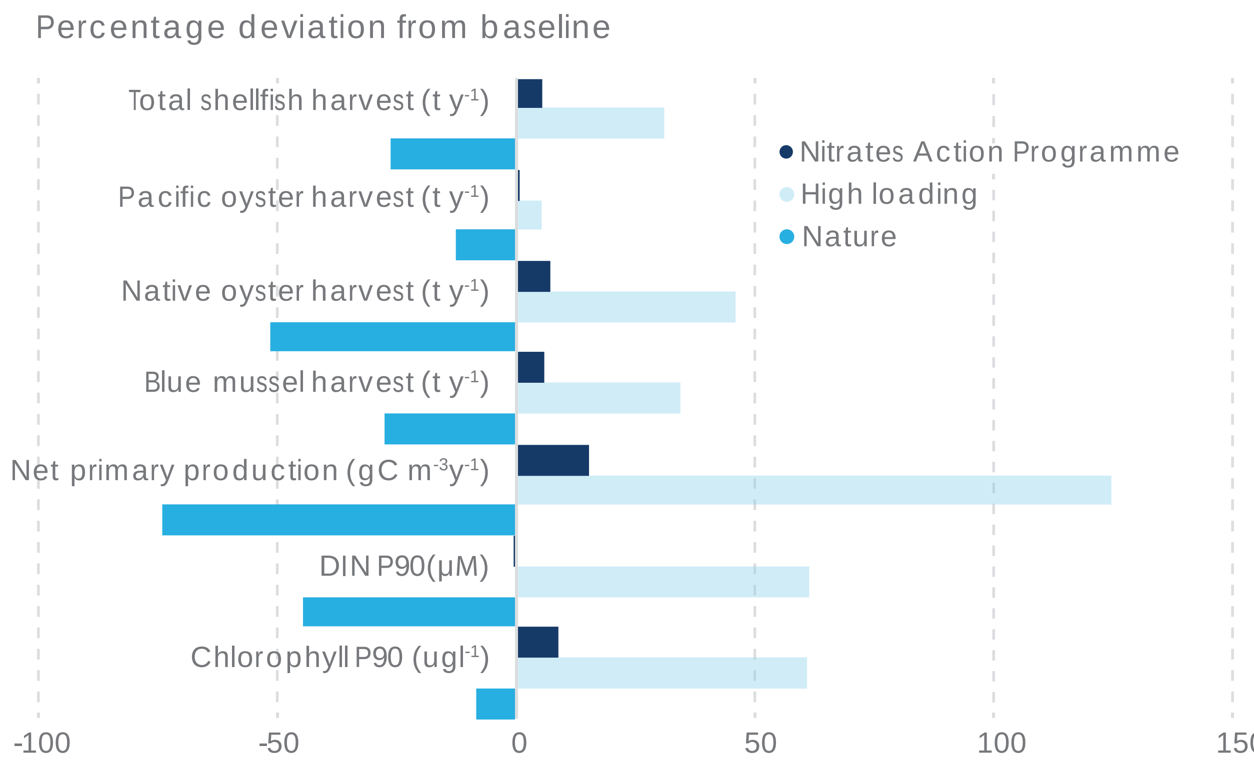


Fig. 35 Percentage change in indicators for eutrophication and shellfish performance for three different scenarios in Lough Foyle.

There is little difference between the Baseline and NAP scenarios for any of the indicators, but where differences are observed, the NAP values are higher than the ones in the standard model. In percentage terms (Fig. 35), the differences are generally below 10%, except for net primary production. A possible explanation considered was the significant reduction in the particulate loading to the lough (-31.2%, Table 12) under the NAP scenario, which could result in enhanced primary production in the upper reaches of Lough Foyle. This was tested by running the NAP scenario model with the original (baseline) TPM loading however, this does not result in a decrease in net primary production.

The difference in the timing of fertiliser application, where the baseline model has inputs in January, and a reduction in nitrogen loading in subsequent months, is the most likely explanation for the difference in NPP. The NAP model reduces the N loading in winter months and increases it as the year progresses to compensate for this, which in turn boosts primary production, phytoplankton biomass, and shellfish productivity.

