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I dedicate this work to my father who I always loved and admired

Assessment of scallop (*Pecten maximus*) stocks in the Irish and Celtic Seas

A Thesis submitted to the University of
Dublin, Trinity College, in candidature for
the degree of Doctor of Philosophy

By

Antonio Hervás Abad
May 2008

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ANTONIO HERVÁS

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Summary

Spatially explicit approaches (differing from the traditional stock assessment theory) to the assessment of scallop off the southeast coast of Ireland were developed. Different stock assessments methods were presented with the objective of providing comprehensive information on: (*i*) the biological parameters and their use in estimating biological reference points (*ii*) stock indicators to determine the state of the stock. Data for assessment were collected from commercial fishery data for the time period 1995-2004 and data from research surveys for the period 2001-2005.

Dredge efficiency was estimated by the Delury-Leslie depletion method. Estimates varied between 5% and 17% and 4% and 25% for commercial sized and undersized scallop respectively. Dredges configured with 65 mm, 75 mm and 89 mm belly rings selected 50% of scallops at 67.4 mm, 82.3 mm and 90.2 mm shell length. The selection range was 8.2 mm, 6.3 mm and 9.4 mm for these dredges, respectively.

Growth data was collected during the period 2001-2004 for scallop beds in Irish and UK waters. Determinants of variability in growth on a fine spatial scale was also studied off the south east coast of Ireland. This fine scale variability in growth was correlated with temperature and seabed current strengths, which accounted for 67% of variability in growth. Growth rate decreased with latitude perhaps reflecting temperature differences. The spatial pattern of variability in growth was along the main axes of variability in hydrodynamic bottom stress and bottom water temperature-inshore offshore and east to west. The condition of the somatic tissue reached the highest value in October 2002 and 2003, however, in 2004 the highest value was found in September. The lowest values were found in May 2003 and in June 2004. Gonad weight reached a peak during spring and summer, decreased at the beginning of autumn and recovered during winter.

Commercial CPUE data were standardised using General Linear Modelling and annual changes in stock abundance indicators were reported for years 1995-2004.

Results indicated that CPUE was stable between 2000-2004. Prior to 1999 the pattern was inconsistent and depended on the data source. The DeLury depletion method was used to model the decline in commercial CPUE over periods of weeks at locally defined fishing areas. Exploitation rates from depletion analysis were estimated to be between 2-7%.

Multibeam acoustically derived sediment maps were used to investigate the relationship between sediment composition and scallop abundance. Results of annual research surveys showed a strong relationship between sediment type and scallop distribution and density. Sands and gravels were the dominant substrates. Approximately 80% of scallops were found on gravel. Log-transformed estimates of scallop density, uncorrected for dredge efficiency, increased linearly with average acoustic backscatter values used to produce the sediment maps. Results of analysis of co-variance showed that the elevation and the slopes of the regression lines of CPUE on backscatter were similar between 2001 and 2005 suggesting that stock abundance was stable during this period. The abundance of scallop over 65mm shell height was estimated to be 55 million for the two beds combined.

The effect of spatial varibility in growth on the definition of the growth overfishing reference points was investigated. F_{max} ranged from 0.4 to 2.2 depending on growth rate. Yield per recruit for a given fishing mortality and natural mortality of 0.15 was higher as the minimum landing size increased. Catch at age data collected during the surveys was used to estimate $F_{current}$ using the catch curve analysis. Estimates of instantaneous fishing mortality rates ranged between 0.6-1.0, indicating that growth overfishing was ocurring.

A comparison of stock assessment methods and outputs was presented in order to evaluate assumption and uncertainties in the different methods of analysis. The weight of evidences suggested that exploitation rates were low and sustainable. The exception to this was the high exploitation rate estimates from the cohort analysis. Although exploitation rate may be low a cautious approach is required in management because of potentially hidden negative impacts of dredging on scallops not captured by the dredge and impacts on the seabed environment. Management measures should take account of particular features of scallop biology and metapopulation structure.

Introduction

The king scallop, *Pecten maximus*, (hereafter referred to as scallop(s)) is a bivalve mollusc belonging to the Family Pectinidae and, together with queen scallop, *Chlamys opercularis*, is the most important commercial species of scallop in the eastern North Atlantic. It occurs along the east coast of the North Atlantic from northern Norway south to the Iberian Peninsula (Brand, 1991) and is commercially exploited off the coast of Scotland, Ireland, North Ireland, England, Wales and France. In Ireland the main fishery occurs off the south east coast and in the Irish Sea. Smaller stocks exist along the west coast in inshore bays and inlets. The scallop stock off the south east coast of Ireland has been exploited since the 1970s mainly by the Irish fleet. The fishery is also open and accessible to UK and French fleets although activity by these fleets in the area has been low. Although effort increased during the 1990s and the fishery increased in value no assessment of the resource was undertaken prior to the work presented here.

In the assessment of exploited marine populations, the biology of the species is important and will determine the most appropriate assessment methods and management measures that may be applied to ensure sustainable development and management of the resource. Scallops are sedentary and are broadcast spawners with external fertilization and pelagic larval development (Shumway, 1991). This poses difficulties for assessment. Traditional stock assessment theory relies on two basic tenets (Caddy, 1975); (*i*) the unit stock concept, that considers that the stock is self-recruiting and closed to immigration from other stocks (*ii*) the dynamic pool assumption, in which the fishing process is considered to be homogeneous within the area occupied by the stock. Traditional stock assessment theory was developed for pelagic fin fisheries for which, to some extent, these two assumptions can be considered valid. However in scallop fisheries they are in almost all cases invalid. Usually, commercial scallop beds are component populations of a metapopulation (Orensanz and Jaimeson, 1998; Orensanz *et al*., 2006; Tully *et al*., 2006a) and this implies that each component population is open to recruitment from other populations of the metapopulation. The connection between scallop beds or populations is determined by the dynamics of larval dispersal from spawning areas rather than due to the movement of adult scallops (Jamieson and Campbell, 1998; Tully *et al.*, 2006a). Secondly, the distribution of fishing for scallops is not random but tends to match the distribution of density, i.e. areas of high density are targeted until the catch rate declines to a given economic level at which point fishing activity switches to a different location. Locations are seldom chosen randomly except in the case of new fisheries where there may be significant exploratory fishing activity. In established fisheries knowledge of previous catch is used to identify and optimise fishing locations. Scallops, being "nearly" sedentary animals, do not disperse after a spatially localised fishing event and therefore losses of individuals due to fishing or fishing mortality (F) varies spatially. Development of stock assessment procedures for scallops therefore needs to differ from the traditional theory as scallops violate the dynamic pool assumption at all scales except at the very local.

In stock assessment the population biology is studied to develop biological reference points (BRPs) that are then used to regulate or manage exploitation of the stock. BRPs are calculable values that quantify the state of the population. When used to set exploitation rates they represent a trade off between the use of the resource and the life traits of the resource. BRPs acknowledge two important characteristics of exploited biological populations; firstly, exploitation levels or removals or losses from the population must be in balance with gains in biomass due to growth. This concept is outlined in the yield per recruit theory of Beverton and Holt (1957). Secondly, the exploitation or the proportion of the biomass that is removed annually or during some other time period must be in balance with the capacity of the population to renew itself through recruitment. This balance will depend on the efficiency of the stock recruitment relationship, which indicates how many recruits may be produced on average from a given level of spawning.

The optimum exploitation rate, that achieves a balance between growth and mortality, is defined by the growth overfishing reference point (F_{max}), which is the fishing mortality that maximises yield per recruit. Growth of scallops is influenced by food supply, temperature, current strength or depth and therefore varies spatially in most environments (Gibson, 1956; Mason, 1957; Baird and Gibson, 1966; Caddy *et al.*, 1970; MacDonald and Thompson, 1985; Shick *et al.*, 1988; Robert *et al.*, 1990; Kenchington *et al.*, 1997; Ignell and Hayness, 2000; Smith et al., 2001; Defeo and Gutierrez, 2003; Harris and Stokesbury, 2006). As a consequence, defining how growth varies spatially and how it may be correlated with population density or with environmental conditions is important. Otherwise the growth parameters may not be representative and the position of the fishery with respect to fishery management reference points may be miscalculated (Smith and Rago, 2004).

The renewal process or recruitment overfishing reference point is the exploitation rate that maintains a level of spawning stock biomass that provides recruitment levels that can sustain the population (Hilborn and Walter, 1992). However in scallop fisheries there is little evidence of spawner-recruit relationships (Orensanz *et al.*, 1991; Smith and Rago, 2004). There are 3 main reasons for this; (*i*) to identify a relationship between stock and recruitment require that both stock and recruitment can be measured with reasonable precision and using the appropriate time lags. This is difficult in the case of scallop, (*ii*) environmental effects on larval survival and settlement may be sufficiently strong to negate any relationship between stock and recruitment. So there may be years of good recruitment and years of poor recruitment that may be caused by environmental conditions rather than spawning stock size and (*iii*) for scallops, and as has been demonstrated off the south east coast of Ireland (Tully *et al.* 2006a), there may not be a single "unit stock" which is traditionally assumed in fisheries assessment and management. A single stock recruitment relationship may therefore not exist in the traditional sense. Scallops in these areas probably exist as a metapopulation with a number of component populations, which are interconnected to varying degrees by larval dispersal processes. Furthermore the degree of connectivity between each population may vary spatially and annually depending on meteorological and oceanographic forcing conditions. Evidence of this for the southeast scallop stock was provided by Tully *et al.* (2006a), Berry and Harnett (2006) and Harnett *et al.* (2006).

In fisheries management the adoption of the precautionary approach is a consequence of the unclear relationship between stock size and recruitment and the fact that F_{max} does not account for changes in abundance or recruitment. The precautionary approach is defined by some fishing mortality target lower than F_{max} that aims to reduce the risk on recruitment failure (Caddy and Mahon, 1995).

Independently of whether the fishery is managed by BRPs, or which BRPs are used, fishery statistics need to be monitored to determine the state of the stock and to ensure that exploitation of the resource is consistent with the BRPs. Measurement of the fishery statistics provide estimates of exploitation rates and/or indicators of the sustainability of the fishery. Indicators of exploitation rate and population trends can be obtained from landings, measurement of fishing effort, abundance indices, abundance estimates, recruitment indices, or related observations on the age structure of the population. A time series of these stock indicators provide information on the possible sustainability of fishing activity and fishery mortality levels imposed on the stock. In fisheries assessment, data on indicators or estimates of stock are usually obtained from fishery independent (data from research surveys) and fishery dependent sources (commercial fishery data).

In scallop resource assessment research surveys are usually used to estimate abundance or relative abundance of adults and juvenile. Research surveys also give information about the spatial distribution of the population, which is essential to understanding of the population dynamics of sessile organisms (Orensanz *et al.*, 1991), although fishery data could also provide this. Research surveys are also used to collect biological information (growth, size and weight data) for the estimation of biological parameters (growth rates, mortality rates) and the subsequent estimation of BRPs.

Commercial catch and effort data provide an indirect method of assessing trends in scallop abundance. The analysis of temporal trends in catch rates has a long tradition in stock assessment. However the use of catch rates in spatially structured stocks, such as scallops, can be misleading if the spatial distribution of fishing effort is not accounted for. Fishing effort is not random and the sedentary nature of scallop determines that density is not redistributed after each fishing event. If catch and effort data are analysed under the dynamic pool assumption, abundance will tend to drop faster than catch rates, the so-called hyperdepletion (Hilborn and Walter, 1992) and changes in CPUE will not be proportional to changes in abundance. Fishing effort targets the densest patches available first, shifting to the next patch as the first is depleted. This is not detected by traditional catch and effort data because the spatial resolution of the fishing activity data is not sufficient.

In this thesis spatially explicit approaches (differing from the traditional stock assessment theory) to the assessment of scallop off the southeast coast of Ireland are developed. Different stock assessments methods are presented with the objective of providing comprehensive information on: (*i*) the biological parameters and their use in estimating biological reference points. (*ii*) stock indicators to determine the state of the stock.

A sampling programme was developed during the years 2001- 2004 to collect data on the biology of scallops for the estimation of biological parameters. Data were obtained from independent research surveys and from the commercial landings. As the physical environment affects growth of scallop and the environment off the south east coast is complex (Hartnett *et al.* 2006), this study investigated which environmental variables were the most important determinants of growth. Growth of scallops was related to bottom water temperature, the hydrodynamic bottom stress and water depth. Environmental physical variables were obtained from a hydrodynamic advection model developed for the area of study by Marcon Computation International Ltd (2006). The understanding of growth in relation to the physical environment provided a means for developing BRPs in a spatially based approach. The seasonal variability in the somatic tissue conditions and the gonad weight was monitored and used in deciding the most appropiate time of the year to harvest the optimum yield estimated by a yield per recruit method.

Fishery independent data were also generated. Five research surveys were carried out from 2001-2005 with the objectives of estimating relative and "true" abundance of juveniles and adult scallops and mapping their distribution. The importance of sediment type on the distribution and abundance of scallops was investigated. To do so research surveys were carried out in combination with multibeam echo-sounder (MBES) sonar systems. MBES was used to map the sediment distribution. Mapping was undertaken by the Coastal & Marine Resource Centre at the University College Cork. The use of multibeam acoustic maps provided a tool to determine the importance of the sediment composition in determining the distribution and abundance of scallops. Hence sediment type was used to stratify the allocation of sampling stations to estimate population abundance. Also, each research survey provided data on size/age and population structure. Data were used to estimate mortality rates using catch curve analysis.

The efficiency of the scallop dredge was estimated to convert relative estimates of abundance into "true" abundance. Dredge efficiency can be defined as the proportion of the number of scallops in the dredge path captured by the dredge and was calculated using the Leslie (1939) depletion method. Dredge efficiency was estimated for the two main substrates, sand and gravel, on which scallops are found. The selectivity of the dredge, which is defined as the number of scallop retained from the total number entering the dredge, was also estimated. The understanding of dredge selectivity is essential in stock assessment as it affects the estimation of total mortality, from catch at age data, which is a parameter needed for most of the population dynamics models, eg. yield per recruit.

Fishery dependent catch and effort data analyses were undertaken using novel approaches that allowed comparison of data from different sources and using different analytical methods. As it has been described above, analysis of catch and effort data for scallops needs to take into account the spatial distribution of fishing effort. The Vessel Monitoring System data (VMS), provided and managed by the Irish Naval Services, was used to indicate the precise locations of fishing and was combined with official logbook sources to indicate the spatial distribution of catch. Four main scallop beds were identified from the VMS activity and analysis of catch and effort data was carried out separately for each scallop bed. Two analyses were carried out; (i) commercial catch per unit effort data (CPUE) was standardised using a General Linear Model (GLM), and annual changes in stock abundance were reported, (ii) a Delury (1947) depletion model was used to model the fishery depletion process in a number of selected areas while minimising any violation in the assumption of this model.

Each assessment method presented in this thesis makes different assumptions, involves a number of uncertainties and all are modelled or statistical estimates of the "true" population. Hence, results obtained from different methods were compared and possible causes of observed differences in the estimates are discussed. This is an important, although not often used, approach to assessment. Where there is uncertainty in the assessment output from one method it is important to be able to compare this with independent estimates using different data sources and methods. The weight of evidence may then point in one direction or another and appropriate management decisions can be taken.

Chapter 1 introduces and describes the fishery and its management off the south east cast of Ireland. Chapter 2 describes and models the dredge efficiency and selectivity, in order to convert abundance indices to "true" abundance. Chapter 3 deals with the estimation of the biological parameters. In particular, spatial variability in scallop growth and its implications for estimation of BRPs is presented. A detailed analysis of commercial catch and effort data obtained from different sources and at different spatial and temporal resolutions is presented in Chapter 4. Data from research surveys carried out from 2001-2005 are presented in Chapter 5. In this chapter relative and "true" abundance of juveniles and adults scallops are estimated. Surveys were designed in combination with the acoustic indicators of ground type to relate the distribution and abundance of scallops to the sediment composition. Chapter 6 uses results of the spatial variability in growth parameters to estimate spatially explicit growth overfishing reference points. Chapter 7 presents a comparison of assessment methods. Here the multiple indicators of the status of the stock provided in Chapters 2-6 are compared and a discussion of the relative quality of the data sets and the assessment methods is presented.

The Biology of Scallops

Biology

Within the temperature and salinity tolerance range the major factors affecting the distribution of scallops are, substrate type, currents and turbidity. The bathymetric range of distribution is from the low tide mark to over 100 m, but it is most common in waters of 20-70 m. King scallops are found on clean firm sand and fine gravel and in currents, which provide good feeding conditions. Scallop can be present in densities of 5-6 m^{-2} although a more normal density is 0.2 m^{-2} (Shumway, 1991).

The life span of *Pecten maximus* possibly extends in extremes cases to greater than 20 years (Tang, 1941, cited in Ansell, 1991), however the average life span is much less than this. The oldest specimens normally reach 10-11 years of age in exploited populations. The most abundant exploited year classes in exploited populations are 4-6 years old (Vigneau *et al.*, 2001; Beukers-Stewart *et al.*, 2003; Howell, 2003).

The life cycle can be divided into the free swimming larval phase and the largely sedentary juvenile and adult phase. The scallop is a filter feeder, drawing in seawater, which is filtered through the gills. It is hermaphroditic, with the gonad divided into a proximal white testis and a distal deep orange-red ovary (Barber and Blake, 1991). In general the potential spawning season is long, from April to September or October, but its timing and duration vary geographically (Barber and Blake, 1991). During spawning gametes are released to the water column and fertilisation occurs externally. Fertilisation success is related to the density of scallop on the seabed as is the case with most species with external fertilisation (Orensanz *et al.*, 1991, Orensanz *et al.* 2006). The larval development period is 2-3 weeks (Le Pennec *et al.*, 2003). Larvae survival is promoted by good concentration and quality of food in the water column (Le Pennec et al., 2003). This condition is dependent on physical conditions such as temperature, nutrient supply and light penetration. Recruitment is usually unpredictable as it depends not only on successful spawning and larval production but also on retention of larvae or transport of larvae into the area suitable for settlement (Smith and Rago, 2004). Settlement in a particular area may be unpredictable leading to unstable age structure. As a consequence of this scallop beds frequently show a regional separation of year classes and spatial variability in age structure (Orensanz *et al.*, 1991, Orensanz *et al.,* 2006; Howell, 2003).

On settlement scallops secrete a byssus thread after metamorphosis for attachment to the substrate on the seabed. Recently settled scallops have been found on stones, empty shells, bryozoans, hydroids and the algae *Laminaria saccharina* and *Desmarestia* (Brand *et al*., 1980 and Mason, 1958). Scallops generally lose the byssus soon after metamorphosis and few scallops larger than 15 mm shell length are found attached (Minchin, 1984). King scallops are usually recessed into the sediment so that the upper (left flat shell, the right shell is cupped) valve is level with or just below the surface of the sediment (Brand, 1991). The juvenile and adults are sedentary and they swim in response to simulation by light, water currents, vibration, fishing gears or predators (Brand, 1991).

Biology and Management

Various aspects of the biology of scallop, described above, are highly relevant to the design of fisheries regulations that may be used to manage scallop stocks.

1. Protection of spawning: Because scallops are broadcast spawners and fertilisation success is related to the proximity of one scallop to the next on the seabed a minimum density should be maintained, at least in some areas, in order to minimise risk of failure in larval production. This has an implication for the efficiency and the shape of the stock recruitment at low population density
2. Protecting recruitment: Recruitment success depends on delivering competent larvae to the existing scallop bed or at least to a favourable seabed environment. Tidal currents will determine the direction of larval transport and the relative importance of different areas as sources of larvae. This information should be used by management to more strongly protect areas that are important sources

of larvae whereas areas which act as sinks for larvae could be exploited at higher levels.

3. The settlement stage is vulnerable to disturbance: The pedi-veliger post larva requires specific types of substrate to settle onto and may be vulnerable to sediment disturbance. Dredging activity during settlement my damage recruitment and any means to reduce disturbance at settlement should be considered as a precautionary management tool
4. Recruitment is usually highly variable: Recruitment failure and weak year classes are common features in scallop stocks. This will contribute to spatial and temporal variability in catch rates
5. Growth rate is spatially variable: If growth rates are variable the yield per recruit and the optimal level of fishing effort will also vary geographically. Combined with point 2 above this suggests that spatial management of scallop fisheries is important

Chapter 1. The Scallop (*Pecten maximus*) Fishery off the Southeast of Ireland.

1.1 Fleet Development

Scallop fishing is a deep-rooted tradition, which in Ireland extends back to at least the 16th century (Mason, 1983). Wild 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 south east coast, however, and in the Irish Sea, 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 beds.

The south and east coast fishery is fundamentally different to the small inshore scallop fisheries on the west coast. The offshore stocks are fished by large vessels 20-36m in length and towing as many as 34 spring-loaded dredges (Table 1.1 and Figure 1.1). This fishery began in inshore waters off the south Wexford coast in the 1970s and gradually expanded offshore and into the south Irish Sea (Figure 1.2). Further expansion occurred in the 1990s and by 2002 the Irish fleet had expanded its range from the south east coast and south Irish Sea to the English Channel and west of France south to 48°N.

In 1997 the total number of dredges in the fishery was 103. This expanded to 498 between 1997-2000 and reached the highest value 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 2003, 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 each of the vessels. These 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 upto October 2005.

Table 1.1. Profile of scallop fleet in year 2001.

Vessel ID	Length overall (m)	Kilowatts	Tonnage
1	30	668	227
2	23	492	102
3	29	526	132
4	25	390	136
5	30	722	198
6	25	477	127
7	30	597	121
8	34	1030	220
9	30	662	145
10	22	221	69
11	27	560	137
12	24	560	65
13	24	524	152
14	35	883	200
15	24	485	155
16	20	149	57
17	36	1177	268

Figure1.1. Scallop vessels at Kilmore Quay (Co. Wexford)

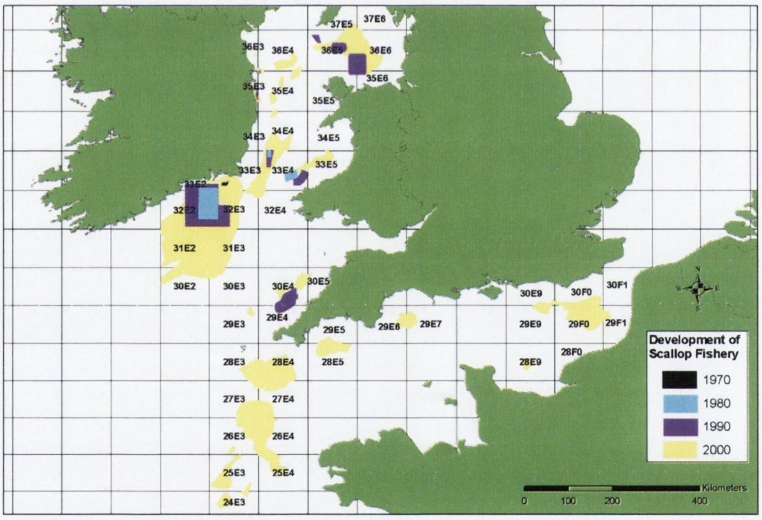


Figure1.2. Distribution of fishing by the Irish registered scallop fleet 1970-2005. Data prior to 2000 is from information supplied by fishermen. Areas fished from 2000-2005 (in yellow) are derived from vessel monitoring system (VMS) data supplied by the Irish Naval Service.

Off the southeast coast of Ireland fishing effort concentrates on four scallop beds, the inshore bed, the B&H scallop bed, the Barrels bed, and the Tuskar bed, which hereafter are referred as Area 1, Area 2, Area 3, and Area 4, respectively (Figure 1.3). In scallop stock assessment the traditional stock assessment approach, in which fishing distribution is considered random, the so-called dynamic pool assumption (Caddy, 1975) has been rejected by a number of authors (Caddy, 1975; Orensanz *et al.*, 1991; Jamieson and Campbell, 1998; Smith and Rago, 2004; among others). In this thesis fishing effort was identified to be far from random. Separate scallop beds were identified from the distribution of commercial fishing activity. This activity is accurately described by the vessel monitoring system (VMS), which gives the location of all vessels every two hours during fishing.

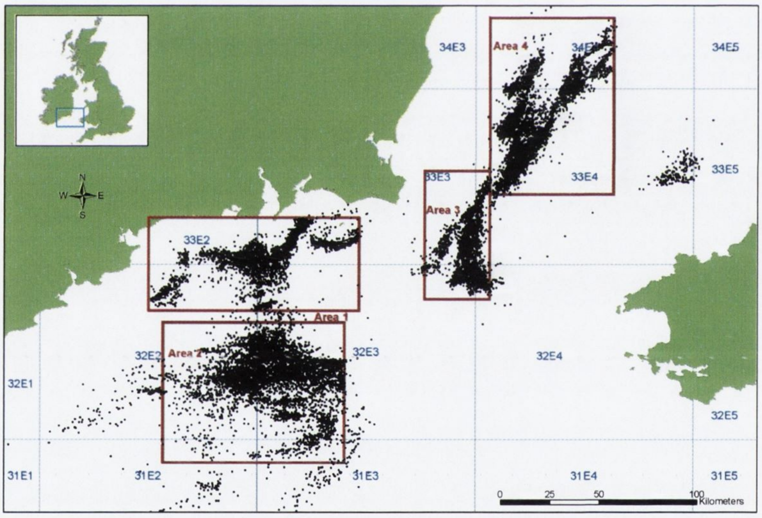


Figure 1.3. Distribution of fishing by the Irish scallop fleet off the south east coast 2001-2004. Data were derived from vessel monitoring system (VMS) information sourced from the Irish Naval Service.

Total fishing effort, expressed as the number of dredge hours, can be accurately reported by combining the VMS and logbook data (Figure 1.4). Fishing effort in Area 1 supported less than 20% of the total effort in the southeast for years 2001-2003 increasing to over 40% in year 2004. Area 2 sustained a high percentage of the total effort between 2000-2003 ranging from 38% to 52% of the total effort in the southeast. However, fishing effort in Area 2 decreased to less that 10% of the total in 2004. Fishing effort in Area 3 ranged between 10 and 30 % of total effort and was highest in 2004. Fishing effort in Area 4 varied between approximately 20% and 40%. Area 4 supported 37% of the total effort in 2002 but this decreased to around 20% of the total in 2003 and 2004 (Figure 1.5).

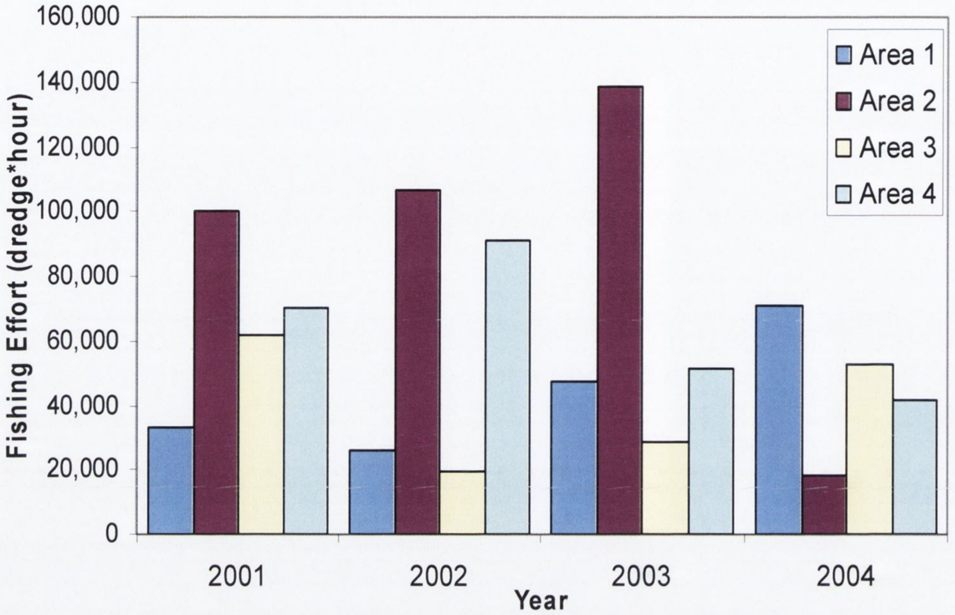


Figure1.4. Annual fishing effort (dredge hours) by Area off the south east coast in 2001-2004.

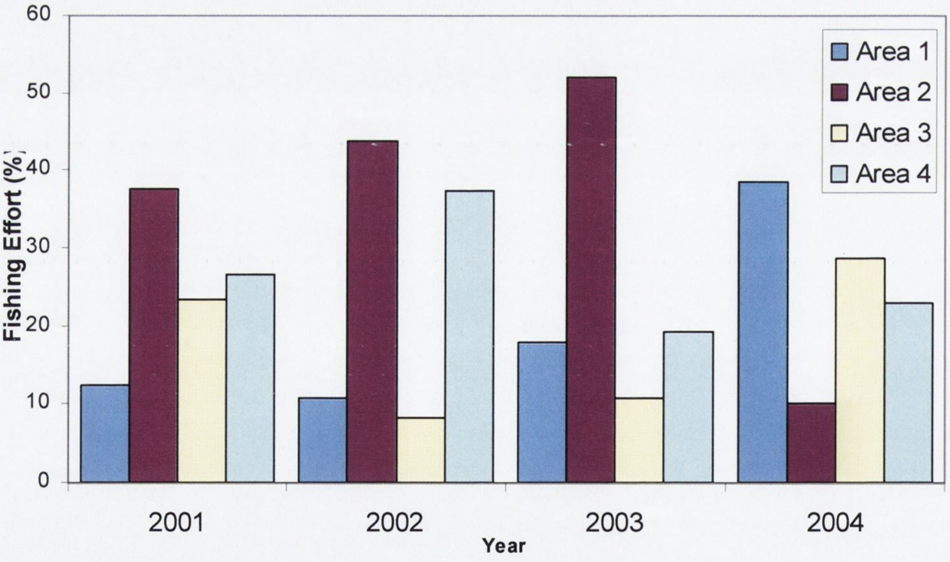


Figure 1.5. Annual percentage of total scallop fishing effort (dredge hours) in each of 4 fishing areas off the south east coast in 2001-2004.

1.2 Landings

Landings of scallop by Irish vessels are reported in the European Community Logbooks (ECL), which are compiled by the Department of Communications, Marine and Natural Resources (DCMNR). For the period 2001-2004, these data were cross-checked for missing values with 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. VMS data, which did not have a related 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 (see Chapter 4 for description of the VMS technology and how it was used in the analysis of catch and effort data).

Annual landings of scallop into Ireland, almost exclusively by Irish vessels, averaged 668 tonnes per annum between 1990 and 1998 (Figure 1.6). Landings increased to 1559 tonnes in 1999. This increase resulted from an expansion of the fleet, especially in 1999, when a number of new bivalve licences were issued. Licences were issued responding to the industry demand driven mostly by the market price at the time of the fleet expansion. Fishing effort expanded to the western English Channel and the Irish Sea with the introduction of these new vessels. Landings reached the highest value 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 were just over €6.5 million in 2004.

Landings from Area 1-4 off the south east coast were between 600-700 tonnes (Figure 1.7) in the years 2001-2004. This accounted for 30-50% of the overall landings into Ireland in this time period. Scallop landings from Areas 1-4 varied between 2001-2004. There was a positive and linear trend between landings and fishing effort (Figure 1.8).

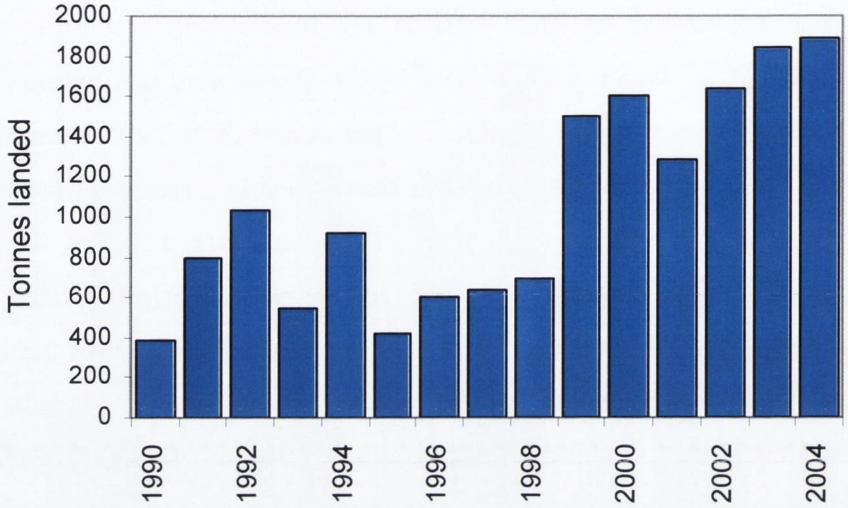


Figure 1.6. Landings of scallop into Ireland 1990-2004.

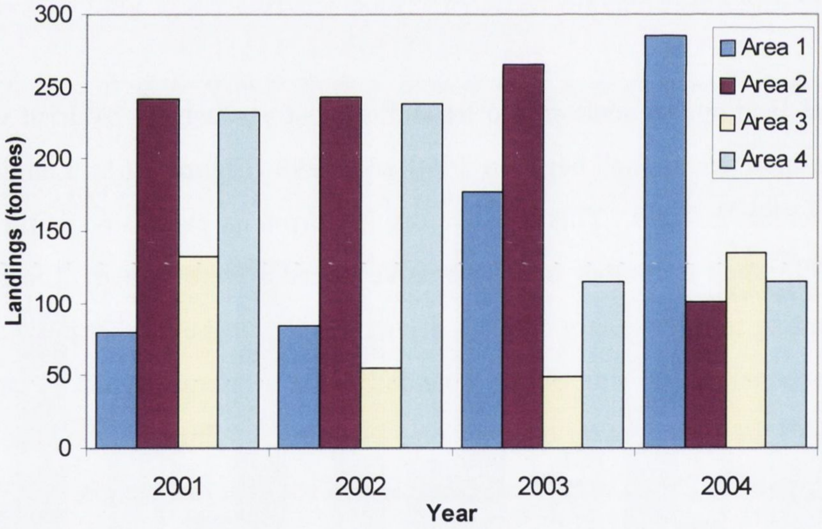


Figure 1.7. Annual landings (tonnes) in each of 4 fishing areas off the south east coast in 2001-2004

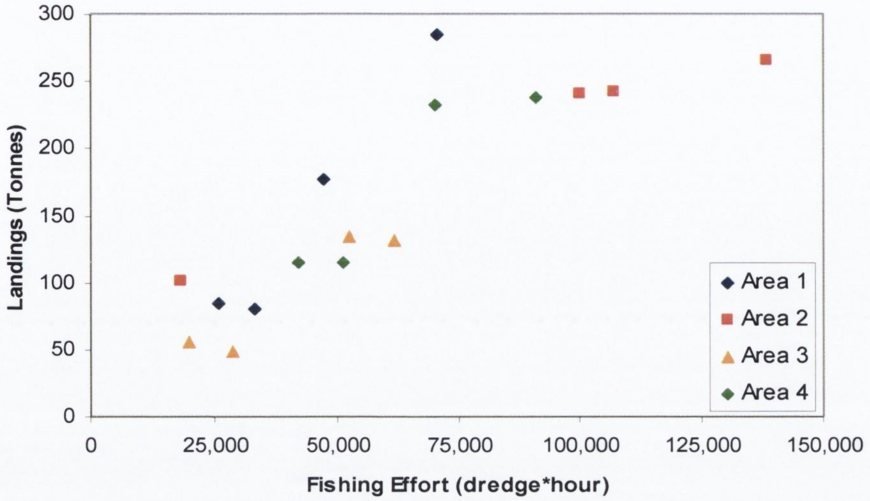


Figure 1.8. Relationship between fishing effort and scallop landings from Areas 1-4. (see Figure 1.2).

1.3 Fishing Gear

The fishing gear used by the Irish fleet is a toothed spring-loaded dredge (Figure 1.9). The dredge consists of a triangular frame leading to a mouth opening 0.83 m wide, a tooth bar with a distance of 65 mm between teeth, length of teeth of approximately 8-10 cm long, and a bag of steel rings (75 mm internal diameter) and netting back (75 mm stretched mesh). The tooth bar rakes through the sediment lifting out scallops and the spring-loaded tooth bar swings back, allowing the dredge to clear obstacles on the seabed. The compression in the springs changes and is set up in order to work in stony grounds and to reduce incidence of stones in the dredge. The dredges are held in series on two beams, which are fished on each side of the vessel (Figure 1.10).

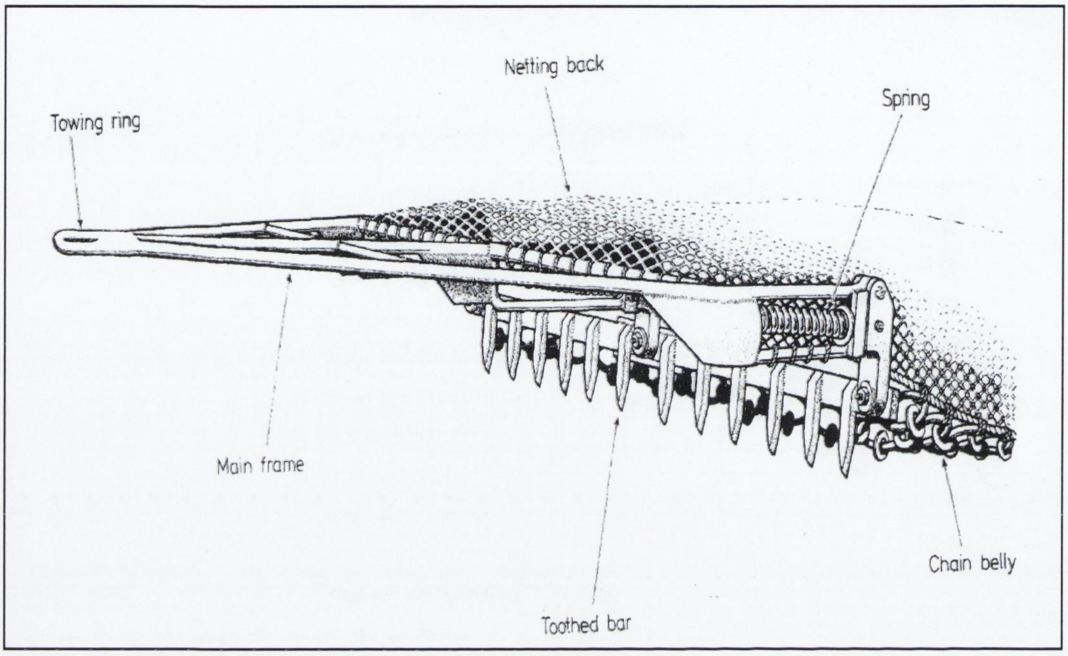


Figure 1.9. Spring-loaded scallop dredge design (Chapman et al., 1977)

Figure 1.10. Commercial spring loaded scallop dredges suspended on a beam being deployed from a commercial fishing vessel.

1.4 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 (Figure 1.11). Processing, or shucking, involves the extraction of the adductor muscle (white meat) with the attached gonads or roe from the shell (Figure 1.12). 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*.

Figure 1.11. Picture showing scallops being processed at one of the processing plants at Kilmore Quay (Co. Wexford).

Figure 1.12. Scallop muscle with gonad attached after being sucked from the shell.

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 $\mu g.g^{-1}$ of tissue as set down in Council Regulation (1997/61). Regulation 2002/226 allows sale of the product if the parts to be marketed contain less than 4.6 $\mu g.g^{-1}$ even if whole body concentrations exceeds 20 $\mu g.g^{-1}$. The toxin is produced by the diatom, *Pseudonitzchia*, 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.

1.5 Legislation Governing the Exploitation of Scallop.

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

In Ireland scallop fishing is licenced under the polyvalent and bivalve segments of the national fleet. The number of bivalve licences is limited and reached the highest number 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. 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 per year (Council Regulation 2004/1415). Kilowatts (kw) days for the fleet are calculated as the product of the days a vessel (v) spends at sea by the kw of the vessel engine summed for all vessels.

$$\sum_{v=1\to n} Days * kw \tag{1.1}$$

Furthermore, to fully comply with this regulation, the effort by all scallop vessels over 10 m was limited to 109395 kilowatt days in the biologically sensitive area (BSA) defined in Council Regulation 1954/2003. The eastern limit of this area is at 7^{o}W, reaches a point on the Irish coast at the Waterford estuary and dissects the main scallop ground south of Waterford. Regulation 2004/1415, therefore, imposed different effort regimes on the eastern and western sections of Areas 1 and 2. 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 10 m 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.

Chapter 2. Scallop Dredge Efficiency and Selectivity

2.1 Introduction

The estimation of dredge efficiency and selectivity is essential for several aspect of stock assessment of scallops. For instance research dredge surveys are one of the most common methods by which scallop abundance is estimated (Orensanz *et al.,* 2006). However, an estimation of dredge efficiency (F) is required if indices of stock abundance or relative abundance from surveys are to be converted into estimates of "true" abundance. Dredge efficiency (F) can be divided into two components (Chapman *et al.*, 1977): the efficiency of capture (E) and the selectivity by size (S). These components are calculated using the following equations:

E= Number of scallop entering the dredge/ Number of scallop in the dredge path (2.1)

S = Number of scallops retained / Number of scallop entering dredge (2.2)

The combination of E and S give the overall efficiency:

$F = S * E =$ Number of scallop caught / Number of scallop in the dredge path (2.3)

Scallop dredges are less than 100% efficient; in fact efficiency estimates of 10-50% have been estimated (Chapman *et al.*, 1977; McLoughlin *et al.*, 1991; Dare *et al.*, 1993; Lasta and Iribarne, 1997; Currie and Parry, 1999; Fifas and Berthou., 1999; Beuters-Stewart *et al.*, 2001; Palmer, 2003). The two most common methods of estimating dredge efficiency (F) are where divers count the number of scallop left on the dredge track after the dredge has past, or depletion experiments, in which an area is sampled consecutively until the catch rate has declined substantially. Estimates of initial population and, therefore, efficiency can then be estimated using Delury (1947) or Leslie and Davis (1939) depletion methods (Figure 4.4). Beukers-Stewart *et al.* (2001)

compared diver surveys and depletion methods and concluded that both were equally effective.

In this study, the Leslie and Davis (1939) depletion method was used to estimate the efficiency of the scallop dredge. The depletion model was applied to undersized and commercial sized scallop to provide separate estimates of stock abundance for these two categories. Substrate type has been recognised as one of the major factors determining the efficiency of capture (E) of the scallop dredge (Chapman *et al.*, 1977; Dare *et al.*, 1993; Fifas and Berthou, 1999; Beuters-Stewart *et al.*, 2001; Palmer, 2003; Orensanz *et al.*, 2006). Therefore, depletion experiments were designed to obtain efficiency estimates for the two main substrate types (gravel and sand) that occur on the scallop grounds off the south east coast of Ireland.

Gear selectivity (S) in relation to fish size follows, in most fishing gear, a logistic function in which the complete size range, or age range, of a fish or shellfish population are not fully exploitated (King, 1995). This general property of fishing gear also applies to scallop dredges (Yochum, 2006; Smith, 2007) and therefore needs to be taken into account in scallop stock assessment in order to estimate, for instance, the real size (or age) composition of the scallop population (Millar and Fryer, 1999). The understanding of dredge selectivity is essential in stock assessment as it influences the estimation of total mortality from catch at age data, which is a parameter required for most population dynamics models, e.g. yield per recruit modelling. Gear selectivity parameters can also be used by fisheries managers to regulate the minimum ring size in the scallop dredge in order to minimise selection and capture of scallops bellow a given size. Millar and Walsh (1992) developed the SELECT (Share Each Length's Catch Total) model to generate the selectivity curves for various fishing gears.

2.2 Source of Data and Method.

2.2.1 Estimation of Dredge Efficiency (F) and Selectivity (S).

2.2.1.1 Statistical Estimation of Dredge Efficiency.

Dredge efficiency (F) was estimated by the Leslie and Davis (1939) depletion method. Depletion experiments consist of fishing or sampling the same area consecutively until the catch declines substantially with each sample (Figure 4.4). A Leslie and Davis (1939) estimate in this case relates the number of scallops caught during each sequential tow against the cumulative catch. The slope of the regression fitted to these data gives a measure of catchability, assuming the area depleted is a closed system, with no gains due to immigration or recruitment or losses due to emigration or natural mortality. Cathability expresses the fraction of scallops in the sampling area which is caught by a defined unit of the fishing effort. When the unit is small enough that it catches only a small part of the stock, it can be used as an instantaneous rate in computing population change. The catch rate is also assumed to be proportional to scallop abundance at all abundance levels. The Leslie and Davis (1939) equation describing the relationship between catch (C_t) and cumulative catch (K) up to time t has the form:

$$C_t = kN_0 - kK_t \tag{2.4}$$

where N_0 is the initial population size given by the intercept on the *x*-axis and *k* is the catchability coefficient. Dredge efficiency (F) was calculated from the proportion of the initial scallop population, N_0, caught by the dredge in the first haul. Depletion analysis was carried out separately for commercial sized (>88 mm shell height) and undersized scallop (<88 mm shell height). Scallops smaller than 65 mm in shell height were not included in the analysis because of the low selectivity of the survey dredge for scallops of this size (see 2.3.2).

2.2.1.2 Statistical Estimation of Dredge Selectivity (S)

The SELECT (Share Each Length's Catch Total) model was introduced by Millar and Walsh (1992) for the analysis of trouser trawls selectivity studies. Millar and Walsh (1992) stated that the traditional method used to estimate size selectivity of fishing gear including trouser trawl, split trawl, twin trawl or alternate hauls do not conform to the assumptions required by conventional statistical methodology for analysing count data. The traditional method has been extensively used for analysis of data from covered codend surveys, in which the number of fish entering the large mesh codend is known and is given by the sum of fish in the codend and the cover. In any of the other survey methods mentioned above the number of fish entering the large mesh size gear is not known because escapement is not observed and the conventional statistical models estimate it to be the number of fish caught in the small mesh size gear or control gear. Under this premise it would not be possible to catch more fish (of any length class) in the large mesh size gear than in the control gear. However, this is not always true and whenever it does occur the number of fish in the large mesh size gear must be set equal to the number obtained in the control gear. Also data might require manipulation to allow for the possible different catches in each of the fishing gears (Pope *et al.*, 1975; King, 1995).

In contrast, the model presented by Millar and Walsh (1992) requires no data manipulation. In this model the number of fish of length class *l* that are caught by the large mesh size gear, *Nil,* compared with the total of fish caught *Ntl* (large mesh size gear *(Nil)* plus control gear (*Ncl)*) is distributed as a binomial (*Nlt, Φ (l)*) random variable, and the proportion of fish caught in the experimental gear relative to the total catch of length *l* fish is given as:

$$\phi_i(l) = \frac{p_i r_i(l)}{p_i r_i(l) + 1 - p_i}, \qquad (2.5)$$

where *r(l)* is the probability that a fish of length *l* is retained and *p* is a 'split' parameter, independent of the fish length *l* in the experimental gear. The split parameters p in the model quantifies differences in the intensities with which data are collected i.e. the sampling effort between the experimental and the control gear (Xu and Millar, 1993).

The selectivity curve *r(l)* can be given by the symmetric logistic function (Millar and Walsh, 1992).

$$r_i(l) = \frac{\exp(a_i + b_i l)}{1 + \exp(a_i + b_i l)} \tag{2.6}$$

where a and b are the parameters that characterised the selectivity curve.

The log-likelihood function for observational data that is modelled from a binomial experiment is:

$$LogL_i = \sum_l [N_{il} \ln \phi_i(l) + N_{cl} \ln(1 - \phi_i(l))] \tag{2.7}$$

where the summation (Σ) is over all length classes. The parameters a and b of the selectivity curve are estimated by maximising equation (2.7) over all possible values of a and b. The split parameter p can also be estimated by maximising the likelihood function. In this selectivity study differences in fishing effort and differences in dredge efficiency (E) between experimental and control gear were considered to be the factors contributing to sampling effort. Denoting fishing effort as Q, the ratio of relative intensity in data collection between the experimental and the control gears can be expressed with the split parameter p as (Xu and Millar, 1993):

$$\frac{p_i}{1 - p_i} = \frac{Q_i E_i}{Q_c E_c} \tag{2.8}$$

where the subscript terms i and c correspond to experimental and control gear respectively. Hence re-arranging equation (2.8) we have:

$$p_i = \frac{Q_i E_i}{\left(Q_i E_i + Q_c E_c\right)} \tag{2.9}$$

Fishing effort for each gear used was known and calculated as number of hours fished times the number of dredges used. Under the assumption of equal efficiency of capture (E), $E_i = E_c$, the split parameter p_i is fixed and equal to the relative fishing efforts $q_i = Q_i/(Q_i + Q_c)$. Otherwise, p_i is to be estimated as function of relative efficiency of capture $e_i = E_i/(E_i + E_c)$. Thus, curves were fitted for the two models, one assuming equal fishing efficiencies with fixed p_i values and the other for estimated relative fishing efficiencies with p_i to be estimated. The goodness of fit in the two models (p_i-fixed and p_i-estimated) was checked using the likelihood ratio test (Millar and Walsh, 1992; Xu and Millar, 1993).

2.2.2 Survey Methods and Dredge Designs

2.2.2.1 Dredge Designs

Dredge efficiency (F) was estimated for the dredge used during the surveys. Dredge selectivity curves were generated for three different dredge designs, which differed from each other in the belly ring diameter and the tooth spacing (Figure 2.1). Dredge designs used in the analysis were:

- *Survey dredge*: a modified commercial dredge with belly ring diameter 65 mm and tooth spacing 44 mm.
- *Commercial dredge*: a standard commercial dredge with belly ring diameter 75mm and tooth spacing 65 mm.
- *Experimental dredge*: Commercial dredge design with 89 mm belly rings.

The inter-ring spacing in the dredge is shown in Figure 2.1. When lying flat, the inter-ring spacing is approximately 10mm greater than the corresponding ring diameter.

This increase can be up to 25mm during fishing operations due to wearing and distortion.

In order to generate the selectivity curves the catch from these three different dredges designs were compared to that of a *control dredge* that consisted of 55mm belly ring diameter and 44mm tooth spacing (Table 2.1). It was assumed that scallops did not escape through 55mm belly rings and therefore the control dredge was considered to be 100% selective with respect to scallop shell length.

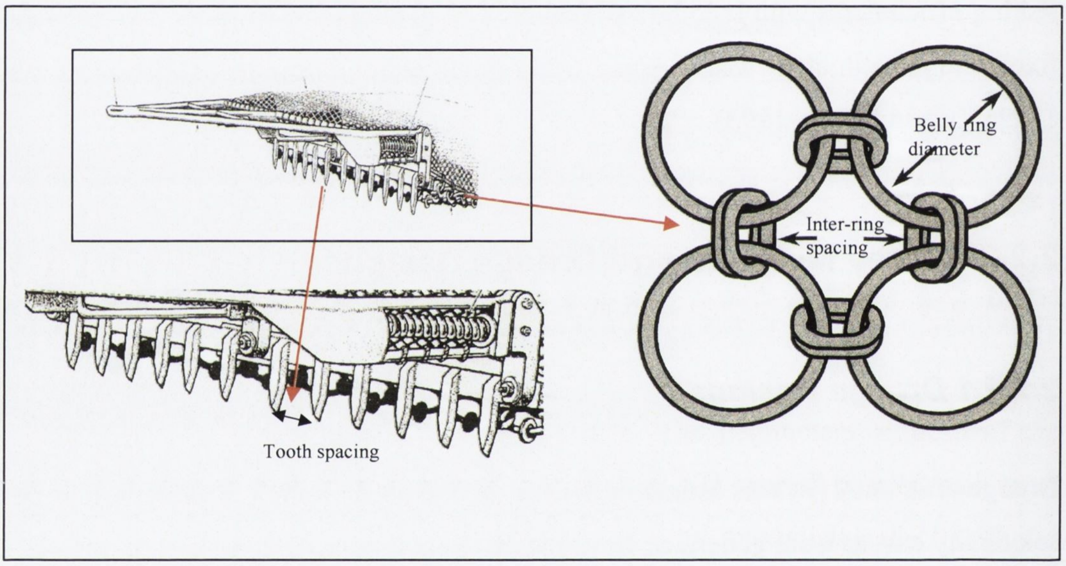


Figure 2.1. Tooth spacing and ring diameter of the spring-loaded scallop dredge. Top left, commercial spring loaded tooth dredge. Bottom left, tooth spacing measurement (Chapman et al., 1977). Right, ring measurements, including the ring diameter ("belly ring"), and the inter-ring spacing (Yochum, 2006).

Table 2.1. Configuration of dredges used to generate selectivity curves.

Dredge Design / Configuration	Belly ring diameter (mm)	Tooth Spacing (mm)
Control	55	44
Survey	65	44
Commercial	75	65
Experimental design	89	65

2.2.2.2 Survey Design

2.2.2.2.1 Dredge Efficiency (F) Survey Design

In July 2004, a depletion experiment was carried out to estimate the efficiency (F) of the scallop dredge used during the research surveys (the survey dredge) (Table 2.1). Twelve survey dredges were placed onboard the MFV Prina Cornelia, 6 on starboard and 6 on portside (Figure 2.2). The depletion experiment was designed to obtain estimates of dredge efficiency on sand and gravel. Ir order to do so four experimental areas were selected, two on sand and two on gravel (Figure 2.3). Areas of different substrate were selected with the use of multibeam acoustic data provided by the Coastal & Marine Resource Centre, University College Cork, onboard the Marine Institute's vessel the Celtic Voyager in 2002. A detailed description of the methodology used to construct acoustic maps and its uses in assessing the scallop stock is given in Chapter 5.

The depletion experiment consisted of towing dredges repeatedly over the same vessel track until the scallop catch was reduced to less than half of the catch at the first tow. Each track was U-shaped and approximately 2000m long by 100m wide (Fgure.2.4). At the end of each tow the catch was landed and sorted on deck. All scallops were counted and shell height was measured to the nearest mm. Navigation was by Differential Global Positioning System and boundaries for each tow were defined and plotted over the acoustic ground type image using ArcView 9.2. To construct tracks of vessel tows, positions were recorded every 10 minutes (Figure 2.4). Any error in the estimates generated as a consequence of vessel tows not overlapping on each other fully, was considered negligible if decline in catch rate was successfully achieved.

Multibeam acoustic backscatter amplitude values for these areas were calculated using the Spatial Analysis tool in ArcMap. Hence gear efficiency estimates in each of the areas could be related to the mean acoustic backscatter values which reflect the type of sediment.

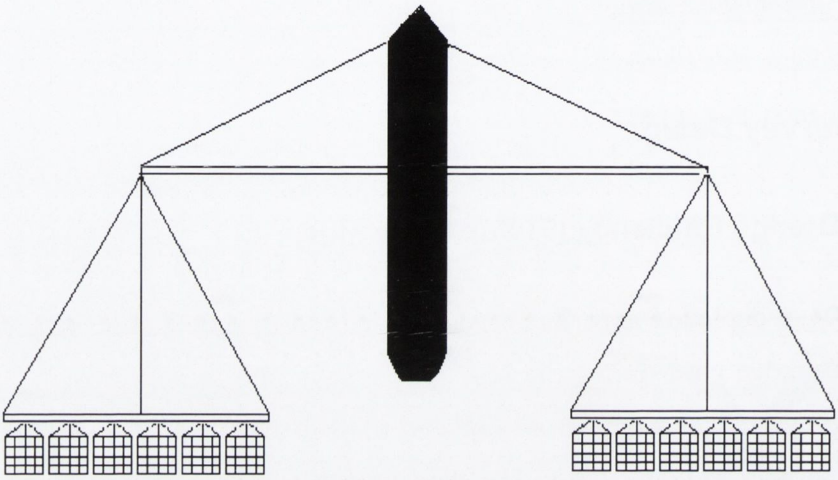
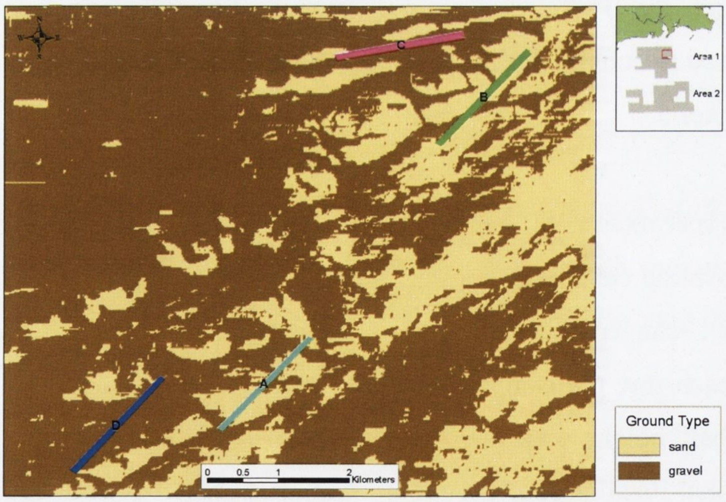
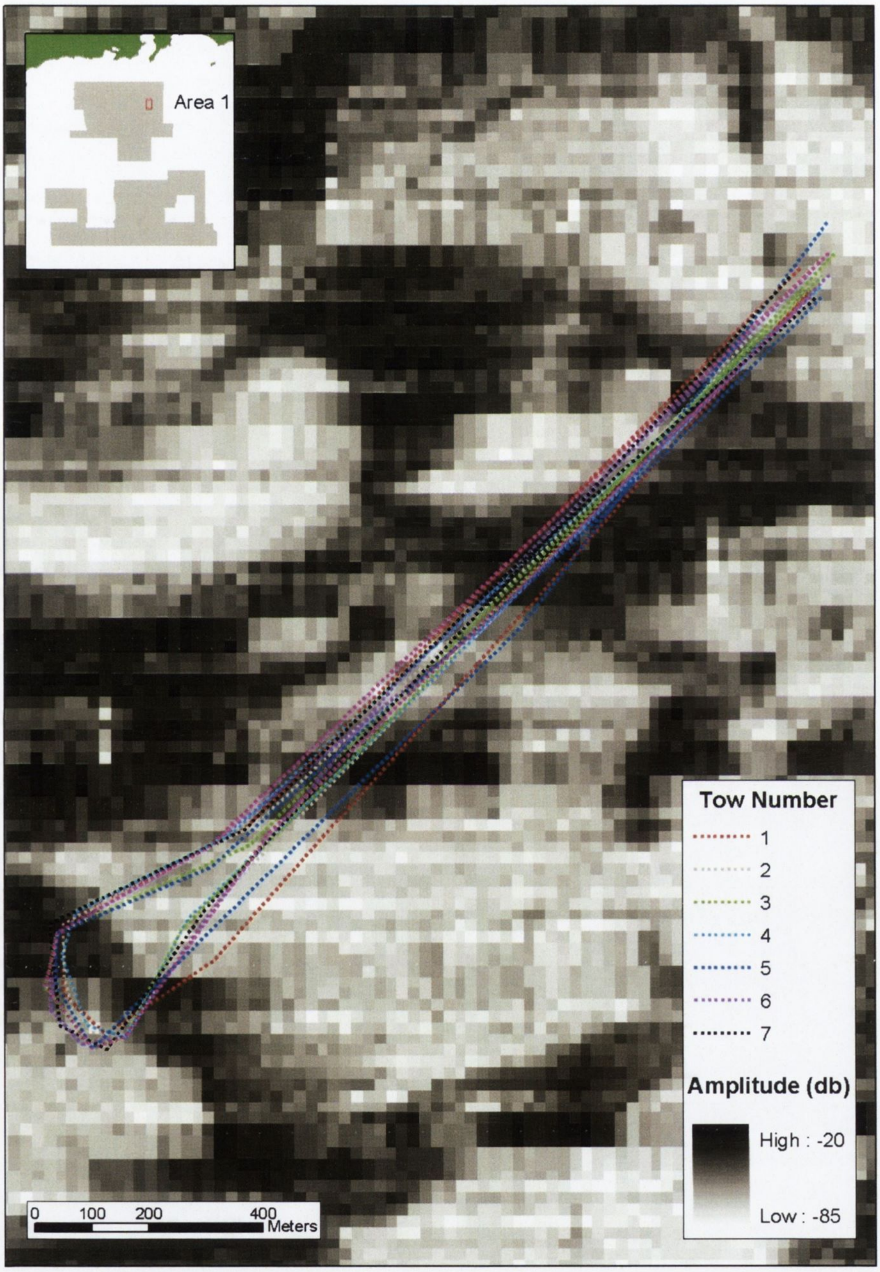


Figure 2.2. Gear configuration used in the depletion experiment. Six survey dredges (65mm belly ring diameter and 44mm tooth spacing) were fished on starboard and six on portside.



2.3. Locations for depletion experiments superimposed on sand (areas A and B) and gravel (areas C and D). Sediment classes were generated with the use of multibeam acoustic data.



Figure

Figure 2.4. Positions of successive U-shaped tows (experimental area A) superimposed on the acoustic backscatter image.

2.2.2.2.2 Dredge Selectivity Survey Design

In July 2003 and August 2004, two research cruises were completed onboard the MFV Prina Cornelia in Area 1 (Figure 2.5). Scallop size data were collected from three dredge designs; the survey dredge, the commercial dredge and an experimental dredge and from one control dredge (Table 2.1).

Catch data from the commercial dredge and the experimental dredge were collected during a cruise completed in July 2003. The initial objective of this cruise was to compare the catch performance of these two dredge types. To do so 10 commercial dredges and 10 experimental dredges were set up on starboard and portside respectively (Figure 2.6a) and during 7 days data on catch rates was recorded by the crew of the vessel. In addition to this, data on shell height was collected for all scallops from each dredge type during the first day of the cruise from a total of 8 fishing tows, each one of approximately 45min duration summing to a total fishing time of 6h.

In 2004, scallop size data from the survey dredge and the control dredge was collected during a 3 days cruise in which 35 fishing tows were completed, each one of approximately 45 minutes summing to a total fishing time of 26.3 fishing hours. Six dredges were used on starboard and portside (Figure 2.6b). All scallop caught during the survey were measured.

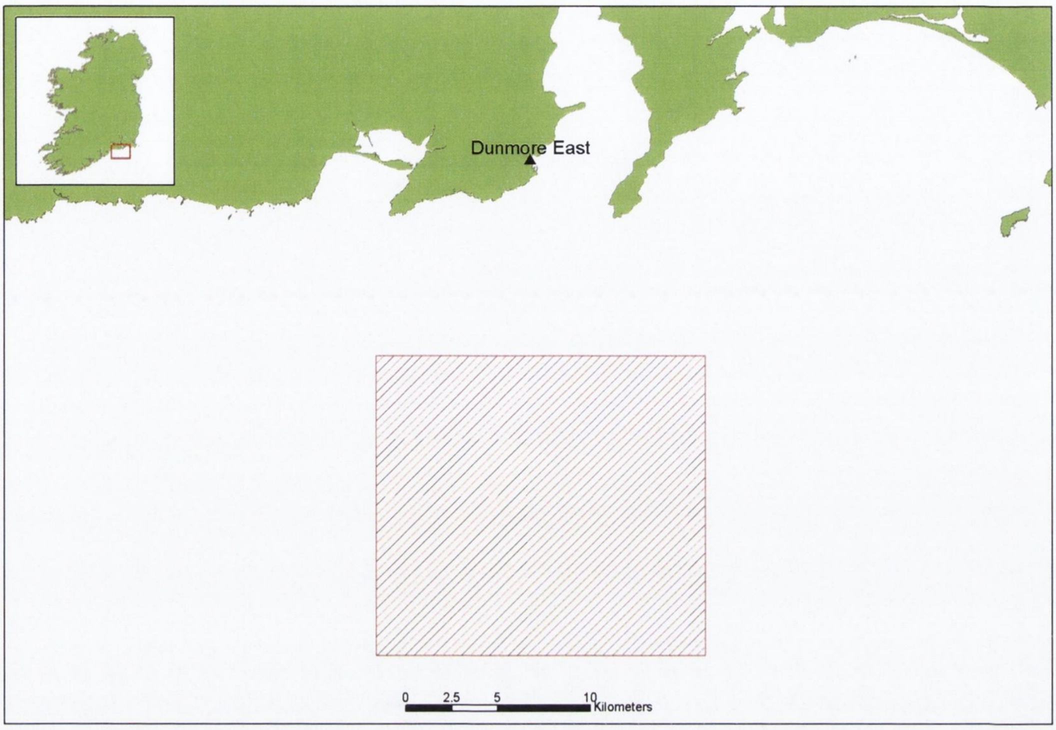


Figure 2.5. Locations for dredge selectivity research cruises.

