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Towards an ecosystem approach to aquaculture: Assessment of sustainable shellfish cultivation at different scales of space, time and complexity

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ABSTRACT

The need for an ecosystem approach to aquaculture has led to the development of several aquaculture analysis tools in recent years, working at different scales of space (farm- to system-level), time (seasonal to annual and/or long-term analysis) and complexity (ease of use to complex process-based modelling). This work has tested the application of a range of complementary tools to the analysis of aquaculture practices and ecosystem impacts in Killary Harbour, Ireland. The selected tools included a system-scale, process based ecological model (EcoWin2000), a local-scale carrying capacity and environmental effects model (FARM) and a management-level eutrophication screening model (ASSETS). Both the system-scale and farm-scale models used ShellSIM to simulate individual shellfish growth. The tools were used to analyse the relationship between shellfish productivity and food sources, the impacts of changes to stocking densities of shellfish, and an overall assessment of the ecological status of Killary Harbour. EcoWin2000 was able to support a complex analysis, but required a significant amount of input data and effort for calibration and result analysis. FARM was able to provide similar (although less detailed) results at the shellfish farm scale with a smaller effort for parameterization and application, but was limited to testing scenarios with relatively moderate changes to present-day conditions. ASSETS provided simple, management-level results with a relatively low level of input data, although it is not appropriate for complex analysis. This paper illustrates the complementary nature of these tools, and how the unique capacities of each can be combined for integrated assessment of aquaculture in a coastal system. For Killary Harbour, the combined application of these tools revealed that: (i) the system's eutrophication status can be classified as Moderate Low, with a future trend of No Change; (ii) there is a large influence of ocean boundary conditions on shellfish food resources in the system; (iii) the maximum mussel production of the system is 4200 ton year^{-1}, but achieving this level would lead to lower harvest weights and longer growth cycles; and (iv) a scenario of lower stocking densities proposed for the system should lead to lower mussel productions, but could result in benefits such as higher mussel weight at harvest and/or shorter growth cycles.

1. Introduction

Global aquaculture currently stands at a reported production of about 52 million tons, with a valuation of over 61 billion euros (Food and Agriculture Organization, 2009). The relative increase in farmed production, compared to wild fisheries, has generated enthusiasm for the so-called blue revolution, a "new" paradigm for the supply of seafood products to world markets, holding the promise of food security (Sachs, 2007). Several authors (e.g. Costa-Pierce, 2010) have prescribed caution with respect to this vision of a marine panacea on the basis of various factors, including the risk that an ecosystem approach to aquaculture (EAA, e.g. Soto et al., 2008) may not accompany this predicted growth. This surge may largely be an "Asian Tiger" phenomenon, and a deregulated increase in aquaculture production may cause regional asymmetries and social conflicts, and pose a threat to food security as a whole.

In Europe, annual growth of aquaculture has declined to 1%, partly because of market factors, but also because the industry is subject to

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stringent regulation and sustainable development is a major consideration (e.g. Ferreira et al., 2008b). Recent environmental legislation, such as the European Union's Water Framework Directive (WFD; 2000/60/EC) and Marine Strategy Framework Directive (MSFD; 2008/56/EC) has implicitly promoted the three objectives of EAA, namely (i) human well-being; (ii) ecological well-being; and (iii) multisectorial integration.

There is a strong focus on ecological carrying capacity of aquaculture in marine systems (e.g. Goldburg and Naylor, 2005; McKindsey et al., 2006; Mirto et al., 2009; Sequeira et al., 2008), leading to the promotion of terms such as ecoaquaculture (Sequeira et al., 2008) and ecological aquaculture (Costa-Pierce, 2010). In Europe, the U.S., and Canada, the ecological and social pillars of carrying capacity (Inglis et al., 2000) are a clear focus for licensing, allied to the more traditional physical and production aspects (e.g. National Research Council, 2010).

Whereas fed marine aquaculture is relatively new to Europe (<50 years), organically extractive cultivation of shellfish has existed for many centuries, i.e. the "blue revolution" is really blue evolution. Various EU directives now regulate European shellfish culture, addressing e.g. water quality appropriate for cultivation (e.g. Directive 2006/13/EC — quality of shellfish waters), or the environmental effects of shellfish, such as eutrophication and organic biodeposition (WFD and MSFD).

Although shellfish aquaculture in Europe has a potential to expand further offshore (Kapetsky et al., 2010), particularly as appropriate cultivation structures develop, together with mixed use models associated e.g. with wind farms, inshore cultivation remains important in ecological, economic, and social terms.

The analysis and management of ecosystem integration and sustainability of inshore shellfish culture is nowadays supported by different tools, which may be applied at the system level or on a finer spatial scale, and can address a significant proportion of the issues that arise from usage conflicts among the various stakeholders of the coastal environment (Hovik and Stokke, 2007). In the EU, from a legislative point of view, with deadlines looming for both the WFD (2015) and MSFD (2020), detailed requirements promote the use of scientific assessments to determine compliance strategies, increasing demands from growers and managers for improved aquaculture management tools. Such tools vary in complexity, scale, and scope of application.

At one end of the scale are tools designed for low data requirements and ease of use (Borja et al., 2008), including ecological status evaluation methods, such as Assessment of Estuarine Trophic Status (ASSETS; Bricker et al., 2003), the OSPAR Comprehensive Procedure (OSPAR, 2005) or the Differential Drivers-Pressure-State-Impacts-Response (DDPSIR; Nobre, 2009). These tools are by definition highly aggregated, and can use both measured data and outputs of other types of models.

A number of tools exist for spatial analysis (Kapetsky et al., 2010; Nath et al., 2000), in some cases coupled with dynamic growth models (Kapetsky et al., 2010). In others, this type of Geographic Information System (GIS) takes into account legislation, point-source discharges, and other factors (Ervik et al., in preparation). At a finer spatial scale, tools addressing production and ecological sustainability are available (e.g. Ferreira et al., 2007b; Weise et al., 2009).

At the other end of the scale are more detailed research models, which resolve the circulation and boundary exchanges of water, dissolved, and particulate substances, together with internal processes (e.g. primary production, cycling of nutrients and organic matter) that interact with shellfish growth. Most of these models address aquaculture production, with a limited focus on ecological carrying capacity (McKindsey et al., 2006). Examples include box models for analysis of mussel carrying capacity (Filgueira and Grant, 2009), ecosystem models for food depletion (Grant et al., 2008), 3-D biogeochemical (Marinov et al., 2007), and ecological models (Ferreira et al., 2008b).

A recent trend has been the integration of multiple ecosystem evaluation methods to address management problems with different levels of complexity (Nobre and Ferreira, 2009). This integration includes complex biogeochemical multi-model approaches (Melaku Canu et al., 2010; Nobre et al., 2010), ecological–economic models (Nobre et al., 2009) or integration between simple and complex tools (Nobre et al., 2005). These approaches play different and often complementary roles in coastal system management, depending on the strengths of each assessment tool. Indeed, there is an outstanding requirement to better understand the relative roles that assessment tools with different levels of complexity can play in multi-method evaluation frameworks.

This paper aims to contribute to the EAA, and therefore to improved management of coastal systems where aquaculture occurs or is at the planning stage, by exemplifying the application of a range of complementary tools to analyse various aspects of blue mussel (*Mytilus edulis*) cultivation in Killary Harbour, Ireland. Three different levels of complexity are addressed, by means of:

1. A system-scale ecological model, EcoWin2000 (Ferreira et al., 2008b);
2. A local-scale carrying capacity and environmental effects model, FARM (Ferreira et al., 2009); and
3. A management level eutrophication screening model, ASSETS (Bricker et al., 2003), capable of qualifying system-scale trophic status.

Together, these tools address the four objectives of this work:

1. To provide an understanding of the role of boundary exchanges and internal processes in the production and environmental effects of shellfish cultivation in different parts of a system;
2. To determine local scale carrying capacity, economic potential, and the role of organically extractive aquaculture, including both positive and negative environmental impacts, as well as other externalities;
3. To evaluate eutrophication status, both for the current situation and in scenarios, supporting the determination of ecological status (*sensu* WFD);
4. To illustrate how combinations of different tools can be used to leverage the potential of each one and provide a robust platform for decision-support in implementing EAA.

2. Methods

2.1. Study site

Killary Harbour (Fig. 1) is a fjord-like inlet, 15 km long and 0.75 km wide, with a total area of 9.9 km^2, average depth of 15 m and an average volume of 4.5×10^9 m^3. It has a maximum depth of 45 m at the mouth, which opens out onto the Atlantic Ocean. Tidal range is 3.7 m with strongest currents at the narrow mouth of the inlet (50 and 30 cm s^{-1} at 1 and 10 m, respectively). The water column is stratified or partially mixed and a pronounced halocline can occur between 3 and 10 m during winter and summer, which can be broken by strong winds.

The average freshwater input to the system is 6.0 m^3 s^{-1}; around 90% of this input is contributed by the Bundorragha, Erriff and Bunowen rivers; streams account for the remainder. The mountainous catchment area is about 250 km^2 with high annual rainfall (2000 to 2800 mm year^{-1}). The population is very sparse: Leenaun is the main centre (150 people), located near the head of the estuary. Farming is extensive, with mountain pastures grazed by sheep, small numbers of cattle grazing lower slopes, and intensive production of grassland and hay. The watershed lies within a designated Special Area of Conservation. The majority of farmers are involved in the Rural Environmental Protection Scheme which brought about a 30% reduction in sheep numbers since 1998, with more cuts planned for the future, to reduce damage from overgrazing.

