



Bord Iascaigh Mhara
Irish Sea Fisheries Board

Monitoring and Assessment of Scallops off the South East Coast of Ireland

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Foreword

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Table of Contents

Summary	1
Introduction	2
The scallop fishery in Ireland	3
Processing and products	4
Legislation governing the exploitation of scallop	5
Technical measures and effort limitation	5
The Management Framework	5
Biology of scallop	5
Landings	5
The physical environment	6
Temperature and circulation	6
Sediment structure	8
Shear seabed stress	9
Stock Structure	10
Larval sources and sinks	10
Connectivity between stocks	10
Landings per unit effort (LPUE)	11
Correlation between biological and physical variables	12
Distribution and relative abundance of scallop and sediment structure	12
Growth, temperature and shear stress	13
Growth and spatial management of yield	15
Biotoxins, growth and temperature	15
Implications for fisheries management	
Stock structure and sources of larvae	16
Scallop abundance and sediment structure	16
Measurement of catch rates	17
Growth rates, yield and biotoxins	17
Summary	17
References	18

Summary

Irish vessels fish for scallops in both inshore and offshore waters off the southeast coast of Ireland, in the Irish Sea and English Channel. Fishing effort potential peaked at 528 dredges in 2002. Landings peaked at 1891 tonnes in 2004. The fleet supports a number of processing plants in south Wexford. Fishing activity of the fleet is limited, by European legislation, to 525012 kilowatt days per annum. The Scallop Advisory Group provides a co-operative forum within which management plans for the fishery are developed.

Hydrodynamic and particle tracking models indicate that temperature and currents off the south east coast control the dispersal of scallop larvae, scallop growth and accumulation of toxins by adult scallops. Seabed maps, developed using multibeam acoustic methods, and annual scallop survey data, indicate that on both broad and fine spatial scales scallops off the south east coast of Ireland are more abundant on gravel and mixed sediments of gravel-cobble but are uncommon on sand.

Catch rates, derived from private vessel diaries and official logbooks, and standardised for vessel and weather effects, declined in some areas by 20-50% between 1995-2004. Catch rates, however, were largely stable in deeper waters between 1999 and 2004.

Fishing activity data needs to be collected at fine spatial scale, ideally using electronic logbook systems, to allow catch rate data to be interpreted correctly. Spatial management of effort is important in order to conserve spawning areas that act as sources of recruitment and to optimise yield per recruit, given that growth rates vary spatially. The seabed maps can be used to reduce dredge effort and increase catch rates and efficiency of the fleet but must be paralleled by additional or alternative management measures in order to give adequate protection to stocks.

Introduction

The scallop (*Pecten maximus*) is an important, commercially exploited, species of bi-valve in northern Europe from Norway south to Spain. It attains a large body size, is a high value species and is also the subject of extensive and intensive aquaculture in northern Europe. In Ireland, the fishery for king scallops occurs mainly off the south east coast, in the south Irish Sea and in the western approaches to England and Wales. Fleets from the UK and Ireland exploit stocks outside of national 12nm territorial limits in these areas.

The stocks of scallop off the southeast coast of Ireland have not previously been assessed. In France and the UK different assessment methods and management measures apply. Some fisheries in France are quota controlled and are assessed by age based analytical methods or by annual survey corrected for dredge efficiencies (Fifas 1991). In Scotland age based virtual population analysis is used together with survey data (Howell *et al.* 2003). Aspects of the biology of scallop pose real difficulties for stock assessment. There is usually significant spatial (geographic) variability in biological characteristics, commercial catch rates, abundance and recruitment within a given stock. The boundaries between stocks and the interconnection, through larval dispersal, between 'populations' of adult scallops are also generally unknown. As a result there may be no apparent relationship between spawning stock and recruitment and recruitment variability is usually considered to be very high. Interpretation of commercial catch and effort data, survey data and forecasting the impacts of management measures, such as minimum landings sizes, effort or catch limitation, under these circumstances, is difficult. Spatially explicit modelling and understanding the processes that give rise to the observed spatial structure and variability in scallop distribution and biology is important if stock assessment, relevant to management of this species, is to progress (Smith and Rago 2004).

This paper presents an overview of a 5-year project, undertaken from 2001-2005, on novel, spatially explicit and multi-disciplinary approaches to the assessment of scallop off the south east coast of Ireland. The project supported work in 3 related areas under the broad objective of developing stock assessment protocols and methods in order to promote sustainable management of these fisheries. A biological sampling program for scallop provided data on distribution, abundance, trends in the fishery and size, age and reproductive data for scallops. A hydrodynamic model of the southeast coastal area was developed to predict the scale and pattern of dispersal of scallop larvae and the stock structure

of scallop in the area. Thirdly, seabed mapping surveys were undertaken to provide detailed information on the distribution and quality of scallop habitat in the area. Ancillary projects included an analysis of spatial variability in the level of the toxin domoic acid (causative agent of amnesic shellfish poisoning) in scallops off the south east coast. Details of these monitoring and research projects will be published separately.

The scallop fishery in Ireland

Scallop fishing is a deep-rooted tradition, which in Ireland extends back to at least the 16th century (Mason, 1983). Scallops are commercially fished in numerous locations in Ireland and are landed into more than 40 ports around the coast. Stocks along the west and south coasts are small and discrete. Off the southeast coast and in the Irish Sea, however, scallops are widely distributed and abundant in both inshore and offshore waters. The extent of these beds is largely known although the fishing fleet is still expanding the commercial boundaries of a number of areas.

The south and east coast fishery is fundamentally different to the small inshore scallop fisheries off the west coast. The offshore stocks are fished by large vessels, 20-36m in length, which may each tow as many as 34 spring loaded dredges. The fishing gear used by the Irish fleet is a toothed spring loaded dredge. The dredge is approximately 0.8m wide. The bag is constructed of 75mm internal diameter metal rings. The length and shape of the teeth, which penetrate the seabed, vary in size and design. The dredges are held in series on two beams, which are fished on each side of the vessel (Fig. 1).

The fishery off the southeast coast began in inshore waters, south of the Wexford coast, in the 1970s and gradually expanded offshore and into the south Irish Sea. Further expansion occurred in the 1990s and by 2002 the Irish fleet had increased its range, from the

south east coast and south Irish Sea to the English Channel and west of France south to 48°N (Fig. 2). In 1997 the total number of dredges in the fishery was 103. This expanded to 498 dredges between 1997-2000 and peaked at 528 dredges in 2002. By 2003 the majority of Irish fishing effort on scallops had transferred from the Irish coast to the English Channel and the Irish Sea due to an apparent decline in stocks off the south east coast. From 2002, however, there was a gradual decline in total fishing effort due to various economic constraints. The physical condition of the vessels, increasing fuel prices and declining market prices for scallops in 2002-2004 all contributed to a reduction in fishing activity. In addition, a days at sea regime was imposed on the Irish fleet by the European Commission (Council regulation 1415/2004) in 2005 which, when transposed to Irish legislation, limited the activity of the vessels. The resultant economic difficulties culminated in the decommissioning of a number of vessels from the fleet in 2005 which had at least 75 days activity in each of two twelve month periods up to October 2005.



Figure 1. Commercial spring loaded scallop dredges suspended on a beam being deployed from a commercial fishing vessel.

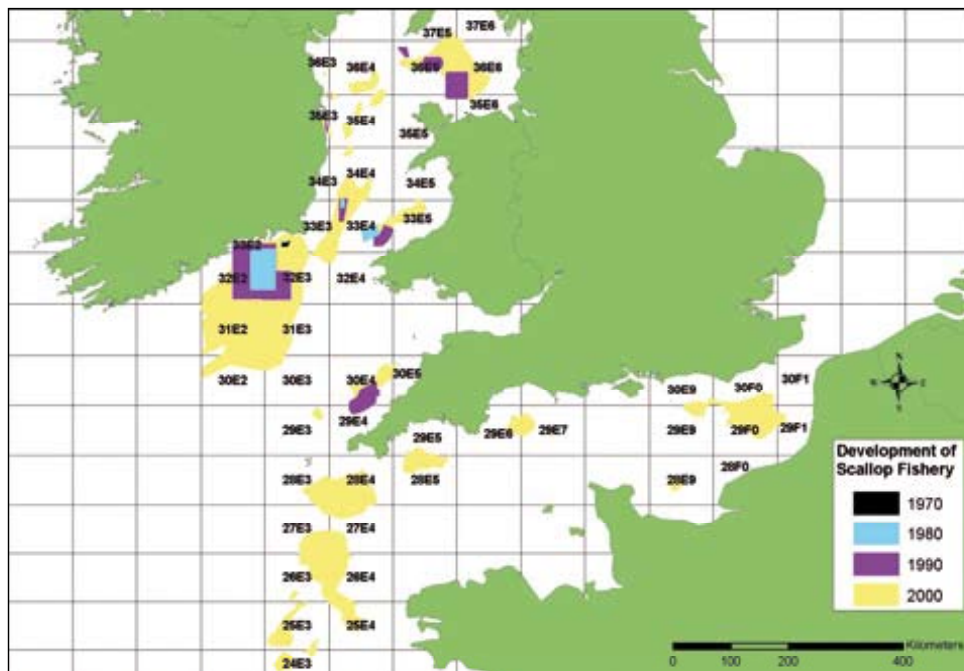


Figure 2. Distribution of fishing by the Irish registered scallop fleet 1970-2005. Data prior to 2000 is from information supplied by fishermen. Areas fished from 2000-2005 (in yellow) are derived from vessel monitoring system data (VMS) supplied by the Irish Naval Service.