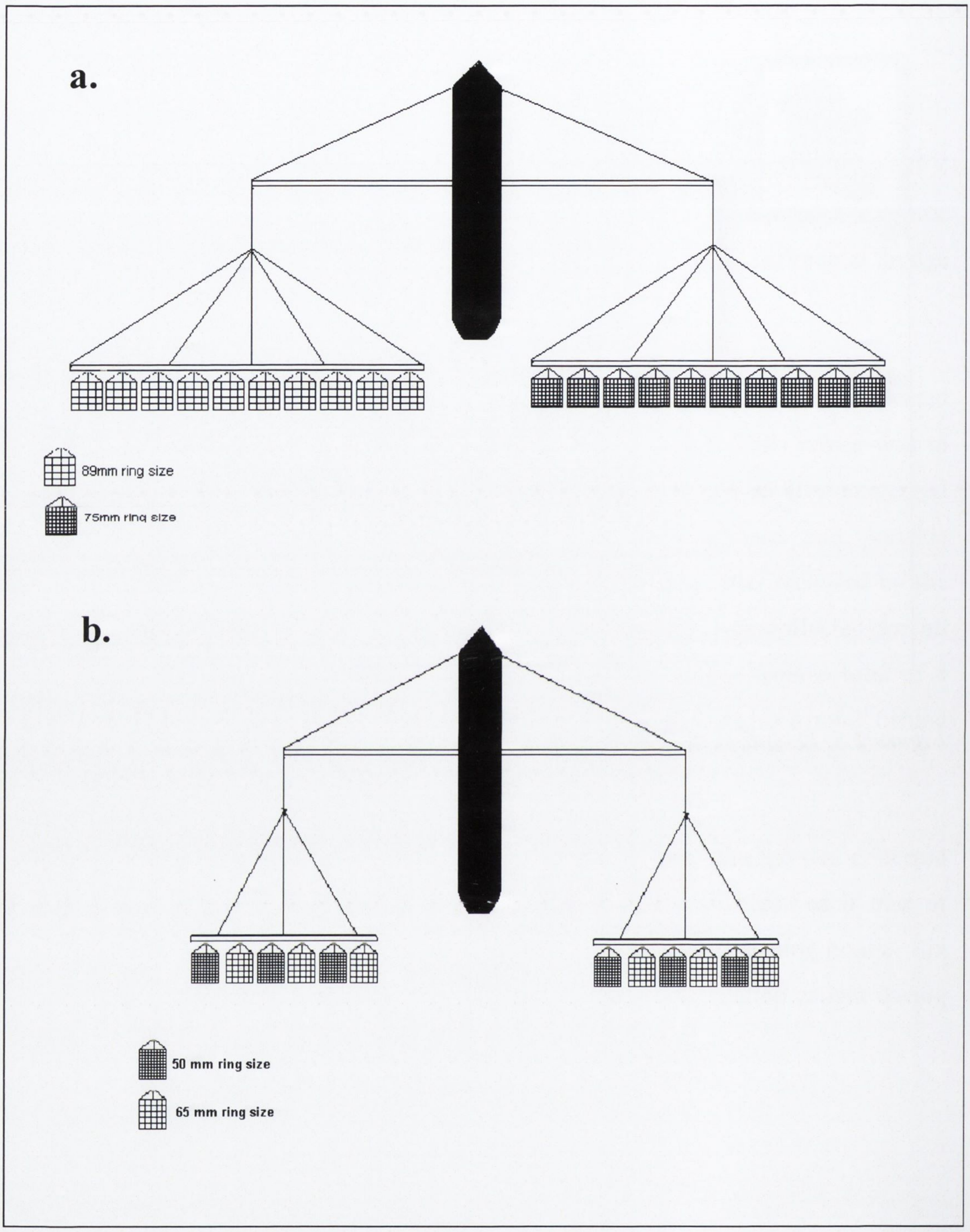


Figure 2.6. Gear configuration for dredge selectivity research: a. Configuration for commercial (75 mm) dredges and experimental (89 mm) dredges, b. Configuration for survey (65 mm) dredges and control (55 mm) dredges.

2.3 Results

2.3.1 Overall Dredge Efficiency (F) Estimates

Mean backscatter values for the areas sampled, showed that Areas A and B were sand and Areas C and D were gravel (Table 2.2). However, standard deviation of the mean values might indicate variability in the substrate type within each of the areas sampled. Water depth in the areas varied between 53 and 57 m.

Table 2.2. Backscatter strength and water depth for each of the areas where dredge efficiency (F) was estimated.

Area ID	Type of ground	Mean Backscatter (db)	S.D	Water depth (m)
A	Sand	-50.30	7.79	55 ± 4
B	Sand	-53.13	6.80	53 ± 4
C	Gravel	-36.20	6.52	55 ± 4
D	Gravel	-40.35	6.88	57 ± 4

Reductions in catch rates relative to cumulative catch for undersized and commercial sized scallop were achieved during the experiment (Figure 2.7 and 2.8). Regressions coefficients of the Leslie and Davis (1939) equation of the relationship between catch C and cumulative catch K of Equation 2.1 were used to estimate the initial population size N_0 and consequently dredge efficiency. N_0 was given by a/k and the dredge efficiency was calculated as the number of scallops captured at the first haul divided by N_0. Estimations were calculated for undersized and commercial sized scallop (Table 2.3 and Table 2.4). Dredge efficiency estimates ranged between 5% and 17 % and 4% and 25% for commercial sized and undersized scallop respectively. Estimates were highest on gravel substrates for both size classes.

During the depletion experiment by-catch of other species included, Brown crab (*Cancer pagurus*) and starfish (*Asterias rubens*) in gravel areas. Dead scallop (*Pecten maximus*) shells and stones were also present in Areas C and D. In Area C stones were particularly common.

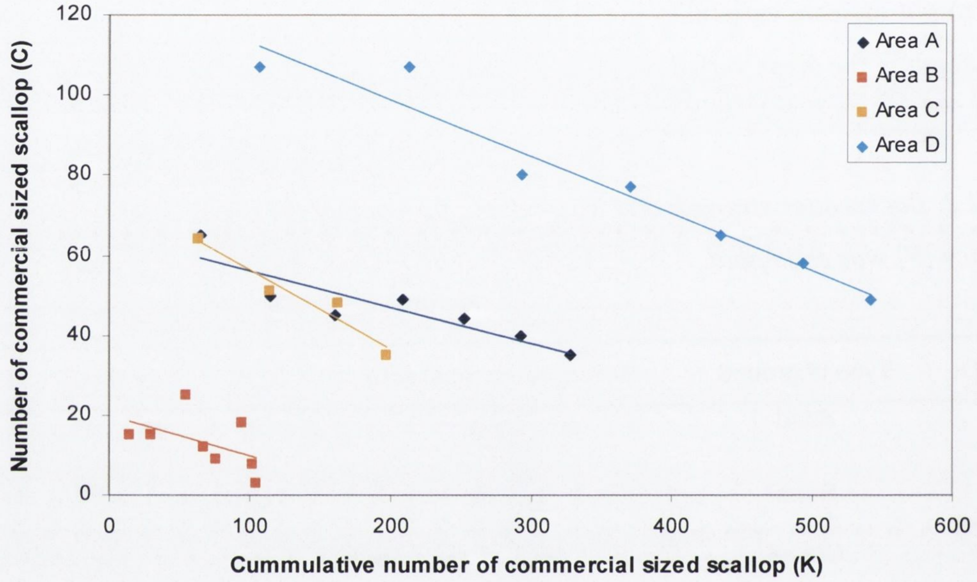


Figure 2.7. Regressions of the relationships between catch (C), and cumulative catch (K), in areas A-D for commercial sized scallop.

Table 2.3. Regressions coefficients and diagnostics of the DeLury equation of the relationship between catch (C) and cumulative catch (K) for commercial sized scallop; a = intercept with y-axis; k = slope; N_0 = Initial population size (number of scallop); NS = Number of scallop; DE=dredge efficiency (F).

Area ID	a=k* N_0	k	N_0=a/k	NS at the first haul	DE%
A	66.03	-0.09	697	65	9
B	20.02	-0.10	198	15	8
C	76.19	-0.20	385	64	17
D	127.25	-0.14	900	107	12

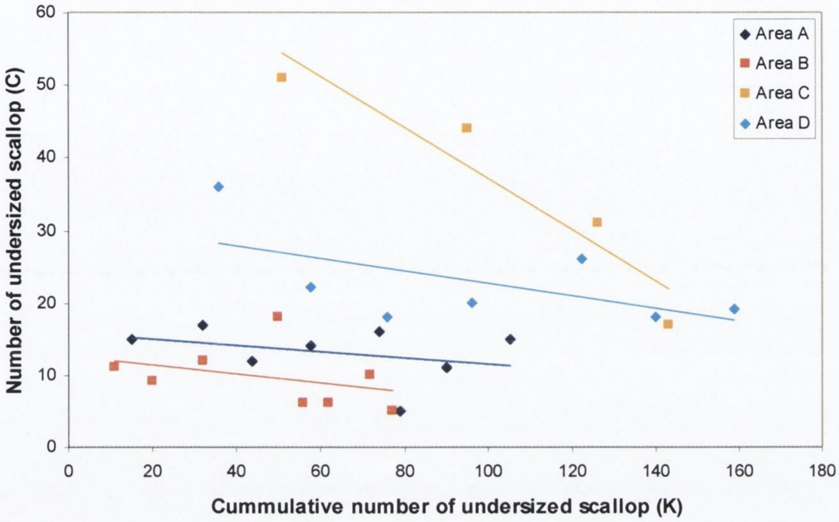


Figure 2.8. Regressions of the relationships between catch (C), and cumulative catch (K), in Areas A-D for undersized scallop.

Table 2.4. Regressions coefficients and diagnostics of the DeLury equation of the relationship between catch (C) and cumulative catch (K) for undersized scallop; a = intercept with y-axis; k = slope; N_0 = Initial population size (number of scallop); NS = Number of scallop; DE= Dredge Efficiency (F).

Area ID	a=k* N_0	k	N_0=a/k	NS at the first haul	DE (%)
A	15.70	-0.04	379	15	4
B	12.64	-0.06	199	11	6
C	72.17	-0.35	206	51	25
D	31.16	-0.09	362	36	10

2.3.2 Dredge Selectivity (S) Estimates

2.3.2.1 Catch Composition

Data obtained in each dredge type were used for the SELECT analysis (Table 2.5). The relative fishing effort of each dredge type was calculated and the fixed split parameter *p* was determined (Table 2.6) and used to fit the model assuming equal dredge efficiency of capture (E) (*p*-fixed).

Table 2.5. Number of scallops caught in dredges of each ring size. Values for each shell height class indicate the middle value of the class range.

Shell Height class	**Ring size of dredge (mm)**			
	55 (control)	**65**	**75**	**89**
22.5	2	0	0	0
27.5	0	0	0	0
32.5	2	2	0	0
37.5	10	6	1	0
42.5	33	2	0	0
47.5	90	0	0	0
52.5	259	10	0	0
57.5	510	93	0	0
62.5	384	176	1	0
67.5	202	254	1	0
72.5	185	382	1	2
77.5	183	356	10	2
82.5	257	590	72	14
87.5	320	814	98	43
92.5	400	914	140	99
97.5	349	870	145	154
102.5	291	725	131	136
107.5	188	418	85	76
112.5	93	184	34	43
117.5	32	77	19	13
122.5	12	13	0	4
127.5	1	3	0	0
Total	3803	5889	738	586

Table 2.6. Sampling effort and values for the p-fixed parameter for each of the dredge designs used in the analysis.

Dredge Type	Hours towed	No. Dredges	Fishing effort (Dredge*hour)	*p-fixed*
Control	23.6	6	141.6	Control dredge
Survey	23.6	6	141.6	0.5
Commercial	6.0	10	60.2	0.298
Experimental Design	6.0	10	60.2	0.298

2.3.2.2 Parameter estimates

The estimated curves of Φ (l) in the two models (*p*-fixed and *p*-estimated) were plotted with values of Φ_l calculated from catch data (Figure 2.9). Table 2.7 shows parameter estimates for each dredge type in the two models; (a_i, b_i, p_i, and e_i), the shell height for 50% retention, l_{50} and selection range (SR), the difference between the 75% and 25% retention lengths (l_{75}-l_{25}), which is a measure of how quickly the 100% retention length is approached, i.e. the steepness of the curve. Selectivity curves (logistic model) obtained for each dredge type are shown in Figure 2.10.

Model selection

The likelihood ratio statistic (twice the log of the likelihood ratio between the full and the current model) (Millar and Walsh, 1992) was calculated to test the fit of the model (Table 2.7). In all six cases containing three dredge configurations in the two models, there was no evidence of lack of fit for the commercial and experimental design dredges and the likelihood ratio test indicated no significant differences between *p*-fixed and the *p*-estimated models (Table 2.7) and therefore the hypothesis of equal efficiency of capture (E) was not rejected. However, the *p*-fixed model showed a lack of fit for the survey dredge with significant differences between the two models (Table 2.7) therefore rejecting the hypothesis of equal efficiency of capture (E). Hence, the p-fixed model with equal efficiency of capture (E) relative to control dredge was the best fit model for the commercial and experimental design dredges while the p-estimated model, with unequal efficiency of capture (E) relative to control dredge, was the model selected for the survey dredge (65mm).

Results of selectivity for three different dredges types can be used to predict the belly ring size needed to attain full size selection for a given shell height. The relationship between shell height at 100% selection and belly ring diameter is linear (Figure 2.11). Using this relationship 100% selection at scallop height of 89mm height, which is the height that corresponds to the minimum legal landing size of 100mm shell length (Figure 5.3), is obtained at a belly ring diameter of 70mm. Selectivity results indicates that the commercial dredge, with 75mm belly ring diameter, reaches 100% selection at 95.8mm shell height and scallops of 89mm shell height, are selected at 90%.

Table 2.7. Parameter estimates of the SELECT model for dredges of each ring size; q = relative fishing efficiency; l_{50} (mm) = shell height of 50% retention probability; SR = selection range defined as l_{75} (shell height of 75% retention)-l_{25} (shell height of 25% retention).

Parameters	**Survey dredge (65)**		**Commercial dredge (75)**		**Experimental dredge (89)**	
	***p*-fixed**	***p*-estimated**	***p*-fixed**	***p*-estimated**	***p*-fixed**	***p*-estimated**
a	-23.448	-17.988	-26.816	-28.420	-22.930	-21.426
b	0.380	0.267	0.326	0.347	0.254	0.234
p	0.500	0.704	0.298	0.288	0.298	0.327
e	0.500	0.704	0.5	0.49	0.5	0.529
l_{50} (mm)	61.7	67.4	82.3	81.8	90.2	91.5
SR	5.8	8.2	6.7	6.3	8.6	9.4
MLL	-6187.9	-5566.5	-1578.5	-1578.1	-1282.6	-1281.4
MLL(full)	-5560.4	-5560.4	-1571.9	-1571.9	-1278.8	-1278.8
Ho: Model fit						
Model deviance	1254.896	12.196	13.174	12.270	7.679	5.288
d.f.	12	11	12	11	12	11
P value	<0.0001	0.349	0.357	0.344	0.810	0.916
Ho: q=0.5						
Model deviance		1242.700		0.905		2.391
d.f.		1		1		1
P value		<0.0001		0.342		0.122

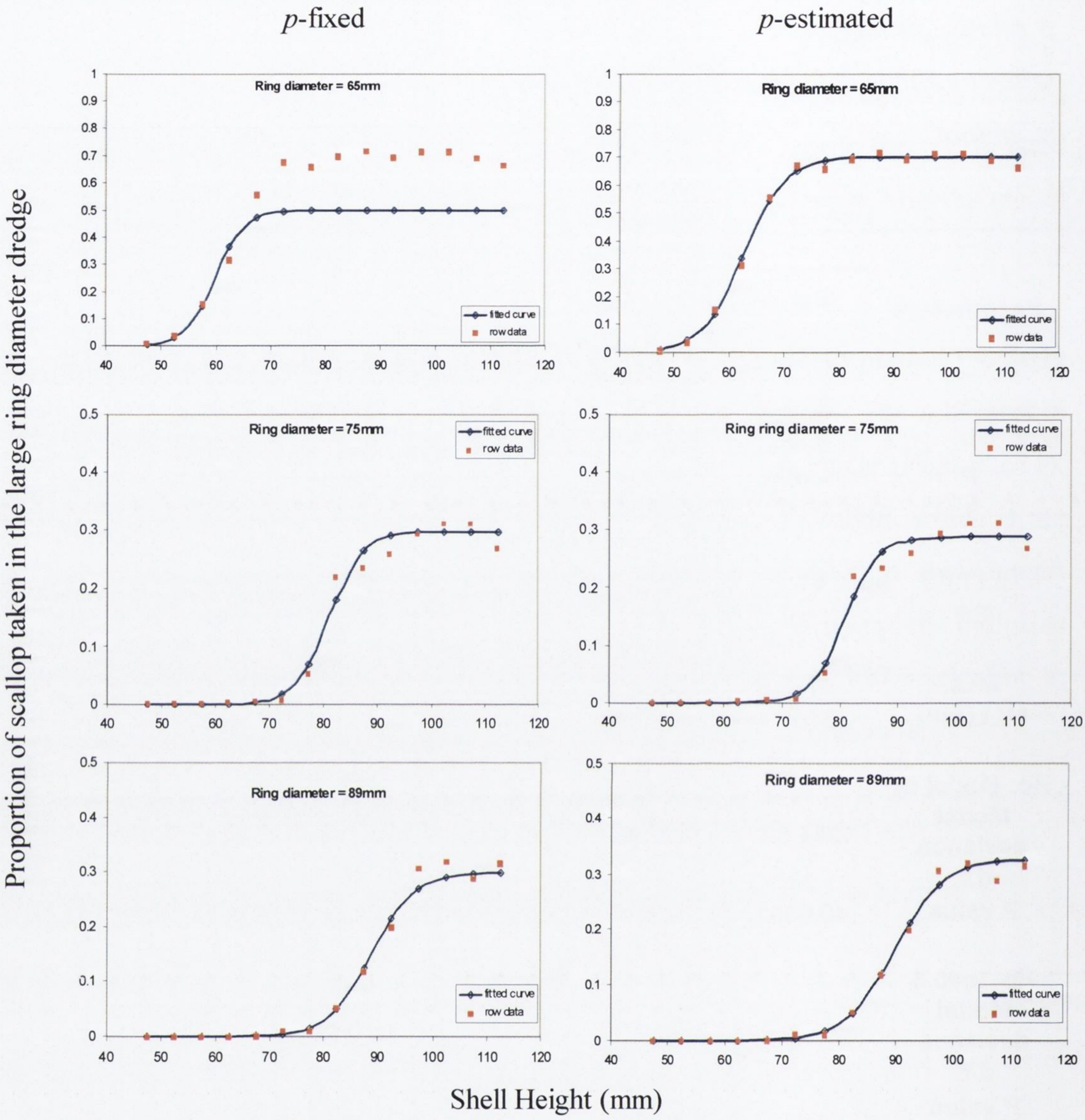


Figure 2.9. Plots of the proportion of scallops taken in the large ring diameter dredge relative to the total catch (raw data) and fitted logistic curves for the p-fixed and p-estimated models.

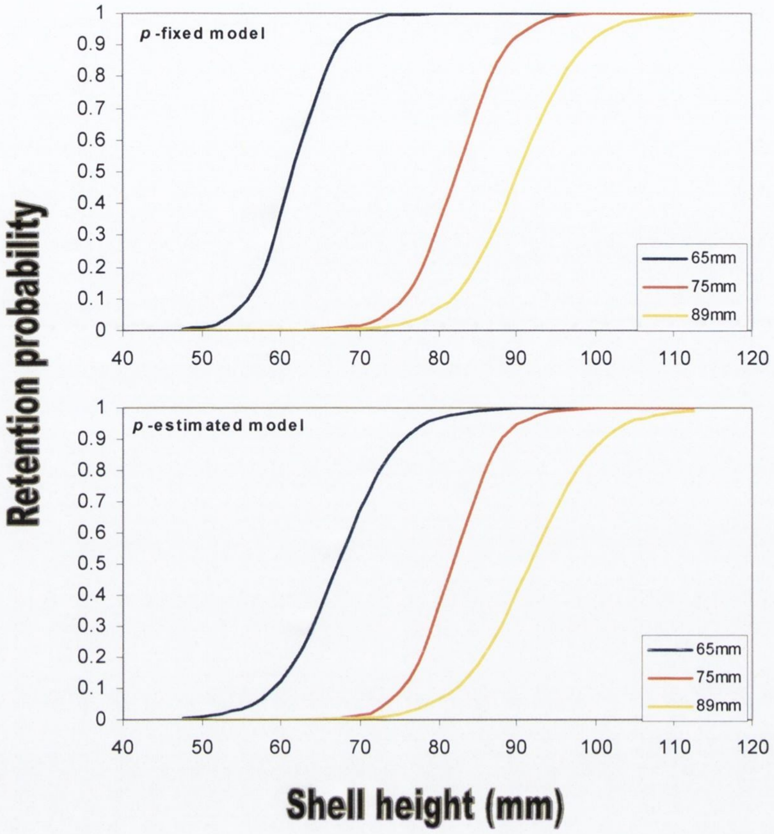


Figure 2.10. Selectivity curve for each dredge type for the p-fixed and p-estimated model.

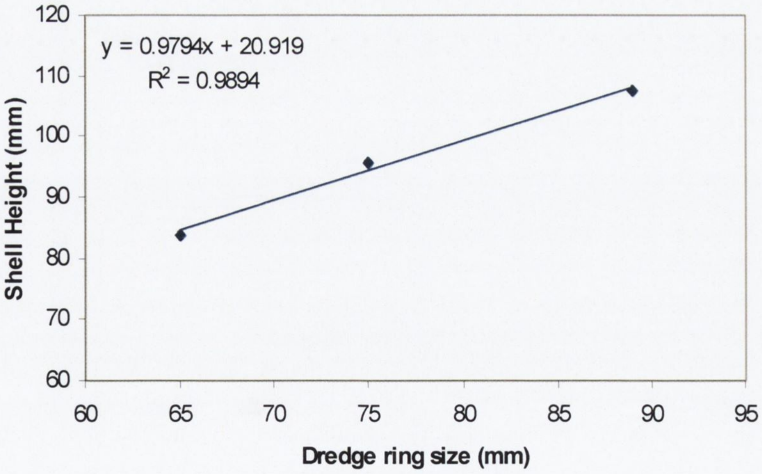


Figure 2.11. Regression of dredge belly ring diameter on scallop shell height at 100% selection.

2.4 Discussion

The Leslie and Davis (1939) and the Millar and Walsh (1992) SELECT methods were used to estimate the efficiency and selectivity of different scallop dredges respectively. These estimates are used in estimating population abundance, and yield per recruit assessment in Chapters 5 and 6 of this thesis, respectively.

Dredge efficiency (F) is the proportion of scallop caught compared with the number of scallops in the dredge path and is separated into two components, efficiency of capture (E) and selectivity (S). The depletion experiment produced estimates of dredge efficiency (F) that was within the range reported in other studies (Chapman *et al.*, 1977; Dare *et al.*, 1993; Beuters-Stewart *et al.*, 2001; Palmer, 2003). Estimates on gravel were moderately, but consistently, higher than those on sand substrates. This occurred for both, undersized and commercial sized scallop. Catch rates did not always decrease during the depletion experiment. This could be due to the cumulative impact of the dredging effect on seabed characteristics that may lead to variability in the dredge performance (Palmer, 2003). The lack of trend in catch rates was more evident for undersized scallop. This is not unexpected, as this size class of scallop ranges from 65 to 88mm in shell height and is not fully selected by the dredge. However, in experimental Area C efficiency estimates for undersized scallop were highest. This might be due to the presence of stones, which might reduce the ability to escape of smaller scallops through the belly rings (Yochum, 2006), thereby increasing the rate of depletion of undersized scallop.

Differences in estimates also occurred within the same substrate type, indicating the inherent variability in dredge efficiency (Dare et al., 1993). There are many factors that can affect the efficiency of capture (E) of scallop dredges. These include, mechanical aspects such as teeth spacing and tooth bar tension, operational factors such as towing speed, duration and warp length, and environmental conditions such as sea state and substrate type. Therefore, the mean estimates and error term should be incorporated when the dredge efficiency estimates are used to raise abundance indices to true abundance. When used in this way the efficiency estimates are obviously critical and every effort should be made to provide robust and precise estimates by increasing the number of depletion experiments undertaken and to do so on different substrates and possibly in different operational conditions. The higher the number of experiments is, the more precise estimates of dredge efficiency will be. This type of experiment is financially costly and therefore the required number of depletion experiment recommended would be a cost effective number, i.e. about 10-20 depletion experiments.

Dredge selectivity for three types of scallop dredge was examined using the SELECT model. Results of these comparative fishing experiments provided parameters for the construction of selectivity curves for these dredges. The interpretation of selectivity curves modelled with either p-fixed or p-estimated is related to factors causing variability in the efficiency of capture (E) of the dredges. Results showed that the efficiency of capture of the survey dredge was significantly higher than the control dredge and therefore, the selectivity curve modelled by estimating the parameter p was chosen as the best model. The survey dredge and the control dredge were towed by the same vessel in the same research cruise and therefore operational or environmental factors, described above, most likely do not explain differences in efficiency of capture (E) between these dredge types. The only difference between the dredges was the belly ring diameter. The control dredge and survey dredge had belly rings of 55mm and 65mm in diameter respectively. This could explain variability in efficiency of capture between these dredges as during the experiment the control dredge caught larger quantities of stones and dead shells. The presence of "trash" could have an effect on the dredge efficiency (Chapman et al, 1977), due to the "obstacle effect" that they produce when a large quantity is caught in the dredge bag, thereby obstructing the entrance of scallop to the dredge bag. On the other hand, the commercial dredge and experimental dredge selectivity curve fitted the with p-fixed model indicating that there were no significant differences in efficiency of capture (E) between these two dredge types and the control dredge.

The relationship between the belly ring size and the shell height at 100% selection estimates that the commercial dredge reaches 100% selection at 95.8mm and that to obtain 100% selection on the actual minimum legal landing size a belly ring of 70mm is needed. It is important to note that differences in size between the dredge belly ring diameter and the scallop shell height at 100% selection are most likely due to the inter-ring spacing that can be up to 25mm greater than the belly ring diameter as consequence of all the mechanical forces that act on the dredge as a result of the fishing process (Yochum, 2006).

A reduction in the ring size of the commercial dredge to attain 100% selection on 89mm scallop shell height would most likely increase the quantity of trash that would get into the dredges during commercial operations, as fishing tows normally have a duration of approximately 2-3 h, making the commercial fishing operation inconvenient in terms of sorting the catch on deck and/or gear damage. On the other hand an increase in belly ring diameter to over 75mm would have a negative effect on catch rates of commercial sized scallops. Therefore, the belly ring diameter of the dredge used by the commercial scallop fleet today in the Irish fishery seems to be the most appropriate compromise between maximising capture of legal size scallop while minimising the catch of unwanted by-catch.

CHAPTER 3. The Estimation of Spatially Explicit Biological Parameters.

3.1 Introduction

The methodology used to assess an exploited population of fish or shellfish usually depends on the data that is available and on the biology of the species and the profile of the fishery in question. The complexities of the methods vary from those that attempt to estimate the sustainable fishable yield as a function of catch and fishing effort, to the more complex methods in which analytical models are used to estimate population parameters to formulate predictions on the sustainability of the stock under different levels of exploitation of the resource (Sparre, 1992). Growth, together with recruitment and mortality, is one of the primary factors that describe the production dynamics of an exploited population. Therefore, analysis of growth is indispensable in providing insight into population dynamics. Its importance and, in some cases the relative ease, by which growth rate can be determined, compared with recruitment and natural mortality rates for instance, has resulted in extensive studies on growth since early in the 20th century (Hilborn and Walter, 1991). The most common mathematical formulation used in fisheries population dynamics, to describe the physiological processes involved in the growth of animals, is the one developed by von Bertalanffy (1938).

Traditionally, in scallop fisheries assessment, growth parameters are estimated for the scallops stock as a whole (Orensanz *et al.*, 1991). However, spatial variability in scallop growth has been reported in many scallop fisheries. In Irish and UK waters variations in growth rates between different populations of *Pecten maximus* were reported by Gibson (1956), Mason (1957), and Baird and Gibson (1966). Other examples of reported spatial variability in scallop growth include, *Zygochlamys patagonica* in the South West Atlantic (Defeo and Gutierrez, 2003), *Patinopecten caurinus* in the Gulf of Alaska (Ignell and Hayness, 2000), and *Placopecten* *magellanicus* in North West Atlantic waters (Caddy *et al.* 1970; MacDonald and Thompson 1985; Schick *et al.* 1988; Robert *et al.* 1990; Kenchington *et al.* 1997; Smith *et al.*, 2001; Harris and Stokesbury, 2006). The estimation of growth parameters, if they are going to be used in assessment models needs to take into account spatial variability. Otherwise bias can result and the position of the fishery with respect to fishery management reference points may be miscalculated.

One of the most commonly used assessment method which uses information on growth is the yield per recruit method of Beverton and Holt (1957). Yield per recruit based reference points indicate the optimum exploitation rate that balances gains in yield due to growth and losses due to mortality. A complete description of the yield per recruit methods and its use in the assessment of scallop populations is given in Chapter 6.

Scallops are filter feeders; the water enters the mantle cavity along the ventral and anterior edge, and exits through the posterior exhalent opening (Hartnoll, 1967). Suspended detrital material and phytoplankton are the main sources of food for scallops (Bricelj and Shumway, 1991). In bivalves, shell growth, together with somatic tissue growth and reproductive output constitute the physiological scope for growth, which is defined as the energy available for production, as a result of energy absorption from food, after respiration and excretion have been accounted for (Bayne and Newell, 1983). Absorption is defined as food ingested by the organism after rejecting particles in the form of pseudofaeces. Production depends on rates of ingestion, absorption, excretion and oxygen uptake, and these rates are influenced either negatively or positively by a number of environmental factors. Food availability and temperature have been considered the main factors which determine growth, the former being the most important in scallop scope for growth (Gruffydd, 1974; Oresanz, 1984; MacDonald and Thompson, 1985;Bayne and Newell, 1983).

In scallop populations comparative growth studies generally use depth as a proxy for differences in either temperature or food availability or both. Examples of early comparative growth studies are Mason (1983), who compared growth of *Pecten maximus* in different areas and at different depths off the British Isles, and Caddy *et al.*

(1970) who similarly investigated differences in growth rate of *Placopecten magellanicus* at different water depths in Atlantic Canadian waters. Generally, growth rates are found to be higher in shallow water, these areas having higher temperature and food supply (Mason, 1983; MacDonald and Thompson, 1985). However, in the Bay of Fundy in the east coast of Canada, MacDonald and Thompson (1985) found that scallop from deep and shallow water had similar growth rate. They suggested that this was caused by the oceanographic conditions of the area where stratification of the water column did not occur and as a consequence a more uniform vertical distribution of food concentration and temperature existed.

The marine environment off the south east coast of Ireland is characterised by a complex physical oceanography. Strong tidal currents in the south Irish Sea and George's Channel prevent thermal stratification of the water column in summer and this area of mixed water extends to part of the south east coast of Ireland. Horsburgh, *et al.* (1998), Brown *et al.* (2003) and Young *et al.* (2004) described the main oceanographic features of the Irish and Celtic Seas. 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. An important result of this is the trapping of a dome of cold water below the thermocline, where seabed temperature remains below 12°C in summer. This bottom water is 4-5°C colder beneath the thermocline compared with bottom water in areas that remain mixed. Scallop populations off the south east coast of Ireland occur throughout the area and are exposed to different temperature regimes and current speeds, depending on the location. Therefore, it is expected that oceanographic conditions will have an important influence on scallop growth.

A sampling programme was developed during the years 2001 to 2004 to collect data for the estimation of growth rate of scallops off the south east coast of Ireland and in other areas. Growth data was obtained from all areas in which the Irish scallop fleet operated during the time period of the study. These included different scallops beds in Irish and UK waters and provide information on scallop growth over broad spatial scales. Variability and causes of variability in growth on a finer spatial scale was also studied in the scallop beds off the south east coast of Ireland. This fine scale variability in growth was correlated with physical environmental variables to identify the main environmental determinants of growth rate of scallop in the area. For this purpose growth data collected in a research survey carried out in the year 2001 was related to predicted bottom water temperature, the hydrodynamic bottom stress, which is a measurement of bottom current strength, and water depth. These physical variables were obtained from a hydrodynamic advection model developed for the area by Marcon Computation International Ltd (2006).

In order to estimate yield per recruit of scallop in relation to spatial variability in growth the scallop ground was divided into 5x5 miles cells and the vonBertalanffy growth function was used to model growth data collected during 2001-2004 in each cell.

Finally the scallop size and weight relationship are presented. Since maximum weight is required as an input for the yield per recruit model (Chapter 6) the allometric relationship between scallop size and weight was produced for different areas with similar growth characteristics. The seasonal variability in somatic tissue condition and the gonad weight were also monitored. Therefore, since the marketable part of *Pecten maximus* is the somatic tissue and the gonad, any significant temporal change in the growth of these tissues could be important in deciding the most appropriate time of the year to harvest resource.

3.2 Source of Data and Methods

3.2.1 Data from the Commercial Landings

The vast majority of scallops fished by the Irish fleet are landed into processing plants in the south County Wexford and Waterford. This makes it convenient to access the landings. Factories are located in Dunmore East (Co. Waterford), Wexford and Kilmore Quay (Co. Wexford). Kilmore Quay has the majority of processing plants (three from a total of five) and the biological sampling of landings was undertaken at these plants between 2002 and 2004.

At the factories the landings were sampled to obtain biological information on a temporal and spatial basis. From each landing, the fishing date, location and vessel name was recorded. Fishing trips normally take from 3 to 5 days. Scallop bags landed into the factory from these vessels were traced to the date and location where the catch was taken. The location of the vessel on that date was provided by the Vessel Monitoring System data (VMS), managed by the Irish Naval Services. A detailed description of the procedure by which the position of the vessel is reported to the Irish Naval Services is presented in Chapter 4.

Scallops are landed in bags each weighting approximately 35 kg. At each landing one bag was selected at random and the shell height of all scallop were measured to the nearest mm. A sub-sample of 30 scallops was also taken from each bag and the following data were recorded; annual growth increments from shells where the annual growth rings were readable, the total wet weight, muscle wet weight and gonad wet weight.

3.2.2 Data from Research Surveys

3.2.2.1 Research Surveys off the Southeast Coast of Ireland

Research surveys were carried out annually in 2001-2005 off the south east coast (Figure 3.1). A detailed description of the survey methodology is presented in Chapter 5. The objectives of the surveys were to assess the relative abundance of scallop throughout the area, to investigate the spatial variability in abundance on a broad and fine scale in relation to the sediment composition and to describe the spatial distribution of the population age structure. In addition research surveys carried out in the years 2001 to 2004 were also used for the collection of biological data. Thus, similar to data collected from the landings, shell height was measured of all scallops caught at all survey stations. A sub-sample of scallop was kept for post survey analysis of total size/weight, muscle wet weight, gonad wet weight and shell growth increments.

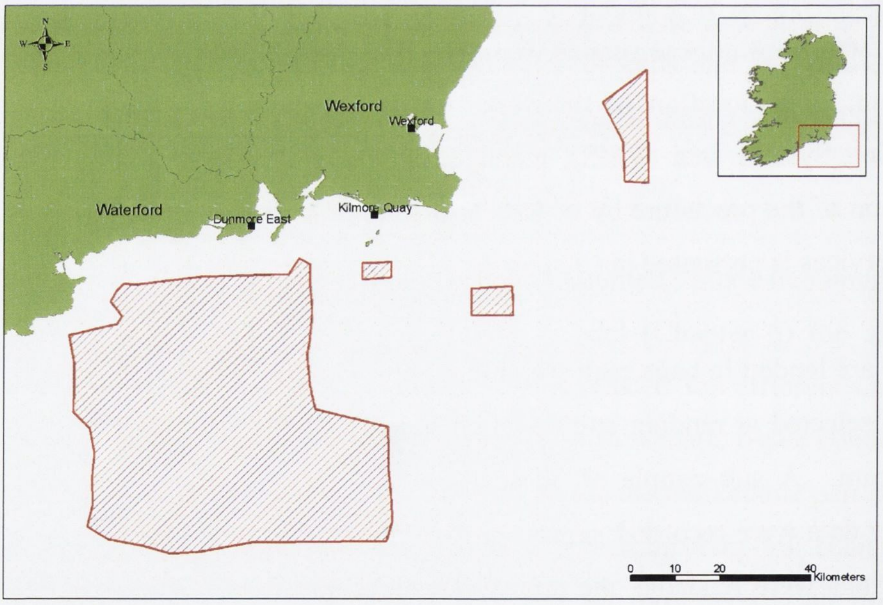


Figure 3.1. Areas surveyed in 2001 to 2005 off the south east coast of Ireland.

3.2.2.2. Research Survey off the North Coast of Ireland

A research survey was carried out east of Malin Head (Figure 3.2) between the 7th of May and the 14th of June 2002 to determine the distribution and abundance of scallop off the north coast of Ireland. Growth data collected during the survey was used for the estimation of growth parameters and to compare these with growth parameters for populations in other UK and Irish waters (see 3.2.3.3).

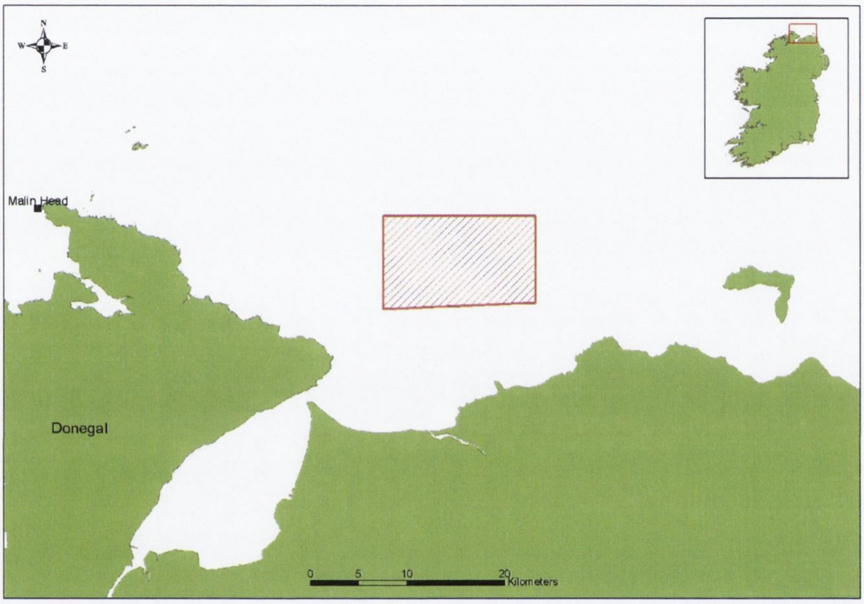


Figure 3.2. Areas surveyed off the northeast coast of Ireland in 2002.

3.2.3 Growth Rates

3.2.3.1 Collection of Growth Data

Growth of *Pecten maximus*, as with most bivalve species in temperate waters, is relatively easy to estimate because of the formation of annual rings or bands on the shell. Growth rings are formed after a winter stage of non-growth or very slow growth that is associated with a decline in water temperature. Hence, the scallop shell contains the animal's complete history of growth. For the purpose of this study the growth history information over the life span of the animal was recorded i.e. the shell height at each age for each of the readable growth rings (Allison *et al.*, 1994) of each scallop shell was used to estimate growth rate parameters. The growth data collected provided information on (1) the *growth history* of the shell and (2) for those shells in which all growth rings were readable *size at age to the oldest growth ring.* However, prior to using the growth history of the shell to model scallop growth a comparison of growth curves from both types of growth data was carried out to investigate if any dependency between successive annual increments in the same scallop biased population growth estimates. This could arise for instance for genetic reasons and would be detected if variation between increments within shells were less than variations in increments between shells.

3.2.3.2 The von Bertalanffy Growth Model

Growth information was collected from a number of individual scallop in which the body size was related to age. These data were used to estimate the population growth parameters. The most common mathematical function used to model size-at-age data is that developed by von Bertalanffy (1938). This function integrates the physiological processes responsible for the observed pattern in growth and has been shown to conform to the observed growth of most fish species (Sparre, 1992). The theory behind this mathematical expression of growth has been described in Beverton and Holt (1957) among others. Basically the mathematical expression for the individual growth of animals, formulated by vonBertalanffy, considers the rate of change in weight as a balance between the rate of anabolism and catabolism. The rate of change in weight is related to the rate of change in size, assuming isometric growth. The growth function is described by a curve approaching an upper asymptote with increasing age, in which size or weight at age data fit the model to give the growth parameters defined by, the asymptotic length or weight, the rate at which size approaches the asymptotic size and the age at length zero. The mathematical expression of the von Bertanlaffy function that models size at age data is given by:

$$H_t = H_\infty\left[1 - \exp\left(-k\left(t - t_0\right)\right)\right] + \varepsilon \qquad (3.1)$$

where H_t is shell height at age t, H_∞ is the asymptotic height, k is the individual growth rate coefficient, t_0 is the estimated age at height zero and ε an error term that is assumed to be normally distributed and to have homogeneous variance.

H_∞ and t_0 lie on the extremes of the growth curve inferring that their estimation is obtained through extrapolation. The degree of extrapolation can affect the parameter estimates. Because of this it is important to use balanced data (i.e. equivalent number of age classes) when comparing curves that may be derived for different areas of years for instance. In the present case the same number of age groups were used to fit the growth function so that growth parameters derived for different areas could be compared.

3.2.3.3 Growth Rate Parameters of Scallop off the Southeast of Ireland

Raw data were used, instead of mean height at age, to fit the von Bertalanffy model using the least square loss function (Haddon, 2001).

The growth history of the shell provided a large quantity of data, which was used to estimate growth parameters at different spatial scales. However, prior to using the growth history of the shell to model scallop growth a comparison of growth curves derived from the growth history of the shell and the size at age to the oldest growth ring was carried out. For this purpose, data collected in the research 2001 survey was used. Growth parameters were estimated and compared by the likelihood ratio test (Kimura, 1980; Cerrato, 1990). The comparison between both types of growth data verified that growth parameters estimates did not differ significantly (see 3.3.1). Therefore the growth history of the shell was used for the estimation of growth parameters as it provided more data and the possibility of exploring scallop growth at a fine spatial scale.

Growth parameters were derived and compared at two different spatial scales. Firstly, growth data collected for different areas of Irish and UK waters was used to model scallop growth for the western Channel, the south coast of Ireland, the south Irish Sea, the Isle of Man and the North coast of Ireland (Figure 3.3). Fine scale variability in growth and how this is correlated with physical environmental variables was also studied off the south east coast (Figure 3.4).

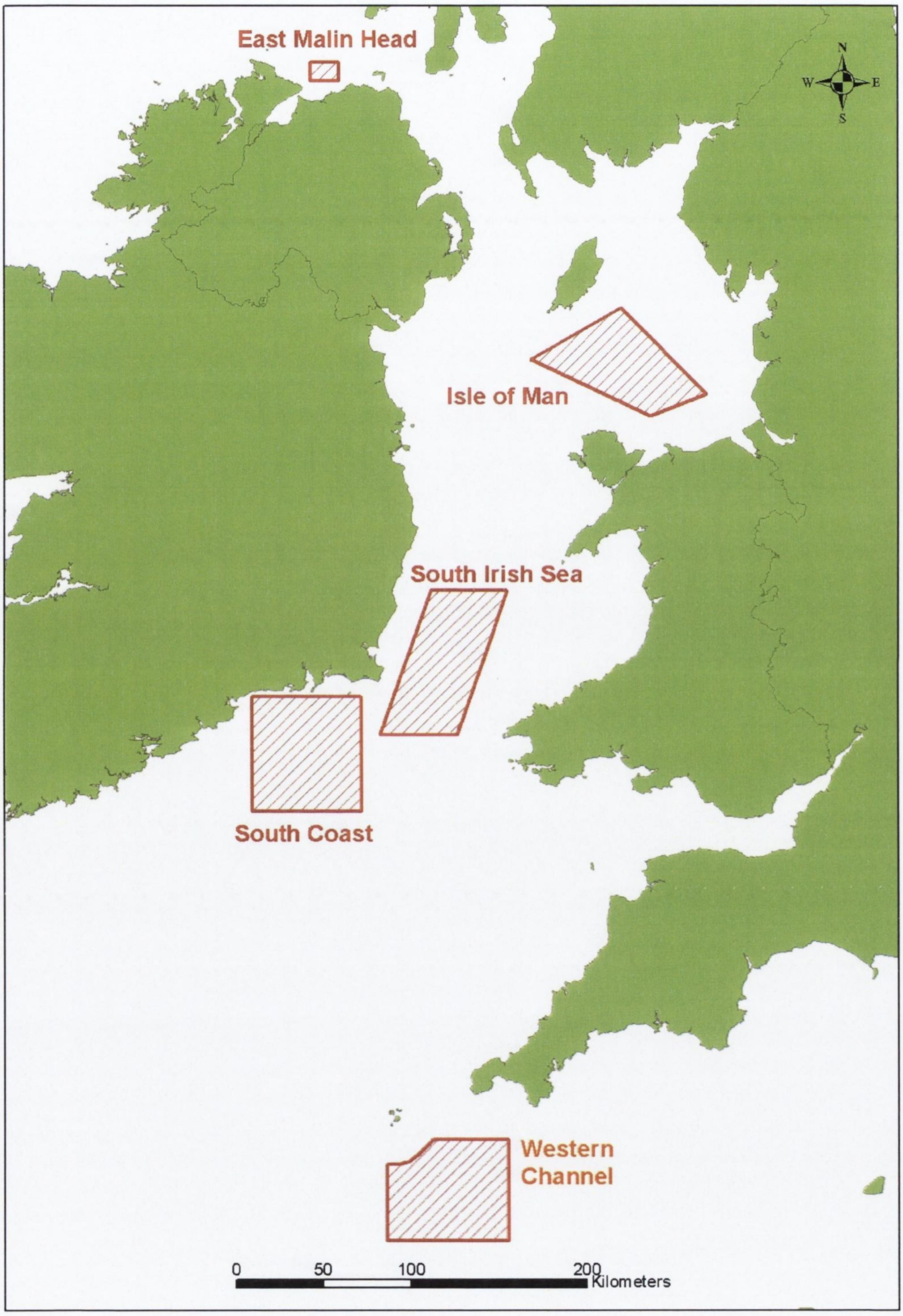


Figure 3.3. Five geographic regions where growth of scallop was studied.

3.2.3.4 Relationship between Growth Rate and the Physical Environment

Growth data collected in the 2001 research survey (3.2.2) and data on the physical environment, predicted by a hydrodynamic model developed for the area of study by Marcon Computations International Ltd (2006) were used to study the relationship between growth performance and the physical environment. The 2001 survey provided growth data from 104 survey stations, distributed in an approximately regular grid, covering most of the scallop ground off the south coast of Ireland (Figure 3.4).

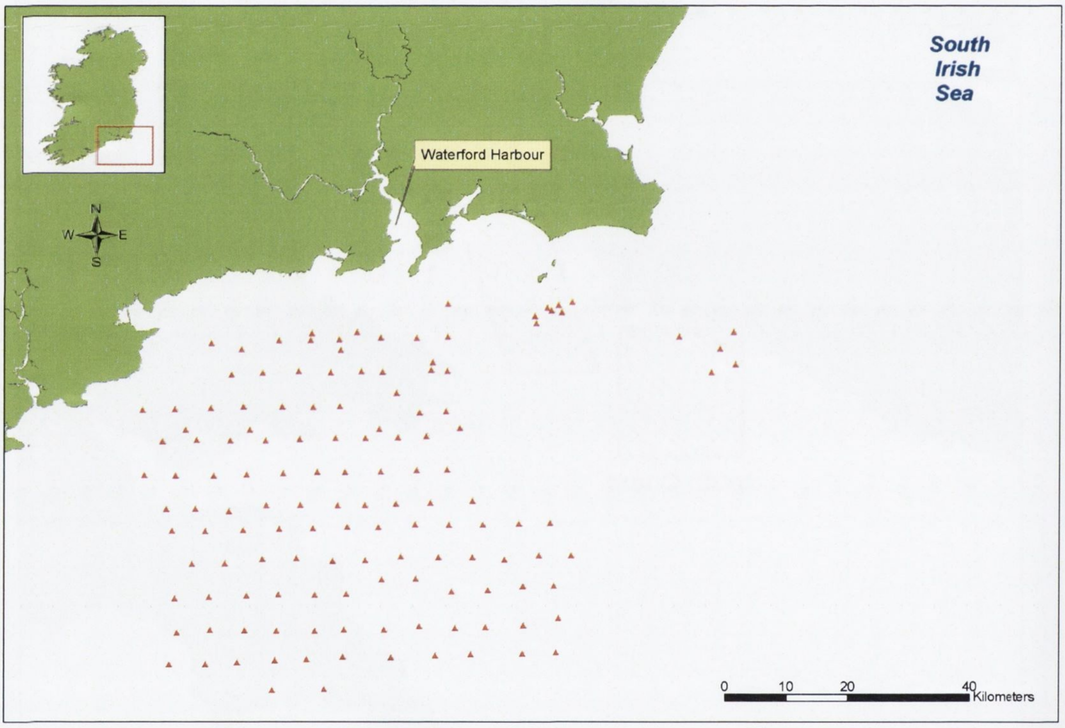


Figure 3.4. Survey grid in 2001 where spatially referenced growth data were collected

The hydro-advection model provided outputs of bottom water temperature at the seabed, and hydrodynamic bottom shear stress. The latter measures the force induced by currents flowing over the seabed (Dare *et al.*, 1994) and is equivalent to the density of the seawater multiplied by the square of the current velocity (Hartnett *et al.*, 2007). The shell height of scallops at age 5 years was used as growth performance index. This method of defining growth performance provided a measurement of the history of growth of scallops, which is determined by the history of the physical environment and effectively integrates the scallop response to environmental conditions over a 5 years period.

The relationship between the growth rate of scallops and the physical environment was analysed as follows. The average condition of temperature and shear bed stress on spring and neap tides was given for each node on a 2km grid. The location and attribute data were imported into ArcMap. Each of the 4 attributes, spring temperature, spring stress, neap temperature and neap stress, were interpolated using an inverse distance weighted (IDW) algorithm to create continuous surfaces. The areas over which scallops were dredged were then digitised using survey information on the start and finish locations of each tow and the width of the vessel. The average value of shell height at age 5 obtained on each tow was assigned to each dredged area and was overlaid on top of the interpolated physical data in the GIS. The Spatial Analyst Tool in ArcMap was used to calculate the average pixel value within each dredged area for each raster image. Water depth was also related to growth performance. Data on depth was obtained from the multibeam echosounder survey in 2001-2002 (Sutton and O'Keeffe, 2006). Finally, the growth rate of scallops was plotted against the corresponding measured physical attributes to highlight any influence the physical environment has on the growth rate of scallops.

A multiple linear regression analysis was used to examine the relationship between growth performance and variables describing the physical environment. It describes the linear relationship between one dependent variable, and several predictor variables with a linear equation (Velleman, 1997). The mathematical form of the equation for (t) predictors is given by:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + \ldots + b_t X_t \qquad (3.2)$$

where the dependent variable Y is defined as the shell height at the age of 5 years, and the predictor variables X as the water bottom water temperature (°C), the hydrodynamic bottom stress (Newton*m^{-2}), and the water depth (m).

3.2.3.5 Spatial Estimation of Growth Rate Parameters

Growth rate parameters were estimated on as fine a spatial scale as possible off the south east coast. For this purpose, growth data from both the commercial landings and the research surveys, for years 2001-2004 (Figure 3.5) were used. The resulting point estimates of growth rate were aggregated to 5mile^2 resolution prior to using the growth information in a yield per recruit model (see Chapter 6).

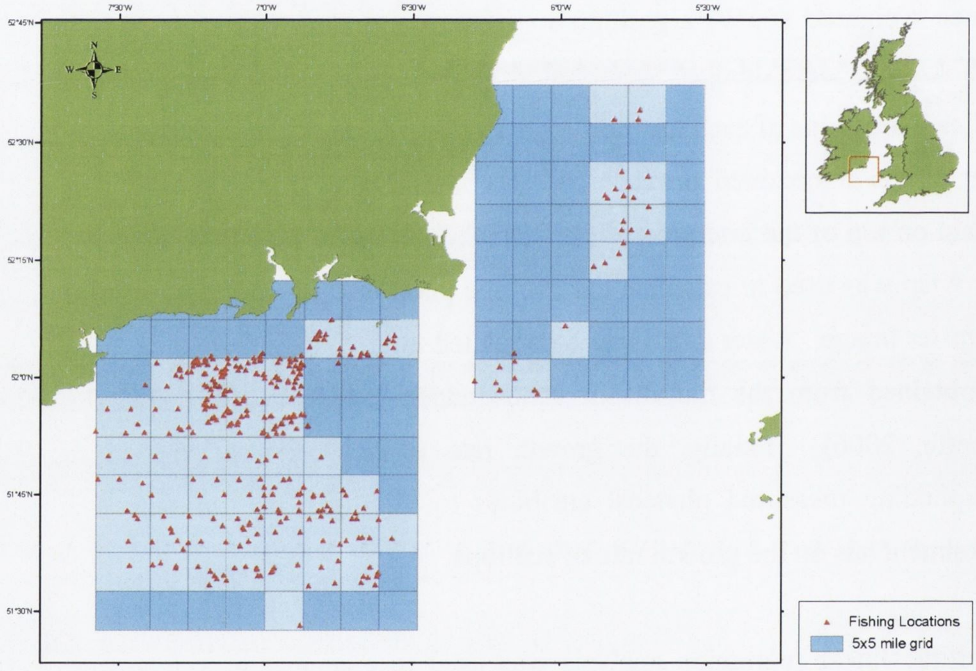


Figure 3.5. Grid map (5 x 5 mile) showing the locations where data on growth was available from research surveys and commercial landings in the years 2001-2004.

3.2.4 Height-Weight Relationships

The relationship between shell height and weight was described by the power function:

$$W_t = qH_t^b \qquad (3.3)$$

where W_t is the weight at age t, H_t is the shell height at age t, b is a constant that is close to a value of 3 if growth is isometric, and q is a constant that is determined empirically. Equation 3.3 is transformed to a linear form using the natural logarithms as:

$$\ln W_t = \ln q + b(\ln H_t) \qquad (3.4)$$

Equation 3.4 has the form of a simple linear regression $(Y = a + bX)$, which relates H_t to W_t. H_∞ of the von Bertalanffy equation can also be expressed in terms of W_∞, which is needed for the estimation of yield per recruit. The parameter b is a measure of the condition of the somatic tissue, since it measures the rate at which weight increases with size. Thus the parameter b was estimated monthly in order to determine the seasonal variability in soft tissue condition.

3.2.5 Gonad Weight Index

Pecten maximus is a protandrous hermaphrodite in which the male and female gonads are combined in a discrete organ, which is readily separable from the rest of the viscera. Scallop gonads are easily removed and weighed to provide a simple method of assessing the gametogenic cycle. As gonad size is related to size of scallop, it is necessary to standardise the gonad weight of a sample containing different scallops sizes (Barber and Blake, 1991). Different standardisations are used: the gonad weight is expressed as a proportion of the body weight in a gonad index (GI). However this method is only accurate when dry body weight is used, as the water content of the body of the animal can cause biases in the estimates. Gonad weight is also standardised as relative gonad height (RGH), which relates gonad weight to the cubic power of height.

However the assumption that shell height is the cube of the gonad weight is questionable. In this study gonad weight was measured for scallops of size greater than 88mm shell height and was found to be linearly related to shell height. As a result in this study the gonad weight index (*GWI*) was estimated with the use of the following equation:

$$GWI = \frac{GWW}{SH} \times 100 \tag{3.5}$$

where the *GWW* is the gonad wet weight(g) and *SH* is the shell height (mm). Gonad weight was estimated monthly from October 2002 to December 2004. Although this method does not provide histological information for the accurate estimation of the different reproductive stages it gives an estimate of the seasonal development of the gonad.

3.3 Results

3.3.1 Growth Data: A comparison between the growth history of the shell and the size at age to the oldest growth ring data

Growth data from the growth history of the shell and the size at age to the oldest growth ring were modelled. Growth curves from the two data sources did not differ significantly (Figure 3.6, Table 3.2). It was therefore assumed that there was no dependency between successive growth increments in the same scallop shell.

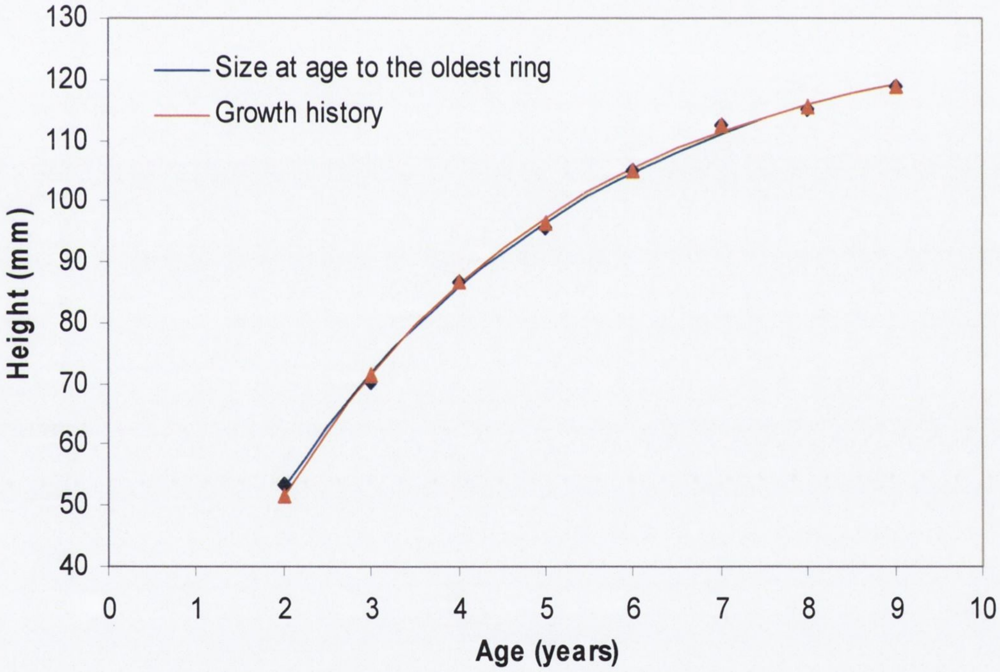


Figure 3.6. Growth curves fitted to growth history data (red) and size at age to the oldest ring (blue) data using the von Bertalanffy growth function.

Table 3.1. Size at age data used to fit growth curves to the growth history of the shell and the size at age to the oldest growth ring (Figure 3.6). Using growth data collected during the 2001 survey. N=Number of measurements; O(H)=Observed mean height; E(H)= Expected height from the von Bertalanffy; CL=Confidence limit (95%).

Type of growth data	Age	2	3	4	5	6	7	8	9
Size at age to the oldest growth ring	N	261	453	341	585	249	79	15	15
	O (H)	53.51	70.31	86.73	95.68	104.83	112.51	115.13	118.80
	E (H)	52.97	71.60	85.77	96.54	104.72	110.95	115.68	119.28
	CL	0.71	0.72	0.79	0.71	1.32	2.83	6.08	4.92
Growth history	N	2238	1905	1420	1022	386	109	30	15
	O (H)	51.39	71.53	86.60	96.25	104.92	112.41	115.40	118.80
	E (H)	51.47	71.40	86.17	97.12	105.23	111.24	115.69	118.99
	CL	0.30	0.40	0.49	0.62	1.13	2.27	3.72	4.92

Table 3.2. Likelihood ratio test comparing von Bertalanffy parameter estimates for the two type of growth data collected; the growth history of the shell and the size at age to the oldest growth ring. Results of the RSS (residual sum of square), the $\chi2$ test and associated statistics of testing for coincidence of curves are shown.

Type of growth data	Parameters	Independence	Coincidence
Size at age to the oldest growth ring	Linf	130.69	129.52
	K	0.27	0.29
	t0	0.10	0.20
Growth history	Linf	128.44	129.52
	K	0.30	0.29
	t0	0.29	0.20
	RSS	9.15	10.76
	X^2		2.92
	DF		3.00
	P		0.40

3.3.2 Growth Rates for Different Scallop Grounds of Irish and UK Waters

Growth data from different geographic areas of Irish and UK waters were modelled (Figure 3.7 and Table 3.3) and growth parameters estimated (Table 3.4). Analysis of variance of size at age 5 for the different geographic areas (Table 3.5) showed that scallop growth is significantly different between areas. Since the error term is assumed to be normally distributed the analysis of variance of size at age 5 provides a simple statistical method of comparing growth. Size at age data (Table 3.3) showed that growth rate generally increases with latitude. The lowest growth rate occurs off south west England and the highest off the North east coast of Ireland.

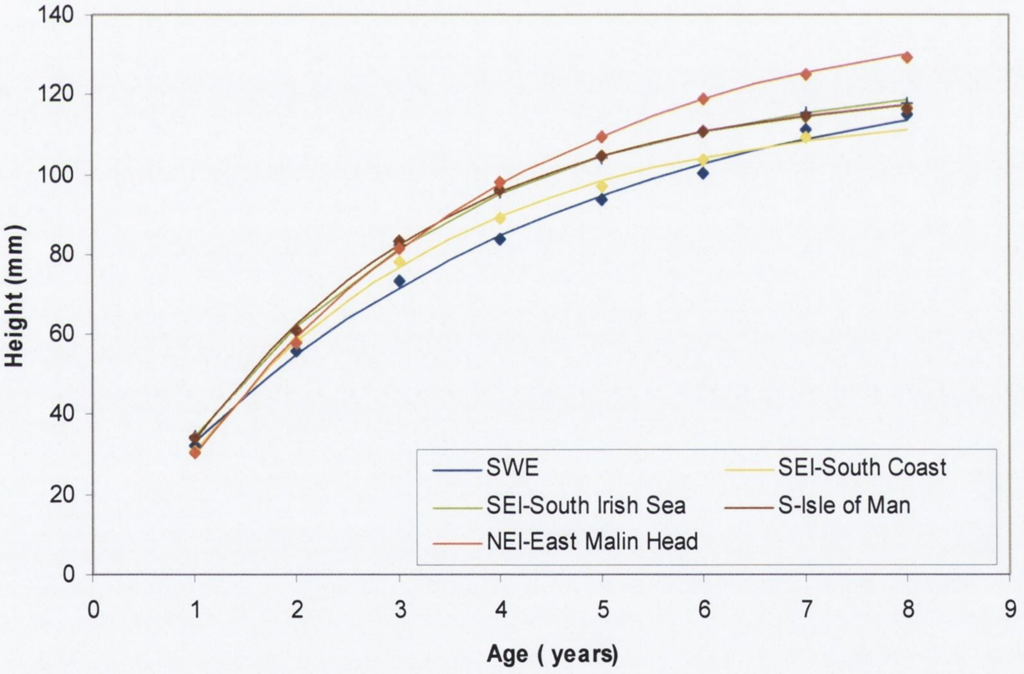


Figure 3.7. von Bertalanffy growth curves for scallops in Irish and UK waters. SWE=South west England, off the Scilly Islands; SEI= South east of Ireland; S=South; N=North coast of Ireland

Table 3.3. Size at age data used to fit growth curves (Figure 3.7) for scallops from Irish and UK waters (Figure 3.3) using growth data collected from the commercial landings. N=Number of measurements; O(H)=Observed mean height (mm); E(H)= Expected height (mm); CL=Confidence limit(95%); SWE=South west England, off the Scilly Islands; SEI= South east of Ireland; S=South; N=North coast of Ireland.