Rope culture of blue mussel (*M. edulis*) in the estuary began in the 1970s. The harbour was designated for aquaculture and mussel farming boundaries were set in 1984. Today's cultivated area is 157 ha, with an annual production of 1632 ton year^{-1} (fresh weight; data for 2006) and a productivity of 10.4 ton ha^{-1} year^{-1}. Mussels are grown on longlines from which 8 m long dropper ropes are suspended, and recent intensification of mussel cultivation has been blamed for poor growth and harvest (Bord Iascaigh Mhara, 2002). An option of decreasing

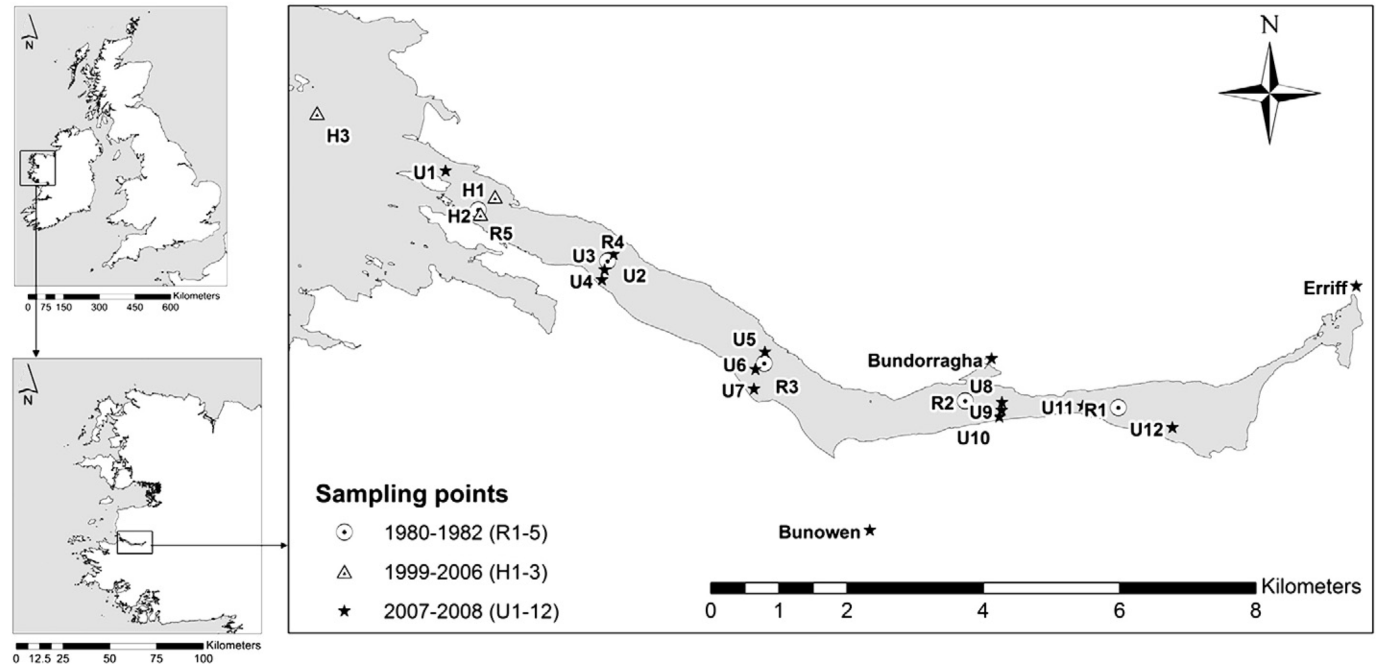

Fig. 1. Location of Killary Harbour (left) and map of sampling points according to campaign dates (right); stations for the 2007–2008 campaign in rivers Bundorragha, Erriff and Bunowen are also shown.

seeding densities to improve mussel growth in the system is currently under discussion by aquaculture stakeholders.

A first oceanographic survey of Killary Harbour took place in 1974 before aquaculture began (Keegan and Mercer, 1986) and includes physico-chemical and ecological information. A more in-depth study was conducted in 1980–1982, when a small amount of mussel cultivation was already present, and was reported by various authors (e.g. Rodhouse et al., 1984; Rodhouse et al., 1985; Rodhouse and Roden, 1987). It focused on the spatial, vertical and seasonal patterns of physical water properties, dissolved and particulate nutrients and carbon, phytoplankton, and on mussel ecophysiology. Water quality sampling for most parameters was performed on a fortnightly basis. Physico-chemical parameters included Secchi depth, salinity, nitrite, nitrate, phosphate, chlorophyll *a*, particulate organic matter (POM) and particulate organic carbon (POC). A more recent survey was conducted in 1999–2006, focusing on differences between the inner and outer parts of the system and also including vertical and temporal variability. Finally, another survey with similar characteristics was conducted in 2007–2008, but with a greater distribution of sampling points inside the system than either of the previous studies. The parameters sampled in the 1999–2006 and 2007–2008 campaigns are shown in Table 1; all parameters were sampled monthly, except in 1999–2007 for nutrients (sampled in winter, once every two months from 1999 to 2001, and monthly since 2002) and chlorophyll (sampled from spring to autumn, monthly). Water samples (Fig. 1) were taken at surface and bottom in both campaigns, with an additional collection at 10 m for 1999–2006, and at 5 m for 2007–2008. Additionally, water current velocity was measured continuously near the sea boundary in 2007–2008.

Monthly mussel samples were collected for ecophysiology and aquaculture productivity during one year (2007–2008), for two age cohorts, at several depths along dropper ropes. For each sample, weight, volume, number of individuals, and length and wet weight of individual mussels were determined; for subsamples, the wet and dry weights of individual mussel tissue and shell were also measured. This was completed with an assessment of mussel productivity and total mussel standing stock via a producers' questionnaire and coupled with some sample collections.

2.2. Site assessment methods

This study applied and compared and combined three assessment methods to evaluate shellfish cultivation practices in Killary Harbour: the EcoWin2000 system-scale ecological model, the FARM local-scale aquaculture growth model and the ASSETS coastal eutrophication assessment tool.

EcoWin2000 (Ferreira, 1995; Ferreira et al., 2008b) is a well-tested ecosystem modelling platform for coastal water bodies. It is able to simulate hydrodynamics, biogeochemistry and aquatic cultivation either by itself or by integrating results from more detailed models. Required information includes hydrodynamic and biogeochemical boundary data (land and/or ocean) and information on cultivated species and practices. Spatial discretisation can be horizontal or vertical, relying on homogenous "model boxes" with variable dimensions. The

Table 1
Measured parameters in the 1999–2006 and 2007–2008 campaigns (marked with X); station location is shown in Fig. 1.

Parameter	1999–2006 (stations H1–3)	2007–2008 (stations U1–12)
Temperature	X	X
Salinity	X	X
Oxygen	X	X
Secchi depth	X	X
NH_3	X	X
NO_3	X[a]	X
NO_2	X[a]	X
Total nitrogen	X[a]	X
PO_4	X[a]	X
Total phosphorus	X[a]	X
Silicate	X[a]	X
Chlorophyll	X[b]	X
Total particulate matter		X
Particulate organic matter		X
Particulate organic carbon		X
Particulate organic nitrogen		X

[a] Sampled from November to March.
[b] Sampled from April to October.

Table 2
Data requirements for EcoWin2000, FARM and ASSETS.

Topic	Data required and sampling frequency[a]			
	EcoWin2000	FARM	ASSETS	Other details
Catchment	–	–	–	
Meteorology and climatology	Monthly[b]	–	–	
River flow	Monthly	–	Long-term average	EcoWin2000 can simulate the impact of strong rainfall events using daily river flow data
River sediment and particulate organic matter	Monthly	–	–	
River nutrient concentration	Monthly	–	Long-term average	
Ecosystem				
Digital bathymetry	Once	–	Once	EcoWin2000 and ASSETS can use system descriptors instead, such as volume, surface area, etc.
Tidal harmonics	Once	–	Once	
Salinity	Monthly	Monthly	Long-term average	Vertical and horizontal profiles
Water temperature	Monthly	Monthly	–	Vertical profiles
Current velocities	–	Spring/neap	–	
Nutrients	Monthly	Monthly	–	NH_4^+, NO_3^-, NO_2^-, PO_4^{3-}
Suspended particulate matter	Monthly	Monthly	–	
Particulate organic matter	Monthly	Monthly	–	
Dissolved oxygen	Monthly	–	Long-term average	EcoWin2000 uses vertical profiles; ASSETS uses preferentially bottom D.O.
Phytoplankton	Monthly	Monthly	Long-term average	Chlorophyll *a*
	Monthly	–	–	Primary production
Macroalgae	–	–	Once	Qualitative data — opportunistic species, e.g. *Ulva*, *Enteromorpha*
Harmful algal blooms	–	–	Once	Qualitative data on frequency, duration and spatial extent
Submerged aquatic vegetation (SAV)	–	–	Once	Cover, trends in spatial distribution
Shellfish				
Culture practice	Once	Once	–	Culture practice for each species at each site: source, size, densities, cultivated areas and timing of deployment for animals for growout, including timing and size at harvest
Cultured species growth, spawning, and mortality	Cycle	Cycle	–	Data describing average mortality and timing of reproduction for each species throughout normal culture at each site
Natural populations of filter/suspension feeders	Seasonal	Once	–	Standing stock, plus any data on feeding and/or growth rates

[a] Minimum sampling frequency required for reasonable model performance.
[b] Not strictly required for model application but extremely useful to understand land-based environmental drivers.

model runs multi-year simulations with sub-daily time-steps. It may be used to examine changes in nutrient inputs (land and/or sea), changes in culture practice, cultivation areas and species, and thresholds for conservation (wild species). However, the system-scale approach does not provide information on farm layout (rope orientation etc.) or farm-scale yields. The model has been extensively applied to coastal systems throughout the world (e.g. Ferreira et al., 2008b; Nobre et al., 2005; Nobre et al., 2010; Nunes et al., 2003).

The Farm Aquaculture Resource Management (FARM) modelling framework applies a combination of physical and biogeochemical models, bivalve growth models, and screening models for determining shellfish production and for eutrophication assessment at the local scale (Ferreira et al., 2007b; Ferreira et al., 2009). Requirements for input data have been reduced to a minimum, since the model is aimed at the shellfish farming community and local managers. Model inputs may be grouped into data on (i) farm layout, dimensions, species composition, and stocking densities; (ii) suspended food entering the farm; and (iii) environmental parameters. The model takes into account food conditions (and depletion) inside a farm, shellfish ecophysiological characteristics, and farming practices.