Processing and products

All scallops landed into Ireland are processed before sale. Whole scallops are landed to processing plants, mainly in Kilmore Quay and Wexford town in Co. Wexford. Processing, or shucking, involves the extraction of the adductor muscle (white meat) with the attached gonads or roe from the shell. This product is sold fresh or frozen on the European market.

Processing is a significant source of employment and potentially adds value to the raw product. In 2004 four processing plants operated in Wexford. These plants rely almost completely on supplies of scallop and the prawn, *Nephrops norvegicus*.

One of the main constraints in the marketing of scallop is the legal requirement that levels of the toxin domoic acid (ASP), the causative agent of amnesic shellfish poisoning, in whole shellfish is below $20\mu\text{g.g}^{-1}$ of tissue as set down in Council Regulation (1997/61). Regulation 2002/226 allows for sale of the product if the parts to be marketed contain less than $4.6\mu\text{g.g}^{-1}$ even if whole body concentrations exceeds $20\mu\text{g.g}^{-1}$. The toxin is produced by the diatom, *Pseudonitzschia*, which is ingested by scallop during feeding. There is, however, high temporal and spatial variability in the level of ASP in scallops. Approximately 90% of ASP occurs in the hepatopancreas and intestine of the scallop. This reduces

the problem of marketing of muscle and roe but severely limits the sale of live scallop in the shell. To ensure that consignments of product are within the regulatory limits for ASP all landings, into Ireland, are monitored by accredited laboratories in compliance with EC regulation 2002/226.

Legislation governing the exploitation of scallop

Technical measures and effort limitation

Scallop fisheries in the Irish and Celtic Seas are managed by a minimum legal landing size of 110mm shell width in ICES areas VIIa and VIId and 100mm in other areas (Council Regulation 1998/850).

In Ireland scallop fishing is licenced under the polyvalent and bi-valve segments of the national fleet. The number of bi-valve licences is limited and peaked in 2002 when twenty such vessels operated off the south east coast. Approximately four polyvalent licenced vessels fished scallops off the south east coast at that time and there were, in total, approximately 528 dredges in the fishery. From 2004 effort in ICES area VII, for vessels over 15 m in length, which included all of the fleet operating off the south east coast, was limited to a maximum of 525012 kilowatt days at sea (Council Regulation 2004/1415). Furthermore, to fully comply with this regulation, the effort by all scallop vessels over 10m was limited to 109395 kilowatt days in the biologically sensitive area (BSA) defined in Council Regulation 1954/2003. The eastern limit of this area, at 7°W, reaches a point on the Irish coast at the Waterford estuary and dissects the main scallop ground south of Waterford (Fig. 2). Regulation 2004/1415, therefore, imposes different effort regimes on the eastern and western sections of this stock, which is locally referred to as the B&H and Inshore grounds. Pursuant to this regulation, national legislation (Statutory Instruments 245/2005 and 294/2005) allowed for the allocation of a restricted number of days at sea to be allocated to individual vessels based on the power of the vessel and fishing track record in 2003-2004. These latter two pieces of legislation were revoked by SI 464/2005, which allowed the number of Irish registered fishing vessels over 10m in length, fishing for scallops, to be restricted. Furthermore, conditions on quantity of gear, total landings or days at sea could apply under this legislation.

The Management Framework

In 2005 institutional arrangements for management of Shellfish in Ireland were agreed (Anon 2005). Within this Framework a Scallop Management Advisory Group, comprising state and industry representatives, was established in order to draw up management plans for the fishery. In 2006 this group worked towards the production of a 5-year management plan for scallop fisheries off the south east coast to cover the period

2007-2011. Ideally this plan would apply to the entire area, over which the stocks are distributed, rather than the area inside the 12nm limit only and to all fleets fishing the stock. Effective management planning for such stocks, which straddle national territorial limits, requires international consensus. The North Western Waters Regional Advisory Council, established in 2005, provides, for the first time, a regional international forum within which scallop fisheries management issues can be discussed.

Biology of scallop

The life cycle of scallop is divided into two distinct phases; a pelagic larval phase and a juvenile and adult benthic phase. Cross-fertilisation of gametes is external and fertilisation success is related to the proximity of male and female spawners and, therefore, to population density of scallops on the seabed. The larval phase lasts from 18-42 days depending on temperature (Le Pennec 2003). Padi-veliger larvae seek suitable substrate on which to settle and from this stage scallops are mainly sedentary, performing only small-scale (meters) movements to avoid predators or to locate suitable substrates. Growth may be related to temperature and food supply and is relatively fast. In Irish waters scallops attain a size of approximately 25mm shell height in the first year after settlement and 40mm at age 2. Significant spawning does not occur until the third or fourth year but this pattern is spatially variable. Annual growth rings are deposited, which allows age to be estimated, although in some areas the annual pattern of ring formation is unclear. Recruitment to the fishery occurs mainly at 4 years. Scallops may live for 10-15 years.

Landings

Landings of scallop, by Irish vessels, are reported in EU logbooks, which are compiled by the Department of Communications, Marine and Natural Resources, Dublin (DCMNR). In this paper, for the period 2000-2004, these data were cross checked, for missing values, with vessel monitoring system (VMS) data which is a record of the complete fishing activity of each vessel in each year. These data are managed by the Irish Naval Service. The VMS data were 'cleaned' to remove non-fishing related activity, such as steaming to and from port and other work, such as supervision of the laying of marine cables, which these vessels were periodically commissioned to undertake during the period. Dates for these alternative activities were obtained by interviewing skippers. Steaming was identified and removed by calculating vessel speed from the rate of change in vessel GPS position over time and removing all values greater than 5 knots. VMS data, which did not have a related

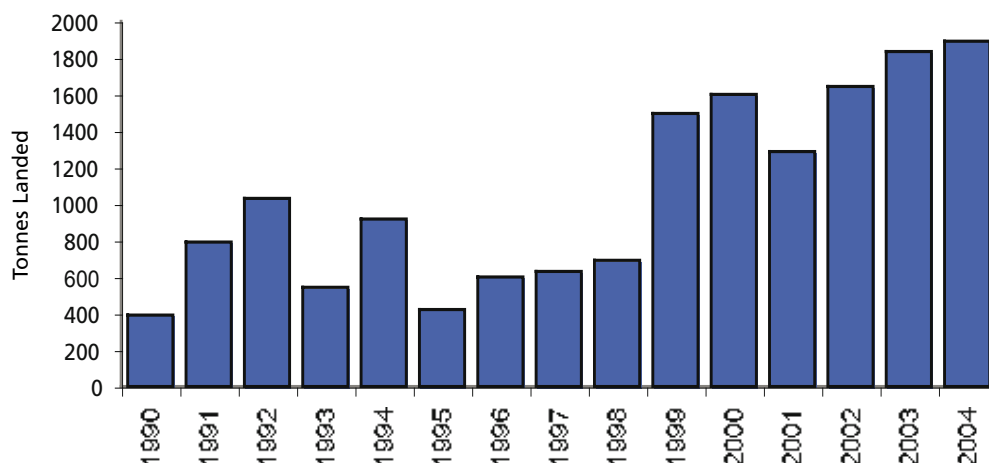


Figure 3. Landings of scallop into Ireland 1990-2004.

figure for catch, were identified and the missing values calculated. The missing values for the year, area and vessel in question were predicted using General Linear Modelling (GLM) of catch rate data.

Annual landings of scallop by Irish vessels averaged 668 tonnes per annum between 1990 and 1998 (Fig. 3). Landings increased to 1559 tonnes in 1999. This increase resulted from an expansion of the fleet, especially in 1999, when a number of new bi-valve licences were issued. Fishing effort expanded to the western English Channel and the Irish Sea with the introduction of these new vessels. Landings peaked at 1891 tonnes in 2004. At a meat (muscle and roe) cut out weight of 23% of live weight and a value of €15 per kg of meats the value of the landings at first point of sale was just over €6.5 million in 2004.

The physical environment

Temperature and circulation

Seabed temperatures and current speeds may have an important regulatory function on the recruitment and growth of scallops (Shumway 1991). The current and temperature fields in an area can, therefore, regulate the productivity of scallop stocks. A hydro-advection model of the Irish and Celtic Sea areas was developed in order to identify how stocks are connected through larval dispersal and to correlate predicted temperature and current stress fields, at the seabed, with the biological characteristics of scallop including growth and levels of Domoic Acid. Various simulations of larval dispersal, which also involved allocation of different behavioural characteristics to scallop larvae, were run by coupling a particle tracking module to the hydrodynamic model. These simulations are described in Berry and Hartnett (2005). The hydrodynamic model was developed by partitioning the study area into a 2x2km

grid comprising a total plan area of 440 x 588km. The numerical model operated on an orthogonal Cartesian x,y grid in the horizontal and a 10 layer sigma co-ordinate grid in the vertical. The model was calibrated using tidal gauge data, meteorological data and seawater temperature data, sourced from various organisations, as described by Berry and Hartnett (2005) for a number of locations throughout the model domain.

