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The Fishery and Ecology of the Scallop *Pecten maximus* (L.) in Guernsey

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ABSTRACT

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Doctor of Philosophy

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The overall aim of this work was to study the exploitation of the scallop *Pecten maximus* (L.) in Guernsey and assess the current management of the fishery. In order to achieve this various aspects of the biology of the local scallop populations were studied as well as the type and intensity of fishing methods used. While doing this work, other studies on the impact of scallop dredging and the behaviour of diver fishermen were carried out to gain a more complete understanding of the fishery in Guernsey.

A review of scallop fisheries in general, and more specifically those in the northeast Atlantic, was carried out as a comparison with the situation in the Channel Islands. The emphasis of this concentrated on the Isle of Man scallop fishery due to the similarity in their situation as an independent island with jurisdiction over their territorial waters. This led to the review of the current situation of scallop fisheries in the Channel Islands, which have been subject to very little study. Again, information from the Jersey fishery was used to assess the similarity between their fishery and the situation in Guernsey. The study of the Guernsey fishery in chapter two included assessments of catch per unit effort (CPUE) for both dredge and diver fished grounds as well as an analysis of the population structure and scallop densities. These were required to estimate mortality, which was used in the stock assessment equations when analysing different management options.

As well as information about the fishery, details of the basic biology such as growth rates and maturity indexes were also required to enable the scallop stocks to be assessed. Hence, growth curves were calculated for all the grounds studied following an initial tagging experiment to confirm the annual growth rings which were used to age the scallops. The decline in the rate of return of these tagged scallops was also later used to gain estimates of both natural ($M=0.2$) and fishing ($F=0.4$ to 1) mortality on this fishing ground. The seasonal reproductive cycle as well as the age at maturity of some of the scallop populations were studied to provide another required input parameter for the stock assessment equations (Beverton-Holt yield per recruit). The study of spat settlement and seasonal gonad cycles provided important information on the recruitment of scallops in Guernsey waters which is required by fisheries managers when assessing management options.

The remaining input parameters were calculated in chapter six and the current state of the fishery and possible management options were modelled using standard stock assessment equations. Recruitment ogives were calculated from size at age data collected from different fishing grounds throughout the study. These were also recalculated for increases in minimum landing size which resulted in only the older scallops being recruited to the fishery which allowed the effect of this management option to be studied. Also, mortality was estimated using a variety of methods from the results obtained in chapter three. From this, the yield and stock of scallops on Guernsey fishing grounds was assessed for the current situation as well as accounting for the effect of future fisheries management options.

Having considered the effect of fishing on the scallop stocks, the impact of scallop dredging on the marine benthos was assessed. This work mainly concentrated on the mortality of commercially important by-catch caused by scallop dredging, as this may become an important factor in the crab fishery if scallop dredging increases significantly from its current low level.

As the scallop fishery in Guernsey appears to be sustainable at the current rate of exploitation, the proposed management recommendations are based on a precautionary approach. The introduction of licences is suggested as this will allow future control of fishing effort if stocks start to decline. This will also allow better monitoring of the landings which will give an indication of possible future problems. The suitability and introduction of other possible management options is also discussed as well as the need for continued monitoring of the fishery.

CONTENTS

The Fishery and Ecology of the Scallop *Pecten maximus* (L.) in Guernsey

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1. General Introduction

Scallops are commercially important shellfish that are exploited throughout the world. This work aims to study the fishery and ecology of one species of scallop, *Pecten maximus* (L.), in the waters around Guernsey in the Channel Islands. Aspects of the biology of this species in local waters, such as growth rates and timing of spawning, were studied and compared with work done elsewhere. This work also involved assessing the current state of the fishery and the effect it is having on both the scallop stocks and other marine benthic species, some of which are commercially important. Finally, the overall aim of this work was to assess the current management of the scallop fishery and suggest possible recommendations for the future.

1.1 The biology of scallops, *Pecten maximus*

There are over 400 species of scallop which together form the family Pectinidae. They are found throughout the worlds' oceans on a range of substrates and depths from the intertidal zone to over 3000m (Brand, 1991). Many of the more accessible species have been exploited by traditional fisheries, e.g. *Argopecten irradians* and *Placopecten megallanicus* in the western North Atlantic, *Pecten maximus* and *Aequipecten opercularis* in the eastern North Atlantic, *Pecten fumatus* and *Chlamys asperrimus* in Southern Australia and *Pecten jacobaeus* in the Mediterranean (Brand, 1991).

In the British Isles, commercial exploitation is limited to two main species: *Pecten maximus* (the 'great scallop') and *Aequipecten* (*Chlamys*) *opercularis* (the 'queen scallop'). Other species found in British waters include: *Pecten jacobaeus, Chlamys varia, C. distorta, C. tigerina, C. striata, C. furtiva* and *C. similis* (Bruce *et al.*, 1963; Ansell *et al.*, 1991) none of which are exploited.

The scallop, *Pecten maximus*, is a bivalve mollusc belonging to the family Pectinidae. They are widely distributed in northeast Atlantic shelf waters from Norway down to the Iberian Peninsula (Pawson, 1995). They occur most often on a range of rough, stony substrates such as gravel or sand and shell mixtures (Rees and Dare, 1993; Pawson, 1995). However, they are also found on finer, silty sediments where there are rocky outcrops (Franklin *et al.*, 1980a). Generally, scallops prefer normal salinity seawater although they are found rarely in the mouths of estuaries. Due to the availability of suitable substrata, scallops are essentially coastal and generally have a patchy distribution (Baird and Gibson, 1956; Rolfe, 1973; Soemodihardjo, 1974). The density of *P. maximus* can be highly variable from up to 5-6 m^{-2} in the English Channel (Franklin *et al.*, 1980a), but more typically 0.1-0.01 m^{-2} on unfished scallop beds (Bannister, 1986; Rees and Dare, 1993).

1.1.1 **Anatomy**

A detailed description of the functional anatomy of scallops (*Pecten maximus*) may be found in Beninger & Le Pennec (1991). The scallop is made up of two valves or shells joined at the hinge. The upper (left) valve is flat and normally a dark orange or red colour. The lower (right) valve is convex and is lighter in colour than the upper valve, usually white or cream. The scallop usually buries itself in the substrate, if possible, so that its upper valve is level with the surface. The scallop may become further camouflaged by silt and fouling organisms settling on the upper valve. Both valves have approximately 15-17 radiating ribs (Mason, 1983) which interlink where the valves join (Figure 1.1).

Inside the scallop the large, white adductor muscle is joined to both valves and is capable of closing the two valves tightly together, to protect it from predation and allow limited swimming. Around this muscle lies the gonad which has both male (testis) and female (ovary) parts. The testis is creamy white in colour whereas the ovary is a darker orange or red. When fully ripe the gonad can make up a large proportion of the internal organs, approximately 35% (Barber and Blake, 1991).

The scallop is a filter feeder and gains its food by drawing water in over the mantle and gills that are also used for gaseous exchange. Food particles are then passed down to the mouth before passing through the digestive system (Bricelj and Shumway, 1991). All the internal organs are enclosed in the mantle, which is a thin membrane that extends to the edge of the shell. Here there are rows of sensory tentacles and light sensitive eye spots used for detecting the environment (Beninger and Le Pennec, 1991).

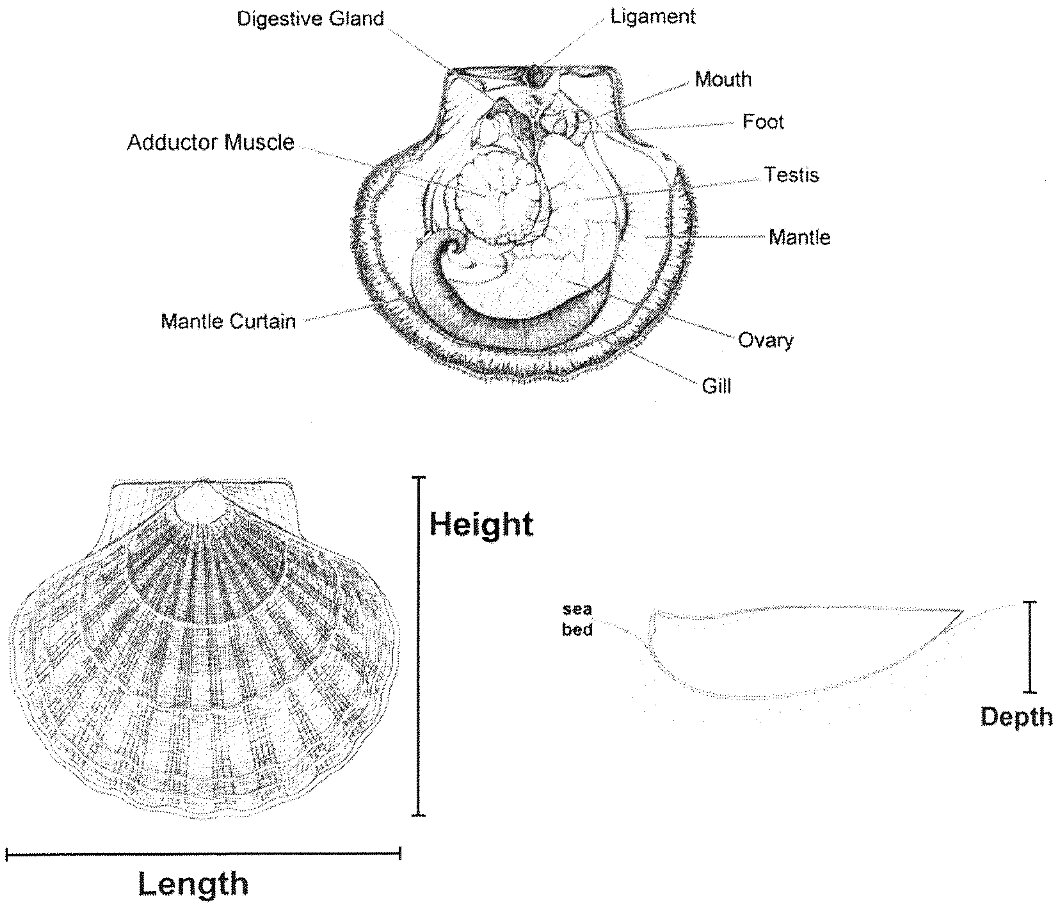


Figure 1.1: Anatomy of the scallop *Pecten maximus*. Top: Right valve and mantle removed to show viscera. Bottom: Top and side view of scallop shell showing dimensions used. (Adapted from Mason, 1983)

1.1.2 Life History

Individuals will reach first maturity at two years and will become fully mature at 3-5 years (Franklin *et al.*, 1980a; Rees and Dare, 1993). When spawning occurs either the sperm or eggs are released first in order to reduce the risk of self fertilisation (Comely, 1972; Mason, 1983; Devauchelle and Mingant, 1991). Approximately 10 million eggs are released in a single spawning depending on the condition of the ovary (Millican, 1997). As sperm is released into the water it may also trigger other scallops to release eggs to be fertilised (Barber and Blake, 1991). Spawning normally occurs in the summer months (April to September), but actual timing and length of spawning do vary in different regions (Paulet *et al.*, 1988; Briggs, 1991; Cochard and Devauchelle, 1993). Fertilisation of the eggs takes place externally with the fertilised eggs developing into larvae which remain in the plankton for a period of time, probably 3-4 weeks (Mason, 1958; Comely, 1972; Mason, 1983; Acosta and Roman, 1994). During this stage the larva moves through the water column via a ring of cilia around its recently developed transparent valves. As the larva becomes larger (~0.3mm) it will sink back to the seabed and find somewhere suitable to settle (Dare *et al.*, 1994a).

The pediveliger larvae, as it is known, will move around the seabed either by flapping the two valves together or with its foot projecting out between the valves. Once a suitable substrate has been found such as seaweeds, hydroids or erect bryozoans, it will attach itself with byssus threads. Here it will feed until it is larger, before releasing itself from the hydroids to rest on the seabed (Minchin, 1978; Beaumont and Barnes, 1992; Minchin, 1992). It is currently thought that spat settle on the same grounds as adults and not on separate nursery beds, due to their poor swimming ability. Indeed Minchin (1978) found spat attached to hydroids, on the seabed and recessed into the seabed of adult grounds. Scallop spat will also settle on artificial substrates such as monofilament netting, which has been used to investigate settlement patterns and potential for aquaculture (Buestel *et al.*, 1979; Brand *et al.*, 1980; Paul *et al.*, 1981; Brand *et al.*, 1991b; Orensanz *et al.*, 1991; Beaumont and Barnes, 1992; Wilson, 1994; Chauvaud *et al.*, 1996; Cashmore *et al.*, 1998).

Newly settled scallops will grow rapidly and will first spawn in the autumn when they have reached the age of two (Mason, 1957). At this point they are known as juveniles and will only spawn once in that year. The following year they become fully mature and may spawn twice, firstly in the spring and then in the autumn. From then on they will usually spawn twice a year with the gonad going through a regular, half yearly cycle from filling to fully spent (Mason, 1957).

1.1.3 **Growth**

In order for the scallop to grow it must first increase the size of its shell. The mantle is involved in shell growth in that it used to secrete material at the edge of each shell to increase the scallops length (Mason, 1957). This gives the shell a series of concentric rings on its outer surface known as striae. Generally these striae are 0.1-0.3mm apart but are packed more tightly together at the annual growth check (Mason, 1957; Mason, 1983). This growth check occurs in the winter and the annual growth ring, which is pale in colour, is slowly deposited in the spring. Following this growth ring the next striae are deposited further apart and have a darker colour. These growth rings can be accurately used to age the scallops as it has been shown that only one ring is deposited per year (Gibson, 1956; Mason, 1957; Pickett, 1978; Franklin and Pickett, 1980; Dare, 1991; Dare and Deith, 1991). However, there is often difficulty in determining the position of the first winter ring, closest to the umbo (Dare and Deith, 1991; Allison *et al.*, 1994). Results from ageing scallops this way has shown that individuals may live for more than 20 years in unfished areas, although usually less than 10 years on commercial beds (Briggs, 1991). As well as these growth rings, disturbance bands can also occur in the shell if the scallop is disturbed by fishing or bad weather. The retraction of the mantle effectively stops or reduces daily growth and results in the formation of a band. However, these bands are usually pigmented allowing them to be distinguished from growth rings (Mason, 1957). Also it has been found that scallops in the western English Channel have indistinct growth bands. Coupled with this there is the problem of spurious rings which makes ageing individuals from these fisheries difficult (Dare, 1991). Using stable oxygen isotope analysis of shell carbonate it was possible to accurately locate winter ring position (Dare and Deith, 1991), but this is a very expensive technique.

Growth rates have been shown to vary from area to area. For example, in the English Channel scallops in Cornwall generally reach 90mm in height in their fifth year, whereas in faster growing areas in the eastern Channel it may only take three years (Franklin and Pickett, 1980). What is more interesting is that for the first two years their growth rates were very similar. However, the reasons for these observed differences are unknown although it may be involved with poor food supply (Franklin and Pickett, 1980).

1.2 Scallop fisheries

There are many fisheries for different species of scallop throughout the world. In North America, the bay scallop, *Argopecten irradians*, forms the most important scallop fishery on the east coast (Rhodes, 1991), whereas on the west coast there is a much smaller fishery for the weathervane scallop, *Patinopecten caurinus* (Bourne, 1991). On the east coast of Canada there is a very large fishery for the sea scallop, *Placopecten magellanicus*, in the Scotia-Fundy region (Sinclair *et al.*, 1985). This fishery has been around for almost 100 years with licences being introduced in 1918. The seas around Australia provide the other main scallop fisheries other than the North Atlantic. Off southern Australia, around Tasmania, *Pecten fumatus* forms the main catch (Zacharin, 1989), whereas off Queensland and western Australia it is the saucer scallop, *Amusium balloti* (Joll, 1989; Neville, 1989). Due to the intensity of fishing in these areas a wide variety of management measures have been implemented (see Table 1.1).

One answer to the problem of declining stocks is to produce more scallops through aquaculture, either by collecting wild spat or producing them in a sophisticated hatchery. China is the world leader on molluscan aquaculture, a business that has been growing rapidly over the past decade. In 1996 they produced one million metric tons of scallops. However, the scallop cultures, which are concentrated in the northern provinces, have been seriously affected by disease and mortality in recent years, possibly due to overstocking (Guo *et al.*, 1999). In the north east Atlantic experimental trials of scallop aquaculture have been tried in the Isle of Man (Paul *et al.*, 1981; Brand *et al.*, 1991b; Wilson, 1994), Ireland (Briggs, 1991), Brittany (Paquotte, 1992; Chauvaud *et al.*, 1996) and Spain (Roman, 1991). However, natural settlement of wild spat on artificial collectors was often too low for commercial use, and hence techniques for the hatchery rearing of *P. maximus* have been developed (Millican, 1997).

There are fisheries for scallops, *P. maximus*, from the north of Scotland down to the Iberian Peninsula (Edwards, 1995). The more important of these are found in the Irish Sea (Brand *et al.*, 1991a), the English Channel (Franklin *et al.*, 1980a; Dintheer *et al.*, 1995), off Scotland (Mason, 1972; Mason, 1978) and off the northern coast of Spain (Roman, 1991).

The other main commercial scallop fishery in the north east Atlantic is for the queen scallop, *A. opercularis.* This is a smaller species of pectinid which has a lower commercial value and tends to be fished during the closed season for *P. maximus* (e.g. in the Isle of Man, Brand *et al.*, 1991) or when particularly dense patches are found and there is a good market for the meat, such as in Guernsey during the early 1970s (Askew *et al.*, 1973). Indeed, the declining yield of the bay scallop *Argopecten irradians* in America led to higher prices for queens caught in the UK. This resulted in many Scottish scallop boats switching to queens in the late 1960s with the trend spreading to the Irish Sea and the English Channel. However, as the American market declined in the mid 1970s the catches fell (Mason, 1983), although they are still fished for commercially.

1.2.1 **English Channel Fisheries**

The fishery for *P. maximus* first started in the English Channel about a hundred years ago (Franklin *et al.*, 1980a). Scallops are now exploited along most of the south coast of England, except for the area around the Isle of Wight. The importance of the fishery increased dramatically in 1975 when catches rose from less than 300 tonnes to almost 3000 tonnes (Figure 1.2) reflecting an increase in both eastern and western Channel fisheries (MAFF statistics, 1996).

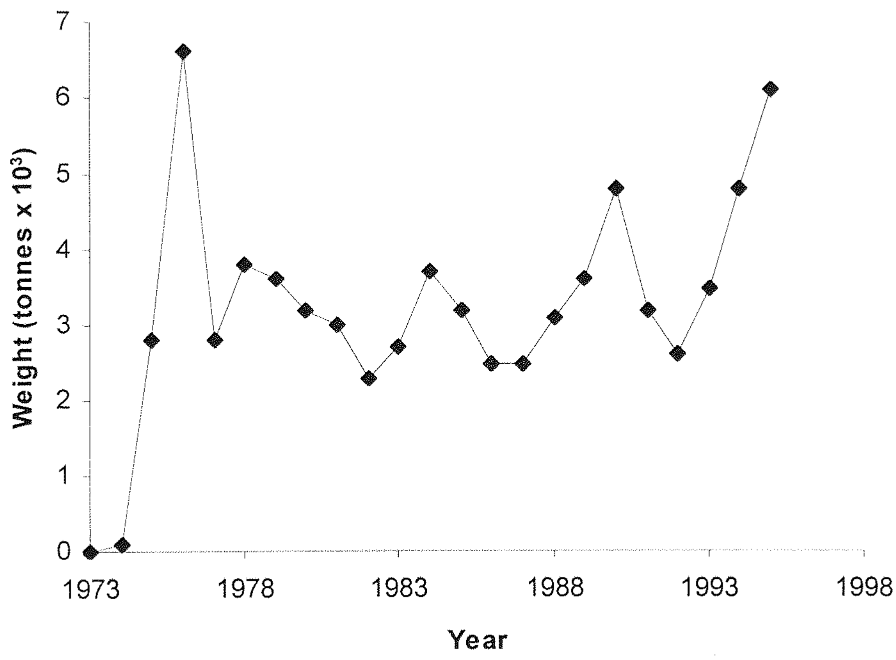


Figure 1.2: Weight of scallop landings in England and Wales (1000's of tonnes). Data from MAFF landing statistics.

The majority of the English Channel fleet is based in either Brixham or Plymouth where they are better situated to exploit the more extensive grounds off Lyme Bay. However, small local boats also fish the inshore grounds and there are also a few divers who fish the shallower beds off Dorset and Devon. In the western Channel, both the spring loaded Newhaven dredge and the large 2m wide French dredge are used depending on the type of ground. The Newhaven dredge is almost exclusively used in the eastern Channel due to the roughness of the grounds and the large amount of stone (Rieucau, 1980; MacKenzie *et al.*, 1997).

Currently, the only legislation controlling the fishery is that of a minimum landing size of 100mm length in the western Channel and 110mm in the eastern Channel. These correspond to the regulations set for ICES areas VIIe & VIId. Also more recently Devon Sea Fisheries have introduced a new closed season for scallop divers from 1st July to 30th September to protect stocks during the breeding season (Aylmer, 1998).

1.2.2 The Isle of Man fishery

The Isle of Man has one of the better studied scallop fisheries in Europe. The fishery for scallops, *Pecten maximus*, began in the Isle of Man in the late 1930s after dense beds were discovered off Bradda Head (Smith, 1938; Brand *et al.*, 1991a). The switch to scallops was also due to the decline in the traditional herring fishery and the loss of the cod and plaice fisheries. Right from the start it became an important and valuable fishery making up 43% of the total value of fish landed in the island in its first year (Brand *et al.*, 1991a). Initially small motor boats were used to tow a few toothed scallop dredges on the inshore grounds. However, as the industry grew, larger boats were being brought in which could tow more dredges and cover a larger area of seabed. With the success of the industry it became necessary to search for more fishing grounds further offshore. By the mid 1980s, at the peak of the fishery, vast beds miles offshore were being fished (Allison, 1994).

Since 1969 there has also been a valuable fishery for the queen scallop, *Aequipecten opercularis*. Queens were being caught before this time as a by-catch in the scallop fishery but there was no use for them. It was not until a frozen food market was discovered in America that the queen fishery took off. Initially the fishery for queens took place in the scallop closed season but it soon proved more profitable to fish for them all year (Brand *et al.*, 1991a). The fishery for queens also opened up new grounds for scallops as often the two species coexist. The main fishing grounds for queens are the Point of Ayre, east of Douglas, south of Port St. Mary and the Targets (Brand and Allison, 1987).

As the Isle of Man implements its own fisheries policy, legislation was quickly brought in to manage the fishery. Initially this involved a closed season from 1st May to 30th September and a minimum landing size (MLS) of 4.5 inches in length. Currently the closed season runs from 1st June to 31st October and the MLS is now 110mm since metrication. A further clause makes it illegal to land a catch with more than 20% spawned individuals (Brand, 1993). The success of the industry has stimulated much research at the Port Erin Marine Laboratory, University of Liverpool, largely funded by the Isle of Man Government. This research has covered every aspect of the scallop fishery including basic biology (Mason, 1957; Mason, 1958), population dynamics of the shellfish (Murphy, 1986; Allison, 1993), fishing effort of the fleet (Brand *et al.*, 1991a; Brand and Murphy, 1992; Brand, 1993; Brand and Allison, 1994), possible aquaculture for scallops and restocking (Brand, 1976; Paul, 1978; Brand *et al.*, 1980; Paul *et al.*, 1981; Brand *et al.*, 1991b; Wilson, 1994) and impact of scallop dredging on the benthos (Brand and Hawkins, 1996; Hill *et al.*, 1996; Kaiser *et al.*, 1996; Hill *et al.*, 1999).

Detailed information on the catch rates has been collected since 1950, although on a patchy basis. These data show that catch per unit effort data (CPUE) has decreased on inshore grounds such as Bradda Head and Peel since 1950. CPUE has been defined as the number of scallops per metre dredge per hour fishing. On the Bradda Head ground CPUE decreased rapidly for the first 3 years and has remained low since the 1960s. On the offshore grounds the case is similar except that fishing started more recently. There are also differences between fishing grounds and from year to year depending on recruitment and exploitation (Murphy, 1986). Also within a ground in a season CPUE will fall as the season progresses, especially on the inshore grounds (Murphy, 1986). Experimental tagging studies carried out on the Bradda Head ground support the CPUE evidence that stocks have declined over the years (Brand and Murphy, 1992).

Although CPUE values have fallen, exploitation rates (the proportion of the fishable stock taken each year) for the Bradda Head ground have remained high since the start of the fishery (Brand *et al.*, 1991a). During the 1987-8 season, exploitation rates were estimated at 37% by tagging experiments for this inshore ground. However, the exploitation rates of the offshore grounds were lower although they are currently rising (5-20%) (Brand and Murphy, 1992). Natural mortality is the death of scallops caused by old age, disease or predation by natural predators such as starfish or crabs (Lake *et al.*, 1987). Estimates of natural mortality (M) for fished populations around the Isle of Man gives values of approximately M=0.15 - 0.20 (Mason *et al.*, 1979; Mason *et al.*, 1980; Murphy, 1986; Murphy and Brand, 1987; Allison, 1993). However, these do not include the indirect fishing mortality caused by dredge damage. Estimates of M=0.31 - 0.61 obtained from tagging experiments on the Isle of Man do include this element (Brand and Murphy, 1992).