This is an interesting consequence of the NAP management measure, designed to reduce nitrogen discharge to the coastal zone, but which increases the expression of primary symptoms of eutrophication in the lough, albeit not significantly

Comparison of Source Control and Bivalve Regulatory Services

This modelling framework was also applied (Fig. 36) to analyse various nutrient loading scenarios, and their effect on chlorophyll concentration. The percentile 90 value was chosen as the appropriate indicator, for consistency with the ASSETS model for eutrophication assessment, and mean values are shown for all the modelling domain.

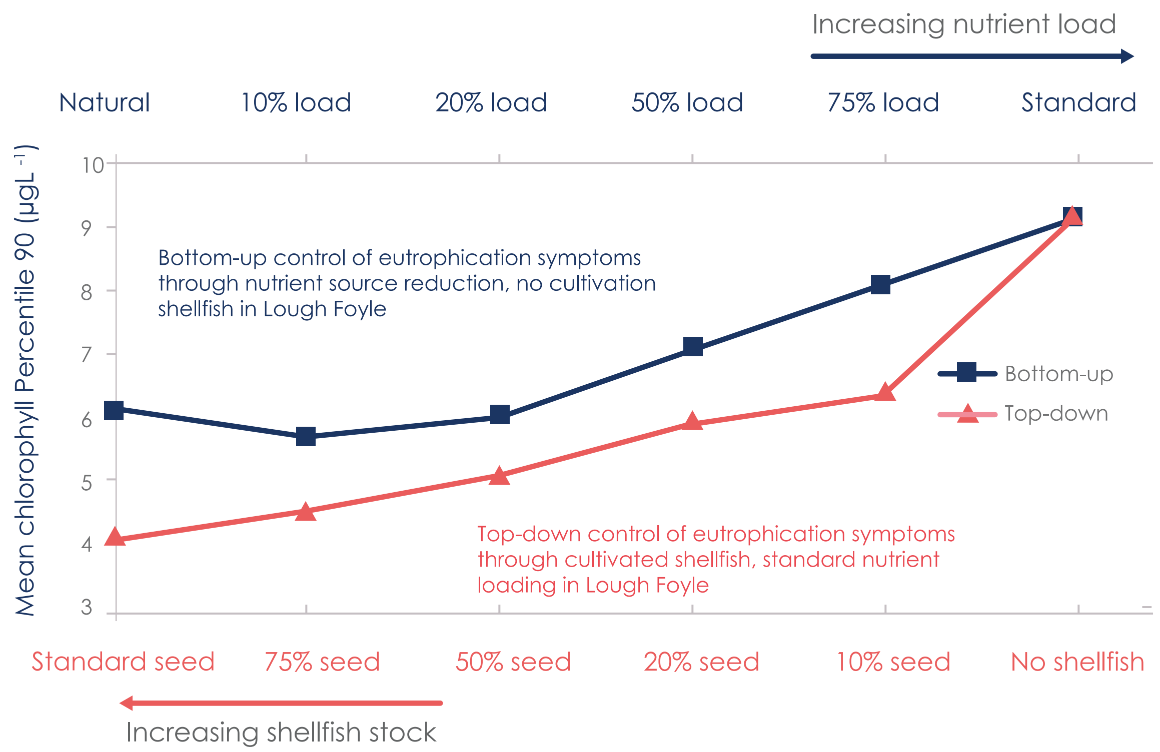


Fig. 36 Chlorophyll drawdown with bottom-up and top-down control simulated with the EcoWin.NET system-scale model.

The top-down control considers the standard nutrient loading and varying stocking densities for bivalves and the bottom-up control represents the effect of source-control on primary production, without any cultivated bivalves in the system. Under natural conditions (no agricultural activity or urban areas), simulated using the SWAT hydrological model, the chlorophyll P90 is about 6 μg L^{-1}, increasing to 9 μg L^{-1} (without bivalves).

Bivalves, under standard nutrient loading conditions, lower the P90 to 4 μg L^{-1}, i.e. (in the model) bivalve filter feeders are considerably more successful in mitigating elevated chlorophyll concentrations in Lough Foyle than nitrogen source control.

The calculations are made separately for the two types of measures, but common-sense dictates that combined solutions should be the preferred option, not least because of the danger of moral hazard in exempting agriculture from better management practices.