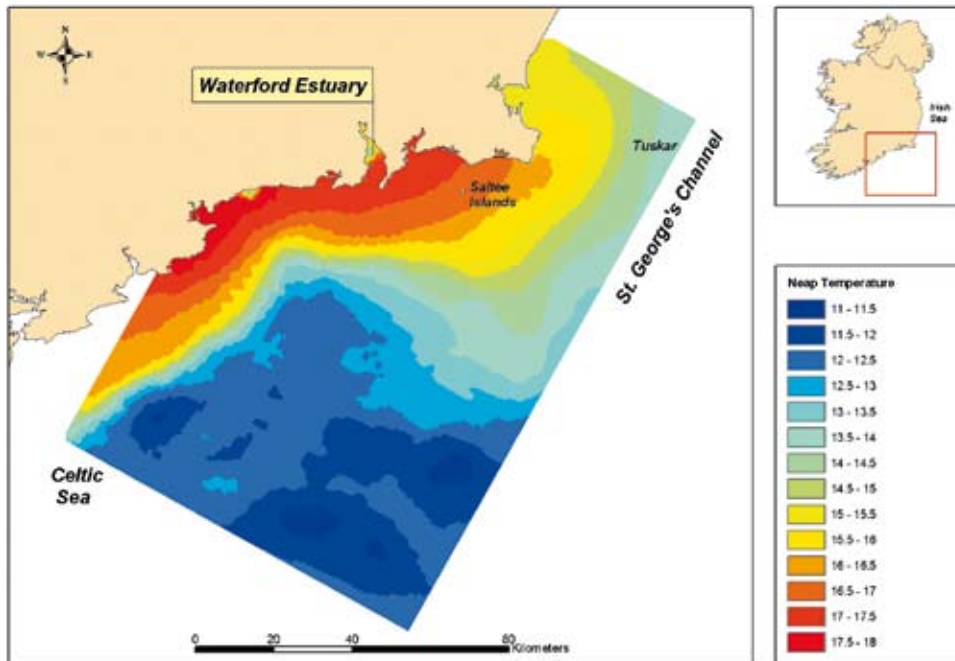
The model reproduces the observed physical oceanographic features and circulation patterns that develop seasonally in the Irish and Celtic Seas. The temperature fields, position of thermal fronts and the circulation patterns, predicted by the model, correspond to the main oceanographic features in the area described by Brown *et al.* (2003) and Young *et al.* (2004). Areas of stratified water develop in late spring and are usually strongly established in July and August. The stability and extent of these areas vary annually depending on meteorological conditions. Anti-cyclonic weather, with low wind speeds and high solar radiation, increases the vertical temperature gradient and the stability of the water column. Even under those conditions, however, other areas remain mixed because of stronger currents and associated vertical turbulence. There is a temperature discontinuity or thermal front in areas where mixed and stratified waters meet (Fig. 4). An important resultant feature of this system is the trapping of a dome of cold water, below the thermocline, where seabed temperatures remain below 12°C in summer. This bottom water, beneath the thermocline, is 4-5°C colder compared to bottom water in areas that remain mixed (Fig. 4, Brown *et al.* 2003, Young *et al.* 2004). The model predicted horizontal differences in bottom water temperature of 4-5°C (11-15°C) on spring tides but these differences were up to 7°C (11-17°C) on neap tides because of the short-term effect of solar heating on shallow water inshore. Differences between surface and bottom

temperatures in the area vary, therefore, between 0 (mixed water) and 7°C (stratified water) depending on the opposing effects of vertical mixing of the water column and solar heat input.

The exact location of the fronts and the relative areas of mixed and stratified waters vary seasonally, annually and on the spring-neap tidal cycle. The front oscillates in horizontal position on the spring-neap cycle during

summer. The area of mixed water along the coast increases on spring tides. The main current flows parallel to the fronts on the mixed side. In summer, when the thermal structures are established, the main current flows north from the Bristol Channel towards St. George's Channel, projects to a varying extent into the southern Irish Sea and then turns south west from the Tuskar area along the Irish south coast and into the Celtic Sea. The main

4a.



4b.

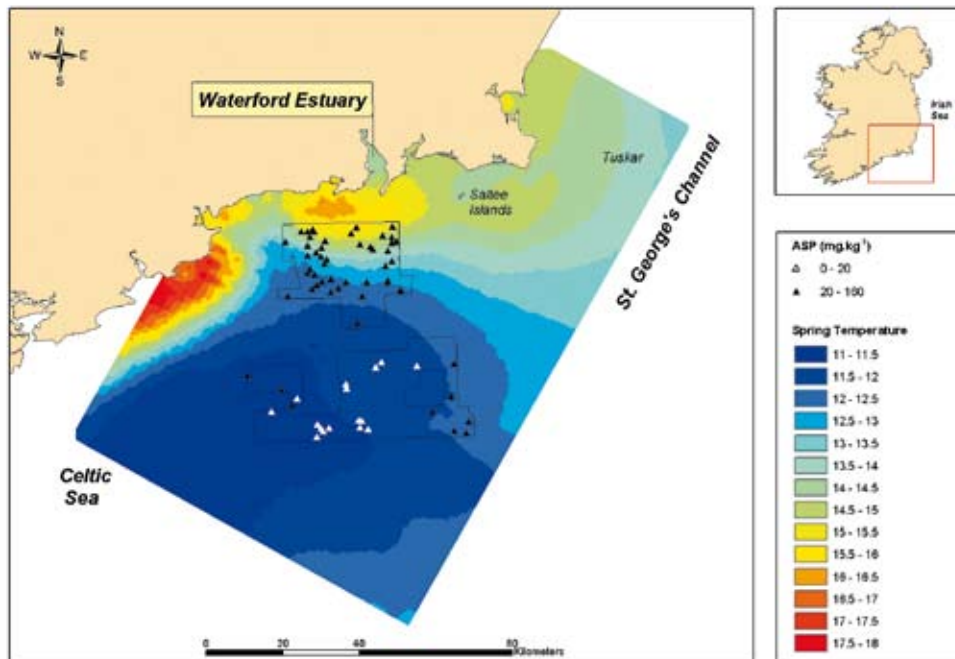


Figure 4. Bottom seawater temperature fields on spring and neap tidal cycles off the south east coast of Ireland predicted by a hydrodynamic model. Levels of ASP in scallops in 2003 are shown in the spring tide map.

current flows are jet like or funnelled in a stream between the offshore front and the south coast of Ireland particularly if the front is well established. This continues in a clockwise flow around the south and southwest coasts. Earlier in the season this flow is weaker as the stream flows in a broader band along the south coast because the offshore front is weakly developed at this time.

Scallops occur throughout the area and are exposed to different temperature regimes depending on their location. Scallops offshore in the southwest of the area live at temperatures of 12°C in summer compared to 16-18°C in inshore areas. This has implication for growth, accumulation of biotoxins and for management of the fishery as described on page 7.

Sediment structure

The type of sediment and turbulence at the water sediment interface are the main factors that affect the settlement of scallop pedi-veligers. Other physical conditions such as siltation and biotic factors, such as presence of adults, may be important (Shumway 1991).

Seabed mapping surveys, using MULTIBEAM acoustic methods, were undertaken on the RV Celtic Voyager in 2002-2004, to characterise and describe the distribution of the main sediment facies in the area that may be suitable for scallop settlement and habitation. Kostylev *et al.* (2003) showed that the pattern of distribution and abundance of *Placopecten magellanicus* (the giant scallop) was related

to sediment type and small scale topographic relief at the seabed on Browns Bank (Nova Scotia, Canada) as indicated by the acoustic backscatter signal derived from multibeam data.

On the Celtic Voyager surveys a Simrad EM 1002 echosounder was used to generate overlapping swathes of sonar coverage within the scallop beds off the southeast coast. These data were subsequently post processed using CARIS HIPS (Hydrographic Information Processing System) and corrected for beam angle to generate acoustic backscatter maps of the seabed. Further details can be found in Sutton and O'Keeffe (2005). The acoustic images, together with ground validation data, in the form of sediment samples and digital images of the seabed, show that the seabed structure varies on a variety of spatial scales. Broad-scale regional distribution of sands and gravels can be recognised. Additional smaller scale features include rock outcrops and, particularly, sand dunes 200-300m in length and 50-100m wide. These are composed of medium coarse sands and are aligned in a northwest to southeast direction in accordance with prevailing currents. Large areas of gravel occur throughout the area (Fig. 5). This gravel area, defined as acoustic backscatter values greater than -45 decibels, is in fact a mixed facies of gravel, cobble and rock but is not readily distinguished spatially because of patchiness at very small scales. Areas with lower backscatter values are largely sands. In all areas, patches of sand are interspersed with areas of gravel, the relative proportion of each substrate