Age structure studies on the populations of *P. maximus* from different fishing grounds show some interesting trends over time. Firstly, on a heavily fished inshore ground (Bradda Head) the data show that before the fishery started in 1937 the population was made up of older individuals. Approximately 50% of scallops were 9 years or older (Tang, 1941). By the 1960s fishing had reduced the most abundant group to the 6-8 year olds (Gruffydd, unpublished results in Brand *et al.*, 1991). For the last 30 years the inshore fishery has been largely dependent on the 4 year old recruiting age group (Brand *et al.*, 1991b). In contrast to this the offshore S.E. Douglas fishing ground had a larger proportion of older individuals, although this is no longer the case as exploitation rates have increased in recent years (Brand *et al.*, 1991a).

Recruitment can be considered to occur in two phases: firstly to the adult population and then to the commercial fishery. The first probably occurs at spatfall whereas the second occurs when the scallop reaches commercial size (110mm). Good spat settlement may give rise to strong year classes in the population age structures if juvenile mortality is low. The strength and regularity of recruitment is an important factor in the maintenance of the Isle of Man fishery. Another important aspect of recruitment is the fact that the most heavily fished grounds have the best recruitment. This is the case for Bradda Head and the Chickens and is thought to be due to the strong tidal currents bringing spat to these inshore grounds (Brand *et al.*, 1991a). In other fisheries, such as the western English Channel, recruitment can be highly variable with some year classes being strongly dominant while others may be totally absent (Rieucau, 1980).

Despite the large fishing effort, a viable fishery for scallops has lasted around the Isle of Man for the past 50 years. This is probably due to steady recruitment each year and to the early introduction of fisheries management measures. This has preserved a large spawning stock by allowing adult scallops 2 to 3 years spawning before recruiting to the fishery. Also the number of boats fishing for scallops may have reached a ceiling due to economic factors, thus helping to preserve stocks.

1.2.3 **The St. Brieuc Bay fishery**

The St. Brieuc Bay fishery is probably the nearest studied scallop fishery to Guernsey. The French fishery for scallops developed on the Atlantic coast and in the Eastern English Channel in the 1950s. However, it was not until 1962 that it extended to the Bay of St. Brieuc in the Western English Channel (Ansell *et al.*, 1991). The catch in this fishery steadily expanded from 0 to 12,000 tonnes in the first ten years. During the 1970s it remained around 15,000 tonnes before declining rapidly in the 1980s (Ansell *et al.*, 1991; IFREMER, 1992). The amount of fishing effort during the first 20 years of the fishery was in the order of 22,000 fishing hours per season. However, during the 1980s the catch has dropped to 1,500 tonnes for 8,000 hours of fishing (IFREMER, 1992) and the fishery has become dependent on recruitment exploitation due to the loss of biomass (Ansell *et al.*, 1991).

As with the Isle of Man this is a dredge-based fishery utilising a standard 2m toothed dredge with a diving plane. National regulations stipulate that the maximum width of dredge is 2m, minimum tooth spacing of 100mm and a minimum diameter of the iron belly rings of 84mm (Dintheer *et al.*, 1995). Other measures to regulate the fishery include a closed season from May to October, a minimum landing size of 100mm (which applies to the whole of ICES area VIIe) and a licensing scheme (Ansell *et al.*, 1991). The licensing is organised by the fisherman's organisation and can be used to enforce a variety of regulations such as the number of licences, size or power of boats, fishing hours and catch quotas.

1.2.4 **Scallop fisheries management**

Due to the level of exploitation in many scallop fisheries it is often necessary for authorities to bring in management measures to conserve stocks and prevent overfishing. These strategies are also useful in minimising major fluctuations in landings, maintaining profits for fishermen and reducing conflict between commercial and recreational sectors (Bull, 1989). These conservation measures require research into scallop population dynamics in order to implement suitable regulations. However, these are often met with disapproval by the fisherman as they will invariably have lower catches initially. There are two types of measure used to conserve stocks, firstly those which increase size at first capture and secondly those which reduce fishing effort (Sinclair *et al.*, 1985; Orensanz, 1986; Bull, 1989; Orensanz *et al.*, 1991; Dredge, 1994; O'Boyle and Zwanenburg, 1996).

By far the most common method of increasing size at first capture is to introduce a minimum landing size (MLS). For example in the western English Channel this is currently set at 100mm in length (anterio-posterior axis). However, it would be better if the undersized individuals were not caught in the first place as this inevitably causes some mortality (Gruffydd, 1972). In a dredge fishery increasing dredge selectivity would achieve this by not catching smaller individuals. The selectivity of dredges is dependent on the length and spacing of the teeth, the diameter of the belly rings and the mesh size of the netting back.

Reducing fishing effort usually involves the introduction of licences except in the most common case of a closed season. The closed season prevents fishing usually during the spawning seasons to help maintain recruitment. For example in the Isle of Man the closed season currently runs from the 1st June to 1st November. Licences can be introduced to reduce fishing effort by limiting the number of boats, their size and engine horsepower and the spread of dredges (Brand, 1993). Other methods that could be used to reduce fishing effort include limiting the length of the fishing day or the number of fishing days per week. However, both these measures would be difficult to enforce and could prove detrimental to the fishermen after a spell of bad weather when they will need to work more to restore their income (Brand, 1993). A summary of some of the management measures used in *P. maximus* fisheries (Table 1.1) and other scallop fisheries around the world (Table 1.2) are shown below.

Table 1.1: Scallop fisheries management measures applied to different *P. maximus* fisheries

Location	Management measures	Source
Isle of Man	MLS: 110mm Closed season: 1st June - 1st November Boat size: <50ft within 3 mile limit	(Brand, 1993)
Scotland	MLS: 100mm	(Ansell *et al.*, 1991)
England and Wales	MLS: 110mm in Irish Sea and Eastern English Channel, 100mm elsewhere French dredges only allowed outside 12 mile limit and on vessels with total beam length <8m	(Ansell *et al.*, 1991)
France	MLS: 110mm in Eastern English Channel, 100mm elsewhere Belly rings minimum diameter of 85mm Closed season: April-May to October-November (depending on region)	(Dintheer *et al.*, 1995)

Table 1.2: Management methods used in other scallop fisheries world-wide

Location	Management measures	Source
New Zealand (*Pecten novaezealandiae*)	MLS Restrict number and size of dredges Closed season (5 months) Licences (limited number) Daylight dredging only Five day fishing week Daily quotas Total Allowable Catches (TACs)	(Bull, 1989)
Southern Australia (*Pecten fumatus*)	Closed season Catch quotas Logbooks Licences (limited number)	(Zacharin, 1994)
Queensland (*Amusium japonicum balloti*)	Number of vessels limited Maximum net size Minimum mesh size MLS Logbooks Maximum vessel size	(Neville, 1989)
Western Australia (*Amusium balloti*)	Closed season (5 months) Number of vessels limited Limits on amount of fishing gear Minimum mesh size Maximum otter board size Daytime dredging only NB: No MLS as controlled sufficiently by net mesh and open season	(Joll, 1989)
Canada (*Placopecten magellanicus*)	Licences Closed season (4 months) Minimum ring size Restrict width of dredges Limit of 100 scallops per day for SCUBA divers	(Sinclair *et al.*, 1985)

One final method of fisheries management is to set total allowable catches (TACs) after yearly stock assessment. However, although these are used by the EEC for finfish, they are not considered appropriate for stocks of sedentary shellfish (Brand, 1993). The main criticism of TACs is that they often do not conserve stocks as they encourage fishermen to catch their quota quickly and cheaply. This often leads to some grounds becoming overfished while those more difficult to fish offshore would be underexploited. The fishermen would normally fish a ground until catches decline before moving on to allow the stock to recover (Wilson, 1994). In this way stocks are conserved due to economic reasons rather than management measures.

1.3 The effects of fishing on the marine benthos

Fishing has direct and indirect effects on marine ecosystems in that fishing gears are designed to remove target species but they can also catch or damage other species in the marine habitat.

1.3.1 Direct effects of fishing gears

There are two types of active gear which have a direct effect on the marine benthos, trawls and dredges. Both these types of gear are designed to catch benthic species and therefore are likely to have an effect on the whole benthic community of fishing grounds. With diminishing yields these gears have become larger, combined with more powerful fishing vessels and are therefore capable of causing more environmental damage (Jennings and Kaiser, 1998).

Trawls can be divided into beam and otter trawls and are used to catch species such as sole, plaice, queenies and shrimp. Otter trawls are made up of a wide net with the mouth of it being kept open by two metal plates joined by a rope. The rope and boards both dig into the sediment and in most cases tickler chains are fitted to increase the catch of flat fish. These chains are designed to dig into the sediment to disturb the fish so that they swim up into the path of the oncoming net. Beam trawls have a horizontal beam to keep the mouth of the net open and have metal shoes at either end to keep the beam off the sea bed. The footrope is attached to the bottom of the shoes and again tickler chains are added in order to penetrate the sediment and disturb flat fish.

The final type of demersal fishing gear are dredges which are either hydraulic or mechanical. Hydraulic dredges 'suck' up the sediment as well as target and non-target species, for further sorting on deck. The type concentrated on here, however, are the mechanical dredges that physically dig target species, such as scallops or clams, out of the sediment. These dredges differ from trawls in that they dig further into the substratum in order to remove the infaunal target species. The typical design of these dredges is a heavy duty metal and net bag attached to a metal frame (Figure 1.3). A metal toothed bar is fixed to the front of the dredge which is designed to dig the target species out of the sediment. In the case of scallop dredges, which are often towed over rough ground, gangs of narrow dredges are used rather than one large dredge as they follow the contours of the bottom better. In extreme cases up to 32, one metre wide dredges are towed behind a single fishing boat at a speed of roughly 2.5 knots (A.Brand, pers. comm.). Due to the size of these dredges and the intensity of fishing in some areas these dredges will have a significant impact on the marine benthos (Gruffydd, 1972; Caddy, 1973; Iribarne *et al.*, 1991; Eleftheriou and Robertson, 1992; Allison, 1993; Thrush *et al.*, 1995; Brand and Hawkins, 1996; Currie and Parry, 1996; Hill *et al.*, 1996; Kaiser *et al.*, 1996; MacDonald *et al.*, 1996; Kaiser *et al.*, 1998a; Hill *et al.*, 1999).

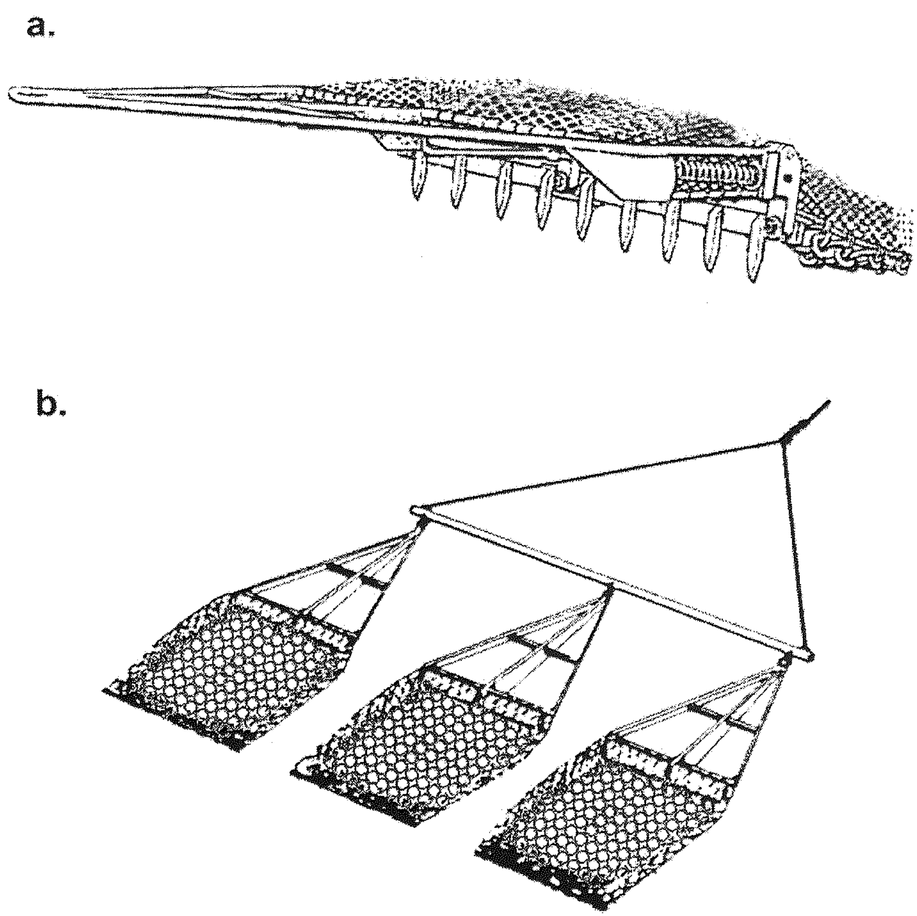


Figure 1.3: (a) Standard scallop dredge with spring loaded tooth bar (adapted from Strange, 1977). (b) Three dredges towed from a single beam (adapted from Chapman *et al.*, 1977).

1.3.2 **By-catch studies**

In both trawls and dredges the gear will contain both target species as well as by-catch species of no commercial value. The by-catch may consist of non commercially important species such as starfish or undersized individuals of the target species, which are illegal to land. These will normally be returned to the sea when the catch is sorted on deck. Fishing gears are often designed to reduce the catch of undersized individuals by increasing the mesh size of nets or the diameter of belly rings on scallop dredges. The survival of undersized individuals, of both target and non-target species passing through the net, has been studied in beam trawls. Animals were collected by attaching a cover over the cod end of a standard beam trawl. It was found that survival varied considerably and was related to the robustness of the species involved (Kaiser *et al.*, 1994; Kaiser and Spencer, 1995). Also the dredges will collect stones on most types of grounds which may increase the damage to species caught in the dredge due to the grinding action.

Studies have been carried out on the by-catch of scallop dredges in the Isle of Man (Brand and Allison, 1994; Hill *et al.*, 1996; Kaiser *et al.*, 1996; MacDonald *et al.*, 1996). This involved looking at both the abundance of different species and their initial damage or mortality. Further work was carried out to examine longer term (72 hours after capture) survival of different species exhibiting varying damage scores (Brand and Hawkins, 1996). The results of these experiments showed that a few species such as *Asterias* were common in the by-catch on most fishing grounds possibly due to their robustness and capacity for regeneration (Hill *et al.*, 1996). Indeed fishing over a long period will alter community structure but may also act to maintain it at a new equilibrium level (Jennings and Kaiser, 1998).

Damage to by-catch has also been used as an indicator of past fishing intensity. Starfish, *Asterias rubens* and *A. irregularis* were examined for arm loss or regeneration in areas of known different beam trawl fishing intensity in the Irish Sea (Kaiser, 1996b). It was shown that the presence of regenerating arms provided a short term biological record of frequency of encounter with demersal fishing gear. This technique was easy to carry out and could therefore be used to examine approximate fishing intensity on a very local scale. Scarring of whelks and bivalves could also be used as an independent estimate of fishing effort as they are known to display scarring due to previous contact with fishing gear. However, an initial study by Brand and Hawkins (1996) proved inconclusive, possibly because commercial gear was used to sample the scarred animals.

1.4 General aims of this work

The dynamics of a fishery can be summarised by the Russell equation (Eq. 1.1).

$$S_2 = S_1 + (R + G) - (F + M) \qquad \text{(Eq. 1.1)}$$

where: S_1 = Weight of exploitable phase of population at end of year one

S_2 = Weight of exploitable phase of population at end of year two

R = Recruitment to stock

G = Growth of individuals

F = Fishing mortality

M = Natural mortality

This is really a descriptive equation and as such it is not mathematically solvable. It does, however, form a useful basis for consideration of an exploited fish stock such as scallops.

In Chapter 2 the size of the stock will be estimated by calculating the density of scallops and the approximate areas of the fishing grounds. Therefore the size of the stock on different fishing grounds as well as the overall Guernsey stock can be calculated. Chapter 3 will look at the growth and recruitment of Guernsey scallops, with the growth parameters being calculated from the von Bertalanffy growth function. In Chapter 6 estimates of the total mortality of the exploitable stock will be made. This will then be split down into values for fishing (F) and natural (M) mortality. In order to calculate a stock recruitment relationship a mathematically quantifiable equation, such as the Beverton-Holt yield per recruit equation (Beverton and Holt, 1957) will be used.

Chapter 4 investigated the behaviour of the diver fishermen and Chapter 5 assessed the impacts of scallop dredging on commercially important by-catch as well as the marine benthos.

2. Scallop Fisheries in Guernsey and other Channel Islands

2.1 Introduction

Scallop fisheries are a small but important part of the Channel Island fishing industry. One of the most interesting factors is the relative importance of the diver fishery compared with dredging. In many other *Pecten maximus* fisheries, such as in the English Channel (Franklin *et al.*, 1980a; Rieucau, 1980; Dare *et al.*, 1994a; Palmer, 1997) and the Irish Sea (Mason, 1983; Brand *et al.*, 1991a), the scallop beds are more suited to dredging and are often inaccessible to divers due to the excessive depths. However, scallop diving makes up a considerable proportion of the catch in Guernsey, Sark and Jersey. Diving is also a viable alternative method used to exploit shallow grounds in Scotland (*P. maximus*), Chile and Peru (*Aequipecten purpuratus*) and the Gulf of California (*Pecten vogdesi*) (Orensanz, 1986).

As there is a world-wide fishery for scallops, much research has been carried out on some of the more important species (see Chapter 1). In the north-east Atlantic the most heavily exploited scallop is *P. maximus*, which is fished for from Norway down to Portugal. However, much of the research has been carried out in the Irish Sea (Smith, 1938; Tang, 1941; Mason, 1957; Mason, 1958; Brand *et al.*, 1980; Murphy, 1986; Murphy and Brand, 1987; Brand, 1991; Brand *et al.*, 1991a; Brand *et al.*, 1991b; Brand and Murphy, 1992; Allison, 1993; Brand, 1993; Allison, 1994; Allison *et al.*, 1994; Brand and Allison, 1994; Wanninayake, 1994; Wilson, 1994; Allison and Brand, 1995; Brand and Hawkins, 1996), the English Channel (Franklin *et al.*, 1980a; Bannister, 1986) and around the coasts of Scotland (Strange, 1977; Mason, 1978; Mason *et al.*, 1979; Mason *et al.*, 1980; Mason *et al.*, 1991).

Collecting data on the age structure of *P. maximus* populations provides a wealth of information on the current state of the stocks as well as variability in recruitment. This information is comparatively easy to collect and analyse due to the annual growth rings laid down by this species (Mason, 1957). Although these are sometimes hard to interpret in more southern populations due to difficulty in locating the position of the first growth check, accurate estimates of age can still be achieved (Mason, 1983; Dare and Deith, 1989; Dare, 1991). Further problems can be encountered when ageing older scallops (>10 years old) as the rings at the outer margin of the shell become more tightly packed together and can suffer erosion and excessive fouling (Murphy, 1986; Allison, 1993). Despite this, ageing of large annual samples of scallop shells is an almost universal tool used to assess both *P. maximus* (Mason, 1983) and other temperate scallop populations (Caddy, 1989).

The overall aim of this chapter was to assess the scallop fisheries in the Channel Islands. First, this involved studying historical landings data from local fisheries departments as well as other organisations such as MAFF and the FAO. However, much of the current data, especially for Guernsey, has been estimated as there is presently no requirement to record landings. Therefore one of the aims was to calculate some estimates for current landings and compare them to previous years.

The specific objectives of this work were to:

- Define exploited population parameters, such as age and size structure of the catch, as well as estimating catch per unit effort (CPUE) to allow comparisons between fishing grounds.
- Estimate absolute density of different age classes of commercial sized scallops on both dredge and diver fished grounds.

In this study all the work on the scallop fishery was carried out on commercial fishing boats rather than research vessels. This was done partly for logistical reasons, but also to obtain results more directly related to the fishery in order to get good estimates of commercial fishing effort, catch per unit effort (CPUE) and find the fishing grounds most commonly used. A new method was used to calculate the density of scallops on diver fished grounds and CPUE for the diver fishery.

2.2 Review of the existing fisheries

Currently the fishery for scallops in Guernsey is restricted to *P. maximus* although there was an important fishery for queens during the early 1970s (Askew *et al.*, 1973). In Guernsey, scallops are caught both by divers and dredgers which makes it quite different to other scallop fisheries. Before November 1997, divers needed to obtain a licence from the Department of Fisheries in order to collect scallops, but the law has recently changed making them no longer a requirement. There were no limits on the number of licences and approximately 200 were issued in 1996. The majority of these went to recreational divers with only approximately 5% going to commercial fishermen (Helyar, 1995b). Currently there are four commercial diving boats, with up to nine divers in total and three dredgers exploiting the scallop stocks (J. Belshaw, pers. comm.). Information on the scallop fishery in Guernsey was very limited due to a lack of research and no requirement for fishermen to declare catches sold locally. A voluntary logbook scheme was started in January 1999 to help in estimating landings of fish and shellfish in Guernsey. The value of scallop exports was rated at £100,000 in 1995, although much of the trade in scallops occurs locally and informally via direct sales. Surveys carried out in 1997 give an estimated annual catch of 65 tonnes from the scallop divers (Sendall, 1997).

2.2.1 Diver fishing

Fishing for scallops by diving is popular in Guernsey mainly due to the type of local fishing grounds. Most of the diver fished grounds are within two nautical miles of land and are no deeper than 40m below chart datum. Also the large number of reefs make it almost impossible for scallop dredgers to come close to land leaving them only accessible to divers. The shelter provided by land and the close proximity of dive sites to the harbour mean that small dive boats can fish in most weathers. Poor underwater visibility due to bad weather or strong tides are usually the only factors which limit the days when fishing can take place. The dive boats are less than 8 metres long and are either operated by two divers or a diver and boatman. The only other costs involved are the initial purchase of the diving equipment and the air that they use (~£5 per day). Most of the divers use a minimum amount of equipment, much of it very basic. So far, the divers studied all use standard air equipment although one other diver was known to use Nitrox which allows longer bottom times, but with associated longer decompression stops.

A survey of licensed scallop divers was carried out by the Department of Fisheries in 1992. This took the form of a questionnaire, covering dive frequency, size of catches and most commonly dived areas. The survey had a relatively high response rate of 51%. It was concluded that the main fishing pressure on the stocks came from the few professional divers who earn their living from scallops, and not from the many recreational divers (Helyar, 1995b). The main fishing grounds are off the east coast of Guernsey with most activity from St. Peter Port harbour down to St. Martins Point (Figure 2.1). The commercial divers also concentrate a lot of their effort at the north of the island around the Platte Fougere, where the fishing grounds are deeper.

The final part of this study focused on the total value of the catch and on fishing effort. It was calculated that the total catch in 1992, for all licensed divers, was approximately 99 tonnes, corresponding to a value of £959,000. However, this assumed that responses came from a broad cross-section of divers, whereas this was actually calculated from responses from approximately half the number of registered divers. This value did not include scallops caught by dredgers as they do not require a licence and do not need to record their catches. The exports for 1992, included in this value, were only 18.5 tonnes, which clearly demonstrates the importance of the local market (Helyar, 1995b).

The frequency of dives and catches for divers, both commercial and recreational are shown in Table 2.1. These results show that the main pressure on the stocks comes from the commercial fishermen and not the recreational divers. However, the recreational divers will be reducing demand and the price of scallops as approximately a third of the total catch can be attributed to them (Helyar, 1995a).

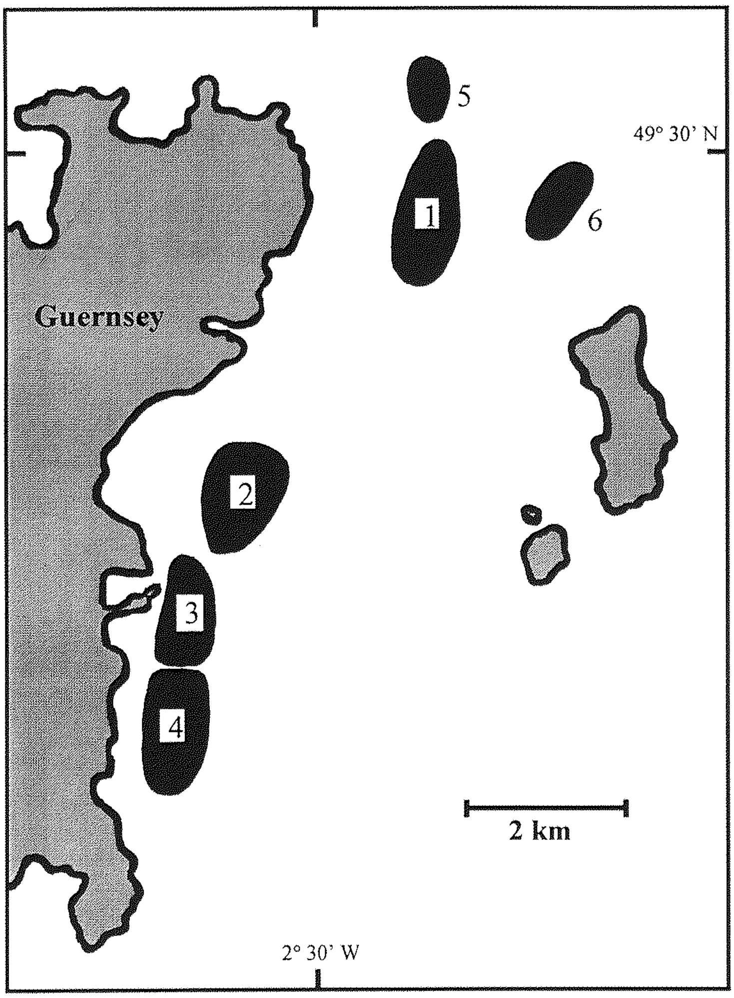


Figure 2.1: Scallop diver fished grounds off Guernsey. 1 – Petite Canupe; 2 – Pipe; 3 – Harbour; 4 – Anfre; 5 – Platte Fougere; 6 – Pensionnaire.