The Assessment of Estuarine Trophic Status (ASSETS) tool evaluates three components: Influencing Factors, Eutrophic Condition and Future Outlook; and combines them into a single overall rating called ASSETS (Bricker et al., 2003; Whitall et al., 2007). The rating uses observations (quantitative and qualitative data) to determine trophic status, and therefore this evaluation can be made both at a system level and at the farm scale, providing information about how aquaculture impacts eutrophication at both scales. The tool is straightforward in both required parameters and calculations (an automated version is available at NOAA/IMAR, 2010), and is designed to provide management-level guidance, including for poorly sampled coastal systems if required. It was originally developed for U.S. coastal system assessment and has been extensively tested in European systems (e.g. Ferreira et al., 2003; Ferreira et al., 2007a), and in other parts of the world (e.g. Xiao et al., 2007).

2.3. Application of assessment methods

EcoWin2000, FARM and ASSETS each have different requirements in terms of parameterisation and the level of calibration and validation data required to estimate confidence in their results.

Table 2 presents a synthesis of the data requirements for the application of each of the three methods.

2.3.1. EcoWin2000 application to Killary Harbour

EcoWin2000 was applied to the entire Killary Harbour system. The Harbour was divided longitudinally into six regions (Fig. 2), with each region divided vertically into two boxes at depths between 0.3 m (upstream boundary) and 3 m (near the ocean boundary). This division took into account water bodies (*sensu* WFD), bathymetry, water quality, river entry points, mussel aquaculture sites, and the strong vertical stratification observed in this system (e.g. Ferreira et al., 2008b). Box volume decreased substantially with distance to the ocean boundary, and surface boxes had a small fraction (8 to 16%) of the volume of the corresponding subsurface boxes. The long mussel cultivation site close to the northern shore of the Harbour, located in box 5 (Fig. 2), was never an active mussel site and was only considered for box delineation purposes.

EcoWin2000 was applied to Killary Harbour in combination with external approaches to simulate (i) three-dimensional water flows

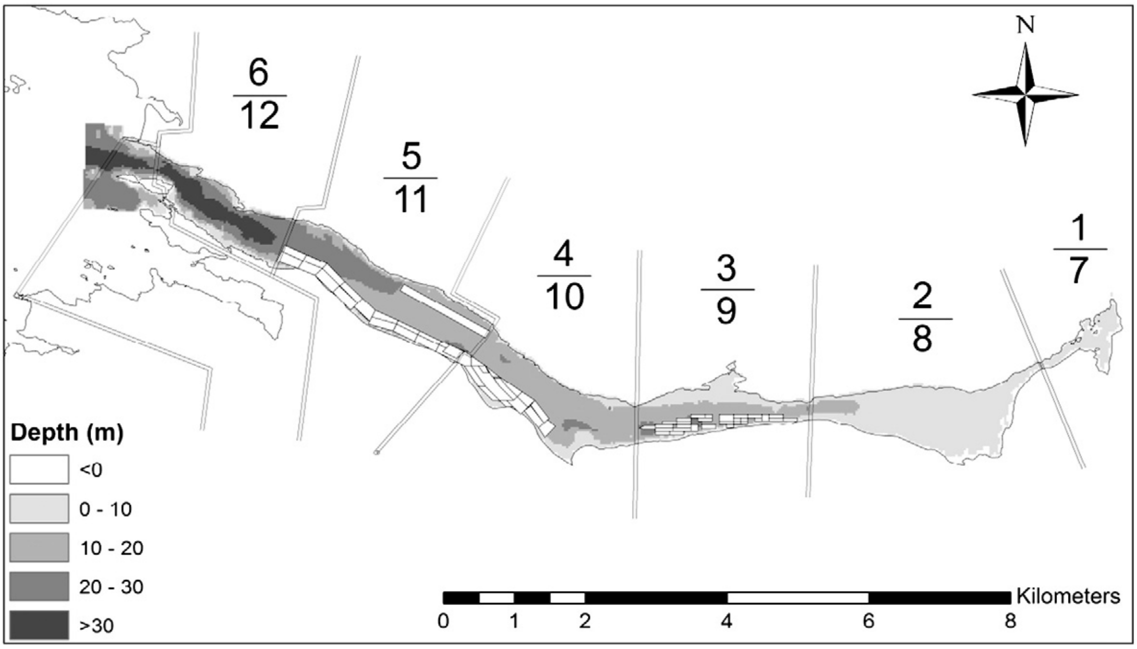

Fig. 2. EcoWin2000 box boundaries for Killary Harbour, with an identification number for the surface and subsurface box; the map also shows bathymetry, with shellfish cultivation areas marked as white polygons.

inside the system, (ii) coastal loadings of water and nutrients, and (iii) resource use by natural populations of filter and suspension feeders; this followed an approach already tested for other systems (e.g. Ferreira et al., 2008b; Nobre et al., 2010).

For Killary, these consisted of:

1. Detailed three-dimensional hydrodynamic modelling using the Princeton Ocean Model (Blumberg and Mellor, 1987). A curvilinear computational mesh consisting of 254×19 horizontal cells and of 11 vertical layers was developed for Killary Harbour. The model was forced with velocities and water elevations at the open ocean boundary located at the mouth of the harbour. Meteorological forcing was applied to calculate the transfer of momentum, heat and fresh water through the ocean surface. Monthly averaged freshwater discharges were specified for the Bundorragha, Erriff and Bunowen rivers. The model was capable of simulating the longitudinal salinity gradient observed in 2007–2008 ($r = 0.95$, $p < 0.01$). These results were integrated in time and space for model boxes to provide vertical and horizontal water flows at their boundaries (Ferreira et al., 2008b).
2. Catchment boundary loads were estimated using a nutrient export coefficient approach based on the CORINE 2000 landcover maps for Ireland and export coefficients estimated from Northern Irish rivers based on soil and river characteristics (Foy and Girvan, 2004). Point sources were assumed to be negligible given the low population. Monthly river flow was estimated by applying the Thornthwaite–Mather water balance method (Thornthwaite and Mather, 1955) to local meteorological data for the 1961–1990 climatological normal, obtained from the National Climatic Data Center (NOAA, 2009). Terrestrial nutrient loads were estimated as 75 ton N $year^{-1}$ and 7 ton P $year^{-1}$. The flows were used to perform a simple proportional partitioning of annual nutrient loads into monthly estimates.
3. Resource partitioning between cultivated and wild species was estimated using the WISE approach (Sequeira et al., 2008). Baseline data came from two surveys, one before aquaculture was introduced in Killary Harbour (Keegan and Mercer, 1986), and another with limited aquaculture activities present (Rodhouse and Roden, 1987). Wild species densities were estimated to be between 1.5 and 9 ind m^{-2}, which are low when compared with present cultivation densities (see below), and in the same range as those reported before shellfish cultivation began, between 1 and 12 ind m^{-2} (Keegan and Mercer, 1986), suggesting little competition for food resources between cultivated and wild shellfish. Filtration by wild species was applied to the bottom layer of the ecosystem model following Sequeira et al., (2008).

Finally, ocean boundary nutrient and phytoplankton loads were estimated using the measured data detailed above.

Shellfish culture density estimates were not available for all farm sites. Density was estimated using two different methods: upscaling existing measurements from individual droppers to the farm scale, and hindcasting from harvested mussel numbers, taking mortality into account, leading to an estimated cultivation density of 400 ind m^{-2}. Seeding was considered to begin in April, followed by a cultivation period of 27 months. Individual shellfish growth was determined using ShellSIM (Plymouth Marine Laboratory, 2007), which was, for this study, fully integrated in EcoWin2000. The model was then used to calculate shellfish population dynamics and its interaction with water quality and primary productivity.

For the concentration of dissolved substances, EcoWin2000 was calibrated and validated using a split sample approach, with the data detailed above. This focused on model estimates for phytoplankton (measured as concentration of chlorophyll *a* and POM, selected to represent available food for mussels, and nitrate, selected to represent available nutrients for phytoplankton growth. In both cases, the model was run for 9 years with the same boundary conditions to allow nutrients, phytoplankton and shellfish to reach equilibrium; year 10 was used for calibration and validation.

The calibration used a “standard year approach”; data for 1999–2006 in the ocean (station H3 in Fig. 1) was used to build a “median year” of ocean concentration of these parameters, by taking the median value of each measurement at surface (0.5 m) and subsurface depths (10 m and below) and the median day of measurement. The model was forced using these values; results for the boundary region (stations H1 and H2, Fig. 1) were used to calibrate the model, using a similar median approach for surface and subsurface depths. Validation used the ocean measurements for 2007–2008 for boundary conditions (station U1 in Fig. 1); model results were evaluated using data collected throughout Killary Harbour (stations U1 to U12, Fig. 1), for surface (1 m) and subsurface (5 m and below) depths. In this case, a synthetic year was built from the data: the beginning of the year used data from January to May 2008, and the rest used data from June to December 2007.

For aquaculture production, the lack of data precluded the use of a similar approach. Instead, the model was calibrated for individual shellfish growth, and validated using system-wide estimates for total mussel biomass in the system in 2007 and aquaculture landings in 2006, using the data referred above; the model results used the 2006–2007 boundary conditions.

2.3.2. FARM application to Killary Harbour

FARM was applied to simulate a typical suspended mussel farm inside the cultivation area of Killary Harbour. After an analysis of individual licensed areas, the simulated farm was considered to be 250 m long and 135 m wide, i.e. with a total area of about 3.4 ha (2% of the total cultivated area). The modelled farm was divided into three sections along the longitudinal axis, and the dropper length was considered to be 8 m (the standard length in Killary Harbour). Water flow was simulated as normal to the farm cross-section, with maximum current speeds ranging from 0.05 m s^{-1} in neap tides to 0.2 m s^{-1} in spring tides, based on the hydrodynamic model results. Environmental drivers (boundary conditions) were taken from a no-shellfish EcoWin2000 model run, averaging results for the cultivation zone (boxes 3, 4 and 5 in Fig. 2). As for the system-scale model, individual shellfish growth was determined through the integration of the ShellSIM (Plymouth Marine Laboratory, 2007) model in FARM. Seeding densities and culture practices were as described above; an annual mortality rate of 40% was estimated, based on experimental data for the first year of cultivation.