The decrease in N load, ΔL (t y^{-1}), was correlated with the corresponding reduction in chlorophyll P_{90}, Δa (μg L^{-1}). The cost of reducing emissions at source was determined by considering a unit cost 10.8 € kg^{-1} N, converted from a value of 12.4 USD kg^{-1} N, estimated by Lindahl et al. (2005) for 47 small stabilization ponds (lagoons) in Sweden, and multiplying by the load reduction ΔL. Load reduction can thus be expressed in monetary units C (M€ y^{-1}), and regression analysis yields Eq. 2, with a correlation coefficient r = 0.999 ($p_{<0.01}$).

$C = 27.2\,\Delta a + 3.37$ (Eq. 2)

Eq. 2 states that for Lough Foyle, a reduction of 1 μg L^{-1} for chlorophyll P_{90} costs 30.57 M€ y^{-1} in terms of source control. Furthermore, the cost per kg applied is low when compared with data for non-point mitigation (Fig. 37). Eq. 2 was used to determine the alternative cost of the regulatory service provided by bivalves in Lough Foyle, by calculating the value associated with the chlorophyll P_{90} decrease for four scenarios, 20%, 50%, 75%, and 100% present bivalve stocking density, when compared to no bivalves in the lough. In parallel, equivalent source-control costs are shown for 4 N loading reduction scenarios, relative to 10% of the present-day load.

Apart from the systematically higher offset provided by bivalves in each scenario when compared to source control, the most striking observation is the difference in the value of the regulatory service provided by bivalves calculated using the different approaches, i.e., nutrient removal (N), and chlorophyll abatement (Δa). The ratio of symptom value (chlorophyll) / causative factor value (N) for the four scenarios varies between 5.8 and 13.7, for the lowest to highest stocking densities (20%, 50%, 75%, and 100%, see Fig. 37).

Fig. 37 Valuation of bivalve ecosystem services in Lough Foyle calculated using the EcoWin.NET system-scale model; negative values (red bars) are the cost of nutrient source control.

This appears to be the first comparative analysis that focuses on eutrophication indicators and suggests that for this particular system the value of regulatory ecosystem services supplied by bivalves—in this case three different species—will be underestimated by an order of magnitude if the approach is based on an equivalence of source control.

The degree to which such an approach can be generalised, without the development of a complex suite of models for different estuaries and bays in the UK, Ireland, or elsewhere, is a question that requires further analysis. In particular, variations in water residence time and underwater light climate will undoubtedly affect the ratio above, since it is well established since the 1950s that physical conditions strongly constrain phytoplankton bloom development.

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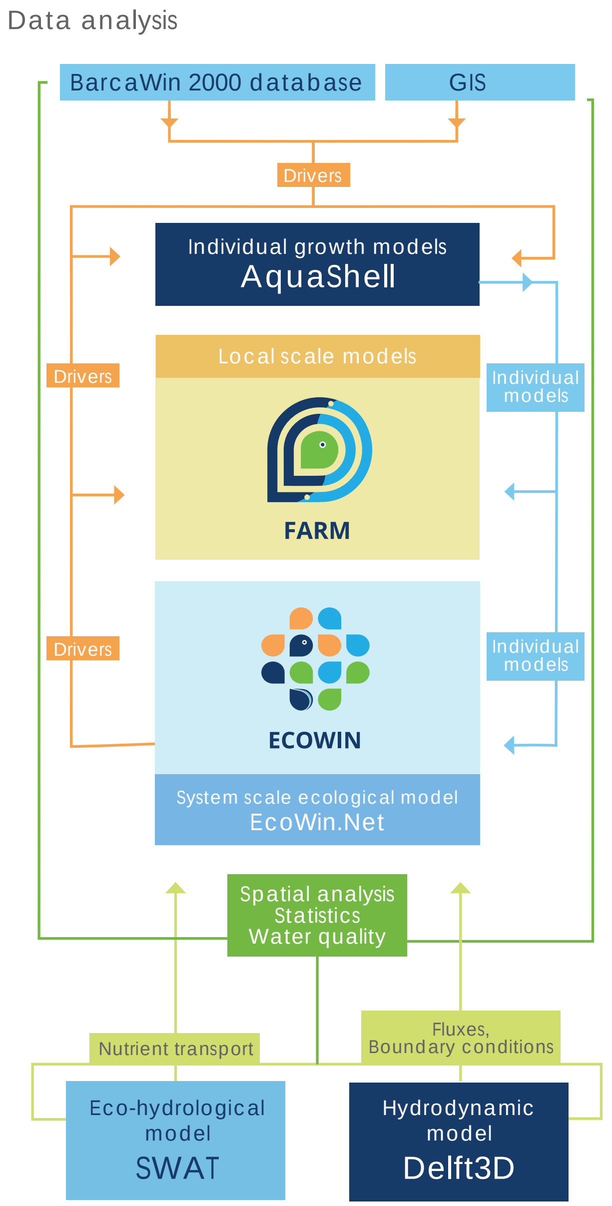
VI. Conclusions