Table 2.1: Average scallop diving patterns (from Helyar, 1995)

Category	Number of dives per person per annum	Catch per dive (no. of scallops)	Total catch per person per annum
Overall	35.5	108	3830
Recreational	16.4	47	933
Professional	495	120	59400

From my study it was found that the divers usually carried out three dives per fishing day, each lasting approximately 20 minutes depending on the depth. On average they caught 48.6 ±1.2 (S.E.) scallops per dive, resulting in a daily catch of about 145 scallops per diver. This figure was lower than the 120 scallops per dive for the professional divers as calculated by Helyar (1995). This may be due to his figures being calculated from a questionnaire where divers might exaggerate their catches or it could reflect a greater abundance of scallops at that time.

2.2.2 **Dredge fishing**

There have been between one and three scallop dredgers operating out of St. Peter Port over the past three year period of this study (1997-1999), although French and Jersey boats do fish on some of the same grounds further offshore. These boats are less than 12m long and usually fish for up to 6 hours a day. They are also not exclusively scallop dredgers in that they also use other demersal gears to target other fish (such as sole and spider crabs) when conditions make it more favourable. The main dredge fished grounds occur slightly further offshore to the diver grounds as they need to avoid the many inshore reefs while towing demersal gear. These grounds are at a depth of between 30m and 50m and extend off the south and east coasts towards Jersey (Figure 2.2).

Analysis of scallop dredging in Guernsey has been carried out on only one of the dredgers, the M.F.V. '*Rosie J*'. This is a 9m vessel that uses 6 standard, 76cm wide, spring loaded scallop dredges, in gangs of three on either side of the boat (Figure 1.3). On each dredge there are nine 9cm long teeth, which get replaced with new ones when they wear down by just 2cm. The belly rings on the dredge have an internal diameter of 72mm, which allow undersized scallops to pass through the dredge reducing the by-catch. The dredges are towed at 2 to 3 knots for a period from 45 minutes up to 2 hours, depending on the ground. Thus individual hauls range from 3 to 15 km. The catch was then hauled and emptied onto the deck before being sorted where trash fish and stones were removed and thrown overboard. Average catch per tow was approximately 150 scallops resulting in a daily catch of 4-500 scallops. Although scallop dredgers catch more scallops per day, they have much higher overheads (e.g. cost of repairing dredges, fuel etc.) than the diver fisherman.

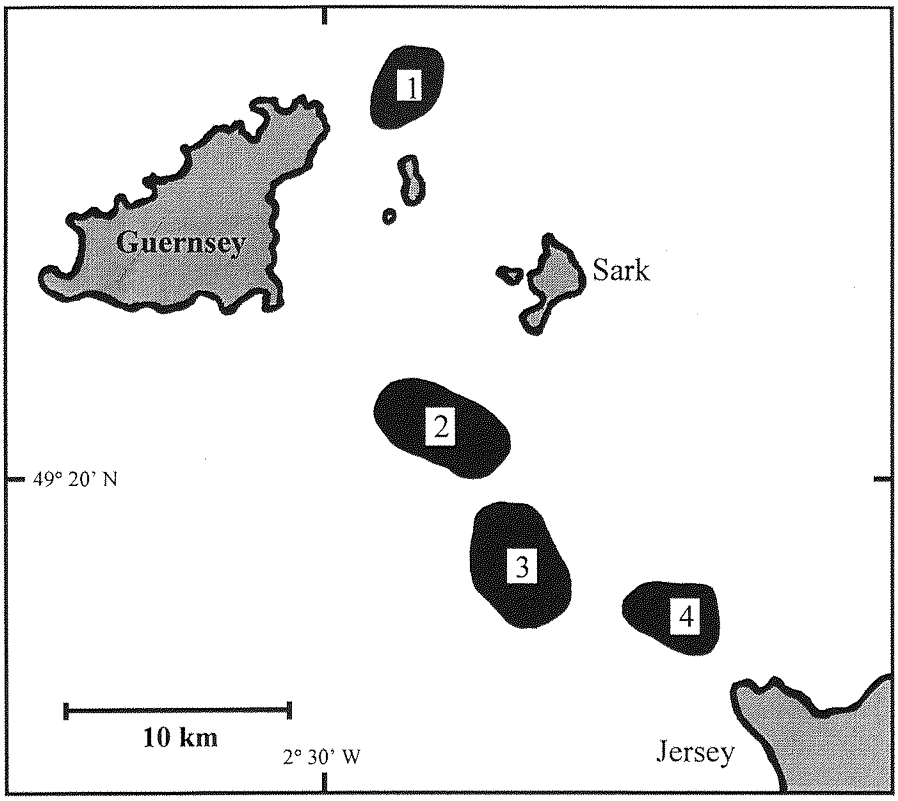


Figure 2.2: Scallop dredge fished grounds off Guernsey. 1 – Tautenay; 2 – Gaudine; 3 – Long Bank; 4 – des Ormes.

2.2.3 **Scallop fisheries in Jersey**

Before 1996 it was illegal to fish for scallops by diving in Jersey and the fishery was dredger-based. Dredging for scallops has been carried out occasionally for many years although since the divers have returned good catches more dredgers have been attracted to the fishery. The main scallop fishing grounds off Jersey are to the north, south and east coasts of the island. The larger dredgers (including some French boats) operate further to the south and south-east of the island (G. Morrel, pers. comm.).

The minimum landing size (MLS) for scallops in Jersey is 110mm, which is 10mm greater than Guernsey and the rest of ICES area VIIe. Scallop divers in Jersey are also required to obtain a permit. Commercial divers permits have unrestricted catch limits whereas recreational permit holders are limited to 24 scallops per day. Another condition of the licence is that fisherman must submit details of their catches at the end of the year. There is no closed fishing season although most fishing by divers takes place from March to October (N. Hutton, pers. comm.).

Landings statistics for the divers and dredgers were only available for 1996-98 when the dive fishery was reintroduced (see Table 2.2). Initially diving permits were just split into recreational and commercial (68 permits), but for the last 2 years the commercial ones have been divided between French (16 permits) and Jersey divers (45 permits). The recreational divers have had a small input and have contributed, on average, 4.4 tonnes per year to the total scallop landings. Overall, total landings have increased over the three years although this has mainly been due to the dredgers as diver landings have fluctuated. Dredge fishing has also always provided the larger component of the total landings figure.

Table 2.2: Jersey scallop landings (1996-8) split into diver and dredge fished (tonnes). (Source: Dept of Agriculture and Fisheries, Jersey).

Year	Landings		Total
1996	Dredging Diving	70.6 53.8	**124.4**
1997	Dredging Diving	109.3 80.3	**189.6**
1998	Dredging Diving	154.9 42.8	**197.7**

Due to the increasing popularity of the fishery the Department of Agriculture and Fisheries in Jersey started a restocking trial in 1998 to try and enhance the stocks on the inshore fishing grounds where most of the diving takes place. A total of 100,000 *P. maximus* spat from Mulroy Bay in Ireland were released onto different sites and monitored by divers every few months. The spat were 15mm in length on release and have grown at a faster rate than Guernsey scallops. So far the trial seems to have successfully increased the abundance of scallops on these grounds and there was no observed influx of predators onto the reseeded sites (G. Morel, pers. comm.).

2.2.4 **Comparison of fisheries**

The relatively small scale of scallop fisheries in the Channel Islands results in them being considerably different to other fisheries that have been studied. In general fishing intensity was fairly low which means few management measures were needed to regulate the fishery and maintain stocks. This is a very different situation to more intensive fisheries that impose a variety of regulations to limit fishing effort and increase size at first capture (See Chapter 1 for review).

Compared with the situation in Jersey, the Guernsey scallop fishery has remained fairly constant over the past 10 or 15 years as diving and dredging have not been limited. The Jersey approach has been more cautious as diving was banned until a few years ago whereas dredging has taken place for some time. However, the success of the diver fishermen resulted in an increase in effort by the dredgers and an increase in the annual landings over the past three years. The Jersey authorities also applied a higher MLS than Guernsey and the rest of ICES area VIIe to help protect the stocks from overfishing. Despite this annual landings in Jersey were greater than those in Guernsey, although this was mainly due to their larger fishing effort. In both these fisheries the main limiting factor appeared to be the number of boats willing to enter the fishery rather than the legislation imposed, unlike more intensive fisheries such as in the St. Brieuc Bay.

2.3 Methods

The remaining sections of this chapter assess the population structure and abundance of *P. maximus* on Guernsey fishing grounds and the effect fishing had on these populations.

2.3.1 Population age and size structures

Population age and size structures were calculated from samples of flat valves collected from commercial fishermen. Samples were only used if individual dives were observed by the investigator to ensure the location of each sample was known. Three commercial divers fished for the scallops from the M.F.V. '*Pierre Marie*' and samples were collected annually, where possible, for three years (1997, 1998 & 1999) around May. If possible the whole days catch was collected and shells from different sites were separated. The diver fishing grounds at the Harbour, Pipe, Anfre and Petite Canupe were sampled annually, whereas others were only sampled occasionally. Samples for dredge fished grounds were collected while on board the M.F.V. '*Rosie J*' from the Tautenay, Long Bank, south of Gaudine and des Ormes fishing grounds.

The samples of flat valves collected from each site were then pooled together and a random sub-sample of approximately 200 flat valves was selected. Each shell was then aged by the investigator using the annual rings (Mason, 1983; Fifas *et al.*, 1991; Allison, 1993; Wilson, 1994), and measured to the nearest millimetre using a customised measuring board (Mason, 1983).

2.3.2 Catch per unit effort (CPUE)

CPUE needed to be calculated differently for the diver and dredge fishery due to the methods employed. Currently there is no requirement for fishermen to return logbooks of their fishing activity in Guernsey so CPUE was calculated from data collected from observed fishing trips only. For the dive fishery, data have been collected from three (out of four) commercial boats and six (out of nine) divers. The number of scallops caught and the duration of each dive (taken as the time from leaving the surface to returning to the surface) was recorded at various times during 1997, 1998 and 1999. Here CPUE was calculated as follows:

$$\text{CPUE} = \frac{\text{No. of scallops caught}}{\text{Dive duration (mins)}} \qquad \text{(Eq. 2.1)}$$

The study of the dredge fishery was done on one out of the three scallop dredgers which fishes out of Guernsey. CPUE was calculated as follows (after Murphy, 1986):

$$\text{CPUE} = \frac{\text{No. scallops / (dredge width} \times \text{no. successful dredges)}}{\text{tow duration (hours)}} \qquad \text{(Eq. 2.2)}$$

2.3.3 **Scallop density**

Estimates of actual scallop density (i.e. scallops.m^{-2}) were necessary to make comparisons between dredge and diver fished grounds, as the measure of CPUE was different for the two fishing methods. On the dredge-fished grounds, the distance of each tow was recorded using a handheld Global Positioning System (GPS). Density was estimated by calculating the total area of sea bed covered and making an allowance for the efficiency of the dredges. Published estimates of dredge efficiency gave a value of about 20% (Rolfe, 1969; Gruffydd, 1974; Chapman *et al.*, 1977; Mason, 1982; Iribarne *et al.*, 1991; Dare *et al.*, 1994b), so this was used in these calculations.

$$\text{Density} = \frac{\text{No. scallops}}{\text{No. successful dredges} \times \text{dredge width} \times \text{tow length} \times \text{dredge efficiency}} \qquad (2.3)$$

For the dive fishery the area covered by the divers was harder to measure accurately. The start and end positions of each dive were marked using a handheld GPS and the distance between them could then be calculated using the Garmin PCX-5 software. However, this assumed that the divers swam in a straight line between start and finish points. In order to calculate the area fished it was assumed the divers could cover a 3m wide track. This area could be easily fished in average visibility, in all but the strongest currents. The efficiency of divers seeing and catching the scallops was assumed to be 80% for the purpose of these calculations. This efficiency was estimated from a single occasion where a diver started from a marked point (a shot line) and swam with the tide up to a large reef. This was then repeated by a second diver who fished the same area. It was assumed the second diver found all the remaining scallops and allowed the efficiency of the first diver to be estimated. Although this trial was not replicated it provided a good starting point for an estimate of diver efficiency. Estimates of absolute density, for both diver and dredge fished grounds only include scallops that have recruited to the fishery ($\geq$ 100mm).

$$\text{Density} = \frac{\text{No. Scallops}}{\text{dive length} \times \text{width of track (3m)} \times \text{diver efficiency (80\%)}} \qquad \text{(Eq. 2.4)}$$

2.4 Results

2.4.1 Analysis of population structure at different sites

The age structures of the scallop populations on some of the fishing grounds sampled are presented in Figure 2.3a-g as age-percentage frequency histograms. These histograms only show the age structure of commercial sized scallops (>100mm in length) as samples of flat valves were only collected from catches.

In general the majority of scallops on the fishing grounds studied were less than 8 years old. This characteristic truncation of the age-percentage frequency distribution after recruitment was due to the selective removal of commercial sized scallops. There were a few grounds with individuals in the 9 and 10+ age groups with scallops over 10 years old recorded very rarely. The dredge fished grounds generally had a more even distribution of age classes than the diver grounds which may indicate a lower exploitation rate. These differences could also be due to high natural mortality on the inshore grounds, recruitment differences or offshore migration. The offshore dredge grounds also had a significant number of 9 and 10+ scallops that were often absent from the diver areas. The oldest scallop found was aged at 13 years old although the rings near the edge of the shell are hard to distinguish when they are tightly packed together. Scallops have been found with up to 22 growth rings off Port Erin (Isle of Man), but it was uncertain whether they corresponded to actual age (Tang, 1941; Mason, 1983). Another overall trend in the data was an increase in the importance in the younger age classes (3 and 4 year olds) in the commercial fishery over the three year period studied (1997 to 1999).

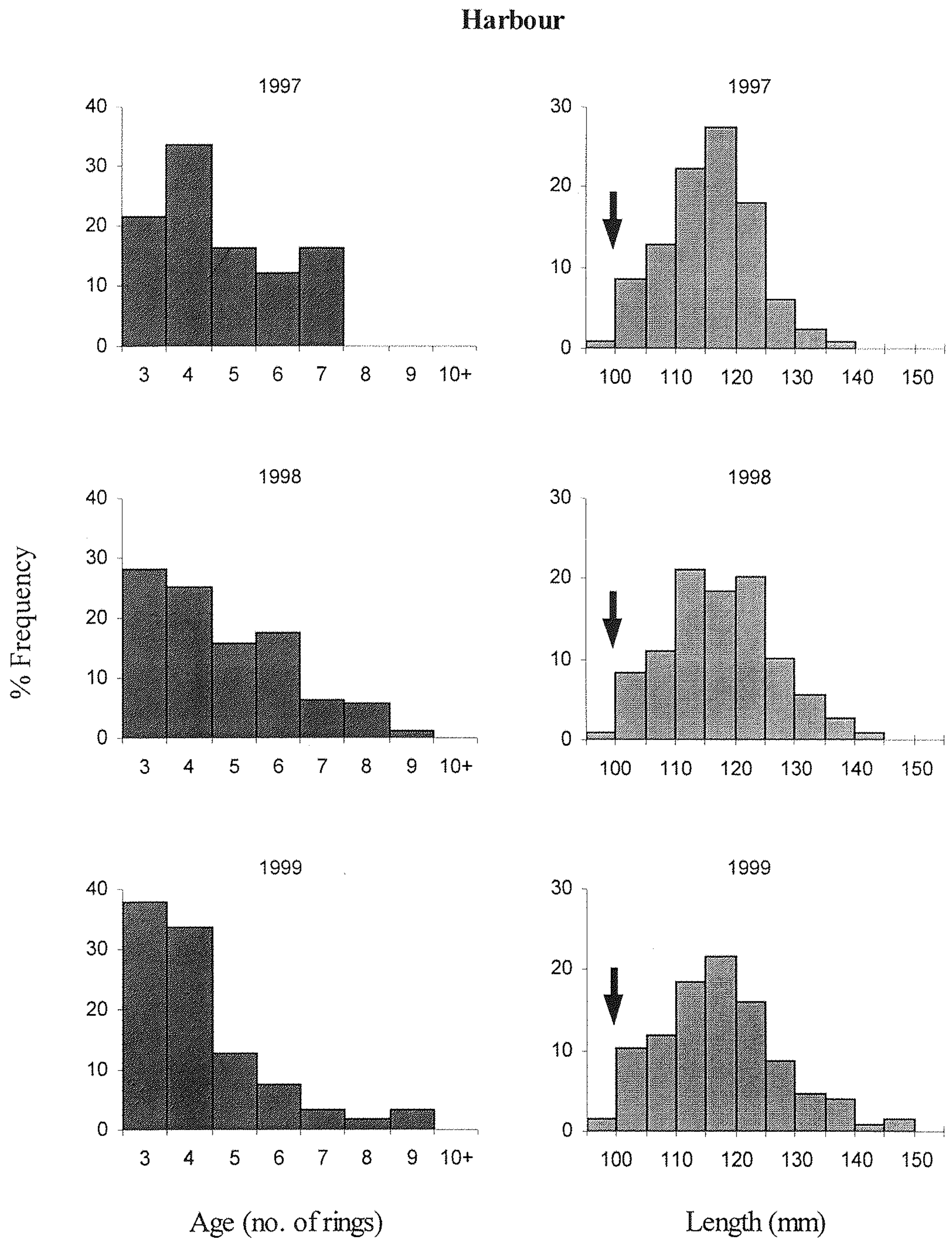
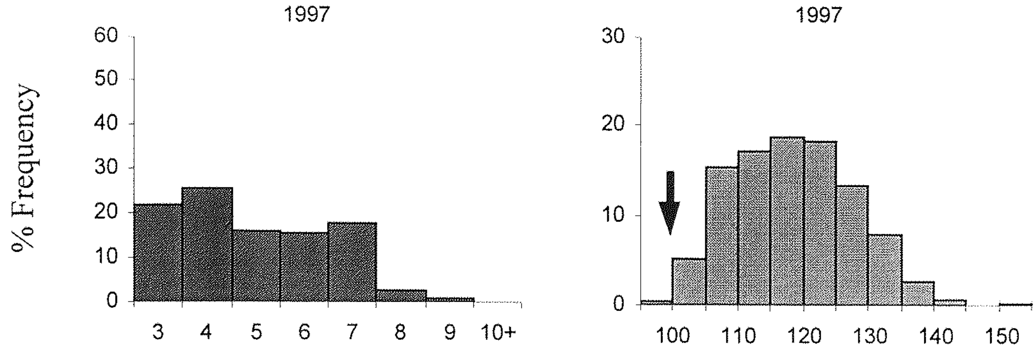


Figure 2.3a: Age and length frequency histograms for populations on scallop fishing grounds around Guernsey, sampled in May over three years (1997-1999). Arrows indicate size at first recruitment to the fishery. (n ≈200).

Pipe



1998 - Not sampled

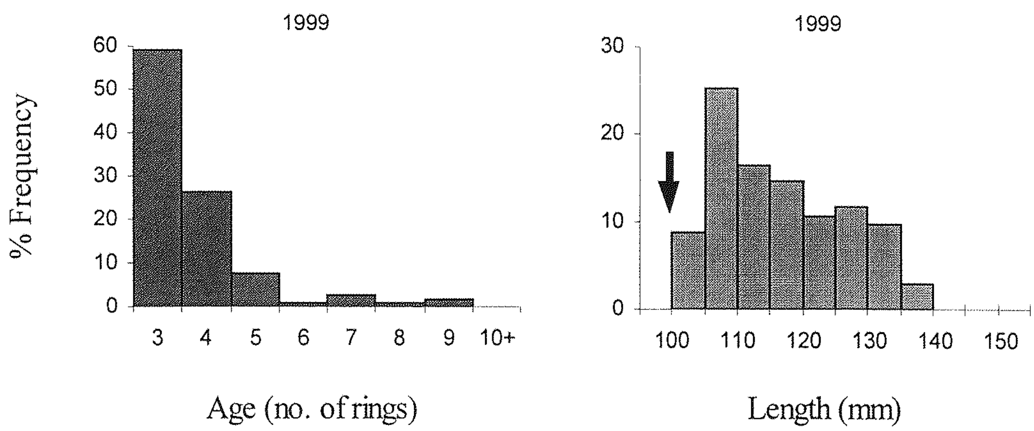


Figure 2.3b (cont.)

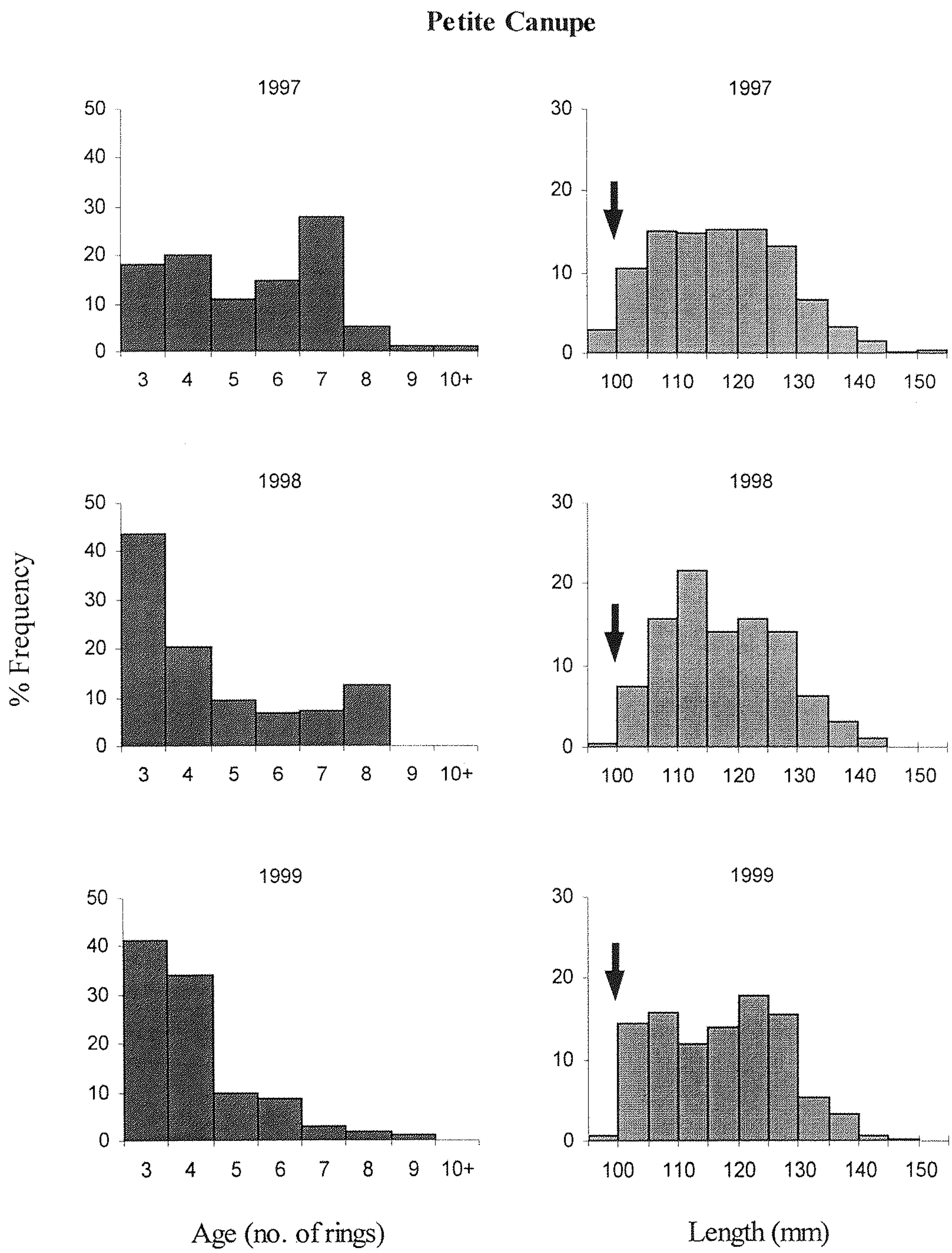


Figure 2.3c (cont.)