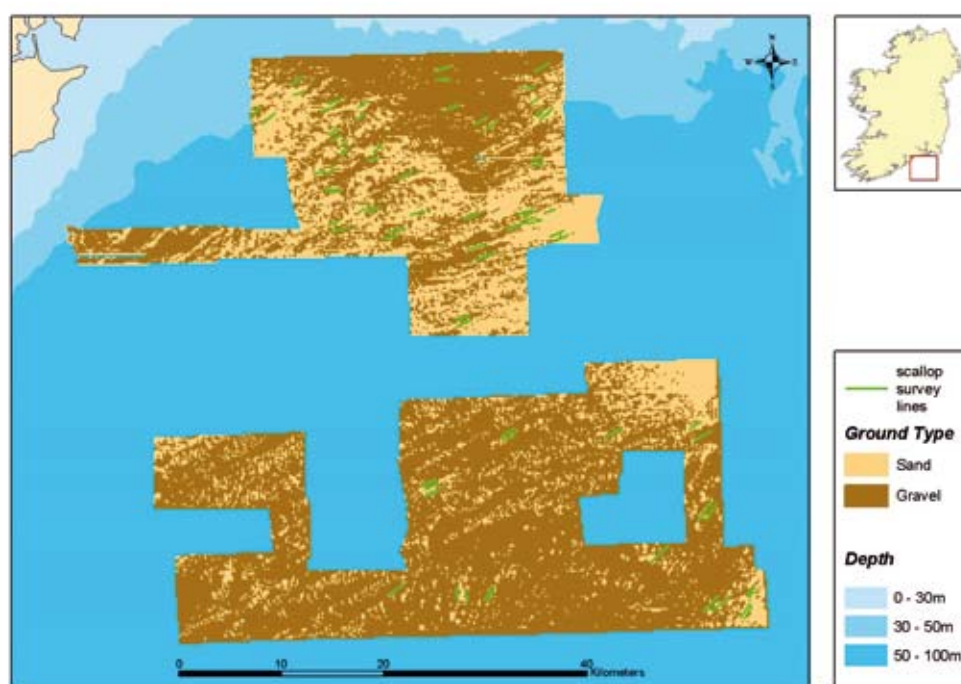


Figure 5. Acoustic backscatter map of the seabed off the south east coast showing 2 main acoustic classes defined here as sand and gravel. Scallop survey positions in 2002-2004 are shown by the green lines.

varying throughout, resulting in a mosaic pattern. This pattern has implications for the distribution of scallops, catch rates in the fishery and for the interpretation of catch and effort data.

Shear seabed stress

Bottom currents flowing over the seabed generate forces on the sediment that can suspend particles, increase sorting of the sediment and alter the sediment structures. Obviously this could have a significant impact on the

suitability of the bed for scallops. For instance Dare *et al.* (1994) found that scallops were confined to areas where the shear stress on the seabed was less than 10 dynes.cm^{-2} in the English Channel.

Shear stress values were generated from the hydrodynamic model. Stress values, which are highly correlated with bottom currents, are highest in the western Georges Channel and particularly near the southeast coast. They decline in a northeast to southwest direction off the south

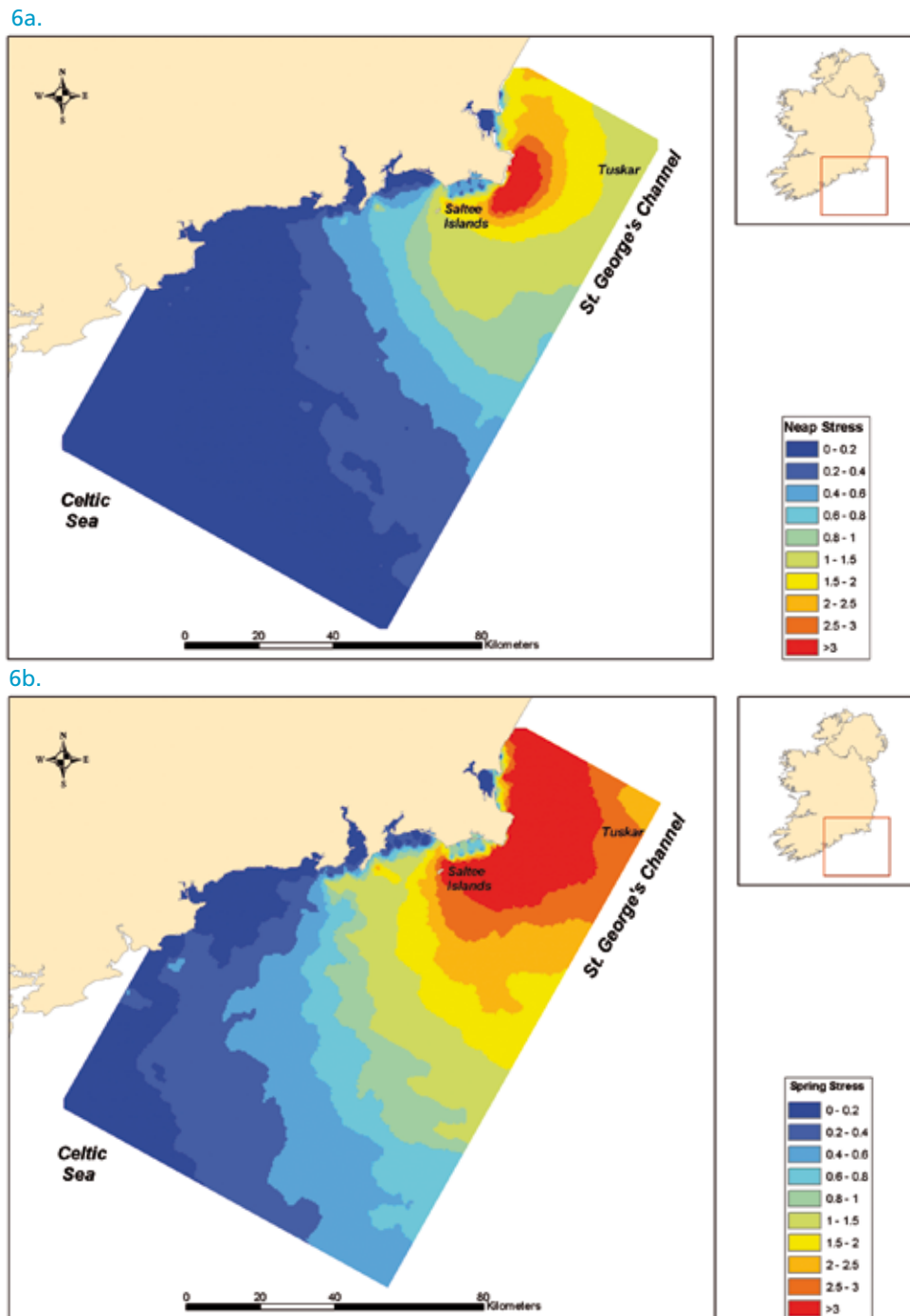


Figure 6. Shear stress fields at the seabed on Spring and Neap tides off the south east coast of Ireland. Units in Newtons.m^{-2}

coast. As expected shear stress values increase on the spring, compared to the neap, tidal cycles and these higher stress levels extend southwest into the Celtic Sea (Fig.6).

Stock Structure

Larval sources and sinks

Scallops settle onto specific types of substrate such as sands and gravels and their distribution is limited and determined by the distribution of these sediments (Shumway 1991). The structure of the stocks, or the connection between scallop beds, is determined by the dynamics of larval dispersal from spawning areas as the juvenile and adult phases are largely sedentary. Ocean circulation patterns, coupled with the behaviour of larvae, result in a given scale and direction of transport or dispersal and determines how stocks are interconnected. Many 'populations' are not completely isolated or completely interconnected. A network of varying levels of connectivities can, therefore, exist which link, to different degrees, the adult spawning

populations. These populations exist, therefore, as a metapopulation. Certain populations may be more critical to the survival of the metapopulation than others if they supply larvae to other beds. Such populations are termed source populations. Others may be sustained entirely by these source populations and contribute no net contribution to population maintenance themselves if their spawning products are dispersed to areas where survival is not possible. These populations are sink populations (Lipcius *et al.* 2001)

Connectivity between stocks

Scallop larvae are distributed throughout the water column in areas of mixed water if the vertical turbulent velocities exceed any directional swimming capacity of the larvae. The behaviour of larvae, in response to thermoclines or vertical turbulence, is not well known. Directed and spiralling upward swimming occurs in early larval life and larvae are thought to occur mainly above the thermocline where one exists. Directed downward swimming and passive sinking

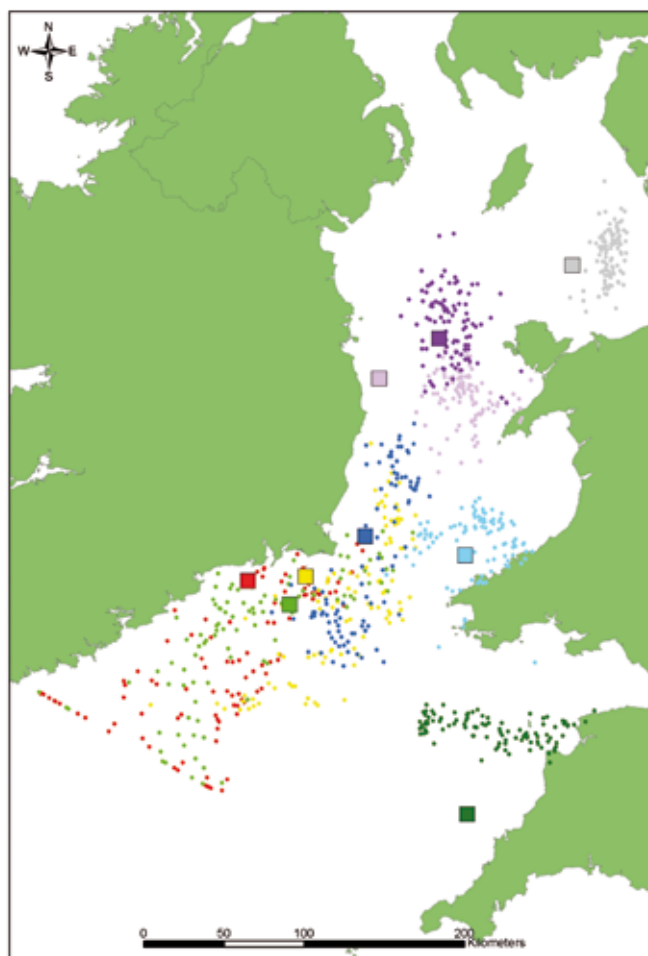


Figure 7. Distribution of passively drifting scallop larvae on May 30th following 30 days of dispersal from 9 release locations (square symbols) in the Celtic and Irish Seas in primarily southerly wind conditions (using wind data from May 1995).

facilitates the settling of late stage larvae. The duration of the larval cycle depends on temperature and varies from 18-42 days (Le Pennec 2003).