Model parameterization followed two assumptions:

1. Mussels at an individual site compete for food resources with other sites, having similar access to available phytoplankton and POM; however, it is difficult to simulate competition for food resources with other farms in FARM, due to the complex vertical current patterns present in Killary Harbour. Therefore, phytoplankton and POM availability for the farm were estimated assuming no other shellfish cultivation in the area, leading to a potential overestimation of food availability.
2. The farm is small enough not to impact overall food resources in other sites. FARM is not an ecosystem-scale model and is therefore not capable of simulating farms which are large enough to affect the cultivation area.

The model was calibrated by comparing measured and simulated individual mussel weights, using the ecophysiological data referred above, and validated using results for total harvest per unit area.

2.3.3. ASSETS application to Killary Harbour

ASSETS was applied to Killary Harbour at the system scale by determining each of its component ratings using a matrix approach, following the procedure described by Bricker et al. (2003). The components were evaluated as follows:

- Influencing Factors (IF) is a combination of a system's natural susceptibility (i.e. flushing and dilution characteristics) and the nutrient load to the system; loads are estimated as the ratio of land (i.e. human-related) and ocean based inputs. This was achieved using, for land-based inputs, the same estimates used for EcoWin2000, and using the ocean nutrient data for 2007–2008.
- Eutrophic Condition (EC) is a combined assessment of five symptoms based on occurrence, spatial coverage and frequency of problem occurrences. The rating is determined from a combination of the average scores for chlorophyll and macroalgae, primary symptoms indicating the start of eutrophication, and the worst score of the three more serious secondary symptoms (dissolved oxygen, submerged aquatic vegetation, and nuisance/toxic algal blooms). The data for 2007–2008 were used for this evaluation but, where possible, historical data were compared to see if there had been any change over time.
- Future Outlook (FO) predicts what future eutrophic conditions will likely be by combining susceptibility and expected changes in nutrient loads to determine whether conditions will worsen, improve, or remain the same. This was done using a qualitative evaluation of trends in IF, particularly expected changes to population.

The ASSETS synthesis was calculated by combining the IF, EC and FO ratings into a single score falling into one of five categories that are colour-coded following international convention: high, good, moderate, poor, or bad. The model cannot by definition be directly validated by means of observations (for an alternative approach of comparison using other eutrophication indices, see e.g. Devlin et al., 2011; Xiao et al., 2007).

2.4. Complementary application of assessment methods

Each assessment method described above was evaluated against typical issues on which decision-makers would require information about a coastal system where shellfish culture occurs. Several management questions were selected which, when combined, provide an image of Killary Harbour's present conditions for aquaculture production, impacts of changes to aquaculture practices, and ecological impacts. The aim was to evaluate the potential (where applicable) of each assessment method to answer the selected questions, and to evaluate if complementary use of different methods, using the most appropriate tool(s) to answer each question, would provide more information for managing coastal systems with multiple uses than the application of any single method.

The selected management questions included:

- Spatial and temporal patterns of nutrients and phytoplankton, external nutrient and phytoplankton sources (especially the ocean boundary), internal currents and movements of phytoplankton, and shellfish productivity in different cultivation areas. This system scale analysis was performed using EcoWin2000 due to the model's capacity to take into account multiple parameters and processes interacting with aquaculture, and to provide detailed results in space and time, while analysing the system globally.
- Evaluation of the impact of changing the stocking density of mussel farms, examining changes to shellfish biomass production and individual weight, as well as system-scale impacts and overall carrying capacity for shellfish growth. This assessment was performed with both EcoWin2000 and FARM, since both models can simulate the relationship between stocking densities, food supply and aquaculture productivity; the former model was applied to the entire system, and the latter was applied at the local scale. This assessment also allowed for a direct comparison between the two models. FARM also allowed a detailed analysis of local environmental interactions among shellfish aquaculture, water column, and sediment.
- Assessment of the ecological status of the Killary Harbour water body (*sensu* WFD), and of the eutrophication footprint of individual farms, together with a prospective analysis. This was performed using ASSETS, focusing on the biological quality elements (BQE) and supporting quality elements (SQE) associated with eutrophication. Apart from a system-level assessment of eutrophication-related components of ecological status, ASSETS was further used in conjunction with both models for analysis of eutrophication scenarios at the local and system scales.

Table 3
EcoWin2000 calibration and validation statistics for phytoplankton and nitrate (RMSE stands for the Root Mean Square Error).

Box	Phytoplankton (μg Chl *a* L^{-1})			Nitrate (μmol L^{-1})		
	Correlation	Bias	RMSE	Correlation	Bias	RMSE
Calibration						
6	0.94***	0.3	0.4	0.94**	0.5	0.8
12	0.75*	−0.1	0.6	0.96**	−0.2	0.4
Validation						
2	0.88***	0.1	0.8	0.82***	0.3	3.1
3	0.86***	0.2	0.7	0.87***	−0.9	2.5
4	0.75***	0.3	0.9	0.90***	−0.7	2.2
5	0.84***	0.3	0.7	0.86***	−1.1	2.7
6	0.90***	0.1	0.7	0.90***	−0.9	2.3
8	0.85***	0.8	1.2	0.84***	−1.9	2.7
9	0.64**	0.1	1.1	0.90***	−2.6	3.3
10	0.63**	0.2	0.8	0.89***	−2.4	3.4
11	0.69***	0.5	0.8	0.86***	−2.0	3.3
12	0.98***	−0.1	0.3	0.92***	−1.0	2.3

* $p<0.05$.
** $p<0.02$.
*** $p<0.01$.

3. Results and discussion

3.1. System-scale model

Table 3 shows the main calibration and validation statistics for the application of EcoWin2000, for phytoplankton and nitrate, when comparing model results with observations for 1999–2006 (calibration) and 2007–2008 (validation). Overall, the model showed a good capacity to simulate phytoplankton and nutrient dynamics although, in the former case, results were markedly better for the surface boxes. Model performance for calibration and validation was similar, indicating few overcalibration problems. However, for the validation data it should be noted that the model shows a tendency to overestimate phytoplankton concentrations while underestimating nitrate, especially for the subsurface boxes.

Fig. 3 shows the seasonal comparison between phytoplankton measurements and simulations (using chlorophyll *a* concentrations as a proxy variable) in detail. An analysis of the figure confirms what was stated above about model performance for phytoplankton, while also highlighting other problems associated with statistical analysis of models based on measured samples. Firstly, samples are taken at point locations within the system (and also vertically) and therefore do not necessarily represent the model boxes, which is highlighted by the variability between sampling stations for the same box. Secondly, the short-term variability shown by simulations of phytoplankton is not captured by the sampling interval, and it is not possible to determine from the data if the variability does not exist or the sampling interval is too long to observe it. Both these problems are also present when validating EcoWin2000 and similar ecological models elsewhere (as discussed by Nobre et al., 2010).

Thirdly, there is a large inter-annual variability of phytoplankton dynamics in Killary Harbour, with generally two peaks, the first in April or May and the second occurring somewhere from June to September; the latter is usually, but not always, greater than the former.

Fig. 3 shows how this issue led to differences between calibration (with a large peak in September) and validation (with two or in some cases three peaks, in April, July and September). According to model results, this is in large part determined by the ocean boundary conditions, which (i) change significantly among years, and (ii) cannot be simulated. This dependence of model performance on a boundary forcing function cannot be adequately assessed by this calibration and validation analysis. Despite these issues, it can be said that the model adequately simulates nitrate and phytoplankton dynamics in Killary Harbour under the conditions tested; this conclusion is also based on the good simulation of longitudinal profiles for surface boxes, shown in Fig. 4.

The simulation of POM was not assessed at the same level of detail, since (i) there were no data for calibration, and (ii) for validation, seasonal data did not include 4 months (March to June). Additionally, there were no seasonal patterns discernible in the sampled data as, in most cases, spatial variability within a box is equivalent to temporal variability; similarly, the data show no important longitudinal gradients, which prevented an analysis of statistical correlations. However, simulated average annual values were similar to measurements (1.7 vs. 1.9 ± 0.3 mg L^{-1}), which indicates a satisfactory performance.