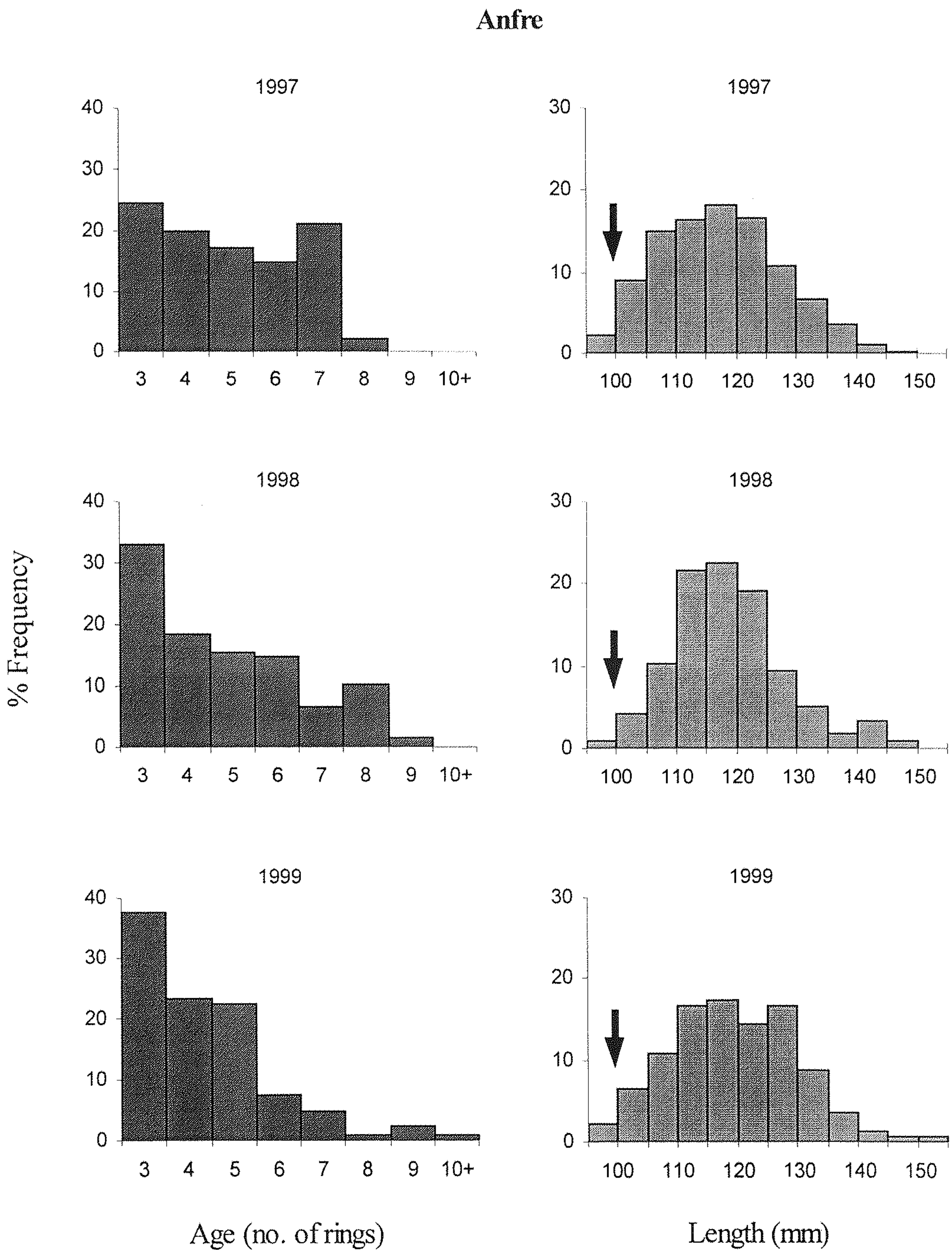
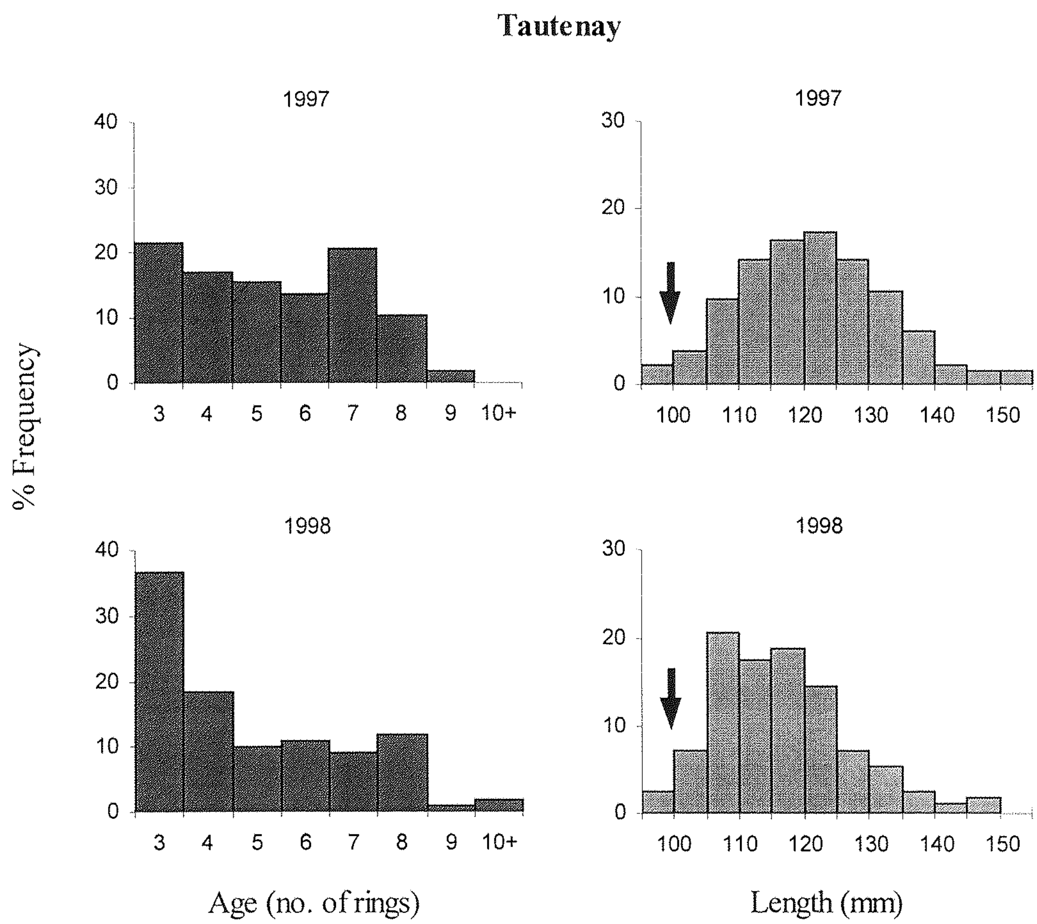


Figure 2.3d (cont.)



1999 - Not sampled

Figure 2.3e (cont.)

Gaudine

1997 - Not sampled

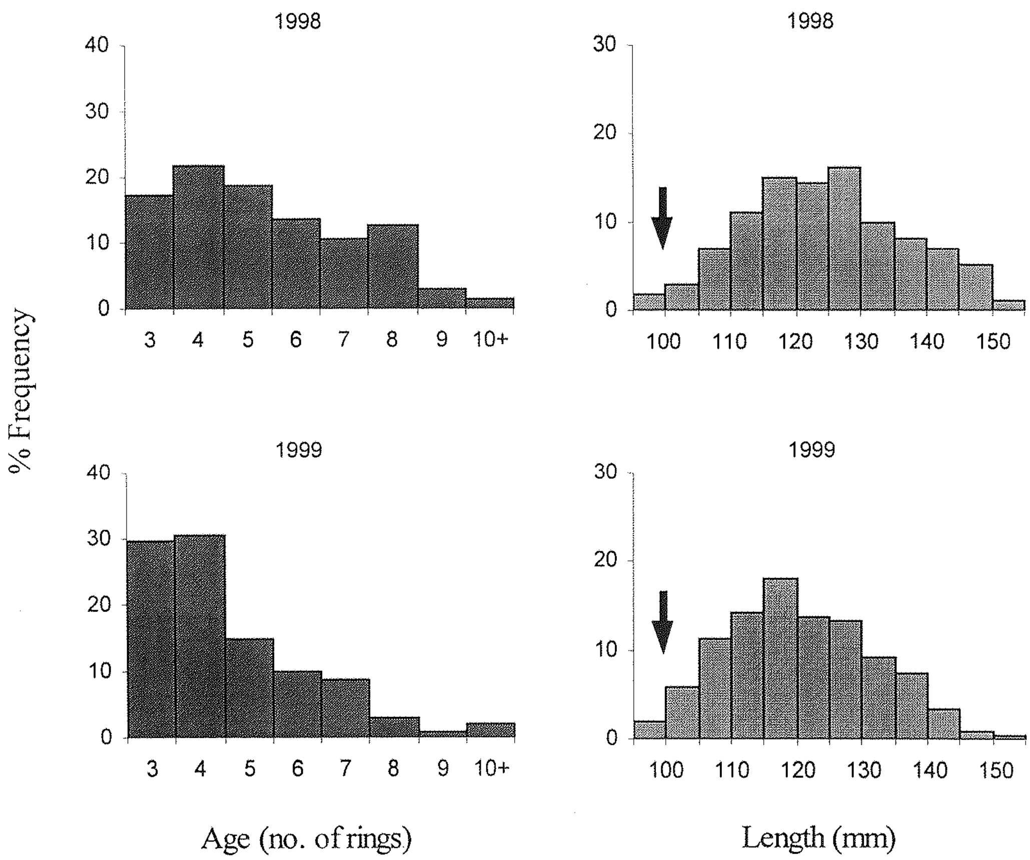


Figure 2.3f (cont.)

Long Bank

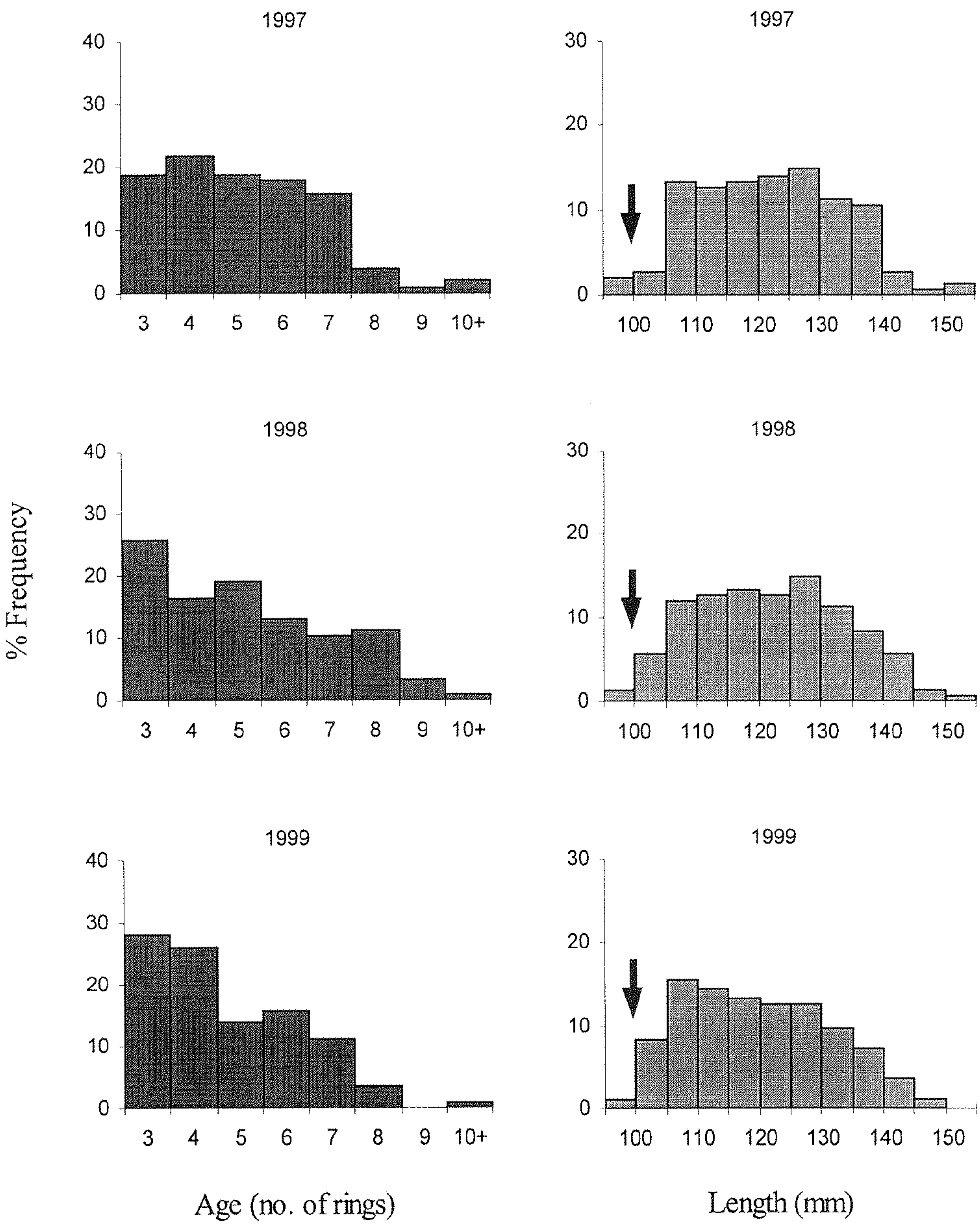


Figure 2.3g (cont.)

Strong year classes were also evident on some sites. For example the large numbers of 7 year olds in 1997 show that there was a particularly good recruitment in 1990. This high settlement resulted in large numbers of scallops which had recruited to the fishery by the end of 1992 (Guernsey Evening Press 11/11/92). This year class was still evident in the samples taken in 1998 and 1999, although to a lesser extent, indicating the strength of the recruitment. Indeed, since this year class declined due to fishing and mortality, the fishery became more heavily reliant on the 3 and 4 year olds. The higher frequency of these younger age classes in the catch could have been due to good recruitment from the 1995 and 1996 spawnings but it may also have been a result of the older scallops being fished out. Some evidence for the latter was shown in the age frequency histograms from some of the fishing grounds. In particular the Pipe and Tautenay grounds had a lower modal size class in later years compared with 1997 and an overall left skewing of the length frequency histogram.

The results from all the grounds in 1997 showed a fairly even distribution of age classes from 3 to 7 years old. Only the further offshore grounds at the Petite Canupe and Long Bank had a significant amount of 9 and 10 year olds (between 1% and 2%). This could be due to less fishing at these grounds as bad weather would have prevented boats getting there as they are further away from the harbour. However, by 1998 some of the more heavily exploited diver and dredge fished grounds like Petite Canupe and Tautenay showed a more truncated age-percentage frequency histogram with a high percentage of 3 year olds. This age class was still prominent in the 1999 samples with another good recruitment from the three year old age class. The Pipe ground was most dependent on the recruiting year class with almost 60% of the catch made up of 3 year olds in 1999.

Length frequency histograms have also been calculated from commercial catches at the same fishing grounds (Figure 2.3a-g). Again these show similar trends in that the offshore ground at Petite Canupe has a wider distribution of sizes than the Harbour, for example, with more large scallops (>145mm in length). This reflects the lower fishing intensity here, but may also be due to the scallops being harder for the divers to see as this ground has a rougher shingle bottom. As the scallops are more cryptic on this type of bottom they are less likely to be caught and have a better chance of reaching a larger size and age. The Harbour site had the lowest modal size group

(115-120mm) and a sharp truncation of the length frequency distribution after 125mm. This site had very few large scallops as they would have often got caught soon after recruiting to the fishery. The small scale dumping of undersized scallops by the fishermen at the harbour mouth may also have increased this effect.

In general the length-frequency distributions were unimodally distributed although there were some examples with a bimodal distribution from the diver grounds in 1998 and 1999 (e.g. Petite Canupe and Pipe). These distributions had peaks around 105mm and 120mm in length, which probably resulted from the high numbers of 3 and 4 year olds respectively. Over the three year period studied the modal size class either decreased or stayed the same at all the sites studied. There was also a gradual left skew in the distributions which was most pronounced in the results from the Pipe. This again demonstrates the fact that the fishery became more dependent on the smaller size and age classes over the three year study.

2.4.2 **CPUE of dredge and dive fishery**

Mean values of CPUE (±S.E.) were calculated for the four dredged fished grounds for the year in which they were sampled (Table 2.3). The values range from 15 to nearly 40 scallops.$m^{-1}.h^{-1}$ which were similar in magnitude to those calculated for research vessels and the commercial fleet off the Isle of Man (Allison, 1993; Brand and Allison, 1994; Wilson, 1994). Due to the lack of data from each ground over the three years it was difficult to interpret variations between grounds and years, although the following patterns emerged. Overall the inshore Tautenay ground had a consistently low CPUE which was probably due to a higher fishing intensity. The des Ormes ground in 1999 had the next lowest value with the Long Bank and Gaudine having generally higher values. The CPUE had declined since 1997 at the Long Bank although there was no significant between year variation on this ground ($F_{2,7} = 3.28$, P is NS).

Table 2.3: CPUE for dredge fished grounds (scallops.m^{-1}.hr^{-1}). Standard errors are shown in brackets.

Site	1997		1998		1999	
	CPUE	N	CPUE	N	CPUE	N
Tautenay	15.4 (3.0)	4	19.5 (3.3)	7	-	-
Long Bank	36.7 (5.3)	5	25.7 (3.1)	13	28.6 (5.8)	8
Gaudine	-	-	32.5 (9.0)	8	26.5 (4.4)	7
Des Ormes	-	-	-	-	21.6 (1.9)	4

Mean values of diver CPUE (scallops.min^{-1}) were also calculated for the diver fished grounds that were studied over the three years (Table 2.4). The units of these values differ from those given for the dredge CPUE, so can only be used for comparison of diver fished grounds. In 1997 six grounds were sampled although only four of these were commonly fished and re-sampled over the next two years. The CPUE at Pensionnaire was the lowest value found which explains why it was rarely fished. The other ground only fished in 1997 was at the Platte Fougere which is adjacent to Petite Canupe, but in deeper water (40m +) and was favoured by one diver who retired in 1998. This leaves four grounds (Anfre, Harbour, Petite Canupe and Pipe) which were sampled annually over the three year study.

Table 2.4: CPUE for diver fished grounds (scallops.min^{-1}). Standard errors shown in brackets.

Site	1997		1998		1999	
	CPUE	N	CPUE	N	CPUE	N
Anfre	2.94 (0.25)	37	2.53 (0.47)	31	2.67 (0.21)	21
Harbour	1.73 (0.13)	41	2.27 (0.19)	37	2.17 (0.26)	17
Petite Canupe	2.29 (0.10)	55	3.31 (0.23)	42	2.76 (0.22)	24
Pipe	2.10 (0.17)	34	4.50 (0.52)	24	1.84 (0.35)	15
Platte Fougere	3.24 (0.30)	7	-	-	-	-
Pensionnaire	1.16 (0.14)	7	-	-	-	-

The CPUE at Anfre and Harbour remained fairly constant from 1997 to 1999, whereas there were some fluctuations at the other two grounds. The most extreme variation occurred at the Pipe which showed a sharp peak of CPUE in 1998 yet declined again to less than half this value in 1999. CPUE was generally higher (3 out of 4 grounds) in 1998 which may be an indication of good recruitment of scallops into the fishery. Individual dive CPUE was also found to increase with depth (see Chapter 4) although the deepest diver fishing ground, Platte Fougere, did not have the highest mean value.

2.4.3 **Scallop density on commercial fishing grounds**

The density at age of recruited scallops was calculated from the age-percentage frequency and overall density on each of the fishing grounds (Table 2.5a & b). Overall the estimated total density of commercial sized scallops was greater on the diver fished grounds compared with the dredged ones. The density of post-recruits ranged from 2.7 to 11.3 scallops per $100m^2$ on the diver grounds and 1.5 to 4 per $100m^2$ on the dredged grounds. This may reflect an actual difference in abundance or result from errors in the different methods used to calculate density. There were clear annual variations in the estimated density of commercial sized scallops although generally they were higher for most grounds in 1998. The highest overall density was found at Anfre in 1998 with over 11 scallops per $100m^{-2}$. However, the calculation of density on dive sites was very sensitive to the width of the dive track. A reduction in the width by one metre (to 2m) would have given a 50% increase in the calculated density. Therefore the results shown give the lower range of possible values. Of the dredge fished grounds, the highest densities occurred on the Long Bank, which had twice that of Tautenay. The values for the dredge grounds were comparable with those calculated for the Irish Sea (1.3 to 3.1 scallops.$100m^2$) where similar methods were used (Wilson, 1994; Allison and Brand, 1995).

The density of individual age-classes showed high variability between grounds and years. The maximum observed density was 3.8 scallops per $100m^{-2}$ for age 3 scallops at Anfre in 1998. The maximum individual densities were all in the 3 or 4 year old age classes. The decline in density of individual cohorts could be studied by adding a year to their age for the samples taken in 1998 and 1999. Generally densities of cohorts declined over the three years with the largest reduction between the 1998 and

1999 samples. This suggests high mortalities during this period possibly due to more intense fishing or natural causes. There were some cases where the density of post-recruits increased from one year to the next, but this generally occurred in scallops aged from 3 to 4. This was due to the 3 year olds not being fully recruited to the fishery in that the cohort would have continued to recruit in their fourth or fifth year (see recruitment ogives, Table 6.1).

Table 2.5a: Estimates of the density (number per 100m^2) of commercial sized scallops (>100mm shell length) on diver fished grounds around Guernsey. These were calculated from the area covered by the divers assuming a 3m wide track and 80% efficiency.

	Petite Canupe			Pipe			Harbour			Anfre		
Age	**1997**	**1998**	**1999**	**1997**	**1998**	**1999**	**1997**	**1998**	**1999**	**1997**	**1998**	**1999**
3	0.57	3.33	1.42	0.60	1.84	1.22	1.31	2.10	1.43	0.87	3.75	1.78
4	0.62	1.55	1.17	0.69	1.17	0.54	2.05	1.87	1.28	0.71	2.09	1.11
5	0.35	0.71	0.34	0.43	0.53	0.16	1.00	1.17	0.48	0.62	1.75	1.07
6	0.46	0.52	0.29	0.42	0.37	0.02	0.74	1.31	0.29	0.53	1.67	0.36
7	0.88	0.56	0.11	0.49	0.47	0.06	1.00	0.47	0.13	0.76	0.75	0.24
8	0.17	0.95	0.07	0.08	0.08	0.02	0.00	0.42	0.06	0.07	1.17	0.04
9	0.04	0.00	0.04	0.02	0.06	0.04	0.00	0.09	0.13	0.00	0.17	0.12
10+	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
Total	**3.13**	**7.62**	**3.44**	**2.73**	**4.52**	**2.06**	**6.10**	**7.43**	**3.80**	**3.56**	**11.35**	**4.76**

Table 2.5b: Estimates of the density (number per $100m^2$) of commercial sized scallops (>100mm shell length) on dredge fished grounds around Guernsey. These were calculated from the area covered by the dredgers and assumed a dredge efficiency of 20%.

	Tautenay			Gaundine			Long Bank		
Age	**1997**	**1998**	**1999**	**1997**	**1998**	**1999**	**1997**	**1998**	**1999**
3	0.32	0.70			0.40	0.90	0.62	1.03	0.80
4	0.25	0.35			0.51	0.93	0.72	0.65	0.75
5	0.23	0.19			0.44	0.45	0.62	0.75	0.40
6	0.20	0.21			0.31	0.30	0.59	0.51	0.45
7	0.30	0.17			0.24	0.27	0.53	0.41	0.32
8	0.15	0.23			0.30	0.09	0.13	0.45	0.11
9	0.03	0.02			0.07	0.03	0.03	0.14	0.00
10+	0.00	0.04			0.04	0.06	0.07	0.03	0.03
Total	**1.48**	**1.91**			**2.31**	**3.03**	**3.31**	**3.97**	**2.86**

2.5 Discussion

2.5.1 Variations in population structure

The age structures of the populations studied indicated that they have been subjected to fairly heavy exploitation over a number of years. Compared with other exploited *P. maximus* populations, such as in the Irish Sea and English Channel, the Guernsey grounds have a young population structure very similar to Manx inshore grounds (Allison, 1993). Indeed the sharp truncation of the age-frequency plots on some of the grounds indicates a particularly high level of fishing. This pattern was more marked on the inshore grounds such as the Harbour, Pipe and Tautenay as they were easily accessible in most weather conditions and thus will attract a greater fishing effort. Not only has the relatively young age of the populations been evident throughout the study but also the importance of the recruiting age classes has increased over the three years. Again this was most evident on the more accessible grounds such as the Pipe where the fishery was almost entirely dependent on the three and four year old scallops in 1999. Here scallops will be caught soon after recruiting to the fishery resulting in a strong left skew in the size frequency distribution.

The increasing importance of the newly recruited scallops may have been due to a number of reasons. The shift to younger and smaller scallops in the catch may have resulted from a gradual decline in a very strong year class. Indeed the 1990 year class which were seven years old at the start of this study were still well represented in the catches in 1997 and 1998. This gives a good indication of the strength of this year class due to its importance in the catch a number of years after recruiting to the fishery. However, as the abundance of this year class declined due to fishing and natural mortality, the smaller and younger scallops became more abundant in the catch. This effect became more prominent due to good recruitment of the 1995 and 1996 cohorts which occurred in the 1999 catches as three and four year olds. This strong recruitment to the fishery was evident in the high densities and CPUEs on most of the fishing grounds in 1998.