The approach, results, and some examples of policy support achieved within the EASE project were presented in this book.

The application of a complex modelling framework is a recognition that processes occurring at different time and space scales cannot be addressed using a single model but are best analysed at their appropriate scales through the type of framework applied in EASE (Fig. 38).

Fig. 38 General modelling framework for the EASE project.



EASE had four key objectives, detailed below:

- To enable Loughs Agency to have an integrated coastal zone management framework, bringing together catchment pressures, aquaculture activities in the loughs and offshore exchanges. This framework will enable managers to address relevant issues associated with the WFD and the Habitats Directive, and potentially also the Marine Strategy Framework Directive;
- To provide tools for aquaculture management both at the system-scale and at the farm-scale;
- To make improvements to the existing SMILE models for Foyle, with a focus on (i) improved simulation of water circulation; and (ii) more accurate representation of the role of wild species;
- To explicitly simulate the catchment processes through the use of detailed hydrological models.

The successful application of the EASE modelling framework has great potential, in particular to:

1. Enable managers to simulate the growth and environmental effects of culture of oysters and mussels in Lough Foyle;
2. Provide indicators of performance for the shellfish industry with respect to yields, income, and impact;
3. Allow decision-makers to analyse different development scenarios for the shellfish industry in the context of changes in cultivation areas, stocking densities, and multiple water uses;
4. Examine the interactions between catchment-scale pressures such as nutrient discharge, which are linked to urban and agricultural drivers, and the performance of cultivated species in Lough Foyle;
5. Analyse different catchment management scenarios.

All the tools in the framework were made available to both AFBI and Loughs Agency—although these tools are freely accessible by the partnership, there is a significant cost in training and staff commitment, which must be considered as part of the EASE legacy programme. Lough Foyle, like any complex system, has multiple actors engaged in a range of activities, and management is further complicated due to its transboundary nature. It is therefore paramount that significant post-project investment guarantees the capacity-building necessary for using these tools effectively.

All the models shown in Fig. 38 can be used independently, providing answers to the questions they were designed to address.

For instance, the SWAT model can be used to examine changes in runoff and nutrient discharge under different Representative Concentration Pathways (RCP, sensu IPCC) for greenhouse gas concentrations, or to simulate changes to river concentrations of a number of variables (elements) used in the WFD.

The Delft3D model can be used to examine changes to circulation due to dredging or engineering construction works, or for dispersion of enteric bacteria from outfalls, to support siting decisions.

The EcoWin ecosystem-scale model can be used to produce sets of environmental drivers for shellfish growth, e.g. under different conditions of stocking density, to drive local-scale individual based models (IBM) such as the Farm Aquaculture Resource Management (FARM) model, that can be used to support the decisions on the location of new shellfish farms.

Taken separately, these models can be used by local specialists to support decisions by policy-makers in a number of technical areas, and in combination they become a powerful resource for informing complex management choices. This framework also has significant value is being able to analyse potential outcomes of different policies for discussion with local stakeholders and thereby promote a more factually-driven consensus.

EASE demonstrates how much can be achieved in a relatively short period by a diverse, transdisciplinary group, and is the second project of this type to be carried out by Northern Ireland within a period of about a decade. The management tools obtained as outcomes of the work performed in SMILE and further developed in EASE are to our knowledge unique, particularly when used as a framework, covering time scales of a few minutes to ten years, and reflecting an end-to-end approach from soil to sea.

EASE

Enhanced Application of the SMILE Ecosystem Model to Lough Foyle

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