Geographic area	Age	1	2	3	4	5	6	7	8
SWE	N	56	55	52	27	10	5	4	4
	O (H)	32.21	56.04	73.25	83.63	93.50	100.33	111.00	115.00
	E (H)	33.20	54.82	71.59	84.59	94.68	102.51	108.58	113.28
	CL	1.06	1.27	1.36	1.88	4.18	7.86	8.82	8.82
SEI-South Coast	N	1352	1103	765	494	267	94	30	8
	O (H)	30.70	58.24	77.87	88.77	97.19	103.76	109.20	116.63
	E (H)	30.95	58.11	76.70	89.44	98.16	104.14	108.23	111.03
	CL	0.25	0.44	0.63	0.90	1.36	2.61	4.59	11.54
SEI-South Irish Sea	N	454	451	444	374	193	120	68	31
	O (H)	34.76	60.87	82.07	95.63	103.90	110.66	115.46	117.74
	E (H)	34.35	62.09	81.42	94.90	104.30	110.86	115.42	118.61
	CL	0.46	0.69	0.74	0.80	1.05	1.33	1.66	2.11
S-Isle of Man	N	210	209	208	172	122	73	50	29
	O (H)	34.10	60.83	83.06	95.80	104.39	110.45	114.42	116.55
	E (H)	33.55	62.45	82.06	95.37	104.40	110.53	114.68	117.50
	CL	1.12	1.30	1.09	1.15	1.53	2.02	2.80	3.72
N-Donegal Coast	N	99	98	95	90	63	31	10	5
	O (H)	30.16	57.72	81.40	97.98	109.25	118.94	124.70	129.00
	E (H)	29.61	59.07	81.00	97.31	109.46	118.49	125.22	130.22
	CL	0.84	1.50	1.84	1.97	2.60	3.09	5.04	6.20

Table 3.4. Growth rate parameter estimates for different scallop grounds in Irish and UK waters. SWE=South west England, off the Silly Islands; SEI= South east of Ireland; S=South; N=North coast of Ireland.

Area	K	H_∞	to
SWE	0.254	130	-0.165
SEI-South Coast	0.379	117	0.189
SEI-South Irish Sea	0.361	126	0.117
S-Isle of Man	0.388	123	0.182
N-Donegal Coast	0.295	145	0.226

Table 3.5. Analysis of variance of size at age 5 in different geographic areas.

Source	df	Sums of Squares	Mean Square	F-ratio	Prob
Const	1	6.28E+06	6.28E+06	69302	< 0.0001
Geographic area	4	8952.42	2238.1	24.689	<0.0001
Error	609	55207.2	90.6522		
Total	613	64159.6			

3.3.3 Variability in Growth in Relation to the Physical Environment

Analysis of variance of the multiple regression of growth performance on temperature, current stress and depth (Figure 3.8) showed that for both neap and spring tides, the hydrodynamic bottom stress was the most important factor determining the variability in scallop growth. Sixty seven percent of the variability in growth was explained by shear bed stress and temperature (Table 3.6 and Table 3.7). Results were similar for neap and spring tides.

Growth of scallops was highest off Wexford south of the Saltees Islands and east and to a lesser extent south of this area in offshore waters. Growth was slower in the west of the area. The range of differences in shell height at the age of 5 was about 30mm (Figure 3.9).

Simple linear regression of growth on each of the predictor variables showed that bottom shear stress accounted for 64.5 and 67.2 % of variability in growth at spring and neap tides, respectively (Figure 3.9). Bottom water temperature explained 19.2% and 13.2% of variability in growth in spring and neap tides, respectively (Table 3.8). Depth did not significantly affect growth rate.

Highest growth rates occurred in areas of high shear bed stress (stronger currents) and highest water temperature. High temperatures, however, did not lead to high growth if seabed currents were low (Figure 3.10). This is evident from the relatively low growth rates in the northwest of the survey area, which have high temperature especially on neap tides but low shear bed stress (Figure 3.8). 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 George's Channel (Horsburgh, *et al.*, 1998; Brown *et al.*, 2003; Young *et al.*, 2004) and which maintains a mixed water column (and higher seabed temperatures) in this area compared with bottom water beneath the thermocline in the west of the area.

Table 3.6. Multiple regression coefficients of scallop growth performance in relation to hydrodynamic bottom stress, bottom water temperature and water depth for neap tides.

R^2 = 68.3% R^2(adjusted) = 67.4%

s = 4.201 with 106 - 4 = 102 degrees of freedom

Source	Sum of Squares	df	Mean Square	F-ratio
Regression	3879.63	3	1293.21	73.3
Residual	1800.47	102	17.6517	

Variable	Coefficient	s.e. of Coeff	t-ratio	prob
Constant	79.7699	12.33	6.47	< 0.0001
Np stress	17.5752	1.386	12.7	< 0.0001
Np Temp	0.619439	0.5419	1.14	0.2557
Depth	0.022554	0.08281	0.272	0.7859

Table 3.7. Multiple regression coefficients of scallop growth performance in relation to hydrodynamic bottom stress, bottom water temperature and water depth for spring tides.

R^2 = 68.2% R^2 (adjusted) = 67.3%

s = 4.207 with 106 - 4 = 102 degrees of freedom

Source	Sum of Squares	df	Mean Square	F-ratio
Regression	3874.8	3	1291.6	73
Residual	1805.3	102	17.699	

Variable	Coefficient	s.e. of Coeff	t-ratio	prob
Constant	75.9925	12.32	6.17	<0.0001
Spr stress	8.00813	0.6929	11.6	<0.0001
SprTemp	1.09225	0.6382	1.71	0.09
Depth	-0.00929	0.07611	-0.122	0.9031

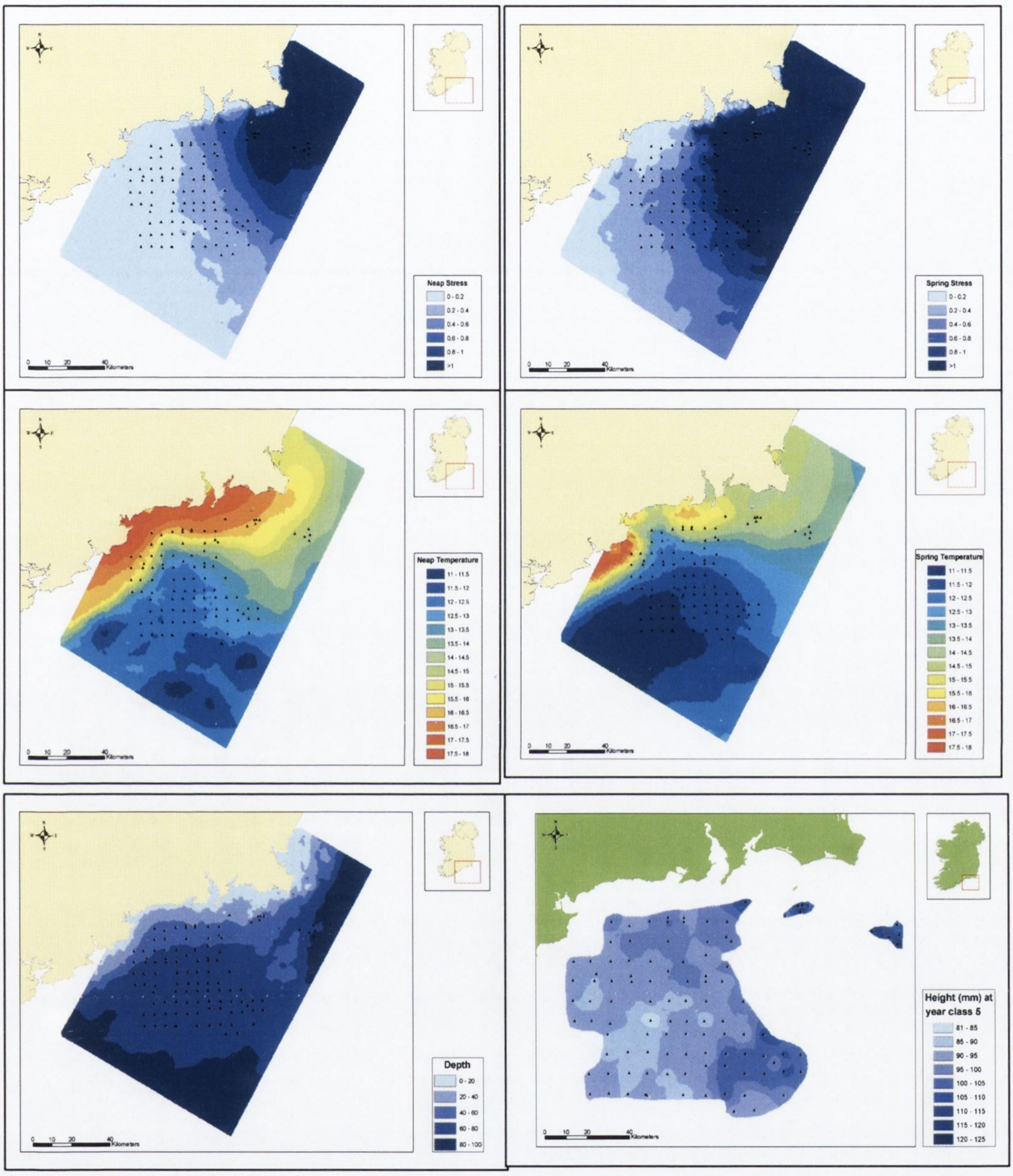


Figure 3.8. Shear stress fields at the seabed (top) and bottom seawater temperature fields (middle) on spring and neap tidal cycles off the south east coast of Ireland predicted by a hydrodynamic model developed for the area of study (Berry and Hartnett, 2005). Depth isolines for the area of study (bottom left) and contour plot of scallop height at age 5 (bottom right) are also shown

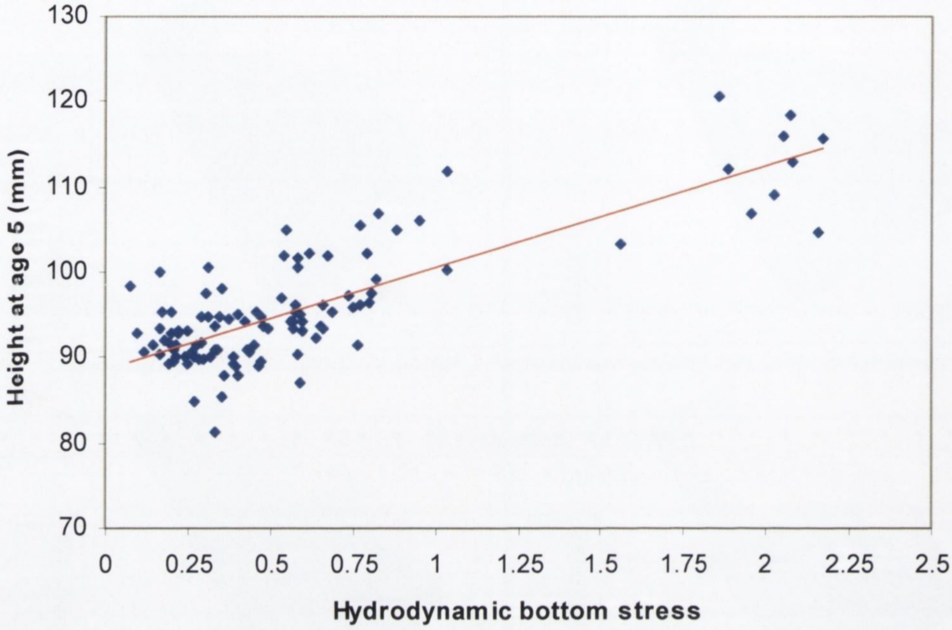


Figure 3.9. Scatter plot of scallop shell height at age 5 on mean values of hydrodynamic bottom stress. Bottom stress values are averages of spring and neap tide conditions.

Table 3.8. Regression coefficients of simple regression lines of growth performance on each of the predictors, hydrodynamic bottom stress, water bottom temperature and depth.

	Spring tide		Neap tide		
	Bottom stress	Temperature	Bottom stress	Temperature	Depth
Df	104	104	104	104	104
F-ratio	189	24.7	213	16	4.5
Prob	<0.0001	<0.0001	<0.0001	<0.0001	0.0362
R^2	64.5	19.2	67.2	13.3	4.2

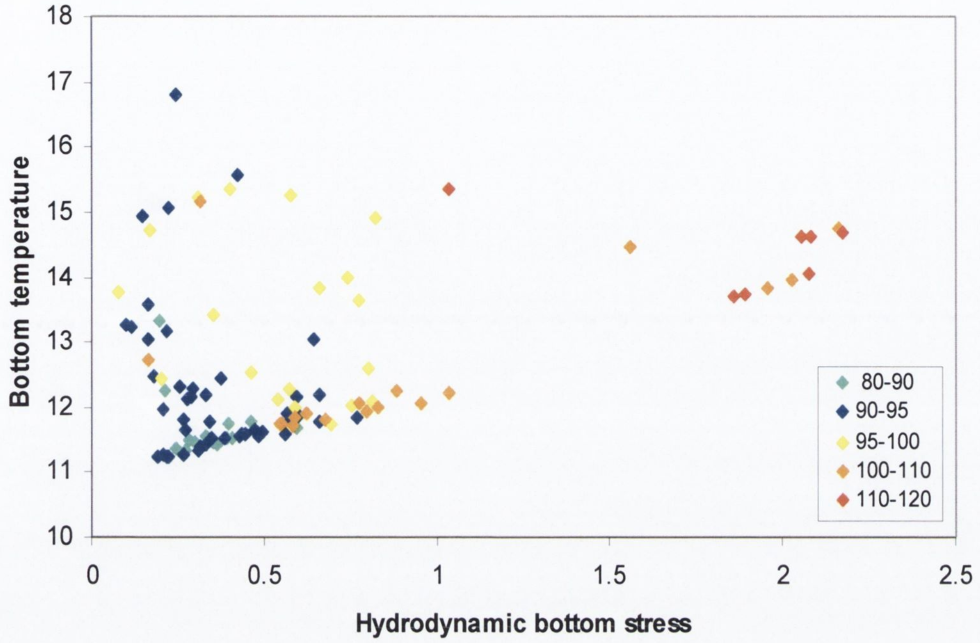


Figure 3.10. Scatter plot of mean values of water bottom temperature, measured in centigrade degrees, versus mean values of hydrodynamic bottom stress. Legend shows scallop growth performance. Each of the colours indicates the value of shell height, mm, at age 5.

3.3.4 Spatial Modelling of Scallop Growth off the Southeast Coast of Ireland

Growth data grouped in 5mile^2 grid were used to model growth spatially to investigate how the spatial pattern in growth variability should be taken into account in defining growth overfishing reference points (see Chapter 6). Differences in growth were modelled as a function of the asymptotic size H_∞ (Figure 3.11). The spatial pattern of variability in growth shows consistency along the main axes of variability in hydrodynamic bottom stress and bottom water temperature–inshore offshore and east to west.

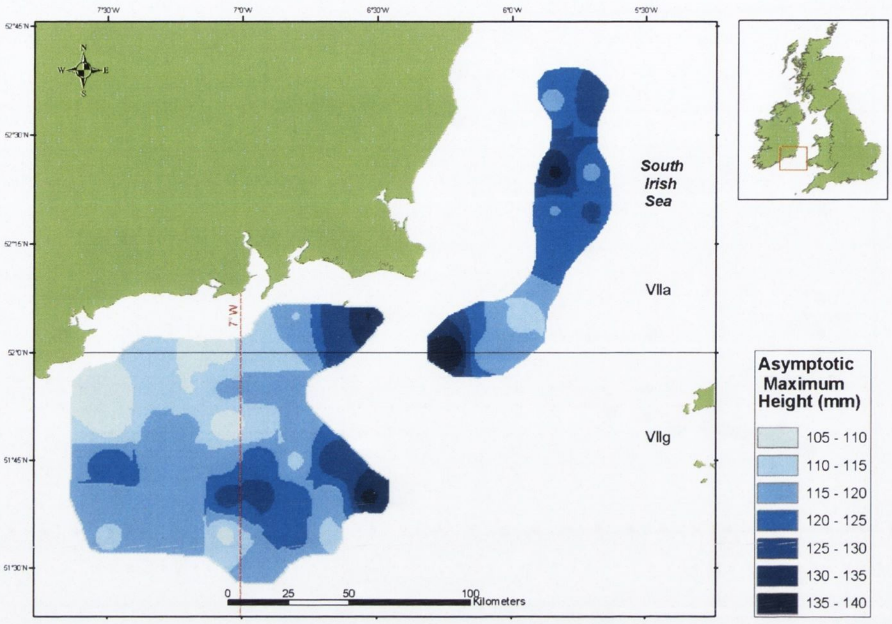


Figure 3.11. Contour plot of estimates of the asymptotic height (H_∞ (cm)) from the von Bertalanffy model of height as a function of age.

The overall area was divided into seven sub-areas within which growth was similar (Figure 3.12). Growth rate estimates (Table 3.10) for the seven sub-areas were then used in fitting the yield per recruit model and deriving fishery management reference points (see Chapter 6). Size at age data showed that growth rate was highest in the Barrels and Saltees Islands beds. Lowest growth rate occurs in the southwest and northwest beds (Table 3.9 and Figure 3.13). Growth rate estimates are shown together with size of the largest scallop in the sample (H_{max}) and environmental values in Table 3.10. Values of H_{max} were approximately similar to H_∞ estimates in all sub-areas. Differences in shear stress values between sub-areas of highest and lowest growth were most important, ranging from 0.4 to 2.8 and 0.15 and 1.4 Newton.m^{-2} for spring and neap tides, respectively. Temperature range was between 11.5-14.5 and 12.5-16.45°C in spring and neap tides, respectively. The Saltees Islands and the Barrel bed were the shallowest and deepest, respectively.

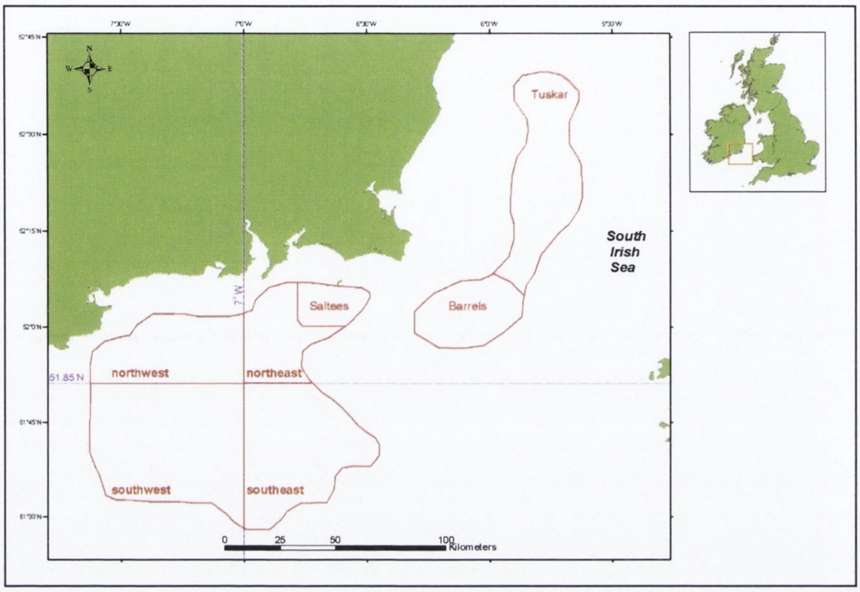


Figure 3.12. The southeast scallop grounds divided into seven sub-areas of similar growth.

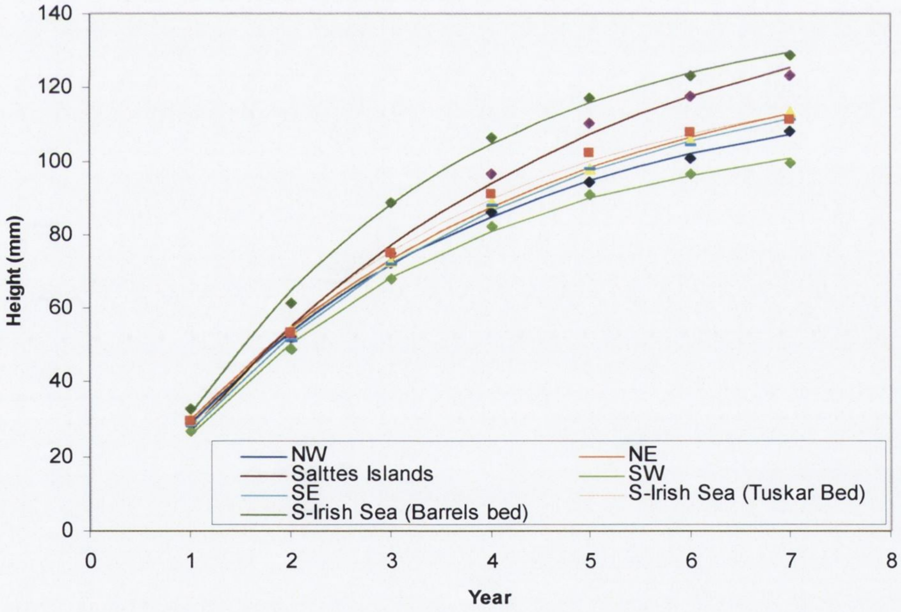


Figure 3.13. von Bertalanffy growth curves for scallops of different sub areas off the south east coast of Irelands. NW=Northwest, SW=Southwest, S=south, NE=Northeast, SW=Southwest. (see Figure 3.12).

Table 3.9. Size at age data used to fit growth curves for scallops of different sub areas off the southeast coast of Ireland (Figure 3.12). N=Number of measurements; O (H)=Observed mean height; E (H)= Expected mean height; CL=Confident limits (95%).

Area	Age	1	2	3	4	5	6	7
NW	N	1917	1772	1421	962	517	139	21
	O (H)	29.22	52.20	72.25	85.98	94.33	100.63	107.83
	E (H)	28.81	53.48	71.60	84.91	94.68	101.85	107.12
	CL	0.39	0.60	0.65	0.75	0.91	1.94	8.50
NE	N	1253	1133	762	508	266	93	25
	O (H)	30.04	53.95	72.54	88.38	97.71	105.44	113.17
	E (H)	29.89	54.28	72.91	87.14	98.01	106.32	112.61
	CL	0.77	0.98	1.37	1.73	2.17	4.15	18.35
SW	N	961	928	805	599	347	78	10
	O (H)	26.71	48.97	68.01	82.13	90.54	96.51	99.40
	E (H)	25.87	50.70	68.35	80.88	89.78	96.10	100.59
	CL	0.26	0.42	0.60	0.67	0.75	1.52	6.23
SE	N	945	848	673	432	269	117	32
	O (H)	28.02	51.07	71.69	87.91	97.79	104.29	111.19
	E (H)	27.21	52.78	71.95	86.34	97.13	105.23	111.31
	CL	0.37	0.62	0.82	1.06	1.22	1.83	2.67
Saltees Islands	N	557	434	297	152	101	37	12
	O (H)	28.71	51.69	74.73	96.21	110.19	117.63	123.00
	E (H)	26.70	54.92	76.84	93.87	107.09	117.37	125.35
	CL	1.33	2.03	2.94	3.10	3.17	4.98	7.33
S-Irish Sea (Tuskar Bed)	N	541	534	496	391	234	155	90
	O (H)	29.49	53.11	74.59	90.67	102.07	107.54	110.87
	E (H)	28.23	55.52	75.25	89.52	99.83	107.29	112.68
	CL	0.68	1.04	1.32	1.58	1.69	1.98	2.49
S-Irish Sea (Barrels Bed)	N	139	139	139	128	91	59	20
	O (H)	33.02	61.53	88.45	106.47	116.91	123.06	128.82
	E (H)	31.66	64.79	88.05	104.39	115.86	123.92	129.58
	CL	1.73	3.03	3.30	2.99	2.71	3.02	4.12

Table 3.10. Growth rate parameters estimates and environmental variables for different sub areas off the southeast coast of Ireland. NW=Northwest, SW=Southwest, T=Tuskar, NE=Northeast, SE=Southeast.

					Shear Stress (Newton*m-2)				Current speed (cm*s-1)				Temperature (C°)				Depth (m)	
					Spring		Neap		Spring		Neap		Spring		Neap			
Sub-area	H_∞	H_{max}	K	t_0	Mean	CL	Mean	CL	Mean	CL	Mean	CL	Mean	CL	Mean	CL	Mean	CL
NW	121.69	119	0.31	0.13	0.401	0.03	0.17	0.01	1.98	0.54	1.28	0.33	13.28	0.18	14.75	0.22	55.30	3.14
NE	133.18	132	0.27	0.06	1.212	0.05	0.56	0.03	3.44	0.73	2.33	0.51	13.58	0.21	15.11	0.25	50.95	6.09
Saltees	153.14	141	0.25	0.24	2.256	0.16	1.05	0.07	4.69	1.26	3.20	0.83	14.54	0.08	16.45	0.08	36.17	5.08
SW	111.60	113	0.34	0.23	0.47	0.01	0.15	0.01	2.14	0.36	1.21	0.24	11.55	0.04	12.50	0.08	73.25	0.63
SE	129.55	134	0.29	0.18	1.042	0.03	0.40	0.02	3.19	0.55	1.96	0.40	11.93	0.03	12.76	0.06	70.72	0.82
B	142.93	141	0.35	0.29	2.835	0.08	1.37	0.03	5.26	0.86	3.66	0.57	13.82	0.05	14.33	0.08	88.07	2.96
T	126.75	130	0.32	0.22	2.56	0.03	1.32	0.01	5.00	0.57	3.58	0.38	13.54	0.02	13.89	0.03	79.61	3.06

3.3.5 Height-Weight Relationships

The relationship between shell height and weight was described by the power function (Equation 3.3) for each of the sub areas off the south east coast of Ireland, for which growth rates were estimated (Figure 3.14). The linear form of the power function (Equation 3.4) was used to estimate the parameters q and b that describe the relationship between size and total wet weight (Table 3.11). Estimates of H_∞ were then converted into the parameter W_∞ which was needed for the yield per recruit model (see Chapter 6).

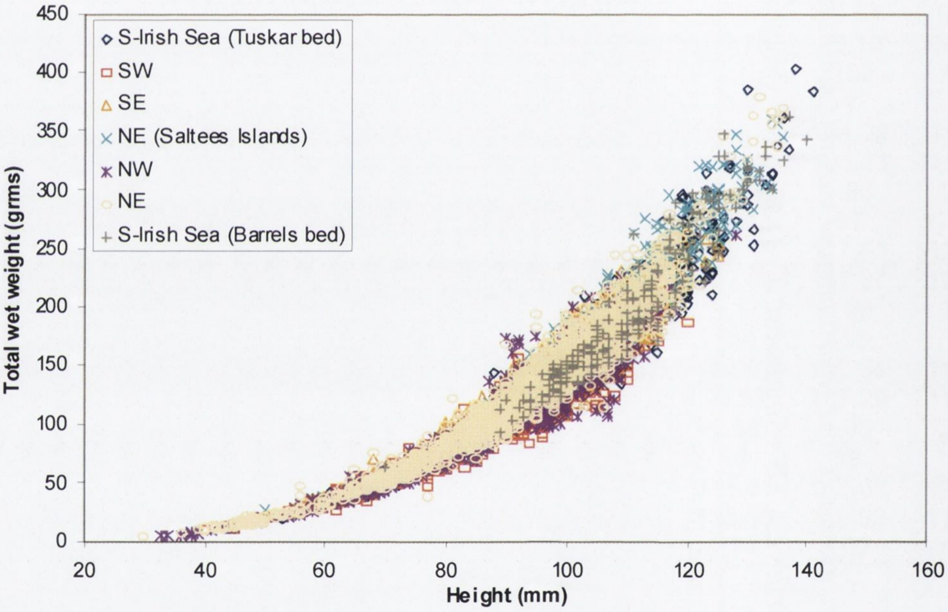


Figure 3.14. Relationship between shell height and total wet weight for each of the sub areas off the south east coast of Ireland for which growth rate parameters were estimated.

Table 3.11. Regression line output for each of the sub areas off the south east coast of Ireland. Regression coefficients (q) and (b) correspond with parameters of the power function (3.3.). DF= Degrees of freedom, SE=standard error

Area	q	b	R	DF	SE (parameter q)	SE (parameter b)
NE	0.00026	2.878	97	2110	0.0494	0.0110
NW	0.00037	2.791	95.7	3149	0.0475	0.0106
SE	0.00050	2.740	95.3	1691	0.0671	0.0148
SW	0.00047	2.732	93.9	1602	0.0784	0.0174
NE-Saltees	0.00037	2.812	95.5	644	0.1117	0.0242
S-Irish Sea (Barrels Bed)	0.00022	2.732	90.6	186	0.3247	0.0686
S-Irish Sea (Tuskar Bed)	0.00039	2.778	92.8	602	0.1458	0.0315

The temporal variability in the condition of the somatic tissue, is represented by the parameter *b* of the power function (Equation 3.3) presented in Figure 3.15. The parameter is the curvilinearty of the height-weight relationship; hence scallops will be heavier or lighter for a given height depending on the value of the parameter *b*, assuming that the intercept of the model do not vary. Monthly estimates of the parameter *b* were obtained from October 2002 to December 2004 for the south east coast. Variability within and between years in *b* occurred. The condition of the somatic tissue reached the highest value in October 2002 and 2003. In 2004 however, the highest value was found in September. The lowest values were found in May 2003 and in June 2004. However in June 2003 the value of *b* increased significantly. Confidence limits indicate also the high variability in monthly estimates. Generally, soft tissue condition was highest at the end of the summer months and the beginning of autumn, and declined in winter, before increasing again in early summer. The understanding of the temporal variability in soft tissue condition is important in fisheries management in order to define the most appropriate time of the year to maximise yield.

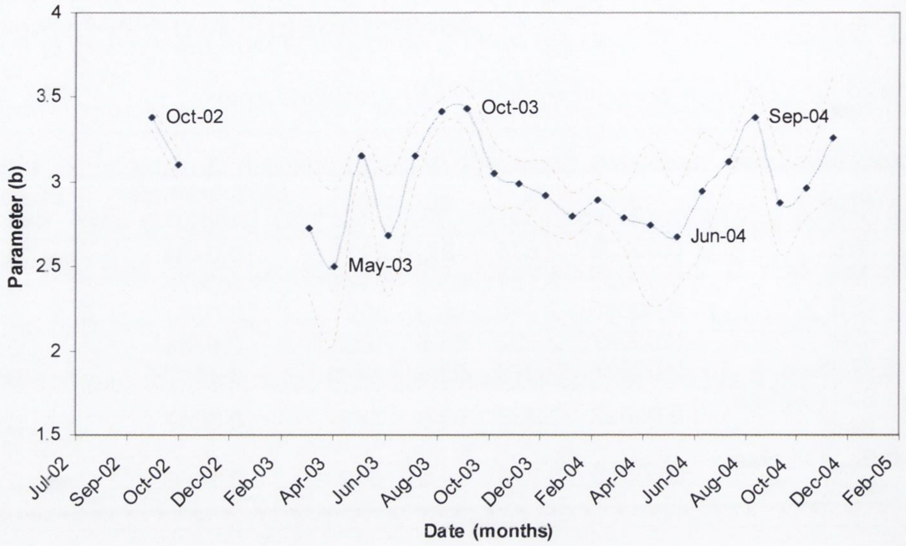


Figure 3.15. Temporal variability in the parameter b of the height-weight relationship equation (3.3) for scallops off the southeast coast of Ireland (all seven sub areas together). In Blue, mean estimates. In red, 95 % confidence limits.

3.3.6 Seasonality in gonad development

Gonad weight was lowest in October in the three years for which data were available (Figure 3.16). From October gonad weight increased and reached a peak in February. From February to September, it slowly decreased. Also, there is an inter-annual variability in gonad weight, with a higher index in the summer months of the year 2003 than in the year of 2004. Generally, for the scallop grounds of the southeast coast of Ireland, gonad weight during the spring and summer months were stable. A decrease occurred at the beginning of autumn with a period of recovery during winter.

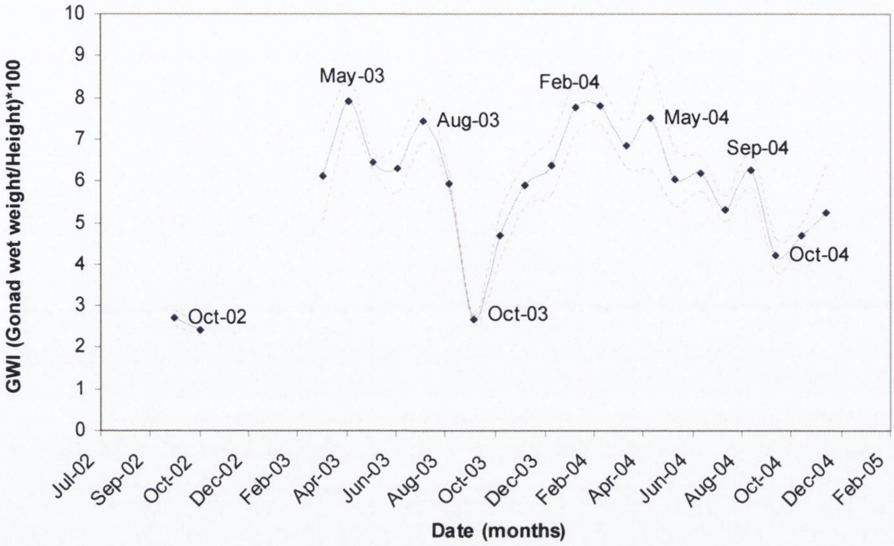


Figure 3.16. Temporal variability of gonad weight index for the scallop ground off the southeast coast of Ireland (all seven sub areas together). In Blue, mean estimates. In red, 95 % confidence limits.

3.4 Discussion

An extensive biological sampling programme in which spatially explicit growth data were collected provided evidence of spatial variability in growth of scallop both between scallop grounds in Irish and UK waters and also on a finer spatial scale off the south east coast of Ireland. The investigation of spatial variability in growth of scallop was carried out using the growth history of the shell. These types of data are extremely useful in the estimation of scallop growth (Smith *et al.*, 2001). The non-dependency shown between repeated measurements within the same shell allowed access to a much larger quantity of data for the investigation of spatial pattern of scallop growth than single estimate of size at age data for each shell.

The mathematical expression of growth derived by vonBertalanffy (1938) is widely used to describe the production dynamics of exploited fish populations (Sparre, 1992; Hilborn and Walter, 1992). However, its validity is often criticised (Haddon, 2001). The main problem of fitting growth data to the von Bertalanffy model is that H_∞ and t_0

are extrapolated from the growth data that are available. Normally, size at age data are available for only a few age classes, especially in fish species that are regulated by a minimum landing size or where exploitation rates are high and few older age classes are available or where young age classes are sampled inefficiently by the sampling gear. The use of the growth history of the shell to study the growth of scallops avoids the problem of not having access to young age classes. As data for the youngest age class are available the estimation of t_0 is more realistic. This is important because t_0 fixes the steepness of the growth curve (Haddon, 2001) and its reliable estimation is important in determining the goodness of fit of the parameter K.

At the other end of the growth curve the estimation of the maximum size that the animal attains is also an extrapolation of the data. Therefore, to realistically estimate H_∞ it is necessary to have a wide range of size at age data representing the majority of the year classes of the animal's life span. Although *Pecten maximus* can live in extreme cases up to 20 years (Mason, 1983), the average life span is much less than this (Ansell et al., 1991). In our study the maximum number of age classes recorded was 12 off the Isle of Man. In the scallop grounds off the south east coast of Ireland the maximum number of growth rings recorded was 9.

Off the south east coast of Ireland seven age classes were available to fit the growth model in order to meet the condition of constant variance and normal distribution of the error term. The estimate of H_∞ was close to the size of the largest scallop in the sample and therefore data were considered adequate to reliably estimate growth parameters.

Spatial variability in scallop growth was correlated with temperature fields and ocean circulation patterns in the area. Highest growth occurred in areas where the water column remains mixed because of strong currents and associated vertical turbulence. Temperatures at the seabed were between 14-17°C in those areas. This temperature range is considered optimum for scallop growth (Laing, 2002). Strong currents and associated vertical turbulence may increase the food availability and feeding conditions by increasing the pelagic supply of algae, from superficial to deeper zones and/or by a higher food supply associated with high current speed (MacDonald and Thompson, 1986).

Larger sizes and faster growth rates are generally associated with areas of relatively strong currents (Bricelj and Shumway, 1991). However there is a threshold at which scallop cannot tolerate an increase in current speed. Different studies examining the relationship between current speed and growth rates of scallops have produced conflicting results on this threshold (Kirby-Smith, 1972; Eckman *et al.*, 1989). Nevertheless in this study high growth are associated with current speeds of 3-6 $cm.s^{-1}$, which appear to provide favourable feeding conditions (Wildish *et al.*, 1987; Eckman, 1987; Eckman *et al.*, 1989).

In scallops it has been observed that ingestion in relation to food concentration is mainly regulated by fluctuations in the clearance rate (Palmer, 1980), which is the volume of water cleared of particles per unit time, and maximum growth rate appears to be achieved at moderate algal concentrations (Malouf and Bricelj, 1989). Given a well-mixed water column and high phytoplankton productivity relative to scallop consumption rates, food consumption and growth of scallops should not be influenced directly by current speed. If water mixing is sufficient to replenish near-bottom food supplies in the immediate vicinity of the filtering organism, growth should be dependent on food concentration alone. No data were provided in this study to relate food supply to seabed current strengths. The correlation between current strength and growth rate may be due to current dependent supply of food.

Low growth rates occurred when bottom stress was low even if temperatures were favourable for growth. This was evident from the relatively low growth rate in the northwest of the survey area. In this area current speed at the seabed, predicted by the hydrodynamic model, can be less than $1cm.s^{-1}$ in neap tides. Low current speed in this area may result in poor food and feeding conditions. This may be explained by either a limited food supply and/or depletion of food concentration during periods of low current speed. Populations of filter feeding bivalves are known to substantially deplete particle concentration in the overlying waters during periods of low flow (Fréchette *et* *al*., 1989). Reduced seston concentration during period of low flow has been proposed as a mechanism to explain spatial gradients in growth in bivalve populations (Fréchette and Bourget, 1985).

Variability in growth, on a larger spatial scale, between different scallop grounds in Irish and UK waters are also most likely owing to physical oceanographic conditions. Off the south coast of the Isle of Man the water column remains mixed during the summer months owing to the formation of the Western Irish Sea Front (Hill *et al*., 1996 and 1997), which is likely to influence, as described above, the scallop growth in this area. Off the North East Donegal coast, the physical oceanography of the area, with strong tidal currents and subsequent mixed water column, accompanied by the proximity of an estuary, supplying the area with nutrients, may account for the high growth of scallops in the area. On the other hand, scallops off the south west coast of England, which is a region that becomes stratified in the summer months, because of low currents speed (Dare *et al*, 1994) have the lowest growth.

The spatial variability in scallop growth rate has a direct effect on the utilization of growth information in assessment methods of scallop populations. Yield per recruit biological reference points are defined as the optimum exploitation rate that balance gains in yield owing to growth and losses owing to mortality, therefore variations in growth will also determine optimum fishing mortality rate. When fishing mortality is higher than that optimum then growth overfishing occurs. The traditional practice in scallop assessment is to calculate growth overfishing reference points by combining growth data over large geographic areas (Smith and Rago, 2004). However, the importance of incorporating the spatial aspect of scallop growth for the development of biological reference points, to prevent growth overfishing, has been recognised in the past (Caddy 1975; Orensanz *et al*., 1991, among others) and discussed recently (Smith and Rago, 2004). Spatial variability in growth was very significant off the south east coast of Ireland suggesting that spatial management of fishing effort and fishing mortality should be used to optimise yields using appropriate biological reference points. The integration of spatially referenced biological reference points for the establishment of fisheries management strategies are discussed in Chapter 6.

The seasonality in the somatic tissue condition and in gonad weight, the two marketable parts of the scallop body, should also be taken into account in order to define the most appropriated time of the year to maximise yield. To maximise weight the most appropriated time period to harvest is when somatic tissue conditions and gonad weight are at a maximum. These conditions are reached in the late summer months. However, in order to protect spawners good practise would be to delay the time of harvesting until the gonad is spent and/or recovering (Mason, 1983), in October/November.

The temporal variability in somatic tissue and gonad weight is related to environmental factors, such as temperature and food availability (McDonald and Thompson, 1985 and 1986; Bayne and Newell, 1983). The variability in the monthly estimates found for both, the somatic tissue and the gonad weight, suggests that there is individual variability in the gonad development and in muscle condition. This may be due to spatial variability in the physical environment and the scallop's response to it. If this is so, then gonad and muscle condition may also vary on fine spatial scales. Unfortunately data available for this study did not allow temporal variability in somatic growth and gonad weight development to be investigated in a fine spatial scale, as was done for scallop shell growth.

This chapter involved a number of different methods and results in the estimation of scallop biological parameters. Here is a summary of the key findings of the chapter:

- Spatial variability in scallop growth was studied on a large and fine geographical scale off the south east coast of Ireland.

- On a fine scale, scallop growth was correlated with hydrodynamic bottom stress and temperature, which accounted for 67% of variability in growth. Differences in hydrodynamic bottom stress values between areas of highest and lowest growth ranged from 0.4 to 2.8 and 0.15 and 1.4 Newton.m^{-2} for spring and neap tides, respectively. Temperature range was between 11.5-14.5 and

12.5-16.45°C. Hydrodynamic bottom stress was the most determinant factor in scallop growth variability.

- The spatial pattern of variability in growth shows consistency along the main axes of variability in hydrodynamic bottom stress and bottom water temperature-inshore offshore and east to west. Growth rate was highest in the Barrels and Saltees Islands beds. Lowest growth rate occurred in the southwest and northwest beds.

- On a large scale, scallop growth rate generally increased with latitude. The lowest growth rate occurred off south west England and the highest off the North east coast of Ireland. Differences in growth with latitude perhaps reflect differences in temperature and food supply.

- The condition of the somatic tissue peaked in October 2002 and 2003, however, in 2004 the highest value was found in September. The lowest value was found in May 2003 and June 2004. Maximum gonad weight was found during spring and summer, decreased at the beginning of autumn and recovered during winter.

Chapter 4. Assessment of Commercial Catch and Effort Data

4.1 Introduction

Commercial catch and effort data are used worldwide in assessing spatial and temporal changes in the abundance of fish stocks. The use of catch rate as an index of abundance assumes that catch rate is proportional to stock abundance. Analytically this can be expressed as:

$$C = q * f * N \tag{4.1}$$

where C is the catch, q is the catchability coefficient which is defined as the fraction of the population that is taken by one unit of effort, f is the measurement of fishing effort (number of fishing hours in a day, number of dredges that a vessel carries, etc) and N is the population abundance. This equation is normally expressed as:

$$C/f = q * N \tag{4.2}$$

which describes the catch in terms of catch rate or catch per unit of effort (CPUE).

If CPUE is proportional to stock abundance then the coefficient q of the above equation must be constant and any changes in C/f in this circumstance is due to changes in N. However, the q coefficient is rarely constant. This has been pointed out by several authors (Gavaris, 1980; Hilborn and Walter, 1992, Quinn and Deriso, 1999) who have highlighted the importance of taking into account changes in catchability when CPUE is used as an index of abundance.

The use of CPUE as an abundance index, therefore, is safe only where factors, other than abundance, that have an effect on CPUE, can be accounted for. This process is referred to as standardisation of CPUE and has been carried out to some extent since the 1950s. Early examples were given by Gulland (1956), and Beverton and Holt (1957). They defined the efficiency of a fishing vessel as its fishing power relative to that of a standard vessel in order to remove differences in catchability among vessels. Although this method was a good approach at the time, when powerful statistical software was not yet developed, the method lacked the ability of dealing with multiples factors and required calibration with a common standard vessel. Therefore, this method could not take into account important factors that can have a spatial and/or temporal effect on the catchability coefficient.

More recently, different methods of standardising CPUE have been developed in which statistical models are fitted to the catch data using additional variables that are thought to affect q. This allows values of CPUE to be estimated for reference levels of multiple variables that are considered important in the analysis and that account for the variability in CPUE. The most common statistical model used in the standardisation of CPUE is the Generalised Linear Model (GLM) (Maunder and Punt, 2004). GLM is attributed to Nelder and Wedderburn (1972) and defines how a linear combination of a set of explanatory variables relate to the expected value of the response variable. The response variable is defined by a link function (identity, logit, logarithmic, etc) that will define the nature of the error distribution (normal, binomial, poisson, etc). This method of standardisation of CPUE has been used in several fisheries, including finfish fisheries (e.g. Maunder and Langley, 2004; Battaile and Quinn, 2004) and shellfish fisheries (e.g. Maynou *et al*, 2003; Sbrana *et al*, 2003; Tully *et al*, 2006b,c). The characteristics of the type of fishing and the biology of the target fish species will determine what explanatory variables should be included in the model.

In the scallop fishery off the southeast coast of Ireland factors that can affect the catchability coefficient include the vessel, environmental conditions and/or fishing location and ground type. Performance of the vessel can vary due to the skill of the skipper or the characteristics of the vessel and the configuration of the fishing gear.

The knowledge and experience of the skipper can influence catch rates. This could be due to the knowledge of the fishing grounds and skill in setting the gear. Vessel characteristics vary by length and/or power. These factors may affect the efficiency of the gear and therefore the catch rates. The operation and efficiency of scallop dredges are affected by sea conditions. Therefore, the weather (wind speed and direction) and tidal conditions may have an influence on the fishing process and consequently on catchability.

The distribution of scallops is far from random. Distribution and abundance is correlated with seabed sediments (Chapter 5) and the oceanographic conditions control larval supply to given areas (Tully *et al.*, 2006a). Catch needs therefore, to be analysed in a disaggregated form at fine spatial scales in order to provide an unbiased index of temporal change, or if large areas are included a spatial effect will need to be included in the GLM.

Even after standardising CPUE data it must be interpreted cautiously. In fisheries where the target species is sessile or nearly sessile, as in the case of scallop, the fishing process can lead to depletion of the local population. Depletion of scallop stocks is directly related to the spatial patterns of effort allocation. Serial depletion and a shifting sequential pattern of effort allocation, described by Orensanz *et al.* (2006), in which fishermen target the densest patches first, shifting to the next patch as the first is depleted, have been observed in many scallop fisheries (e.g Gibson, 1956; Dredge, 1986; Ansell *et al.*, 1991). Therefore, within year fishing activity that can lead to depletion of the stock locally but where this effect can be hidden by annual abundance index estimations, aggregated for the fishery as a whole, should be explored.

Local depletion of stocks over short time scales and at fine spatial scales can be estimated under certain conditions. Leslie and Davis (1939) and Delury (1947) developed, what today, are known as the classic depletion methods to determine population estimates (Hilborn and Walter, 1992; Addison, 2003). They examine how successive measured removal of individuals (catch) influence the catch rate of the remaining population. The depletion process is modelled and the catchability is estimated from the decline in catch rate which is then used to estimate initial abundance. The model assumes a closed system, with no gains or losses in biomass, and a random distribution of the fishing effort and considers that all individuals have the same probability of being caught.

Depletion experiments are usually used in scallop fisheries to estimate the efficiency of the fishing gear (see Chapter 2). Commercial catch and effort data are not usually used to model the depletion process due to fishing. This is probably because estimation of scallop abundance is normally done by independent surveys that also give information on the distribution pattern. In addition, the spatial scale in which commercial data are available does not normally permit the application of depletion methods because the assumptions of the model are usually violated by such data.

The vessel information system (VMS) technology available today for European fisheries[1] and for most of the fisheries worldwide (FAO, 2007) provides the geographic location (latitude and longitude) of the vessel on a regular basis. These data are used in real time to control the location where fishery fleets can fish. The detail and quality of fishing location data has been improved greatly by this technology and consequently it has a wide range of applications for fisheries stock assessment. The VMS allows the distribution of fishing to be mapped. With additional knowledge on the amount of fishing gear used by the vessel it can be used to analyse the distribution of actual fishing effort and to study the local depletion process without violating the assumptions of the depletion model.

In this chapter, two analyses are undertaken:

1. Commercial CPUE data are standardised using a GLM, and annual changes in stock abundance indicators are reported.

2. A Delury (1947) depletion model is applied to a number of local fishing areas. The depletion process is studied and local population estimators calculated.

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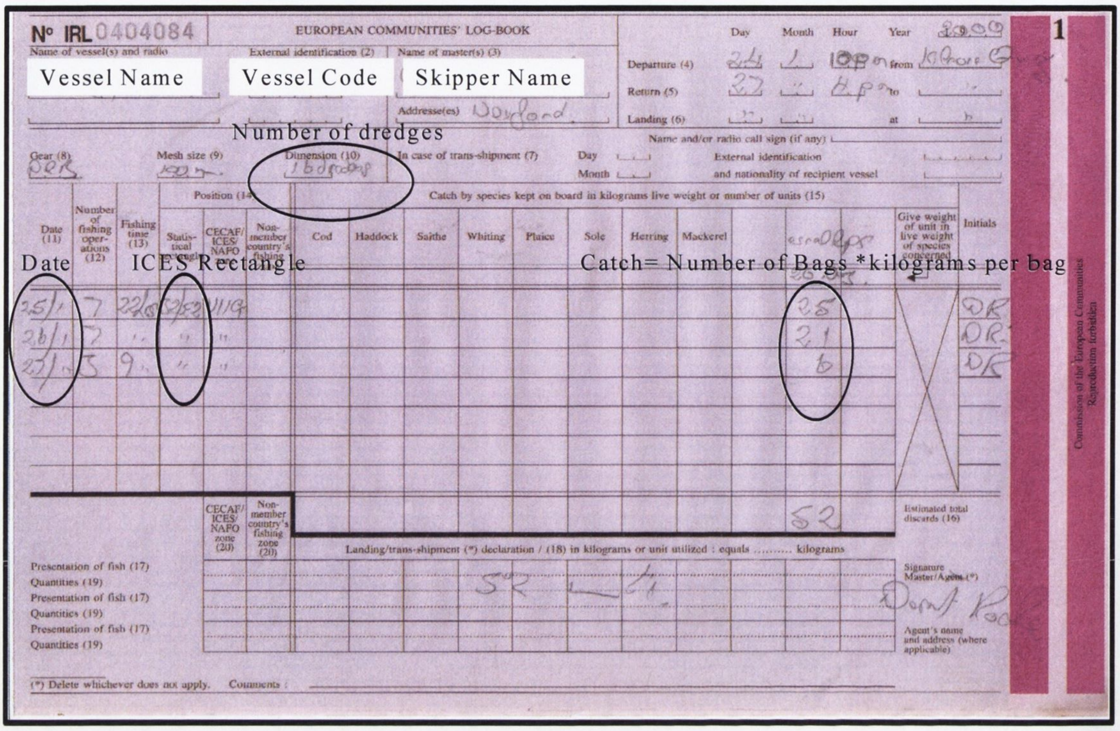
[1] www.europa.eu/comm/fisheries/)

4.2 Source of Data and Methods

4.2.1 Catch and Effort Data

4.2.1.1 European Communities' Logbooks (ECL)

The Department of Communication, Marine and Natural Resources (DCMNR) compile information on catch and effort reported in the European Communities' Logbooks (ECL) for all licensed vessels in the Irish fishing fleet. Data on scallop catch and effort were compiled for the period 1994-2004. The ECL is compulsory for vessel over 10m in length, which includes all of the scallop fleet fishing off the south east coast of Ireland. Catch rates in the ECL was expressed as kilograms of scallops caught per day. The number of dredges was also recorded and fishing location was given as statistical ICES rectangle (Figure 4.1).



N° IRL 0404084 EUROPEAN COMMUNITIES' LOG-BOOK 1

Name of vessel(s) and radio | External identification (2) | Name of master(s) (3)

Address(es) Wexford

	Day	Month	Hour	Year 2009	
Departure (4)	24	1	10pm	from	Kilmore
Return (5)	27	"	4pm	to	"
Landing (6)	"	"		at	"

Gear (8) DRB
Mesh size (9) 100 m
Dimension (10) 16 dredges
In case of trans-shipment (7) Day Month
Name and/or radio call sign (if any)
External identification and nationality of recipient vessel

Date (11)	Number of fishing operations (12)	Fishing time (13)	Position (14) Statistical rectangle	CECAF/ ICES/ NAFO zone	Non-member country's fishing zone	Cod	Haddock	Saithe	Whiting	Plaice	Sole	Herring	Mackerel		escallops 20 kg		Give weight of unit in live weight of species concerned	Initials
25/1	7	22/6	32/E2	VIIG											25			DR
26/1	7	"	"	"											21			DR
27/1	3	9	"	"											6			DR
															52		Estimated total discards (16)	

Catch by species kept on board in kilograms live weight or number of units (15)

Landing/trans-shipment (*) declaration / (18) in kilograms or unit utilized : equals .... kilograms

CECAF/ ICES/ NAFO zone (20) | Non-member country's fishing zone (20)

Presentation of fish (17)
Quantities (19) SR 4
Presentation of fish (17)
Quantities (19)
Presentation of fish (17)
Quantities (19)

Signature Master/Agent (*)
Agent's name and address (where applicable)

(*) Delete whichever does not apply. Comments :

Commission of the European Communities Reproduction forbidden

Figure 4.1. European Communities' Logbook (ECL). The information that a vessel reports is shown. In each ECL vessel name, vessel code and skipper name are recorded. Catch and effort information used in the analysis is shown. Catch data are recorded on a daily basis, in which the catch is recorded in number of scallops bags. The bag weight is also recorded. The catch can, therefore, be expressed in kilograms caught per day and as the number of dredges used is recorded this can be re-expressed in kilograms per dredge per day for each ICES rectangle.

4.2.1.2 Vessel Monitoring System data (VMS)

Since December 2003 the use of VMS technology has been compulsory for vessels of length greater than 24 m. From January 2004 the use of VMS became mandatory for all vessels over 18 m in length and from January 2005 for all those over 15m in length[2]. In Ireland, since June 2000 the VMS was used to monitor the location of fishing of all scallop vessels at regular intervals using satellite communication technology. The system works by sending vessel information via satellite to a land

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[2] www.europa.eu/comm/fisheries/

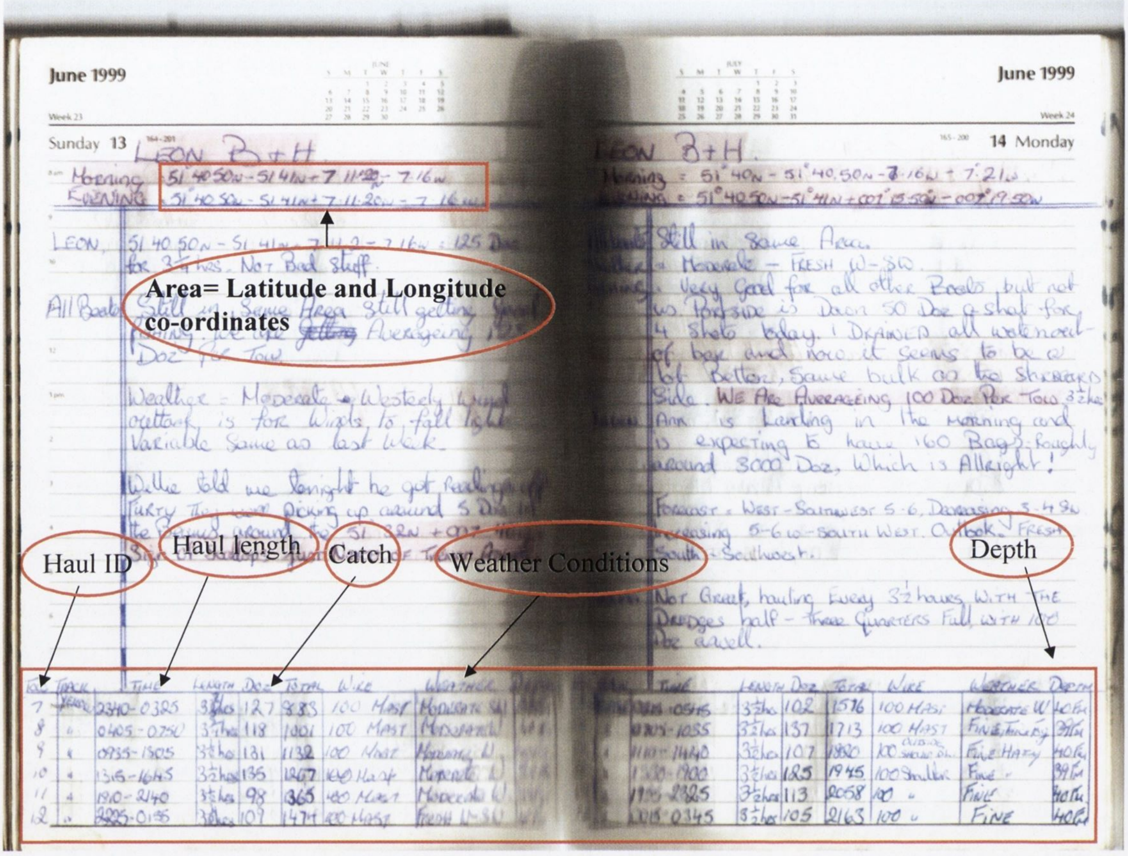
based station (The Fisheries Monitoring Centre, FMC, Naval Base, Haulbowline, Co. Cork). Thus automatic transmission of data on vessel identification, latitude and longitude and date and time is sent from the vessel to the FMC. The data are transmitted once every hour or every two hours depending on the technical capabilities of the system or the operational needs of the FMC. Fishing effort given by the VMS data is available for this study from January 2000 to December 2004.

"Cleaning" VMS data

Not all VMS points reported to FMC represent fishing locations. VMS points are also logged when the vessel is steaming to the fishing ground or between fishing grounds. These points have to be removed to calculate actual fishing effort. To do this all VMS points were plotted in ArcGIS and the distance between points was calculated. The time between the recording of successive positions and the distance between the positions were used to calculate the ships speed. All points relating to vessel speeds greater than 5 knots were deemed to be associated with steaming rather than fishing and were removed. The resulting distribution of fishing activity provides an indicator of the distribution of the stock in well-developed scallop fisheries (Orensanz *et al.*, 1991, 2006). An area/scallop bed identification was given to each cluster of VMS points identified.

4.2.1.3 Private diaries

Private diaries were obtained from five scallop vessels. The catch and effort information in these diaries was given for every fishing haul. For each fishing haul, the hours fished, the number of scallops caught and the fishing location (latitude and longitude) of each tow were recorded (Figure 4.2). The number of dredges for each haul was always equal to the number of dredges carried by the particular vessel. This information was obtained from the ECL and by interviewing the skipper of the vessel.



June 1999
Week 23
Sunday 13 164-201

LEON B+H.
Morning 51 40 50N - 51 41N + 7 11.20W - 7.16W
Evening 51 40 50N - 51 41N + 7.11.20W - 7.16W

LEON, 51 40 50N - 51 41N - 7 11.2 - 7.16W : 125 Doz for 3¾ hrs. Not Bad stuff.

All Boats Still in Same Area still getting [illegible] fishing. We are ~~getting~~ Averageing [illegible] Doz Per Tow.

Weather - Moderate Westerly wind outlook is for Winds to fall light Variable Same as last Week.

Willie told me tonight he got [illegible] Turty they were picking up around 5 Doz in the [illegible] around to 51 32N + 007 [illegible]

Tow	Track	Time	Length	Doz	Total	Wire	Weather	Depth
7	[illegible]	2340-0325	3¾hrs	127	883	100 Mast	Moderate SW	[illegible]
8	"	0405-0750	3¾hrs	118	1001	100 Mast	Moderate W	[illegible]
9	"	0935-1305	3½hrs	131	1132	100 Mast	Moderate W	[illegible]
10	"	1315-1645	3½hrs	135	1267	100 Mast	Moderate W	[illegible]
11	"	1910-2140	3½hrs	98	365	100 Mast	Moderate W	[illegible]
12	"	2225-0155	3½hrs	109	1474	100 Mast	Fresh W-SW	[illegible]

June 1999
Week 24
165-200 14 Monday

LEON B+H.
Morning = 51°40N - 51°40.50N - 7.16W + 7.21W.
Evening = 51°40.50N - 51°41N + 007°15.50W - 007°19.50W

Still in Same Area.
= Moderate - Fresh W-SW.
= Very Good for all other Boats but not us. Portside is Down 50 Doz a shot for 4 shots today. I Drained all water out of box and now it seems to be a lot Better, Same bulk as the Starboard Side. We Are Averageing 100 Doz Per Tow 3½hrs
Ann is Landing in the morning and is expecting to have 160 Bags roughly around 3000 Doz, Which is Allright!

Forecast = West-Southwest 5-6, Decreasing 3-4 SW Increasing 5-6 W-South West. Outlook = Fresh South - Southwest.

Not Great, hauling Every 3½ hours With The Dredges half - three Quarters Full with 100 Doz as well.

Time	Length	Doz	Total	Wire	Weather	Depth
[illegible]-0545	3½hrs	102	1576	100 Mast	Moderate W	40Fm
[illegible]-1055	3½hrs	137	1713	100 Mast	Fine, [illegible]	39Fm
[illegible]-1440	3½hrs	107	1820	100 outside shoulder	Fine Hazy	40Fm
1530-1900	3½hrs	125	1945	100 Shoulder	Fine "	39Fm
1955-2325	3½hrs	113	2058	100 "	Fine	40Fm
0015-0345	3½hrs	105	2163	100 "	Fine	40Fm

Figure 4.2. Private Diary. Catch and effort data are given for every single haul. The catch is given in dozens of scallops. The duration of the haul is recorded, together with additional information, such as weather conditions and depth. Latitude and longitude co- ordinates give the fishing area in which the vessel is operating.

4.2.2 Environmental Data

Environmental data were compiled for use in the General Linear Modelling (GLM) of catch rate data (see 4.2.3). The meteorological station at Rosslare Harbour Co. Wexford supplied data on wind speed and direction. Predicted tidal height, measured as metres at maximum height, were obtained using TideComp software[3]. The software allowed the collection of tide data on a daily basis. Tidal predictions were obtained for Rosslare Harbour and south of the Waterford estuary.

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[3] www.pangolin.co.nz/tidecomp.phd

4.2.3 Generalised Linear Modelling (GLM) of Catch Rate Data

4.2.3.1 The Model

In its simplest form, a linear model specifies the (linear) relationship between a dependent (or response) variable (Y), and a set of predictor variables, the (X's), so that

$$Y = b_0 + b_1 X_1 + b_2 X_2 + \cdots + b_t X_t \tag{4.3}$$

In this equation (b_0) is the regression coefficient for the intercept and the (b_i) values are the regression coefficients (for variables 1 through *k*) computed from the data. Generalised linear models allow the incorporation of non-normal distributions and transformations of the response variable to linearity (Nelder and Wedderburn, 1972). The general form of the GLM is:

$$f(y_i) = \beta_0 + \sum_{J=1}^{N} \beta_j x_{ij} + \varepsilon_i \tag{4.4}$$

where (y) is the response variable, e.g catch rate in a fishery or its transformation, and ($f(\cdot)$) is the link function that is used to achieve linearity in the vector (β) of size (N), that specifies the explanatory variables (x) for the (i_{th}) value of the dependent variable (y). The error term (ε) will have a statistical distribution that will depend on the nature of the link function. In this study the response variable (y) was defined as the log-transformation of the CPUE. GLMs were fitted assuming a normal distribution of errors (ε) using the identity function. Models were fitted using the R-statistical package. The linear combination of explanatory variables was year and vessel incorporated in the model as categorical variables and wind speed, wind direction and tidal height which were included in the model as continuous variables.

4.2.3.2 Analysis of ECL and VMS Data

ECL and VMS data were available for years 1995-2004 and 2000-2004 respectively. As the two set of data were available for two different time periods, two different analyses were carried out; GLM of ECL data (not using VMS data) for the period 1995 to 2004, and GLM of ECL data linked to the VMS data for the period 2000 to 2004.

In the analysis of ECL data, not coupled with VMS data, CPUE was expressed as kilograms of scallops per dredge per day in each ICES rectangle. The area effect (ICES rectangle) was included in the GLM model as a categorical factor. Two broad areas were considered separately:

- Areas 1 and 2: The data for this area consisted of 3,634 records, covering the period January 1995 to December 2004 for 20 vessels and ICES areas 33E3, 33E2, 32E3 and 32E2 (Figure 4.3) (see Appendix 4.1).

- Area 3 and 4: This area consisted of three ICES rectangles (32E4, 33E4 and 34E4) (Figure 4.3). The data consisted of 762 records, covering the period January 1997 to December 2004 for 13 vessels (see Appendix 4.1).

In the analysis of ECL data, coupled with VMS data, catch and effort information was aggregated to each fishing day. This provided the following data for analysis:

- Number of hours fished per day, estimated using the fishing time range provided by the VMS data.
- Catch in kilograms of scallops
- Location given by the global positioning system and associated area ID (Figure 4.3). A number of locations were given by the VMS data (one location every one or two hours) in the same day. The average latitude and longitude was calculated from all the positions given in a same day in order to designate a daily location. Daily EU-logbook catch records that had associated VMS data from more than one area ID were not considered for analysis.

Unfortunately fishing activity recorded by the VMS did not always have corresponding ECL or private diary catch data. Table 4.1 summarises the number of daily records of fishing effort and the number and percentage of which have associated catch data.

Table 4.1. Total number of fishing events per area, and number of fishing events with catch data record associated. NFE=number of fishing events.