The scale and direction of dispersal of 'inactive' larvae, or larvae which were given no behavioural characteristics, was predicted by coupling the particle tracking model with the 10 layer hydrodynamic model described above. The connectivity between known beds of scallop were investigated by releasing 100 'larvae' from 9 specific locations (Fig. 7) into the model on May 1st 2003 after running the model for the previous 5 months to develop the correct salinity and temperature fields throughout the model domain. Prevailing winds during the simulated dispersal were south westerly. Scallop larvae released in May in the Irish Sea and Celtic Sea are dispersed widely. However, scallop populations in the eastern Irish Sea and south of the Bristol Channel appear to be isolated from other stocks. Transport of larvae across St. Georges Channel does occur but can be in both directions depending on the location of release. Larvae released in the Tuskar area, in southerly winds, can be transported north but can also be entrained in the main cross channel and southwesterly current flows and be re-distributed off the south Wexford coasts.

Other simulations of larval transport off the southeast coast under different scenarios of larval behaviour, wind direction and spawning time are described in Berry and Hartnett (2005). Current flows in the area vary seasonally, depending on the position of the thermal fronts, suggesting that the transport of larvae from

early or late spawning will also be different. The main uncertainty, in predicting how larvae are transported, is the vertical migratory behaviour and position of the larvae in the water column. Larvae distributed close to the surface will follow a wind driven path modified to varying degrees by physical oceanographic features in the area. Larvae remaining deeper in the water column follow current driven and wind independent flows.

Landings per unit effort (LPUE)

Landings per unit effort (LPUE) data were derived from private diaries of vessel owners and from EU logbooks for the period 1994-2004. LPUE from private diary data were expressed as kgs per dredge per hour. LPUE derived from EU logbook data were expressed as scallops per dredge per day in a statistical rectangle, as the number of hours fished each day was unknown. However, VMS data was used to calculate fishing time as described above and the logbook data was, therefore, re-expressed as scallops per dredge per hour. This also allowed the data to be aggregated to different spatial scales. As the VMS reported vessel position only every 2 hours the error in estimated fishing time per day could have been as high as 4 hours.

The VMS data for all vessels for the period 2000-2004, indicating the spatial distribution of fishing effort, is shown in Fig. 8. The main fishing areas were off the south coast (Inshore and B&H grounds – Area 1 and 2 respectively) and in the south Irish Sea (Barrels and Tuskar grounds – Area 3 and 4 respectively) (Fig. 8).

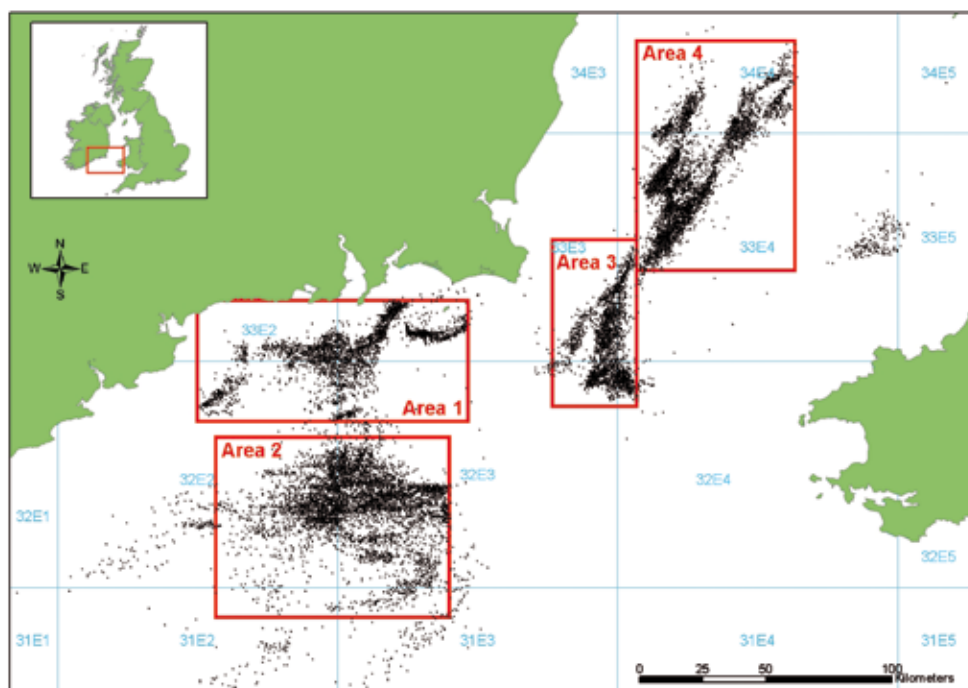


Figure 8. Distribution of fishing by the Irish scallop fleet off the south east coast 2000-2004. Data were derived from vessel monitoring system (VMS) information sourced from the Irish Naval Service, Hawlbowlne, Co. Cork.

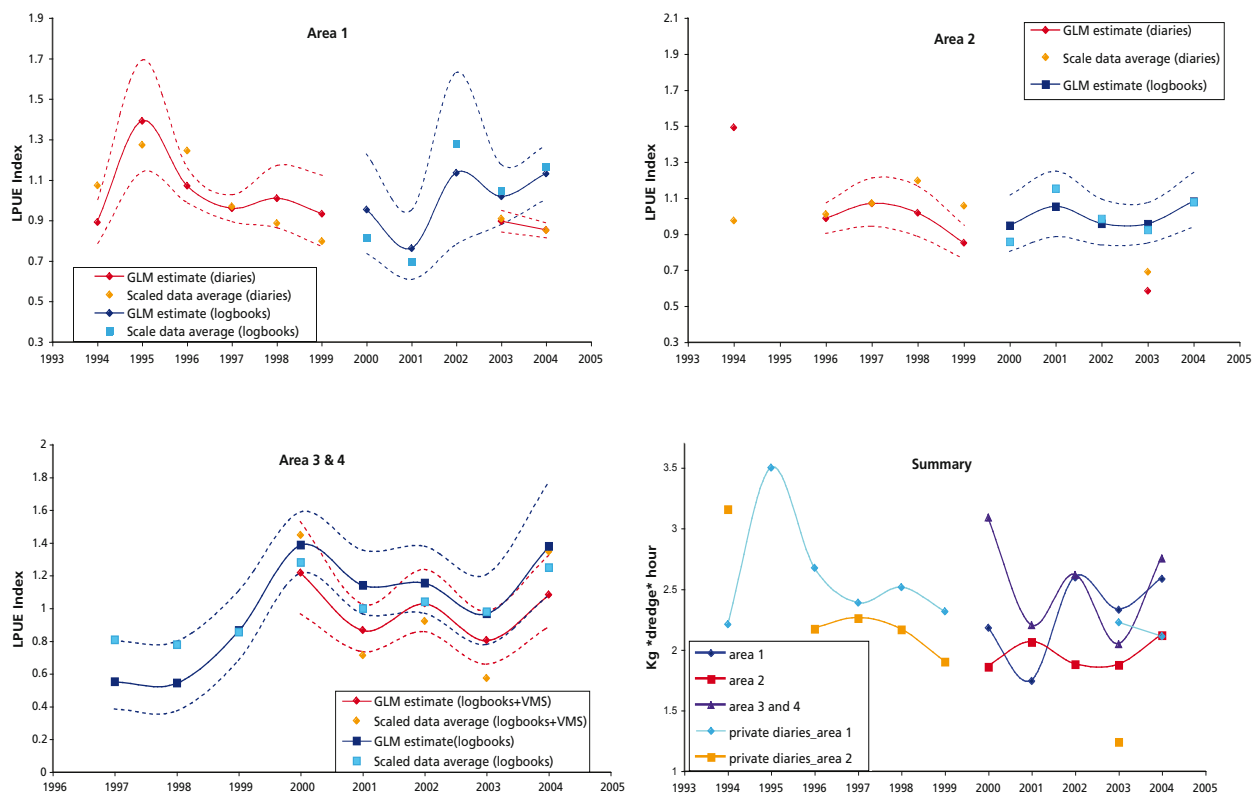


Figure 9. Landings per unit effort indices for scallop for 4 areas (Fig. 8) off the south east coast 1994-2004. Estimates are observed (data) and standardised (GLM) scaled annual averages. The summary panel data is not scaled.

LPUE data from both logbooks and private diaries were standardised for potential bias due to vessel and weather effects using a General Linear Model (GLM) and scaled to long-term averages. Details of the model are given in Hervas *et al.* (2006). Data were analysed separately for each of the four main centres of fishing activity off the south east coast (Fig. 8). The GLM of the private diaries showed a slow decline in LPUE in Area 1 from 1995-2004 and a somewhat steeper decline in Area 2. By 2003 both observed and standardised LPUE were about 20-50% lower than in the mid 1990s. The logbook data from 2000-2004 showed an increase in LPUE in Area 1, especially after 2001. In Area 2 LPUE, from logbook data, was relatively stable. LPUE increased in Area 3 and 4 from 1997-2000 and fluctuated, thereafter, depending on the source of data (Fig. 9).