Table 4 shows the calibration statistics for mussel single individual weight in the model boxes with shellfish cultivation. Overall, the simulation followed observed values closely, although there was a trend to overestimate growth in surface boxes and underestimate it in subsurface boxes, especially towards the ocean boundary, although

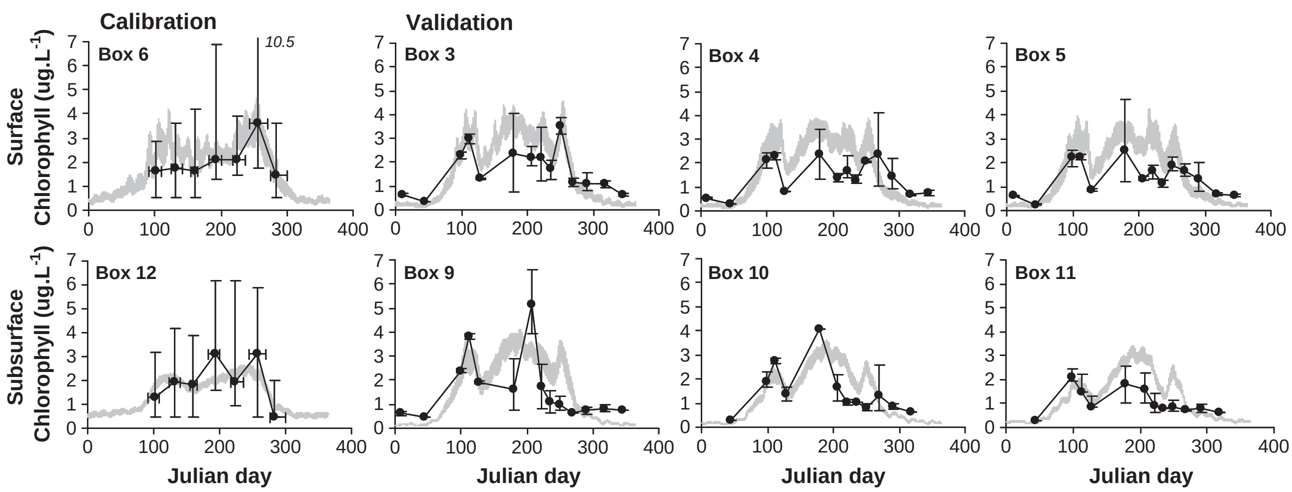

Fig. 3. Comparison between simulated (grey) and observed (black) chlorophyll a concentrations for surface (top) and subsurface (bottom) boxes; for calibration, model results are shown for the outer regions of Killary Harbour (first column, boxes 6/12), while for validation, model results are shown for the main shellfish cultivation areas (three columns to the right, boxes 3/9, 4/10, 5/11). Vertical error bars show the minimum and maximum measured value, while for calibration, horizontal error bars show the minimum and maximum sampling date for a given point.

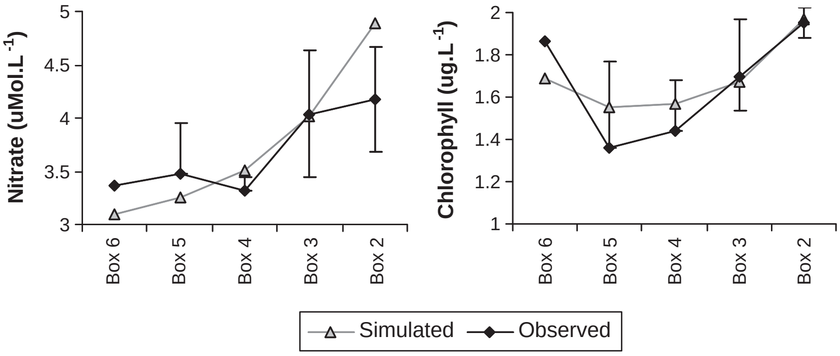

Fig. 4. Simulated and observed average annual nitrate and phytoplankton concentrations for surface boxes along a longitudinal profile; error bars represent the variability among sampling stations.

the earlier note about the difference between the representativity of single measurement points and model boxes also applies for this case.

Fig. 5 compares the average individual growth simulations with measured values in more detail, showing that the model is capable of simulating the observed two-stage growth pattern of mussels. The figure also compares mussel weight at the end of each growth cycle, at three different locations: "inner", "middle" and "outer" correspond roughly to boxes 3/9, 4/10 and 5/11 in Fig. 2; these results indicate that the model is able to reproduce the differences in individual weight observed along the system.

The validation of these results compared the simulated annual harvest and total mussel biomass in the system at harvest time – 1820 ton year^{-1} and 3925 ton – with observed values in 2006–2007, 1630 ton year^{-1} and 3230 ton respectively. Overall, the results indicate that EcoWin2000 successfully simulates shellfish growth at the individual and system scale in Killary Harbour.

3.2. Farm-scale model

Fig. 6 shows the calibration results: a comparison between simulated and observed mussel individual weight. The model shows good results, with a correlation of 0.99 ($p<0.01$), bias and RMSE of 0.9 and 1.1 g TFW, although with a tendency for overestimation. With respect to validation, FARM predicted an annual harvest of 12.3 ton ha^{-1} year^{-1}, which compares well with observed values of 10.4 ton ha^{-1} year^{-1} when considering typical model performance results at this scale, but again with a tendency for overestimation. The bias could be attributed to the use of model simulations without shellfish to estimate drivers, which do not take into account the consumption at the system scale.

3.3. System-scale analysis

Integrated system-scale model results include the simulated concentrations of nutrients, phytoplankton, dissolved oxygen, etc. for different parts of Killary Harbour. Given the detailed spatial sampling in 2007–2008 (Fig. 1), the model did not provide new information on the spatial distribution of these parameters, except for boxes 1 and 7 (Fig. 2). Similarly, the model did not provide new information on seasonal patterns, but did provide additional information on likely shorter-term patterns such as the daily variability of phytoplankton concentrations (indicated by the grey lines in Fig. 3). Furthermore, the model's potential to provide information in unsampled regions and periods is exemplified in Killary by the results obtained for the entire system using the ocean boundary conditions for 1999–2006.

The model also provided additional information on the influence of ocean boundary conditions on the ecological status of Killary Harbour. The role of ocean exchanges on the phytoplankton concentration inside the system has been highlighted by previous research (Roden et al., 1987; Rodhouse and Roden, 1987), and was also reflected in the dependency of EcoWin2000 results for phytoplankton.

This is highlighted by the simulated mass balance for phytoplankton, using the 2007–2008 ocean boundary conditions, shown schematically in Fig. 7 for each model box. It should be noted that the annual mass balance was not closed, partly due to an inexact closure of the tidal pattern into the annual cycle supplied by the Princeton Ocean Model; however, the differences were small when considering the total inputs and outputs (6% of the averaged absolute value for inputs and outputs for the entire system, ranging between 0 and 8% per box). Also, an analysis of the values should take into account the large differences in volume between boxes, both horizontally and vertically, as referred earlier. An analysis of Fig. 7 shows three distinct regions:

- An outer region (boxes 6 and 12), close to the ocean boundary, where phytoplankton circulated inwards in the subsurface part, and outwards in the subsurface part; vertical circulation was downwards. Net Primary Production (NPP) was positive in the upper box and negative in the lower box, due to the sinking and horizontal advection of phytoplankton below the photic zone. The upper box was a net phytoplankton source and the lower box a sink.
- A cultivated region (boxes 3 to 5 and 9 to 11), which showed the same horizontal patterns of phytoplankton circulation, but where the net vertical circulation changed from downwards to upwards towards the inner system. NPP was positive in the upper boxes and negative to balanced in the lower boxes, probably owing to the decreasing depth of surface boxes (as referred earlier) and therefore to the greater proximity of the lower boxes to the water surface. In these boxes, mussel consumption played a large role in phytoplankton mass balance. In the upper boxes, phytoplankton sources and sinks were approximately balanced, although there was a large amount of horizontal and vertical circulation; the lower boxes were sinks.
- An inner region (boxes 1, 2, 7 and 8) where horizontal phytoplankton circulation patterns changed, with outwelling in both surface and subsurface boxes; vertical circulation continued the upward trend of

Table 4
EcoWin2000 calibration statistics for mussel single individual weight (RMSE stands for the Root Mean Square Error), in grams Total Fresh Weight (TFW).

	Mussel individual weight (g TFW)		
Box	Correlation	Bias	RMSE
3	0.97***	0.7	1.1
4	0.97***	1.1	1.4
5	0.95***	1.4	1.8
9	0.98***	0.0	0.6
10	0.97***	−0.5	1.0
11	0.88***	−0.8	1.4

*** $p<0.01$.

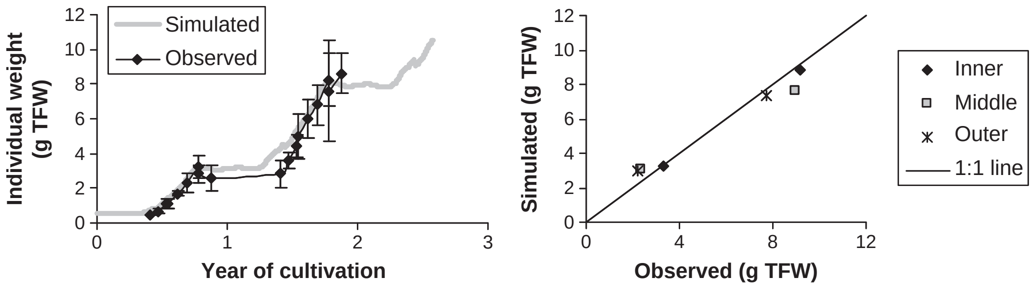

Fig. 5. Top: simulated (EcoWin2000 integrating ShellSIM) and observed mussel individual weight (average of all simulations and observations), with error bars representing the standard deviation of observations; bottom: simulated and observed mussel individual weight after 1 and 2 years of cultivation, for three culture sites along Killary Harbour.

the cultivated region, but was downward in the innermost boxes. Catchment boundary loads were important in box 1. NPP was positive in all boxes, also due to the decrease in surface box depth. All boxes were net phytoplankton sources.

A summary of model results for the system, as well as for surface and subsurface boxes, is shown in Table 5. Model results indicated that the system was, overall, a net sink of phytoplankton, imported from the catchment and ocean boundaries (26 and 74%, respectively). Imports were estimated as 22% of total inputs to the system. However (Fig. 7), the fact that the system is a phytoplankton sink did not indicate that local NPP was for the most part consumed inside the system; results for sources/sinks and exchanges were different for surface and subsurface boxes. In subsurface boxes, there was a net import of phytoplankton from the ocean boundary, which was mostly either consumed by mussels or exported to surface boxes. In contrast, in surface boxes there was a large phytoplankton input from NPP, combined with imports from the deeper layer; these inputs were, in roughly equal parts, consumed by mussels and exported back to the ocean. In global terms, surface boxes were an internal source of phytoplankton, while subsurface boxes were an internal sink; also, subsurface boxes were a net importer of phytoplankton, while surface boxes were a net exporter.

These results suggest a circulation pattern for phytoplankton, imported from the ocean by the subsurface boundary, moving upwards into the system, and exported back to the ocean through the surface boundary, explaining for the partial dependency of phytoplankton on ocean concentrations discussed earlier. However, it should be noted that a part of the net boundary exchange from the ocean could be due to the mass balance closure errors discussed earlier, especially when considering that the ocean exchange value corresponds to the net residual from the total amount of phytoplankton imports and exports throughout the year.