Area ID	NFE	NFE with catch data associated	% NFE with catch data associated
1	912	376	41.2
2	1430	506	35.4
3	508	255	50.2
4	901	476	52.8

Areas 1 and 2 south of Waterford estuary were analysed separately. Areas 3 and 4 were analysed together (Figure 4.3). CPUE was expressed as kilograms of scallop per dredge per hour since the hours fished per day were estimated from the VMS data. The number of CPUE records for Areas 1, 2 and 3 and 4 was 325, 509, 642 respectively covering the period June 2000 to December 2004. CPUE records were provided by a number of 11 vessels for areas 1 and 2 and 12 vessels for areas 3 and 4 (see Appendix 4.2).

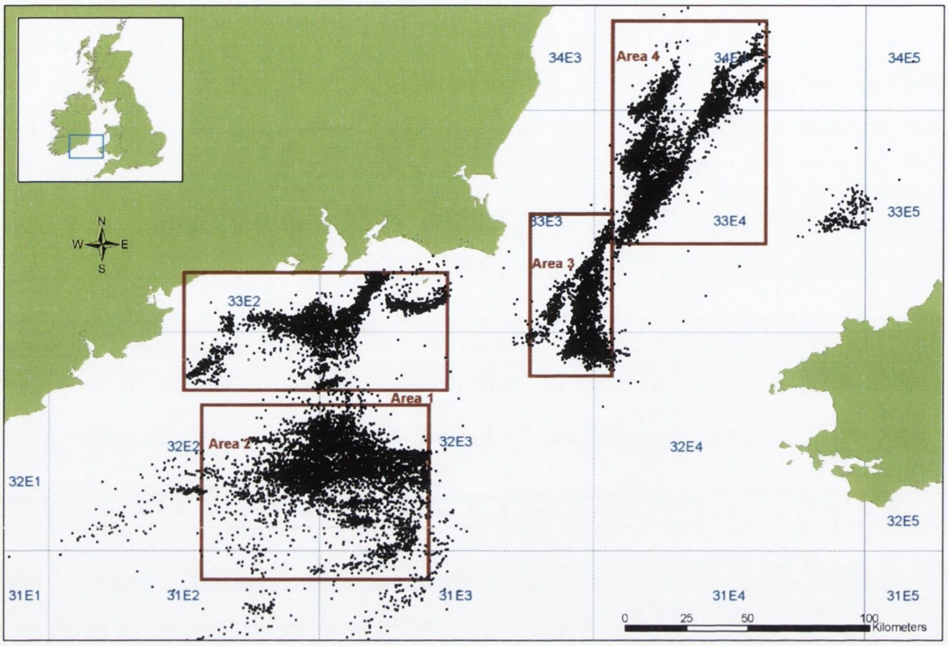


Figure 4.3. Fishing points, derived from vessel monitoring system data, from year 2000 to 2004 off the south east coast of Ireland.

4.2.3.3 Analysis of Private Diaries

Private diaries were provided by five vessels for Areas 1 and 2 (Figure 4.3). Records were given in number of scallops per tow, with associated data on fishing effort (number of dredges and tow time) and fishing location (latitude and longitude). CPUE was calculated as the catch (number of scallops) per dredge per hour. Effectively private diary data is of similar spatial and temporal resolution as ECL data when it is coupled to VMS data.

The data consisted of 1,666 and 604 records for Areas 1 and 2 respectively covering the period 1994-1999 and 2003-2004. Data were available for 4 vessels in Area 1 and 5 vessels in Area 2 (see Appendix 4.3).

4.2.4 Depletion Models

The classic depletion methods, formulated by Leslie and Davis (1939) and Delury (1947) have been discussed by Hilborn and Walter (1992) and Addison (2003) in the fisheries context. The Leslie estimator is based on declines in the rate of catch as the total removals from the population accumulates. The Delury estimator describes the decline in catch rate with increasing expenditure of effort (Figure 4.4). Both the Leslie and Davis, and Delury models have a linear form and can be fitted by linear regression.

The availability of spatially and temporally specific effort data provided by the VMS, allowed the Delury depletion model to be used for the estimation of local scallop populations where a given level of fishing activity occurred in a specific area over a short period of time. The Delury method was chosen for analysis because some catch data was missing thereby limiting the application of the Leslie method. Using the Delury method a predicted catch rate could be estimated for those fishing events with missing catch data by using the equation that describes the linear form of the Delury model. Hence the total removal, the initial population and exploitation rates could be estimated.

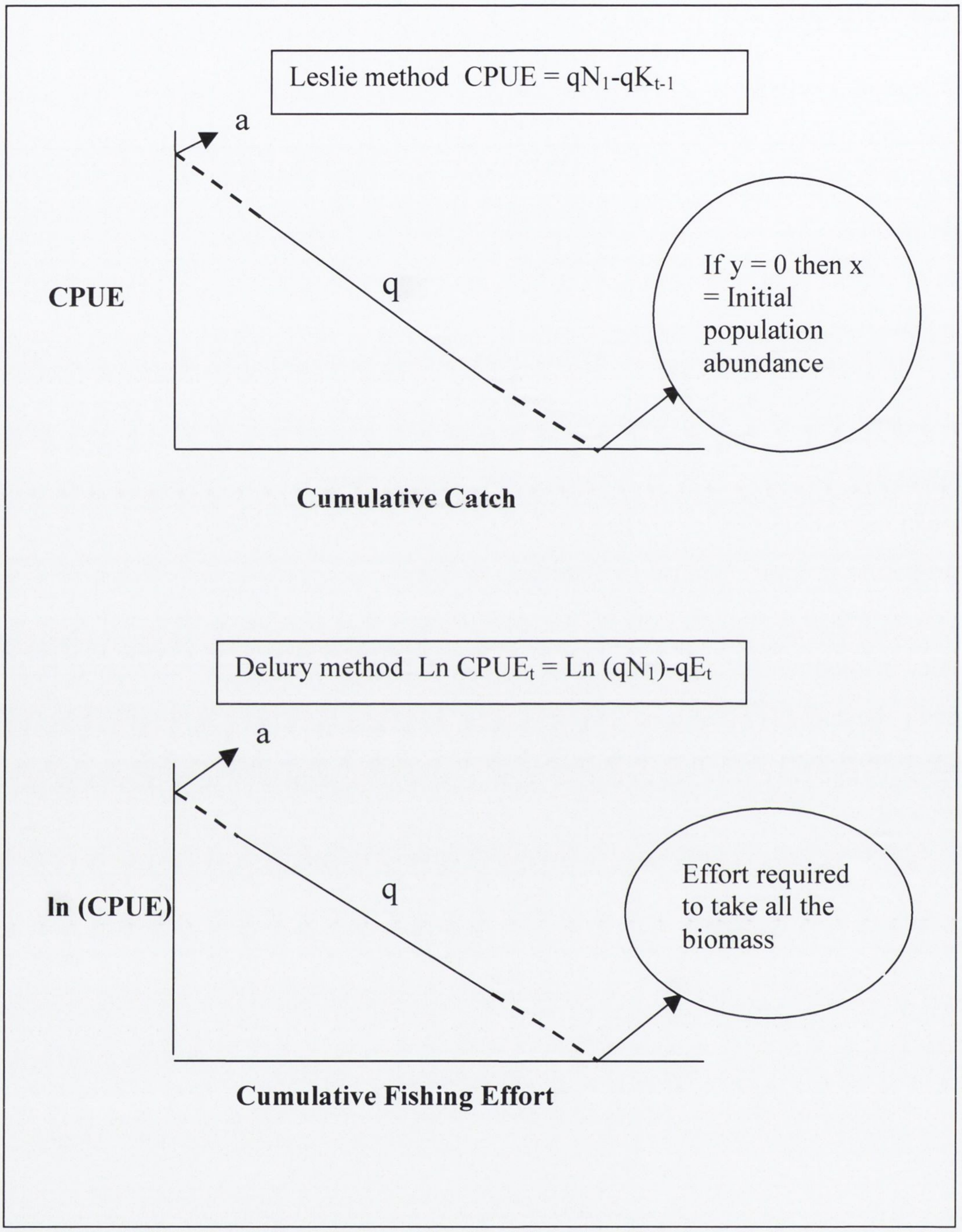


Figure 4.4. Graphical illustration of Leslie (above) and Delury (below) estimators. In both methods the slope of the regression line (q) defines the catchability coefficient. The initial population (N_1), is defined in the Leslie method by the intercept on the x-axis and by the formula e^a/q, where a is the intercept on the y-axis and q is the slope.

4.2.4.1 Delury Model

Delury estimators are obtained from the exponential model:

$$Y_t = qN_1 e^{-qE_t} \tag{4.5}$$

Where (Y_t) is the abundance index, given by the catch per unit effort (CPUE), in the fishing episode (t), (q) is the catchbility coefficient, which is defined as the fraction of the population that is taken by one unit of effort and is based on the probability that an individual in the population coming into contact with the fishing gear has a probability of capture (Ricker, 1975), (N_1) is the initial population before fishing take place and (E_t) is the cumulative effort up to time (t). The following assumptions must be met if (Y_t) is to be regarded as an unbiased population estimator:

1. The catch rate is proportional to abundance as defined by the expression $Y=q*N$, where q is the catchability.

2. The population in the study area is closed except for the removals. There is no immigration, emigration, recruitment, growth or natural mortality.

3. The catch rate (C) is directly proportional to a measure of fishing effort (f) that is

   ${dC}/{dt} = q * f$ (Hilborn and Walter, 1992), thus the cumulative effort (Et), is given by the integral of (f) which determines the exponential form of the Equation 4.5.

4. The catchability coefficient is constant. The fishing effort and the fish resource are considered randomly distributed and all fish are equally vulnerable to the fishing gear.

The Delury estimators were obtained from the linear form of Equation 4.5:

$$LnY_t = Ln(qN_1) - qE_t \tag{4.6}$$

where the dependent variable is the catch rate (Ln Y_t) and the independent variable is the cumulative effort (Et) prior to time (t).

The estimators from the Delury model are:

1. Initial population (N_1): Equation (4.6) has the form of a linear regression line $Y=a+qx$, where the negative slope is q and the intercept (a) is equal to Ln (qN_1). Therefore the initial population is given by $N_1=e^a/q$.

2. Exploitation rates: Given by the percentage of the biomass removed from the initial population (N_1). Note, as mentioned earlier for the estimation of exploitation rates, all of the fishing effort expended must be known.

The distribution of fishing effort was described by the VMS data. Thus different fishing episodes, in which the temporal and spatial scale was satisfactory to investigate the depletion process, and where the assumptions of the Delury method were met, could be selected for analysis. Catch data used for analysis was obtained from the ECL coupled to VMS data. Fishing events reported by the VMS did not always have an associated logbook catch, so some areas could not be included in analysis. The procedure for selection of study areas was as follows:

1. The VMS data was used to calculate fishing effort (expressed in dredge*hours) each day for each vessel. The total effort expended, for each Area 1-4, was then estimated for every week in order to determine periods of time with relatively high levels of fishing effort (Figure 4.5).

2. Intervals of weeks in which fishing effort was higher than 2000 dredge*hours were selected so that the probability of observing depletion in

CPUE was high. For the intervals of time thus selected the daily average position of each vessel was mapped in ArcGIS 9.0.

3. Once the daily position of each vessel was mapped, spatially aggregated fishing events, considered to be exploiting the same local scallop patch over a short period of time, were selected for analysis. The local scallop patch was defined as that population within which all scallops had equal chance of being caught by the fishing events selected for analysis.

4. The parameters of the Delury model were estimated by means of linear regression. Therefore, study areas selected in which catch data did not meet the assumption of log normality and constant variance were removed from the analysis. Figure 4.6 and 4.7 show areas selected for analysis and in Table 4.2 the periods of time for each of the study areas are presented.

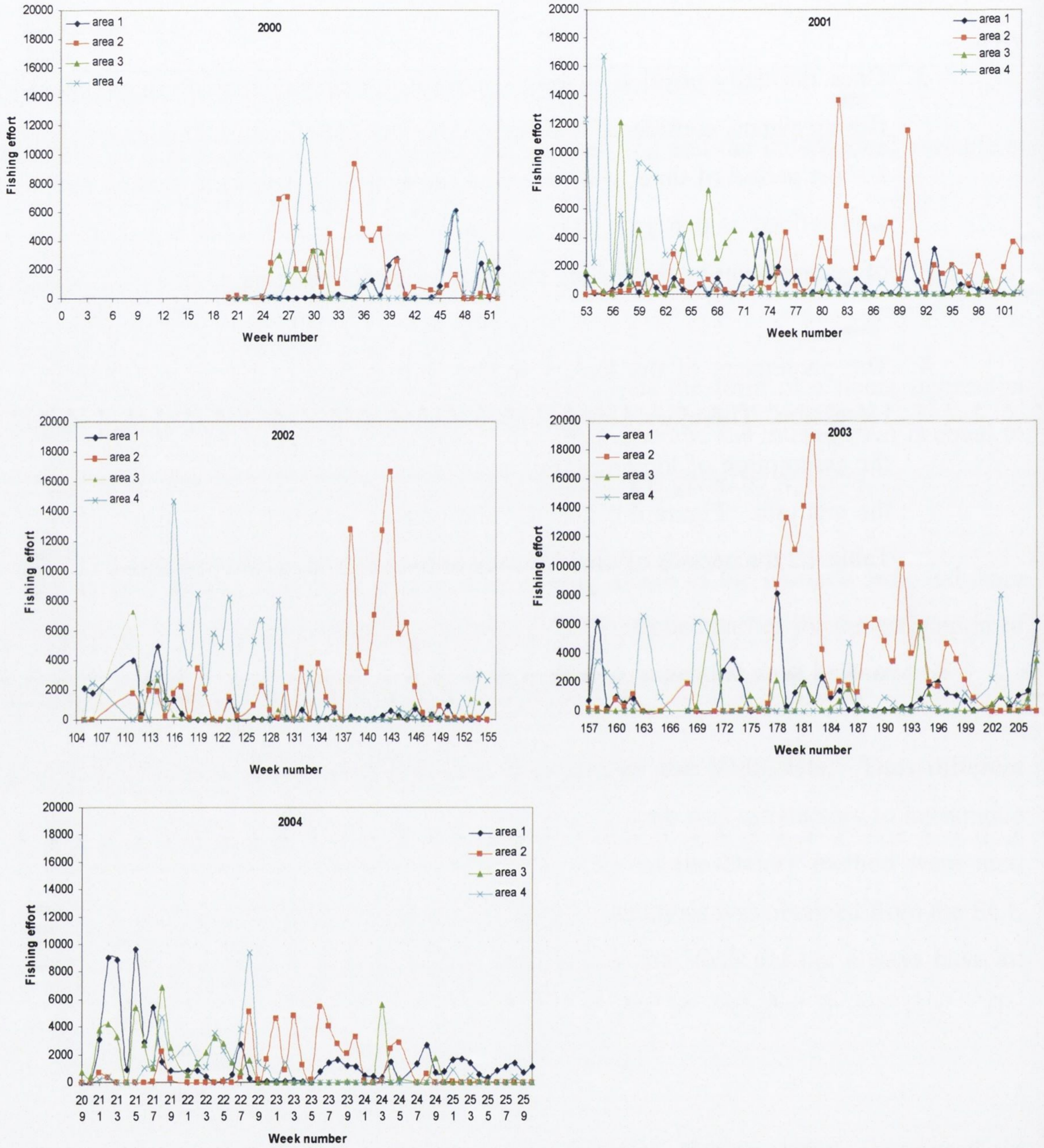
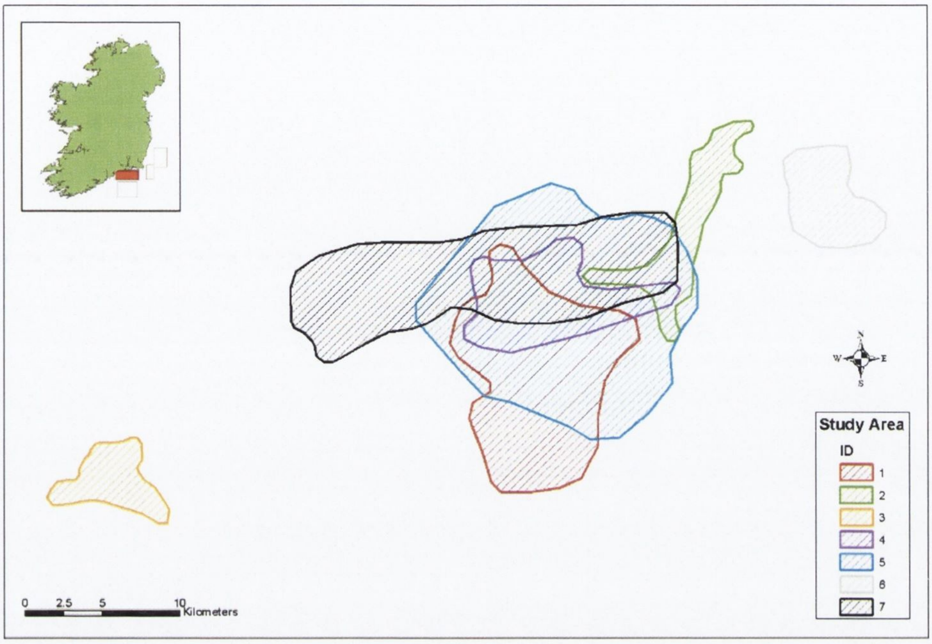


*Figure 4.5. Weekly fishing effort (dredge*hours) for the period of time June 2000 to December 2004. Fishing effort is calculated separately for each of the fishing areas.*



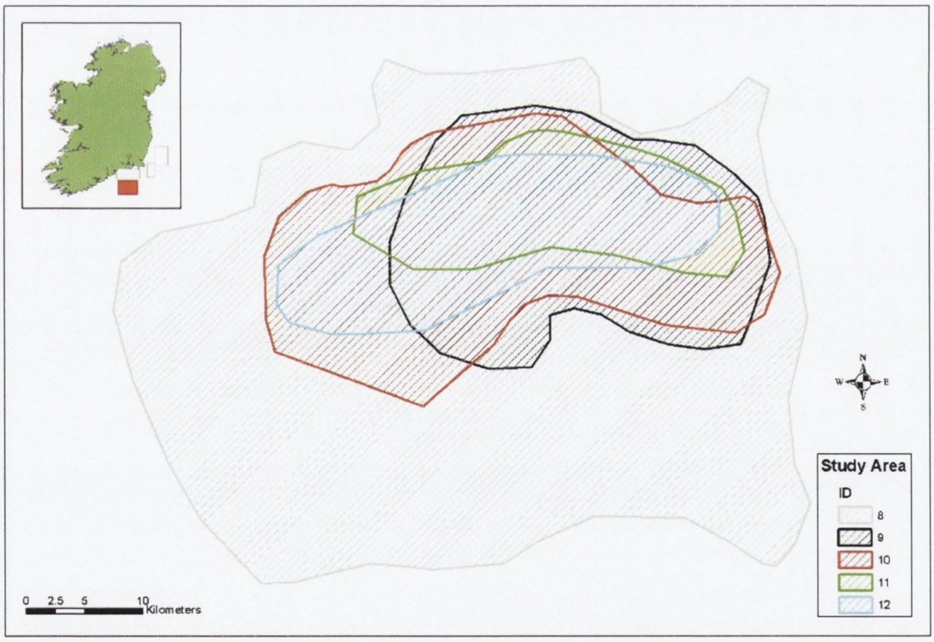


Figure 4.6. Study areas selected in management areas 1(above) and 2(below) for depletion analysis. The fishing effort expended in each study area and when it occurred is shown in table 4.2.

Figure 4.7. Study areas selected in management areas 3(above) and 4(below). The fishing effort expended and when it occurred in each study area is shown in table 4.2.

The depletion model was successfully used to estimate dredge efficiency in Chapter 2. However, under commercial fishing conditions although declines in CPUE can be observed it is more difficult to verify that these are due to real decline in abundance rather than changes in catchability, brought about for instance by weather conditions and dredge operational efficiency. If the observed declines in CPUE are due to real depletion then the rate of depletion (the coefficient q of Equation 4.6) should be related to intensity of fishing effort.

To compare the rate of depletion or decline in CPUE between different study areas the total fishing effort in an area was divided by the size of the area to develop an effort intensity index. Also the cumulative area covered by the fishing gear in each of the study areas was calculated. The expression used to calculate the total area dredged was:

$$\sum NHF_{ij} * 2.7 * \left(\frac{WD * ND_{ij}}{1852} \right) \tag{4.7}$$

where (NHF_{ij}), is the number of hours fished by the vessel (j) in the day (i), 2.7 knots/h is the assumed tow fishing speed, (WD) is the width of the dredge, which has a value of 0.83m for the entire fleet, (ND_{ij}) is the number of dredges used by a vessel (j) in the day (i), and 1852 is the number of metres in one nautical mile. Therefore, for each study area, the sum of the areas covered by each vessel each day gave the total area covered by the gear. Area estimations were given in square miles.

For each of the study areas selected Delury regression coefficients were estimated. Thus the rates of depletion, given by the catchability coefficients q for each area, could be examined. Negative slopes were regarded as significant at probability level of 0.1 and considered to show depletion or decline in catch rate. Initial population (N_1) and exploitation rates were estimated in study areas in which the null hypothesis (slope=0) was rejected. The initial population was estimated as described above (see 4.2.4.1).

To estimate exploitation rates requires that all catch data for all fishing events during the specific period in the specific area are known. Some catch data was missing. These missing values were estimated from the regression equation $LnCPUE = a - bE_t$. That is, once the intercept and the slope were estimated, the catch could be predicted for any value of cumulative fishing effort. Finally the exploitation rate could be easily estimated by dividing the total removal by the initial population.

*Table 4.2. Time periods, area size (square miles), fishing effort (dredge*hours) and a fishing effort intensity index, given by Effort/Area and %AC for each of the depletion data sets selected for analysis. %AC= percentage of the total area covered by the dredges. Week number = cumulative week from January 2000 to December 2004.*

Scallop Bed	Study Area ID	Week Number	Area Size	Fishing Effort	Effort/ Area	AC (sq miles)	%AC
Area 1	1	36-40	62	5,206	84	7	11
	2	45-47	19	7,363	393	9	50
	3	71-73	12	5,864	500	8	65
	4	172-174	30	8,386	279	10	35
	5	178-185	110	15,365	140	19	17
	6	205-207	16	4,784	294	6	34
	7	211-217	77	26,720	347	33	43
Area 2	8	25-40	1106	55,546	50	68	6
	9	138-145	303	62,762	207	73	24
	10	178-200	364	119,646	329	152	42
	11	228-233	157	15,005	95	19	12
	12	236-240	199	11,958	60	17	8
Area 3	13	57-59	98	16,613	170	21	22
	14	64-74	105	35,252	337	45	43
	15	111-115	99	10,778	108	15	15
	16	194-195	67	7,008	105	9	13
	17	211-228	207	42,613	206	53	26
Area 4	18	27-30	177	16,171	91	22	12
	19	50-59	205	40,133	196	50	24
	20	63-66	35	4,597	132	7	19
	21	116-126	187	45,547	244	54	29
	22	158-160	91	8,113	89	10	10
	23	163-165	14	3,391	241	5	38
	24	169-171	38	5,986	156	10	25
	25	199-205	91	7,341	80	11	12
	26	221-228	111	20,411	184	25	22

4.3 Results

4.3.1 Generalised Linear Modelling (GLM) of Catch Rate Data

4.3.1.1 Variability in Commercial Catch Rate Data

The factors determining variability in catch rates are presented separately for each data source analysed:

- ***EU-logbooks data 1995 to 2004:***

ANOVA of commercial catch rate data for Areas 1 and 2 showed that vessel, area and wind speed affected scallop catch rates off south Waterford (Table 4.3). These factors accounted for 20.4% of the variance in the data. Vessel and tide were important contributors to variability in catch rate in the south Irish Sea (Table 4.4) and accounted for 12.7% of the variability.

Table 4.3. ANOVA of catch rate data in the scallop ground off the Waterford estuary. Data source: EU-log books 1995 to 2004.

Factors	DF	SS	MS	F-Ratio	P
Year	9	169.67	18.85	34.37	< 0.0001
Vessel	19	331.42	17.44	31.8	< 0.0001
ICES Rectangle	3	20.05	6.68	12.18	< 0.0001
Wind Speed	1	7.28	7.28	13.27	0.0003
Wind Direction	1	0.00008	0.00008	0.0001	0.9906
Tidal Height	1	1.23	1.23	2.25	0.1339
Residuals	3599	1974.04	0.55		

Table 4.4. ANOVA of catch rate data in the south Irish Sea scallop ground. Data source: EU-log books 1995 to 2004.

Factors	DF	SS	MS	F-Ratio	P
Year	7	21.67	3.1	6.39	<0.0001
Vessel	12	30.16	2.51	5.19	<0.0001
ICES Rectangle	2	0.71	0.35	0.73	0.4817
Wind Speed	1	2.71	2.71	5.60	0.0182
Wind Direction	1	1.20	1.20	2.484	0.1155
Tidal Height	1	8.81	8.81	18.19	<0.0001
Residuals	737	356.95	0.48		

– ***EU-logbook data with Vessel Monitoring System data:***

ANOVA indicated that the vessel effect was the most important factor influencing scallop catch rates in each of the areas analysed (Tables 4.5-4.7). Environmental effects were not statistically significant in comparison with the vessel effect in this analysis. The area effect between areas 3 and 4 was not significant and so GLM analysis of these catch rate was carried out together. Factors accounted for 10%, 6% and 7% of the variance in the data in Areas 1, 2 and 3 and 4 respectively.

Table 4.5. ANOVA of catch rate data in Area 1.

Factors	DF	SS	MS	F	P
Year	4	7.08	1.77	5.43	0.0003
Vessel	10	10	1	3.07	0.001
Wind Direction	1	2.24	2.24	6.87	0.0092
Wind Speed	1	0.06	0.06	0.17	0.6769
Tidal Height	1	0.22	0.22	0.69	0.4081
Residuals	307	100.06	0.33		

Table 4.6. ANOVA of catch rate data in Area 2.

Factors	DF	SS	MS	F	P
Year	4	26.47	6.62	38.82	<0.0001
Vessel	10	61.66	6.17	36.17	<0.0001
Wind Direction	1	0.02	0.02	0.12	0.7336
Wind Speed	1	0.97	0.97	5.69	0.0175
Tidal Height	1	0.05	0.05	0.30	0.5808
Residuals	442	75.35			

Table 4.7. ANOVA of catch rate data for Areas 3 and 4.

Factors	DF	SS	MS	F	P
Year	4	9.05	2.26	4.15	0.0025
Vessel	11	14.47	1.32	2.42	0.0061
Wind Direction	1	0.007	0.007	0.01	0.9126
Wind Speed	1	0.13	0.13	0.24	0.6202
Tidal Height	1	0.30	0.30	0.55	0.4595
Residuals	1	0.008	0.008	0.01	0.9062

- ***Private diaries catch per unit effort data:***

ANOVA of private diaries showed, again, that the vessel effect had an effect on catch rates. Environmental effects on catch rates were also statistically significant with both the sea conditions and the tidal strength having an important effect on catch rates (Tables 4.8 and 4.9). The model accounted for 11% and 30% of the variance in the data in Areas 1 and 2, respectively.

Table 4.8. ANOVA of catch rate data for Area 1.

Factors	DF	SS	MS	F	P
Year	7	31.54	4.51	19.74	<0.0001
Vessel	3	12.01	4	17.54	<0.0001
Wind Speed	1	1.17	1.17	5.12	0.0238
Wind Direction	1	2.47	2.47	10.83	0.001
Tidal Height	1	0.85	0.85	3.71	0.0542
Residuals	1652				

Table 4.9. ANOVA of catch rate data for Area 2.

Factors		SS	MS	F	P
	DF				
Year	6	42.64	7.10	83.78	<0.0001
Vessel	4	5.00	1.25	14.74	<0.0001
Wind speed	1	2.66	2.66	31.39	<0.0001
Wind Direction	1	0.95	0.95	11.14	0.00089
Tidal Height	1	0.51	0.51	5.97	0.015
Residuals	590	50.04	0.08		

4.3.1.2 Annual Standardised Indices of Commercial Catch Rates

Annual indices of scallop abundance are presented for the different sources of catch per unit effort data below.

- ***EU-logbooks data 1995 to 2004 by ICES rectangle:***

Area 1 and 2

CPUE for Areas 1 and 2 was standardised for vessel, area and wind speed. The annual index increased 3 fold between 1995-1999. A 23% decline occurred from 1999 to 2000. Catches were stable between 2000 and 2004 (Figure 4.8).

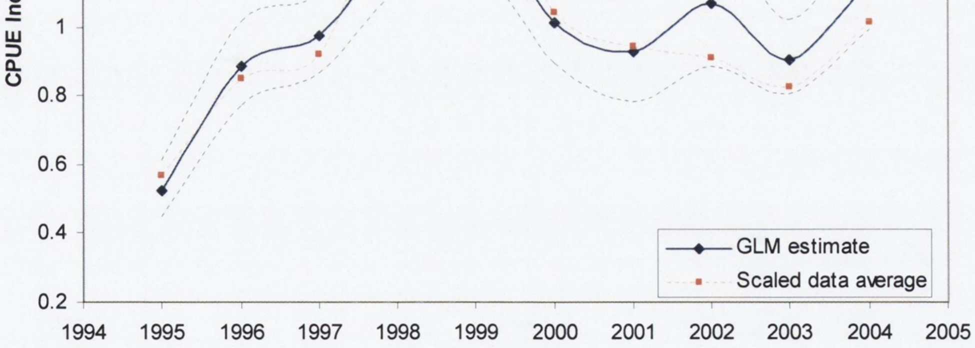


Figure 4.8. Trends in the standardised annual commercial CPUE index in Area 1 and 2. GLM estimates (95% C.I) are shown together with unadjusted data averages, scaled to the same mean and standard deviation.

Areas 3 and 4

Catch rate data in the south Irish Sea were standardised for vessel and tide effects. The index increased almost three fold between 1997 and 2000. A decline of 30% occurred between years 2000 and 2003 followed by an increase of 42% in 2004 (Figure 4.9). Catch rates were approximately similar, therefore, in 2000 and 2004.

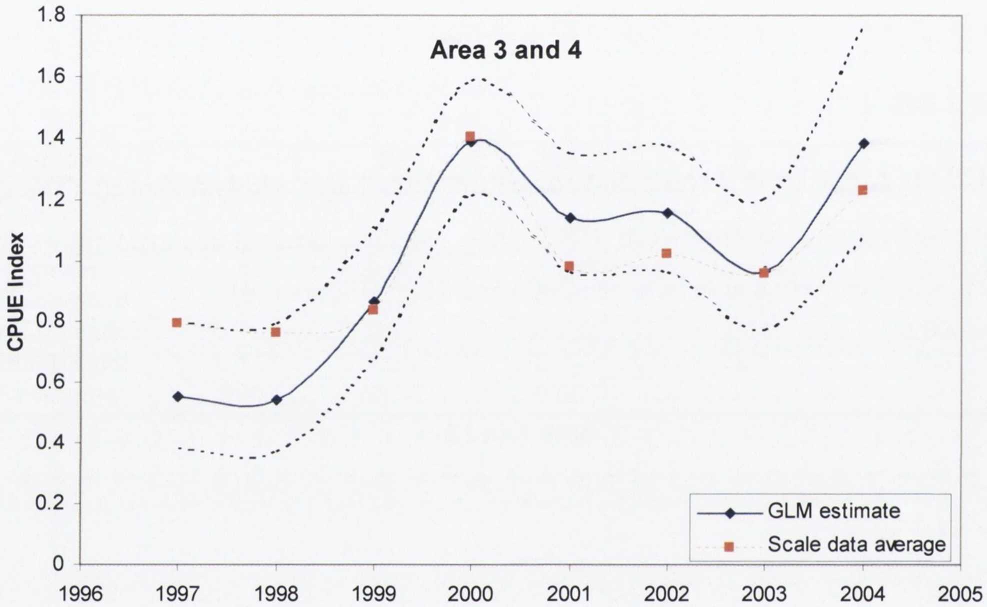


Figure 4.9. Trends in the standardised annual commercial CPUE index in Areas 3 and 4. GLM estimates (95% C.I) are shown together with unadjusted data averages, scaled to the same mean and standard deviation.

- ***EU-logbook data using the Vessel Monitoring System data:***

Area 1

CPUE in Area 1 was standardised for vessel and wind direction effect. The index increased by 19% between 2000 and 2004 (Figure 4.10).

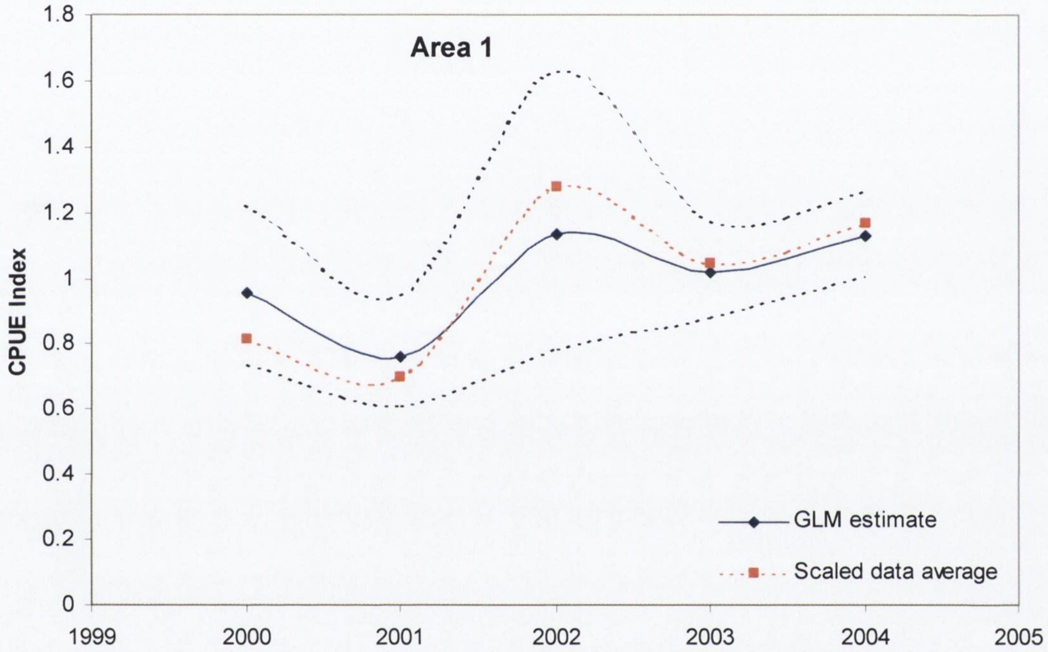


Figure 4.10. Trends in the standardised annual commercial CPUE index in Area 1. GLM estimates (95% C.I) are shown together with unadjusted data averages, scaled to the same mean and standard deviation. The annual scaled effort in dredge hours is also shown.

Area 2

CPUE data for Area 2 were standardised for vessel and wind speed effects. Fluctuations of 10% in the average index value occurred between 2000-2004. The confidence intervals of these estimates, however, were approximately 10-20% of the mean. The standardised index could therefore be regarded as stable during the period (Figure 4.11).

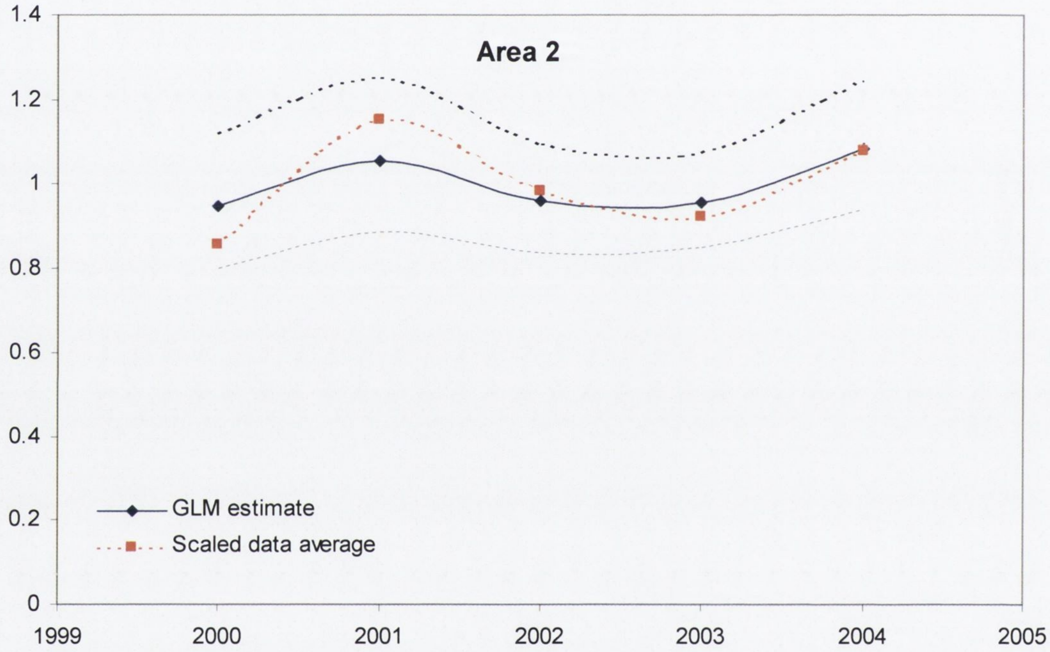


Figure 4.11. Trends in annual CPUE for Area 2. GLM estimates (95% C.I) are shown together with unadjusted data averages, scaled to the same mean and standard deviation.

Area 3 and 4

The vessel effect was the only factor included in the GLM model of Areas 3 and 4. Model estimates show annual changes in catch rates varying by about 20-30%. A decline occurred from 2000 to 2001. Catch rates were stable from 2001-2004 (Figure 4.12).

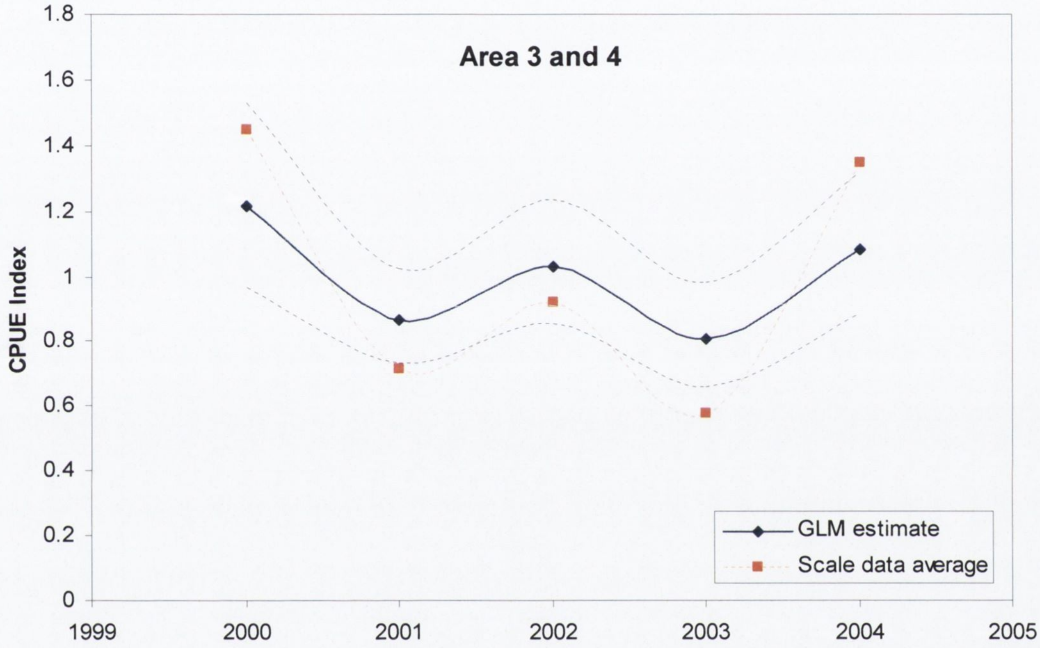


Figure 4.12. Trends in the annual standardised commercial CPUE index in Area 3 and 4. GLM estimates (95% C.I) are shown together with unadjusted data averages, scaled to the same mean and standard deviation

- ***Private Diaries*:**

Area 1

Vessel and wind were included in the model for the standardisation of catch rates in Area 1. Catch rates reached the highest value in 1995 and were followed by a decline of approximately 30% between 1995-1999. No data are available for 2000-2002. The estimates for 2003 and 2004 show that catch rates were similar to those in 1998-1999 but lower than the 1994-1996 period (Figure 4.13).

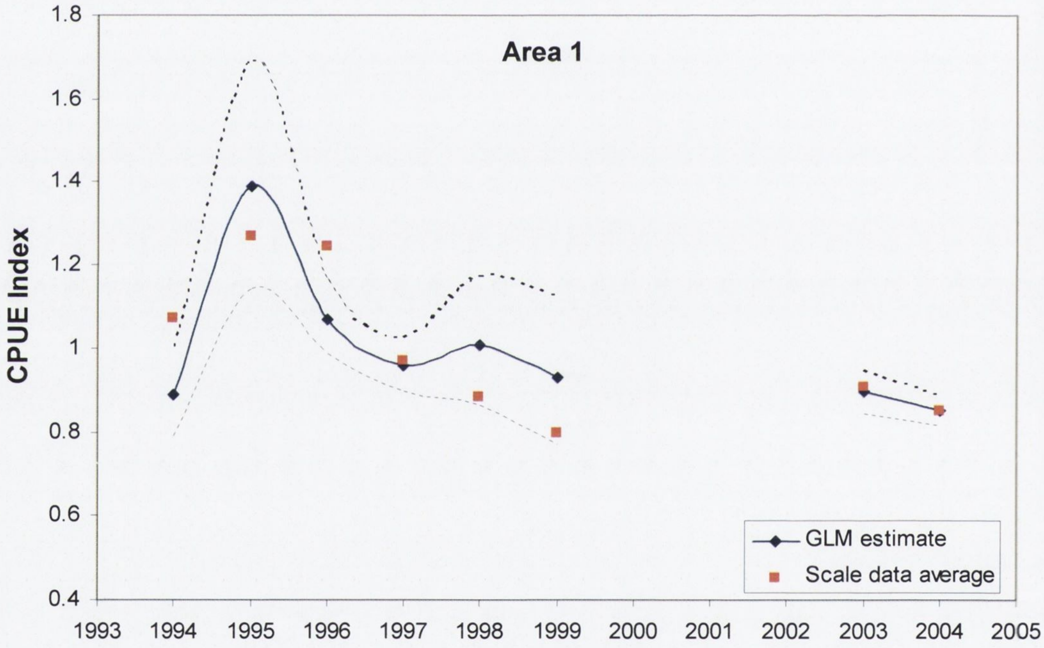


Figure 4.13. Trends in the annual standardised commercial CPUE index in Area 1. GLM estimates (95% C.I) are shown together with unadjusted data averages, scaled to the same mean and standard deviation.

Area 2

As in Area 1 vessel and wind effects accounted for a significant proportion of variability in catch rates and therefore were included in the GLM model. Peak catch rates occurred in 1994. This was followed by a decline in catches between 1994 and 1999 of approximately 40% and a decline of 35% between 1999 and 2003 (Figure 4.14).

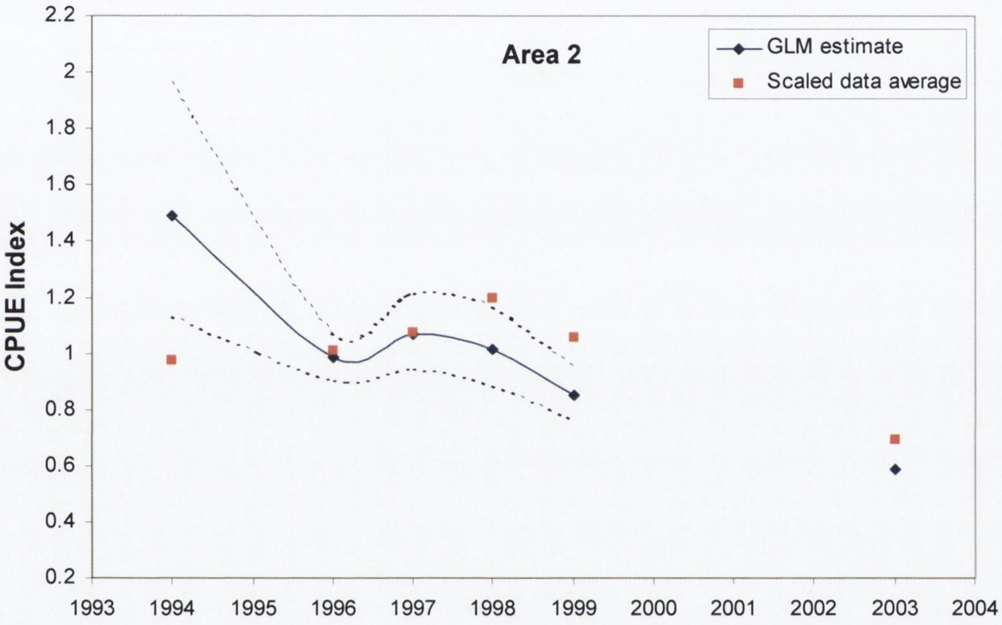


Figure 4.14. Trends in the annual standardised commercial CPUE index for Area 2. GLM estimates (95% C.I) are shown together with unadjusted data averages, scaled to the same mean and standard deviation.

4.3.1.3 Interpretation of Catch Rate Data

The following catch and effort data sets were presented:

- ECL data reported as kilograms of scallops per dredge per day for 1995-2004 and reported by ICES rectrangle
- ECL data re-expressed as kilograms of scallop per dredge per hour using VMS data for 2000-2004
- Private diary data 1995-2004 reported as number of scallops per dredge per hour.

These data covered a period of expansion of the fleet, which occurred mainly during the late 1990s. The first set of data is the least precise as the catch can only be expressed as kilograms per day and reported by ICES rectangle. Re-expressing the logbook catch data using the VMS, from which the fishing time per day can be calculated, essentially made it directly comparable with private diary data both of which could be aggregated to different spatial levels and be expressed as kilograms of catch per dredge per hour.

The vessel, environmental conditions and the fishing area all affected catch rates. However, the vessel was the most important factor in determining catch rates in all data sets. Although this could be due to the skipper or the characteristic of the vessel, most likely it is due to the spatial variability in the allocation of fishing effort between vessels. Figure 4.15 shows how the spatial distribution of fishing effort varied among vessels within each of the fishing areas. This can lead to variability in CPUE as the distribution of scallop abundance varies at small spatial scales (see chapter 5).

The weather conditions also had an important effect on catch rates. The nature of the scallop fishing operation (see Chapter 1), in which the dredges are towed along the seabed, suggests that the sea swell will have an effect on the dredges catchability. The sea swell can be affected either by the wind speed, together with the wind direction, and the tidal strength. In addition handling the scallop fishing gear can be dangerous in poor weather. As a result scallop fishing tends to occur in relatively good weather conditions and although to some extent the weather affected catch rate, the vessel effect was the most dominant.

The data showed the following trends:

- ECL data (no VMS) showed significant increases in CPUE from 1995-1999 followed by stability or small declines in some areas during the period 1999-2004
- ECL data re-expressed using VMS showed stable catch rates from 2000-2004
- Private diary information showed a decline in catch rate from 1995-1999 followed by a period of relative stability from 1999-2004 although there was some indication of decline in Area 1 in later years.
- All 3 data sets, therefore, show relatively stable catch rates during the period 1999-2004 and this pattern applied to all 4 areas. Prior to 1999 the pattern is inconsistent and depended on the data source. The conflicting pattern prior to 1999 between logbook data and diary data cannot be readily resolved or accounted for but factors, such as longer fishing days (hours per day), could account for the increasing catch rates in the logbook data as the fishing time per day is not accounted for.

The most plausible interpretation is from the skipper private diaries data, which showed that CPUE declined during the period 1995-1999 in parallel with the expansion in effort (see Chapter 1). This was followed by a period of relative stability, as the increased fishing capacity was re-distributed to the Irish Sea and English Channel.

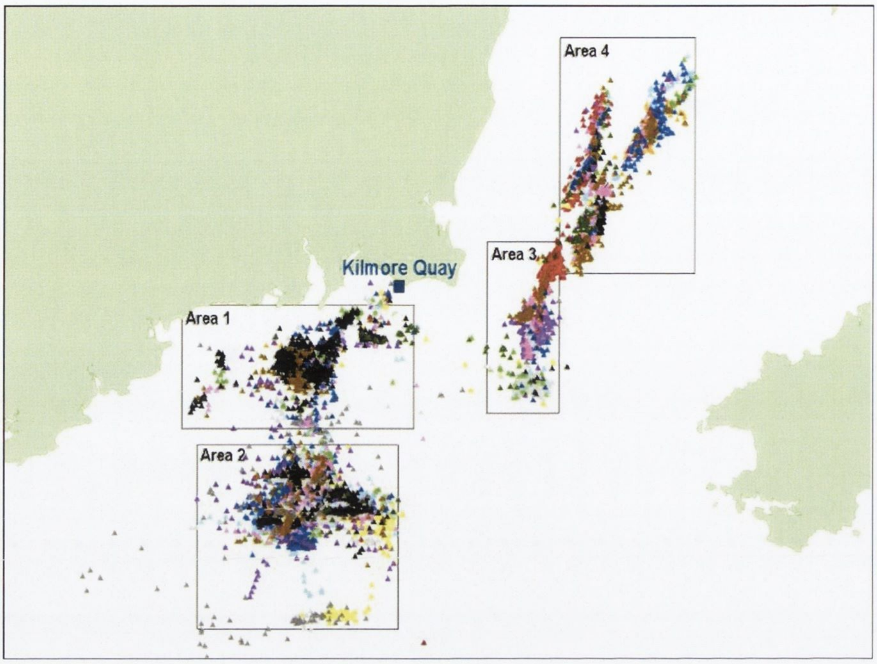


Figure 4.1 5. Distribution of fishing effort for each vessel in 2003 off the southeast coast of Ireland. Each colour represents a single vessel.

4.3.2 Delury Depletion Analysis

Of the 26 study areas selected for depletion analysis 22 showed decline of CPUE with increase in fishing effort (Table 4.10 and Figure 4.16). However only 10 had significant and negative depletion leading to rejection of the null hypothesis ($p<0.1$). Generally the variance around the mean was high with low R^2 values between 5-55% for the regressions with negative slope.

Total removal, initial population biomass and exploitation rate in the study areas in which the depletion process was observed are shown in Table 4.11. Exploitation rates varied between 2-7%.

The coefficient q, which describes the rate of depletion, was plotted against fishing intensity to explore trends in the relationship (Figure 4.17). Regression analysis showed there was an increase in the rate of depletion with an increase in cumulative fishing effort, however this was not statistically significant (*$P=0.34$*). The relationship between estimated exploitation rates (Table 4.11) and intensity of fishing effort was also explored, with a negative but statistically not significant (*P=0.2*) trend in the relationship (Figure 4.18). Fishing intensity, expressed as the proportion of the total area swept by the fishing gear varied between 6-65% (Figure 4.17 and Figure 4.18) indicating that the scallop population was exploited under relatively low fishing effort in some cases but relatively high in others.

Table 4.10. Regression coefficients of the Delury model.

Scallop Bed ID	Study Area ID	DF	F-ratio	q	P	R^2 (%)
Area 1	1	11	0.773	-1.00E-04	0.3979	6.6
	2	14	1.74	-6.74E-05	0.2081	11.1
	3	12	3.64	-7.53E-05	**0.0805**	16.9
	4	18	4.45	-1.00E-04	**0.0491**	15.4
	5	43	7.44	-5.87E-05	**0.0092**	12.8
	6	13	1.62	-1.00E-04	0.2252	4.2
	7	28	11.4	-2.94E-05	**0.0022**	26.3
Area 2	8	93	4.68	-9.89E-06	0.0331	4.8
	9	54	4.26	-5.88E-06	**0.0438**	7.3
	10	220	13.9	-3.09E-06	**0.0002**	5.9
	11	17	4.23	2.88E-05	0.0553	19.9
	12	14	2.28	-3.94E-05	0.1532	14
Area 3	13	29	0.46	-1.52E-05	0.5031	1.6
	14	80	1.98	-6.44E-06	0.1638	2.4
	15	16	1.39	-2.78E-05	0.2552	8
	16	11	1.38	-8.71E-05	0.2649	11.1
	17	60	0.0334	0.00	0.8556	0.1
Area 4	18	48	4.01	-4.19E-05	**0.0508**	7.7
	19	56	1.67	6.40E-06	0.2014	2.9
	20	16	0.466	-3.90E-05	0.5047	2.8
	21	54	2.99	-6.76E-06	**0.0893**	5.3
	22	8	1.01	-1.77E-05	0.3485	12.6
	23	6	7.07	-3.37E-04	**0.0376**	54.1
	24	16	2.6	-7.34E-05	0.1200	14
	25	8	1.28E-04	0.00	0.9912	0
	26	19	1.1	-2.62E-05	0.308	5.5

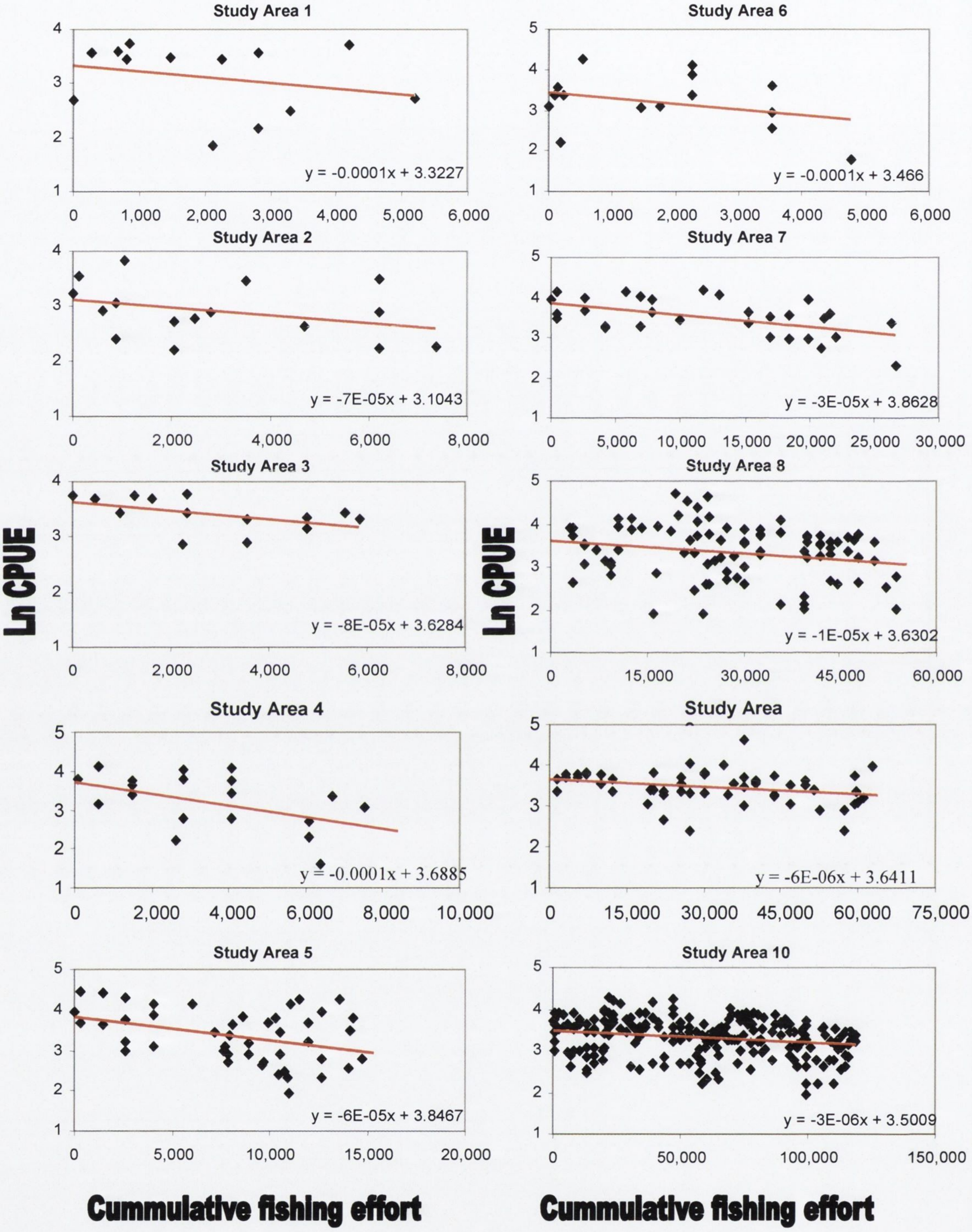
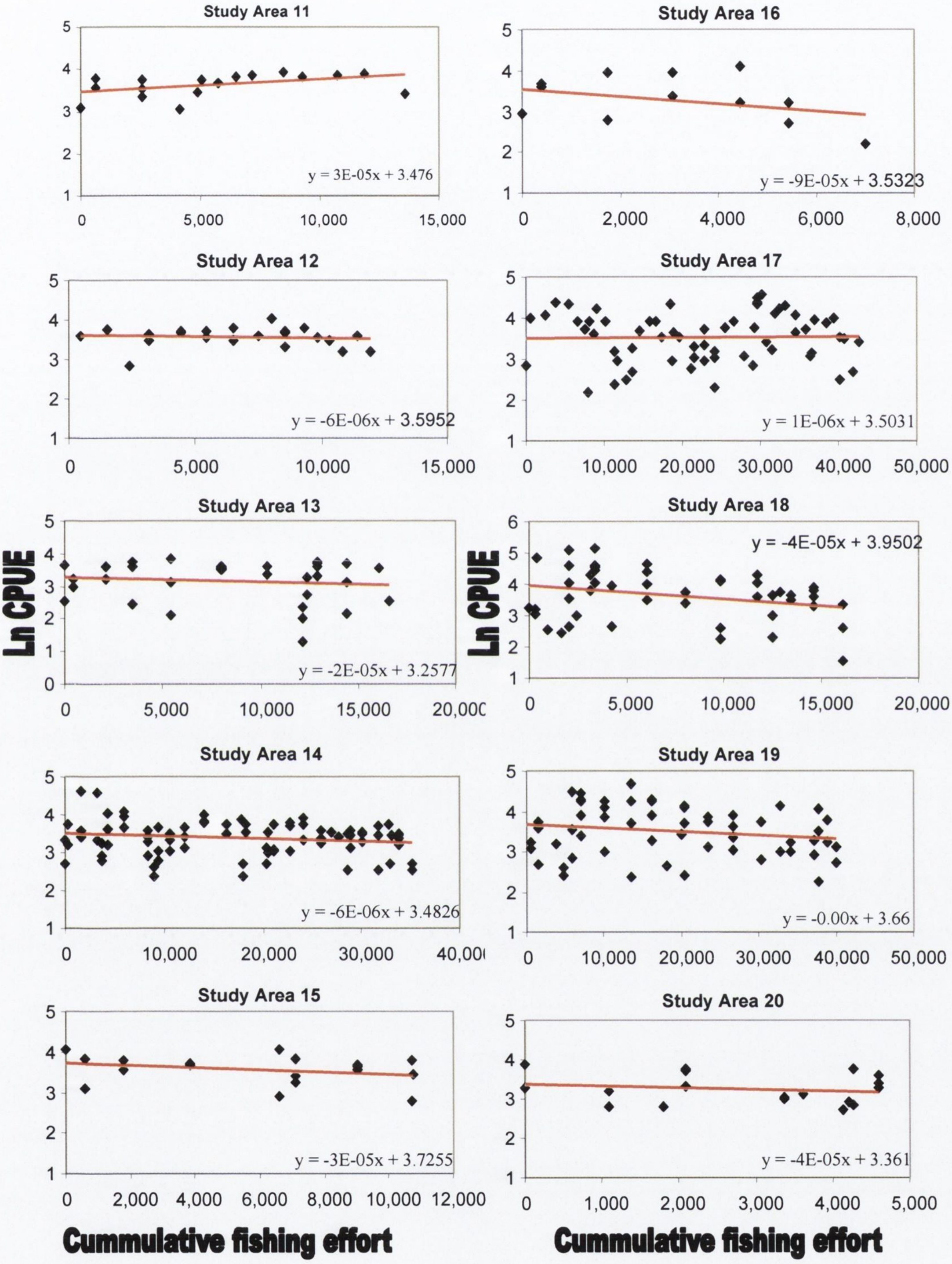
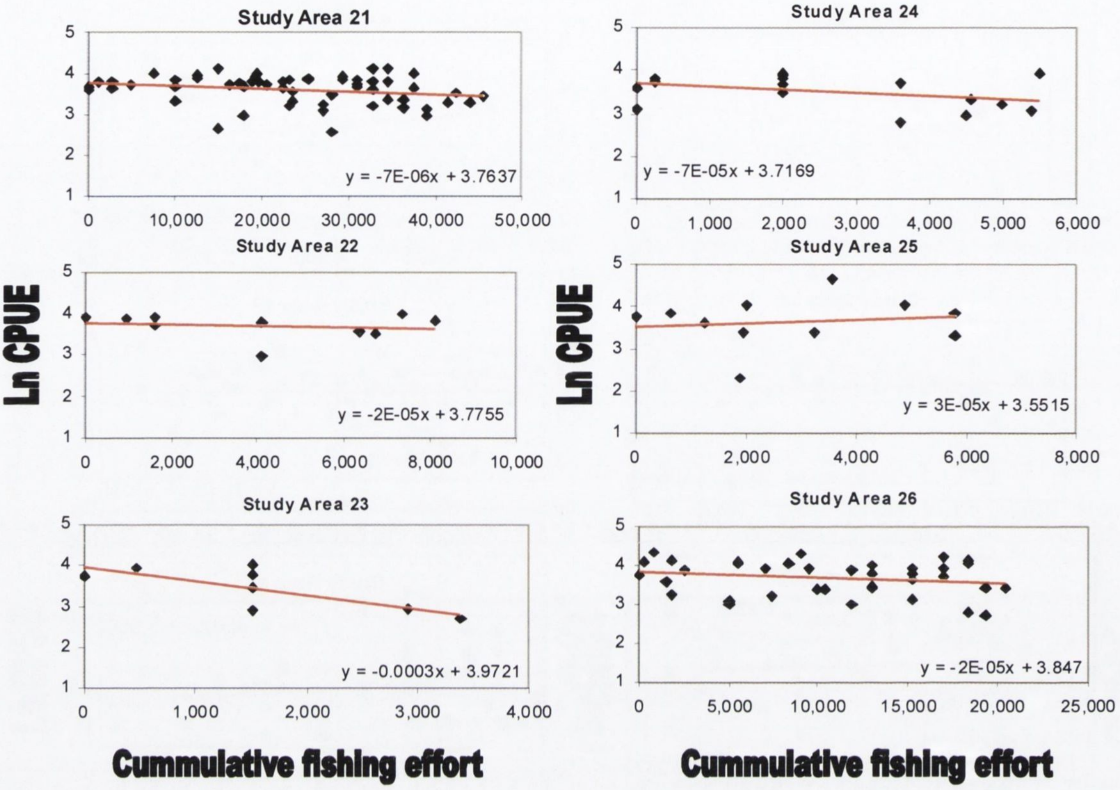


Figure 4.16. Relationship between CPUE and cumulative effort for study areas 1-10.



Continue Figure 4. 16. Relationship between CPUE and cumulative effort for study areas 11-20.



Continue Figure 4.16. Relationship between CPUE and cumulative effort for study areas 21-26.

Table 4.11. Delury population estimators. Total scallop removal and initial biomass is given in kilograms. Exploitation rates are expressed as percentages. Estimates are given for study areas where significant decline of CPUE was observed.

Study Area ID	Total removal	Initial Biomass (N_1)	Exploitation rate (%)
3	12,105	500,127	2.42
4	20,238	399,848	5.06
5	50,463	798,358	6.32
7	54,263	1,618,020	3.35
9	129,904	6,355,817	2.04
10	240,122	10,726,732	2.24
18	84,180	1,238,314	6.80
21	102,219	6,367,692	1.61
23	10,196	157,323	6.48

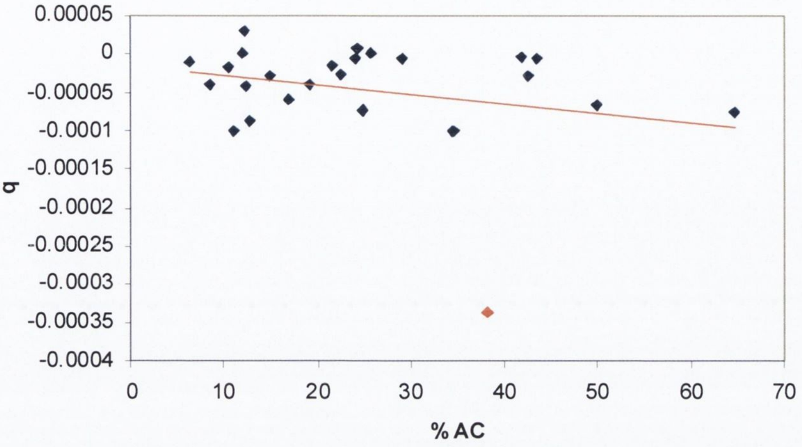


Figure 4.17. Linear regression of rate of depletion (q) on the level of fishing effort (expressed as the ratio of area swept by the fishing gear from the total fishable area). R^2 = 6.6%; F-ratio = 0.953; P = 0.34. The point in red was not included in the regression.