Correlation between biological and physical variables

Distribution and relative abundance of scallop and sediment structure

Annual scallop surveys were undertaken between 2001-2005. The first survey, in 2001; in Areas 1 and 2, covered a regular grid of stations, known to be fished commercially, in order to identify the distribution of scallops in the area. The

2001 survey showed that scallop catch rates varied over broad geographic scales with higher catch rates occurring on large gravel patches in the centre of the survey domain south of the Waterford estuary. This broadscale pattern could, however, be due to larval supply or higher settlement of larvae in this area rather than any functional relationship between scallop abundance and sediment type. Surveys in 2002-2004 were, therefore, specifically designed to investigate the relationship between catch rates and acoustic backscatter at spatial scales where variation in larval supply was unlikely to operate. Pairs of stations placed close together, and usually less than 200m apart, were identified from the acoustic backscatter maps so that the backscatter profile of each station in each pair contrasted (Fig. 5). Catch rates at each station, in all station pairs, were then compared. These surveys confirmed that a strong relationship existed between acoustic backscatter and scallop catch rates. In 2005 the acoustic backscatter map was, therefore, used to establish a random stratified survey. Two strata, representing sand and gravel sediments, were established within which stations were randomly allocated to a grid of cells each cell measuring 4 km². As the abundance of scallop in the 2002-2004 surveys was at least 4-5 times higher on gravel 80% of stations in the 2005 survey were allocated to gravel (Hervas *et al.* 2006).

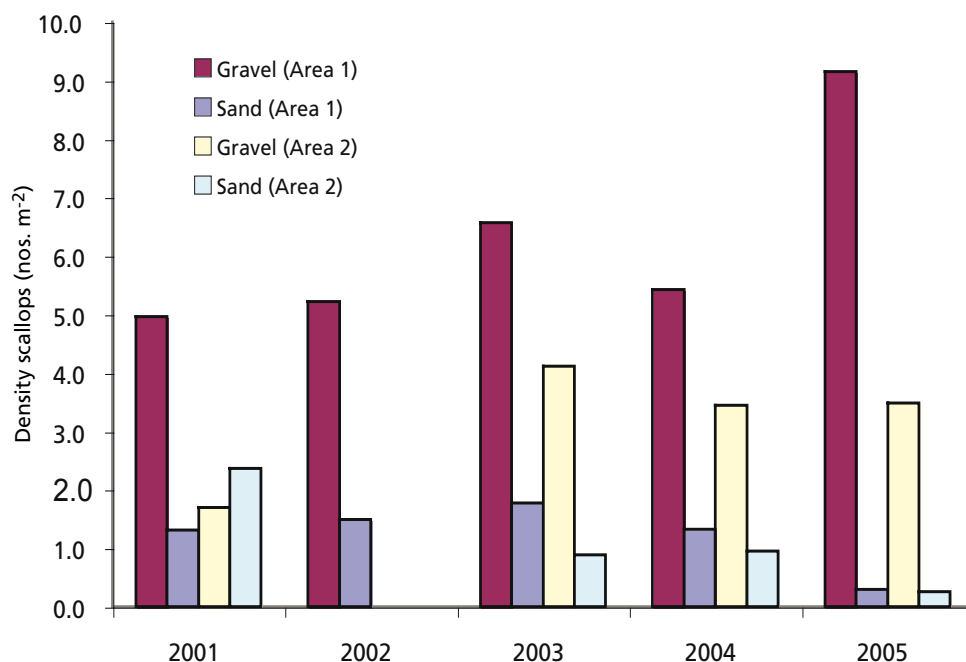


Figure 10. Catch rates of scallop (numbers m^{-2} uncorrected for dredge efficiency) on gravel and sand (derived from acoustic backscatter values) substrates in Area 1 and 2 during annual surveys 2001-2005.

During surveys the size distribution of scallops was measured and a sub-sample of shells were aged at each station in order to identify spatial variation in size and age composition and growth rates.

Scallop catch rates on gravel, in both Area 1 and 2, were substantially higher on gravel than on sand in all years except 2001 where the abundance on sand was slightly higher. The 2001 survey tracks were, however, not specifically allocated to sand or gravel substrates. Their acoustic profiles were estimated after the survey and when the acoustic map became available (Fig. 10).

Square root transformed catch rates, calculated for the area along the dredge line, increased linearly with average backscatter values, and on average explained 54.7% of variability in scallop catch rate (Fig. 11). The linear relationship between catch rate and backscatter values suggests that scallops discriminate, not only between sand and gravel but also between different grades of these sediments.

Different catch rates on sand and gravel might arise because of differential survival of settling larvae, substrate selection by settling larvae or lateral movement of juvenile and adult scallop to preferred sediments. As dredge efficiency is lower on high backscatter grounds (Hervas, unpublished data) the substrate related differences in actual density are probably greater than observed.

The relationship between acoustic backscatter and scallop density provides a means of standardising both survey

data and commercial catch rate data if backscatter values are available by dredge tow. Simple regression diagnostics or analysis of co-variance (backscatter) of the relationships could provide useful stock indicators. The elevation of the regression of catch rate on backscatter is an index of stock abundance over all ground types and should change if scallop density is reduced by fishing or environmental effects on recruitment. Analysis of residuals from this regression may point to particular backscatter or ground types where the density is changing due to local depletion by fishing or other environmentally mediated changes in the stock distribution.

The relationship between catch rates and backscatter is unlikely to be linear outside the range of values shown here. There is a limited range of sediment types on which scallops can survive and their density will decline at the extremes of this range. The functional relationship between the acoustic backscatter and scallop density may, therefore, be defined as a quadratic or other non linear function which may become apparent if a broader range of sediments becomes available for analysis.

Growth, temperature and shear stress

Geographic variation in growth rate of scallops has been reported in many fisheries. This variability is likely to be environmentally determined in most cases (Orensanz *et al.* 1991). Off the southeast coast of Ireland the growth of scallops is highest south of the Saltee Is and south

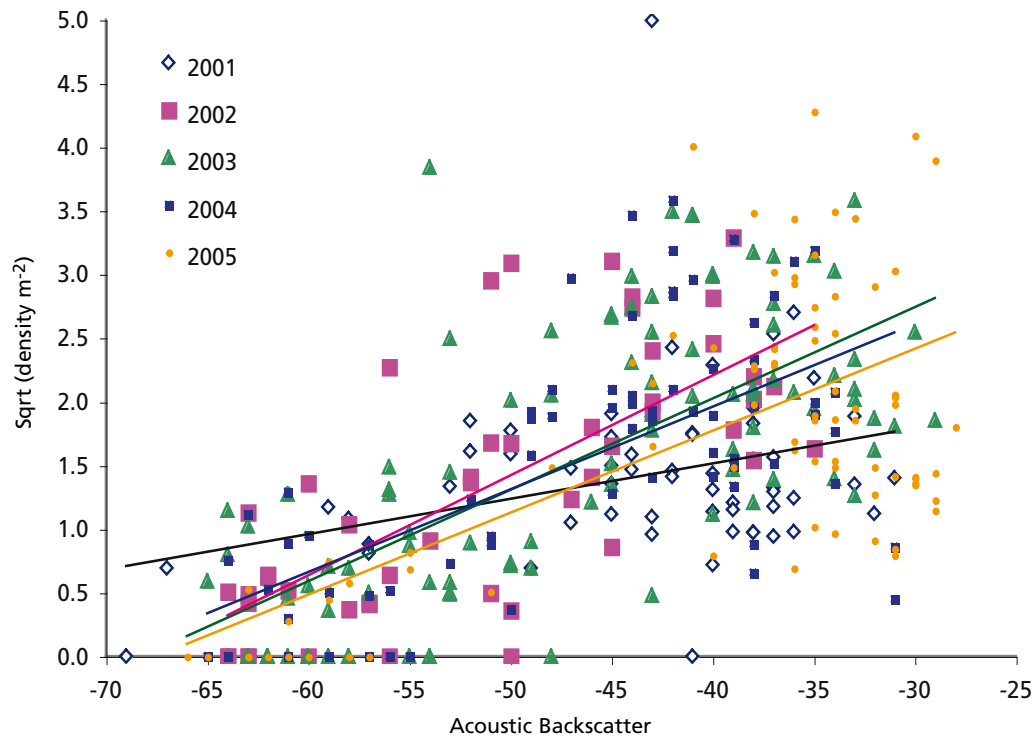


Figure 11. Relationships between acoustic backscatter (decibels) and scallop density (square root transformed) estimates in Area 1 and 2 combined from annual surveys in 2001-2005.