EcoWin2000 provided detailed, system-wide understanding of Killary Harbour. The model outputs indicate that nutrient and phytoplankton concentrations were low in all boxes, which did not suggest the occurrence of eutrophication problems; concentrations of

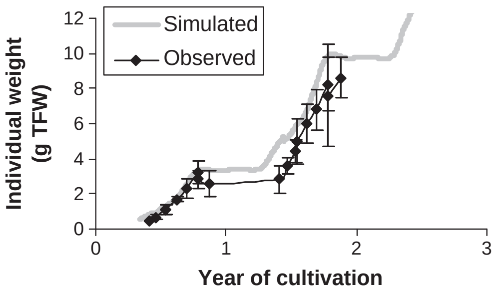

Fig. 6. Simulated (FARM integrating ShellSIM) and observed mussel individual weight (average of all simulations and observations), with error bars representing the standard deviation of observations.

5 µg L^{-1} or less are considered low for most water bodies by most countries (see Borja et al., 2009). Additionally, the model showed large exchanges with the ocean boundary, linking the ecosystem status of the Harbour with that of the nearby coastal system. Finally, the model provided insights into the circulation patterns of phytoplankton inside the system and the food sources for mussels in the upper and lower sections of longline droppers.

3.4. Farm-scale analysis

3.4.1. Environmental impacts and externalities

FARM provides a number of outputs related to environmental effects, both positive and negative, of farming activities. The standard model run indicated that over the 820 day production cycle the animals cleared an annual total of 7056 kg $year^{-1}$ of phytoplankton carbon, corresponding to about 140 kg $year^{-1}$ of chlorophyll *a*. The annualised net removal of nitrogen from the water, through the uptake of both phytoplankton and organic detritus, was determined as 5438 kg N $year^{-1}$, which equates to 1648 population-equivalents (PEQ). The nitrogen removed from the water column through mussel bioextraction lowers the level of expression of the primary symptom (Bricker et al., 2003) chlorophyll *a* by 10%, corresponding to a decrease in the percentile 90 concentration from 4.32 µg L^{-1} at the farm inflow to 3.86 µg L^{-1} at the outflow.

This removal of phytoplankton from the water column can be considered as an ecosystem service furnished by the bivalves, which not only helps to increase light penetration in the water column but avoids the secondary symptoms related to degradation of organic matter from phytoplankton decomposition, and the corresponding reduction in dissolved oxygen. The model indicates that mussel respiration within the farm does not affect the dissolved oxygen concentration.

The substitution cost of land-based nutrient removal is 49 k€ $year^{-1}$, using a conversion factor of 30 € PEQ^{-1} $year^{-1}$ (Lindahl et al., 2005). Because the price differential of mussels is low, with a difference between mussel seed and harvested mussel of about 0.35 € kg^{-1} (Browne et al., 2007), the value of the positive externality of nutrient bioextraction is slightly greater than the product value: the combined total income for the farm would be about 91 k€ $year^{-1}$ if a catchment scale nutrient credit trading scheme were in operation. The ASSETS score at the farm scale (a simplified version of the system-wide method) remains unchanged in the standard model, the inflow is already at high ecological status (*sensu* WFD), and remains so in the outflowing water.

A farm is, however, also responsible for biodeposition to the sediments below, that may in turn generate organic enrichment and cause a reduction in benthic biodiversity, potentially increasing sediment oxygen demand. The model analyses the benthic footprint of suspended culture (Ferreira et al., in press), providing worst-case (i.e. precautionary) results. For the standard culture density simulated (see below for scenarios), the total annualised deposition was about 8 kg DW POM m^{-2} $year^{-1}$; this included both natural sedimentation of

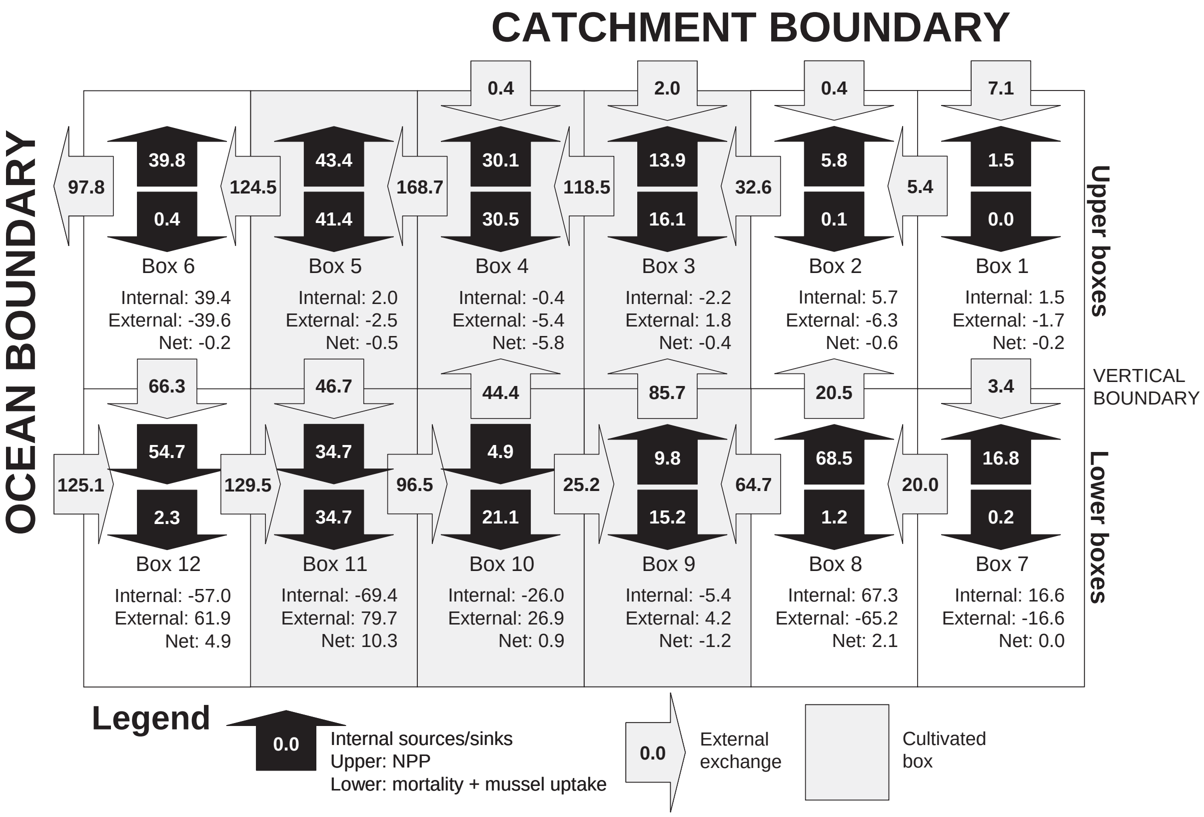

Fig. 7. EcoWin2000 results for phytoplankton mass balance for the boxes shown in Fig. 2 with all values in ton C year^{-1}; the system is represented in a vertical and longitudinal transect, with upper boxes above and lower boxes below, the ocean boundary to the left and the innermost part to the right. Box and arrow size are not scaled.

particulate organic matter (algae and detritus) and mussel faeces and (perhaps) pseudofaeces (Giles et al., 2009). The biodeposition component attributable to the culture itself was about 40% of the total deposition. The particulate waste from the mussels was responsible for 0.9% organic enrichment of the bottom (not considering erosion, diagenesis, or dispersion external to the farm limits), for a sedimentation rate of 1 mm year^{-1}. Although these are negative environmental impacts, they have very little expression, with correspondingly negligible externality costs; these results agree with other authors who report that sediment enrichment effects are not significant in sustainable longline mussel culture (Danovaro et al., 2004; Fabi et al., 2009).

Local scale environmental impacts can be evaluated by models such as FARM, but are beyond the scope of system-scale models, because the boxes used are too large to provide meaningful results at the farm scale.

Table 5
Mass balance for phytoplankton in Killary Harbour, 2007–2008, calculated using EcoWin2000.

Component	Mass balance (ton C year^{-1})		
	Surface	Subsurface	System
Phytoplankton NPP[a] (1)	134.6	0.8	135.5
Phytoplankton mortality (2)	−1.6	−9.6	−11.2
Mussel phytoplankton uptake (3)	−86.9	−65.1	−152.0
Net sources and sinks (1+2+3)	46.1	−73.9	−27.8
Vertical inputs (4)	150.6	116.4	–
Vertical outputs (5)	−116.4	−150.6	–
Net vertical exchange (4+5)	34.2	−34.2	–
Ocean exchanges (6)	−97.8	125.1	27.4
River exchanges (7)	9.8	–	9.8
Net boundary exchanges (6+7)	−87.9	125.1	37.2
Total inputs	295.0	242.3	172.6
Total outputs	−302.7	−225.3	−163.2
Net balance	−7.6	17.1	9.4

[a] Net Primary Production.

The use of a denser grid, typically used by models such as the Princeton Ocean Model, could provide results at the scale of e.g. 200 m × 200 m, i.e. 4 ha (whereas in this simulation FARM deals with segments of about 1 ha), but would require (i) a modelling framework which has a high run time (of the order of days to simulate one year); (ii) the inclusion of a substantial number of additional state variables, further slowing down the model; and (iii) produce large output files, not particularly suited to management analysis. It is thus more appropriate to use a broader scale ecological model to analyse the system as a whole, providing an integrated analysis of carrying capacity and suitability of different regions, useful for marine spatial planning, and a farm scale model to look at site selection, local environmental effects, and optimal production.