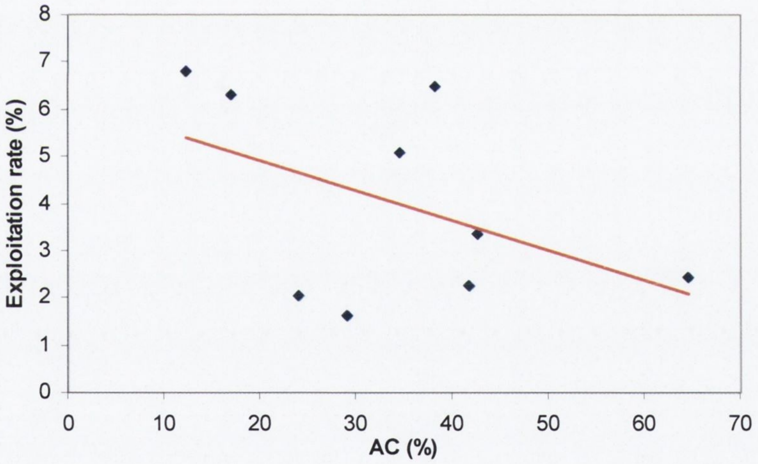


Figure 4.18. Plot showing the relationship between exploitation rates and fishing effort. Fishing effort is expressed as the ratio of area swept by the fishing gear from the total fishable area. R^2 = 11%; F-ratio = 1.99; P = 0.2.

4.4 DISCUSSION

Caddy (1975) reported that the use of catch and effort data for the assessment of temporal trends in scallop population and other sedentary species under the “dynamic pool” assumption were invalid. Data aggregated over large spatial scales can mask the response of scallop population to fishing due mainly to serial depletion. Therefore the interpretation of catch and effort data must be done cautiously if the CPUE index is to be used as an index of abundance or used to calculate exploitation rates (Jamieson and Campbell, 1998).

Catch and effort data was analysed taking into account the spatial distribution of fishing effort. The analysis was undertaken using novel approaches that allowed comparison of data from different sources and using different analytical methods. Two analyses were undertaken: (*i*) Annual indices of abundance were estimated in a disaggregated form and were standardised using general linear modelling to account for factors, other than abundance, that can have an effect on catch. (*ii*) The within year trends in scallop abundance were modelled using a Delury (1947) depletion model. A number of local fishing areas were selected for analysis and the applicability of this method to model the decline in commercial CPUE was explored. Trends in CPUE from both methods of analyses indicated that from 2000-2004 exploitation rates were relatively low.

In the standardisation of CPUE the reliability of the estimates depends on how well the variability in CPUE is represented by the factors included in the analysis (Maunder and Punt, 2004). In the analysis presented factors including vessel, weather conditions, and area effects, accounted for 6-30% of the variance in CPUE, and the vessel effect was the most significant factor. It was suggested that the variability in the allocation of fishing effort among different vessels at fine spatial scales was the main cause for this. Scallop abundance varies at small spatial scales (see Chapter 5) and therefore CPUE is expected to be different when vessels target different local populations. However there are other factors that can have an effect on the vessel performance. For instance the skill of the skipper in setting up the gear or the characteristic of the vessel could have an important influence on the catch (Dare *et al.*, 1993). The compression of the springs of the scallop dredges is set up depending on the ground fished (see Chapter 1) and the correct compression is need to optimise dredge efficiency. In addition the length and type of teeth, of the age of the dredge also have an effect on the performance of the gear. If these factors were included in the analysis and the effect that they have on the variance of CPUE were accounted for then the GLM model may account for a higher percentage of variability in the data.

If the indices of abundance are considered to be reliable the similarity in the observed and the GLM estimates means that changes in CPUE were mainly due to changes in abundance. Unreliability or uncertainties of using CPUE as an index of abundance, in sedentary species, are mostly related to the spatial structure of the stock (Caddy, 1975; Orensanz *et al.* 1991; Jamieson and Campbell, 1998; Orensanz *et al.*, 2006). Abundance indices estimated for the scallop stock off the southeast were undertaken for each scallop bed reducing thus uncertainty in the estimates. VMS data allowed spatial pattern of fishing effort to be identified. The boundaries of four main scallop beds were defined and an assessment of annual changes in scallop abundance indicators was carried out in this disaggregated form. This suggests that CPUE data analysed in this form provided a reasonable index of scallop abundance.

In Europe, the VMS is mainly used for compliance and enforcement purposes but the possibilities it has for fisheries assessment purposes need to be recognised (Laurec, 1999). Despite this, the use of the VMS in the analysis of catch and effort data has not been incorporated formally in European scallop assessment or for assessment of other sedentary stocks (www.ices.dk). The VMS data also allowed changes in abundance indices on fine spatial and temporal scales to be investigated. The application of the Delury depletion method was used to investigate if depletion of local populations was hidden in annual indices of abundance. Results indicated a general stability in CPUE and consistent with the relatively low exploitation rates which ranged between 2-7%.

The low exploitation rates were estimated using the DeLury depletion model. The main assumption that may have been violated during these analysis was that of randomness in distribution of fishing or that each scallop in the area had equal probability of capture. Because the VMS is recorded only every two hours the ships position is not known at all times. Clearly, for species such as scallop, which are effectively sedentary in comparison with the fishing process, lack of precision in estimates of the ships position will lead to violation of this assumption. Accurate recording of the exact area of ground over which to apply the depletion assessment is therefore important. Local patchiness in abundance within the area being assessed, within which effectively there may be very fine scale sequential depletion taking place would lead to under estimation in depletion rates. In order to be certain that the small-scale variability in fishing effort distribution and scallop abundance is detected by the VMS data the frequency with which the ships position is logged would need to be reduced to minutes. Catch data would then need to be associated with the VMS track. A direct way of achieving this is to use an electronic logbook system that automatically logs the ships position at user defined frequencies and electronic logging and transmission of the associated catch. This system has been introduced for the Irish scallop fishery of the south east of Ireland and is currently in use (project number 01SMT102, Marine Informatics International Ltd. and BIM). The provision of data at individual tow level will allow interpretation of data at fine spatial scales and increase the option for stock assessment. The use of spatial referenced catch and effort data will most likely reduce the uncertainty in the results of the depletion analysis.

The use of VMS data to model the depletion process has been proven successful in other scallop fisheries. In the Western Australia scallop (*Amusium balloti*) fishery the VMS data is used in assessment to model the depletion of commercial catch rates and exploitation rates are estimated (Kangas, 2007). Gedamke *et al.* (2004) used VMS data to estimate the efficiency of the scallop dredge used in the scallop (*Placopecten magellanicus*) in the USA George Bank. Assuming that the conditions of the model are met, the rate of depletion depends on fishing effort intensity and dredge efficiency. Gedamke *et al.* (2005) estimated that 70% of the fishable area was effectively dredged and dredge efficiency was estimated between 40-50%. Similarly the gear efficiency used in the Western Australia scallop fishery is approximately 50% and the fishery is subjected to 60% exploitation rates. *Amusium balloti* is a short living scallop species and therefore 60% exploitation rates are considered sustainable. Off the south east coast of Ireland the effective area fished was calculated between 10-60% and dredge efficiency was estimated in Chapter 2 between 8-17%. Therefore the reason for the lack of significant depletion in most of the study areas was most likely due to low exploitation rates rather than to violation of the assumption of randomness in fishing effort distribution.

Assuming that the methods and results are valid it can be said that annual scallop abundance indices were stable and exploitation rates were low and probably sustainable in all areas and in years 2000-2004. For the period of 1995-1999, assuming reliability in the skipper private's diaries, there was a decline in scallop abundance in areas 1 and 2. Causes of this decline could have been due to high fishing effort, recruitment limitation, or episodes of elevated natural mortality. The increase in fishing effort experienced in the mid-late 1990s with an increase in the number of dredges from 103 to 498 (see Chapter 1) might be a reason for the decline in observed catch rate. However poor recruitment could also have occurred. Recruitment in commercial scallop fisheries is variable (Smith and Rago, 2004) with "good" and "bad" years and is influenced to a large extent by the physical environment, which determines the larval survival and settlement. The most important predators of scallop are starfishes and crabs (Brand, 1991; Orensanz *et al.*, 1991). An increase in mortality by predators has been associated with intensive dredging and related to the opportunistic behaviour of predators (Lart *et al.*, 2003). Scallops are probably more vulnerable to predators when they have been stressed, weakened or the dredge has disturbed their habitat. The higher fishing effort experienced in the 1990s might have contributed to an increase of natural mortality due to predators.

Appendix 4.1. Catch per unit effort records by year and vessel ID for EU-logbook data of Area/Scallop Bed 1 and 2. Records are given in kilograms per dredge per day.

Year/Vessel ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1995		68								53				48			19			
1996		88	21							70				60		14	83		24	
1997		65	36						72	35				40		98	60		80	
1998		12	23	14					75	40				40	88	105			34	
1999		2	40	80	15	109	50		60	66	44	62	21	13	65	33	68		16	4
2000	26	34	9	3	9	37	57	14	3	70	30	61	58	11	59	45	42	17	37	1
2001						6	37					31			11	28		14		10
2002		2				25	6					27			11	14		6		2
2003		5			39	54	28	60		20		38	8		23	69				
2004	3				8		5	38		1		49			22	98				

Cont. Appendix 4.1. Catch per unit effort records by year and vessel ID for EU-logbook data of Area/Scallop Bed 3 and 4. Records are given in kilograms per dredge per day.

Year/Vessel ID	1	2	3	4	5	6	7	8	9	10	11	12	13
1997		4	3	8	8								
1998				13	8								
1999			15	6	11	18	5	3					
2000		23	20		22	15	79	20	28	3	5	11	
2001						4	35	3	26	8	24	35	
2002		3				41	18	15	27	12	9	14	
2003	14	12	8			5	8	5	13	10			10
2004			7			8	8	17					10

Appendix 4.2. Catch per unit effort records by year and vessel ID for EU-logbook data using the vessel monitoring data in area 1. Records are given in kilograms per dredge per hour.

Year/Vessel ID	1	2	3	4	5	6	7	8	9	10	11
2000	2			1	2	8	1	8	8	5	8
2001					4			8		23	
2002				4	4			5		1	
2003		5	3	17		14	5	10	4	49	
2004			8			16	2	12		88	

Cont. Appendix 4.2. Catch per unit effort records by year and vessel ID for EU-logbook data using the vessel monitoring data in area 2. Records are given in kilograms per dredge per hour.

Year/Vessel ID	1	2	3	4	5	6	7	8	9	10	11
2000	41	14	2	7	10	8	13	15	4		9
2001				6	7			3	14	4	11
2002		2		16				21	10	12	7
2003			45	29	26	51	12	25	10	15	
2004					5	18		16	17	4	

Cont. Appendix 4.2. Catch per unit effort records by year and vessel ID for EU-logbook data using the vessel monitoring data in area 3 and 4. Records are given in kilograms per dredge per hour.

Year/Vessel ID	1	2	3	4	5	6	7	8	9	10	11	12
2000		10		23		8	13		3	1	11	5
2001				78			58		8	4	7	21
2002		3	38	25			32		13	15	4	12
2003	14	14	16	8	11	12	21	7	11	7		
2004	31				21	8	34	7	8	20		

Appendix 4.3. Catch per unit effort records by year and vessel ID for private diaries in area 1. Records are given in number of scallops per dredge per hour.

Year/Vessel ID	1	2	3	4
1994	128			
1995		24		
1996	104	104		
1997	89	228		
1998		33	60	
1999			23	18
2003		261		16
2004		510		68

Cont. Appendix 4.3. Catch per unit effort records by year and vessel ID for private diaries in area 2. Records are given in number of scallops per dredge per hour.

Year/Vessel ID	1	2	3	4	5
1994	26				
1996	6			55	
1997				21	
1998			73		
1999		82	134		
2003		66		93	12
2004		16		20	

Chapter 5: Distribution and Abundance of Scallop in Relation to Sediment Composition

5.1 Introduction

Research surveys provide a directed sampling method for the assessment of abundance or relative abundance of scallop and their spatial distribution. While abundance can also be estimated through the use of other assessment methods (e.g. Depletion Models, see chapter 4) research surveys give information about the spatial distribution of the population, which is essential to understanding of the population dynamics of sessile organisms (Orensanz et al., 1991; Orensanz et al., 2006). This is achieved by sampling over the area of interest in a relatively short period of time (days, weeks), assuming that during the period of time the survey is carried out there is no growth or mortality, and hence population estimates are directly comparable in the area surveyed. A time series of research surveys can provide standardised indices or absolutes estimates of abundance and its spatial distribution.

Research surveys can also be used to collect biological information (growth, size and weight data) for the estimation of biological parameters (growth rates, mortality rates) and the subsequent estimation of biological reference points. For sessile species these parameters may be spatially variable and in commercial species where the fishery also has a particular spatial distribution spatial analysis is particularly important (Caddy, 1975; Smith and Rago, 2004). Estimation of growth and mortality population parameters are presented and discussed in chapter 2 and chapter 6, respectively.

Most scallop species of commercial interest are distributed over large geographic areas (ten to a hundred of kilometres) in depth ranges of 10-200 m (Brand, 1991). Due to this, sampling methods are restricted to the use of some form of fishing gear towed by a vessel. The type of survey gear used is usually similar to that used in commercial fisheries. However, gear design can be modified in order to select particular scallop sizes and in particular juvenile scallops that can be used to estimate recruitment (Azarovitz, 1981; Clark, 1981; Vigneau, 2001; Smith and Lundy, 2002).

In the estimation of the spatial distribution of abundance the most common type of approach is a random allocation of sampling stations or the randomisation based inference method (Orensanz *et al.*, 1991 and 2006) in which the population is assumed to be composed of a finite number of sampling units and estimation methods are determined by the survey design. Hence, inference from data collected is used to estimate means, totals and their respective standard errors. Random allocation of sampling stations is usually stratified on variables that are correlated to density to account for the variance of the mean estimator. Variables used for the stratification of sampling schemes vary depending on the information available. In Scotland, for example, the location of sampling is based on the skipper's knowledge of the distribution of abundance of *Pecten maximus* (Howell *et al.*, 2003). The saucer scallop (*Amusium japonicum*) off the coast of Queensland in Australia was surveyed in 2000 (Dichmont et al., 2000) using a stratified random design in which sampling intensity was stratified according to information on commercial catch per unit effort data (CPUE). A number of strata were defined, according to the spatial resolution in which CPUE data was given and sampling intensity within the strata was based upon a weighting process, using CPUE multiplied by the stratum area. Off the west coast of Canada stratification of sampling stations allocation is based on depth ranges for the assessment of the *Chlamys rubida* and *Chlamys hastata* fishery (Lauzier et al., 2000). In the George Bank scallop ground, off the east coast of North America, USA, scallop distribution (*Placopecten magellanicus*) is assessed by basing the sampling scheme in different depth strata and allocating numbers of sampling stations in proportion to the size of the stratum (Serchuk and Wigley, 1987). The same George's Bank scallop ground is assessed by Canada, but in contrast, strata are defined using commercial CPUE, differentiated into areas of low, medium and high CPUE and concentrating sampling in areas of high abundance (Robert and Jamieson, 1986). The precision of density estimates using depth and CPUE as stratifying factors by the USA and Canada were compared (Serchuk and Wigley, 1987) and reported to be similar.

The fundamental reason for stratifying the allocation of sampling stations is to increase the precision of the mean estimator. However, this is not always guaranteed. Smith and Robert (1998) reported that the stratification of sampling schemes based on CPUE did not provide gains in precision over that obtained from simple random sampling for the same survey, reporting that high CPUE areas did not have a higher associated variance. In the same study they showed that with the incorporation of simplified maps of sediment structure as an additional variable within each of the CPUE strata, an increase in precision could be obtained.

Scallops are distributed on gravel and coarse-to-fine sands (Brand, 1991; Dare *et al.*, 1994; Stokesburry and Himmelman, 1994; Zaixo, 1996). This restricted distribution is probably due to mortality, particularity of early settlers or juvenile scallop, on fine sediments where the gills can be clogged by silt and reduced absorption efficiency occurs in adults. High concentration of inorganic material and low concentration of dissolved oxygen close to the seabed also occurs in such areas. The turbidity property of muddy seabeds is related to low survival of juvenile scallops due to the inhibitory effect of silt on the ciliary activity of the gills (Bricelj and Shumway, 1991) and the fact that they cannot respire anaerobically (Orensanz *et al.*, 1991). Suspended sediment in the water column near the seabed also has an effect on the growth of adult scallops as the feeding efficiency decreases due to siltation (Bricelj and Shumway, 1991). Although *Pecten maximus,* like other scallops species, is able to tolerate some silt or mud in the substrate (Mason, 1983), high abundance is normally found in areas with little mud (Brand, 1991).

Scallop species are characterised as sessile and although they have swimming capacity (with some species able to travel large distances), *Pecten maximus* travels only very short distances at any one time and in the scale of tens of metres (Howell and Fraser, 1984). Sedentary behaviour, selective mortality of settlers, reduced growth and possible survival of adults on fine sediments suggests that sediment type is important in determining distribution and abundance and that sediment classes should be used to stratify surveys to increase precision in abundance estimates.

The last decade has seen the development of different techniques for mapping the seafloor and its characteristics. Among those techniques multibeam echosounder (MBES) sonar systems have become a common choice (Le Gonidec et al., 2003; Sutton & O'Keeffe, 2006). The acoustic information of the seafloor that this system provides in combination with some form of ground truthing enables the generation of sediment maps which have an extensive application in examining the distribution of scallop species.

The suggestion of Smith and Robert (1998) of introducing sediment type in the design of surveys were investigated by Kostylev et al. (2002) using multibeam echo-sounder (MBES) sonar systems. They correlated the abundance of Placopecten magellanicus with the distribution of sediments (as predicted by acoustic backscatter strength), on the Browns Bank east of Canada and showed that a strong link between bottom type and scallop abundance existed and should be used in developing survey designs for the estimation of stock abundance. In Nova Scotia, Canada, multibeam acoustic data has been incorporated in the design of scallop research surveys since 2005 and has improved the precision of the abundance estimates from previous surveys which did not consider the sediment structure of the seafloor (Smith, 2006).

In this chapter annual research surveys, carried out between 2001 and 2005 in combination with MBES sonar surveys are presented. The relationship between survey catch rates and acoustic backscatter strength, which is a proxy for sediment structure, is investigated.

5.2 Source of Data Methods

Annual research surveys were carried out on scallop grounds off the south east coast of Ireland during the years 2001 to 2005. During this time the investigation was approached in three different stages that are summarized as follows:

1. In 2001, a systematic sampling scheme was carried out to describe the distribution of scallops in the area.
2. In the years 2002-2004 surveys were carried out in conjunction with multibeam data to investigate the distribution and abundance of scallop in relation to substrate type using multibeam acoustic data.
3. In 2005, multibeam data was used to design a stratified random survey to estimate total abundance and its distribution.

Although three different commercial vessels were used in the investigation (Table 5.1) the sampling gear used was the same for all years and, therefore, catchability among the vessels was assumed to be the same. Sampling gear consisted of twelve modified scallops dredges (6 on port and 6 on starboard) with 65 mm belly ring diameter and a tooth spacing of 44 mm, which captured scallops prior to recruitment to the fishery (Figure 5.1). Sampling consisted of towing in a straight line for 20-30 min at a vessel speed of 2.5-3 knots. Navigation was by Differential Global Positioning System and for each sampling station the Latitude and Longitude was recorded at the start and at the end of the tow. Geographical positions were display in an ArcGIS® environment and the length of each sampling station was calculated using the Arcmap® package. Survey catches were then standardised to 1000 m transect length, assuming a linear relationship between catch and tow length.

At each sampling station the scallop shell height, to the nearest mm, was recorded for every scallop and commercial and undersized scallops in the catch were counted. Minimum legal landing size of scallop in the area of the study is 100 mm shell length. Scallops greater than 100 mm are defined as commercial sized or recruits and scallop smaller than 100 mm are defined as undersized or pre-recruits. However, shell height is the measurement of biological interest in order to relate size to age because this is the main axis of shell growth (Figure 5.2). Therefore, data on shell height and shell length were collected and the relationship between both variables was constructed to determine what shell height corresponded to the minimum legal landing size. A linear relationship was obtained between the variables with a predicted value of 89mm shell height for 100mm shell length (Figure 5.3). Hence density estimates were calculated for those scallops greater than or equal to 89 mm in shell height (commercial sized) and for those under 89mm in shell height (undersized). In addition to shell measurements a sample of scallops was kept for post survey analysis of total size/weight, muscle wet weight, and gonad wet weight and growth increments. This information was used for the estimation of biological parameters of the population. Estimation of growth and mortality are presented and discussed in Chapters 3 and 6, respectively.

Table 5.1. Length and engine power of vessel used during research surveys in years 2001 to 2005.

Vessel Name	Length (m)	Engine Power (H.P)	Year of survey
Leon	29.8	800	2001, 2002, 2003
Prina Cornelia	24	750	2004
Vrijheid	19.5	450	2005

Figure 5.1 Scallop dredge used during the scallop survey. Above, view of six dredges on tow bar. Bellow, close view of dredge frame.

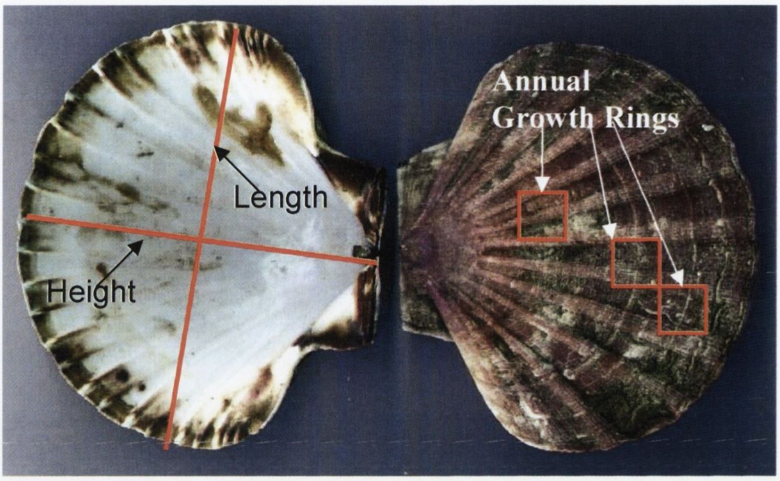


Figure 5.2. Pecten maximus right and left shell. Shell length, height and annual growth rings are shown.

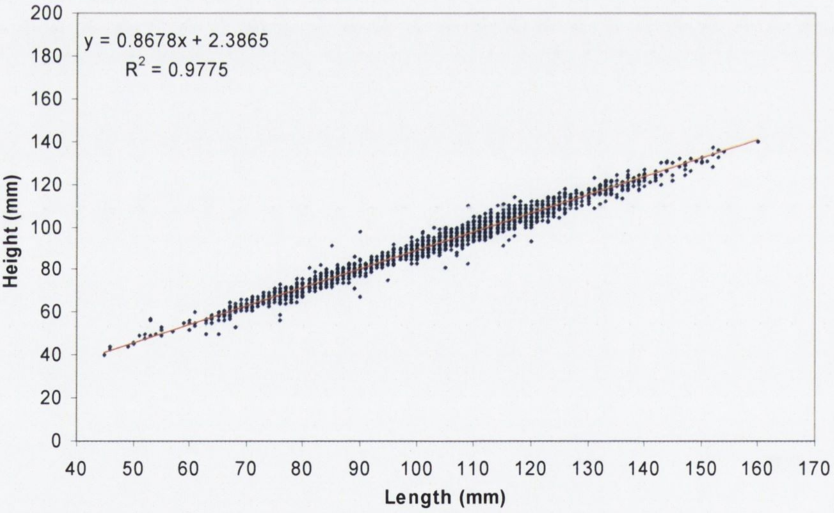


Figure 5.3. Regression line of scallop shell height on shell length. Data was collected in the research survey carried out in the year 2001.

5.2.1 Survey 2001

In November 2001 a research survey was conducted off the south east coast of Ireland to investigate the spatial distribution of scallop in the area. This geographical area has been the traditional scallop ground since the 1980s. However research surveys have not been undertaken in the area prior to the work presented here. Hence the survey area was identified from the distribution of commercial fishing activity in the area. A total of 131 sampling stations sampled on an approximate regular grid with each station separated by 5 nautical miles (Figure 5.4).

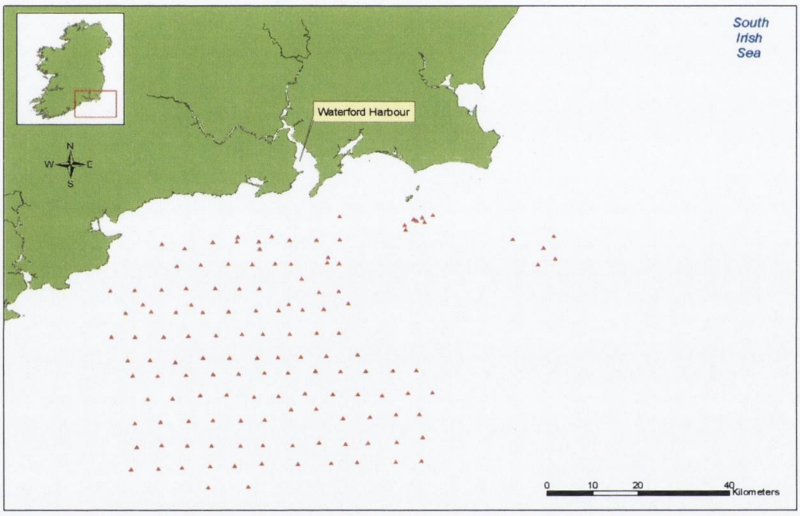


Figure 5.4. Sampling stations during the 2001 research survey off the south east coast of Ireland.

Survey data of relative abundance of undersize and commercial sized scallop was estimated and visualised in ArcGIS 8.2. Relative abundance is defined as the density of scallop uncorrected for dredge efficiency. An interpolated map of relative abundance was produced. Interpolation techniques use algorithms to estimate a value for an unknown area based on the closest sampling points. The influence the nearby sampling points have on the final estimation depends on the number of sampling points selected and the distance between the known points and the unknown area. The Inverse Distance Weighting (IDW) algorithm was used to create contour maps of scallop relative abundance. IDW weights the influence of neighbouring points according to the distance from each sampling station to the area of interest.

Point data were displayed in ArcMap. All data were projected to a common reference frame in UTM based on the WGS 84 geographic datum. The interpolated image was colour coded to show density contours.

5.2.2 The Distribution and Abundance of Scallop in Relation to Multibeam Acoustic Backscatter

5.2.2.1 Acoustic Mapping

A seabed acoustic survey, using multibeam echo-sounder (MBES) sonar system was undertaken by the Coastal & Marine Resource Centre, University College Cork, onboard the Marine Institute's vessel the Celtic Voyager in 2002. Survey stations were set in areas of high scallop density obtained in the 2001 survey. Multibeam acoustics send sound waves to the seafloor from equipment mounted to the ship's hull and measures the time it takes for the signal to return. This time is directly related to water depth. The strength (or backscatter) of the reflected signal – recorded as sound in decibels (db) – gives information about the hardness and texture of the substrate (Le Gonidec et al., 2003).

A Simrad EM1002 echo-sounder was used to generate overlapping swathes of sonar coverage within the survey area. This system produces 111 narrow beams and operates by ensonifying a narrow strip of the seabed across the beam of the survey vessel. The swath of seafloor imaged on each survey line is typically 5-6 times the water depth in 100 m-water depth. All MBES data were initially managed and post-processed using CARIS^{TM} HIPS (Hydrographic Information Processing System, CARIS, 2003) by Eimear O'keeffe at National University of Ireland, Galway. This software removes erroneous depth values and facilitates the reduction of all sounding data to a common vertical datum (e.g. Mean Sea Level) through application of tidal corrections.

The amplitude of the returning echo corresponds to the substrate underneath. Each beam hits the ocean floor at a different angle, varying from 0° directly beneath the ship to 60–65° at the edge of the swath. The strength of the returning signal is affected by this varying angle of incidence and all backscatter data must be corrected to an angle of incidence of 45°. Data output files in text-file format giving the geographic location, beam number and amplitude value of all acoustics soundings were filtered and corrected to remove any angular effects. The backscatter values mostly affected by a varying angle of incidence are the acoustic responses directly below the transducer (the specular zone) and the reflected signals from the outer beams. A procedure was thus adopted where the data derived from these beams was deleted, and corrective procedures applied to the acoustic data between these two zones (O'Keeffe *pers comm.*) (Figure 5.5).

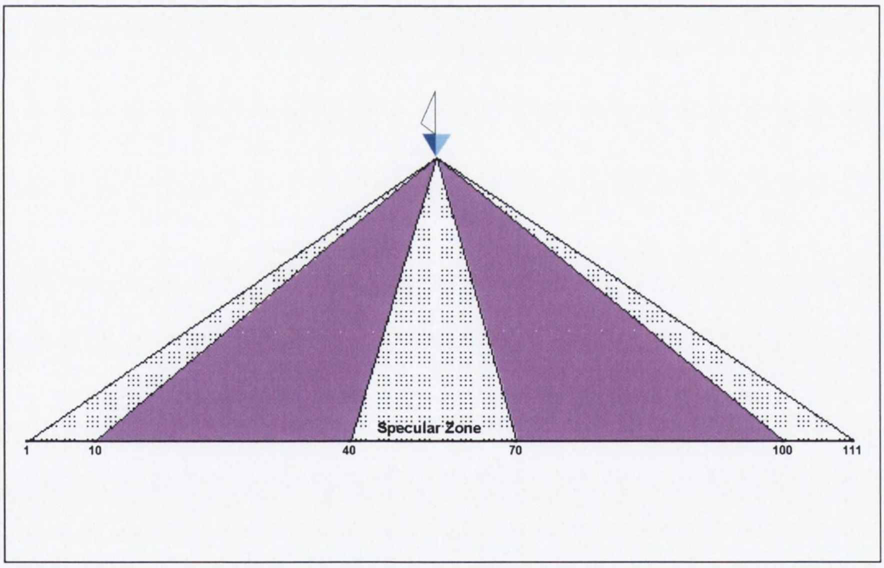


Figure 5.5. Schematic drawing of swath identifying specular zone and outer beams.

Backscatter values from two sections of the swath-obtained from beams 10 to 40 and from 70 to 100 – were corrected to an angle of incidence of 45°. The corrected amplitude values were imported into ArcMap as a table and displayed as a point file. The points were interpolated to create a continuous surface and the resulting ground type image, displaying a range of backscatter values. The acoustic backscatter data was provided for Areas 1 and 2 (see Chapter 1) off the south east coast of Ireland.

Backscatter data were analysed in combination with ground truthing information from video imagery and sediment samples to classify acoustic data into predominant sediment facies. For details of seabed classification analysis see Sutton and O'Keefe (2006). Acoustic backscatter data was classified into two principal ground type-substrates dominated by either sand or gravel. Seabed classification analysis showed that high backscatter values, represented by the darker tones of the acoustic image (Figure 5.6), defined by an acoustic range between –20 and –45 decibels, represent areas predominantly composed of gravel and coarser sediment. In contrast, the lighter region of the acoustic image was where sand sediments predominated, and were defined by an acoustic range between –50 and –90 decibels. The backscatter amplitude range from –45 to –50 decibels was defined as a transition zone between the two main sediment facies.

5.2.2.2 Scallop Surveys 2002-2004

The acoustic backscatter map was used to investigate the variability of scallop abundance in relation to the sediment type. Three scallops surveys were conducted in 2002, 2003 and 2004. A number of paired sampling stations were strategically placed on low (sand) and high (gravel) backscatter areas on the two scallop beds (denoted as area 1 and area 2) for which acoustic maps were developed (Figure 5.6) and, thus, the variability of scallop abundance on a fine spatial scale could be investigated. Survey stations were placed close together, in pairs where one station in each pair was on gravel and one was on sand, to remove the possibility that differences in scallop abundance on different sediments could be incidental due to for instance differences in larval supply. This could not be discounted if broad areas of sand and gravel were compared. The geographic location of sampling stations was repeated during the three years so that repeatability of results could be evaluated.

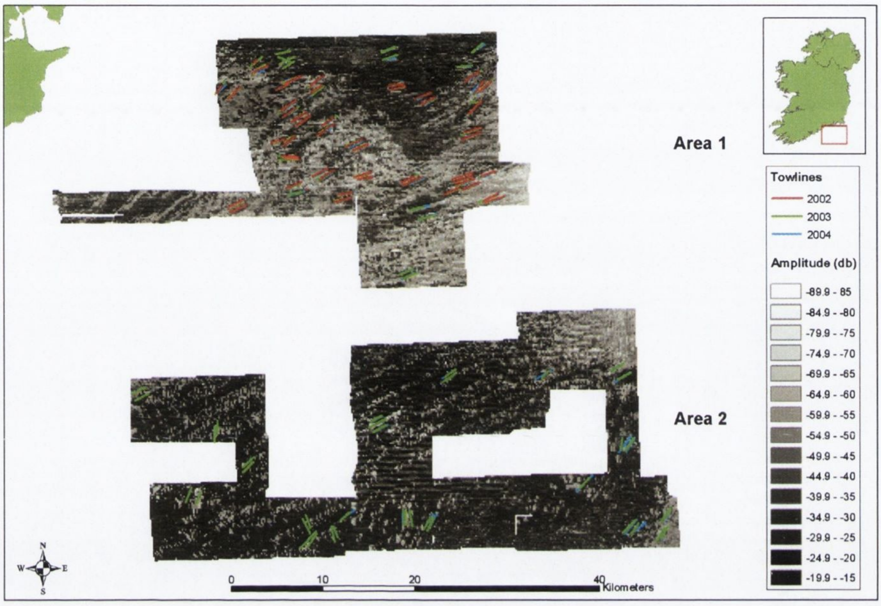


Figure 5.6. Backscatter intensity image for the survey area depicted in grey scale. Legend shows sampling units locations in the years 2002, 2003 and 2004 colour coded and amplitude values denoting backscatter signal strength.

The area covered by the fishing gear in each of the sampling stations was calculated as:

$$\text{Area} = \text{Length of the tow} * \text{Dredge width} * \text{Number of dredges} \qquad (5.1)$$

As described above, navigation was by Differential Global Positioning System and for each sampling station the latitude and longitude was recorded at the start and at the end on the tow. Geographical positions were displayed in an ArcGIS environment and a buffer zone, describing the area covered by the fishing gear was created using Arcmap. The length of the sampling station and the width of the fishing gear gave the buffer zone (Figure 5.7).

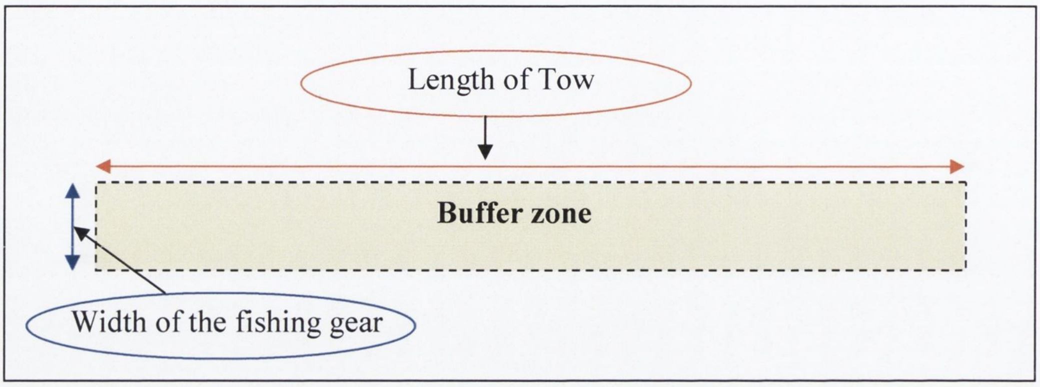


Figure 5.7. Diagram showing the buffer zone created to obtain backscatter amplitude.

The width of the path, dredged by the fishing gear, was 9.96 m (0.83 m dredge width*12 dredges) and the average length was 1554 m (standard deviation = ±302 m). Backscatter amplitude values for the buffer zone at sampling station was then extracted using the Spatial Analysis tool in ArcMap. Hence, relative scallop abundance obtained in each sampling station could be compared to the average backscatter value at that station.

One hundred sampling stations (50 paired sampling stations) were placed over the multibeam image and sampled in the years 2002, 2003 and 2004. However, the number of stations completed in different years varied due to logistical constrains (weather condition and days available for sampling). In Table 5.2 are shown dates and number of stations for each of the surveys.

Table 5.2. Date, number of days and number of sampling stations carried out in each of the scallop ground/Area ID and years. N = number.

Date		Ground/Area ID			
Year	Day/Month	*Area 1*		*Area 2*	
		N of days on survey	N of stations sampled	N of days on survey	N of stations sampled
2002	31/10-17/11	5	49		
2003	17/09-10/10	5	62	3	37
2004	18/08-06/09	6	49	4	24

A least squares linear statistical model was used to examine the relationships between scallop relative abundance and backscatter strength. As described in Chapter 3 a linear model specifies the (linear) relationship between a dependent (or response) variable y, and a set of predictor variables. The least squares linear statistical model can be used to fit data with any function of the form:

$$f(y_i) = \beta_0 + \sum_i \beta_j x_{ij} + \varepsilon_i \tag{5.2}$$

where y is the response variable, i.e. scallop relative abundance or its transformation, and (f(·)) is the link function that is used to achieve linearity in the vector β of size n, that specifies the explanatory variables x for the ith value of the dependent variable y. The error term ε will have a statistical distribution that will depend on the nature of the link function. In this study backscatter strength is the only explanatory variable x and therefore Equation 5.1 can be re-expressed as:

$$f(y_i) = \beta_0 + \beta_1 x_i + \varepsilon_i \tag{5.3}$$

where β_0 is a constant and β_1 is the slope coefficient, which specify the steepness and rate of change of scallop catch rate with acoustic backscatter. A least squares linear statistical model was used to fit the data separately for commercial sized and undersized scallops and for each area surveyed, as the influence of the fishery on the relationship could not be discounted. Substantial differences in relative abundance were found between sand and gravel substrates such that the acoustic data was used *in 2005 to design a stratified random survey in order to estimate global abundance of scallop in the area.*

5.2.2.3 Survey 2005.

In 2005, a random sampling scheme was designed on the basis of proportional abundance of scallop on the two main sediment types to estimate scallop distribution and absolute (corrected for dredge efficiency) and relative abundance. Following classification of acoustic backscatter data into two main substrate types, sand and gravel, and observed differences in scallop density between sediment types, the survey was designed as follows:

1. In order to account for the observed greater abundance and variance in relative abundance, 80% of the 100 stations were allocated to gravel.

2. The acoustic backscatter surface was colour-coded to display sand and gravel areas as a base layer in a GIS (Figure 5.8). The area occupied by gravel and sand sediments was calculated for *Area 1* and *Area 2* and stations were allocated to each area in proportion to area size (Table 5.3).

3. *Area 1* and *Area 2* were divided into 541 2 x 2 km cells for the random allocation of sampling stations (Figure 5.8). An identification number was given to each cell. A random generator[4] provided the 541 cells in random series. Starting from the first cell given, sampling stations were allocated to sand or gravel, depending on the sediment characteristics associated with the cell. The sampling station consisted of a straight transect of 2 km in length. Those cells were composed of both, gravel and sand sediments, that did not allow the allocation of 2 km transect on the same substrate type were rejected.

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[4] www.random.org

Cells were selected following the random series until the allocation of sampling units on both substrates and areas was completed.

Table 5.3. Number of sampling units allocated to each stratum in relation to the area size.

	Gravel		Sand		Total	
	Area (Km^2)	Number SU	Area (Km^2)	Number SU	Stations	Area (Km^2)
Area 1	384	26	299	12	38	683
Area 2	801	54	200	8	62	1001
Total	1185	80	499	20	100	1684

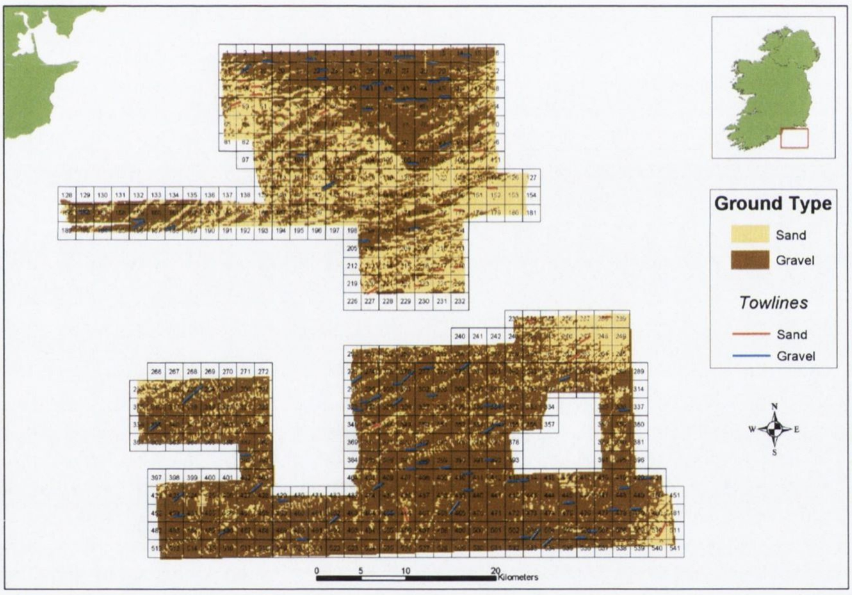


Figure 5.8. Colour coded display of sand and gravel substrates derived from multibeam backscatter data and the superimposed 2005 scallop survey grid showing station allocation to sand and gravel.

As previously explained (see 5.2.2.2), a buffer zone displaying the sampling station area was created and placed over the ground type image to calculate area dredged. Amplitude values for each towed area were extracted using the Spatial Analysis tool in ArcMap.

5.2.2.4 Estimation of Scallop Abundance

Scallop abundance was estimated for four acoustic classes, each class with a range of 10 decibels. Ten decibels acoustic range was considered to be appropriate to highlight the different ground types (Sutton & O'Keeffe, 2006). The relative scallop abundance and its confidence interval for a given acoustic class $(A_i \pm a_i)$ were then calculated by raising the relative scallop abundance per square meter and its confidence interval to the total area of a given acoustic class:

$$(A_i \pm a_i) = (N_i \pm n_i) * A_i \qquad (5.4)$$

where $(N_i \pm n_i)$ is the number of scallop per square meter and its confidence interval for a given acoustic class i, and A_i is the area (m^2) for a given contour *i.*

The total relative scallop abundance and its confidence interval $(R \pm r)$ for a given scallop bed (*Area 1 or Area 2*) were then estimated by summing each acoustic class estimate $(A_i \pm a_i)$ within each scallop bed. Confident intervals were calculated following Elliott (1977).

$$(R \pm r) = \sum_{i=1}^{n} (A_i \pm a_i) = \sum_{i=1}^{n} A_i \pm \sqrt{\sum_{i=1}^{n} a_i^2} \qquad (5.5)$$

Estimations of relative abundance of commercial and undersized scallop were corrected for dredge efficiency to produce estimations of total abundance. Estimates of dredge efficiency were presented in Chapter 2. Dredge efficiency was estimated from grounds of acoustic ranges corresponding to either gravel (>-45db) or sand (<-50 db). Thus estimations of total abundance for each of the 10db acoustic range were corrected for dredge efficiency using the following calculation. Confident intervals were calculated following Elliot (1977):

$$(T_i \pm t_i) = (A_i \pm a_i) * (F_j \pm f_j) = A_i * F_j \left(1 \pm \sqrt{\frac{a_i^2}{A_i^2} + \frac{f_j^2}{F_j^2}} \right) \qquad (5.6)$$

where $(T_i \pm t_i)$ is the total abundance of scallop of the 10db acoustic range i, and $(F_j \pm f_j)$ is the mean dredge efficiency obtained in j substrate type. That is, $(F_j \pm f_j)$ estimates corresponding to sand substrates (Areas A and B Chapter 2) was used to correct $(A_i \pm a_i)$ estimates of acoustic backscatter ranges between –50 and –70 decibels, and $(F_j \pm f_j)$ estimates corresponding to gravel substrates (Areas C and D Chapter 2) was used to correct $(A_i \pm a_i)$ estimates of acoustic backscatter ranges between –25 and –45 db. Estimation of total scallop abundance for the acoustic backscatter range –45 to –55 db was calculated by using a $(F_j \pm f_j)$ estimated from all experiment areas (Areas A to D), as this was classified as a transition zone between sand and gravel substrates. Estimates of $(F_j \pm f_j)$ used to correct $(A_i \pm a_i)$ of commercial and undersized scallop are presented in Table 5.4 and Table 5.5 respectively.

Table 5.4. Mean dredge efficiency estimates (F) for commercial sized scallop in sand, gravel and transition zone substrates types. f= Confidence limits.

Substrate Type	(%)	CL
Sand	4.7	1.5
Gravel	17.4	14.6
Transition zone	11.1	9.3

Table 5.5. Mean dredge efficiency estimates (F) for undersized scallop in sand, gravel and transition zone substrates types. f= Confidence limits.

Substrate Type	*F* (%)	*f* (%)
Sand	8.5	1.7
Gravel	14.5	4.6
Transition zone	10.5	6.9

5.3 Results

5.3.1 The Distribution and Relative Abundance of Scallop in 2001

The distributions of commercial and undersized scallop in 2001 are shown in Figure 5.9 and Figure 5.10, respectively. Abundance estimates were highest in an area directly south of the Waterford estuary. This patch extended south to almost the southern end of the sampling grid at 51.5 N. Over 90% of the sampling stations yielded scallops suggesting that they are distributed throughout the area rather than in discrete patches. Highest distribution of scallop abundance off the Waterford estuary appeared to cover the large area of gravel identified from the acoustic surveys (Figure 5.8). This initial finding suggested that the sediment composition might have an important effect in the distribution of scallop.

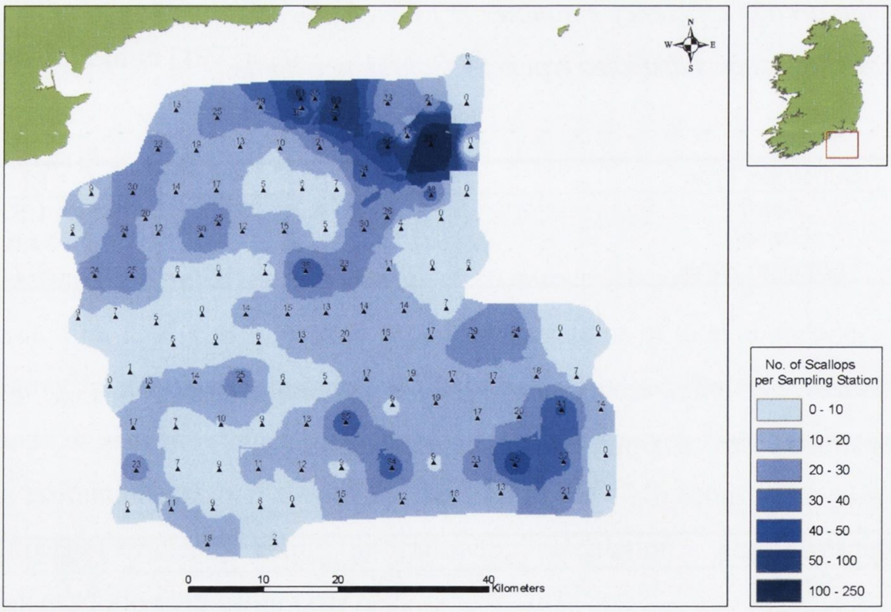


Figure 5.9. Distribution of relative abundance of commercial sized (>89 mm shell height) scallop off the south east coast in 2001. Values are number of scallops per sampling station. Standardised to 1000 m transect length.

The distribution pattern of undersized scallop (<89 mm shell height) was similar to that of commercial sizes. The highest abundance was again found directly south of the Waterford estuary. This extended south towards the southern edge of the survey area. The lower relative abundance obtained for undersized scallop in comparison to commercial sized scallop was most likely due to the lower selectivity of the dredge on undersized scallop (see Chapter 2).

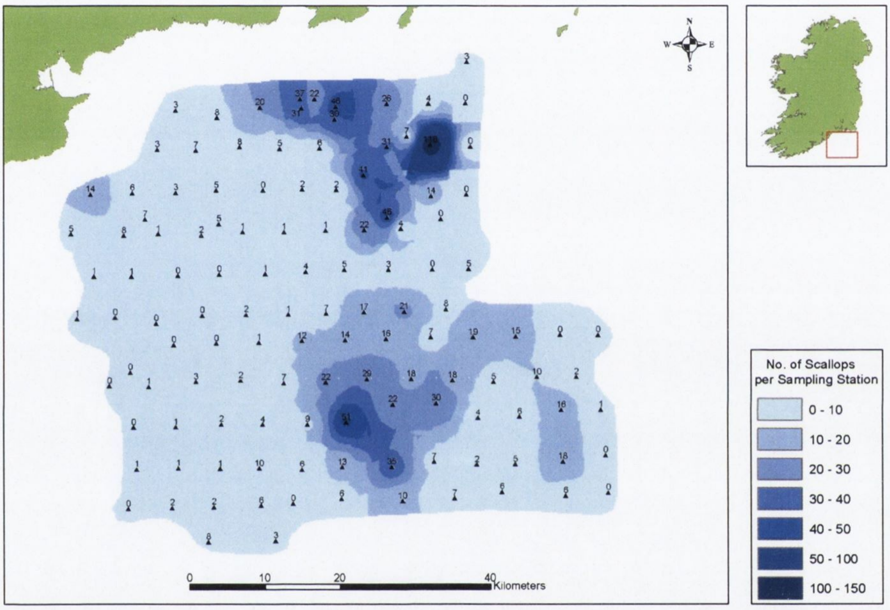


Figure 5.10. Distribution of undersized (<89 mm shell height) scallop off the south east coast in 2001. Values are number of scallops per sampling station standardised to 1000 m transect length.

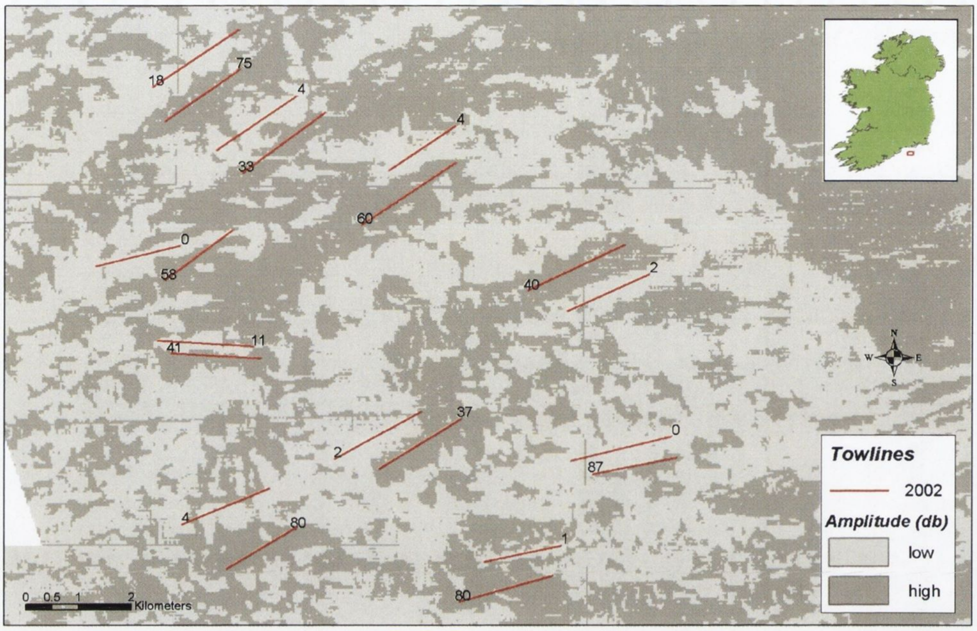
5.3.2 The Distribution and Relative Abundance of Scallops in Relation to Sediment Structure

Scallop relative abundance was strongly correlated with acoustic backscatter strength in 2002-2004 surveys. A paired t-test was carried out to test differences between paired sampling stations strategically placed on low and high backscatter areas (Table 5.6). Test results confirmed the contrasting differences in catches of both undersized and commercial sized scallops, at stations that were separated by average distance of 660m (standard deviation=250) (Figure 5.11).

Table 5.6. Paired t-test of scallop abundance of paired sampling station placed strategically on low (sand) and high (gravel) backscatter areas. The test is shown for commercial sized scallop and undersized scallop in each of the grounds surveyed (area 1 and area 2) and years 2002-2004. P=Probability; Ho=Null hypothesis; df=degrees of freedom (n-1).

test Ho: μ(Sand-Gravel) = 0 vs Ha: μ(Sand-Gravel) $\neq$ 0	*Area 1*						*Area 2*			
	2002		2003		2004		2003		2004	
	Commercial Sized Scallop	Undersized Scallop	Commercial Sized Scallop	Undersized Scallop	Commercial Sized Scallop	Undersized Scallop	Commercial Sized Scallop	Undersized Scallop	Commercial Sized Scallop	Undersized Scallop
Mean of Paired Differences	-44.15	-18.95	-59.08	-29.98	-42.28	-37.73	-28.628462	-9.7676	-30.254	-6.9088
t-Statistic	-7.28	-4.70	-7.724	-4.43	-4.47	-3.74	-3.299	-4.109	-2.409	-2.951
df	23	23	30	30	19	19	12	12	8	8
Reject Ho at Alpha 0.05										
P	<0.0001	<0.0001	<0.0001	<0.0001	0.0003	0.0014	0.0064	0.0014	0.0426	0.0184

Relative Abundance of Commercial Sized Scallop in Area 1



Relative Abundance of Undersized Scallop in Area 1

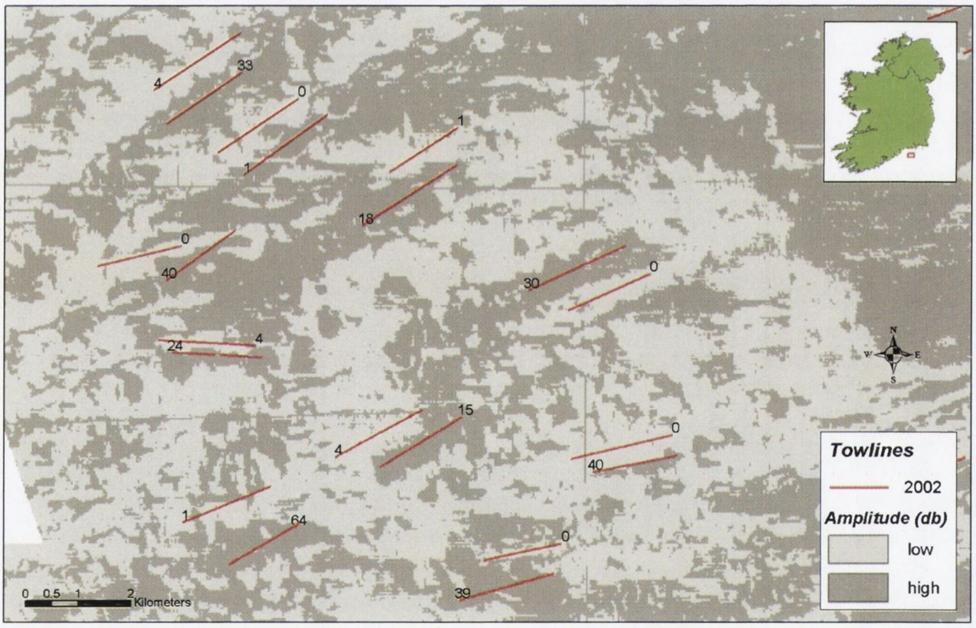


Figure 5.11. Plot showing a number of paired stations and associated scallop abundance sampled in research survey from year 2002. Above, commercial sized scallop relative abundance. Bellow, undersized scallop relative abundance. In appendix 5.1-5.10 are shown results of scallop abundance for all paired station carried out in research surveys 2002-2004.

Scallop abundance was positively related to acoustic backscatter (Figure 5.12 and Figure 5.13). Both legal and undersized scallop showed a similar positive relationship with backscatter. The shape of the relationship was exponential. This was more obvious in *Area 1* as data on scallop density was available for the entire range of backscatter. In both areas, in the acoustic range corresponding to gravel substrates, the abundance was significantly higher than in the areas corresponding to sand and had a higher associated variance.

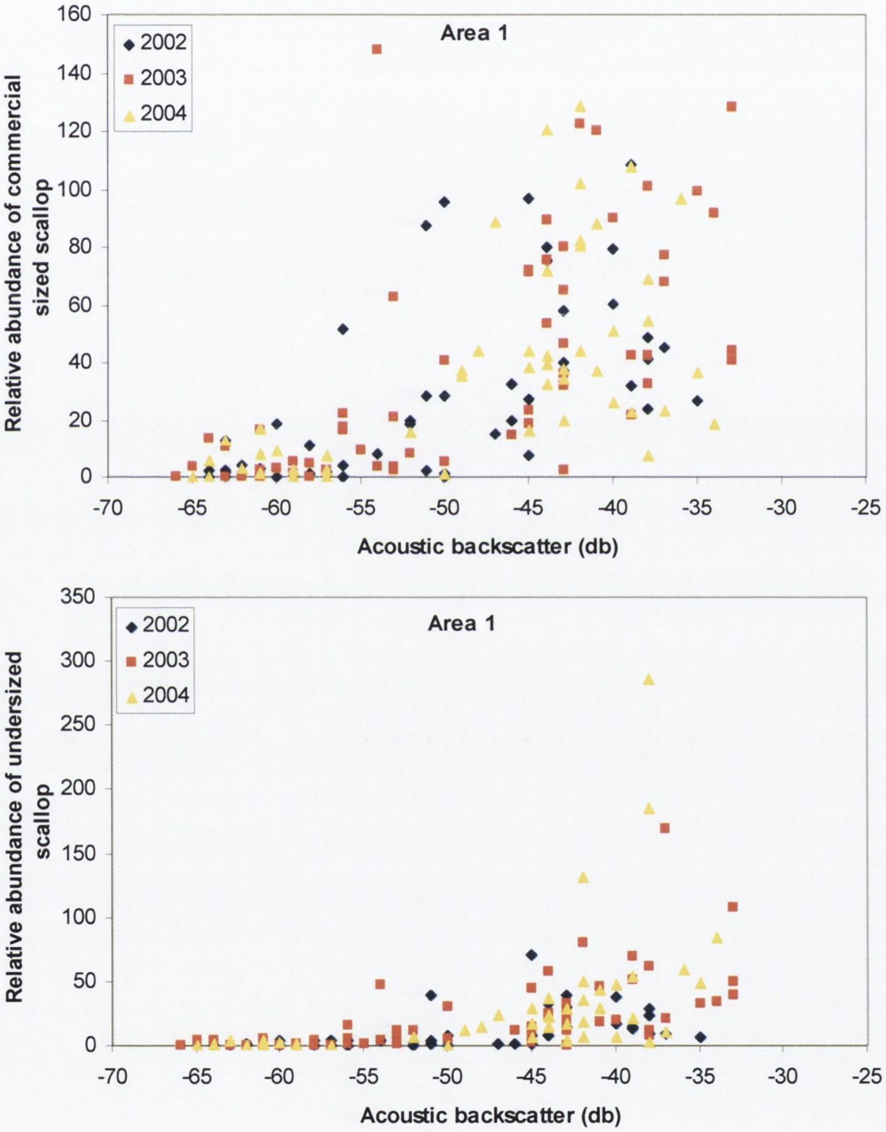
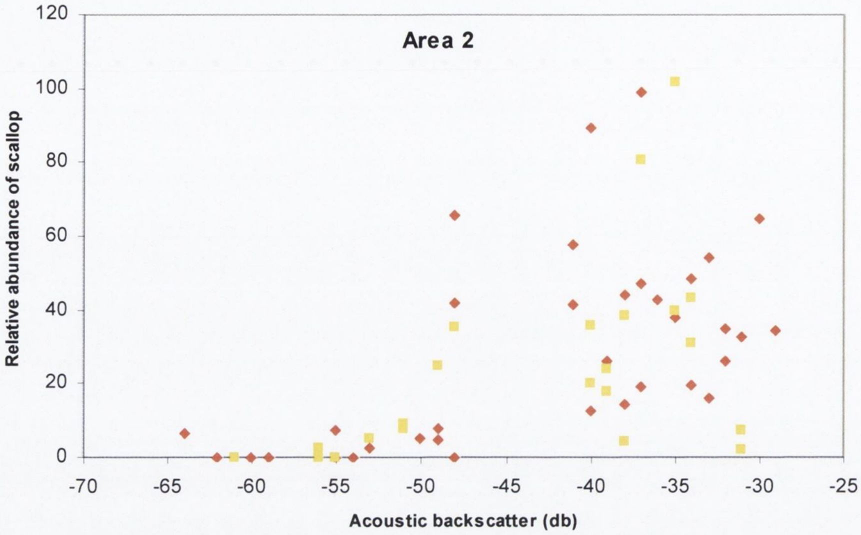


Figure 5.12. Relative abundance of scallop plotted against acoustic backscatter for each of the annual surveys for 2002 to 2004 in area 1. Estimates are expressed in number of scallop captured in a standardised sampling station of 1000 m.



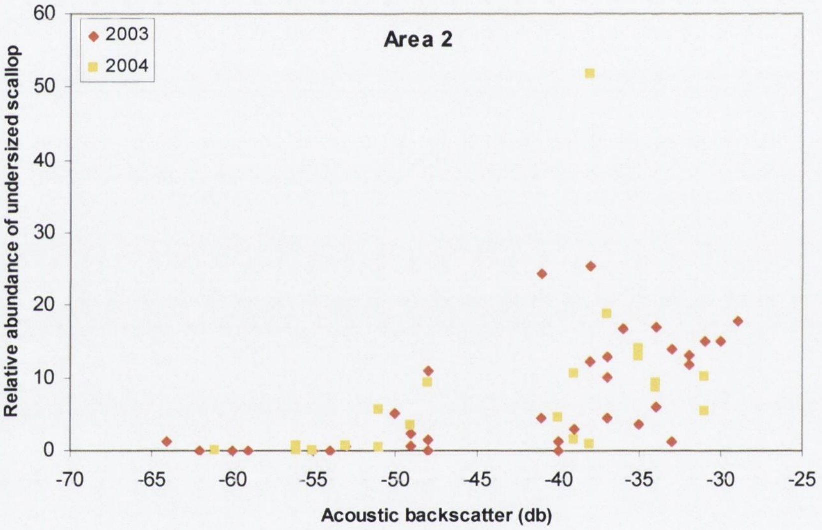


Figure 5.13. Relative abundance of scallop plotted against acoustic backscatter of research surveys conducted in years 2003 and 2004 in area 2. Estimates are expressed in number of scallop captured in a standardised sampling station of 1000 m.

In *Area 1* log-transformed scallop abundance plotted against backscatter (Figure 5.14) gave the best statistical fit to the data. Regression lines were fitted to the data and tested for normality and homogeneity of variance. Regression coefficients (Table 5.7) showed that backscatter accounted for between 57-67 % of the variability in scallop relative abundance (*p<0.001*) in both commercial and undersized scallops respectively.