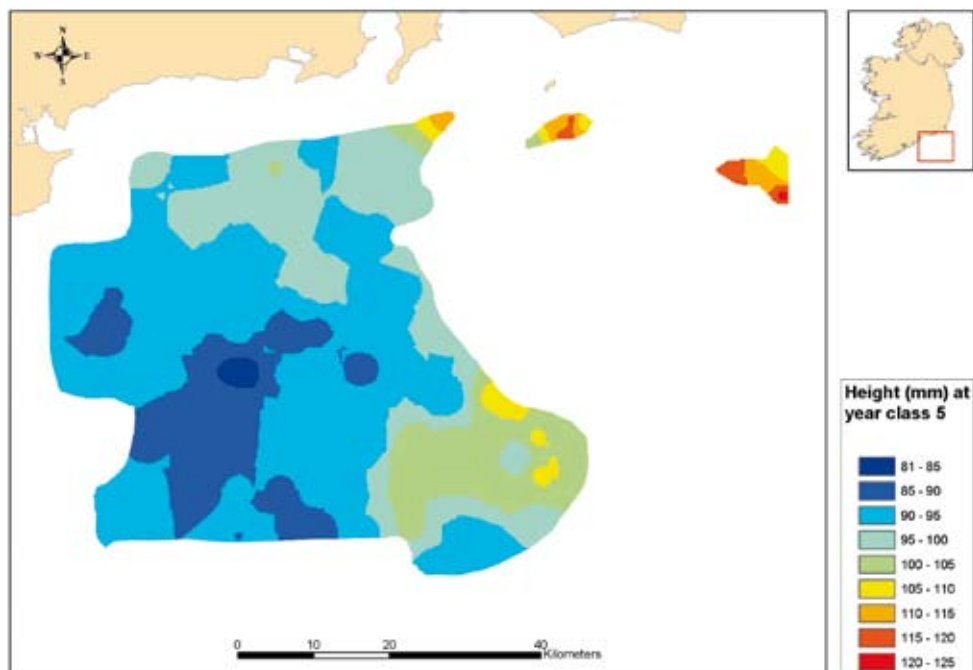


Figure 12. Absolute size of scallop at age 5 off the south east coast in 2001.

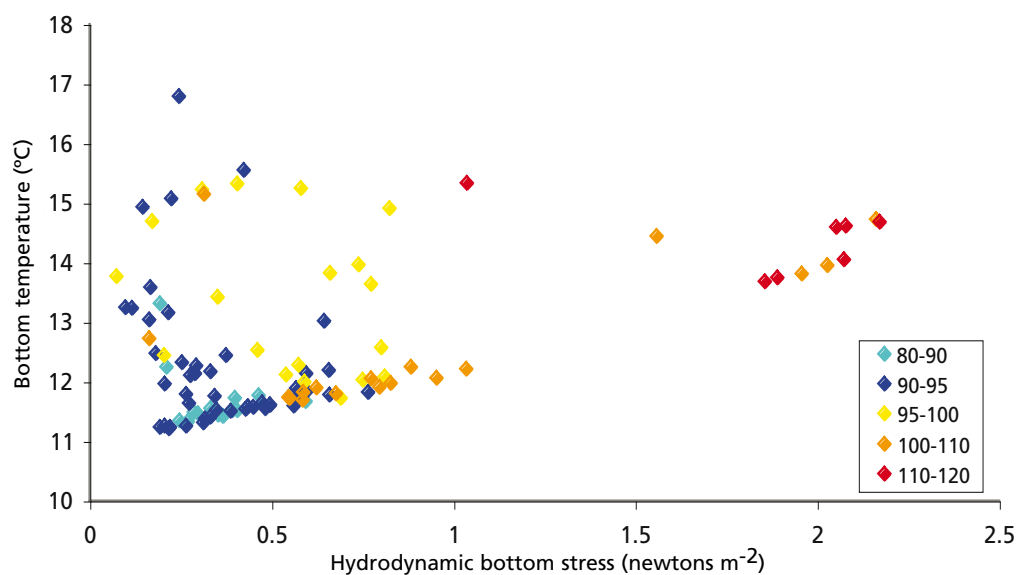


Figure 13. Relationship between size at age 5, bottom temperature and shear stress on the seabed.

east of this area in offshore waters. Growth is slower in the west of the area. These differences are quite significant resulting in up to 30mm difference in size at age 5 (Fig. 12).

Highest growth rates occur in areas of high shear bed stress (stronger currents) and highest water temperatures. High temperatures alone do not lead to high growth if seabed currents are low. This is evident from the relatively low growth rates in the northwest of the survey area (Fig. 12), which have high temperatures especially on neap tides (Figs. 4 and 13) but low shear bed stress (Fig. 6 and 13). Higher growth rates offshore in the south east of the survey area appear to be related to strong seabed currents and relatively high temperature caused by the jet like flow originating from St. Georges Channel and which maintains a mixed water column (and higher seabed temperatures) in this area compared to bottom water beneath the thermocline in the west of the area.

Growth and spatial management of yield

Growth and natural mortality data, in relation to size at first capture or minimum landing size, can be used to determine fishery management reference points, or the fishing mortality rate (F_{max}) that optimises the yield per recruit. Values of F_{max} , for fishing areas 1 and 2, were calculated for each 5x5 square mile area using spatially referenced growth rate data from annual scallop surveys (Hervas *et al.* 2006). Estimates of F_{max} are higher where growth is relatively low in relation to the assumed annual rate of natural mortality (M) of 0.2 (Fig. 14). Spatial management of fishing effort, that optimises yield per recruit, should therefore delimit fishing activity along the main gradient in F_{max} , which is mainly in the inshore

offshore direction and east to west. The F_{max} reference point, however, does not take into account impacts of fishing mortality on stock abundance or recruitment and should be used in combination with other reference points or regulatory measures in the development of fishery management strategies for the area.

Biotoxins, growth and temperature

Levels of Domoic acid (ASP) were measured in scallops collected during the 2003 survey (see Fig. 5) by Bogan *et al.* (2005). As the toxin is present due to ingestion of the diatom *Pseudonitzschia* the levels of the toxin may be related to environmental conditions, which promote the development of this species of diatom and which increase the feeding rate of scallops.

Levels of ASP, in all tissues combined, exceeded the legal limit of 20 mg.kg⁻¹ in the majority of stations. However, levels were below the legal limit in the majority of stations where the hydrodynamic model predicted that the water column was stratified and, therefore, where bottom temperatures were less than 12°C in August (Fig. 4). Three stations on the western side of this area exceeded the limit but here ASP was less than 30 mg.kg⁻¹ compared with much higher levels inshore. On the eastern side of this cold water offshore area levels ranged from 30-40 mg.kg⁻¹. Temperatures in this area increase on neap tides due to movement of the front. Although the observed pattern does not explain the mechanisms which give rise to high levels of ASP they show that, for this area, low levels of the toxin are associated with low seabed temperatures and to some degree low current speeds both of which are negatively correlated with the growth rate and feeding rate of scallops.

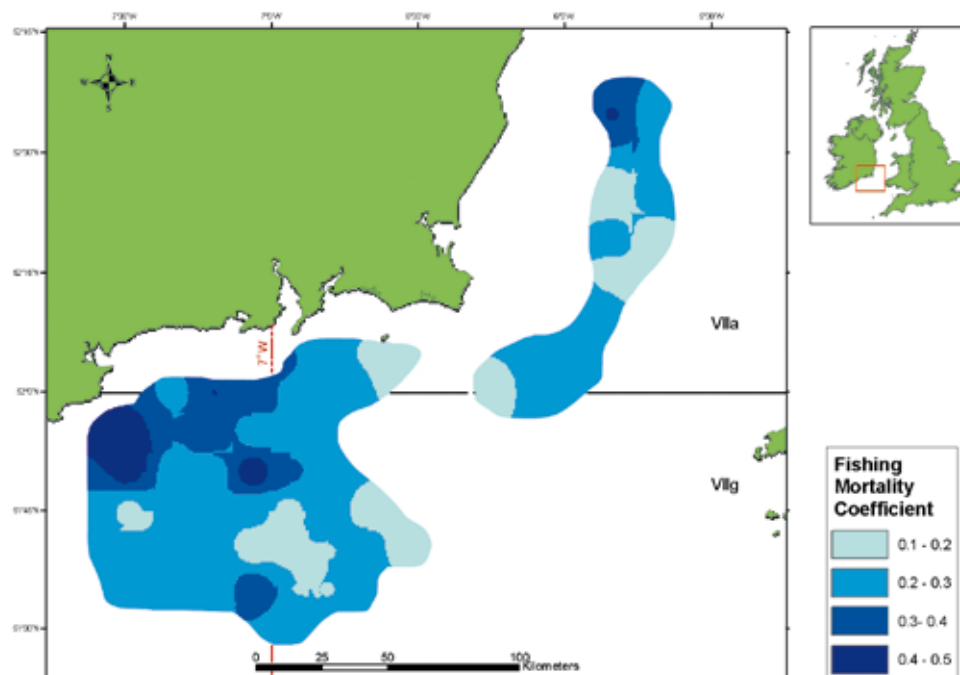


Figure 14. Values of F_{max} , or fishing mortality that optimises scallop yield per recruit, calculated using growth data collected between 2001-2004 in each 5 x 5 mile area off the south east coast of Ireland.

Implications for fisheries management

The physical environment, as shown above, controls important aspects of the biology of scallop. These processes operate at various geographic scales and have implications for the way in which scallops may be assessed and managed.

Stock structure and sources of larvae

Physical oceanographic processes determine broadscale dispersal of larvae and inter-connection between scallop beds. This information should be used in developing management strategies and to ensure persistence of all component 'stocks' in the metapopulation. Scallop beds that are important sources of larvae can be conserved more stringently than areas which act as sinks for larval populations in area based management. This would mean lower fishing effort and maintenance of higher scallop densities in source populations. In this study the Tuskar area was identified as a source area for the south east coast and the general direction of dispersal was southwest from the south east coast. In this area, therefore, recruitment may be sourced mainly from scallop beds in the east and north east, while the west and south west of the area may be less important. Regulation of fishing effort in the west and south west may therefore be less important considering also that growth rate is also lower in this region (see below).