3.4.2. Changes to stocking density in current farms

EcoWin2000 and FARM, (each coupled with the same version of ShellSIM) provided standardised simulations of shellfish growth and harvest, such that system- and farm-scale approaches could be compared using a similar set of mussel stocking density scenarios. These ranged from 0.1× to 20× current densities, to simulate conditions from a very low to an extreme pressure on food resources, and also to explore the maximum carrying capacity for mussel cultivation in Killary Harbour. Particular attention was given to the scenario of 0.53× current densities, which are similar to one of the scenarios for future cultivation practices under discussion by local aquaculture stakeholders. These changes were applied to all farms in EcoWin2000, i.e. to a global farmed area of 157 ha, while FARM was used to represent a single farm, about 2% of that area.

Although not applied here, given the focus on changes in mussel growth and biomass, ASSETS can be used to predict water quality differences under different scenarios as a component of the FARM model (e.g. Ferreira et al., 2007b; Ferreira et al., 2009), and it can be used to assimilate modelled outputs (e.g. EcoWin2000 results reflecting

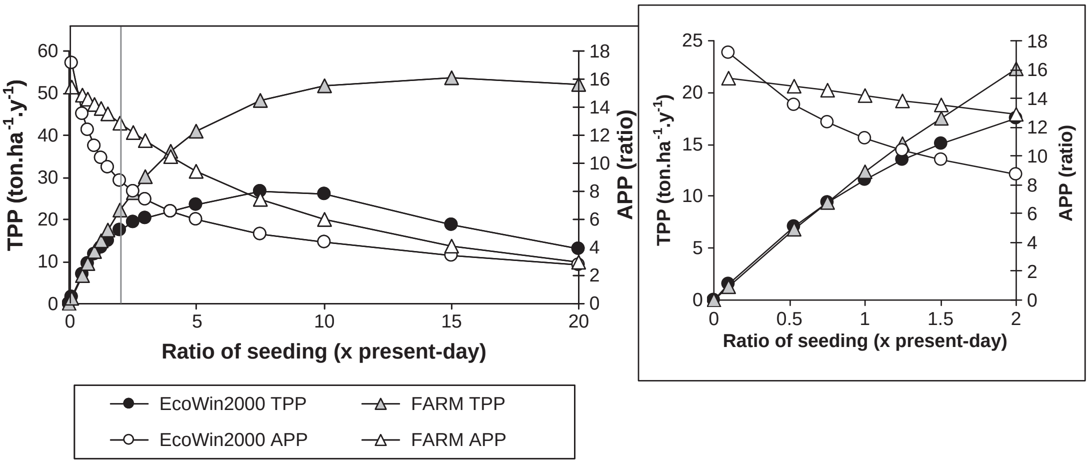

Fig. 8. Impacts of different mussel stocking densities on Total Physical Product (TPP) and Average Physical Product (APP, the ratio between seeded and harvested biomass) as simulated by EcoWin2000 (system scale, per unit of cultivated area) and FARM (single farm); the right-hand pane shows a magnification (between 0.1× and 2× current seeding) of the left-hand pane (between 0.1× and 20× current seeding).

changes in seeding densities or other factors) in the full ASSETS system scale application.

Fig. 8 shows model results for different harvest-related parameters. In both cases, an increase in stocking density led to an increase in harvest (henceforth also Total Physical Product — TPP), but with smaller gains per increase. This was shown by the decrease in the productivity, or harvested biomass (output) to seeded weight (input), termed Average Physical Product, with increase in cultivation density, as an increase in shellfish led to a greater competition for food resources in the system. As stocking density was increased beyond a certain threshold (7.5× and 15× current densities, as predicted by EcoWin2000 and FARM respectively), this competition became large enough to prevent an increase in TPP.

There were also important differences between the results for the two models. FARM predicted a much larger increase in TPP per increase in stocking density, when compared with EcoWin2000; the difference was particularly noticeable after increases of 3× current densities. This was due to different predictions of the relationship between APP and seeding density. Both models predicted a decrease in APP per increase in stocking density but, as seen in Fig. 8, the local-scale model predicted an approximately linear relation between these parameters while the system-scale model predicted a non-linear relation with much larger decreases in APP for small increases in seeding density. These differences between model predictions can be attributed to two main factors:

- FARM only takes into account resource depletion at the local scale, while EcoWin2000 takes into account depletion at the system scale (i.e., caused also by surrounding farms).
- FARM assumes a simplified harvest system in which all harvestable mussels are collected at the end of a single growth cycle. EcoWin2000 assumes more realistic culture practices, including multiple growth cycles with the presence of mussels at different growth stages, and a harvest component that can adjust the growth period if mussels are too small for harvest; this leads to a competition between newly seeded and half-grown mussels for food resources, which may increase if mussels require longer growth periods to reach a harvestable weight.

Model results also indicated that an increase in stocking density and competition for food resources led to slower growth, as shown in Fig. 9 for individual mussel weight after a 27 month growth cycle. The limits for harvestable weights (between 40 and 50 mm shell length) are also shown.

While there was an important difference between the mussel weights predicted by both models, they agreed in their predictions that an increase in stocking density above 7.5× current values would prevent mussels from reaching a harvestable weight in 27 months;

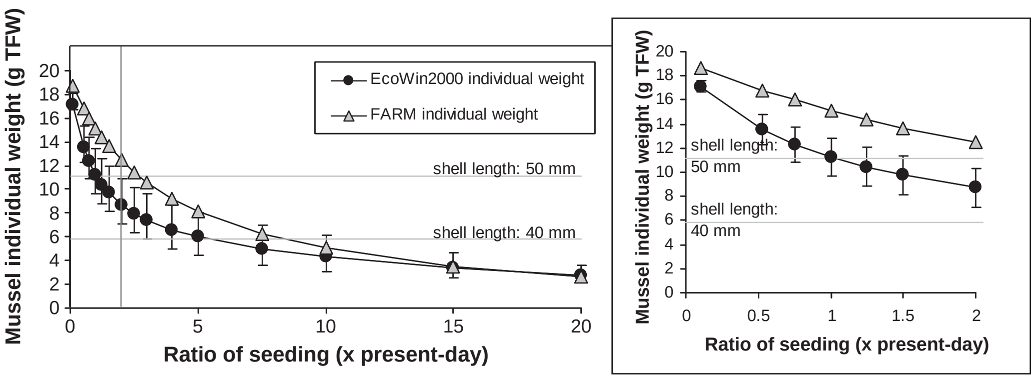

Fig. 9. Impacts of different mussel stocking densities on individual mussel weight after 27 months of cultivation as simulated by EcoWin2000 and FARM, with the bars in the EcoWin2000 results representing variability for different locations in Killary Harbour; the right-hand pane shows a magnification (between 0.1× and 2× current seeding) of the left-hand pane (between 0.1× and 20× current seeding).

mussel aquaculture in Killary Harbour would therefore require longer growth cycles. This prevented the analysis of optimal stocking densities; while EcoWin2000 shows the maximum TPP for a stocking density of 7.5× current rates, this does not take into account the fact that shellfish growers could prefer lower TPPs with larger mussel individual weight (fetching higher market prices) and/or shorter growth cycles (reducing the possibility of losses due to storms or fouling, and improving financial execution, particularly with respect to loan requirements).

For the decreasing stocking density scenario (0.53× current density), model results predicted a decrease in TPP (−39% and −45%, predicted respectively by the system- and local-scale models), compensated by an increase in APP (15% and 5%) and individual mussel weight (20% and 11%). Predictions from EcoWin2000 were more optimistic, in terms of aquaculture harvest, than those from FARM, probably due to the system-scale model taking into account the decrease in food competition inside the entire system and not only in a single farm. Nevertheless, the predictions by both models were comparable, especially when considering the inherent margin of error in mussel growth simulations (see Figs. 5 and 6). The expected increase in individual mussel weight would bring added value for growers by virtue of an increase in sale price or, alternatively, the possibility of shorter growth cycles if mussels are harvested at the same weight as in current practices.

For the extreme pressure scenarios (2× to 20× current stocking density), model predictions differed substantially, not only in the seeding density allowing for maximum TPP but also in the maximum possible TPP inside the system. The maximum predicted TPP by EcoWin2000 was 26.6 ton ha^{-1} $year^{-1}$, 2.3× above current values; this led to a maximum production of 4200 ton $year^{-1}$. In contrast, FARM predicted a maximum TPP of 53.5 ton ha^{-1} $year^{-1}$, 4.3× over current values, and a maximum production 8400 ton $year^{-1}$. Given the difference in model assumptions detailed above, especially the inclusion of system-wide competition for food resources, the results by EcoWin2000 would appear more credible; it should be noted that maximum TPP compares well with predictions by Rodhouse and Roden (1987) of 3000 ton $year^{-1}$. With current growth cycles, the system-scale model shows a maximum increase in stocking density of 2.5×, leading to a TPP of 19.3 ton ha^{-1} $year^{-1}$.

Overall, this comparison showed that both models can provide similar results for small changes in farm aquaculture characteristics that only affect local food resource conditions.

Fig. 8 would indicate that model results are in reasonable agreement for changes to seeding density between 0.5× and 2× current rates. In this case, the low data requirements by FARM would make it a more appropriate choice. For large changes, however, FARM is unable to simulate the limitations imposed by system-wide competition for food resources, and is therefore inappropriate; an analysis at this scale would require the use of a system-scale model.

3.5. Ecological status: eutrophication

ASSETS results for ecosystem status in Killary harbour were based on its eutrophication rating for the system, calculated from the matrix combination of ASSETS elements. The rating of each component is summarized in Table 6.

Table 6
ASSETS assessment results for Killary Harbour.

Assessment component	Rating	Subcomponent	Rating
Influencing Factors	Moderate Low	Susceptibility	Moderate
		Nutrient load	Low
Eutrophic Condition	Moderate	Chlorophyll *a*	Low
		Macroalgae	Low
		Dissolved oxygen	No problem
		Nuisance/toxic algal blooms	Moderate
		Seagrasses	Not applicable
Future Outlook	No change	Susceptibility	Moderate
		Future nutrient load	No change
ASSETS rating	Good		

For Influencing Factors, the calculation of the ratio of human versus oceanic influence on nutrient inputs in this system gives an Influencing Factors model result of 0.18 indicating a Low contribution of nutrients from land based sources. The susceptibility in this system is Moderate due to the moderate capability to both dilute and to flush incoming nutrient loads. The combined Moderate susceptibility and Low nutrient input give an overall Influencing Factor rating for this system of Moderate Low.