An increase in fishing effort would also have the same effect of narrowing the age structure in the catches. This rise in fishing mortality would reduce the chances of individual scallops reaching the older age classes. Some evidence of this was seen on the inshore grounds, which have shown a stronger reduction in the older age classes than the grounds further offshore, which may have lower fishing pressure. This same effect has been observed on fishing grounds off the Isle of Man where the modal age class in the catches gradually reduced soon after exploitation began (Brand *et al.*, 1991a). Again this effect was less marked in the offshore grounds where fishing effort was less. However, it was most likely that a combination of the above factors has resulted in the Guernsey inshore fishery becoming more heavily reliant on the recruiting age classes.

2.5.2 **Assumptions in calculating density and CPUE**

As the two methods used to calculate CPUE were not comparable, the values for density were used to compare dive and dredge fished grounds. Again two methods were used to estimate density and each of these relied on certain assumptions. For the dredge fishery, published estimates of dredge efficiency were used to derive a value to use in the calculations. This value of 20% has been used to study scallop density in the Irish Sea and allows easy comparison between studies (Murphy, 1986; Allison, 1993; Wilson, 1994). However, experimental work on dredge efficiency gives a wide range of values from 12 to 65% (Rolfe, 1969; Gruffydd, 1974; Chapman *et al.*, 1977; Mason, 1982; Iribarne *et al.*, 1991). In estimating the density it has also been assumed that gear efficiency remained constant on all types of ground.

The assumptions made for the dive fishery could also have a large effect on the estimated density. Efficiency of the divers in seeing and catching scallops was estimated at 80% after a small scale experiment. This value was also assumed to remain constant for each diver on all the fishing grounds, which may not be the case as inexperienced diver fishermen caught considerably fewer scallops on some types of seabed. Variation in underwater visibility between sampling periods would also effect catches, but again this was assumed to remain constant. However, more crucially, after discussions with the divers, the width of the 'track' was estimated to be 3m and it was assumed they swam in a straight line from starting point to finish. Although these various assumptions could greatly effect density estimates they still provided a good comparison between grounds fished using the same method and they also allowed a comparison between methods as the values of density are in the same units. Direct assessments of scallop density would be useful in order to confirm these estimates and check some of the assumptions made. The following section assumed the overall higher densities on the diver fished grounds were due to actual differences in abundance but it must be considered that they may have been due to error in the calculations from the assumptions made.

2.5.3 Comparison of diver and dredge fished grounds

The density of scallops on the dredge fished grounds was similar to published estimates for the Irish Sea (Gruffydd, 1972; Brand and Allison, 1994). The lower estimates of density also occurred on the inshore ground at Tautenay where fishing effort was expected to be higher. The diver fished grounds had, on average, a density one and a half times greater than the dredged grounds, and in a few cases up to three times the density. This result helps explain why the diver fishing has remained viable on these grounds for so many years. This higher density at the diver sites was probably due to the lack of dredging in these areas as the divers had a smaller impact on the stocks. The impact of different fishing methods must be considered as some undersized scallops will suffer mortality following contact with a scallop dredge, whereas virtually none will be affected by divers (see Chapter 5).

Although CPUE was calculated using different methods the patterns of change within each fishery can be compared. The main difference between the two types of fishery was the amount of variability between fishing grounds. Mean CPUE was relatively constant between diver grounds, although there was a large variation between individual dives. This variation shows how unpredictable the success of each dive was and may also be due to the fishermen moving to other sites when catches declined. This unpredictability or patchiness of scallops was more noticeable in the dive fishery as they covered a considerably smaller area than the dredgers; 1000m^2 for an average dive compared to 40,000m^2 for an average tow. As the dredgers covered a large area of seabed they tended to average out the small scale variation in the density of scallops. However, in the dredge fishery, CPUE varied between grounds with the lower values occurring on the inshore ground. Although there was no significant difference, the same pattern was seen on the diver grounds with the lowest CPUE at the Harbour and generally higher values at the Petite Canupe which is further offshore.

The results of this work have shown that both the dive and dredge fishery in Guernsey have remained sustainable over the period of this study (1997-1999). Indeed, past information on the scallop fishery has also indicated that it has suffered few problems in recent times. This was probably due both to the relatively low level of exploitation which has changed little in recent years and also the reliability of annual recruitment. The scallop population has also been boosted in some years by exceptionally high recruitment, such as the 1990 year class, which was still forming significant proportions of the catch four years after recruiting to the fishery. Therefore, in the future the fishery should remain sustainable, providing exploitation rates do not increase and recruitment remains reliable, as the fishery is relatively reliant on the recruiting age class.

3. Growth and Reproduction of Scallops in Guernsey

3.1 Introduction

The biology of scallops, *Pecten maximus*, has been studied throughout the North-east Atlantic (e.g. English Channel, Franklin *et al.*, 1980; Irish Sea, Mason, 1957, 1958). These studies showed large variations in growth rates and reproductive cycles (e.g. single or double peaks in spawning). Thus it was important to study these parameters in Guernsey. For example, growth parameters can then be used to calculate simple Yield per Recruit (Y/R) models. Information on the population growth rates and seasonal spawning cycles are vital for fisheries managers in order to implement appropriate management measures (Beverton and Holt, 1957). The settlement of scallop spat was also studied to investigate variations around the island and assess the viability of spat collection in Guernsey.

Significant variations in the growth of many Pectinidae have been found even at a small geographical scale (Mason, 1957; Franklin and Pickett, 1980; Sinclair *et al.*, 1985; Bannister, 1986; Murphy, 1986; Dare, 1991; Orensanz *et al.*, 1991; Allison, 1993; Acosta and Roman, 1994; Bell *et al.*, in press). This spatial variation in growth rates has been attributed to several environmental factors such as temperature, substrate type, depth, current and food availability (see Bricelj & Shumway, 1991, for review). A considerable amount of work on the growth rates of *P. maximus* has been carried out in the Irish Sea (Tang, 1941; Mason, 1957; Murphy, 1986; Brand and Murphy, 1992; Allison, 1993), and the English Channel (Franklin and Pickett, 1980; IFREMER, 1992; Palmer, 1997; Bell *et al.*, in press), but none has been done in the Channel Islands. Many studies have also been carried out on collecting natural scallop spat for the purposes of restocking or aquaculture (Brand, 1976; Pickett, 1977; Brand *et al.*, 1980; Paul *et al.*, 1981; Brand *et al.*, 1991b; Thouzeau, 1991; Wilson, 1994; Chauvaud *et al.*, 1996; Cashmore *et al.*, 1998).

Variation in reproduction and recruitment is also common in *P. maximus* populations (Mason *et al.*, 1980; Thouzeau, 1991; Allison, 1993; Dare *et al.*, 1994a) as well as other species of scallop (Joll, 1989; Fuentes, 1994; Wanninayake, 1994), although the factors causing this are often unknown (Caddy, 1989). One of the main problems in finding the cause of this variability is in determining which adult population is responsible for the observed recruitment. Due to the length of the pelagic stage of *P. maximus* (up to 4 weeks Franklin *et al.*, 1980a), the larvae can be carried a significant distance by residual currents. Therefore it is important to determine the timing and strength of local spawning to see if there is a correlation with settlement of spat.

In general studies of scallop populations have been carried out from research vessels on known fishing grounds and surrounding areas (e.g. Palmer, 1997). The approach taken in this study differed as all the work was carried out on commercial boats during normal fishing activity. This will result in the information being more directly related to the fishery than research vessel surveys.

The overall aims of this chapter were to investigate the growth rates and spawning cycles of scallops in Guernsey. In order for this to be carried out successfully, the laying down of annual growth rings needed to be confirmed so the scallops could be accurately aged. Also, as seasonal cycles were to be studied for two further years, a comparison of methods was carried out to determine the best method in order to continue the work and still obtain useful data. The specific objectives of this work were to define the growth parameters, study the seasonal spawning cycle of scallops in Guernsey and compare the results with other studied populations. The timing and spatial variation in spat settlement around the island was also assessed using artificial spat collectors.

3.2 Methods

3.2.1 Growth studies

Samples of flat valves from different fishing grounds were collected from the diver fishermen in April 1997. Samples for the dredge fishery were collected from different grounds during May in 1997, 1998 and 1999. Sub-samples of 200 flat shells were randomly selected if the samples were too large. The shells in each sample were then aged using the annual growth rings, similar to the method used by Mason (1957). The length and height (Figure 1.1) of each flat valve was measured using a specialised scallop measuring board (Mason, 1983). It was decided not to calculate growth curves from these measurements as the 2 and 3 year olds in the sample would have given a higher than average result. This was due to the samples being collected from commercial fishermen as any 2 or 3 year olds would have had to reach the minimum legal landing size of 100mm, so smaller individuals of this age would not have been included. To try to get around this problem the distance perpendicular to the hinge of each annual ring was measured on the flat shells using dial callipers. For this analysis up to 30 shells from each age group were measured with more scallops being chosen from the older age groups. Annual growth in shell height of the scallops was then described by fitting the von Bertalanffy growth equation (von Bertalanffy, 1938; 1964) to the height at age data of each sample.

$$H_t = H_\infty(1-e^{-k(t-t_o)}) \qquad \text{(Eq. 3.1)}$$

where:

H_t = height at age t
H_∞ = asymptotic height
k = Brody / Bertalanffy growth coefficient
t_o = age at length = 0

The von Bertalanffy growth equation was fitted to the raw height at age data from each site using the non-linear regression procedure of SPSS. This method fits data to user defined models iteratively using the Levenberg-Marquadt algorithm. Initial estimates of the three parameters, H_∞, k and t_0, were taken from the literature as the procedure was capable of converging to the same answer from a wide range of values.

3.2.2 **Comparing growth on different grounds**

In order to compare the growth curves of scallops from different fishing grounds a growth performance index was required. The ω parameter (Gallucci and Quinn, 1979) uses two parameters from the VBGF (Eq. 3.2) and was fairly simple to calculate. This is a better way of comparing growth curves than just comparing L_∞ and k separately, as these two parameters from the VBGF are usually highly negatively correlated. Therefore a significant difference in ω is likely to represent a difference in growth rather than just a reciprocal change in L_∞ and k (Pauly and Munro, 1984).

$$\omega = L_\infty k \qquad \text{(Eq. 3.2)}$$

Confidence intervals for ω can be calculated by replacing L_∞ in the VBGF (Gulland, 1983; Allison, 1993):

$$H_t = \frac{\omega}{k}(1-e^{-k(t-t_o)}) \qquad \text{(Eq. 3.3)}$$

Again all the data, rather than means, were used to calculate the confidence intervals using the non-linear regression method in SPSS. Graphical analysis of these values will allow growth rates on different grounds to be compared as the assumptions of an ANOVA cannot be met (the distribution of the ω parameter is not known). Therefore visual comparisons of the 95% confidence limits will be used, although these will only be strictly valid when variances are equal. This also increases the problem of making a type I error due to multiple comparisons

3.2.3 **Tagging study**

Tagging was carried out over five days on board the M.F.V *'Pierre Marie'*. Scallops were collected by commercial scallop divers using SCUBA gear and brought to the surface in mesh bags. It was decided to only tag undersized individuals as the main aim of this work was to investigate the growth of the scallops. This allowed the scallops time to grow before they could be legally caught by the fishermen and returned for the £1 reward. The tagging was carried out as soon as possible in order to reduce physical stress and the scallops were kept on board for no more than half an hour. The tagging operation was performed at the stern of the boat where tagged scallops were kept either in a container of fresh seawater or in a mesh bag over the stern of the boat, before being released.

Scallops were tagged in batches of about 20 as this reduced the amount of time they were kept on deck. The tags used were red 16mm Petersen tags, which were individually numbered. It was decided to glue the tags close to the umbo of the flat valve. The tagging procedure involved four main stages: preparation of the scallop, attaching the tag, recording the information and releasing the scallops back onto the fishing grounds. Scallop shells were prepared for tagging by wire brushing and lightly sanding the flat valve close to the umbo. The area was then dried with tissue and wiped over with alcohol to remove any remaining water. A tag was then glued to the flat valve using 'Plastic Padding Chemical Metal'. The tags were first roughened up with sandpaper and a knife and temporarily stuck to pieces of tape for easy storage and handling. The age, number of rings, length, height and tag numbers were all recorded while waiting for the glue to dry hard (approximately 10 minutes). The scallops were released back onto the fishing grounds as the boat motored from one dive site to another. The density of released scallops was controlled by dropping them one at a time, roughly every 7 metres (approximately one boat length). Initially 500 undersized scallops were tagged; following this a further 50 were double tagged in order to estimate tag loss. The procedure for double tagging was the same as before, except that a second tag was glued to the flat valve, further ventrally than the first. These double tagged individuals were released over the whole fishing ground used for this tagging experiment; from the sewage pipe down to Anfre (Figure 2.1).

Once the tagging had been completed the fishermen needed to be informed of what to do when they caught a marked scallop. An article in the local paper (see Appendix 1) indicated that to obtain the reward the flat shell should be returned to the investigator with information about where and when it was caught. Collection points were arranged both at the harbour, where most of the commercial divers have their air cylinders filled, and at the Department of Fisheries. In addition, letters informing fishermen what to do with tagged scallops were sent to local divers via Sarnia Skin Divers who mailed them out with their bills. Mark-recapture experiments like these have been carried out on the Isle of Man in order to study the growth of scallops (and queens) and to estimate mortality rates (Murphy, 1986; Allison, 1993; Allison and Brand, 1995).

3.2.4 **Seasonal gonad cycles**

Sampling of *Pecten maximus* was carried out on approximately a monthly basis for the period of 1 year, starting in January 1997. The samples were collected from the Harbour fishing ground off the east coast of Guernsey (Figure 2.1), at a depth of 15-40m. The sampling was carried out on a commercial fishing boat using scallops caught by diver fishermen.

Sixty scallops were randomly selected on each sampling occasion from the day's catch and purchased from the fishermen. The dates of sampling were as follows: 14/01/97, 08/03/97, 02/04/97, 29/05/97, 05/07/97, 09/08/97, 13/09/97, 15/10/97, 15/11/97 and 16/12/97. There was no sample collected in February due to bad weather. Local demand for scallops also affected the date samples were collected as fishermen. These samples were then kept frozen until they could be processed.

Dry Weight Gonad Index

For the dry gonad weight analysis, a sub-sample of 30 scallops in the size range 110mm-120mm were randomly selected from each monthly sample and defrosted at room temperature. The flat valve was then scrubbed clean and each scallop was aged by counting the number of growth rings on the shell. The following measurements were then made using a customised measuring board.

1. Overall length (anterior-posterior axis)

2. Overall height (dorso-ventral axis)
3. Flat shell length
4. Flat shell height

The flat valves were then removed and the gonad assigned to one of Mason's (1958) five adult gonad stages. The adductor muscle and gonad were then removed, separated from the other viscera and placed on paper towel in order to remove any surface moisture. Each muscle and gonad were then weighed in separate, marked and pre-weighed aluminium foil tubs. The remaining viscera (mantle, foot, guts etc.) were drained and placed in a third aluminium foil tub for each scallop. All the tubs were placed in a drying oven at 60°C for 48 hours in order to dry the contents to constant weight. These were then re-weighed and the dry weights of the adductor muscle, gonad and remaining viscera calculated.

Individual dry gonad index and monthly means with 95% confidence intervals were calculated as follows:

$$\text{Dry gonad index} = \frac{\text{Dry weight of gonad}}{(\text{Dry weight of gonad + adductor + viscera})} \times 100 \quad \text{(Eq. 3.4)}$$

Gonad Staging

The same samples for the dry gonad index were also used for this method of determining the seasonal spawning cycles. For the samples of 60 scallops collected each month the scallops were shucked and the gonads assigned to one of Mason's (1958) five adult gonad stages. Also at other convenient times, gonads were staged while the fishermen shucked their catch. For this method approximately 100 gonads were staged and the percentage of each stage (3-7) in the population calculated.

3.2.5 **Seasonal changes in meat yield**

Changes in meat yield involve variation in the weight of the adductor muscle and the gonad rather than the whole scallop as this is the marketable yield of the scallop. Both dry and wet weight of the muscle and gonad were measured in the monthly samples of 30 scallops used for the dry gonad index analysis. From this, monthly marketable yield could be calculated by adding the wet weights of gonad and adductor muscle. Monthly means were calculated with 95% confidence intervals.

3.2.6 **Spat collectors**

The aim of the spat collection study was to compare settlement of scallop and queen spat around the island. Single line spat collectors were used as resources were limited and they were more appropriate for the strong local tidal conditions than the longline systems which have been used in the Isle of Man (Brand *et al.*, 1991b; Wilson, 1994). The basic unit of each collector rope was a 'standard onion bag' spat collector. These were made by stuffing an onion bag (750mm x 500mm) with 2m^2 of 12mm x 12mm Netlon plastic mesh. The bags were attached to the rope by tying the drawstring through the lay of the rope as well as using a plastic cable tie to secure the bag and prevent compaction of the mesh filling. The onion bags were attached at 2m intervals with the lowest bag being 2m above the bottom. Each rope (12mm diameter) was 18m long and had a 50kg weight secured at the bottom with a 200mm solid subsurface float tied at the top. This would ensure that the rope would remain tight and near vertical in the water column. A surface marker buoy with 12m of rope was attached to the top of the collector rope to enable easy location and recovery (Figure 3.1).

As the aim of this study was to investigate spat settlement around the island, collectors were sited off the east, south and west coasts (Figure 3.2). Two sites were chosen on each coast with the ones on the east coinciding with diver fished grounds (Petite Canupe and Anfre). Three collector ropes were deployed at both sites on the east coast while only 2 were put at the remaining sites due to a lack of time. All the collectors were deployed from 30/6/98 to 1/7/98 at a depth of 20m below chart datum. The ropes on the east coast were checked from the surface every few weeks to see if they had been moved by the tide. One of the collector ropes at Anfre was lost by mid August, probably due to it being washed into deeper water. Another rope at Petite Canupe was lost during September and a further 3 off the west and south coasts were not found during hauling. The losses were probably due to the ropes being too short causing the surface buoys to go flat and sink. One rope of collectors from the Petite Canupe site was brought in on 29/8/98 to see if there had been any settlement, the remainder being hauled from 24/9/98 to 4/10/98 (Table 3.1).

Table 3.1: Deployment and return dates for spat collector ropes at different sites.

Site	Deployed	No. Deployed	Returned	No. Retrieved
Petite Canupe	30/6/98	3	27/8/98 & 4/10/98	2
Anfre	30/6/98	3	24/9/98	2
Icart	1/7/98	2	27/9/98	1
La Moye	1/7/98	2	27/9/98	2
Lihou Island	1/7/98	2	4/10/98	1
Grand Rocques	1/7/98	2	3/10/98	1

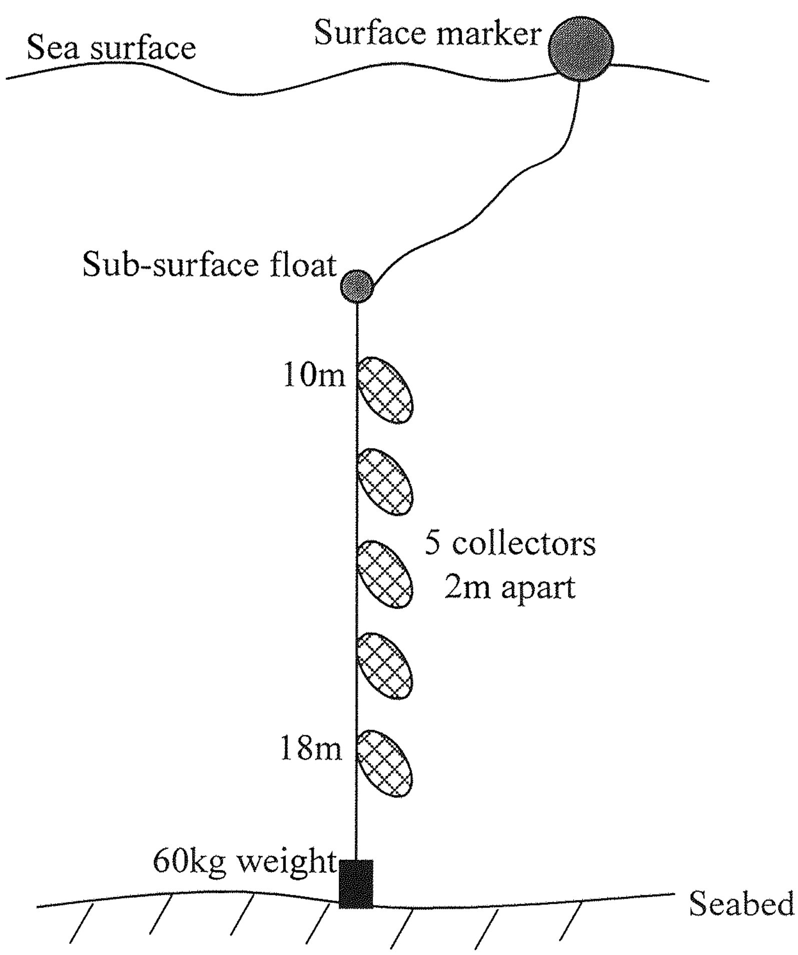


Figure 3.1: Design of single line spat collectors (redrawn from Wilson, 1994)

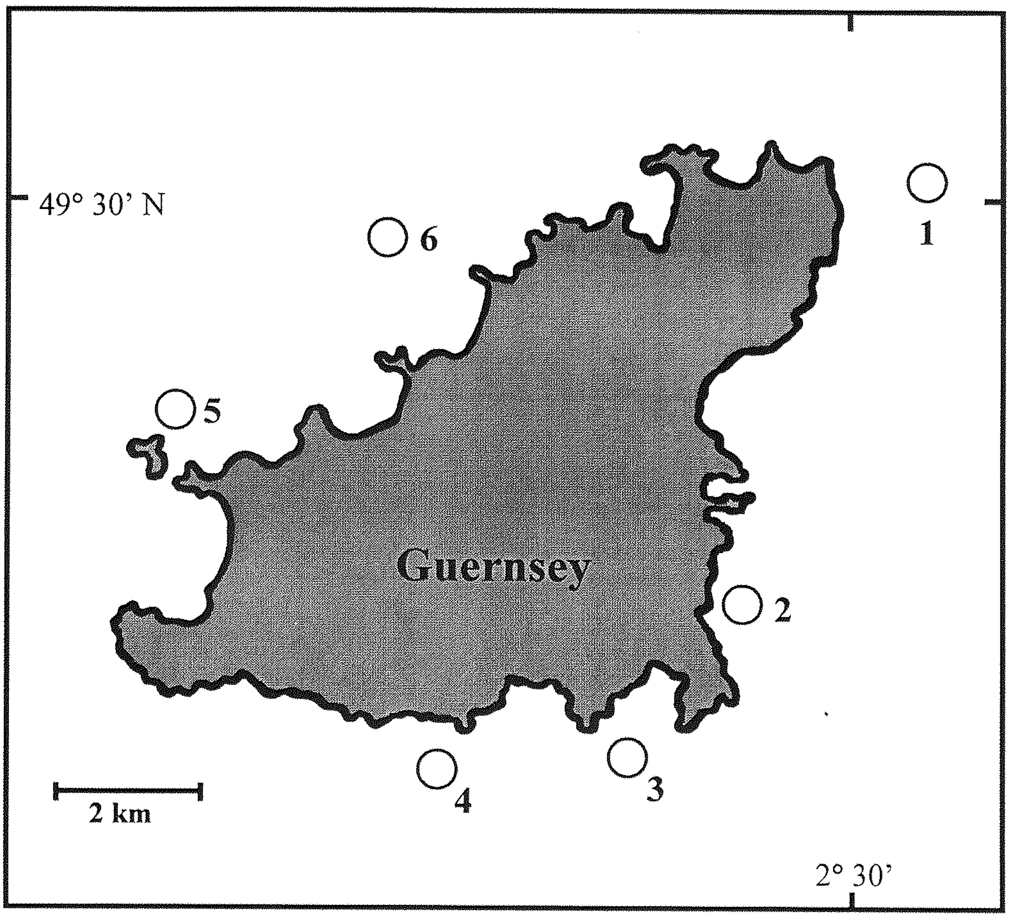


Figure 3.2: Scallop spat collector sites around Guernsey. 1 - Petite Canupe; 2 – Anfre; 3 – Icart; 4 - La Moye; 5 - Lihou Island; 6 - Grand Rocques.

All the spat collectors were sorted using the same method. On hauling, the bags were left attached to the rope and each rope was stored in a 45l dustbin full of seawater. Individual onion bags were cut from the rope and placed in a 25l tub of seawater, before being opened and their contents removed. The bag and net filling were thoroughly rinsed in the tub for up to 5 minutes to remove all the pectinids as well as other settled organisms. The water from the tub was then passed through a 1mm sieve and the contents of each collector bag transferred to a separate plastic bag. All the samples were frozen before being analysed in the laboratory.