Scallop abundance and sediment structure

Acoustic backscatter, which is an indicator of sediment composition, accounted for approximately 55% of variability in scallop abundance off the south east coast. The acoustic backscatter map can be used to improve, very significantly, the catch rates of commercial vessels by guiding the vessel along particular tracks characterised by the highest backscatter values and avoiding areas (sand) which contain few if any scallop. Although the fleet does this on a broad scale basis it cannot search efficiently for gravel patches in areas of mixed ground. Within areas where gravel predominates the ground is mixed with varying proportions of sand. Commercial fishing effort in these areas, therefore, involves dredging over varying amounts of sand for little benefit. The acoustic backscatter map can reduce dredging time, reduce potential impacts of the fishing gear on the sea bed and lower fishing costs per unit of scallops landed. Reduction of dredging time as far as possible should also be a precautionary management objective because of the possible impacts of dredging on recruiting scallop, incidental mortality of scallops which come in contact with the dredge, but are not captured, and potential damage to the habitat into which scallops recruit. These are important potential benefits in an economic environment of increasing costs and declining catch rates, which had already contributed to the decline of the Irish commercial fleet in 2004. The introduction

of technology that increases the catching capacity of fishing vessels, however, obviously needs to be balanced by the introduction of measures that adequately protect scallop stocks.

Measurement of catch rates

The small scale variability in scallop abundance shown here indicates the importance of collecting spatially referenced catch and effort data if these data are to be used to show trends in stock abundance. The catch rate data, although standardised for potential weather and vessel effects on catch, yielded somewhat ambiguous results and varied according to the level of aggregation and the source of data. This is almost certainly due to spatial variability in scallop density and serial depletion of fishing areas over small spatial scales. Acoustic backscatter (and sediment structure) at least partially determines scallop abundance over broad and fine spatial scales and can be used to provide annual standardised indices irrespective of location of fishing if the data are standardised for the backscatter effect. This method could also be applied to commercial catch rate data if the track that the vessel followed was precisely known. VMS data provides this information although the frequency with which the ships position is logged would need to be reduced to minutes rather than the two hour frequency currently used. Catch data would then need to be associated with the VMS track as in this report. This is time consuming and a more direct way of achieving the same result is to use electronic logbook systems that automatically logs the ships position at user defined frequencies and electronic logging and transmission of the associated catch. Such a system is now available for use on Irish scallop vessels (project number 01SMT102, Marine Informatics International Ltd. and BIM). Provision of data at individual tow level would allow interpretation of data at fine spatial scales and increase the options for stock assessment. Depletion analysis of spatially referenced catch rate data is one such promising method for scallops (Hervas *et al.* 2006). In addition the distribution of catch rates or densities can be analysed spatially and the concentration profile of scallop density can be monitored. This is important as high density areas can be fished down with a resultant decrease (depensation) in spawning success.

Growth rates, yield and biotoxins

Growth rates of scallop are related to environmental temperature and current strength at the seabed. These variables control the metabolic and feeding rates and supply of food to scallop. Spatially variable growth rates affect the optimum fishing effort that will maximise yield per recruit and the rate at which commercial

stocks recover from fishing. Assuming that natural mortality rates are not spatially variable, higher fishing effort should be placed in areas where growth is slow. Off the south east coast, these areas are to the west and southwest of the scallop beds. Such areas are also less important as sources of larvae in the region suggesting that high fishing effort would not necessarily be detrimental to recruitment. These observed patterns contradict the current regulation (Council regulation 1415/2004) which imposes more rigorous effort control west of 7°W where growth is slow. Minimum sizes, rotational area management and other management measures all need to take into account both the spatial variability in growth and the relative importance of different areas as a source of larvae to the wider area.

The apparently predictable relationship between levels of biotoxin and bottom seawater temperatures in particular open the possibility of marketing live scallop from this area. Although testing would still be mandatory the probability of failing the test could be sufficiently low to encourage investment in onshore live holding facilities and marketing of whole live or fresh scallop.

Summary

This paper has given an overview of a multidisciplinary project designed to improve the methods for assessment and management of scallop fisheries in Ireland. Significant progress towards sustainable management of these fisheries now seems possible because of recent developments in research, policy and fleet management. Legislation in 2005 allowed for the controlled entry of vessels to the fleet. Decommissioning and restructuring of the fleet in 2005 reduced effort potential to more sustainable levels. Seabed maps, which will be extended in 2006, are available to significantly improve the economic efficiency of scallop vessels and in parallel reduce potential impacts of dredging on the environment and on scallop recruitment. A database of biological information on scallop, which allows for new approaches to resource assessment is available. A model of stock structure and the relative importance of different beds as sources of recruitment off the south east coast has been developed. Finally, a co-operative Management Framework was established in 2005, within which the Scallop Advisory Committee, using the developments outlined in this paper, can develop informed management plans for the fishery.

References

- Anon 1995. The Management of Ireland's inshore fisheries: The Framework for Shellfisheries; structures, functions and process. Department of Communications, marine and Natural Resources and BIM, Dublin, 15 pp.
- Berry, A. and Hartnett, M. 2005. An investigation into scallop larvae transport and settlement off the southeast coast of Ireland. Final report of project 01SMT107, BIM, Dublin.
- Bogan, Y.M., Bender, K., Hervas, A., Kennedy, D.J., Slater, J.W., Hess, P. (2006). Spatial variability of domoic acid concentrations in king scallops *Pecten maximus* off the southeast coast of Ireland. Harmful Algae (in press) doi:10.1016/j.hal.2006.05.004
- Brown, J., Carrillo, L., Fernand, L., Horsburgh, K.J., Hill, A.E., Young, E.F., and Medler, K.J. 2003. Observations of the physical structure and seasonal jet-like circulation of the Celtic Sea and St. George's Channel of the Irish Sea. Continental Shelf Research, 23, 533-561.
- Dare, P.J., Darby, C.D., Durance, J.A. and Palmer, D.W. 1994. The distribution of scallops, *Pecten maximus*, in the English Channel and Celtic Sea in relation to hydrographic and substrate features affecting larval dispersal and settlement. pp. 20-27, In: Bourne, N.F., Bunting, B.L. & Townsend, L.D. (eds.). Proceedings of the 9th International Pectinid Workshop, Nanaimo, B.C., Canada, April 1993, Vol. 1. Canadian Technical, Report of Fisheries and Aquatic Sciences, 1994
- Fifas, S. 1991. Un modele empirique de capturabilite pour le stock de coquilles Saint-Jackues (*Pecten maximus* L.) en Baie de Saint-Brieuc (Manche, France). CIEM, Shellfish Committee, CM 1991/K:37, 20 pp.
- Hervas, A., Tully, O., O'Keeffe, E. and Hickey, J. 2006. The king scallop (*Pecten maximus*) fishery: Analysis of the resource in 2004-2005. BIM, Dun Laoghaire, Co. Dublin, 77pp.
- Howell, T.R.W., Davis, S.E.B., Donald, J., Bailey, N. and Tuck, I. 2003. Report of Marine Laboratory Scallop Stock Assessment. Fisheries Research Services Internal Report No 07/03, Marine Laboratory, Aberdeen, Scotland, 140pp.
- Kostylev, V.E., Courtney, R.C., Robert, G. and Todd, B.J. 2003. Stock evaluation of giant scallop (*Placopecten magellanicus*) using high-resolution acoustics for seabed mapping. Fisheries Research, 60, 479-492.
- Le Pennec, M. 2003. The pelagic life of the pectinid *Pecten maximus* – a review. ICES Journal of Marine Science, 60, 211-223.
- Lipcius, R.N., Stockhausen, W.T. and Eggleston, D.B. 2001. Marine reserves for Caribbean spiny lobster: empirical evaluation and theoretical metapopulation recruitment dynamics. Marine and Freshwater Research, 52, 1589-98.
- Mason, J. 1983. Scallop and queen fisheries in the British Isles. Farnham, Surrey, England. Fishing News Books.
- Orensanz, J.M., Parma, A.M. and Iribarne, O.O. 1991. Population dynamics and management of natural stocks. In: Shumway, S. (ed.) Scallops: Biology, Ecology and Aquaculture. Elsevier (Amsterdam and New York).
- Shumway, S. 1991. Scallops: Biology, Ecology and Aquaculture. Elsevier (Amsterdam and New York).
- Smith, S.J. and Rago, P. 2004. Biological reference points for sea scallops (*Placopecten magellanicus*): the benefits and costs of being nearly sessile. Canadian Journal of Fisheries and Aquatic Sciences 61, 1338-1354.
- Sutton, G. and O'Keeffe, E. 2006. Seabed mapping: Multibeam bathymetry, backscatter and video imaging of the seabed in the south east coast scallop grounds. Final report of project number 01SMT107 Annex II. BIM Dublin, 20pp.
- Young, E.F., Brown, J., Aldridge, J.N., Horsburgh, K.J., and Fernand, L. 2004. Development and application of a three-dimensional baroclinic model to the study of the seasonal circulation in the Celtic Sea. Continental Shelf Research, 24, 13-36.