The calculation of Eutrophic Condition was based on an analysis of primary and secondary symptoms (Bricker et al., 2003). For primary symptoms, the 90^{th} percentile concentrations of chlorophyll *a* for 2007–2008 were Low in both mixing (4.24 µg L^{-1}) and seawater (2.99 µg L^{-1}) zones, the overall system-wide rating for chlorophyll *a* is low. The rating based on data from 1980–1981 (Rodhouse and Roden, 1987) was Moderate in the mixing zone and Low in the seawater zone (5.12 and 4.61 µg L^{-1}, respectively) though the overall rating was Low suggesting that chlorophyll *a* conditions have not changed significantly during the past two decades. The rating for seaweeds is Low given results of the Irish Environmental Protection Agency (EPA) monitoring program for 2001–2003 (Toner et al., 2005) which do not report excessive growth of seaweeds in this system. It should be noted that the EPA report was based on site observations and at the time there were no formal quantitative criteria or thresholds for eutrophication with respect to macroalgal abundance; these criteria are presently under development at the EPA. The overall primary symptom rating is Low based on the Low ratings for chlorophyll *a* and for macroalgal symptom expression.

For secondary symptoms, there were No Problems with dissolved oxygen in Killary Harbour, with 10^{th} percentile concentrations for 2007–2008 in the mixing zone (6.51 mg L^{-1}) and seawater zone (5.91 mg L^{-1}) above the hypoxic threshold (4 mg L^{-1}). As for nuisance/toxic blooms, prior to October 1995, toxicity closures in Killary were attributed to the presence of DSP in mussels. However in October 1995 several illnesses reported in Holland were traced back to Killary Harbour mussels contaminated with dinoflagellate-derived azaspiric acid (AZP). Since 1996, annual closures have been attributed to both AZP and DSP. In 2000, the harbour was closed to shellfishing 46% of the time and was closed 52% of the time in 2001 (Bord Iascaigh Mhara, 2002). The overall rating for nuisance/toxic blooms is Moderate because they occur annually, despite the fact that they may originate offshore. Finally, no data or information was found for changes in seagrass spatial coverage and it is unlikely that there have ever been seagrasses in this system due to the depth. The rating for seagrasses is Not Applicable. The overall secondary symptom rating for Killary is moderate.

The Eutrophic Condition rating for this system is Moderate Low based on Low primary and Moderate secondary symptom expression ratings.

For Future Outlook, population is expected to increase by 30% in the Western Region of Ireland by 2026 (Central Statistics Office, 2008). At the same time, proposed management measures, particularly the new major sewage scheme for Leenaun – the only main population center interfacing directly with Killary Harbour – are expected to counterbalance projected increases in input from the population (Bord Iascaigh Mhara, 2002), thus there is No Change expected in nutrient loads. The combination of Moderate susceptibility and No Change in future nutrient inputs gives a Future Outlook rating of No Change.

Finally, the combination of ratings of Moderate Low for Influencing Factors and for Eutrophic Condition and No Change for Future Outlook gives an ASSETS rating of Good. This indicates that, when considering eutrophication only, the ecological status of Killary Harbour can also be considered as good.

A comparison of the ecological status assessment provided by EcoWin2000 and ASSETS shows that EcoWin2000 cannot provide an indication of status *per se*; this would require an application of some sort of threshold, e.g. nutrient or phytoplankton concentrations defined for the system type by means of legislative instruments such as the WFD, MSFD, or U.S. Clean Water Act (33 U.S.C. §§1251–1387, 1972), or a status indicator integrating model results.

EcoWin2000 provides detailed estimates of nutrient and phytoplankton concentrations in different parts of the system; although this was not necessary for 2007–2008 in Killary Harbour, due to the unusually high spatial and temporal frequency of measurements, these model results become particularly informative in systems where this level of data collection is inexistent. However, model results did provide additional information and understanding of the current ecological status in terms of nutrients and phytoplankton, especially with respect to the large role played by ocean concentrations and the difference in surface and subsurface conditions. This is of great relevance for management decisions on appropriate implementation of response measures, as discussed below.

On the other hand, ASSETS provided a simple classification of ecological status based on water column concentrations and other parameters, including the high level of exchanges with the ocean, albeit focused on eutrophication. The large amount of data, system knowledge and effort required to apply EcoWin2000, when compared with ASSETS, should be noted. While EcoWin2000 and ASSETS agreed in terms of trophic status based on nutrient and phytoplankton concentrations (which was expected, since both are based on the same measured data), ASSETS classified eutrophication in Killary Harbour as Moderate Low due to the occurrences of nuisance and toxic blooms, a state variable which is not simulated in this application of EcoWin2000. This highlights the advantages of using a wide spectrum approach when evaluating ecosystem status, which is itself a broad-ranging definition encompassing multiple parameters and processes.

Compared with complex, system-scale research models, ASSETS provided a simple approach to assessing ecosystem status, requiring less data and work in its application, and was therefore more useful in providing a management level assessment of Killary Harbour, with an emphasis on eutrophication. However, the results obtained from EcoWin2000 in the system-scale analysis, especially the insights on the phytoplankton mass balance, could potentially provide in-depth insights into the functioning of Killary Harbour, useful in understanding primary production in the system, identifying future research questions, and helping to optimize aquaculture operations in the future. EcoWin2000 was more useful as a basis for an in-depth analysis of ecological status in the system, because ASSETS highlights the status of the water body in its assessment of state, whereas EcoWin2000 focuses on the underlying processes and mass flows which lead to that state.

4. Conclusions

This work tested three assessment models with different levels of complexity and spatial scope – EcoWin2000, FARM and ASSETS – for their ability to support decision making in coastal systems.

The results provided relevant information about Killary Harbour and local aquaculture practices. In particular:

- EcoWin2000 results show a large influence of ocean boundary conditions on phytoplankton biomass inside the system. The results show a strong longitudinal and vertical circulation of phytoplankton, with both strong imports from the ocean and exports of internal primary production to the ocean.
- EcoWin2000 results indicate that the maximum mussel production (TPP) of Killary Harbour is 4200 ton year^{-1}, or 27 ton ha^{-1} year^{-1}, corresponding to 2.3× above present production, but with a much lower APP; in this scenario, the model indicates the need for longer growth cycles to achieve harvestable weights.
- EcoWin200 results also indicate that the maximum TPP, keeping the current growth cycles, is 19 ton ha^{-1} year^{-1}, 1.7× above present production, with a decrease in APP and mussel individual weight (−24%).
- EcoWin2000 and FARM results suggest that the scenario of lower stocking densities (−47%) proposed for the system would lead to a decrease in TPP (−39 to 45%), compensated by an increase in APP (5 to 15%) and individual mussel weight (11 to 20%), with the potential for higher aquaculture returns through higher sale prices or reduced growth cycle; TPP would drop from 12 to 7 ton ha^{-1} year^{-1}.
- ASSETS indicates an eutrophication status of Moderate Low, with a future outlook of No Change and an overall ASSETS rating of Good.

EcoWin2000 provides a tool for a more in-depth analysis; however, model results are difficult to analyze and condense into a single ecosystem status indicator. The model was shown to be a useful tool to address more complex problems that could justify the amount of data collection and work involved in its application; in Killary Harbour, these included the longitudinal and vertical patterns of phytoplankton biomass sources and sinks, and the total carrying capacity of the system for aquaculture production. FARM is a simple tool to apply, providing good results on a local scale, with respect to shellfish production, environmental effects, and profitability inside single farms. However, it was difficult to extrapolate FARM results from farm to system scale as farming intensity increased. ASSETS can use measured data, modelled outputs, or a combination of both to screen a system for ecological status assessment.

In EU coastal systems which are thought to be at risk of being below Good Ecological Status (GES), i.e. where one or more water bodies are classified at Moderate or lower status, measures should be put in place to improve the classification to GES. In other parts of the world, regardless of the legislative instruments in place, the concept of integrated coastal zone management based on a DPSIR framework is equally applicable.

System-scale ecological models that incorporate catchment inputs (i.e. drivers and pressures), either modelled (see e.g. Ferreira et al., 2008a) or estimated, and can build the bridge with economic models (see e.g. Nobre et al., 2009) running on decadal time scales, are important tools to assist in the determination of such measures.

On a broader scale, regional climate models may be used to drive system-scale biogeochemical models coupled to aquaculture growth models (e.g. Melaku Canu et al., 2010) in order to examine effects of climate change on local production.

In many parts of the world the blue revolution promises to be anything but green (Costa-Pierce, 2002; Lubchenko, 2003), with e.g. mangrove areas shrinking at an alarming rate (Islam and Wahab, 2005), much of the production offering profit and luxury foods to developed countries, and alarmingly little food security and improved living standards to the nations where cultivation occurs. With striking similarities to what has occurred with industrial production in the western world, aquaculture activities have migrated to other regions where production costs are lower and the environmental consequences of non-sustainable production are largely ignored. These external costs will be borne locally by future generations, potentially manifested through symptoms such as losses in ecosystem services, greater incidence of disease, and increased occurrence of harmful algal blooms.

In this respect it is fundamental that the steps taken to manage coastal ecosystems sustainably, accounting for multiple uses, including aquaculture where applicable, are well documented and scientifically transparent. In the European Union and the United States, as well as other parts of the world, the legal instruments and social contracts for EAA already exist, and generate the need for the kinds of models presented herein. For other world regions, all too often those with the least management resources and highest and most asymmetric aquaculture growth, it is important to exemplify what can be achieved by means of virtual decision-support tools in order to promote greater social equity and awareness of both the opportunities and risks of aquaculture.

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