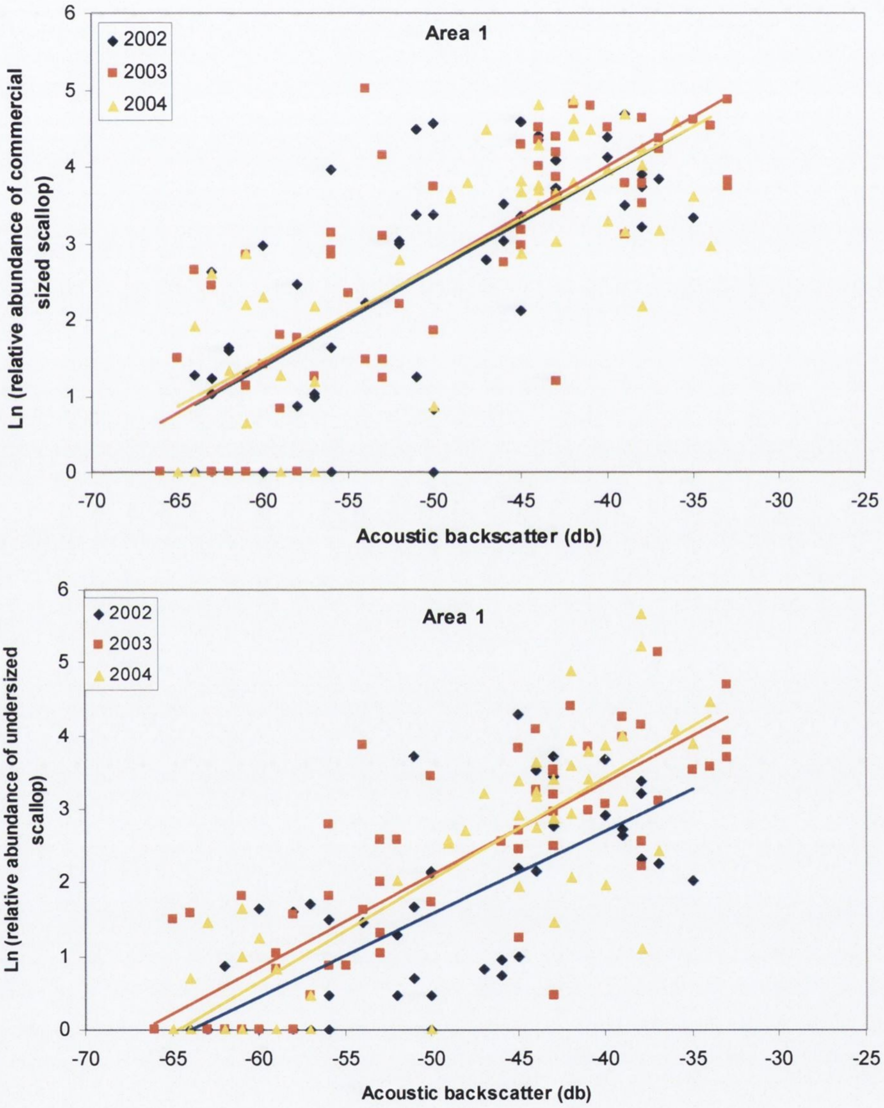


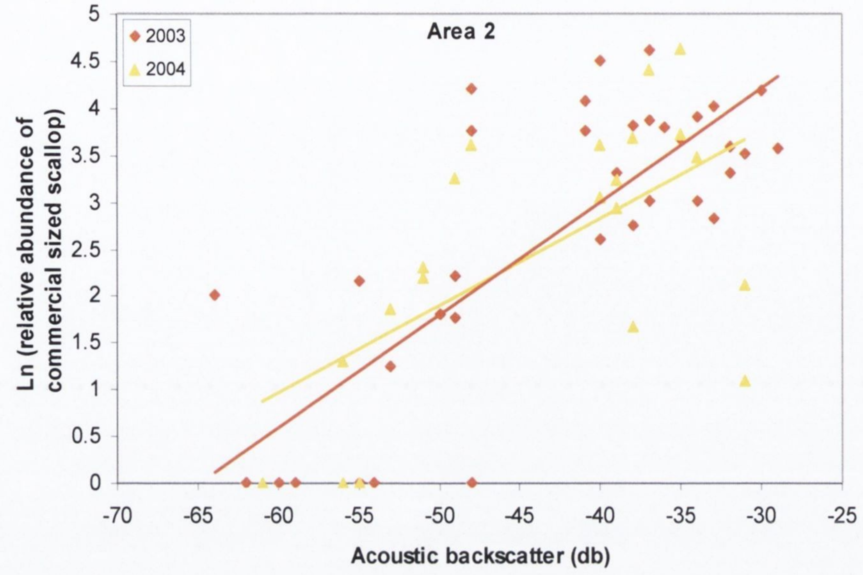
Figure 5.14. Regression line of log-transformed relative scallop abundance of scallops against acoustic backscatter in area 1 in 2002-2004. Above, commercial sized scallop. Bellow, undersized scallop.

Table 5.7. Regression diagnostics of each of the annual research surveys in area 1.

Year	Df	Commercial sized			Pre-recruits		
		F-ratio	P	R^2%	F-ratio	P	R^2%
2002	48	65	<0.0001	57.1	71.2	<0.0001	59.4
2003	61	87.9	<0.0001	59.2	117	<0.0001	65.9
2004	50	73.2	<0.0001	59.1	103	<0.0001	67.2

In *Area 2* data on scallop relative abundance was not available for the entire range of backscatter. The number of sampling stations in this area did not provide data to meet closely conditions of homogeneity of variance and normality in the error distribution. However it was assumed, following results obtained in *Area 1*, that a log-linear regression model gave the best statistical fit to the data (Figure 5.15). Regression coefficients (Table 5.8) showed that backscatter accounted for between 61.9 % and 36.9 % of the variability in commercial sized scallop relative abundance ($p<0.001$) and 63.1 % and 50.8 % of the variability in undersized scallop relative abundance ($p<0.001$).

The average relative abundance, in each of the research surveys during 2002-2004, of undersized and commercial scallop for sampling units on acoustics ranges that correspond to either sand (<-50db) or gravel (>-45) substrates are shown in Figure 5.16 and Figure 5.17 and Table 5.9. Mean density estimates were significantly higher on gravel than on sand. This pattern was consistent for both size classes and on both Areas 1 and 2.



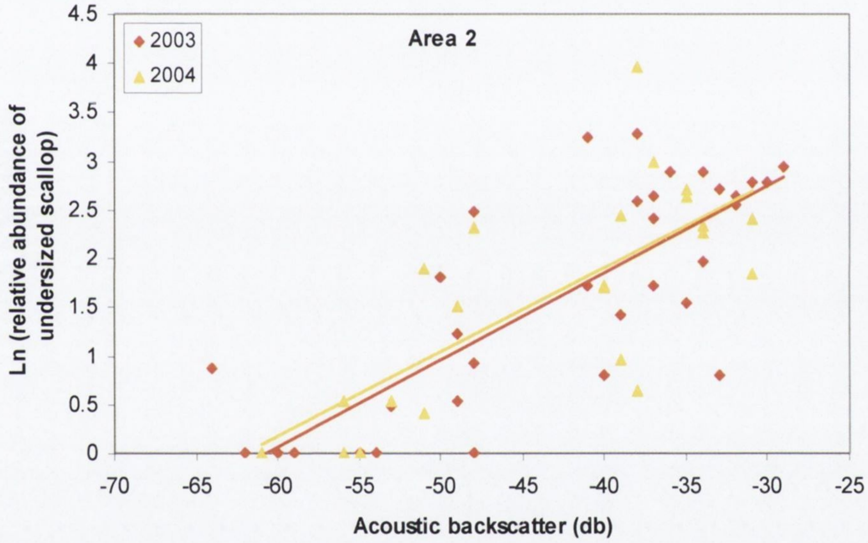
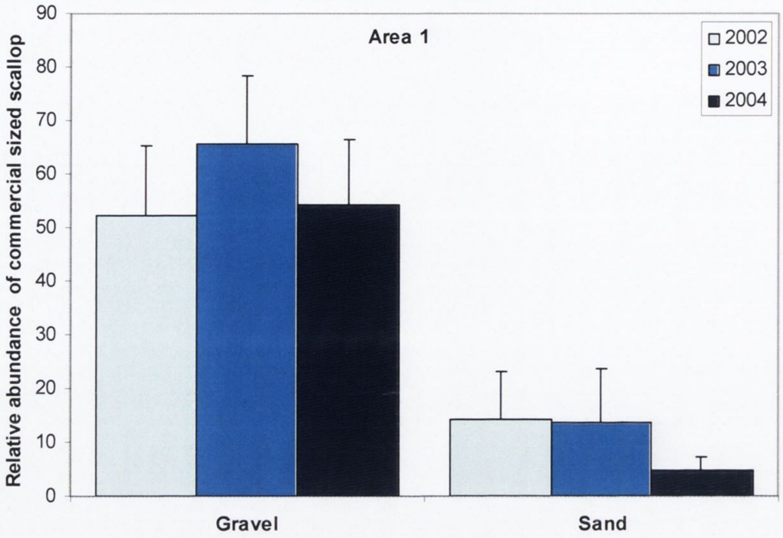


Figure 5.15. Regression line of log-transformed relative scallop abundance against acoustic backscatter in Area 2 in 2003-2004. Above, commercial sized scallop. Bellow, undersized scallop.

Table 5.8. Regression diagnostics of each of the annual surveys in Area 2.

Year	df	Commercial sized			Pre-recruit		
		F-ratio	P	R^2%	F-ratio	P	R^2%
2003	36	59.5	<0.0001	61.9	60.8	<0.0001	63.1
2004	21	13.3	0.0016	36.9	22.7	0.0001	50.8



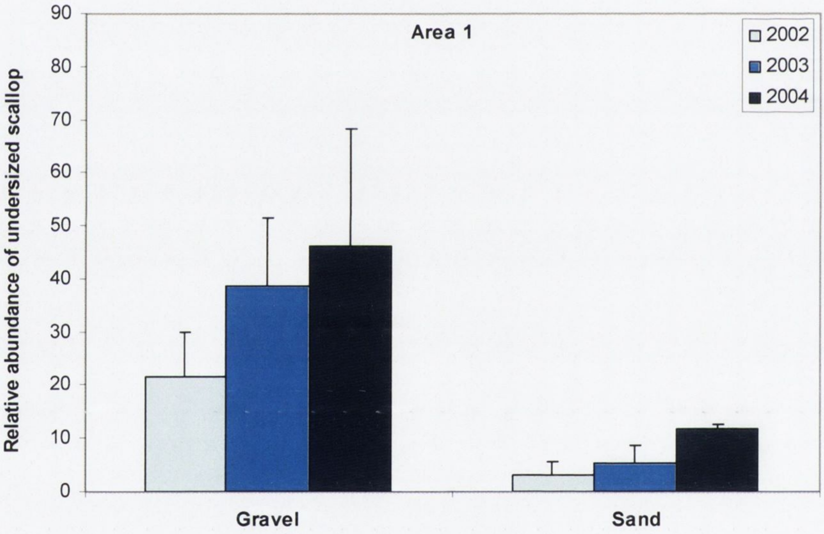
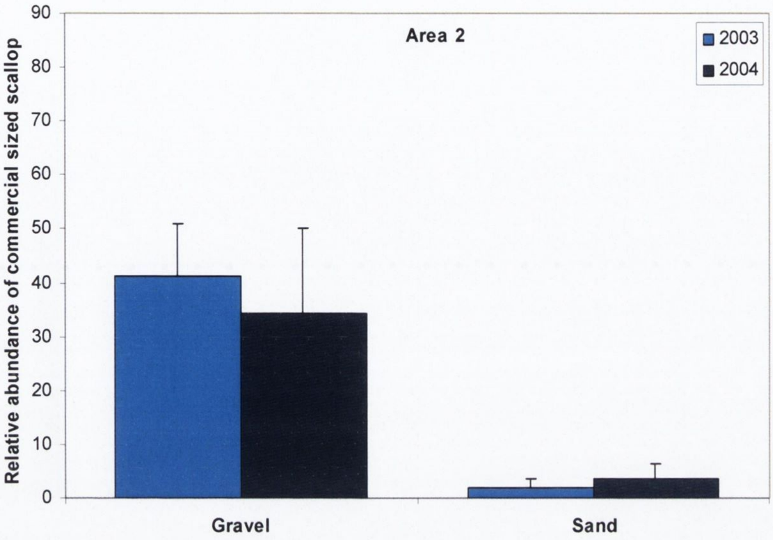


Figure 5.16. Relative abundance and 95% confidence limits of commercial sized (above) and undersized (bellow) scallop on gravel and sand substrates in Area 1. Estimates are expressed in number of scallop captured in a sampling station standardised to 1000m-tow length.



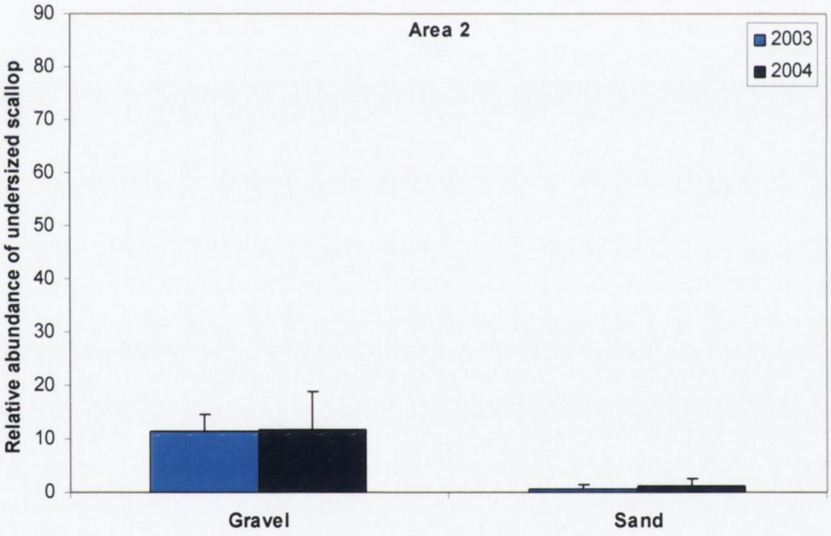


Figure 5.17. Relative abundance and 95% confidence limits of commercial sized (above) and undersized (bellow) scallop on gravel and sand substrates in Area 2. Estimates are expressed in number of scallop captured in a sampling station standardised to 1000m tow length.

Table 5.9. Relative abundance and 95% confidence limits of commercial sized and undersized scallop in area 1 and area 2. Estimates are expressed in number of scallop captured in a sampling station standardised to 1000m-tow length.

Area 1

Commercial sized

		Gravel			*Sand*	
Year	N	Mean	95% CL	N	Mean	95% CL
2002	20	52.2	13.2	29	14.2	8.9
2003	31	65.7	12.6	31	13.6	9.9
2004	29	54.2	12.2	22	04.7	2.6

Undersized

		Gravel			***Sand***	
Year	No. SU	Mean	95% CL	No. SU	Mean	95% CL
2002	20	21.6	8.3	29	2.9	2.7
2003	31	38.6	12.8	31	5.3	3.5
2004	29	46.1	22	22	5.3	3.5

Area 2

Commercial sized

		Gravel			*Sand*	
Year	N	Mean	95% CL	No. SU	Mean	95% CL
2003	21	41.2	9.8	16	2	1.8
2004	13	34.4	15.8	9	3.6	2.9

Undersized

		Gravel			*Sand*	
Year	N	Mean	95% CL	No. SU	Mean	95% CL
2003	21	11.5	3.1	16	0.6	0.9
2004	13	11.8	7.1	9	1.1	1.5

5.3.3 Abundance Estimates from Random Stratified 2005 Survey

In 2005 the variability in the relative scallop abundance was, as in previous research surveys, well explained by backscatter (Table 5.10 and Table 5.11). However, the number of sampling stations completed in the 2005 survey did not provide data for the entire range of backscatter (Figure 5.18 and Figure 5.19). As a consequence of this, the least square linear model fitted to 2005 data did not meet conditions of homogeneity of variance and normality in the error distribution and therefore bias could be raised in the estimation of means and confidence limits.

In order to obtain scallop data for the entire range of backscatter for the estimation of scallop abundance, the relationships obtained in all surveys (2002-2005) were compared and tested for similarity through an analysis of covariance. Statistical similarity between relationships would allow the use of data from different surveys together to estimate scallop abundance. This procedure is described below in 5.3.3.1.

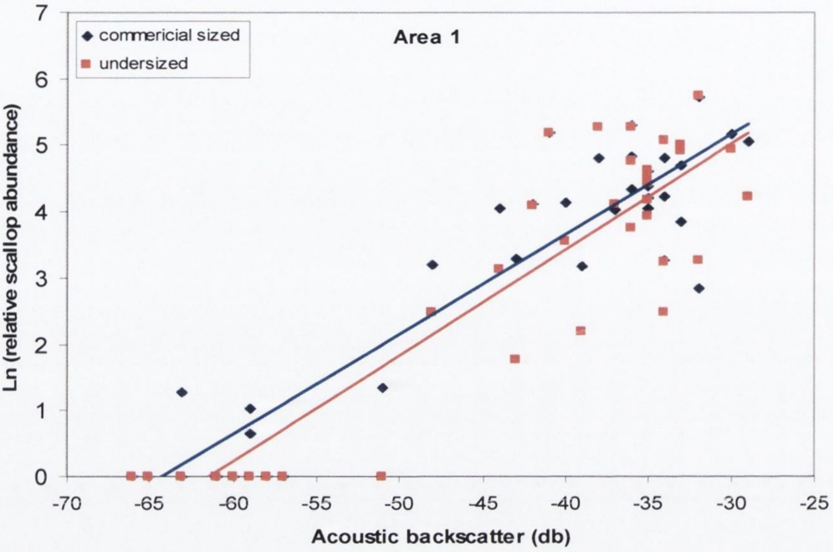


Figure 5.18. Regression line of the log-transformed scallop relative abundance on acoustic backscatter in Area 1 in survey 2005. In blue, commercial sized scallop. In red, undersized scallop.

Table 5.10. Regressions diagnostic of relationships showed in figure 5.18.

Area 1	Commercial sized scallop	Undersized scallop
df	35	35
F-ratio	201	162
P	<0.001	<0.001
R (adjusted)%	84.8	81.7

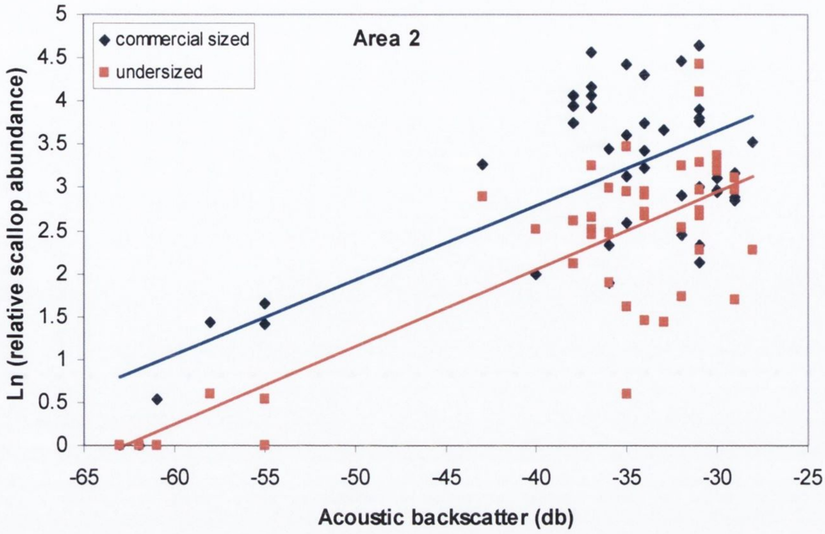


Figure 5.19. Regression line of the log-transformed scallop relative abundance on acoustic backscatter in Area 2 in survey 2005. In blue, commercial sized scallop. In red, undersized scallop.

Table 5.11. Regressions diagnostic of relationships showed in figure 5.19.

Area 2	Commercial sized scallop	Undersized scallop
df	44	44
F-ratio	45.8	65.4
P	<0.0001	<0.0001
R (Adjusted)%	49.9	58.9

5.3.3.1 ANCOVA of Annual Survey Data in Relation to Backscatter

Area 1

An analysis of covariance was used to compare regression lines of scallop catch rate and acoustic backscatter from annual research surveys. Results (Table 5.12) showed that the slopes and intercept of regression lines obtained in years 2002 to 2005 were statistically similar for commercial sized scallop ($p>0.05$). However, comparison of relationships of undersized scallops (Table 5.13) showed that, although there was no interactive effects i.e. the slopes were similar ($p>0.05$), intercept values differed significantly ($p<0.05$). Scheffes post hoc test (Table 5.14) revealed that the intercept value obtained for 2002 differed statistically from the others survey (2003-2005). Therefore, 2002 data was removed from the analysis of covariance (Table 5.15). Relative abundance of commercial sized and undersized scallop, uncorrected for dredge efficiency was estimated using data from 2002-2005 and 2003-2005 surveys respectively (Figure 5.20).

The relative population size in *Area 1*, uncorrected for dredge efficiency, was thereby estimated to be 2.7 million and 1.8 million of commercial and undersized scallops respectively (Table 5.16).

Table 5.12. Analysis of co-variance (backscatter) of commercial sized scallop relative abundance of years 2002-2005. BS = Backscatter (db); Df = Degrees of freedom; P = Probability

Source	Df	Sums of Squares	Mean Square	F-ratio	P
Constant	1	1592.81	1592.81	1776.2	< 0.0001
BS	1	334.159	334.159	372.63	< 0.0001
Year	3	5.21816	1.73939	1.9396	> 0.1
BS*Year	3	2.51418	0.83806	0.93455	> 0.1
Error	190	170.383	0.896754		
Total	197	512.275			

Table 5.13. Analysis of co-variance (backscatter) of undersized scallop relative abundance of years 2002-2005. BS, Df, and P as in Table 5.9.

Source	Df	Sums of Squares	Mean Square	F-ratio	P
Constant	1	854.951	854.951	1059.4	< 0.0001
BS	1	312.699	312.699	387.48	< 0.0001
Year	2	0.451167	0.225583	0.27953	>0.5
Error	145	117.016	0.807007		
Total	148	430.167			

Table 5.14. Scheffe's Post Hoc Tests of undersized scallop relative abundance of years 2002-2005. S.E = Standard Error, P = Probability

Year	Difference	S.E.	P
2003 - 2002	0.458134	0.1711	<0.01
2004 - 2002	0.411306	0.179	<0.05
2004 - 2003	-0.04683	0.169	> 0.5
2005 - 2002	0.348386	0.2	<0.1
2005 - 2003	-0.10975	0.1891	>0.5
2005 - 2004	-0.06292	0.1946	>0.5

Table 5.15. Analysis of co-variance (backscatter) of undersized scallop relative abundance of years 2003-2005. BS, Df, and P as in Table 5.9.

Source	Df	Sums of Squares	Mean Square	F-ratio	Prob
Constant	1	931.83	931.83	1202.3	< 0.0001
BS	1	385.353	385.353	497.19	< 0.0001
Year	3	6.53859	2.17953	2.8121	< 0.05
BS*year	3	5.5242	1.8414	2.3758	> 0.05
Error	190	147.261	0.775056		
Total	197	544.677			

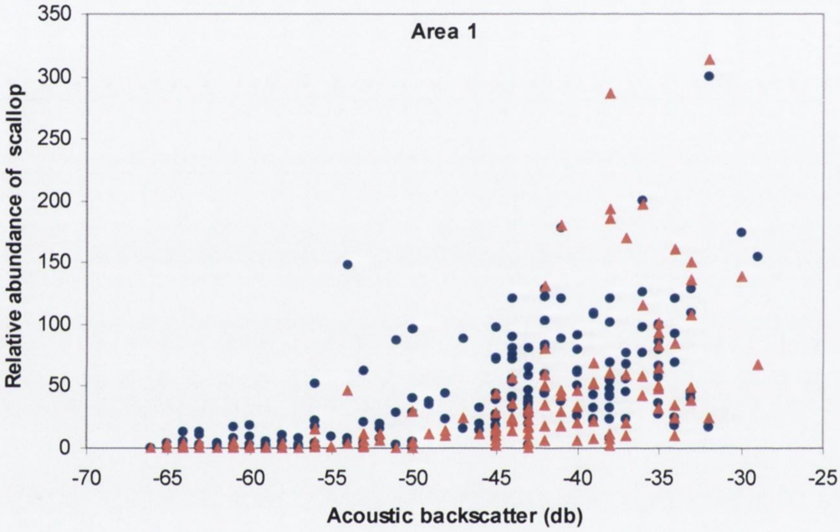


Figure 5.20. Number of scallops plotted against acoustic backscatter in area 1. Estimates are expressed in number of scallop captured in a standardised sampling station of 1000 meters. In blue, commercial sized scallop. In red, undersized scallop.

Table 5.16. Estimates of relative abundance, uncorrected for dredge efficiency, of commercial sized and under sized scallops in the north bed. CL = 95% confident limits.

Amplitude (db)	Commercial sized	CL	Undersized	CL
(-25 - -35)	737,836	248,924	710,877	260,431
(-35 - -45)	1,353,919	187,453	929,328	259,655
(-45 - -55)	482,661	201,745	148,792	68,255
(-55 - -65)	99,933	42,252	23,870	12,171
Total	2,674,349	373,615	1,812,867	374,235

Area 2

Analysis of covariance showed that the relationships between the relative abundance of commercial and undersized scallop and backscatter obtained in 2003 and 2004 did not differ from that obtained in 2005 in Area 2 (Table 5.17 and Table 5.18). Relative abundance of commercial sized and undersized scallop, uncorrected for dredge efficiency was estimated using data from 2003-2005 surveys (Figure 5.21). The population sized in Area 2, uncorrected for dredge efficiency, was thereby estimated to be 2.6 million and 1 million commercial and undersized scallops respectively (Table 5.19).

Table 5.17. Analysis of co-variance (backscatter) of commercial sized scallop relative abundance for years 2003-2005. BS, Df, and P as in Table 5.9.

Source	Df	Sums of Squares	Mean Square	F-ratio	P
Const	1	70.8463	70.8463	727.86	<0.0001
BS	1	12.5219	12.5219	128.65	< 0.0001
Year	2	0.017547	0.008774	0.090139	>0.5
BS*year	2	0.003018	0.001509	0.015501	>0.5
Error	98	9.53878	0.097335		
Total	103	26.826			

Table 5.18. Analysis of co-variance (backscatter) of undersized scallop relative abundance for years 2003-2005. Bs, Df, and P as in Table 5.9

Source	Df	Sums of Squares	Mean Square	F-ratio	P
Const	1	806.34	806.34	932.72	<0.0001
BS	1	104.673	104.673	121.08	< 0.0001
Year	2	0.771684	0.385842	0.44632	>0.5
BS*year	2	2.32242	1.16121	1.3432	>0.1
Error	99	85.5855	0.8645		
Total	104	193.352			

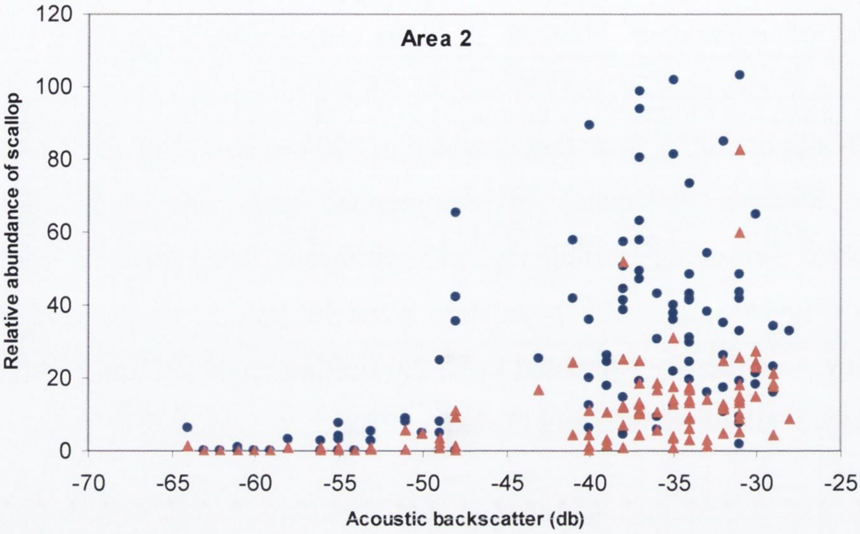


Figure 5.21. Number of scallops plotted against acoustic backscatter in area 2. Estimates are expressed in number of scallop captured in a standardised sampling station of 1000 meters. In blue, commercial sized scallop. In red, undersized scallop.

Table 5.19. Estimates of relative abundance, uncorrected for dredge efficiency, of commercial sized and under sized scallops in the south bed.

Amplitude (db)	Commercial sized	CL	Undersized	CL
(-25 - -35)	1,296,630	202,085	598,823	162,453
(-35 - -45)	1,109,221	270,854	340,165	105,714
(-45 - -55)	137,330	98,221	25,278	18,239
(-55 - -65)	12,291	14,418	2,742	3,328
Total	2,555,472	352,215	967,008	194,706

5.3.4 The Estimation of Absolute Scallop Abundance

Estimates of total abundance of commercial and undersized scallop in Areas 1 and 2 are presented in Table 5.20 andTable 5.21. In Area 1, estimates of commercial sized and undersized scallop were 20.2 million (±4.2, 95% confidence limit) and 11.3 million (±6.3, 95% confidence limit) respectively. In Area 2, estimates were lower at 18 million (±4.6, 95% confidence limit) for commercial sized scallop and 5.7 million (±3.5, 95% confidence limit) for undersized scallop.

Table5.20. Total abundance estimates (and 95% confidence limits (CL)) of commercial sized and undersized scallop in Area 1. Estimates are shown for every 10-db acoustic backscatter range for which the relative scallop abundance was estimated.

Area 1	Commercial sized scallop		Undersized scallop	
Backscatter (db)	Abundance	95% Confidence Limits	Abundance	95% Confidence Limits
(-25 - -35)	737,836	3,382,617	4,085,500	3,740,564
(-35 - -45)	1,353,919	2,386,280	5,340,966	4,723,421
(-45 - -55)	482,661	1,426,892	1,340,468	1,280,413
(-55 - -65)	99,933	367,017	507,872	305,501
total	20,198,350	5,415,087	11,274,806	6,167,278

Table5.21. Total abundance estimates (and 95% confidence limits (CL)) of commercial sized and undersized scallop in Area 2. Estimates are shown for every 10-db acoustic backscatter range for which the relative scallop abundance was estimated.

Area 2	Commercial sized		Undersized	
	Abundance	95%CL	Abundance	95%CL
3 (-25 - -35)	8,942,276	3,171,794	3,441,511	3,034,884
4 (-35 - -45)	7,649,800	3,070,849	1,954,971	1,749,274
5 (-45 - -55)	1,307,905	1,273,711	227,730	251,802
6 (-55 - -65)	144,600	172,071	58,340	73,216
total	18,044,581	4,598,080	5,682,553	3,512,726

Scallop total abundance was calculated for 10db acoustic range and the backscatter image were then colour coded to display the abundance and distribution of scallop in the areas surveyed. Figures 5.22 and 5.23 show distribution of commercial sized and undersized scallop abundance in *Area 1* and *Area 2*.

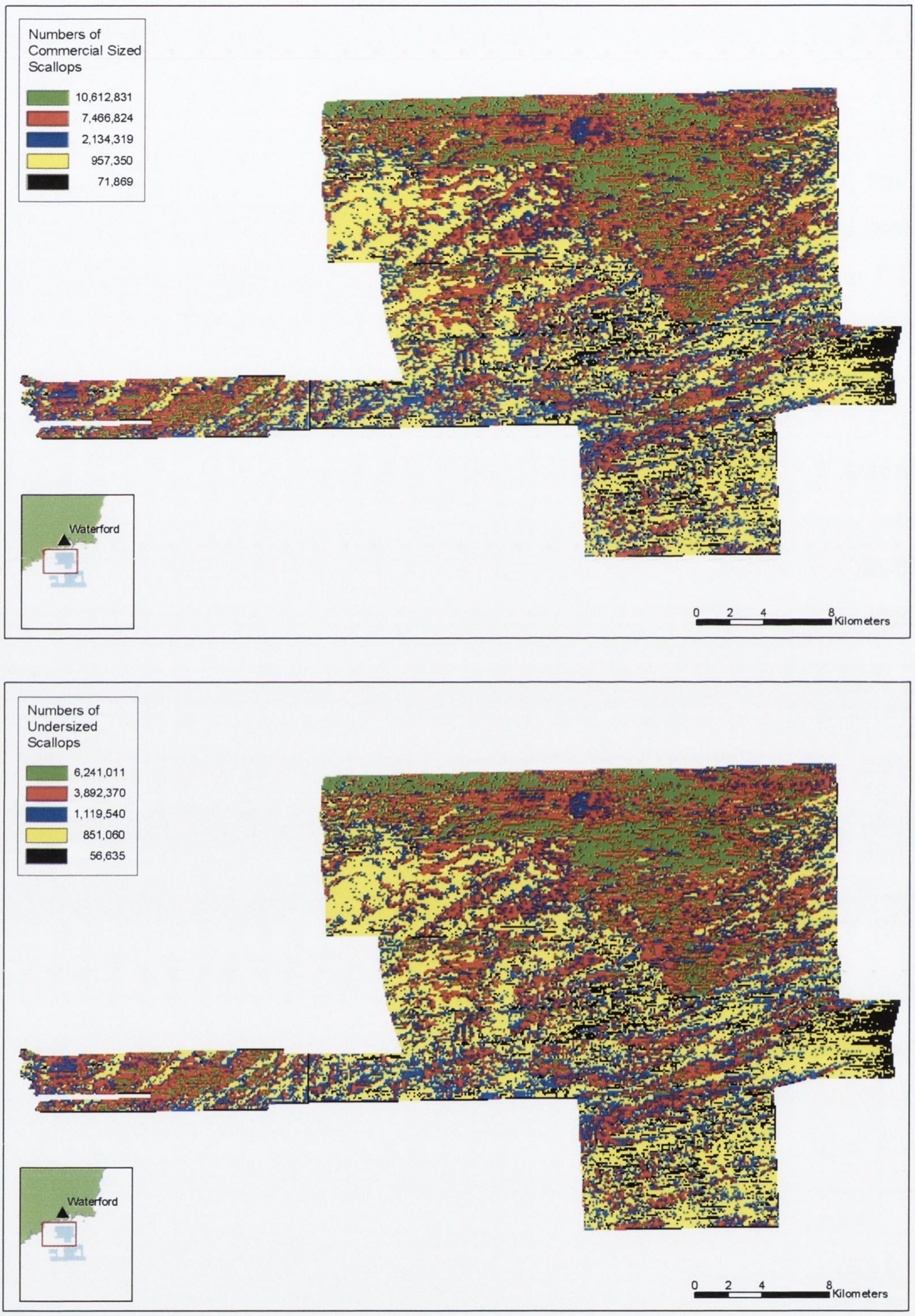


Figure 5.22. Acoustic backscatter imagery of Area 1 (above) and Area 2 (bellow) colour coded showing predicted total abundance estimates of commercial sized scallop for 10 five-db acoustic backscatter values range (see legend) and its spatial distribution.

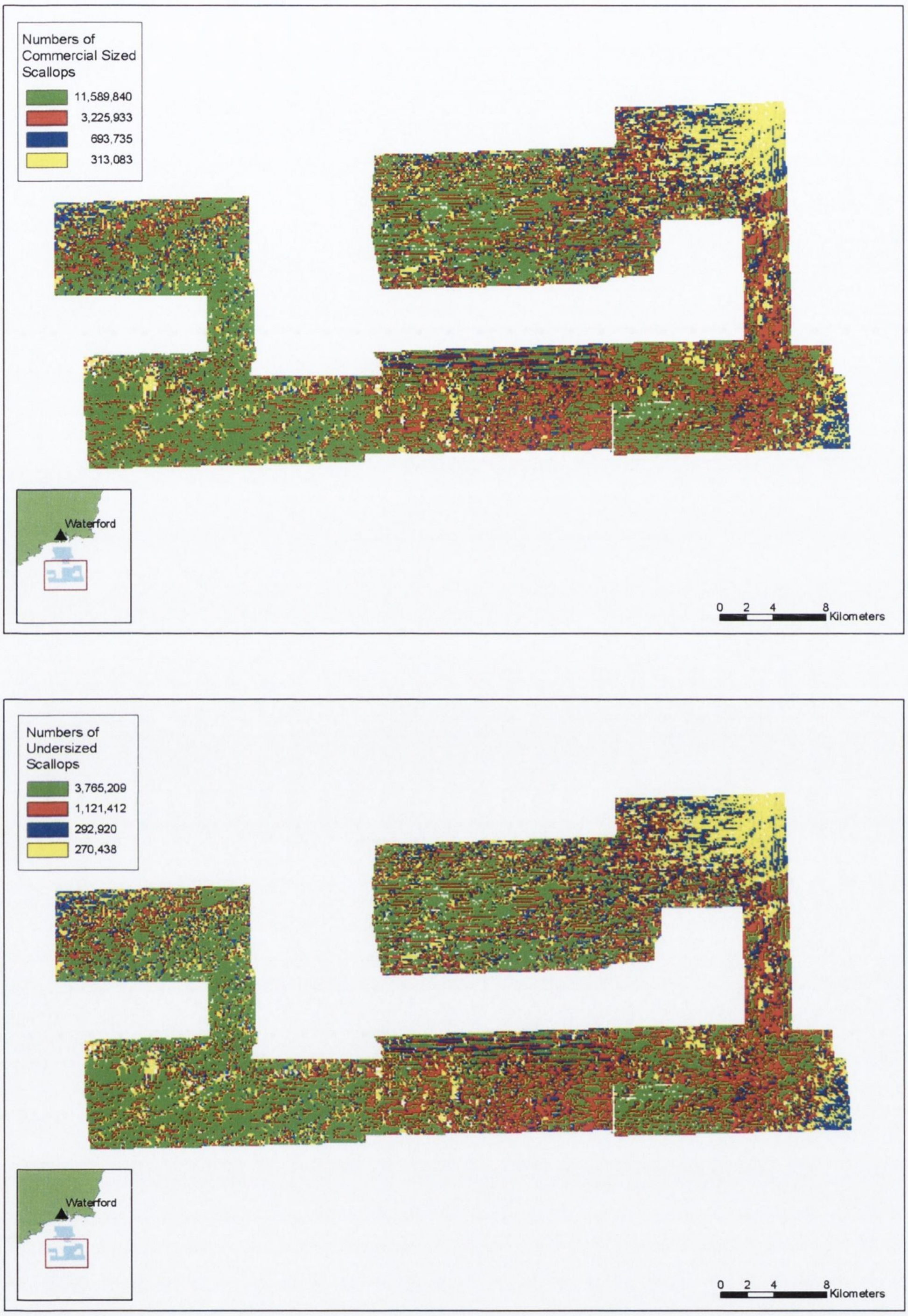


Figure 5.23. Acoustic backscatter imagery of Area 1 (above) and Area 2 (bellow) colour coded showing predicted total abundance estimates of undersized scallop for 10 five-db acoustic backscatter values range (see legend) and its spatial distribution

5.4 Discussion

A highly significant correlation between sediment type, predicted by acoustic backscatter data, and scallop abundance was found off the southeast coast of Ireland. The abundance of scallop was much higher on gravel than on sand.

The high contrast in scallop abundance obtained between paired sampling stations located strategically on low and high acoustic backscatter values (sand and gravel respectivey) indicated the preference of scallops for gravel substrates on a fine spatial scale (the distance between paired sampling stations was of an average of 660m in an scallop ground of approximately 2500 square kilometres). This pattern was shown for undersized and commercial sized scallop. The proximity between paired sampling stations permitted the rejection of the possibility that differences in scallop abundance between gravel and sand substrates was due to larval supply and, therefore, incidental. As described in the introduction of this chapter, and reported in the literature on scallop biology, the preference of scallop for gravel substrates is most likely due to the higher survival of early life stages of scallops and/or to a more suitable feeding condition for adult scallop (Bricelj and Shumway, 1991).

The log-linear relationship between scallop abundance and backscatter values suggest that scallop discriminate, not only between sand and gravel but also between different grades of sand and gravel. Kostylev and Todd (2005) demonstrated the existence of a log-linear correlation between acoustic strength and average grain size from sediment samples, where the variability in grain sizes (i.e. how well he sediment is sorted) in a sample generally decreases with backscatter intensity. Therefore the sediment type gradually may become more suitable for scallop species as the acoustic backscatter intensity increases or as the sediment grain size increases. It is suggested that scallops may actively select the most suitable available grain size sediments similarly to the cockle species *Cerastoderma edule* (Huxham and Richards, 2003). Scallops and cockles regulate ingestion by a reduction in the clearance rate. Bricelj and Malouf (1984) hypothesized that this physiological mechanism is the reason why cockle or scallops cannot tolerate high concentrations of suspended sediments in contrast to organisms such as mussels or surf clams, which control ingestion by increasing pseudofeces production, and are not so vulnerable to high concentrations of suspended sediments. Active selection of scallops for most suitable sediment types was evidenced in a laboratory experiment carried out by Wong et al (2006) to examine sediment selection by juvenile sea scallops (*Placopecten magellanicus*). Scallops were offered four sediment types: glass representing a homogeneous, hard bottom, sand, and gravel. Results indicating that scallops tend to avoid glass and tend to select gravel sediments.

In this study log-transformed scallop abundance was linearly related to acoustic backscatter strength. However it is unlikely to be log-linear, as there is probably a range of sediment types on which scallop can survive and their density will decline at each extreme of this range. The functional relationship between the acoustic backscatter and scallop density may therefore be defined as a quadratic function or other non-linear function, which may become apparent if a broader range of sediments types becomes available for analysis. Tully and Hillis (1995) investigated the population structure of *Nephrops norvegicus* in the Irish Sea. They found a negative relationship between abundance and the percentage of silt clay in the sediments. However they emphasised that the relationship they observed held only for the restricted range in silt clay content in the Irish Sea sediments. *Nephrops norvegicus* biomass has quadratic relationship with silt clay content when the relationship is studied with a wider range of sediment. The log-linear relationship between scallop abundance and acoustic backscatter intensity is, therefore, most likely restricted to the range of sediment type that represent the scallop ground off the south east of Ireland.

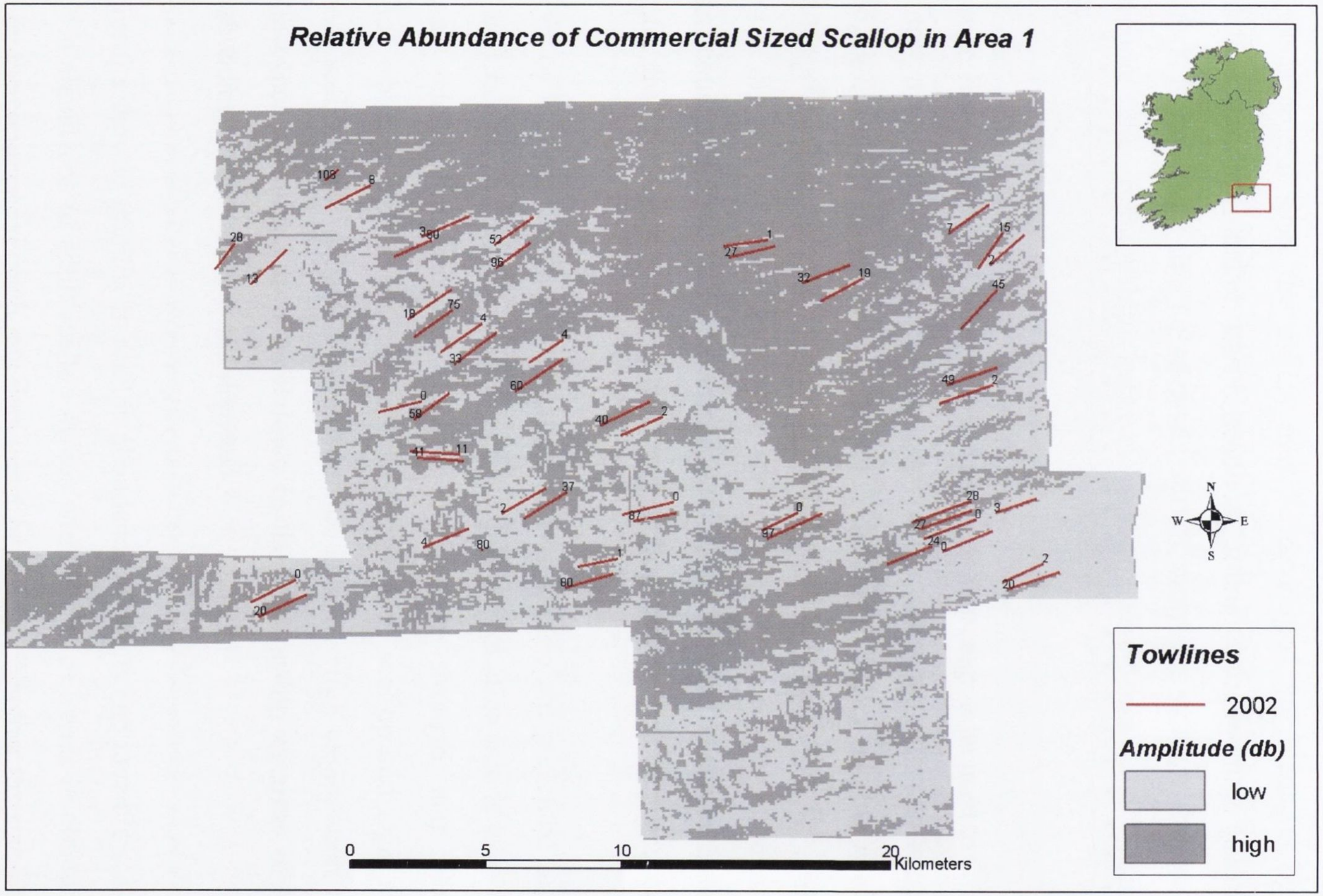
The relationship could be used as a stock indicator; simple regression diagnostics or analysis of covariance (backscatter) of the relationships could be used to examine temporal trends in population abundance. The elevation of the regression of scallop abundance on backscatter is an index of stock abundance over all ground types and should change if scallop is reduced by fishing or environmental effects on recruitment. Analysis of residuals from the regressions may point to particular backscatter or sediment types where the density is changing due to local depletion by fishing or other environmentally mediated changes in the stock distribution.

The utilization of independent research surveys is considered the most appropriate method to estimate the distribution of scallop abundance (Orensanz et al., 1991; Orensanz et al., 2006) and it is used regularly in the assessment of scallop fisheries (Vigneau, 2001; Howell, 2003; Smith, 2006, among others). A precise estimate of abundance is crucial since the fishery may be developed and managed by i.e. establishing catch limits and/or season length according to the biomass estimates. Therefore it is suggested that an adequate survey sampling strategy should take into account the relationship between scallop abundance and sediment composition.

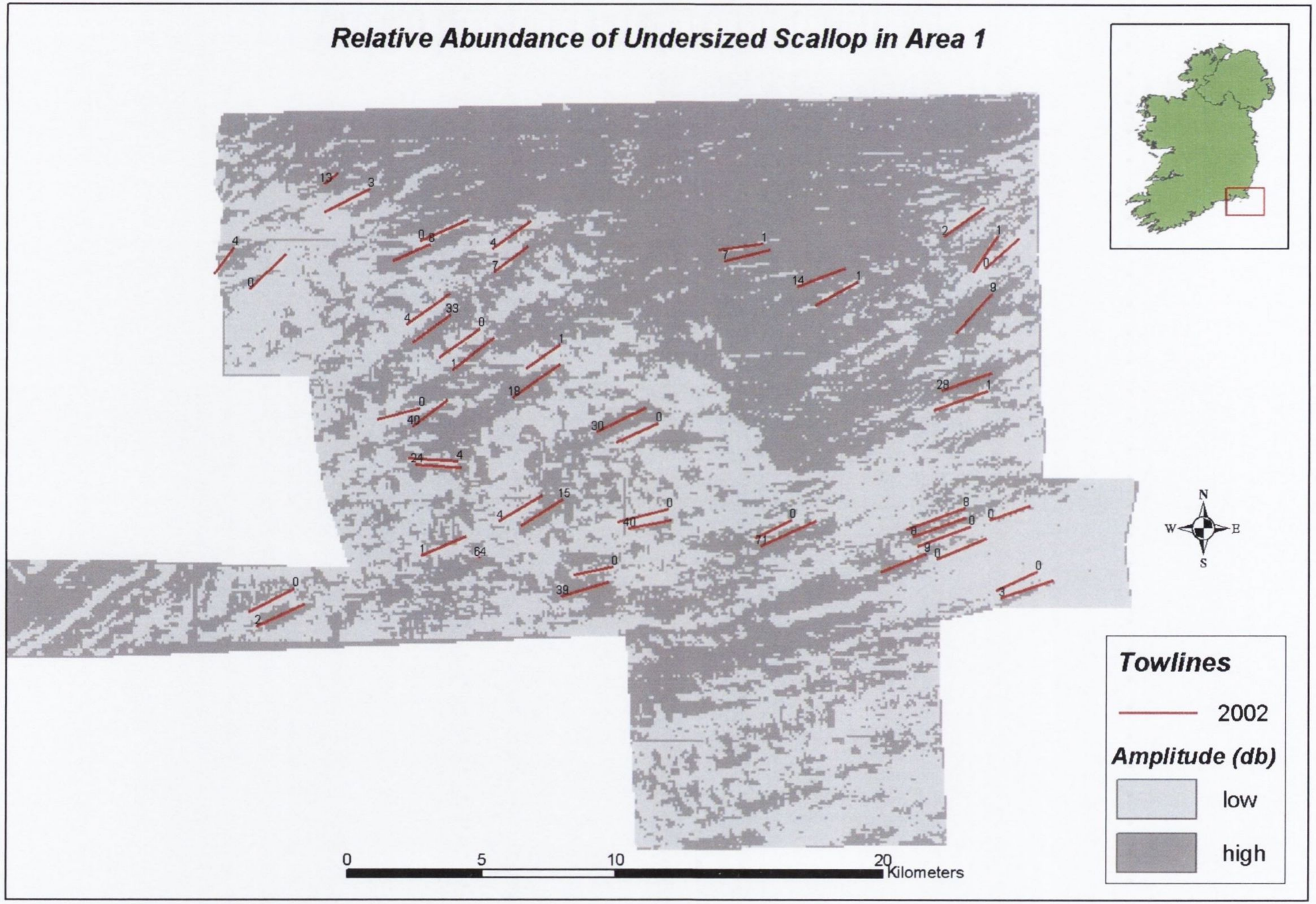
The relationship found in this study allowed the sediment map to be used to stratify survey design in 2005 and to allocate most of the sampling effort to areas of expected high scallop abundance i.e. gravel. The linear model relating acoustic backscatter to scallop abundance also enables the abundance index for scallop provided at discrete points by the scallop survey to be predicted for all areas for which an acoustic backscatter value existed. By raising the scallop survey index to account for dredge efficiency map of predicted scallop abundance was produced.

A number of indicators of the exploitation rate of scallop are presented in this thesis (see Chapter 7). These estimates suggest that exploitation rate is low. The significant relationship between acoustic backscatter strength and scallop abundance which is similar for undersized (unexploited) scallop and legal sized (exploited) scallop also suggests exploitation rate is low. High exploitation rates would be expected to lead to a breakdown in the relationship as areas of high scallop abundance were targeted and depleted.

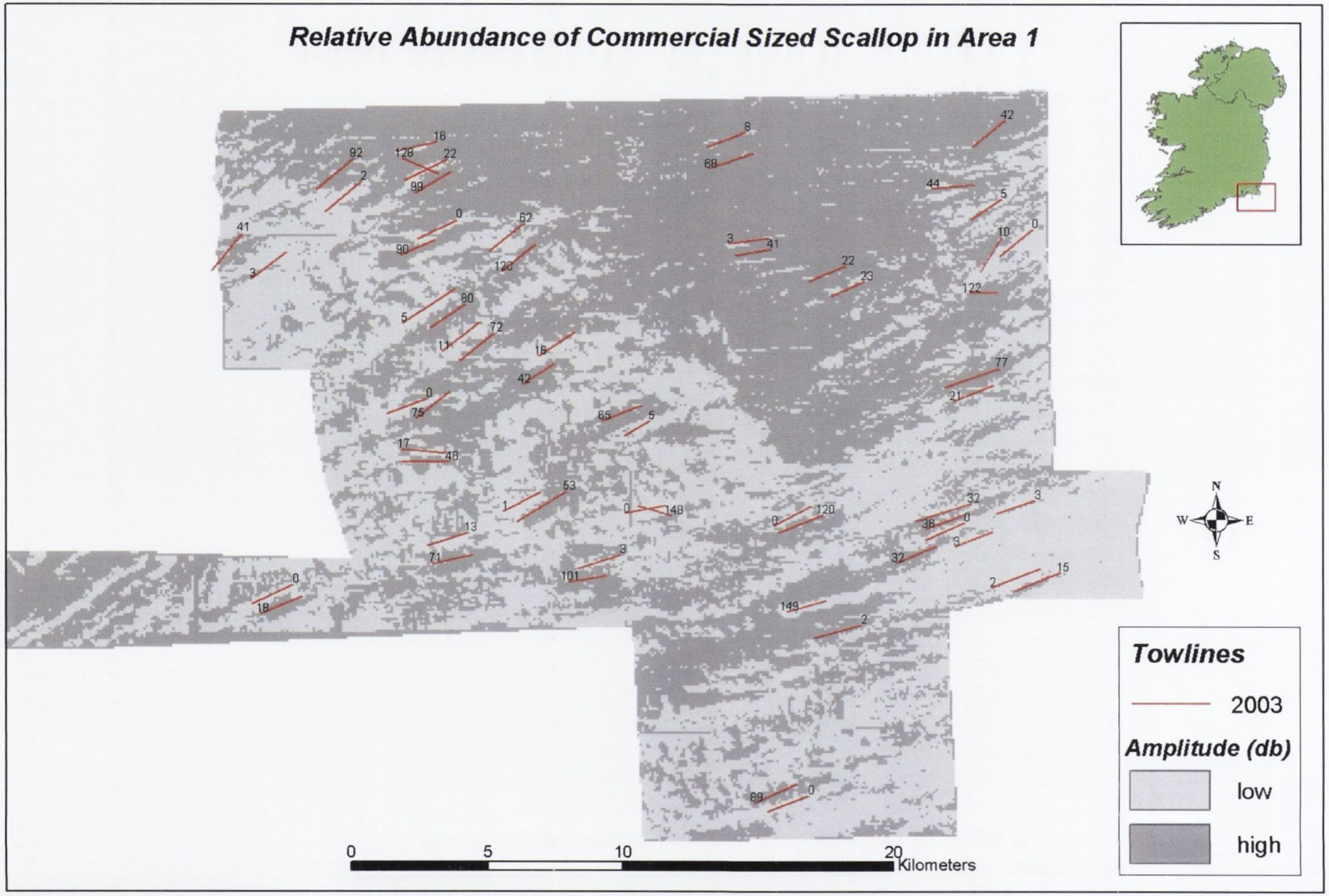
Survey results showed stability in scallop abundance of adults and juvenile scallop. Stability in abundance of adult scallop agrees with results of trends in abundance showed by the commercial catch rate data (see Chapter 4). Whether the stability in pre-recruits was due to low exploitation rates or to favourable environmental condition or both is difficult to determine. The environmental effects on larval survival and settlement and the metapopulation structure of the scallop stock make it difficult. However the stability in the trend of abundance of pre-recruits scallop might be related, to some extends, to the stability in the trend of abundance of adult scallop shown by the research surveys and the commercial catch catches.



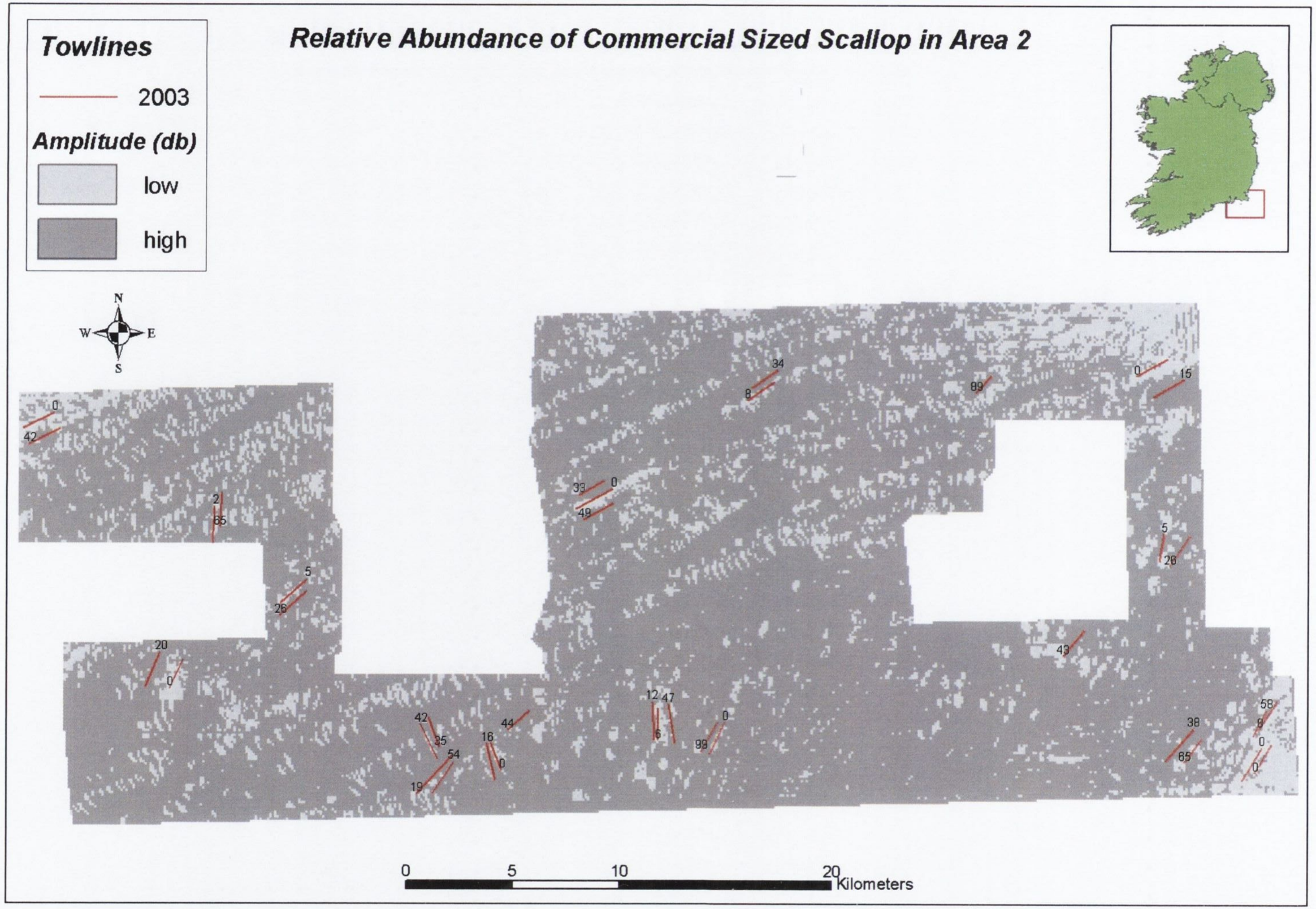
Appendix 5.1. Plot showing paired stations and associated commercial sized scallop abundance sampled in research survey from year 2002.



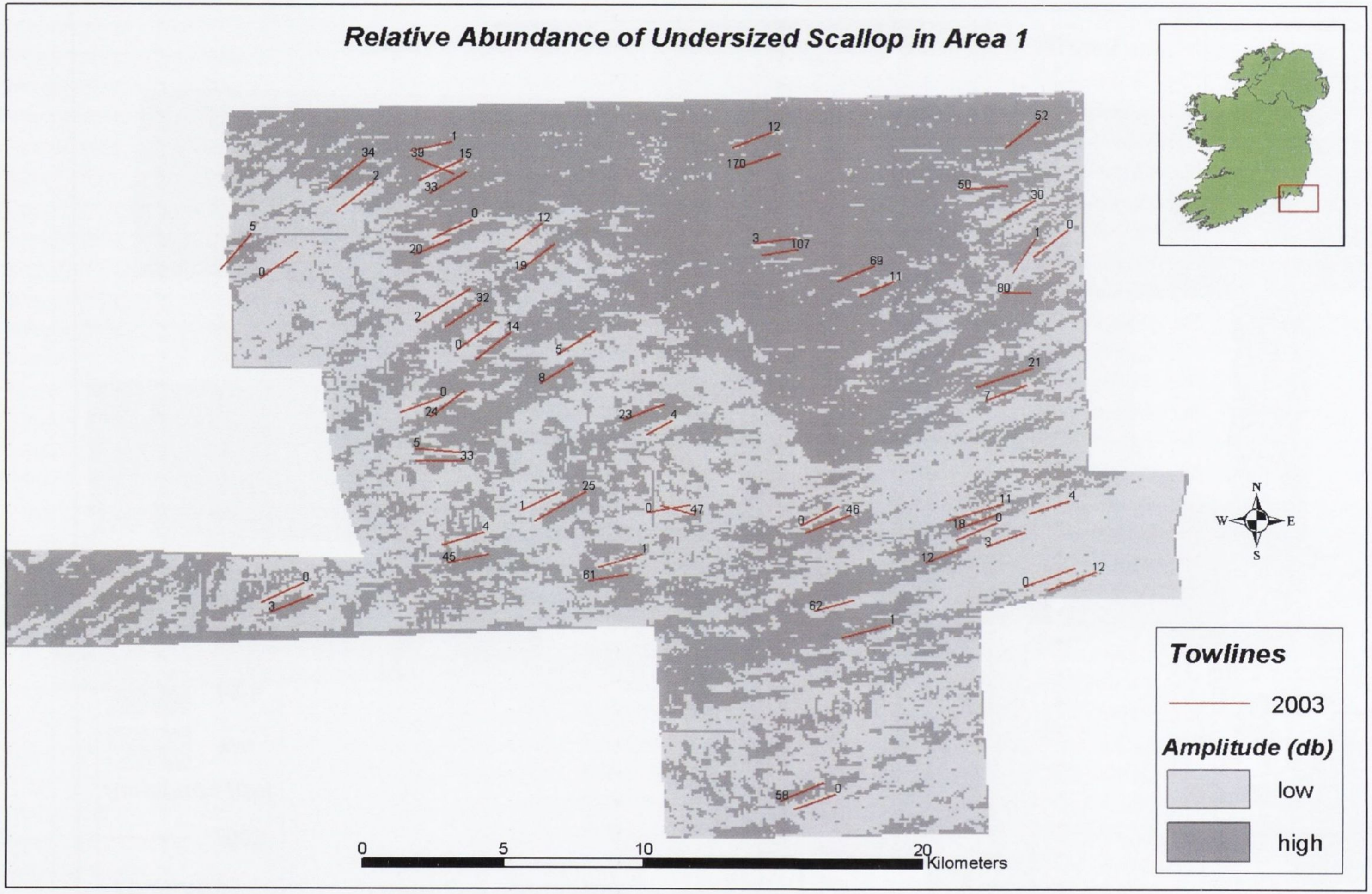
Appendix 5.2. Plot showing paired stations and associated undersized scallop abundance sampled in research survey from year 2002.