In the laboratory the samples were defrosted and rinsed in a 1mm sieve before being thoroughly mixed and spread out on a plastic tray. Four random sub-samples were taken using a 20cm^2 quadrat, the contents of which were identified and counted. The remaining sample was quickly checked for the presence of any other species, then stored in 70% alcohol.

3.3 Results

3.3.1 Length/height relationship

Linear regressions were calculated using the ordinary least squares (OLS) method in MS Excel for the relationship between length and height of both the flat valve and whole scallop (Figure 3.3). The lines were fitted to the raw data from various samples where all four measurements were taken. These equations (Table 3.2) could be used to convert measurements from one type to another as they all had high r^2 values.

Table 3.2: Regression equations used to convert different shell measurements into length of the whole scallop. Length and height refer to the measurements of the whole scallop, whereas flat shell length and height refer to the measurements taken from the flat or upper valve. The r^2 value shows how well the regression lines fitted the data.

Conversion equation	r^2	n	
Length = (1.172 × Height) – 4.858	0.989	827	(Eq. 3.5)
Length = (0.983 × Flat shell length) + 3.956	0.970	295	(Eq. 3.6)
Length = (1.098 × Flat shell height) + 6.805	0.842	295	(Eq. 3.7)

3.3.2 Growth curves

Von Bertalanffy growth functions (VBGFs) were calculated for five of the diver fished sites and three of the dredged sites (Figure 3.4). In general the VBGFs give a good fit to the height at age data (r^2 values range from 0.94 to 0.97) for samples from both the dive and dredge fishing grounds. The small error bars which represent the standard deviation show low variability in the raw data and explain the very good r^2 values. However, all the curves pass below the mean height for one year olds and above the point for the two year olds. This could indicate that either the VBGF does not provide a good fit for scallops under two or may be due to the position of first growth ring being overestimated.

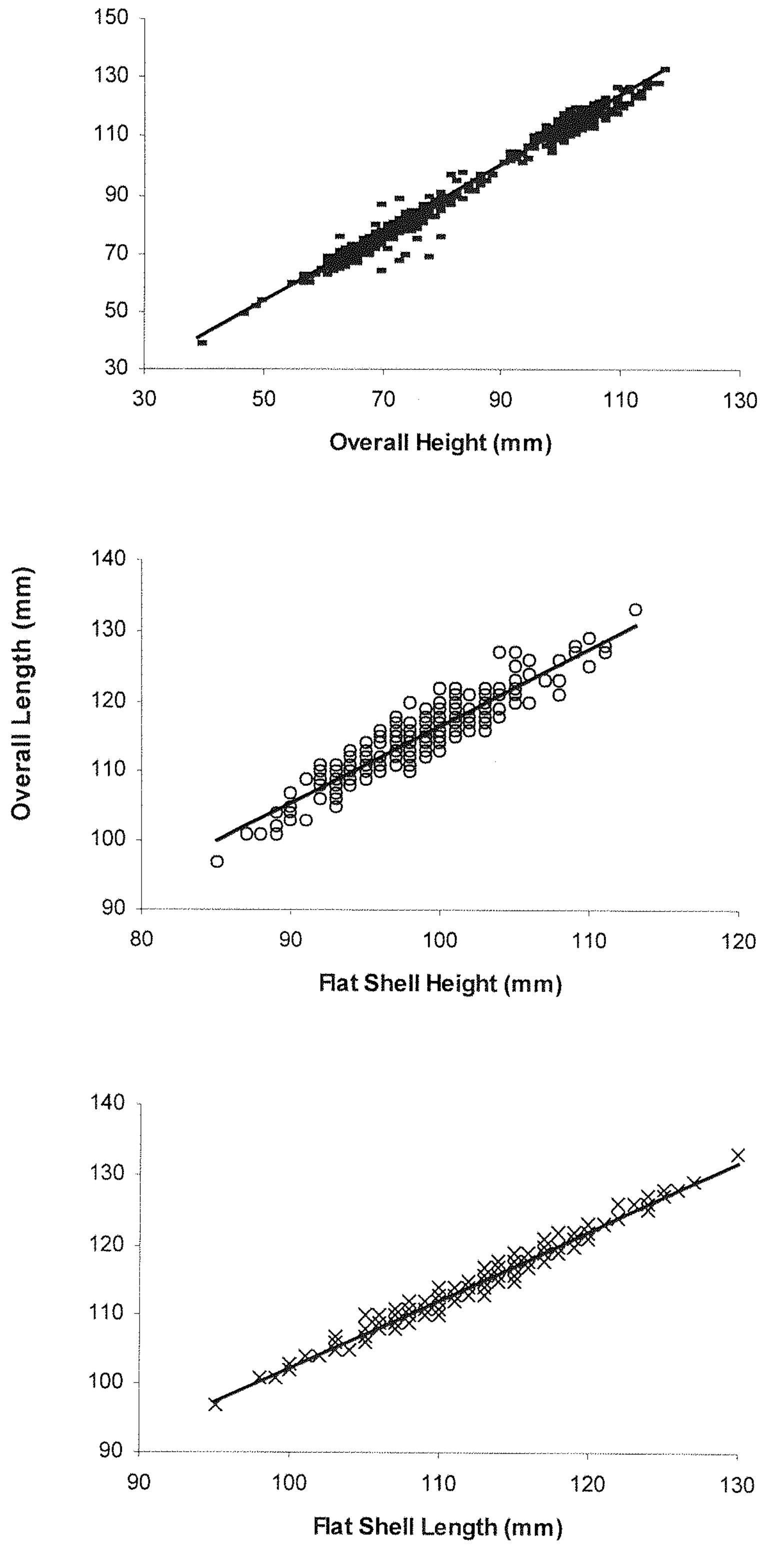


Figure 3.3: Overall shell length plotted against overall height, flat length and flat height of Guernsey scallops.

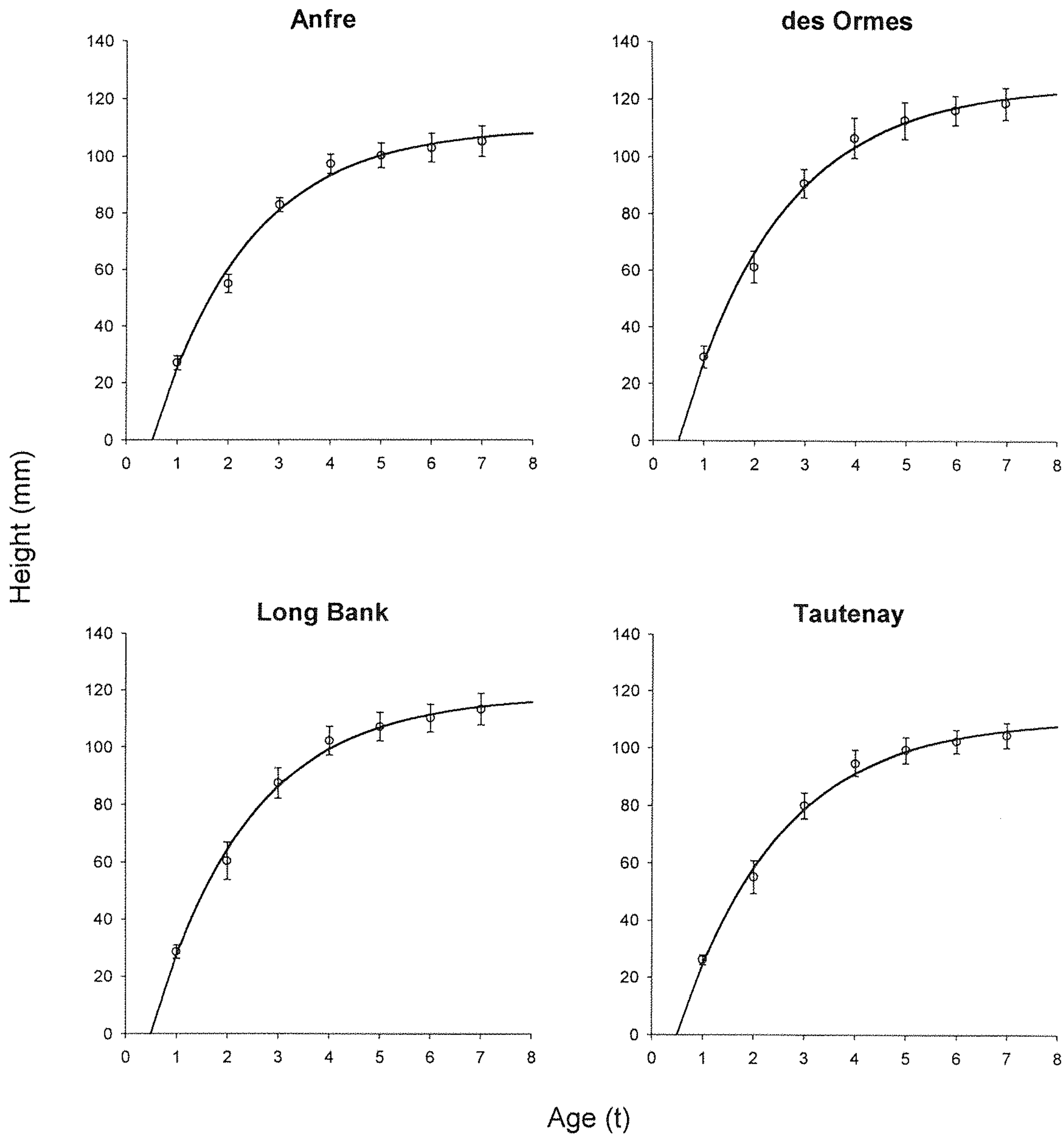


Figure 3.4: VBGF curves for different fishing grounds in Guernsey. Error bars show standard deviation.

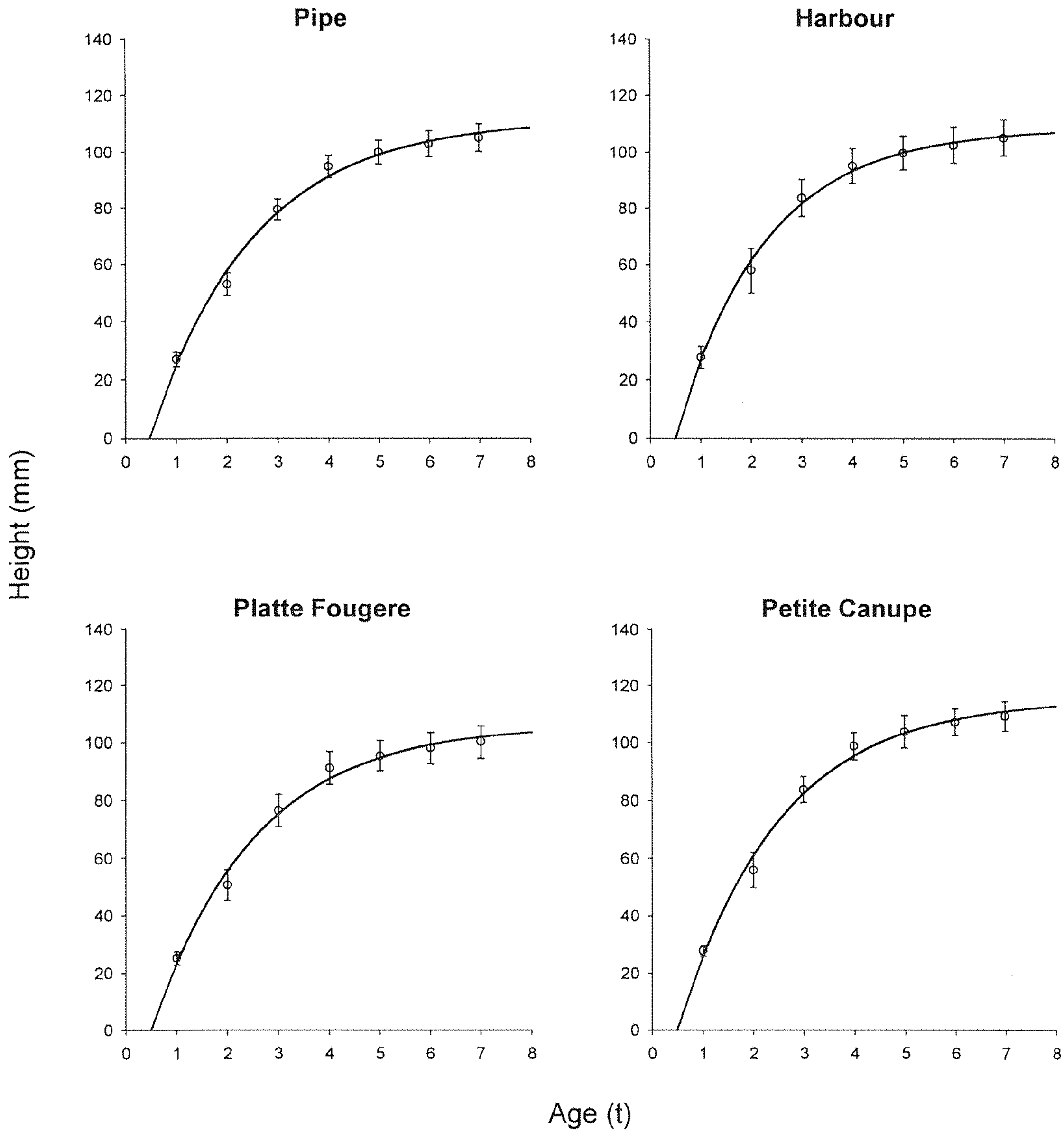


Figure 3.4: (cont.)

The H_∞ values from the VBGF were converted to L_∞ using the equations above to allow easier comparison with other results (Table 3.3). These values for the maximum overall length give fairly realistic results similar to those found in the field. The t_0 values are supposed to represent the theoretical age at which individuals have no length with most of the results being about 0.5 (6 months). However, the age of the scallops was assessed by counting the annual growth rings on the shell. These are laid down in April although spawning does not take place until July. Therefore scallops with one ring were only 10 months old, those with two rings were 22 months old, etc. This will result in a value of t_0 which was closer to zero.

The growth rates on different fishing grounds were compared using the ω parameter of Gallucci and Quinn (1979) (Figure 3.5). Growth rates were assumed to be statistically significant if the 95% confidence intervals of ω did not overlap. Two of the dredge fished grounds, des Ormes and Long Bank, have a significantly higher growth rate than the diver grounds at the Pipe and Platte. The remaining grounds all lie somewhere between these and do not differ significantly. However, the Harbour and Anfre grounds have an almost significant greater growth rate than the Pipe and Platte.

An analysis of the correlation between two of the VBGF parameters, H_∞ and k, showed no significant correlation ($r = -0.19$) (Figure 3.6). This was unusual as these parameters are normally negatively correlated in that fast growing individuals reach a smaller asymptotic height. However, a similar analysis of these parameters on north Irish Sea fishing grounds also found no correlation (Allison, 1993).

Table 3.3: Parameters of the VBGF for different sites in Guernsey. Also shown are the ω parameter and L_∞ which was calculated from H_∞ using Eq. 3.7. The values shown in brackets are standard errors.

Area	N	r^2	H_∞	k	t_0	ω	L_∞
Long Bank	248	0.97	118.17 (1.12)	0.52 (0.02)	0.50 (0.03)	61.88 (1.91)	136.62
Tautenay	279	0.97	110.41 (1.09)	0.50 (0.02)	0.50 (0.03)	55.06 (1.66)	128.10
Anfre	304	0.97	109.94 (0.94)	0.54 (0.02)	0.52 (0.03)	59.37 (1.68)	127.58
des Ormes	226	0.96	125.28 (1.56)	0.50 (0.03)	0.51 (0.04)	62.80 (2.42)	144.43
Harbour	379	0.94	108.53 (1.21)	0.56 (0.03)	0.50 (0.04)	60.60 (2.39)	126.03
Pipe	284	0.97	111.63 (1.70)	0.48 (0.02)	0.47 (0.03)	53.55 (1.54)	129.44
Platte	217	0.95	106.26 (1.28)	0.50 (0.02)	0.50 (0.04)	52.55 (1.92)	123.54
Petite Canupe	319	0.96	115.72 (1.44)	0.50 (0.02)	0.50 (0.04)	57.46 (2.21)	133.93

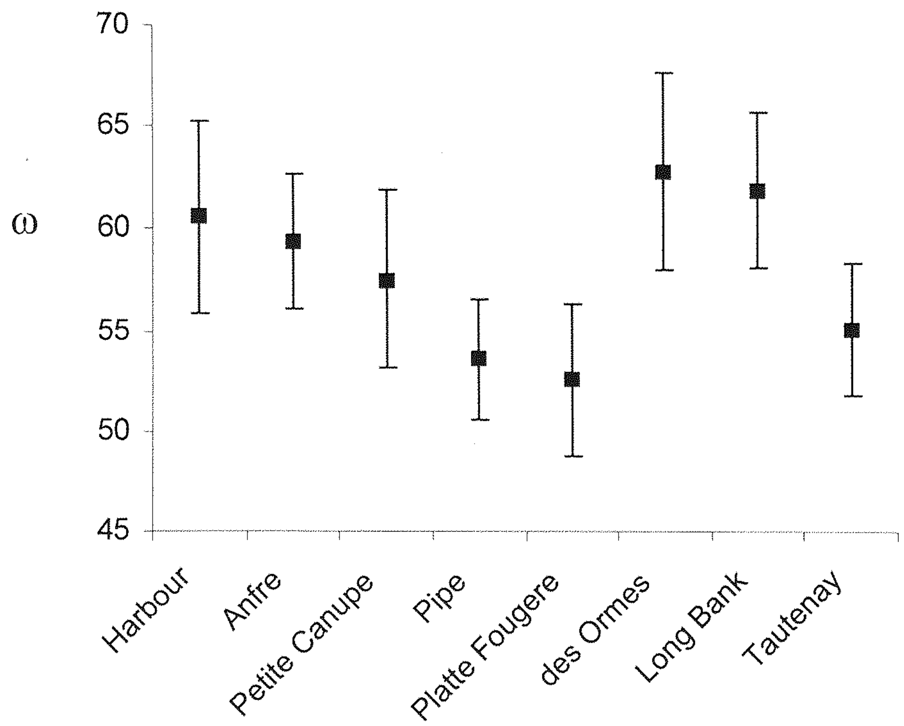


Figure 3.5: ω parameter of Gallucci and Quinn (1979) for the eight sites studied. The first five sites are diver fished grounds and the final three are from the dredge fished ground. The error bars show the 95% confidence intervals.

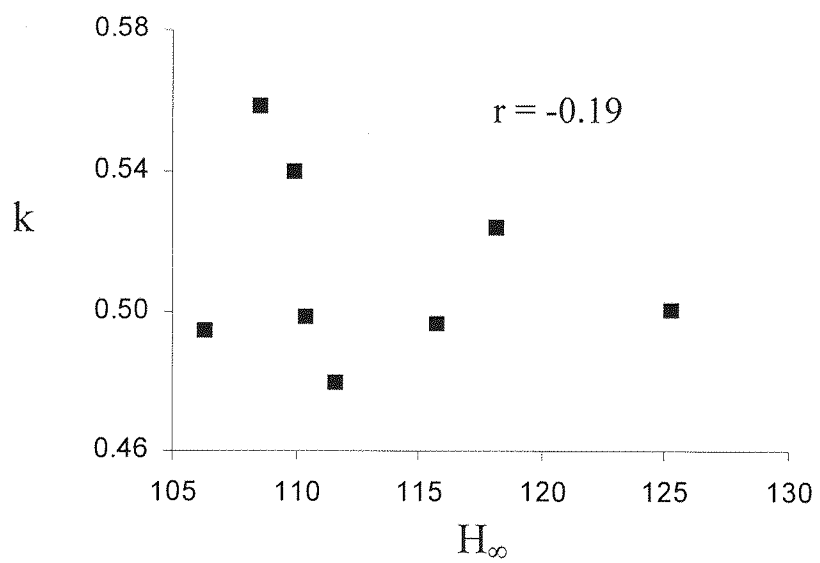


Figure 3.6: Correlation between H_∞ and k on Guernsey fishing grounds.

3.3.3 Tagging results

Of the 560 tagged scallops released at the end of April 1997, 264 were returned to the investigator by the end of September 1999. The first returned scallop was caught after 4 months having reached legal size. Most of the tagged scallops had just laid down their second growth ring, although a few undersized were three and four years old. Figure 3.7 shows the growth of the returned two year old scallops and also the von Bertalanffy growth function (VBGF) for the site where they were collected and released. The first line of points on the graph shows the height of individual two year olds on release and the group of points shows the mean height of returned scallops of each age (in years and days). The three year olds are displayed in a similar way and can be identified by a different marker.

All the points plotted are above the line of the VBGF which was probably due to three reasons. Firstly, as the scallops were initially undersized the first scallops to be caught would be the ones which grew quickest and recruited to the fishery. Undersized tagged scallops which were caught would have to be returned to the sea as they had not yet reached minimum legal size. Secondly, scallops caught after November would be unlikely to grow any more until the following spring due to the annual growth check. Therefore these individuals would be the same size when they laid down their third growth ring, so the second half of the group of data points could be pushed further right to age 3 rather than 2.5 due to the seasonality of their growth. This would give much closer agreement with the back calculated VBGF and confirms the annual nature of the growth rings in Guernsey populations. Finally, the VBGF has been back calculated from scallops caught on popular fishing grounds, resulting in the older individuals being smaller than average. This is due to size selective mortality with the faster growing scallops from a cohort reaching MLS sooner and increasing the chances of them being caught before they reach the older age groups (6+). This has resulted in a flattening of the VBGF for the older age classes, the Rosa Lee phenomenon (Lee, 1912; Jones, 1958), and a slower overall growth curve.

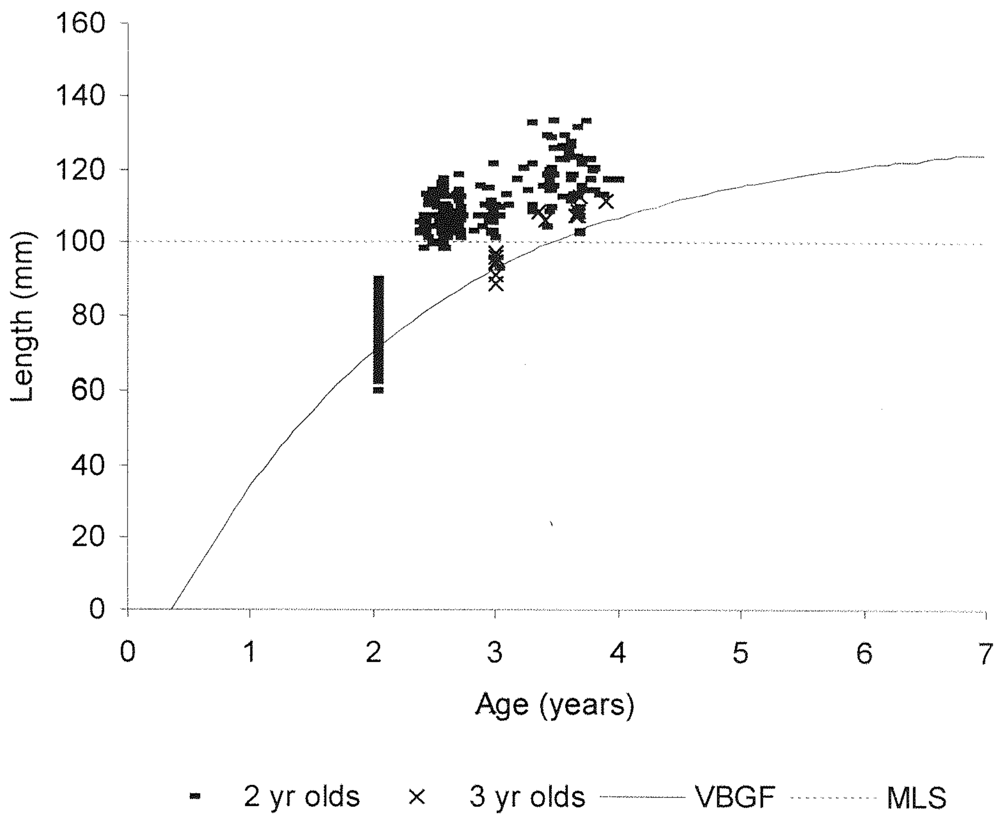


Figure 3.7: Growth data from tag returns for 2 and 3 year olds. Also shows von Bertalanffy growth curve and minimum landing size.

An analysis of the movement of the tagged scallops showed that from the information collected, the scallops had not moved any great distance except in a few cases. Here, the movement could be accounted for by divers catching them whilst undersized and moving them to more favourable dive sites such as the harbour. In one case 5 tagged scallops were found in 3m of water off Brehon Tower, which is over 2km from where they were released.

3.3.4 **Analysis of spawning season**

The results of both methods of assessing spawning season are shown in Figure 3.8. The data from the subjectively assessed gonads using Mason's (1958) stages have been converted using Table 3.4 to allow comparison with the dry gonad index in 1997. In general, over the last three years the gradual ripening of the gonads has taken place from January to the end of May with spawning beginning at the start of July. The decrease in dry gonad index due to spawning during July was fairly rapid with the remainder of the spawning continuing to the end of September. This was followed by a gradual re-conditioning of the gonad over the winter. The percentage of each gonad stage also shows the same pattern (Figure 3.9) in that from March to July, full and three quarters full gonads make up the largest proportion of the gonads. By August these stages only make up approximately 10% of the population. Also the large percentage of spent gonads from September onwards showed that spawning had occurred and was virtually finished by then. Recovery of the gonads had begun by December in that the percentage of filling gonads had increased.