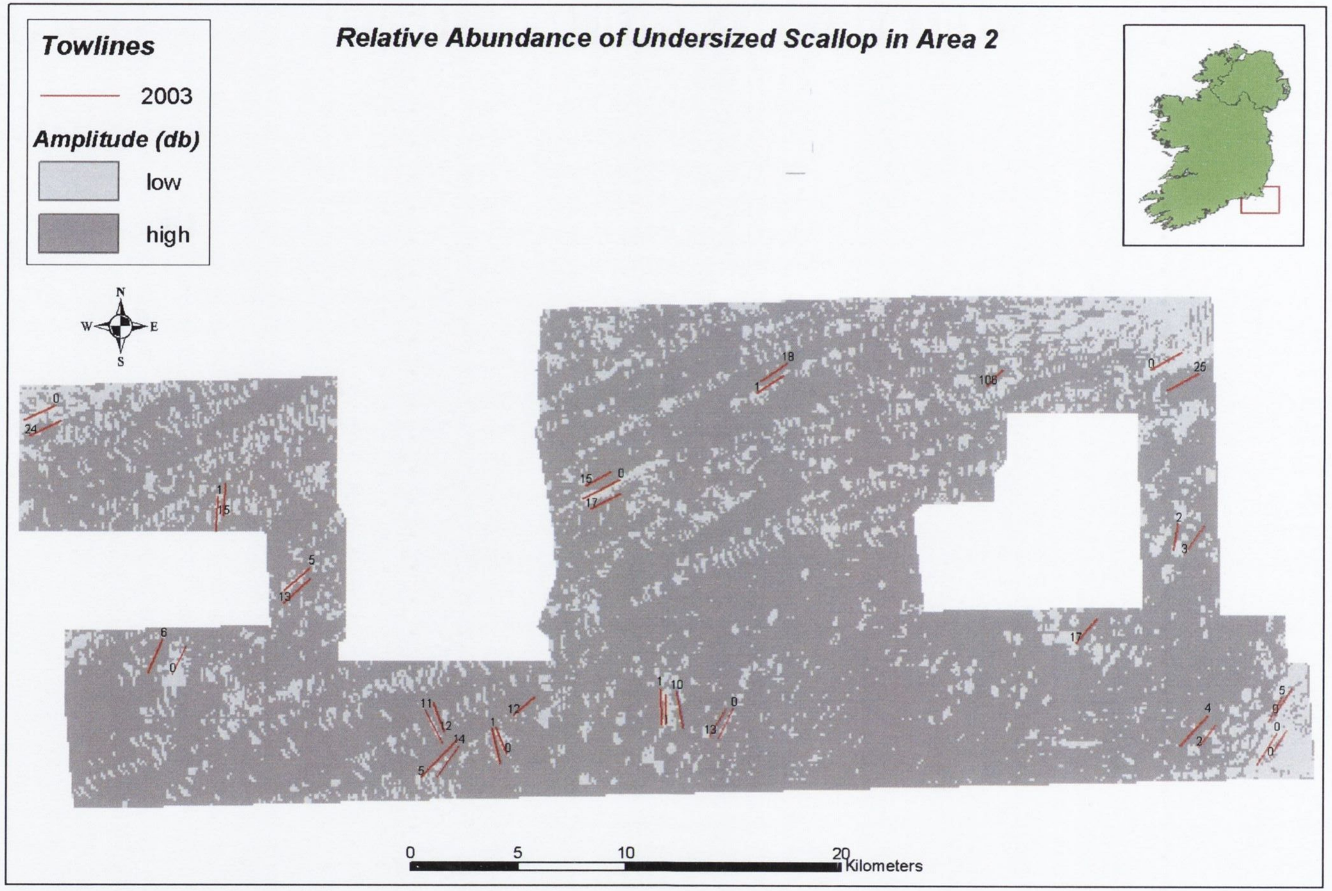
Appendix 5.3. Plot showing paired stations and associated commercial sized scallop abundance sampled in research survey from year 2003.



Appendix 5.4. Plot showing paired stations and associated commercial sized scallop abundance sampled in research survey from year 2003.

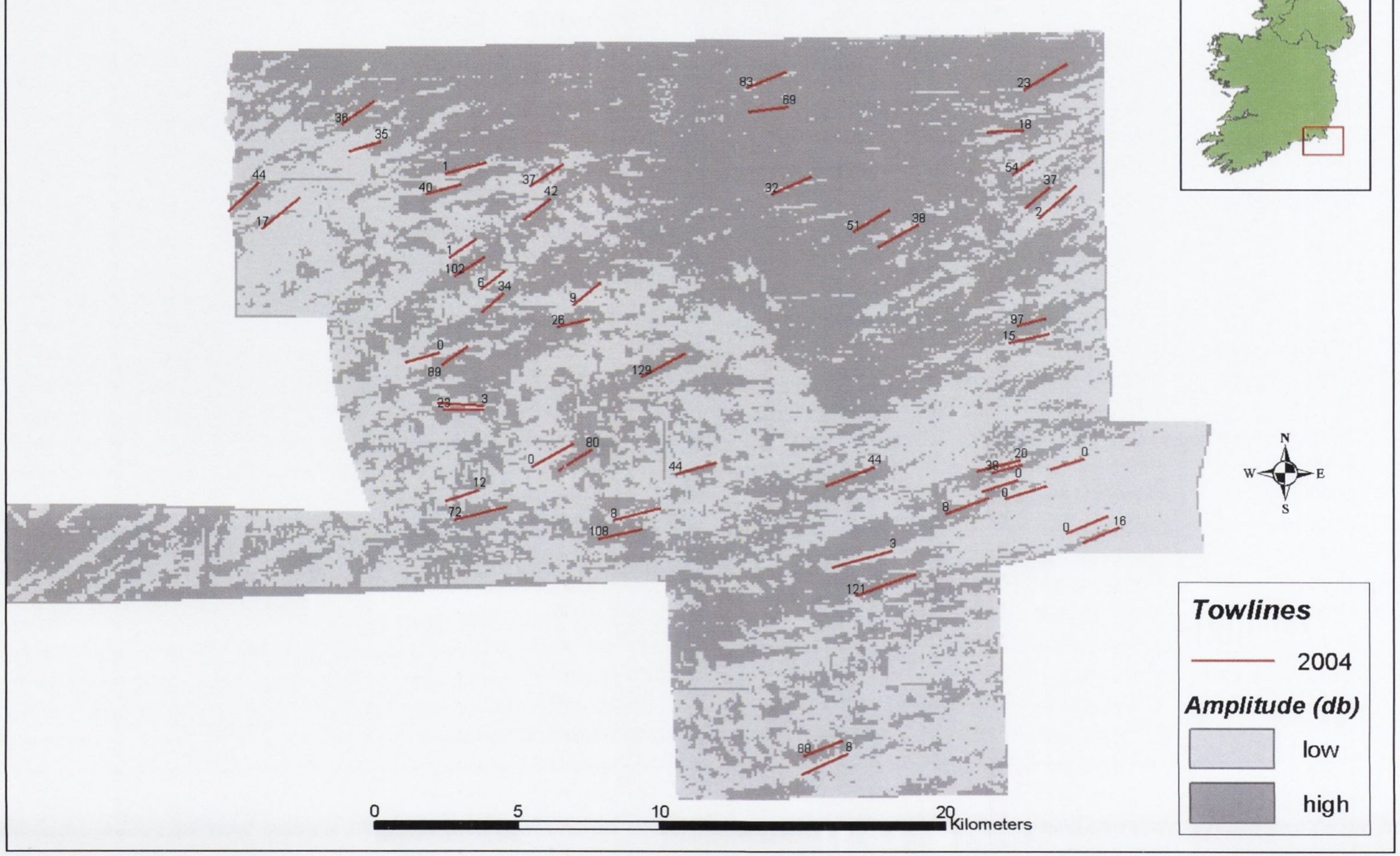


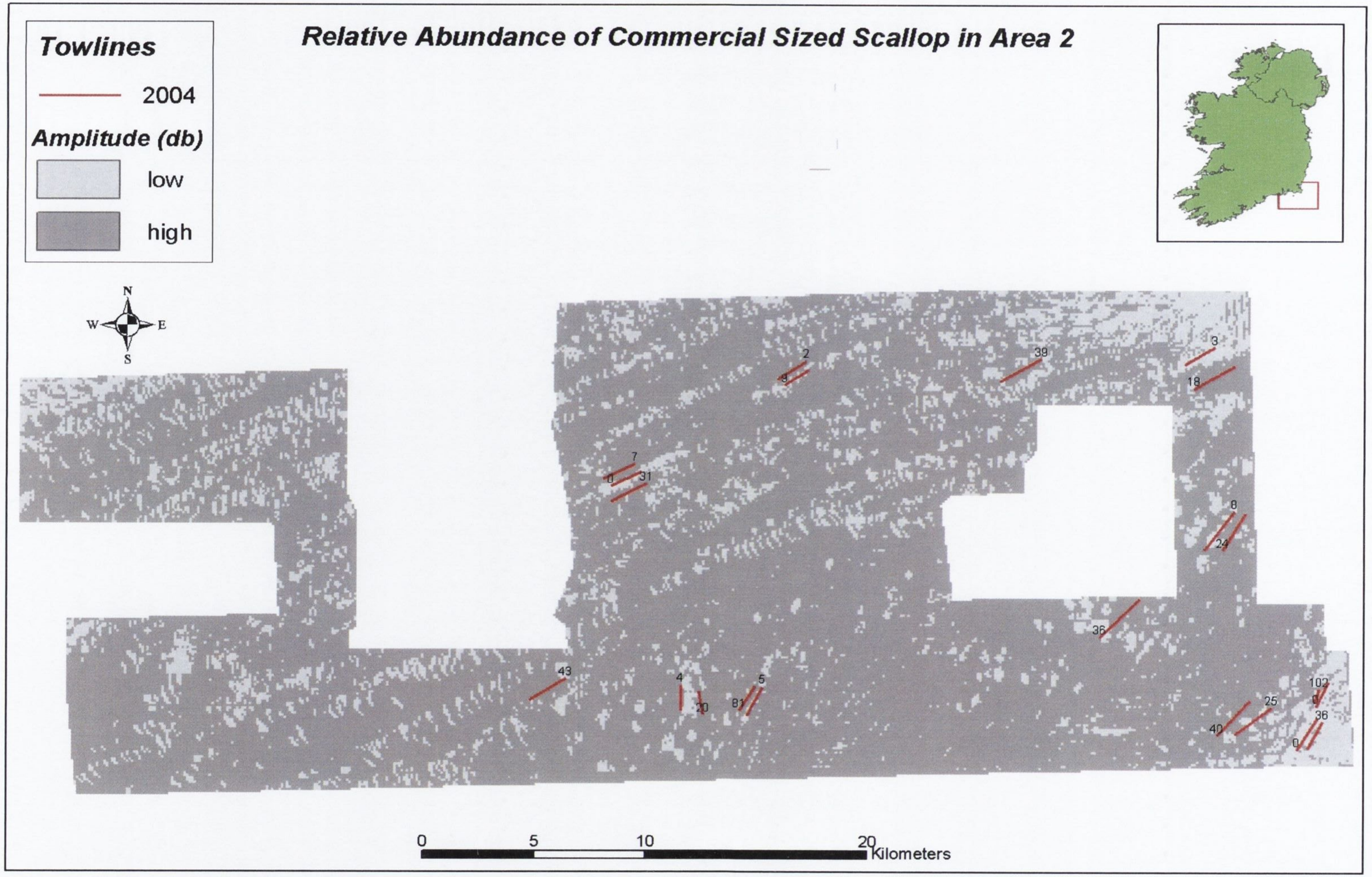
Appendix 5.5. Plot showing paired stations and associated undersized scallop abundance sampled in research survey from year 2003.



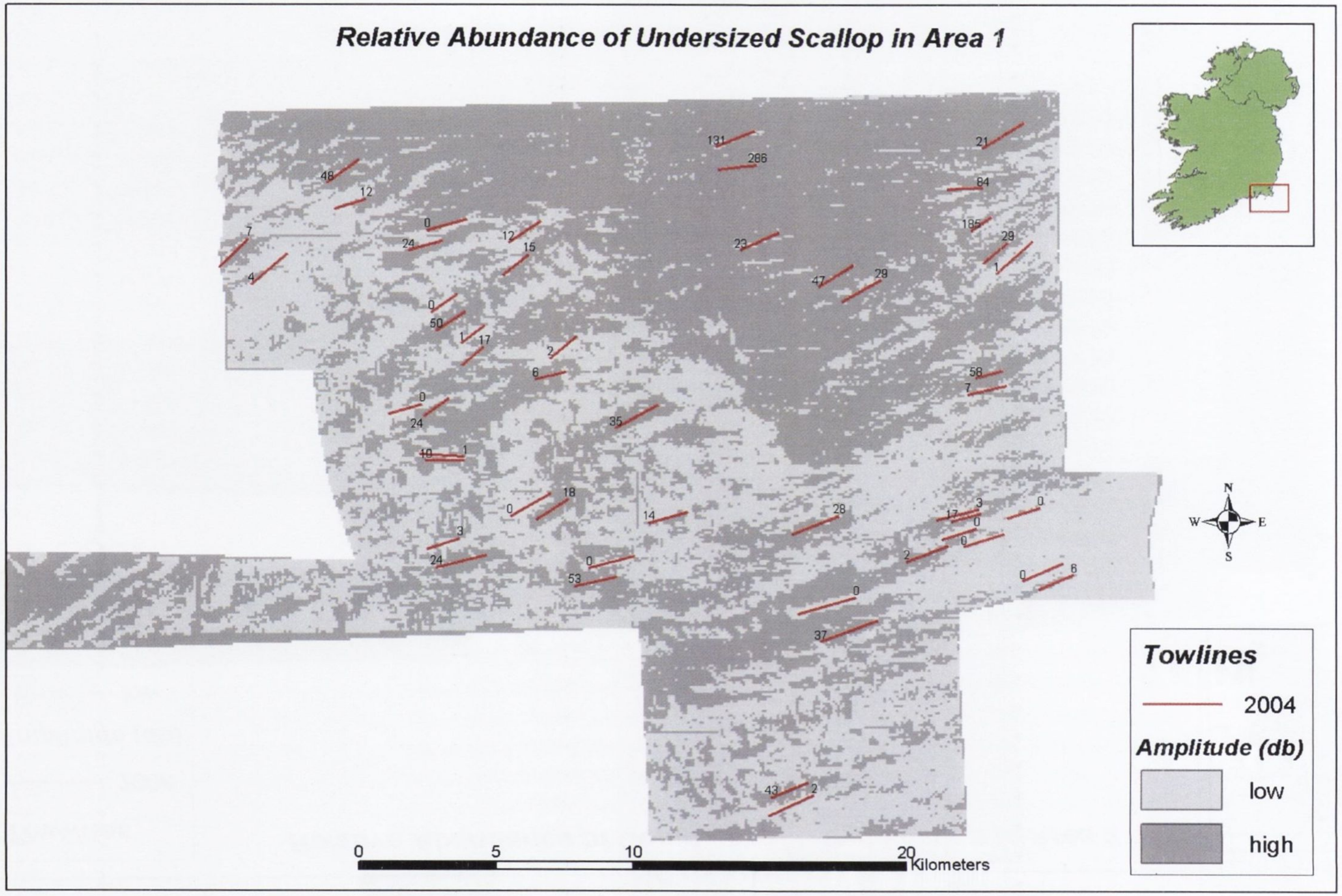
Appendix 5.6. Plot showing paired stations and associated undersized scallop abundance sampled in research survey from year 2003.

Relative Abundance of Commercial Sized Scallop in Area 1

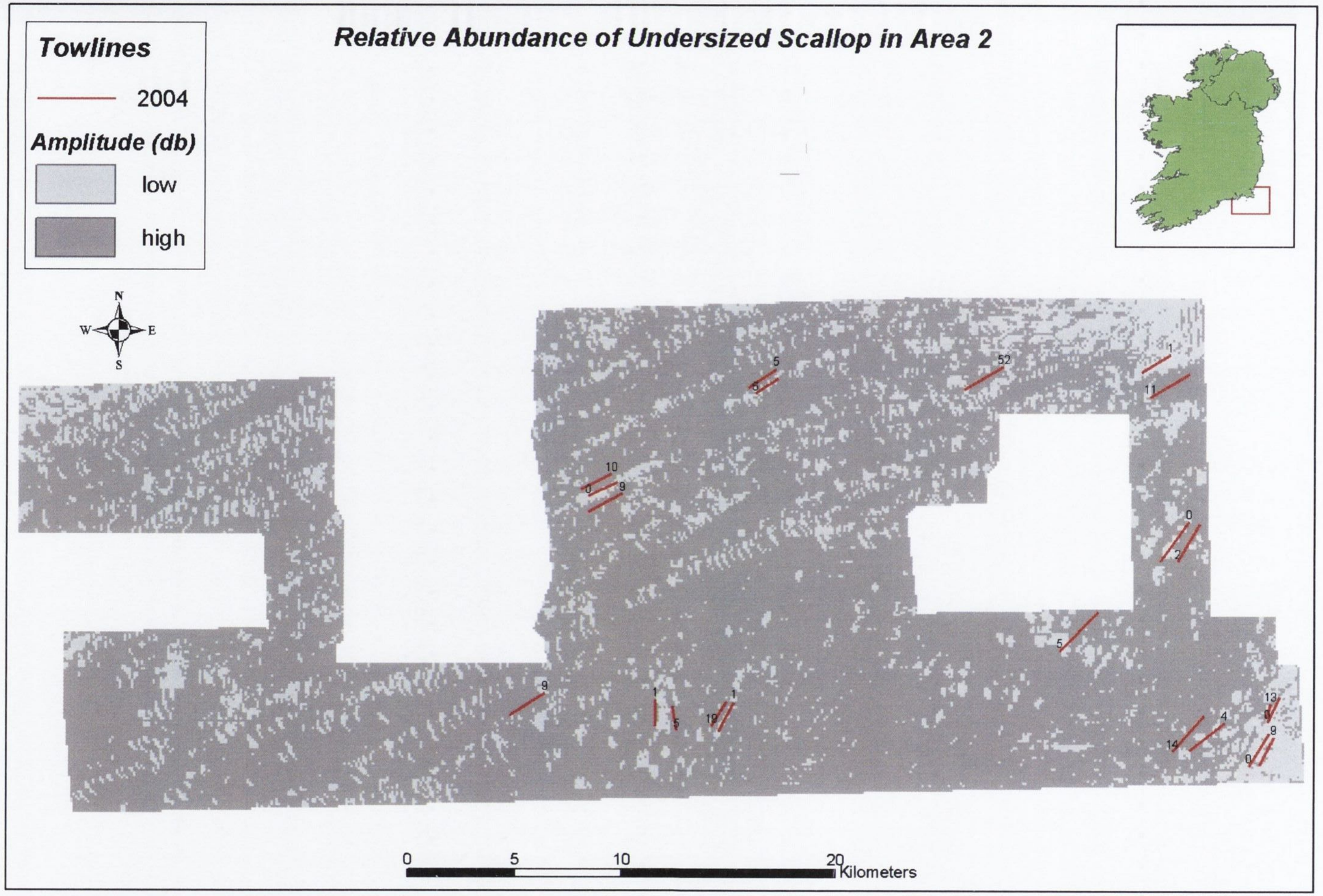




Appendix 5.8. Plot showing paired stations and associated commercial sized scallop abundance sampled in research survey from year 2004



Appendix 5.9. Plot showing paired stations and undersized scallop abundance sampled in research survey from year 2004.



Appendix 5.10. Plot showing paired stations and associated undersized scallop abundance sampled in research survey from year 2004.

Chapter 6: Yield per Recruit Assessment

6.1 *Introduction*

In fisheries assessment the understanding of the production dynamics of a fish stock and the effect that exploitation has on production are needed in order to identify fisheries reference points. Reference points can be defined as conventional values that describe the state of a fishery or population and are considered useful for management advice (Caddy and Mahon, 1995).

Two types of overfishing can be distinguished, growth and recruitment overfishing. The yield per recruit model, first developed by Beverton and Holt (1957) is used in the assessment of fisheries to provide growth overfishing reference points that indicate the optimum exploitation rate, which balances gains in yield due to growth and losses due to mortality. Growth overfishing occurs when fish are captured before they have grown large enough to maximize yield per recruit (Smith and Rago, 2004). The yield per recruit analysis of Beverton and Holt (1957) assumes that the population is in a stationary state or the population is not changing with respect to size composition, growth rates, mortality and/or recruitment over time. Under the stationary state assumption the total annual yield from the population at any one time is the same as that from the fishable lifespan of any one of its component year classes. Scallop populations are usually not in a stationary state. Recruitment variability for instance is usually high (Smith and Rago, 2004; Orensanz *et al.,* 2006). However, under a given exploitation rate, even if recruitment is highly variable, all cohorts will produce the same yield per recruit, provided other assumption of the model hold.

Recruitment overfishing reference points are defined by the exploitation rate that maintains an optimum spawning stock biomass that provides recruitment levels that do not compromise productivity of the population (Hilborn and Walter, 1992). The definition of recruitment overfishing reference points requires that a relationship between spawning stock biomass and recruitment is established and for most invertebrates stocks it has not been possible to demonstrate such a relationship (Orensanz *et al*., 1991; Smith and Rago, 2004). In scallops, the poorly understood stock/recruitment relationship is due in part to the larvae pelagic phase in which dispersal over long distances results in a complex meta-population structure. Tully *et al*. (2006a) developed a hydro-advection model of the Irish and Celtic Seas in order to identify how scallop stocks are connected through larval dispersal. They showed that the structure of the stocks is determined by the dynamic of larval dispersal from spawning areas, which is determined by the ocean circulation patterns coupled with the behaviour of larvae. Meta-population structure and high mortalities in the larvae and the early settled life stages (Le Pennec *et al*., 2003) makes it difficult to identify the stock/recruitment relationship and therefore recruitment overfishing reference points for scallops are difficult to define. Recruitment of scallop is usually monitored through independent research surveys where the type of gear used is designed in order to select juvenile scallops that can be used to provide an index of recruitment (see Chapter 5).

This chapter provides information on yield per recruit of scallops using the Beverton and Holt (1957) model. This model attempts to find a balance between growth and mortality that will give maximum yield for a given natural mortality and age at recruitment. The fishing mortality rate that maximises yield per recruit is defined as F_{max}. Growth of scallop varies spatially (see Chapter 3) and therefore mortality rates that maximise yield will also vary spatially. Thus, the objective of this study was to investigate and discuss how the spatial variability in growth affects the definition of growth overfishing in yield per recruit analysis. Analysis was carried out for different sizes at recruitment to investigate the implications of changes in minimum landing size on yield per recruit. In addition to F_{max}, the marginal yield criterion $F_{0.1}$ was also estimated. Gulland and Boreman (1973) introduced the use of $F_{0.1}$ for fisheries management, which is the fishing mortality rate at which the increase in yield per recruit in weight for an increase in a unit of effort is only 10% of the yield per recruit produced by the first unit of effort on the unexploited stock. It corresponds to the point on the yield per recruit function where the slope is 10% at the origin. Growth overfishing reference points, F_{max} and $F_{0.1}$, at different size at recruitment were estimated and their application in the management of the scallop stock was discussed.

The yield per recruit analysis was used in combination with the spawning biomass per recruit analysis (SSBR). The spawning stock biomass (SSB) is the total weight of all sexually mature individuals in the population and the SSBR give a measure of the reproductive potential of an average recruit. The ratio of the fished and the unfished magnitude of the reproductive potential of an average recruit is the spawning potential ratio (SPR). SPR at F_{max} and $F_{0.1}$ was calculated to provide a measure of the impact of fishing mortality on the potential productivity of the stock (Goodyear, 1993).

In addition the current fishing mortality rate, $F_{current}$, was estimated and compared with F_{max} and $F_{0.1}$. Current fishing mortality rates were estimated from catch curves analysis. The catch curve method uses the age structure of the catch to follow the decline of each individual cohort, or year class, in the population through time (Hilborn and Walter, 1992). Data from annual research surveys, between 2001-2005 were used for the analysis.

6.2 Source of Data and Methods

The biomass of a given number of recruits at a given rate of natural mortality and growth will increase as long as production due to growth exceeds losses due to mortality. A point is reached where biomass is at a maximum biomass after which it declines. The greatest possible yield will be obtained if the minimum landing size is set at a size at which biomass is greatest, and all individuals are then harvested ($F_{max}= \infty$). However, if individuals are harvested at sizes smaller than the size at which biomass is greatest then the fishing mortality rate have to be adjusted in order to allow some fraction of the animals to survive and grow to balance the low yield that resulted from harvesting at small size. In practice and because of variability in growth the exploitation of a given cohort will take place over a period of time and over a range of fish sizes for that cohort.

6.2.1 Mapping Growth Overfishing Reference Points (F_{max})

The yield per recruit analysis estimates optimum fishing mortalities (F_{max}), in terms of yield, for a given growth and mortality rate. Growth parameters were estimated on a 5 x 5 mile spatial scale (see Chapter 3) and natural mortality value of 0.15 were used to map F_{max} using equation 6.21 of Quinn and Deriso (1999). $M = 0.15$ was chosen following a number of estimated values of M, for *pecten maximus* in the British Islands, that ranged between 0.1-0.2 (Gruffydd, 1974; Franklin *et al.*, 1980; Mason, 1983). $M = 0.15$ has also been used in other yield per recruit analysis of scallops (Orensanz *et al.*, 1991; Hart, 2003). Although the value of F_{max} will change depending on the value of M, this will not have consequences on how spatial variability in growth will affect the definition of F_{max}, assuming that M is constant spatially.

$$F_{\max} = \left(\frac{k}{\left(\sqrt{\left(1 - {W_c}/{W_\infty}\right)\left(1 + {k}/{M}\right)} - 1 \right)} \right) - M \qquad (6.1)$$

where k is the curvature parameter of the von Bertanlanffy growth equation, W_∞ is the asymptotic weight, W_c is the weight at age of recruitment, and M is the natural mortality. Growth was modelled using size at age data and weight at recruitment and weight asymptotic was calculated from the shell height/weight allometric relationship described in 3.2.3. Weight at age at recruitment was the weight that individuals reached at 89mm shell height, or 100mm in shell length, corresponding to the minimum landing size (see 5.2).

Quinn and Deriso (1999) formulated Equation 6.1 by modelling weight at age using a difference equation form of the vonBertalanffy model developed by Deriso (1980). Rather than specifying growth as a continuous curve Deriso (1980) used a single value for each annual interval of the curve and modelled weight at age as a linear function, where:

$$W(t) = W_\infty\left(1 - e^{-k(t-t_0)}\right) \qquad (6.2)$$

Equation 6.2 is strictly concave, so it is appropriate only to model growth for those fisheries in which the inflexion point in growth occur before size/age at recruitment (t_c). This is valid for scallop growth (Smith and Rago, 2004). Quinn and Deriso (1999) used Equation 6.2 to derive the yield per recruit theory of Beverton and Holt (1957) as it is more simple to use the linear function than the cubic weight at age function given by the vonBertalanffy growth model, to formulate fisheries equation such as Equation 6.1.

6.2.2 The Computation of Yield per Recruit Curves

The total yield from a population can be expressed algebraically as (Gulland, 1956):

$$Y = \sum w_t N_{ct} \qquad (6.3)$$

where w_t is the weight at age t and N_{ct} is the number of individuals caught at age t. Having estimated growth rate parameters that give information on how the weight of individuals increase with age, on an annual basis, and having fixed natural and fishing mortality rates to model the decline of individuals through cohorts the yield to be obtained from the population given by Equation 6.3 can be estimated. The equation describing the decline of a cohort through time is:

$$N_{t+1} = N_t e^{-z} \qquad (6.4)$$

where N_{t+1} and N_t are the number of individuals at ages t+1 and t respectively and Z is the total instantaneous mortality rate that includes losses due to natural (M) and fishing (F) mortality. The number of individuals lost at any time N_z is given by:

$$N_z = N_t - N_{t+1} = N_t - N_t e^{-z} = N_t\left(1 - e^{-(M+F)}\right) \qquad (6.5)$$

and losses due to fishing mortality, N_{ct}, are simply the fraction (F/Z) of the total losses due to natural and fishing mortality (Z). This can be expressed algebraically as (Haddon, 2001):

$$N_{ct} = \left(\frac{F}{F+M} \right) * N_t * \left(1 - e^{-(M+F)}\right) \tag{6.6}$$

Shell height at age was obtained from the vonBertanlaffy growth function described by Equation 3.1. Shell height at age was converted into a weight at age by using the shell height/weight relationship described in 3.2.4.

Age at first capture was calculated by rearranging the vonBertalaffy growth equation (3.1):

$$t_c = t_o - \left[\frac{1}{k} \left(Ln \left(\frac{L_\infty - L_t}{L_\infty} \right) \right) \right] \tag{6.7}$$

where t_0, K, and L_∞ are the growth rate parameters and L_t is the size at recruitment. Yield per recruit analysis was carried out for 90mm, 100mm, and 110mm (shell length) size at recruitment. Therefore, once the growth parameters are known the calculation of the age at first capture (t_c) is straightforward.

Fishing and natural mortality (F and M) were assumed to be independent of age. M was applied starting at the age at recruitment of the lowest harvest size (90 mm shell height) for all three different sizes at recruitment to the fishery and was fixed at 0.15.

Fishing mortality was given by $F(h) = F_0 J(h)$, where F_0 is the fully recruited fishing mortality rate and $J(t)$ is the selectivity of the gear at size (h). Full fishing mortality was applied to those scallops of age equal or greater than the age at first capture (t_c) and mortality due to discarding was considered negligible (Sangster *et al.*, 2003). The selectivity curve $r(l)$ for the commercial scallop dredge, given by the symmetric logistic function (Millar and Walsh, 1992), were calculated in Chapter 2.

Hence, by fixing natural and fishing mortality, the numbers of individuals caught per year class N_{ct} were estimated. Total yield was given by the sum of the yield from t_c to t_{max} and, therefore, yield per recruit was calculated by dividing the total yield by the number of recruits introduced in the model at t_c.

The sum of the fractions of biomass remaining each year (t) gave the spawning stock biomass. This can be expressed algebraically as:

$$SSB = \sum_{t=t_0}^{t=t_{\max}} N_t * w_t \tag{6.8}$$

where t_0 and tmax are the initial age (age at 90 mm shell height) and the ending age of the simulation. The SSBR was calculated by dividing SSB by the initial number of recruits.

The spawning potential ratio was calculates as:

$$SPR = \frac{SSBR_{fished}}{SSBR_{unfished}} \tag{6.9}$$

where $SSBR_{\text{fished}}$ and $SSBR_{\text{unfished}}$ are the spawning stock biomass per recruit of the fished and unfished population respectively.

The model was run for 1000 recruits from t_0=age at 90 mm shell height to $t_{\max}=30$, which gave a sufficiently large number of years to run the cohort to extinction.

6.2.3 The Estimation of Mortality Rates from Catch-curves

Quantifying the loss of individuals from a population through death is usually described, for stock assessment purposes, as an instantaneous mortality rate (Z) and can be defined as the proportion of individuals from a fish population that die in a very short interval of time due to natural mortality (M) and due to fishing mortality (F) (Sparre, 1992; Hilborn and Walter, 1992; King, 1995; Quinn and Deriso, 1999; Haddon, 2001).

The equation that describes the survival of a cohort that is subject to fishing is given by:

$$N_t = N_0 e^{-Z_t} \tag{6.10}$$

where Nt is the number of individuals at time t, N_0 is the number of individuals at the start of the time interval for which mortality rates are estimated, and Z_t is the instantaneous mortality rate from t=0 to t=t.

Equation 6.10 describes a negative exponential decay of a population. As mentioned above the instantaneous mortality rate (Z) is partitioned into mortality rate due to natural causes (M) and due to the fishing process (F):

$$Z = F + M \tag{6.11}$$

Catch curves, in which the number of individuals of a cohort are estimated for different time periods, can be used to estimate mortality rates assuming that the age structure of the catch represent the age structure of the population. Equation 6.10 can be linearised to the form of the classical catch curve introduced, for the estimation of mortality rates, by Beverton and Holt (1957):

$$\ln N_t = \ln N_0 - Z_t \tag{6.12}$$

The instantaneous mortality rate that applies to time interval t=0 to t=t is defined by the slope of Equation 6.12. Assuming that natural mortality is known once Z is estimated the estimation of F is straightforward by using equation 6.11.

Data for the estimation of instantaneous mortality rates were obtained from annual scallop research surveys between 2001-2005. The number of scallops sampled were standardised to 1000m transect length, assuming a linear relationship between catch and tow length. As described in Chapter 5, all scallops caught during research surveys were measured to the nearest mm and a sub-sample was aged. Hence data on scallop size structure could be converted into age through the use of an age-length key.

Mortality rates were estimated from two different catch curves analyses; catch curves from all age classes present in a particular year (*pseudocohort catch curve*) and catch curves that followed the fate of single cohorts (*true cohort catch curve*). *Pseudocohort catch curves* assumes that the system is in equilibrium and treats the proportions of the different age classes as if they were the product of a single cohort. Equilibrium in this context means that recruitment and fishing mortality have been constant across years for the period represented by all age classes in the sample. *True cohort catch curves* assumes that age classes included in the analysis are fully recruited (this assumption is also needed for pseudocohort analysis) and catchability of the dredge is the same between years (Beverton and Holt, 1957).

6.3 Results

6.3.1 Estimation of growth overfishing reference points

Estimates of F_{max} were higher where growth was relatively low, at the assumed rate of natural mortality, and lower where growth was relatively high with values ranging from 0.4 to 2.2 (Figure 6.1).

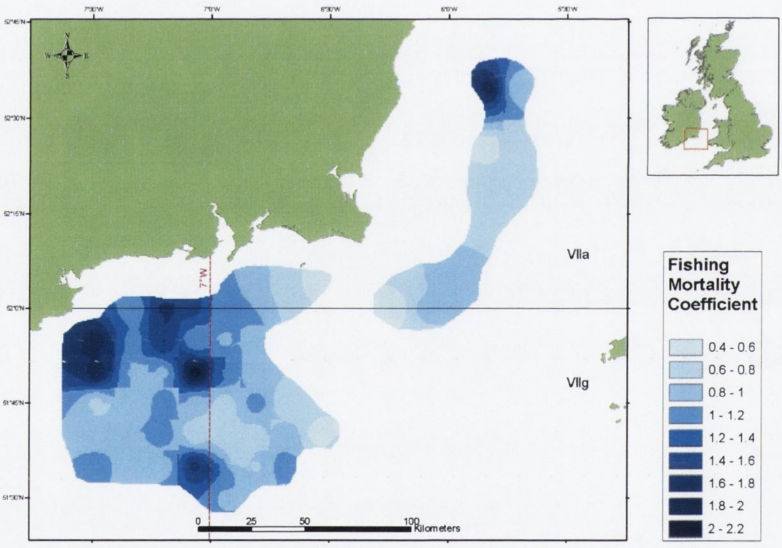


Figure 6.1. Estimates of the fishing mortality that maximises yield per recruit (F_{max}) based on vonBertalanffy growth model and minimum landing size of 100mm in shell length.

The overall area was divided into seven sub-areas within which growth was similar. Growth rate estimates for the seven sub-areas were then used in fitting the yield per recruit model and deriving fishery management reference points. The Spawning potential ratio at different levels of fishing mortality was also computed. The SPR at F_{max} and $F_{0.1}$ was used as an indicator of the productivity of the stock (Figure 6.2 and Table 6.1).

In general an increase in minimum landing size from 100 mm to 110 mm would increase yield per recruit at F_{max} and $F_{0.1}$. Increases of 5-7% and 2-4% in yield were achieved at F_{max} and $F_{0.1}$, respectively, in all areas except in the southwest area where yield per recruit decreased by 4% at $F_{0.1}$. Decrease in minimum landing size from 100 mm to 90 mm in shell length would reduce yield per recruit by 1-4% and 1-3% in yield per recruit at F_{max} and $F_{0.1}$, respectively

The spawning potential ratio (SPR) ranged between 0.1-0.3 and 0.3-0.5 at F_{max} and $F_{0.1}$ respectively. In general an increase or decrease in the minimum landing size did not determine significant changes in the spawning potential ratio at F_{max} and $F_{0.1}$ (Table 6.2). The exception of this was in the southwest area. An increase in the minimum landing size from 100 mm to 110 mm produced a decrease in SPR of 35% and 25% at F_{max} and $F_{0.1}$ respectively.

The shape of the yield per recruit curves depended on how close to the critical age i.e. the age/size at which scallops reach their peak in biomass, the size/age at recruitment was. Low growth produced flat-topped curves. This occurred for all areas except for the Saltees Islands and Barrels Bed. F_{max} was poorly defined in flat-topped curves. The extreme case was observed in the southwest area were Fmax was not reached at size at recruitment of 110 mm. In the Saltees Islands and Barrels Bed growth was higher and the curves were non-flat topped and Fmax was well defined.

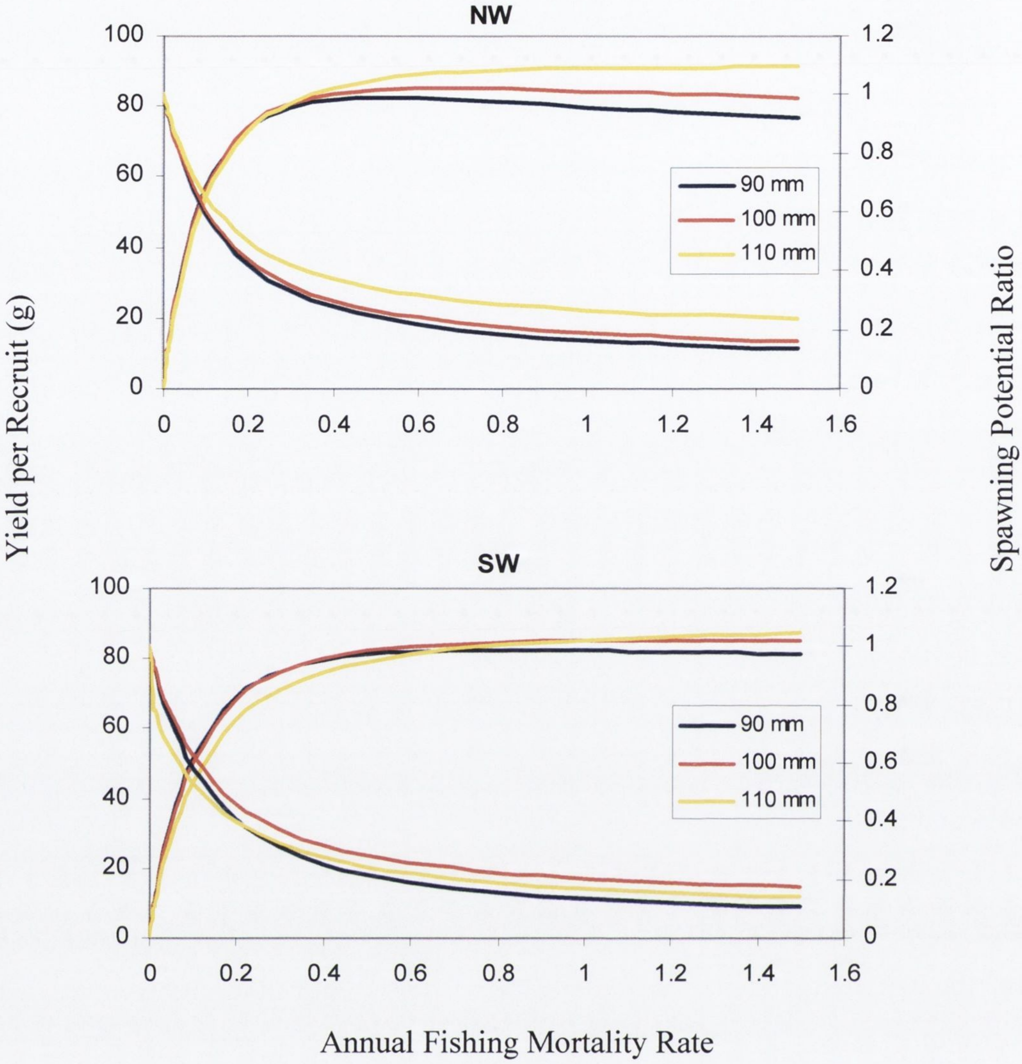


Figure 6.2a. Yield per recruit and biomass per recruit curves for the northwest (above) and the southwest (bellow) areas for sizes at recruitment 90, 100, and 110 mm in shell length (see legend). Biomass per recruit is expressed in terms of spawning potential ratio.

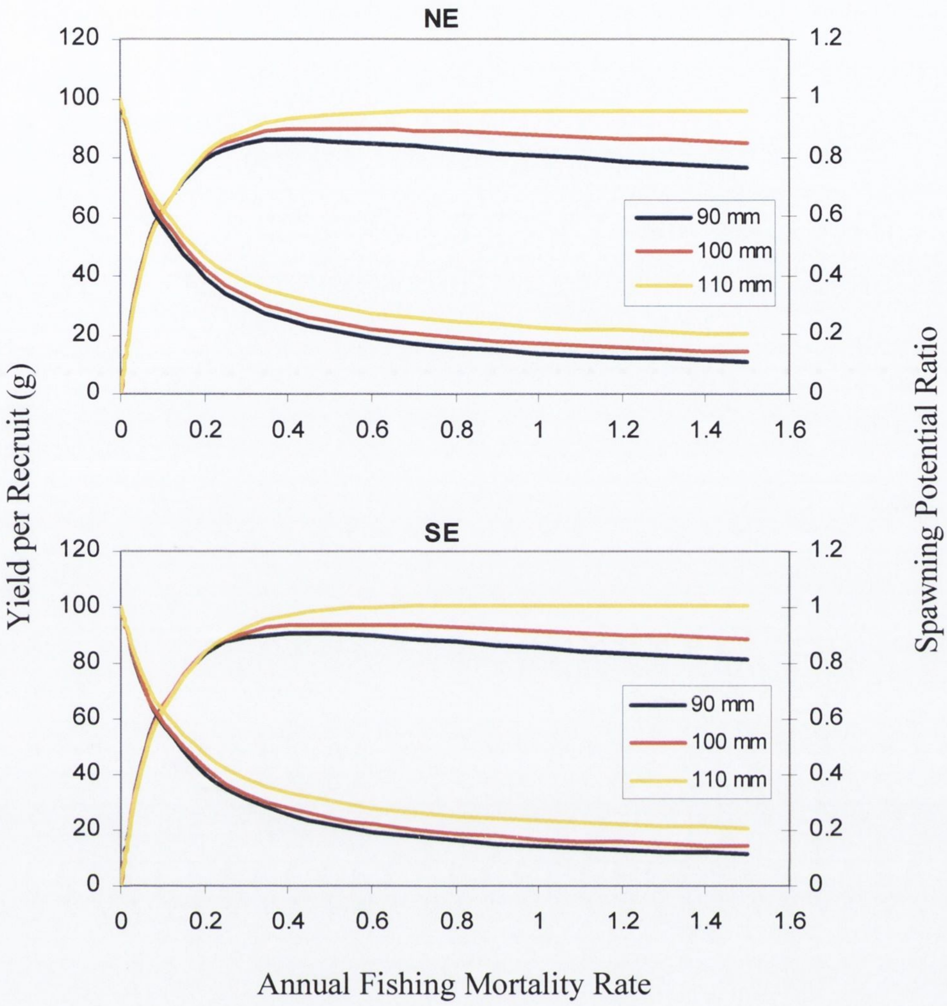


Figure 6.2b. Yield per recruit and biomass per recruit curves for the northeast (above) and the southeast (bellow) areas for sizes at recruitment 90, 100, and 110 mm in shell length (see legend). Biomass per recruit is expressed in terms of spawning potential ratio.

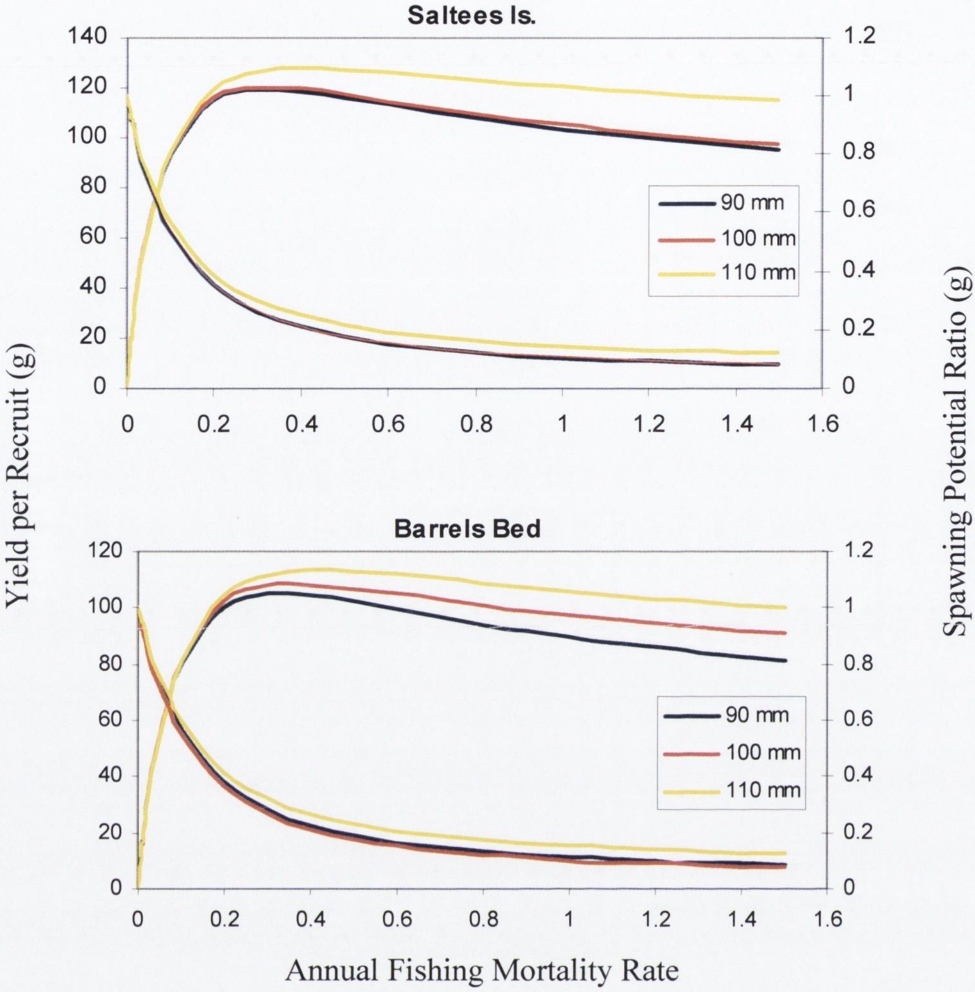


Figure 6.2c. Yield per recruit and biomass per recruit curves for the Saltees Islands (above) and the Barrels Bed (bellow) areas for sizes at recruitment 90, 100, and 110 mm in shell length (see legend). Biomass per recruit is expressed in terms of spawning potential ratio.

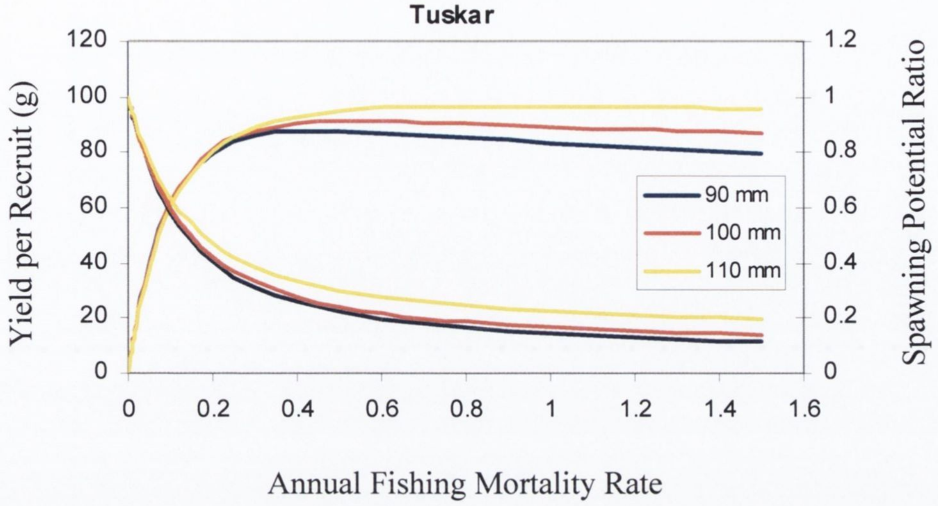


Figure 6.2d. Yield per recruit and biomass per recruit curves for the Tuskar area for sizes at recruitment (MLS) 90, 100, and 110 mm in shell length (see legend). Biomass per recruit is expressed in terms of spawning potential ratio.

Table 6.1. Calculated values of F_{max}, Y_{max}, SPR_{max}, *and* $F_{0.1}$, $Y_{0.1}$ *and* $SPR_{0.1}$ *for minimum landing sizes (MLS) of 90,100, and 110 mm in shell length.* Y_{max} *= yield per recruit at* F_{max}; $Y_{0.1}$ *= yield per recruit at* $F_{0.1}$; SPR_{max} *= Spawning potential ratio at* F_{max}; $SPR_{0.1}$ *= Spawning potential ratio at* $F_{0.1}$; t_c*= age at recruitment.*

Area	MLS	t_c	F_{max}	Y_{max} (g)	SPR_{max}	$F_{0.1}$	$Y_{0.1}$	$SPR_{0.1}$
Northwest	90	3.7	0.52	82.41	0.24	0.20	73.54	0.42
	100	4.4	0.64	85.28	0.23	0.21	74.99	0.45
	110	5.4	1.49	91.22	0.24	0.24	76.60	0.47
Southwest	90	4.0	0.80	82.40	0.16	0.23	71.55	0.37
	100	4.9	1.22	85.22	0.19	0.24	72.24	0.42
	110	6.4		87.43	0.14	0.28	69.63	0.34
Northeast	90	3.5	0.42	86.02	0.24	0.19	78.69	0.41
	100	4.2	0.51	89.74	0.24	0.20	80.69	0.42
	110	5.0	0.94	95.92	0.23	0.22	83.23	0.44
Southeast	90	3.6	0.44	90.71	0.24	0.19	82.32	0.41
	100	4.2	0.52	93.91	0.24	0.20	84.28	0.42
	110	5.1	0.98	101.00	0.23	0.22	86.78	0.45
Saltees Is.	90	3.2	0.32	119.63	0.25	0.16	110.23	0.41
	100	3.7	0.32	120.44	0.25	0.17	112.19	0.40
	110	4.3	0.41	128.11	0.25	0.18	116.50	0.42
Barrels	90	2.7	0.33	105.04	0.26	0.17	96.95	0.42
	100	3.0	0.36	108.36	0.23	0.18	99.80	0.39
	110	3.6	0.43	113.53	0.26	0.19	102.87	0.43
Tuskar	90	3.4	0.46	87.76	0.23	0.20	79.80	0.40
	100	4.0	0.55	91.00	0.23	0.21	81.73	0.41
	110	4.8	0.85	96.49	0.24	0.23	83.74	0.44

6.3.2 The Estimation of Fishing Mortality Rates

Population size and age structure obtained from each of the surveys carried out in years 2001-2005 and in each of the growth areas (northeast, northwest, southeast and southwest areas) is presented in Figure 6.3 – 6.6. Age-length keys, used to convert size structure into age structure, are presented in Tables 6.2-6.5. The age-length keys were constructed for each scallop ground for which mortality rates were estimated using catch curve analysis.

Age classes 2-7 and 2-8 were obtained in the catch for the west and east areas respectively. Although there were small differences in age structure between years and areas, generally the age structure of the population was stable in all areas for the years 2001-2005.

Estimates of mortality rates, assuming constant recruitment, were given by the slope of the line that describe the decay in abundance of different cohorts from each year population structure (red arrows in Figures 6.5 and 6.6). Estimates of mortality rates for non-constant recruitment were given by the slope of the line that describes the decay in abundance of individuals cohort (black arrows in Figures 6.5 and 6.6).

Instantaneous fishing mortality rates ($F_{current}$) in each growth area, from the two methods of analysis, were similar (Table 6.7). Estimates of $F_{current}$ in each growth area were compared with the yield per recruit reference points to determine whether growth overfishing was occurring (Table 6.7). $F_{current}$ was 0.69 and 0.98-0.93 in the northeast and northwest areas respectively, or to the right of the yield per recruit reference points. In the southwest F_{max} was estimated in 1.22 and $F_{current}$ was 0.76-0.93. $F_{current}$ in the southeast area was 0.58-0.59 and F_{max} was estimated in 0.52. $F_{current}$ was above $F_{0.1}$ in all areas (Table 6.7). A reduction of 0.77, 0.52, 0.5 and 0.38 from the mean $F_{current}$ would be required to get to $F_{0.1}$ in the northwest, southwest, northeast and northwest, respectively.

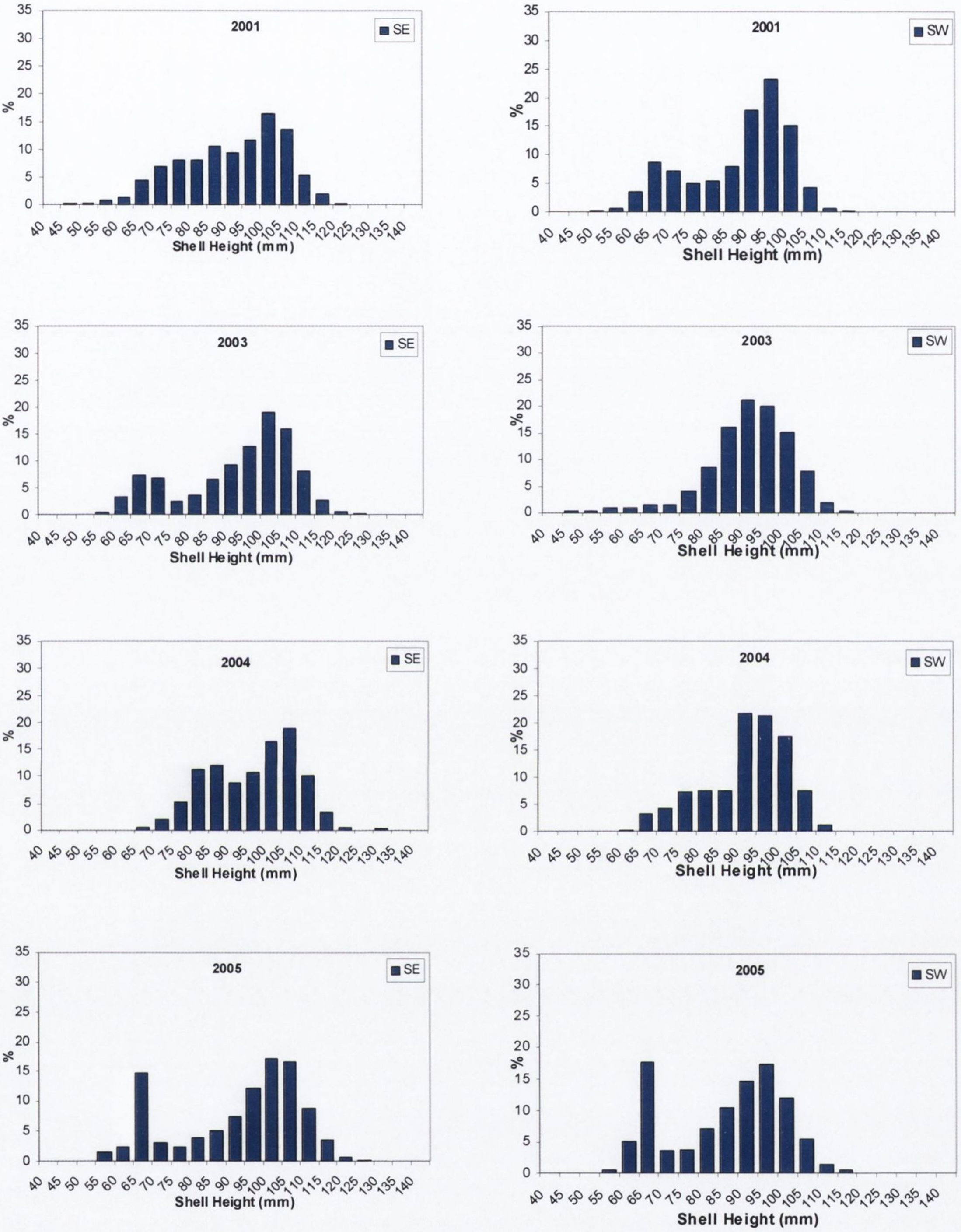


Figure 6.3. Scallop size structure from the northeast (left) and northwest (right) areas for survey years 2001-2005.

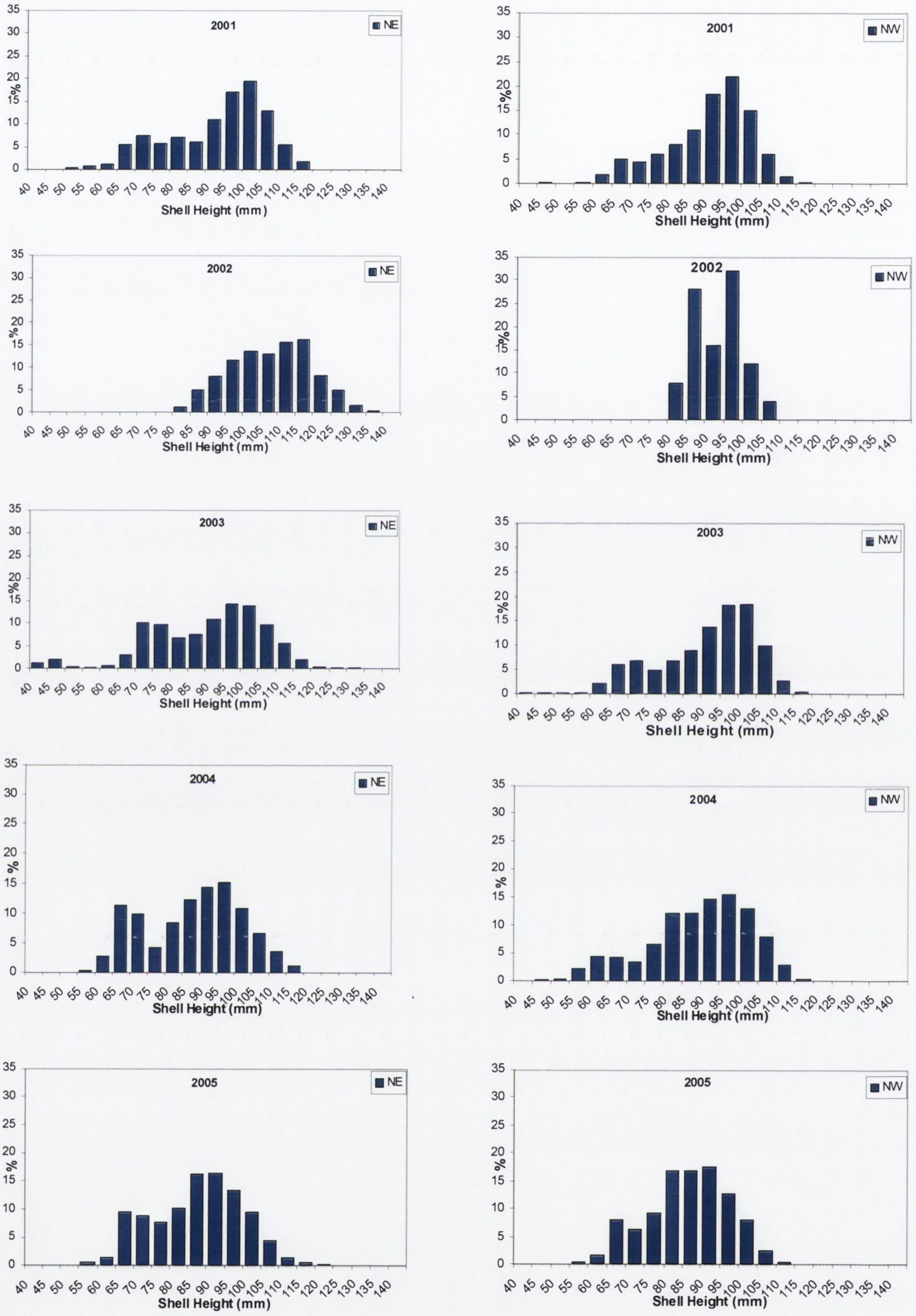


Figure 6.4. Scallop size structure from the southeast (left) and southwest (right) areas for survey years 2001-2005.

Table 6.2. Age length key for scallops in northeast scallop ground. Data from the 2001-2004 surveys. Numbers are the number of scallops for which individual and cumulative annual growth increments were measured.

Height (mm)	Number by size and age in northeast sub-area									Proportion of age class by size in northeast sub-area							
	1	2	3	4	5	6	7	8	totals	1	2	3	4	5	6	7	8
20-25	92								92	1.00							
25-30	511								511	1.00							
30-35	405								405	1.00							
35-40	96								96	1.00							
40-45	81	49							130	0.62	0.38						
45-50	29	198							227	0.13	0.87						
50-55	14	324							338	0.04	0.96						
55-60		228	10						238	0.00	0.96	0.04					
60-65		191	60	1					252	0.00	0.76	0.24	0.00				
65-70		92	151	2					245	0.00	0.38	0.62	0.01				
70-75		25	208	19					252		0.10	0.83	0.08				
75-80		4	164	83	4				255		0.02	0.64	0.33	0.02			
80-85			90	133	20				243		0.00	0.37	0.55	0.08			
85-90			40	127	61	7	2		237			0.17	0.54	0.26	0.03	0.01	
90-95			16	74	66	20	1		177			0.09	0.42	0.37	0.11	0.01	
95-100			1	30	54	22	5		112			0.01	0.27	0.48	0.20	0.04	
100-105				14	27	14	3	1	59				0.24	0.46	0.24	0.05	0.02
105-110				5	14	13	6	1	39				0.13	0.36	0.33	0.15	0.03
110-115				2	9	6	3	2	22				0.09	0.41	0.27	0.14	0.09
115-120					4	5	2	1	12				0.00	0.33	0.42	0.17	0.08
120-125						3	1		4						0.75	0.25	
125-130					1		1		2					0.50		0.50	

Table 6.3. Age length key for scallops in northwest scallop ground. Data from the 2001-2004 surveys. Numbers are the number of scallops for which individual and cumulative annual growth increments were measured.

Height (mm)	Number by size and age in northwest sub-area								Proportion of age class by size in northwest sub-area						
	1	2	3	4	5	6	7	totals	1	2	3	4	5	6	7
20-25	254							254	1.00						
25-30	750							750	1.00						
30-35	461							461	1.00						
35-40	215	10						225	0.96	0.04					
40-45	174	156						330	0.53	0.47					
45-50	53	461						514	0.10	0.90					
50-55	10	467	3					480	0.02	0.97	0.01				
55-60		299	36					335		0.89	0.11				
60-65		248	190	5				443		0.56	0.43	0.01			
65-70		108	398	10	1			517		0.21	0.77	0.02	0.00		
70-75		20	336	62	2			420		0.05	0.80	0.15	0.00		
75-80		3	268	210	18	1		500		0.01	0.54	0.42	0.04	0.00	
80-85			151	274	66	5		496			0.30	0.55	0.13	0.01	
85-90			34	240	128	12	3	417			0.08	0.58	0.31	0.03	0.01
90-95			3	110	151	39	6	309			0.01	0.36	0.49	0.13	0.02
95-100			2	38	93	43	4	180			0.01	0.21	0.52	0.24	0.02
100-105				12	36	24	4	76				0.16	0.47	0.32	0.05
105-110				1	15	8	2	26				0.04	0.58	0.31	0.08
110-115					7	4	1	12						0.33	0.08
115-120						2	1	3						0.67	0.33
120-125						1		1						1.00	

Table 6.4. Age length key for scallops in southeast scallop ground. Data from the 2001-2004 surveys. Numbers are the number of scallops for which individual and cumulative annual growth increments were measured.

Height (mm)	Number by size and age in southeast sub-area in 2001-2004 survey									Proportion of age class by size in southeast sub-area in 2001-2004 survey							
	1	2	3	4	5	6	7	8	Totals	1	2	3	4	5	6	7	8
20-25	163								163	1.00							
25-30	436								436	1.00							
30-35	272								272	1.00							
35-40	72	16							88	0.82	0.18						
40-45	2	92							94	0.02	0.98						
45-50		213							213		1.00						
50-55		275	5						280		0.98	0.02					
55-60		153	26						179		0.85	0.15					
60-65		83	89						172		0.48	0.52					
65-70		15	162	3					180		0.08	0.90	0.02				
70-75		1	176	29	1				207		0.00	0.85	0.14	0.00			
75-80			114	64	5				183			0.62	0.35	0.03			
80-85			70	115	17	4			206			0.34	0.56	0.08	0.02		
85-90			23	90	47	6			166			0.14	0.54	0.28	0.04		
90-95			8	75	60	14	5		162			0.05	0.46	0.37	0.09	0.03	
95-100				35	61	24	2	1	123				0.28	0.50	0.20	0.02	0.01
100-105				18	40	27	7	1	93				0.19	0.43	0.29	0.08	0.01
105-110				3	25	19	6	1	54				0.06	0.46	0.35	0.11	0.02
110-115					13	15	4	1	33					0.39	0.45	0.12	0.03
115-120						8	7	1	16						0.50	0.44	0.06
120-125							1		1							1.00	

Table 6.5. Age length key for scallops in southeast scallop ground. Data from the 2001-2004 surveys. Numbers are the number of scallops for which individual and cumulative annual growth increments were measured.

Height (mm)	Number by size and age in south west sub-area								Proportion of age class by size in south west sub-area						
	1	2	3	4	5	6	7	totals	1	2	3	4	5	6	7
20-25	239							239	1.00						
25-30	462	1						463	1.00	0.00					
30-35	194	0						194	1.00						
35-40	51	23	1					75	0.68	0.31	0.01				
40-45	13	182	0					195	0.07	0.93					
45-50		298	0	1				299		1.00		0.00			
50-55		247	14	0				261		0.95	0.05				
55-60		118	70	1	1			190		0.62	0.37	0.01	0.01		
60-65		51	174	2	1			228		0.22	0.76	0.01	0.00		
65-70		8	211	20	1			240		0.03	0.88	0.08	0.00		
70-75			182	68	1			251		0.00	0.73	0.27	0.00		
75-80			111	158	17	1		287		0.00	0.39	0.55	0.06	0.00	
80-85			33	151	42	2	1	229		0.00	0.14	0.66	0.18	0.01	0.00
85-90			9	121	96	6	0	232			0.04	0.52	0.41	0.03	
90-95				55	107	27	0	189				0.29	0.57	0.14	
95-100				20	58	23	4	105				0.19	0.55	0.22	0.04
100-105				2	17	10	3	32				0.06	0.53	0.31	0.09
105-110					4	6	0	10					0.40	0.60	
110-115					2	1	2	5					0.40	0.20	0.40
115-120						2		2						1.00	

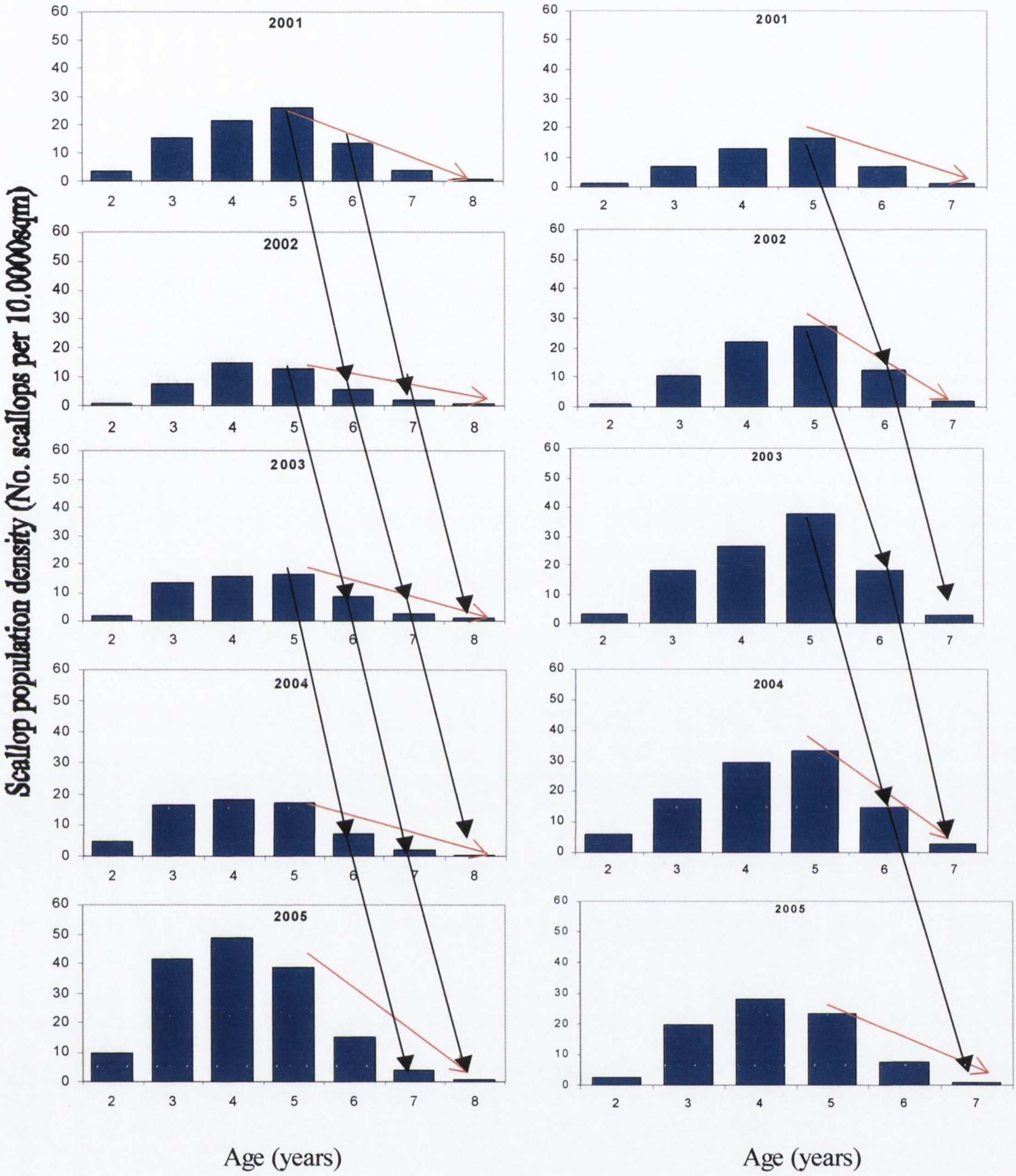


Figure 6.5. Age structure of scallops, from surveys 2001-2005 in the northeast (left) and northwest (right) areas. Arrows show the fate of the cohorts from which mortality rates were estimated . In red, cohorts assuming constant recruitment. In black, fate of individuals cohorts.

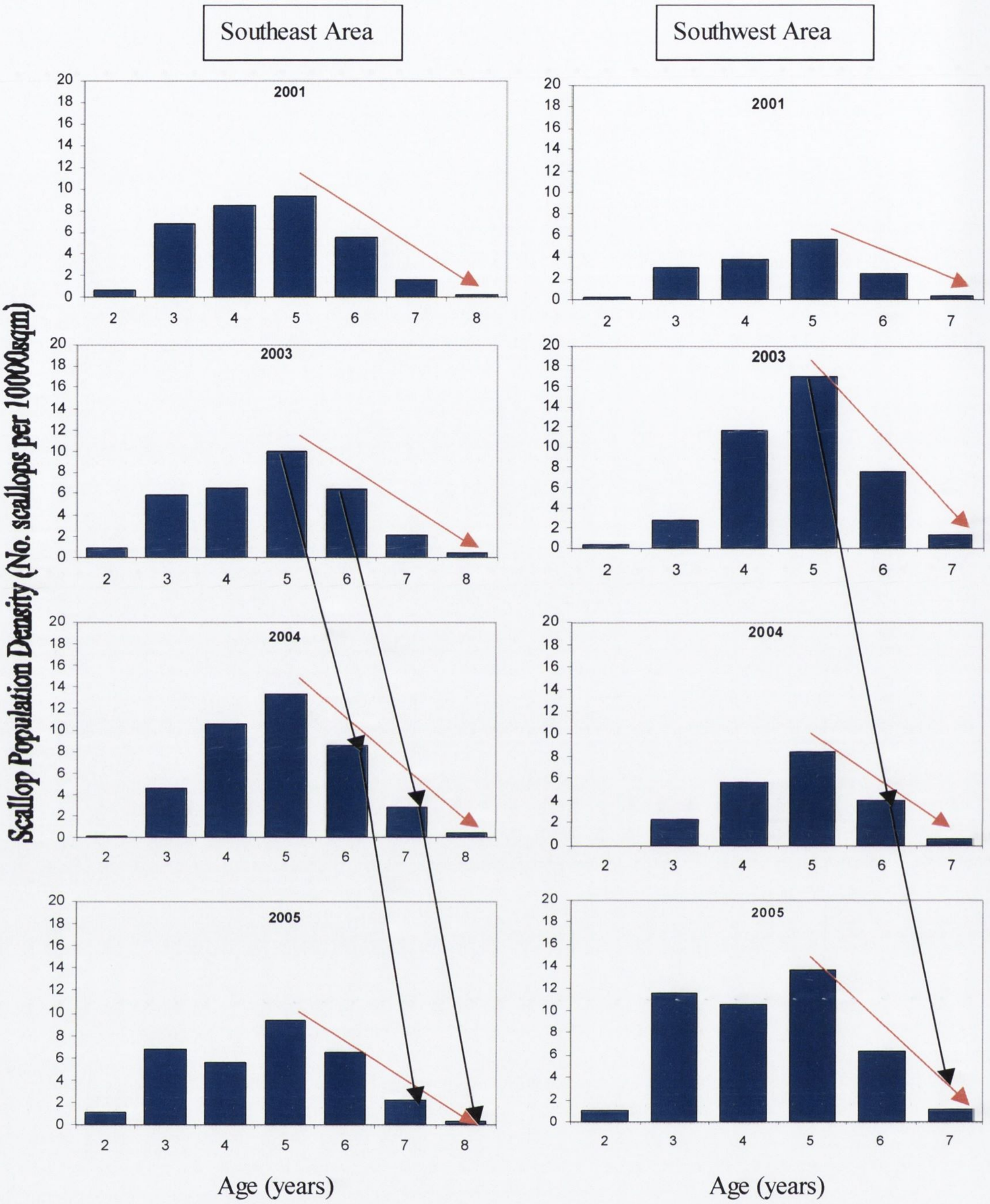


Figure 6.6. Age structure of scallops from surveys 2001-2005 in the southeast (left) and southwest (right) areas. Arrows show the fate of the cohorts from which mortality rates were estimated . In red, cohorts assuming constant recruitment. In black, fate of individuals cohorts.

Table 6.6 Total mortality rate (Z) and fishing mortality rate (F) estimates for each scallop growth area. Estimates area shown for pseudocohort and true cohort analysis. Cohort year is given by the year at recruitment.

		Pseudocohort			True cohort		
Growth Area	Cohort (recruitment year)	Z	F	Time period	Z	F	Time period
Northeast	1999				1.06	0.91	1999-2003
	2000				0.931	0.781	2000-2004
	2001	0.874	0.724	1997-2001	0.736	0.586	2001-2005
	2002	0.669	0.519	1998-2002	0.655	0.505	2002-2005
	2003	0.787	0.637	1999-2003			
	2004	0.848	0.698	2000-2004			
	2005	1.065	0.915	2001-2005			
Northwest	2000				0.72	0.57	2000-2003
	2001	1.06	0.91	1998-2001	1.04	0.89	2001-2004
	2002	1.125	0.975	1999-2002	1.45	1.3	2002-2005
	2003	1.12	0.97	2000-2003			
	2004	1.13	0.98	2001-2004			
	2005	1.21	1.06	2002-2005			
Southeast	2001	0.718	0.568	1997-2001	0.855	0.705	2001-2005
	2002				0.62	0.47	2002-2005
	2003	0.72	0.57	1999-2003			
	2004	0.777	0.627	2000-2004			
	2005	0.693	0.543	2001-2005			
Southwest	2001	0.77	0.62	1998-2001			
	2002				1.08	0.93	2002-2005
	2003	1.035	0.885	2000-2003			
	2004	0.875	0.725	2001-2004			
	2005	0.98	0.83	2002-2005			

Table 6.7. Growth overfishing reference points and mean $F_{current}$ estimates using pseudocohort and true cohort analysis in each growth area.

Growth area	Growth overfishing reference points		Mean $F_{current}$ estimates			
			pseudocohort		True cohort	
	Fmax	F0.1	Mean	s.d	Mean	s.d
North East	0.51	0.2	0.699	0.14	0.696	0.18
North West	0.64	0.21	0.979	0.05	0.920	0.37
South East	0.52	0.2	0.577	0.04	0.588	0.17
South West	1.22	0.24	0.765	0.12	0.930	

6.4 Discussion

The yield per recruit model of Beverton and Holt (1957), applied to spatially explicit data on scallop growth, showed that spatial variation in growth of scallop should be considered in the development of appropriate fisheries reference points and management strategies to prevent growth overfishing in scallop off the south coast of Ireland. Spatial management of fishing effort, to optimise 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 (Smith *et al.*, 2001; Caddy, 2004; Smith and Rago, 2004; Orensanz *et al.*, 2006; Tully *et al.*, 2006b).

Management strategies designed to control fishing mortality rates in scallop fisheries are usually based on either inputs controls, such as fishing effort (number of dredges, size of vessel or engine, number of fishing days), or output control such as catch quotas (Orensanz *et al*, 1991). Adapting either input or output controls to spatially optimise F_{max} may not be practical from the point of view of management as it would be very difficult to implement. Rather than using a contoured plot of F_{max} areas where growth rate was similar were identified (i.e. growth areas) and an F_{max} point identified for each. Using fixed growth and natural mortality parameters yield per recruit analysis was computed for three different minimum landing sizes, which corresponded to three different ages at recruitment, with the objective of investigating the benefits of either increasing or decreasing the actual minimum landing size.

Yield per recruit curves were constructed for seven areas, within which growth was found to be relatively constant, and the F_{max} and $F_{0.1}$ for three different sizes at recruitment were estimated. Results indicated that an increase in the size at recruitment from 100mm to 110mm shell height would produce increases of 5-7% and 2-4% in yield at F_{max} and $F_{0.1}$ respectively in all areas off the south east coast except in the southwest area. Growth of scallops in the southwest area is lowest.

As a result of the low growth experienced in the southwest area, yield per recruit did not increase as the minimum landing size increased. The estimated reproductive potential did not vary significantly between the different minimum landing size. This, together with the reduced increase in yield determines that changes in minimum landing sizes would probably not contribute to a higher yield and/or a higher reproductive potential.

The effect that changes in fishing mortality has on yield per recruit, at a given size at recruitment, depends on the shape on the yield per recruit curve. Yield per recruit is insensitive to changes in F in flat-topped curves and therefore the definition of F_{max} is not important to maximise yield. However yield per recruit is sensitive to changes in fishing mortality in non-flat topped curves and therefore the definition of F_{max} will be important to maximise yield per recruit. The shape of the yield per recruit curves give information about the proportional reduction in fishing mortality required to achieve F_{max}.

The definition and achievement of optimal yield per recruit is, however, only one management objective. This reference point ignores the recruitment process and therefore growth and yield of the population. The relationship between stock and recruitment determines how efficient spawners provide recruitment to the next generation. The stock recruitment relationship is unclear for scallops so the fishing mortality or the sustainable exploitation rate for a given population is essentially unknown (Orensanz et al., 1991, 2006; Caddy, 2004; Smith and Rago, 2006).

The marginal yield criterion, $F_{0.1}$, is far more conservative than F_{max}, in that $F_{0.1}$ is always to the left of F_{max} on the yield per recruit curve and is usually adopted in fisheries management to prevent recruitment limitation (Deriso, 1987). However $F_{0.1}$ is more an economic than a biological reference point in that is usually the point at which most fisheries managers consider that a further increase in fishing mortality is not economically worthwhile (Caddy and Mahon, 1995). This precaution does not necessarily deliver levels of exploitation that are sustainable and which do not limit production. In per recruit terms this will depend on the relationship between size, age, size at maturity and the size fecundity relationship.

Features of the biology of scallop should be taken into account when designing management measures to optimise yield per recruit and to protect recruitment. These features include (*i*) The relationship between scallop density and fertilisation success, (*ii*) the seasonal pattern of reproduction and spawning, (*iii*) The size/age at maturity in relation to size/age at recruitment. (*iv*) The connectivity between populations within a metapopulation through the dispersal of larvae.

In broadcast spawners, generally, the closer individuals are to each other the more likely the success in the fertilization process is (Orensanz, 1986; Caddy and Defeo, 2003). $F_{0.1}$ define, in most cases, an economic threshold, but density of scallop might be too low at $F_{0.1}$ to achieve successful fertilization. An example of this was experienced in the Queenland scallop fishery, *Amusium balloti*, in the 1980s (Dredge, 1988). The high scallop prices allowed fishermen to target the species at very low densities, sometimes as low as one scallop per $300m^2$, and the threshold density for fertilisation was estimated in one scallop per $120\text{-}150m^2$.

The seasonality of reproduction and spawing is also important in terms of the renewal process. In order to protect recruitment good practise would be to delay the time of harvesting until the gonad is spent and/or recovering (Mason, 1983), in October/November (see Chapter 3). If heavy fishing effort occurs during settlement there may be a negative impact due to disturbance, effectively reducing the efficiency of the stock recruitment relationship.

$F_{0.1}$ can be too conservative if spawning occurs earlier than the age/size at recruitment (Clark, 1973). *Pecten maximus* reaches first maturity at 2 years and full maturity at 3-5 years (Shumway, 1991). The yield per recruit model presented in Chapter 6 predicted that an increase in the minimum legal landing size (MLS) from 100 to 110mm in shell length would increase yield per recruit at any given fishing mortality rate. If the MLS was increased scallops would recruit into the fishery at the age of 4-6 depending of growth rate. Therefore in areas where growth is slow $F_{0.1}$ might be too conservative

The asymmetrical flow of larvae between component populations within the complex meta-popaultion structure determines that some areas are more important as sources of recruitment than others. McGarvey *et al.* (1993) commented on the role of source populations for the George Bank scallop (*Placopecten magellanicus*) stock. He found that over 80% of recruitment originated from a small area of the bank. Scallop beds that are important sources of larvae should 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. On the south east coast of Ireland Tully *et al.* (2006a) identified the *Tuskar* and the *Barrels growth areas* as the likely source areas for the south east coast and the general direction of dispersal of larvae was in a south westerly direction. The stable age structure of the *southwest, northwest, northeast and southeast growth areas* shown in this study indicates that the recruitment process, and possibly the delivery of larvae to these areas, is surprisingly stable and reliable. Recruitment is generally thought to be highly variable in scallops and few stocks have stable age distributions like those off the south east coast (Howell *et al.* 2003).

Different mechanisms can be used in scallop fisheries management to incorporate aspects of the growth and recruitment of scallops. These include (*i*) A minimum legal landing size that ensure that scallops reach full maturity before they recruit to the fishery; (*ii*) Closed seasons to protect reproduction and spawning. This measure is used in the *Pecten maximus* fishery of the Isle of Man (Beukers-Stewart *et al*, 2003a), where the fishery is closed from May to October and (*iii*) *Area closures*, which are gaining increasing popularity worldwide as a method of managing fisheries and marine habitats (Hart, 2006). In scallop management the main objective of such a measures would be to increase abundance and fecundity in order to increase the fertilization success and thus enhancing the source of larvae to areas outside of the closed area (Beukers-Stewart *et al.*, 2003b; Dredge, 2003; Hart and Rago, 2004; Jebreen *et al.*, 2005). Experiences of permanent closures generally have shown an increase in biomass and recruitment in adjacent areas. The most notable example was shown in the George's Bank fishing ground (USA) where a permanent closure of five years provided 25 times higher yields than prior to closure and adjacent areas benefited from the dispersal of larvae from the closed area (Hart and Rago, 2004; Gedamke *et al.*, 2005).

The stock structure of the scallop population (Tully *et al.* 2006b) off the south east coast of Ireland indicates that the east of the scallop ground should be more protected from fishing than areas in the west in order to reduce the risk of recruitment limitation. These areas correspond to fast growth areas and, therefore, a lower fishing effort will also maximise yield per recruit. Fishing effort could be higher in areas where growth is slow. Off the south east coast these areas are to the west and southwest of the scallop beds. These areas are also less important as sources of larvae in the region suggesting that high fishing effort would not necessarily be detrimental to recruitment. Minimum size limits should also take into account the importance of a given scallop population in its contribution to recruitment to the overall meta-population.

Chapter 7: Comparison of Assessment Methods and Outputs

7.1 Introduction

In the assessment of a fish or shellfish stock data on the dynamics and biology of the species and on the behaviour of the fishing fleet are collected to provide scientific information on the state of the stock. However, the scientific advice used in the management of fish and shellfish stocks does not always lead to sustainable fishing of the resource (Hilborn and Walter, 1992). This is due to uncertainty in the stock assessment outputs. Unsustainable fishing practices or incorrect management advice may result if uncertainty in the scientific advice is not accounted for. Uncertainty can be inherent in the data and/or in the model used to fit the data. In addition there is also uncertainty due to natural variability (e.g. inter-annual variability in recruitment) that cannot always be predicted. So although the model may predict that the stock or yield from the stock may respond in a given way the actual response departs from that prediction. This can be due to changes in environmental conditions, trends in environmental variables not seen in the past or other changes in biological responses that have not been incorporated in the model. The biological characteristics of the species need to be estimated without bias and with precision in order to minimise uncertainty. In the case of scallops this would involve paying special attention to spatial variability in the dynamics and biological characteristics of the population (Caddy, 1975). This would also be the case for most species which are largely sedentary and whose biology is influenced by the local physical and biological environment. The quality of the data that are used in assessment models is crucial in order to obtain reliable outputs from the model and the problem of using poor data in fitting assessment model has been recognised to be a major problem in the unreliability of the scientific advice for the management of marine species (Hilborn, 2001; Chen, 2003; Caddy, 2004; Smith and Rago, 2004; among others).

It is important to assume that there is always going to be a degree of uncertainty in stock assessment outputs. If there is uncertainty in each indicator used to describe the stock dynamics then it is important that more than one indicator used. The use of multiple indicators has become common in modern stock assessment procedures (Caddy, 2004). All possible information about the stock and its productivity is collected and is used to generate several indicators that provide information about the status of the stock.

In this thesis a number of different indicators and assessments of the size and status of the scallop stock off the southeast coast of Ireland were presented. Data for assessment were collected from fishery dependent (commercial fishery data) and fishery independent sources (data from research surveys).

The vessel monitoring system data (VMS) was an essential tool in the analysis of the commercial fishery data. This system allowed commercial catch and effort data to be analysed in a disaggregated form and at fine spatial scales. This is necessary to account for the sedentary and spatially variable biological characteristic of scallop and the local nature of the fishing operations, an important aspect in the assessment of scallops that has long been recognised (Caddy, 1975; Orensanz *et al.*, 1991; Bell and Palmer, 2001; Smith and Rago, 2004).

An assessment of commercial catch and effort data was presented. Annual indices of catch rates were standardised, using general linear modeling (GLM), to assess annual trends in relative abundance of scallop. Catch rates were standardised to account for factors, other than abundance, than could have had an effect on catch rates following procedures outlined by Maunder and Punt (2004).

Catch and effort data were also used to model the depletion process due to fishing at fine temporal and spatial scales. Serial depletion of local scallop patches and a shifting sequential pattern of effort allocation to other beds have been observed in several scallop fisheries (e.g. Gibson, 1956; Dredge, 1986; Ansell et al., 1991). This fishing behaviour has significant implications for how commercial catch and effort data can be used in assessment. Therefore fishing events were modeled locally using the Delury depletion method in such a way that minimized violations of the assumptions inherent in this model. VMS data allowed particular study areas to be selected within which the Delury conditions of random distribution of fishing effort were met. Population abundance and exploitation rates were estimated within these areas.

Independent research surveys were carried out to investigate the distribution and relative abundance of scallop. The influence of the sediment composition on the distribution and abundance of scallop was used in designing the research surveys. A stratified random survey was designed using the seabed acoustic data, which identified sediment composition. The strong relationship found between sediment composition and scallop abundance determined the importance of using sediment composition to define the strata. These surveys also confirmed that there were important spatial patterns in the biological characteristics of scallops in this area that were correlated with environmental variables.

Scallop dredges do not capture all scallops in the path of the dredge and therefore dredge efficiency was estimated to convert survey relative abundance estimates into “true” abundance. Dredge efficiency estimates were derived using a Delury-Leslie depletion method. A controlled area was sampled consecutively until the catch declined substantially with each sample. The estimation of dredge efficiency, therefore, gives a measure of the rate at which a local population can be depleted. Scallop abundance from research surveys in combination with scallop landings were then used to estimate exploitation rates. The depletion experiments used to derive dredge efficiency also gave an impression of how easy or difficult it might be under commercial conditions to deplete local patches of scallop.

Annual scallop research surveys provided data on size/age structure of scallops between 2001-2004. The age structure of the catch was assumed to represent the age structure of the scallop population and catch curve analyses were used to estimate the instantaneous fishing mortality rate (F) of fully recruited scallops, assuming a natural mortality (M) of 0.15 (Orensanz *et al.*, 1991). There are a number of assumptions and uncertainties in this method; errors in transposing size to age, possible size related differences in catchability, an assumption of equilibrium conditions, an assumption of constant rates of natural mortality that are not affected by local environmental conditions or density dependent effects.

Each assessment method presented in this thesis makes different assumptions, involves a number of uncertainties and all are modelled or statistical estimates of the "true" population. If the different estimates are similar then it increases confidence that they are unbiased and sufficiently useful to use in management of the resource. This chapter brings the results of the different assessment methods together and in particular evaluates, based on the different assessment outputs, what the true exploitation rate on the population might be.

7.2 Methods

7.2.1 Exploitation Rates Estimates

Exploitation rates can be defined as the ratio of biomass of scallop removed to the total biomass of scallop in the population. Exploitation rates were estimated by a number of methods. In addition to this, other data presented provided indicators of what the exploitation rate may be.

Exploitation rates were estimated from:

1. The ratio of the landings to the total population abundance (from independent research surveys).
2. The ratio of the removals from the estimated initial population biomass using the Delury depletion method applied to commercial catch and effort data
3. From estimates of annual fishing mortality (F) obtained from catch at age data

Indications of exploitation rate were obtained from:

4. Leslie-Delury (1947) depletion model to estimate dredge efficiency
5. The relationship between scallop abundance and ground type
6. The proportion of the scallop beds that were fished annually
7. The temporal pattern of catch rate from 1995-2004
8. The relationship between total landings and total effort
9. The relationship between catch rate and total effort between 1995-2001

7.2.1.1 Estimation of Exploitation Rates using Landings and Population Abundance from Research Surveys.

Scallop population abundance was estimated for the two main scallop beds off the southeast coast of Ireland from research surveys carried out in years 2002-2004 (Chapter 5). Landings data were obtained from the European Communities' Logbook (ECL) for all scallop vessels in the Irish fleet. To increase the spatial resolution of the ECL data the catch and effort information was linked to the VMS data and thus different scallops beds could be treated separately in the analysis. Landings data were crosschecked with the VMS data and missing values of catch for the year, area and vessel in question were predicted using General Linear Modelling (GLM) of catch rate data (Chapter 4). Scallop landings in combination with estimations of total population abundance, in each year and for each scallop bed were then used to estimate annual exploitation rates.

7.2.1.2 Depletion Estimates from Commercial Catch and Effort Data

In Chapter 4 the Delury (1947) depletion method was used to determine if fishing activity at local scales and over defined periods of time could lead to local depletion of stock. The Delury estimator describes the decline in catch rate with increasing expenditure of effort. The availability of spatially and temporally specific effort data provided by the VMS data allowed the application of the Delury depletion model for the estimation of scallop abundance while minimising violations in the model assumptions. Delury estimators are obtained from the exponential model $Y_t=qN_1e^{-qE_t}$ (Equation 4.5) where Y_t is the catch rate, q is the catchability coefficient, E_t is the fishing effort and N_1 is the initial abundance. The linear form of equation 4.3 is used to give the Delury estimators, the initial population and the exploitation rate.

A number of study areas were selected for analysis such that the assumptions of the model were met. Thus, different fishing episodes of relatively short period of time (in the order of weeks), in which the temporal and spatial scale was satisfactory to investigate the depletion process, were selected for analysis.

7.2.1.3 Depletion Estimates from Experimental Depletion

In Chapter 2 the efficiency of the dredge used during the research surveys was estimated using the Delury-Leslie (1947) depletion methods. The experiment consisted in sampling an area consecutively until the catch declined substantially with each sample. The Delury-Leslie model relates the number of scallop caught during each sequential tow (C_t) against the cumulative catch (K_t). The relationship has the algebraic form $C_t = kN_0 - kK_t$ (Equation 2.1), where N_0 is the initial population size and its estimation is given by the intercept on the x-axis, and k is the catchability coefficient that is given by the slope of the regression line described by equation 2.1. The experiment was carried out in four controlled areas to estimate dredge efficiency on sand and gravel substrates. Estimates were used to convert survey stock index to "true" abundance. In this Chapter, dredge efficiency estimates are used as an indicator of the potential exploitation rate or the capacity of this type of fishing gear to deplete local patches of scallop under normal fishing operations.

7.2.2 Estimation of Mortality Rates from Catch-curves

Chapter 6 identified growth overfishing reference points, F_{max} and $F_{0.1}$, taking into account spatial variability in scallop growth. In addition, the current fishing mortality rate, $F_{current}$, was estimated from catch curve analyses using survey catch at age data. $F_{current}$ estimates were compared to growth overfishing reference points, F_{max} and $F_{0.1}$.

Mortality rates were estimated from two different catch curves analysis; *pseudocohort catch curve* analysis and *true cohort catch curve* analysis. *Pseudocohort* catch curves considers all age classes present in a particular year for analysis and assumes constant recruitment and equilibrium conditions. In contrast, *true* cohort analysis follows the fate of a single cohort through time.

Exploitation rates were calculate from instantaneous fishing mortality rates obtained from the catch curves according to Haddon (2001)

$$E = 1 - \exp(-F), \tag{7.1}$$

7.3 Results

7.3.1 Fishing Effort and Landings

Four main scallop beds were identified (Figure 7.1) from the fishing activity data and thereby treated separately in the assessment of catch and effort. There was a positive relationship between fishing effort and landings (Figure 7.2, 7.3)

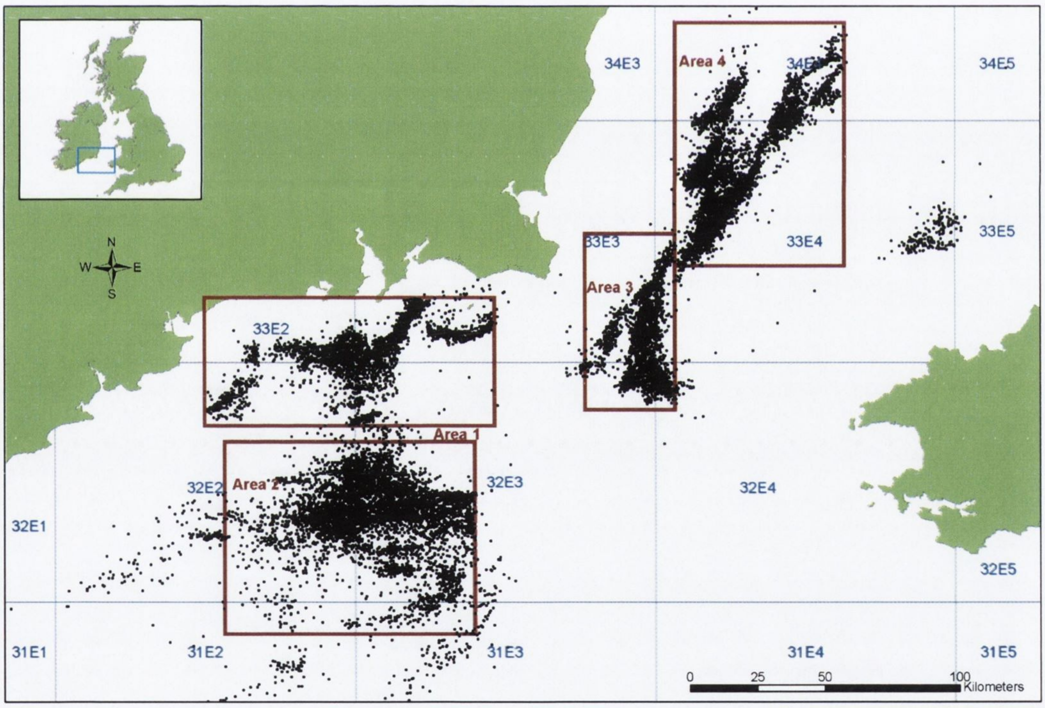


Figure 7.1. Fishing points, derived from vessel monitoring system data, from year 2000 to 2004 off the south east coast of Ireland.

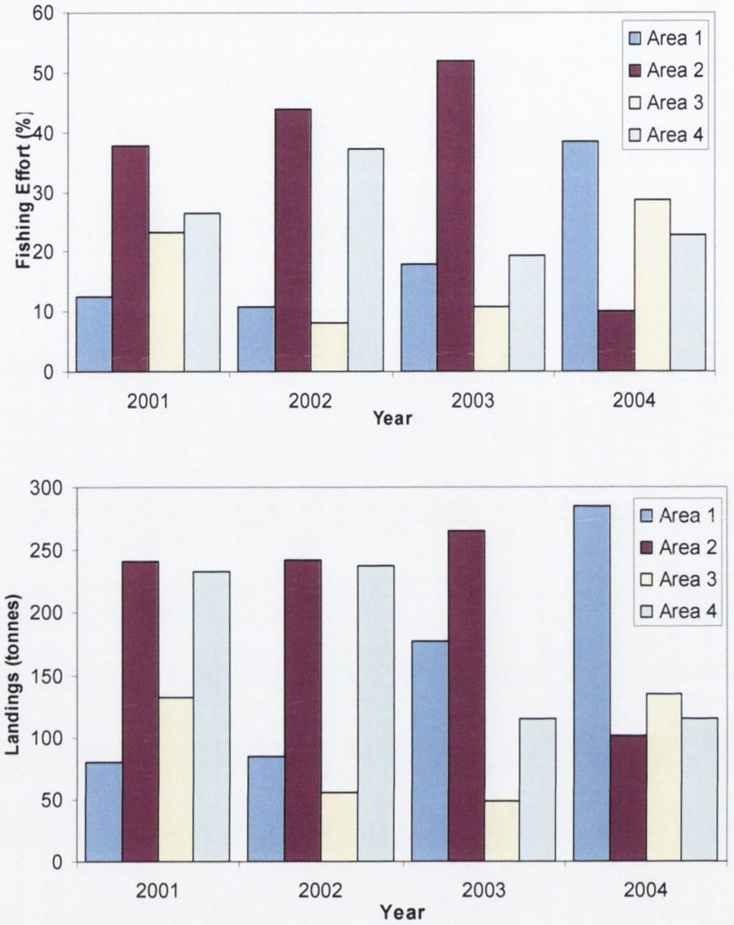


Figure 7.2. Annual percentage of total scallop fishing effort (dredge hours) and landings (tonnes) in each of 4 fishing areas off the south east coast in 2001-2004.

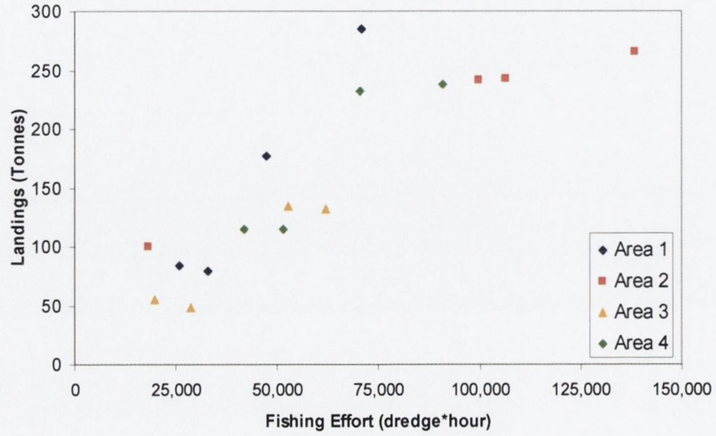


Figure 7.3. Relationship between landings and fishing effort in years 2001-2004 for each scallop area (Figure 7.1).

7.3.2 Estimation of Exploitation Rates using Landings and Population Abundance from Research Surveys

Exploitation rates were calculated from the ratio of annual landings to the population abundance (Table 7.1, Table 7.2). Exploitation rate estimates were between 3.55% and 12.01% in Area 1 and between 4.73% and 12.5% in Area 2. The intensity of annual fishing effort, measured as the ratio of the area swept by the dredges to the overall area of scallop bed, increased steadily in Area 1 from 13.7% to 39.2% from 2002 to 2004, and decreased from 14% to 5% in Area 2. Scallop population abundance was similar in the years 2002-2004 (Chapter 5). Therefore the observed increase in landings was related to an increase in exploitation rates.

Table 7.1. Scallop landings used to calculate exploitation rates. Scallop weight in Area 1 = 122.4 g (± 2.9). Scallop weight in Area 2 = 118.9 g (±3.6).

	Area 1					**Area 2**				
	Landings			Abundance		Landings			Abundance	
Year	Weight (Kg)	Number of Scallops		Mean	CL	Weight (kg)	Number of Scallops		Mean	CL
		Mean	CL				Mean	CL		
2002	84,331	717,195	5674	21,198,350	5,415.087	242,496	2,062,323	16,317	18,044,581	3,512,726
2003	177,168	1506737	11,921	21,198,350	5,415.087	265,266	2,255,972	17,849	18,044,581	3,512,726
2004	285,153	2425105	19,188	21,198,350	5,415.087	100,281	852,842	6,748	18,044,581	3,512,726

Table 7.2. Exploitation rates (%) estimates (mean values ±95% confident limits) in Area 1 and Area 2 and years 2002-2004.

	Area 1				**Area 2**			
Year	Area Size (mile^2)	Exploitation rates (%)		Swept area	Area Size (mile^2)	Exploitation rates (%)		Swept area
		Mean Values	CL			Mean Values	CL	
2002	251	3.55	0.73	13.7	626			
2003	251	7.46	1.52	28	626	12.50	3.47	27.2
2004	251	12.01	2.45	39.2	626	4.73	1.31	9.0

7.3.3 Delury Depletion Estimates using Commercial Catch and Effort Data

In Chapter 4 the Delury depletion model was used to explore the depletion of local patches of scallop. The depletion was considered significant ($p<0.1$) in 10 of the 26 study areas selected for analysis. Exploitation rates estimates, rate of depletion (defined by the catchability coefficient q), fishing effort (tracked dredge area) and time period and year in which the experiment took place are shown in Table 7.3. Using this method the exploitation rate was similar in each of the four main areas and varied between 2% and 7%. Fishing effort, measured as the ratio of the area swept by the dredges from the overall study area ranged between 12% and 64%. There was no apparent relationship between fishing effort and exploitation rates (Figure 7.4).

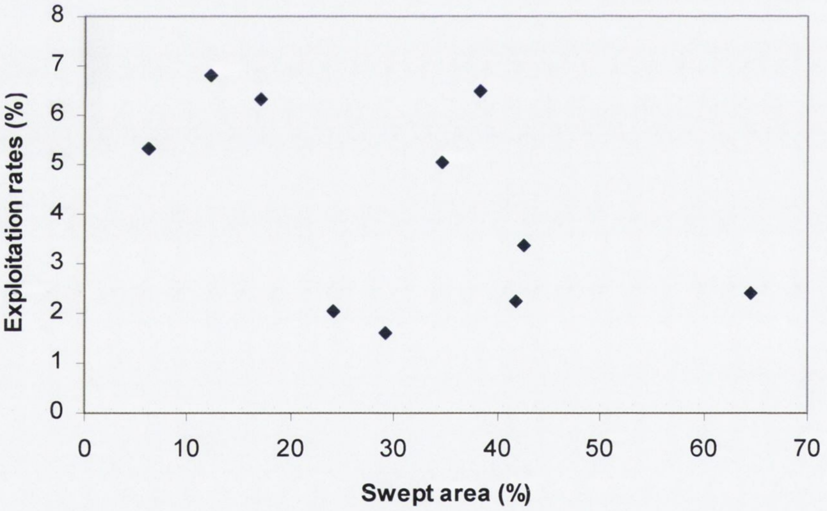


Figure 7.4. Plot showing the relationship between exploitation rates and fishing effort. Fishing effort is expressed as the ratio of area swept by the fishing gear from the total fishing area.

Table 7.3. Delury depletion estimators from study areas where depletion of catches was significant (p<0.1). The following information is shown; coefficient q (which gives a measure of the rate of depletion), area size, fishing effort (measure as the ratio (%) of the area swept by the fishing gear from the total size of the study area), total removal (± CL (confident limits)), initial abundance estimates (± CL (confident limits)), and exploitation rates (± CL (confident limits)). Mean scallop weight used to convert scallop weight into number of scallops in each Area was: Area 1 = 122.4g (± 2.9), Area 2 = 118.9 g (±3.6), Area 4= 159.6 g (± 4.2). Note that there was not significant depletion in areas selected in Area 3.

		Date		**q**	**Area Size (mile^2)**	**Fishing effort**	**Total removal**		**Initial abundance**		**Exploitation rates (%)**	
Area	**Study Area**	**Year**	**Number of weeks**				**Mean values**	**CL**	**Mean values**	**CL**	**Mean value**	**CL**
Area1	**3**	2001	3	$-8*10^{-5}$	12	64.62	98,897	2,289	4,086,001	94,568	2.42	0.08
	4	2003	3	10^{-4}	30	34.56	165,343	3,827	3,266,734	75,607	5.06	0.17
	5	2003	8	10^{-4}	110	17.02	412,278	9,542	6,522,535	150,961	6.32	0.21
	7	2004	6	$-3*10^{-5}$	77	42.58	443,324	10,260	13,219,121	305,949	3.35	0.11
Area 2	**8**	2000	16	10^{-5}	1,105	6.19	1,709,584	1,610,768	32,088,293	943,003	5.33	5.02
	9	2002	8	$-6*10^{-6}$	303	24.08	1,092,551	927,342	53,455,151	1,570,927	2.04	1.74
	10	2003	13	$-3*10^{-6}$	364	41.81	2,019,527	1,607,586	90,216,414	2,651,258	2.24	1.78
Area 4	**18**	2000	4	$-4*10^{-5}$	177	12.26	527,574	13,625	7,760,802	200,429	6.80	0.25
	22	2002	11	$-7*10^{-6}$	187	29.07	640,632	16,545	39,907,823	1030650	1.61	0.06
	24	2003	3	$-3*10^{-4}$	14	38.29	63,902	1,650	985,982	25,464	6.48	0.24

7.3.4 Exploitation Rates from Controlled Depletion Experiment

The capacity of the survey dredge to deplete an area under a controlled experiment was assessed. This assessment provided estimates of dredge efficiency. Four areas were depleted and the ratio of number of scallops taken from the total number of scallop in the dredge path was estimated (Table 7.4). Results showed that, although depletion of all areas was achieved, the rate of depletion was low with values of dredge efficiency ranging between 8% and 17%. This means that on a single pass of the dredge over an area of ground between 8-17% of the available legal sized scallop biomass may be captured. Exploitation rates higher than this could only be achieved by repeated fishing of the same area.

Table 7.4. Regressions line coefficients and diagnostics of Leslie-DeLury equation of the relationship between catch (C) and cumulative catch (K) for commercial sized scallop; a = intercept with y-axis; k = slope; N_0 *= Initial population size (number of scallop); NS = Number of scallop; DE = Dredge efficiency*

Area ID	a=k*N0	k	N0=a/k	NS at the first haul	DE%
A	66.03	-0.09	697	65	9
B	20.02	-0.10	198	15	8
C	76.19	-0.20	385	64	17
D	127.25	-0.14	900	107	12

7.3.5 Estimation of Fishing Mortality Rates and Exploitation Rates from Survey Catch-curves

Estimates of $F_{current}$ from pseudocohort and true cohort catch curve analyses were given for four growth areas (Figure 7.5, Table 7.5). Estimates of exploitation rates vary from 37-73%. These estimates are in marked contrast to estimates or indicators of exploiation rate provided by other methods.

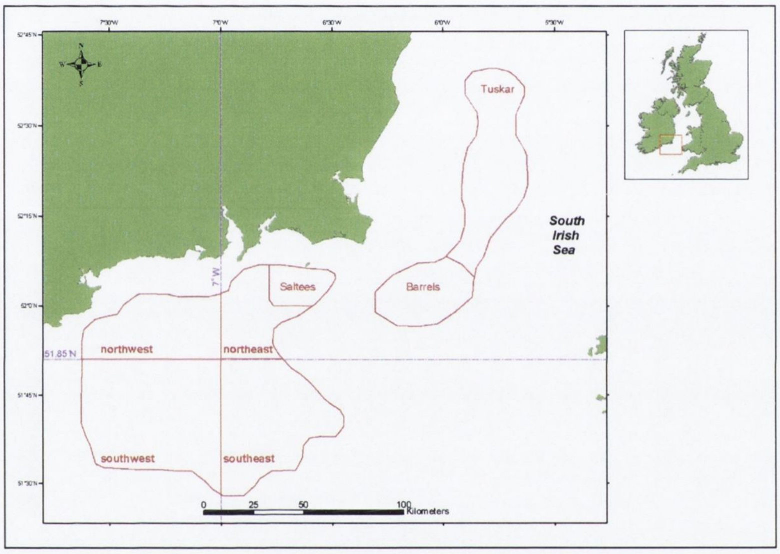


Figure 7.5. The southeast scallop grounds divided into seven sub-areas of similar growth.

Table 7.5 Total mortality rate (Z) and fishing mortality rate (F) estimates for each scallop growth area. Estimates area shown for pseudocohort and true cohort analysis. Cohort year is given by the year at recruitment.

		Pseudocohort			True Cohort		
Growth Area	Cohort (year class)	Time period	F	H (%)	Time period	F	H (%)
North East	1999				1999-2003	0.91	60
	2000				2000-2004	0.781	54
	2001	1997-2001	0.724	52	2001-2005	0.586	44
	2002	1998-2002	0.519	40	2002-2005	0.505	40
	2003	1999-2003	0.637	47			
	2004	2000-2004	0.698	50			
	2005	2001-2005	0.915	60			
North West	2000				2000-2003	0.57	43
	2001	1998-2001	0.91	60	2001-2004	0.89	59
	2002	1999-2002	0.975	62	2002-2005	1.3	73
	2003	2000-2003	0.97	62			
	2004	2001-2004	0.98	62			
	2005	2002-2005	1.06	65			
South East	2001	1997-2001	0.568	43	2001-2005	0.705	51
	2002				2002-2005	0.47	37.5
	2003	1999-2003	0.57	43			
	2004	2000-2004	0.627	47			
	2005	2001-2005	0.543	42			
South West	2001	1998-2001	0.62	46			
	2002				2002-2005	0.93	61
	2003	2000-2003	0.885	59			
	2004	2001-2004	0.725	52			
	2005	2002-2005	0.83	56			

7.4 Discussion

A number of estimates of scallop exploitation rate, calculated by different methods, were presented. The real question here is whether the fishing mortality or exploitation rate, which is the proportion of the biomass of scallop removed annually, is such that the fishery is operating sustainably. Giving a definitive answer to this question is difficult given the state of knowledge of scallop stocks generally and that off the southeast coast in particular. In fact it remains a problematic area in fisheries assessment and management (Hilborn and Walter, 1992; Francis and Shotton, 1997; Smith and Rago, 2004; Caddy, 2004) generally because the answer depends on the relationship between spawning biomass or population egg and larval production and recruitment. Various estimates of the proportion of the biomass that needs to remain in the population, on average, to prevent recruitment limitation have been given in the literature and depend on the biological characteristics of the species concerned (Caddy, 2004). No stock recruitment relationships exist for scallops so the levels of exploitation that are sustainable are essentially unknown (Orensanz *et al.*, 1991; Caddy, 2004; Smith and Rago, 2004; Orensanz *et al.*, 2006;). However, the methods and data presented here provide a weight of evidence for or against the proposal that exploitation rate is for instance high or low and therefore, taking into account evidence from other fisheries and species, whether the fishing activity is sustainable. The weight of evidence for and against the conclusion that exploitation rates are low in this instance together with qualifying statements on the strengths and weaknesses in each data set and assessment method is presented in Table 7.6.

Exploitation rates (E) or indicators of what the exploitation rate may be were calculated by various methods and provide the following evidence:

1. The ratio of the annual landings compared with abundance estimates derived from surveys suggest an annual E of 3-15%.
2. Delury estimates of E from commercial catch rate data, analysed over small spatial and temporal scales which comply with the assumptions of the Delury model, suggest E of 2-7% and in most cases no evidence of depletion could be found.

3. Dredge efficiency was estimated at 8-17%. This means that between 8-17% of scallops are removed from each area of seabed over which a dredge passes each time it passes over that particular location.
4. VMS and fishing effort data show that between 10-60% of the fishable area or the area over which scallops are distributed is fished annually.
5. The low dredge efficiency (3) combined with the relatively low proportion of ground fished (4) suggested an exploitation rate in single figures.
6. Commercial catch rates, for the period 2001-2005, were stable suggesting that exploitation rates were sustainable during the period.
7. Annual stock indices from research surveys were stable from 2002-2005.
8. There was a positive and linear trend between catch and effort suggesting that maximum sustainable yield had not been reached.
9. Cohort and pseudocohort estimation of annual fishing mortality suggested annual E of 37-73%.

All estimates or indicators of exploitation rate, except that given by the scallop age structure data, suggest that E was low and sustainable during the period. E of 37-73% from the catch curve analysis is exceptional compared to the other estimates, can be regarded as high and, if real, probably unsustainable. The weight of evidence however suggests that E is low.

The data and methods used to derive each indicator or E have strengths and weaknesses (Table 7.6). Uncertainty in stock assessment is inevitable and it can rise from different sources, such as the process of collecting fishery data and/or the models used to fit the data (Francis and Shotton, 1997). In this thesis the VMS data was an essential tool in the application of assessment models in order to reduce uncertainty in the analysis of catch and effort data. This allowed the data to be analysed in a disaggregated form at fine spatial scale.

Uncertainty in the accuracy of the catch data reported by the ECL has been a central issue in the assessment of fish stock regulated under quota systems as underreporting of catches can bias estimates of fishing mortality and exploitation rate (Bell, personal communication). In the present study this was not considered a significant problem, as the scallop fishery is not regulated by quota. A significant problem with the commercial catch data used was missing ECL data. The VMS data provided a means of identifying what proportion of the catch was not reported. Catch was estimated for those fishing events based on catch rates predicted from the GLM. Thus the relationship between landings and fishing effort was reconstructed. The positive and linear relationship between landings and fishing effort also supports the hypothesis that E is low or at least that areas of fishing ground yielding high catch rate were available for different levels of annual effort observed.

The Delury assessment of commercial catch and effort data showed a lack of depletion of catch rates over short time (weeks) and fine spatial scales suggesting low exploitation rates. However, the scallop distribution is strongly related to the sediment along small spatial scales (in the order to hundreds of meters) as shown in Chapter 5 indicating some uncertainty in the depletion estimates (see discussion in Chapter 4). The main assumption that may have been violated during these analyses was that of randomness in distribution of fishing or that each scallop in the area had equal probability of capture.

The low proportion of the scallop bed fished annually and the low dredge efficiency support the Delury analysis of catch and effort data, which suggests that exploitation rate, is low. Stability in annual commercial catch rates and in annual survey indices were also generally stable in the four scallops areas in years 2000-2004 supporting the results of the DeLury assessment. Low (and variable) dredge efficiency can be considered as a source of some uncertainty in these data; can a dredge which is less than 20% efficient in catching those scallops which are in its path provide a reliable index of abundance? Although the dredge is highly inefficient survey catch rates were strongly related to the sediment composition, which seems to be a proxy for scallop abundance in the areas studied (Chapter 5). This suggests that catch rate data provide a reasonable index of scallop abundance.

The stability in catch rates and the constancy in the population age structure (Chapter 6) may also indicate that the exploitation rates are low. If the scallop population is exposed to high levels of exploitation (in the order of 37-73% estimated by the catch curve analysis) then catch rates and recruitment indices (survey results) would be expected to be less stable. High exploitation rates (37-73%) were shown by Howell *et al.* (2003) to result in high variability in catch rates and recruitment of the scallop stocks in Scottish waters. However, the scallop beds off the southeast coast of Ireland are interconnected by larval dispersal and form a metapopulation In this situation, catch rates and recruitment of scallop in beds that act as larval sinks, which may be Area 1 and Area 2 in this case (Tully *et al.*, 2006a), could lead to stability even if exploitation rates in these areas were high because of the external larval subsidy they receive. Beukers-Stewart *et al.* (2003a,b) reported that the catch rates on scallops in the fishery of the Isle of Man were stable despite exploitation rates of 40%. They attributed the stability in scallop abundance to recruitment supported by the supply of larvae from adjacent beds.

The high E estimated by the age structure of the surveys catch rates is difficult to explain given the weight of evidence from other data that E is low. Survey catch at age data are assumed to represent the age structure of the population. However some factors could cause a deviation between the catch at age data and the true population age structure. This could be due to problems in sampling design and/or variability in the vulnerability of different age classes to be capture by the dredge i.e. age or size dependent differences in catchability. Therefore, if old age classes were underrepresented in the catch it would result in an overestimation of mortality rates. Biased catch at age data due to problems in the sampling design has been discussed extensively (Orensanz *et al.*, 1991; Hilborn and Walter, 1992). Usually those problems are common when sampling fish or shellfish species in which cohorts are spatially disaggregated or migratory movement of individuals must be taken into account. Although scallops are capable of swimming, *Pecten maximus* do not swim large distances. Fraser and Howell (1984) reported that *Pecten maximus* travels only very short distances at any one time and in the scale of tens of metres. The spatially referenced age structure data from the surveys did not show any evidence of spatial segregation of age classes. Different age classes might not be equally vulnerable to the scallop dredge. Two stages in the relationship between dredge efficiency and scallop size have been reported (Chapman *et al.,* 1977; Fifas *et al*., 2004). In a first stage the probability of scallop to be caught increases with size. This is expected as the selectivity of the dredge on scallop increases with size. However, there seem to be a second stage in the relationship, in which the probability of scallop to be caught decreases with size (or weight). Fifas *et al*. (2004) suggested that this could be due to physical factors, and passive and/or active behaviour factors. As the bulk of the dredge is filled with scallops, with by-catches and/or with trash during fishing the hydrodynamics forces that are induced by the water passing through the dredge belly rings are reduced a bow wave may be created in front of the dredge and catchability may be reduced. As a result of this heavier scallops might be less susceptible to capture by the dredge. Also large scallops probably recess more deeply in the sediment and therefore they might be more able to avoid dredges passively. In addition larger scallops may be more effective at avoiding the dredge particularly if a leading bow wave in front of the dredge results in disturbance thereby giving increased time for escapement (Dare *et al*., 1993).

If the output of scallop assessments are to be used for the management of the resource all information available should be used in a unified framework in order to make coherent decisions on the sustainability of the resource. The purpose of stock assessment, which is to provide support for decision-making in fisheries management, needs to take into account uncertainty, which is inherent in stock assessment process (Francis and Shotton, 1997; Hilborn, 2001; Caddy, 2004). In the assessment of species, such as scallops, the use of multiple indicators become essential in order to formulate reliable advice on the sustainability of the resource under a given level of exploitation.

Table 7.6. Evidence of low and high exploitation rates and statements on its strength and weaknesses.

Evidences of low exploitation rates from:

1. The ratio of annual landings compared to abundance estimates derived from survey estimates.
2. Delury estimates of E from commercial catch rate data.
3. Estimates of dredge efficiency.
4. VMS and fishing effort data shows low proportion of the fishable area exploited.
5. The low dredge efficiency (3) combined with the relatively low proportion of ground fished (4) suggested an exploitation rate in single figures.
6. Commercial catch rate indices were stables suggesting that exploitation rates were sustainable.
7. Annual stock indices from research surveys were stable.
8. There was a positive and linear trend between catch and effort suggesting that maximum sustainable yield had not been reached.

Quality statement (strength (S) and weaknesses (W) of the evidences):

1. S: Landings data were crosschecked with the VMS data and missing values were predicted improving the reliability of the data.
   W: Uncertainty related to the estimation of missing landings.
   S: Random stratify survey design using sediment composition as stratification variable.
   W: Low and variable dredge efficiency.

2. S: The vessel monitoring system (VMS) data provided high quality of fishing effort data that allowed the selection of suitable areas to explore the depletion process under the condition of the Delury model.
3. W: Uncertainty related to the model assumption.

4. S: It can be assumed that mean dredge efficiency is low (from estimates presented here and from estimates given in the literature).
   W: Uncertainty related to the model assumption.

5. S: Reliable

6. S and W described in (3) and (4).

7. S: Standardisation of CPUE to account for factors that can have an effect on catch rates other than abundance through the use of General Linear Modeling.
   W: Uncertainty in using catches rates as a measure of abundance in sedentary species.

7. S: Random stratify survey design using sediment composition as stratification variable.
   W: Low dredge efficiency.

8. S: The use of VMS data allowed distinguishing between four different scallop beds of constant temporal geographic extension .
   W: However, landings were not totally independent from fishing effort as some landings were missing and were derived from fishing effort (VMS) and the expected average catch rate

Evidences of high exploitation rates:

1. Cohort and pseudocohort estimation of annual fishing mortality suggested unsustainable exploitation rates. High instantaneous mortality rate calculated as the number of individual of a cohort lost from one year to the next.

Quality statement (strength (S) and weaknesses (W) of the evidences):

1. S: Large quantity of size/age data. Catch curve analysis was carried out for each sub-areas to account for spatial variability in F. Spatial variability in growth was taken into account in order to covert size to age (using age-length key).
   W: Uncertainty on dredge efficiency on old age class scallop. Uncertainty on accuracy of aging by eye as a method.

General Discussion

Stock assessment provides scientific advice for the sustainable management of marine species. The reliability of the scientific advice, however, depends of the degree of uncertainty inherent in the assessment methods and outputs used to provide advice (Hilborn, 2001). Although uncertainty is inherent in stock assessment (Smith *et al*., 1993), if the assessment is carried out in accordance with the biology of the species, it can support reliable advice to managers (Jamieson and Campbell, 1998).

This thesis focused on developing stock assessment methods of scallops. Assessment methods for scallop are poorly developed and not well validated. There is currently no European (ICES) forum for the assessment of this species and regulation of scallop fisheries in Europe are not well designed. For example, days at sea regulations which limit fishing effort does so by ICES area rather than by stock structure and has not considered metapopulation structure or spatial variability in growth within the main ICES areas. There is no unified approach with respect to an acceptable assessment methodology for scallop fisheries in Europe. Current assessment methods that are in use vary from population dynamics models such as VPA (Scotland) (Howell, 2003), to annual stock surveys to estimate biomass (France) (Vigneau *et al*., 2001), to long term monitoring of catch and effort and age structure (Isle Of Man) (Beukers-Stewart *et al*., 2003a; Vause *et al*., 2003; Vause *et al*., 2005). Spatially explicit approaches to assessment are being developed in the English Channel by CEFAS (Addison *pers comm*.). The work presented in this thesis has explored a number of options, some of which are standard routines and some of which are novel using a combination of data from different sources. When assessment methodology for a species is underdeveloped and when there are particular biological characteristics of that species that need to be considered in the assessment and management process then it is appropriate to explore, compare and contrast a number of assessment methods. Broad scale agreement in the output of a number of methods substantially increases confidence that the methodologies and outputs are useful for management. This was the result in the present case; there was substantial weight of evidence from a number of data sources and analytical methods that exploitation levels were low. This was contradicted, however, by cohort analysis undertaken in two separate ways. The difference in the exploitation rates estimated from cohort analysis on the one hand and catch effort data, survey indices and depletion analysis on the other were substantial. Other evidence from the relationship between catch and effort, dredge efficiency and the stable age structure also lent weight to the proposition that exploitation rates were low. Cohort analysis and the related Virtual Population Model is commonly used to assess scallops and other species but in the present case seemed to give anomalous results. The reasons for the differences are not known but clearly cohort and VPA need to be used very cautiously in the assessment of scallop and related species.

The evaluation of strength and weaknesses of the evidences provided by each method of assessment, and summarised in Chapter 7 concluded that:

"If the output of scallop assessments are to be used for the management of the resource all information available should be used in a unified framework in order to make coherent decisions on the sustainability of the resource. In the assessment of species, such as scallops, the use of multiple indicators becomes essential in order to formulate reliable advice on the sustainability of the resource under a given level of exploitation".

In the lobster (*Homarus gammarus L.*) and the crab (*Cancer pagarus*) fishery of Ireland a multiple indicators system is used in assessment and management (Tully, 2004; Tully *et al*., 2006b). Indicators that provide information on the biology and socio-economics are used in a traffic light approach. The traffic light approach works by assigning a colour to each indicator depending of the their value with respect to a reference point. Three colours used are, green for conditions indicating stability or improvement, red where there are clear problems with overexploitation and amber for an intermediate or uncertain position situation. Indicators used include trends in CPUE, measurement of fishing effort, abundance indices, recruitment indices, observations on the age structure of the population, and indicators related price, quality and income from sale of fish. Reference values are defined based on analysis and biological knowledge in the case of biological indicators and by consultation with the industry for socio-economic indicators.

It is suggested here that a system of multiple indicators, that include stock indicators from a number of assessment methods, and socio-economic indicators should be used in assessment and management for the scallop fishery off the south east coast of Ireland. The traffic light approach has been proven to facilitate the communication between scientists, managers and industry and provides clear direction for each indicator on management actions that may be required.

The weight of evidence provided here suggested that exploitation rates were low (in single figures) and, therefore, sustainable although the fleet had developed significantly during the decade in question. The very low efficiency of the dredge seems to be the main reason for maintenance of low exploitation rate when the fleet was expanding. Given that the spring loaded dredges used in this fishery potentially have significant impact on the seabed and perhaps also on scallops that are not actually caught (Maguire *et al.*, 2002; Lart *et al.*, 2003) a cautious approach to fleet development should be used even though scallop fishing opportunities may be lost in the short term by being precautionary. Insidious effects on recruitment, damage to scallops not captured by the dredge, changes in the benthic environment and the quality of that environment (Harrington *et al.*, 2005; Schejter *et al.*, 2005; Harrington *et al.*, 2007; Hunt *et al.*, 2007; Kaiser *et al.*, 2007; Kenchington *et al.*, 2007; Schejter and Bremec, 2007) for recruitment of scallops may be some of the effects that, in the longer term, may affect the sustainability of scallop fishing. In this regard, increasing the efficiency of the gear and the technology available to the vessels would be a positive development. One method of doing this was identified as a result of the work presented in this thesis; high resolution sediment maps provided by multibeam acoustic data would allow vessels to capture scallops more efficiently by directing them to areas of high density. Dredge effort required to catch a unit weight of scallop would, therefore, be reduced, profitability would increase and any impacts on the environment that the dredge may have would be reduced. This would also mean that the fishery would be best managed by quota rather than by days at sea (output as opposed to input control). Increasing the technology available to vessels is generally seen as potentially counter productive and to lead to non-sustainable levels of fishing through technology creep. However there are a range of controls that can be used to balance the effective fishing effort and the productive capacity of the stock. Penalising the operation of the vessel when at sea, by not making available technology, would not seem to be a useful approach. The measures that could be used to manage scallop fisheries include:

- Gear restriction: Number of dredges allowed could be adjusted to vessel size and/or by fishing area or distance to the coast. This is more a socio-economic than a biological management measure and promotes the balanced development of a fleet with different vessel sizes, some of which will be predominantly small scale coastal and others specialising in fishing offshore. It could also be used to take account of the spatial variability in scallop biology.

- Seasonal closure. This management measure is used in the Isle of Man and is designed in order to protect spawners (Beukers-Stewart *et al*., 2003a). Off the south east seasonal closure could be applied to areas that are important sources of larvae and of recruitment.

- Temporal or permanent area closure. This has been proven to be extremely successful in other scallop fisheries in order to increase scallop density and reproduction output (Beukers-Stewart *et al*., 2003a; Dredge, 2003; Jebreen *et al*., 2005; Hart and Rago, 2006). Off the southeast coast such closure would probably be best located in the Tuskar and the Barrel Bed areas, which most likely provide larvae to the wider area. Area closures could contribute to an increase in population densities, fertilisation success and recruitment.

- Size limits. At present the minimum landing size is 100mm shell length for all areas off the southeast coast. Size at recruitment are usually designed to ensure that reproduction occurs before recruitment into the fishery and therefore, it depends on growth. Therefore the size at recruitment should differ between areas of low growth and areas of fast growth.

- Quota system management. This is used in scallop fisheries including France (Vigneau *et al*., 2001) and Canada (DFO, 2007). Novel approaches to the estimation of scallop abundance were presented in this work providing the information needed for the application of a quota management system. The proportion of the biomass that may be removed annually however is not clear as no stock recruitment relationship has been developed. Quota controls if developed would need to be done cautiously and with an understanding that adjustments would need to be made over time in an adaptive management regime.

Whatever measures are used to manage the fishery there are two objectives; the scallop resource has to be adequately protected and the economic viability of the fleet has to be secured. The fleet must therefore constrain or limit its activity to the productive capacity of the resource and management must ensure that unnecessary costs are not imposed on the fishery through regulation. In fact the vessels should be facilitated to be as efficient as they can be. Today they are using fishing gear that is only 10-20% efficient. Research to increase the efficiency of the gear would reduce fishing costs and protect the environment by reducing dredge effort. A reliance on technical conservation measures such as minimum landing sizes or dredge limits will increase fishing costs per unit of landing and affect the economic viability of the fleet. Some of the information provided in this thesis provides an opportunity to increase the efficiency of the vessels. If the sediment maps were used on the vessels the catch rate per hour of dredging could be increased as the maps guide the vessels along particular tracks where abundance is high. To protect the stock against this increase in efficiency a total allowable catch could be introduced for each scallop bed. Furthermore, to protect the market, e.g. quota for scallop could be determined on an individual basis.

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