Table 3.4: Converting Mason's stages to a new value to enable plotting

Gonad Condition	New value	Mason's stages (1958)
Full	5	6
3/4 Full	4	5
1/2 Full	3	4
1/4 Full	2	3
Spent	1	7

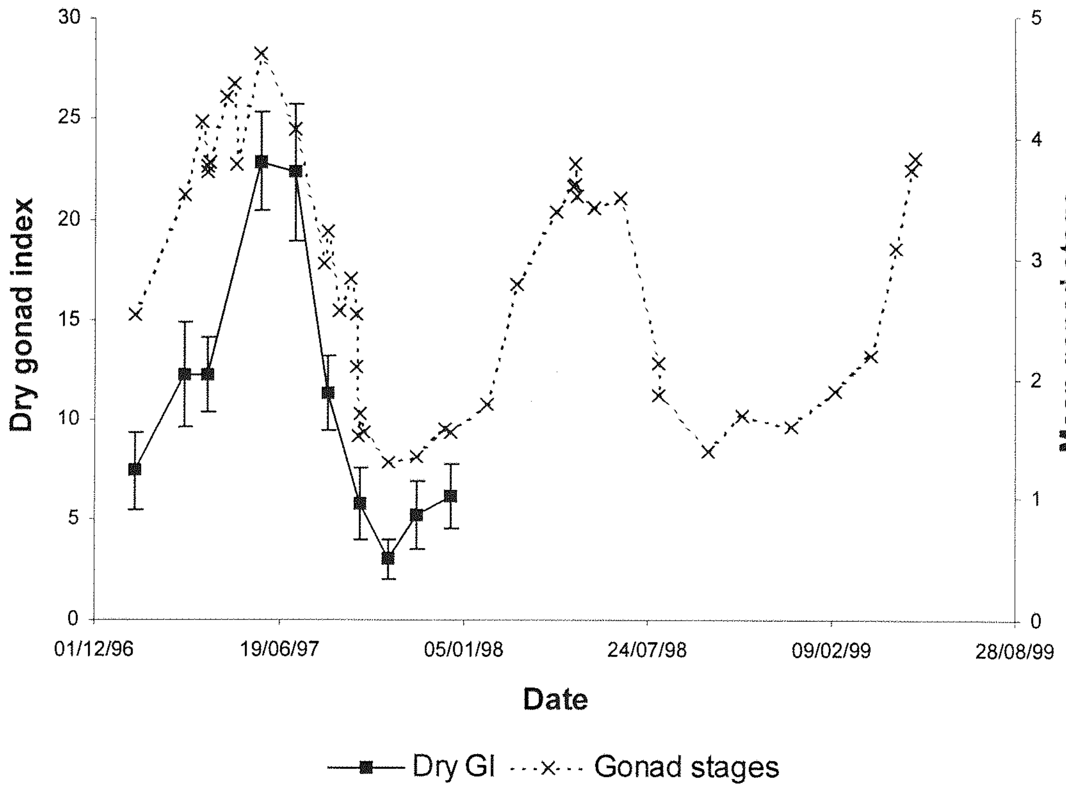


Figure 3.8: Variations in dry gonad index and gonad stages over a two year period on the Harbour fishing ground. Error bars on gonad index show 95% confidence intervals.

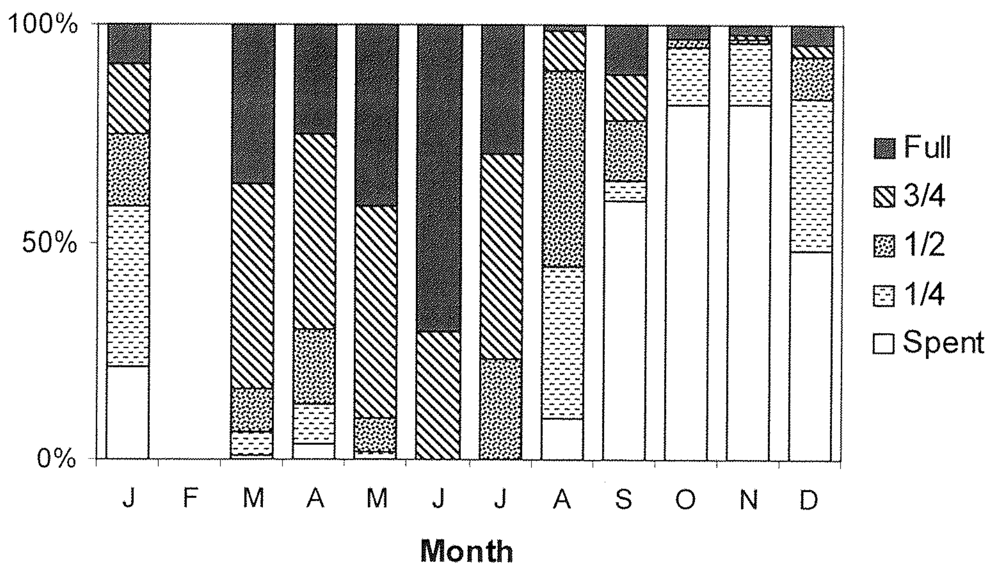


Figure 3.9: Percentage of each gonad stage in the monthly samples from the Harbour ground in1997. There was no sample collected in February due to bad weather.

Figure 3.8 also shows that the easier method of assigning stages to gonads gives the same information about spawning cycles as the more detailed dry gonad index analysis. The important points were the gradual recovery of gonad condition from January to May and that spawning took place from June to the end of August. There is also some evidence for gradual 'trickle' spawning during April and May.

Comparing the spawning cycle over the three years of the study does highlight a few small differences. In 1999 the gonads developed very slowly with the average only being a quarter full by the end of March. In the previous two years they had reached this stage by the end of February. However, despite the late development of the gonads they still reached a maximum by the end of April as in 1997 and 1998.

3.3.5 **Variation in meat yield**

The wet weights of the marketable parts of the monthly samples of scallops are shown in Figure 3.10. This shows the meat yield with the two components (gonad and adductor muscle) shown separately. The overall meat yield was highest at the end of May when the gonad was fullest prior to spawning. The variation in marketable yield appears to be due to seasonal changes in the weight of the gonad as the wet weight of the muscle varied very little. However, the dry weights of the adductor do appear to vary seasonally, reaching a peak weight at the end of the spawning season in September.

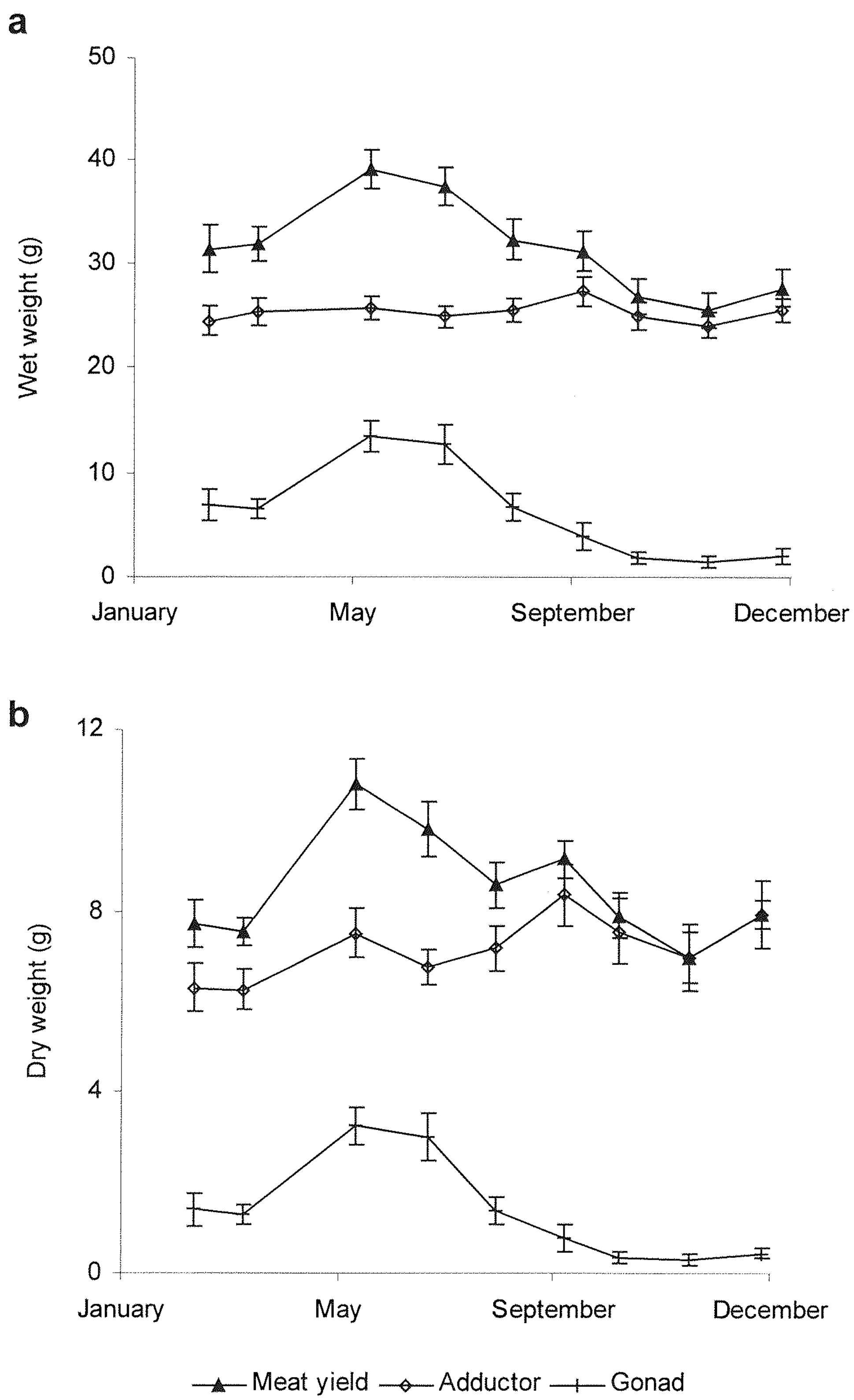


Figure 3.10: (a) Seasonal changes in wet weights of marketable parts of scallops, showing 95% confidence intervals. (b) Seasonal changes in dry weights of marketable parts of scallops, showing 95% confidence intervals. The meat yield was the weight of adductor muscle plus gonad. Data for 1997.

3.3.6 Scallop spat settlement

The aim of the scallop spat settlement study was to investigate timing and spatial variations in spat settlement off the three coasts in Guernsey (east, south and west). Although the associated settled community was also studied, the results of this are dealt with in Appendix 2. In general the settlement of *A. opercularis* on the collectors far outweighed that of *P. maximus.* On average there were approximately 200 *A. opercularis* for every *P. maximus* which had settled in the collectors. These types of onion bag collectors have been shown to be more successful with queens than scallops, but never to this degree. Previous studies have had a success rate of approximately 10 queens settling for every king scallop (Paul *et al.*, 1981; Brand *et al.*, 1991b; Wilson, 1994). The overall settlement of queens was higher than in some previous studies with some collector bags containing over 1000 queen spat (Table 3.5).

Table 3.5: Mean number of spat settled per bag at collector sites around Guernsey. Figures in brackets show standard errors.

Site	*A. opercularis*	*P. maximus*
West		
Grandes Rocques	452 (50.2)	2 (0.7)
Lihou Island	197 (38.9)	0
East		
Petite Canupe	808 (40.1)	3 (0.9)
Anfre A	1022 (55.0)	3 (0.8)
Anfre B	1109 (80.6)	5 (1.0)
South		
Icart	732 (34.8)	1 (0.2)
La Moye A	471 (43.5)	0
La Moye B	287 (49.3)	0

The settlement of the scallop, *P. maximus*, appears to vary on the different coasts studied, although the total numbers found were very low. The bulk of these spat were found on the east coast at a rate of approximately 5 per bag, whereas only 1 or two per bag were found on the west and south coasts. A similar situation was also found with the spat of the queen scallop, *A. opercularis*, which settled in the highest densities on the east coast. The highest density was found at the Anfre site where one bag contained over 1400 spat. The size of the *P. maximus* spat ranged from 3mm to 15mm whereas *A. opercularis* ranged from 1mm up to 23mm in length.

The variation of queen spat settlement with depth was also investigated (Figure 3.11). The results show no clear increase or decrease in abundance with depth in that settlement appears to be fairly constant at each site. This may be the result of too small a range of depths used, as a difference may have been found over a wider range of depths. Previous studies have shown variations in settlement with depth but these have sometimes been attributed to excessive silting up of collectors nearer the bottom (Paul *et al.*, 1981; Wilson, 1994). In this study none of the collectors silted up, but they had all suffered heavy fouling from *Jassa falcatta*. The bottom collector bag at Grandes Rocques had been damaged through chaffing on a reef but all the rest were in good condition on hauling.

Due to the low numbers of *P. maximus* found, the variability of spat settlement was analysed using the *A. opercularis* data. A two factor nested ANOVA was carried out using GMAV5 (Underwood *et al.*, 1998). In designing the experimental analysis, 'coast' was used as the first factor with three levels (east, south and west). The second factor was 'site' and this was nested in coast as there were two sites on each coast (i.e. Petite Canupe and Anfre on the east coast). The five onion bags at each site were taken as replicates, as settlement did not significantly vary between bags at different depths (Figure 3.11). The results showed no significant difference between coasts ($F_{2,3} = 5.41$, $P = 0.1$) although the east coast had the highest mean settlement. However, there was a significant difference between sites on each coast ($F_{3,24} = 14.66$, $P<0.001$). The SNK tests showed that the two sites on each coast differed at the $P<0.01$ level. The lack of a significant difference between coasts was probably due to the low power of the analysis and the high variability between sites on the same coasts.

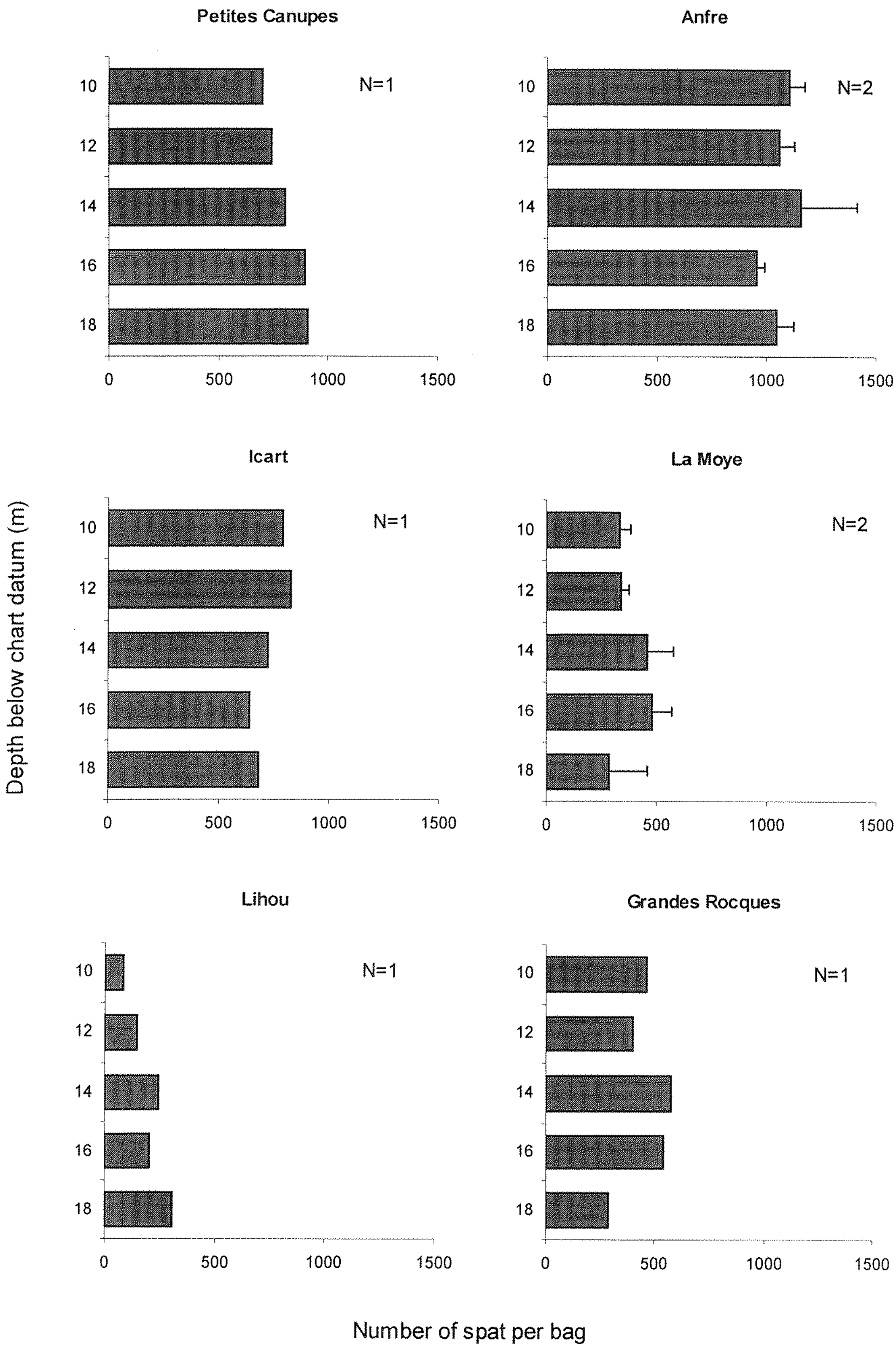


Figure 3.11: Settlement of queen spat (*A. opercularis*) on collector bags set at different depths below chart datum. Error bars show standard error at sites where replicate ropes were recovered.

3.4 Discussion

The results of this chapter have provided useful estimates of some of the population variables of the exploited scallops in Guernsey. Some of the growth and reproductive parameters will be input into standard fish stock assessment equations in Chapter 6 to assess the current state and management of the fishery. This work has also provided information on an unstudied, yet long running fishery which has enabled a comparison to be made with other scallop fisheries.

3.4.1 Variations in growth rates on Guernsey fishing grounds

The growth rate of scallops was found to vary between the grounds studied. However, although the different fishing grounds were distinct from each other they often bordered onto one another or were within a few kilometres. This means that observed differences between adjacent grounds may not be entirely due to environmental factors, as these would only vary to a small extent. Indeed, the observed Rosa Lee phenomenon (Lee, 1912; Jones, 1958) of the flattening of growth curves for the older age classes demonstrates the effect fishing has had on the scallop populations. This was due to the size selective removal of scallops which have reached minimum landing size. In exploited populations like this, slower growing individuals were more likely to survive to the older age classes as ones that grow quicker will be vulnerable to fishing at a younger age and stand a higher probability of being caught.

The results from the different grounds demonstrate the effects long term fishing can have on growth curves. Generally the grounds further offshore, such as des Ormes and the Long Bank, have a higher growth rate (ω) and a larger maximum size (L_∞) which may reflect lower fishing intensities. Conversely the inshore grounds like the Harbour have more depressed growth curves which indicate higher fishing intensities. Another indication of the long term effect of fishing can be seen in the growth curve plots (Figure 3.4). For all the curves, the mean size of the three and four year olds in the samples was always greater than what would be predicted from the growth curves. This may have been due to the VBGF not being a good model for the growth of

Guernsey scallops. Equally it may have been due to the older age classes in the samples being made up of slower growing individuals which resulted in a lowering of the growth curves.

3.4.2 **Comparison of population parameters with other scallop fisheries**

Although this study was carried out during commercial fishing trips the results obtained were comparable with studies of other fisheries using research vessels. The main disadvantage with this type of method was that it was difficult to obtain sufficient numbers of undersized individuals, as commercial dredges are designed to reduce by-catch and divers only collect legal size individuals. However, undersized samples were occasionally collected by the divers or retained in the dredges.

Growth rates of scallops in the western English Channel are known to be less than those in the eastern basin (Franklin and Pickett, 1980). This is reflected in the different minimum landing sizes for the two areas, 100mm in the west and 110mm in the east. Comparing the VBGF calculated for Guernsey with those calculated for the Isle of Man (Mason, 1983) again shows a lower growth rate and a smaller asymptotic size. However, both the populations appeared to recruit to the fishery at the same age (~3½), which was due to the difference in the minimum landing size of 10mm.

The analysis of the spawning season shows that the peak spawning period occurs from July to August, which agrees with the work of Paulet *et al.* (1988) in the Bay of St. Brieuc, France. Over the three years studied there did not appear to be two annual spawnings as there has been found in the Isle of Man (Mason, 1958). However, significant variation in spawning season has been found on a relatively small spatial scale elsewhere in the English Channel. A comparison of two populations, one in the Bay of St. Brieuc and the other in the Bay of Seine, found that one population had a single, synchronous annual spawning whereas the other had multiple spawning periods throughout the summer (Ansell *et al.*, 1991). It was also found that populations retained their spawning behaviour even when transferred to the other location, indicating that spawning season may be genetically determined.

The marketable meat yield of scallops was found to only vary due to the condition of the gonads as the wet weight of the muscle did not vary from March to October (Figure 3.10). This is different to the case of the eastern Channel where muscle wet weight was found to increase over late summer into August (Connor, 1978). However, the total meat yield did not significantly vary over the year as the good condition of the gonads made up for the low muscle weight at the start of the summer (Connor, 1978; Faveris and Lubet, 1991).

3.4.3 **Temporal and spatial variation in recruitment**

Temporal variation in spat settlement was evident from the peaks and troughs in the age frequency distributions from different years (see Chapter 2). Strong recruitment to the fishery (e.g. on the Pipe ground in 1999) may be due to good settlement of scallop spat following a successful spawning season. The causes of this variability in recruitment are not fully understood although in invertebrates they are believed to be influenced by environmental variability rather than determined by the size of the adult spawning stock or the amount of egg production (Drinkwater and Myers, 1987). This is commonly thought to be the case in demersal fish stocks where environmental factors, such as temperature, are only thought to have a secondary effect on variability in recruitment, although stock recruitment relationships are still rare (Shepard *et al.*, 1984).

Although the success of different spawning seasons was not studied, the timing and length of spawning on the Harbour fishing ground remained relatively constant throughout the three year study. However, the success of these spawnings cannot be easily determined until 2000 when these scallops will have recruited to the fishery. More importantly, it may be that scallops recruited to Guernsey fishing grounds have resulted from spawnings in other populations, such as the English Channel or the St. Brieuc Bay, and have been carried here by currents during their larval stage. Indeed, the strength of local currents around the Channel Islands could result in larvae being carried over large distances.

Local currents may also have an important effect on the spatial variation in scallop recruitment. The results from the spat collectors showed relatively poor settlement of *P. maximus* at all sites around Guernsey. The most consistent spat settlement occurred on the east coast where the most important diver fishing grounds are found. The numbers of queen spat (*A. opercularis*) settling at each site also backed up this result. Although there was no significant difference between coasts due to high variability between sites on each coast, the highest settlement again occurred at all three sites on the east coast. These spat were likely to have originated away from the diver fished grounds, as adult *A. opercularis* were rarely seen by divers throughout the study. This indicates that *P. maximus* may also be recruiting to Guernsey fishing grounds from external populations and helps to explain the stability of the dive fishery despite relatively intense fishing on small areas of seabed. This scenario would tend to result in a fishery that is more heavily reliant on the recruiting age class.

The results of this work have shown that the scallop populations on Guernsey fishing grounds have similar growth rates and spawning seasons to other fished populations in the western English Channel. Only small variations in growth were found between different local grounds which may have may have been due to lower fishing intensity on the grounds further offshore. The timing of spawning has remained relatively constant throughout this study with a single peak at the end of June. This information is of importance in order to set appropriate fisheries management measures and will be used in Chapter 6 to assess the current state of the fishery.

4. Foraging Behaviour of Diver Fishermen

4.1 Introduction

Divers who fish professionally for scallops were initially studied in order to investigate scallop populations and fisheries in Guernsey. However, observation of the diving practices of the fishermen showed that it would also be interesting to study their foraging behaviour. It appeared that there might be a trade off between catch and the safety of the divers, in that to increase catch it was necessary to use more risky diving practices. Indeed, the divers did not consider safety to be paramount as they only used the bare essentials of diving equipment. Thus the behaviour of the divers parallels that of many animals that have to balance returns from foraging with risks (Stephens and Krebs, 1986; Krebs and Davies, 1997; McCleery, 1997). However, many of these foraging models assume that the animal does not consciously think about its actions, and that they have evolved through natural selection. This is not necessarily the case when studying humans (Smith, 1983) and these diving behaviours have certainly not evolved.

In studying this risk sensitive foraging behaviour it was necessary to assess the limiting factors and the decisions made by the divers. The factors which limited foraging time were considered to be the amount of air in the divers cylinder, the nitrogen absorbed by the body and the depth of dive. An increase in either foraging time or depth resulted in an increase in risk to the divers. The decisions made by the divers were the depth and duration of dives and the surface interval between dives.

As well as trying to maximise their profit by catching as many scallops as possible, the divers may have also been trying to optimise their use of different scallop patches. The marginal value theorem predicts that foragers should leave a patch they are feeding in when the net rate of energy intake in that patch falls below the average for the habitat (Krebs and Davies, 1997). Fishermen have been shown to exhibit optimal foraging behaviour by choosing grounds which maximise their catch and moving on to new areas when CPUE falls below a certain level (Orensanz, 1986). It has also been found that in the Oregon trawl fishery, fishermen try to optimise the value of their catch by discarding low value fish at the start of a trip to save room in the hold for more valuable fish (Gillis *et al.*, 1995). Similarly the scallop fishermen should move to a new area or patch if catches fall below the average for Guernsey fishing grounds. However, this area of optimal foraging theory was not explored any further as the behaviour of other diver fishermen would need to be considered as well as the reason for changing patches which could be affected by the weather or visibility.

The overall aim of this chapter was to study the scallop divers fishing behaviour and try to relate it to an optimal foraging model in order to predict their behaviour. The results will also be considered in the broader context of fisheries management as the behaviour of the diver fishermen would need to be considered if regulation of fishing effort was required. Therefore the specific objectives of this work were to assess the safety of the dives made by scallop fishermen and quantify an incentive for fishermen to dive deeper. Factors which may be limiting foraging time were also defined. The results of this study were used in the broader context of fisheries management as the behaviour of the fishermen is an important consideration when implementing appropriate management measures.

4.2 Methods

4.2.1 Dive Sampling and data collection

This work was carried out purely on an observational basis and no attempt was made to experimentally manipulate the behaviour of the diver fishermen. It was assumed that the presence of the investigator had no effect on the behaviour of the divers. Individual dives of scallop fishermen were sampled on board the M.F.V. *'Pierre Marie'*. Although four different fishermen dived from this boat only two of them fished regularly throughout the three years studied (1997 to 1999). For each dive the date, depth, diver, location, dive time and number of scallops caught was recorded. All dives were sampled on fishing trips when the investigator was present.

At the start of each dive, the current position was recorded using a Garmin 45XL global positioning system (GPS) receiver. This saved the position at the start of the dive along with the date and time. The depth of each dive was either taken from the maximum depth gauge of the diver (if they had one) or the depth on the sounder at the start of the dive. At the end of each dive, the position was stored again so that start and finish positions and times were recorded. The number of scallops in the catch was counted, not including any undersized scallops which were brought to the surface and subsequently thrown back.

4.2.2 Table limits for safe diving

Whilst diving and breathing air under pressure the body absorbs more nitrogen than when breathing air at atmospheric pressure (Martin, 1997). Also during deeper dives, air is breathed at a higher pressure resulting in nitrogen being absorbed at a faster rate. This means that deeper dives should have a shorter dive time to avoid decompression sickness. Decompression sickness or 'the bends' occurs when a diver with too much nitrogen absorbed into his body ascends too quickly causing bubbles of nitrogen to form. These can result in a variety of symptoms from painful joints to an embolism in the brain which is potentially fatal. Standard BSAC 1988 decompression tables (Hennessy, 1988) were used to calculate the safe maximum dive times as they are commonly used in Britain.

For the first dive of each day the fishermen should be following the limits as set by table A because they would have 'cleared' their body of any nitrogen built up from the dives of the previous day. As the divers tended to leave about an hour between deep dives, the nitrogen remaining in their body would allow them to start any consecutive dives on at least table E and in most cases table D. It was assumed that the divers carried out at least some decompression, or the tables would not have allowed them to dive as deep as they did. The main problem with this approach was that the tables assumed that the diver remains at the deepest depth for the duration of the dive. This would result in the safe dive time being underestimated, but this was the only approach available. A dive computer would probably allow longer safe dive times as it constantly recalculates the amount of nitrogen absorbed depending on the dive profile.

4.2.3 **Amount of air and rate of use**

Dive time was not only limited by safe limits regarding decompression but also by the amount of air the divers carry and the rate at which they used it. The volume and working pressure of the cylinders determines how much air (in terms of time) they have, which will change with depth. The equation for the amount of air available is as follows:

$$\text{Air available (mins)} = \frac{\text{Volume of cylinder (l)} \times \text{Pressure of cylinder (atm.)}}{\text{Rate of air use (l/min)} \times \text{Pressure at depth (atm.)}} \qquad \text{(Eq. 4.1)}$$

Two separate lines were calculated assuming a rate of air use of 20 and 25 litres per minute, which are standard text book values (Martin, 1997). These calculations assume that the entire duration of the dive was spent at the maximum depth. Again, this will result in maximum possible dive times being underestimated as divers rarely spend the whole dive at the deepest depth.

4.3 Results

4.3.1 Incentives to dive deeper

The analysis of catches of scallops at different depths showed that there was an incentive for the divers to go deeper (Figure 4.1). There was a significant positive correlation between depth and CPUE for both the divers studied (Table 4.1). However, as deeper divers were shorter in time than those in shallower water, it would be more appropriate to study whether catch per dive also increased with depth. These results show that there was a significant weak, positive correlation between depth and catch (or number of scallops) per dive (Table 4.1). Therefore, despite having shorter dives at deeper depths the divers still caught more scallops per dive than in shallower water. A line fitted to the observed data for each diver using the least squares method showed that diver 1 had larger catches than diver 2 (Figure 4.1). This may be due to diver 1 being more experienced and better at seeing and catching scallops, as both divers fished from the same boat.

Table 4.1: Number of dives observed (N) and correlation coefficient (r) between depth and CPUE (number of scallops per minute) and catch (number of scallops per dive) for the two scallop divers studied. ($P<0.01$ for all values of r).

Diver	N	r	
		CPUE	Catch
1	110	0.55	0.28
2	99	0.56	0.30

4.3.2 Dive times and theoretical safe limits

The results of depth against dive time show that the divers tended to do their first dive of each day at the deeper depths (>30m up to a maximum of 42m), whereas second and third dives tended to be spread over the range from 15m to 30m (Figure 4.2). Theoretical safe time limits for the range of depths observed were calculated from BSAC '88 decompression tables (Hennessy, 1988). These showed that the first dive of each day could be considered safe as the dive times remained inside the limits of Table A with one minutes decompression. The second and third dives of each day had much

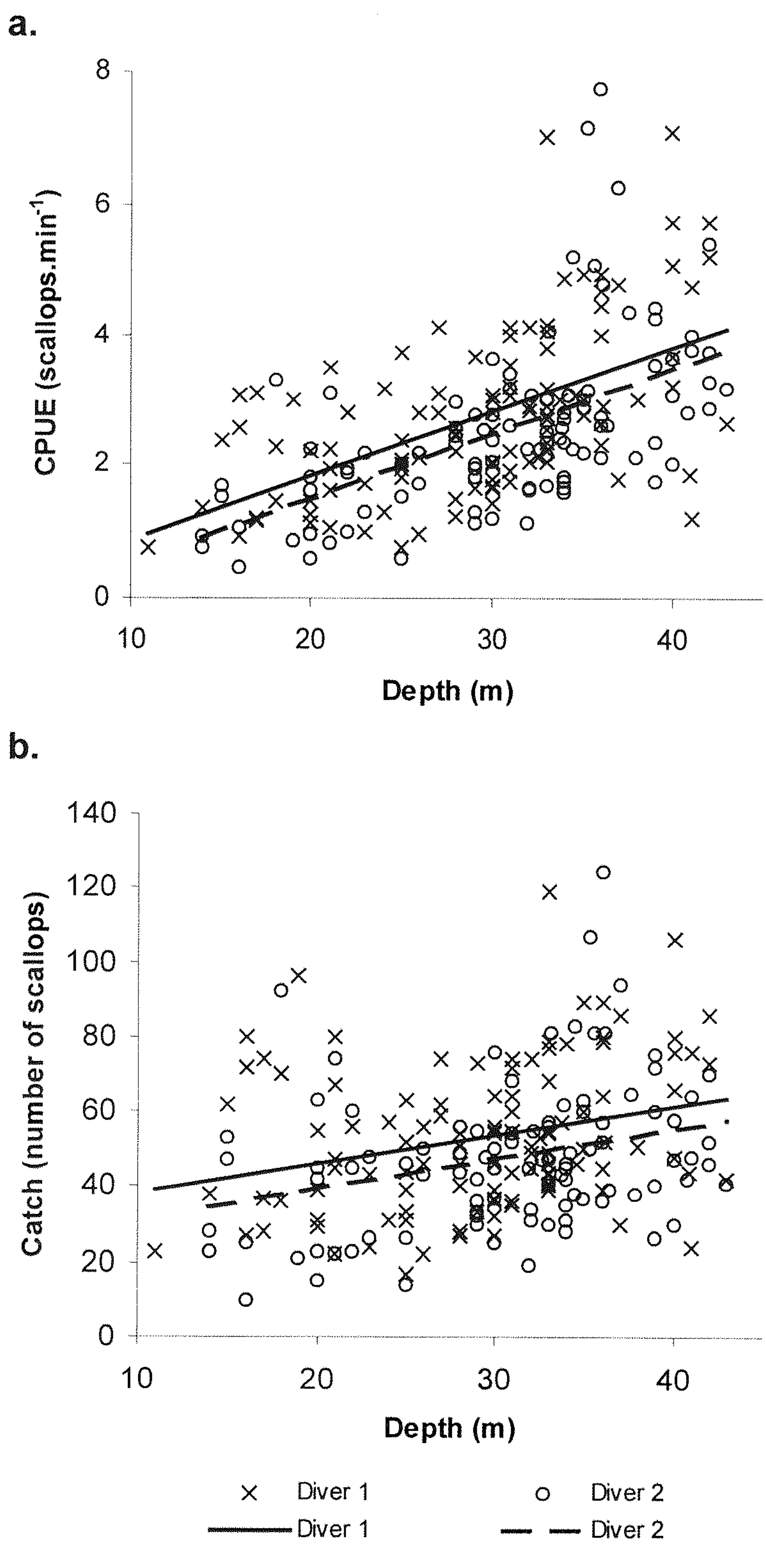
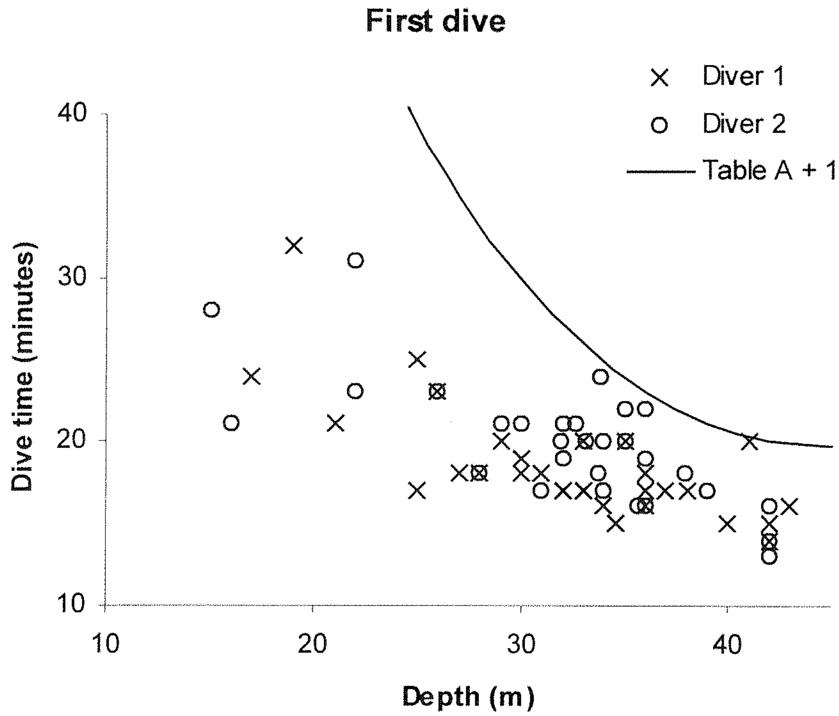


Figure 4.1: (a.) CPUE (scallops.min^{-1}) and (b.) catch per dive correlated with depth (m) on the diver fished grounds in Guernsey for the two divers studied.



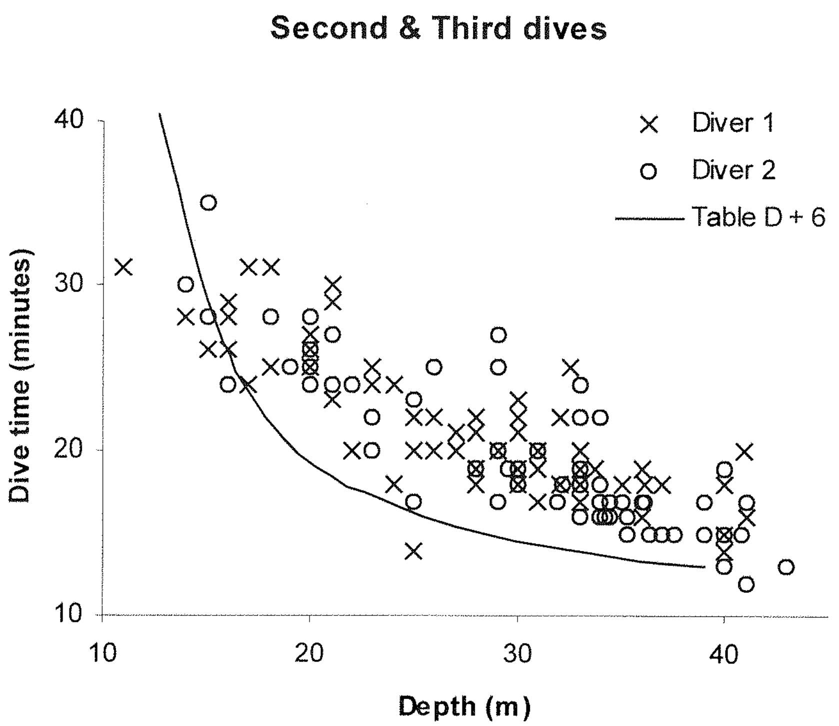


Figure 4.2: Safety of individual dives in terms of dive times at different depths for two scallop divers. The first dives of each day were considered safe if they were below the line for Table A with one minutes decompression. Second and third dives were grouped together and were considered safe if they were below the line for Table D with six minutes decompression.

lower safe time limits as Table D with six minutes decompression needed to be used. This resulted in most of them being considered unsafe if they were working within the limits of these dive tables.

The correlation between risk and profit was also analysed using these data to see if dives that were considered more risky resulted in a greater catch. This risk was calculated from the 'distance' of each dive from the theoretical safe limit (Table A plus one minute decompression) (Figure 4.3). Individual dives that were closer to the 'safe' limit were considered more risky than those further away to the left of the line. This value of risk was then correlated with the catch for each individual dive. The results showed that there was no significant correlation between risk and catch ($r = -0.1$, P is NS) in that dives which were more risky did not result in better catches.

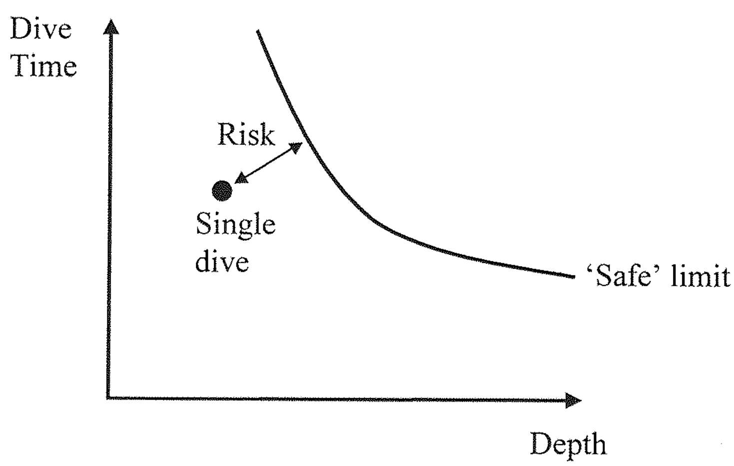


Figure 4.3: Method used to calculate the risk of each individual dive.

These estimations assumed that risk did not alter with depth, which was often not the case, as deeper dives would be more dangerous than shallower ones. In retrospect, a better way of assessing the risk of each dive would have been to calculate the vertical distance to the safe limit line. This would have result in deeper dives being more risky as they would have been a much shorter distance from the safe limits. This method would have also assumed that divers chose the depth at the start of the dive and could alter duration depending on conditions, which is closer to the real situation.

4.3.3 Air as a limiting factor

The amount of air carried by the divers would also limit the amount of time they could spend at different depths. Figure 4.4 shows the depth and duration of each dive studied and a theoretical maximum dive time assuming an air consumption rate of 20 litres per minute and a 12 litre cylinder. As virtually all the individual dives were below this line, air consumption was generally greater than 20 litres per minute. To try and estimate the divers actual air consumption, an equation of the form of Eq. 4.1 was fitted to the data using the non-linear regression function in SPSS. This resulted in an air consumption rate of 26.9 litres per minute ($r^2 = 0.64$), which gave a good fit to the data. This was assumed to be the same for the two divers although air consumption can vary widely between different divers. This was not surprising since the most important factor in limiting dive time was the amount of air carried. This was bound to be the case, as if the air runs out, the diver must surface immediately, which may result in decompression sickness or other diving related injuries.

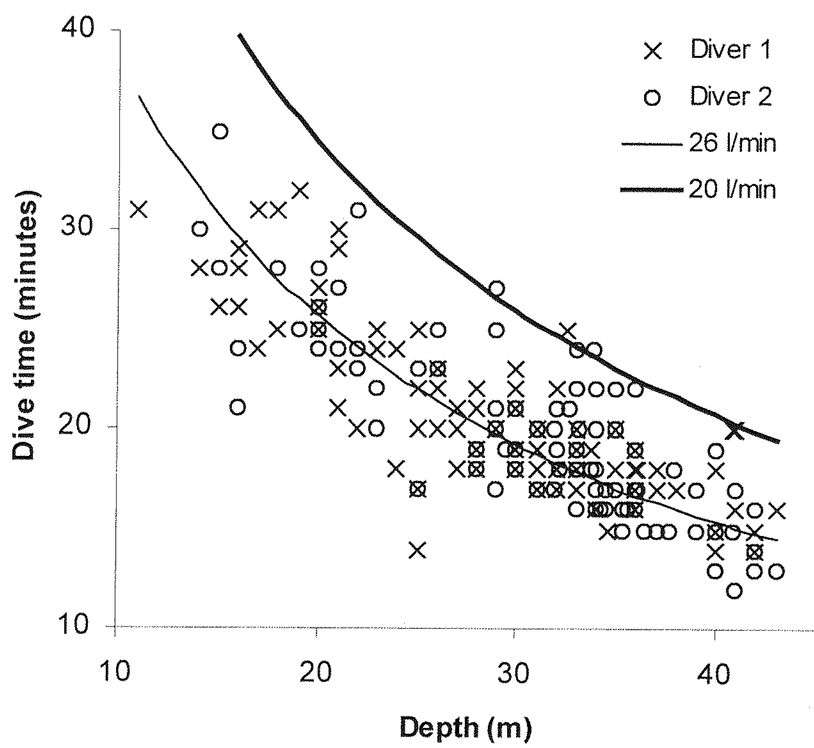


Figure 4.4: Air use for two scallop divers in Guernsey. Individual points show dive times at different depths. The 20 litres per minute line indicates the limiting factor on dive time at different depths. The 26 litres per minute line was calculated by fitting the equation (Eq. 4.1) to the observed data.

4.4 Discussion

This study has shown that there was a short term incentive for scallop divers to dive deeper as they will catch more scallops per dive and thus increase their profit per day. The main reason for the better catches at deeper depths was the higher density of scallops on these grounds (see Chapter 2). These higher densities may have resulted from lower fishing intensities on deeper fishing grounds, although this would not appear to be the case for the commercial divers who preferred to dive deeper if conditions permitted. However, the impact of recreational divers should also be considered as they are less likely to dive for scallops at the deeper depths and could have an effect of reducing the stocks on shallower grounds (Helyar, 1995b). Also, although scallops can be found locally at depths as shallow as 10m, they may be naturally more abundant at 30m to 40m as environmental conditions may be more suitable (e.g. better food supply, less disturbance).

The results show that the scallop divers were pushing the limits of safe diving by exceeding the bottom times for the depth of dive and reducing the amount of decompression time necessary. These safe limits were calculated from dive tables that are designed for general recreational use and are therefore quite conservative. They also assume that the diver spends the entire dive at the deepest depth, which may have often not been the case, for example, if they were working up a sandbank. This means the divers could safely exceed the table limits without risking injury, but the amount they could exceed the limits would be almost impossible to calculate without a dive computer which can take into account all parameters of the dives. In hindsight it would have been better to give the divers a dive computer rather than rely on tables, to obtain more accurate information on the depth and profile of their dives. However, the divers were also observed exceeding the safe limits of a dive computer (when used), by either shortening the time spent at decompression stops due to lack of air or starting a consecutive dive too soon.

Despite this, initial symptoms of decompression sickness (DCS) such as aching joints or 'itchy shoulders' were rare, occurring only 4 or 5 times out of over 300 dives observed. Another possible reason for the lack of DCS could be due to an adaptation to diving work, which may allow them to exceed established decompression limits. This was thought to be the case for diver fishermen in the Pescadores who use a hookah system that provides them with an unlimited air supply from the surface. Here the divers far exceed the safe limits, yet with relatively few cases of DCS, only 180 cases reported per year out of 140 fishermen making numerous dives (Lee *et al.*, 1994). Also as the divers have considerable experience (30 years in one case), they may have learnt their own safe limits due to past symptoms of DCS. Indeed, different people will have slightly different tolerances to the amount of nitrogen in the body and the decompression tables or computers used apply to the general population and are always set on the precautionary side (Hennessy, 1988).

As the divers seem to be maximising their dive time it was possible that they were applying an optimality model in order to maximise their catch. This is similar to an optimal foraging model for diving ducks, which face a trade off between obtaining oxygen at the surface and food underwater (Carbone and Houston, 1994). There is also an optimal amount of time that can be allocated for diving (Houston and Carbone, 1992), but this must be within safe limits. For the divers, the trade-off was between short term profit (i.e. catching scallops) and the risk of DCS and long term damage such as other diving related illnesses (Martin, 1997). The risks of DCS were increased by the fact that there were incentives to dive deeper as well as longer as both will result in a larger catch. However, there was no correlation between profit and the calculated risk of each dive, although deeper dives should be considered more risky than shallower ones. This shows that the divers do not need to risk diving beyond the safe limits of the table, but that there was an incentive to dive deeper to catch more scallops. In theory, there should be an optimum dive time and depth, which will maximise catch. At some point the higher abundance of scallops will not compensate for the shorter time available to fish for scallops at deeper depths. However, this optimum does not appear to be reached (Figure 4.1). This may be due either to them not carrying enough air to make full use of the available bottom time at deeper depths, or that they were not diving beyond the optimum catch level.

5. Impact of Scallop Dredging

5.1 Introduction

Scallop dredging can have an enormous impact on the marine benthos due to the types of gear used and the amount of area dredged (Jennings and Kaiser, 1998). Of particular interest is the effect of scallop dredging on commercially important by-catch species such as the crabs, *Maja squinado* and *Cancer pagarus* because of the important fisheries they support in the Channel Islands and the English Channel in general (Bannister, 1986; Pawson, 1995). These crabs, as well as many other benthic species, are caught as by-catch in scallop dredges and can make up a large proportion of the total biomass landed on deck.

Discarded by-catch can be defined as 'non-target' species caught in the fishing gear that will normally be thrown back either because they have no commercial value or they are below the minimum landing size. For scallop dredges this will include benthic species such as starfish and sea urchins as well as under-sized, commercially important crabs and scallops. The term by-catch also refers to 'non-target', commercially valuable species caught in the fishing gear which can be sold along with the catch (or target species). This would include edible crabs (e.g. *Cancer pagarus*) and benthic fish (e.g. *Solea solea*, *Lophius piscator*) which can get caught in scallop dredges but are not specifically fished for using this type of gear.

Studies of the effects of fishing on non-target species are a relatively new area of fisheries science as generally it has been more important to assess the state of the exploited species. However, towed fishing gear such as beam trawls and dredges can have an enormous impact on benthic species, some of which are commercially important. Early work concentrated on describing the diversity and abundance of by-catch (de Groot and Apeldoorn, 1971; Margretts and Bridger, 1971), whereas more recently the aim has been to quantify the whole effect that demersal gear has on the marine benthos (see Jennings and Kaiser, 1998 for review).

Previous studies have investigated the effects of both trawls (Kaiser, 1996a; Engel and Kvitek, 1998; Kaiser *et al.*, 1998b; Philippart, 1998; Thrush *et al.*, 1998) and scallop dredges (Eleftheriou and Robertson, 1992; Thrush *et al.*, 1995; Brand and

Hawkins, 1996; Hill *et al.*, 1996; Kaiser *et al.*, 1998a; Hill *et al.*, 1999) as well as a comparison of the two fishing methods (Kaiser *et al.*, 1996). Generally these have found a decrease in diversity and biomass of the benthic communities although there is often an increase in abundance of scavenger and predatory species (Kaiser, 1996a). Other studies have also examined the survival of discarded by-catch (Kaiser and Spencer, 1995; Brand and Hawkins, 1996; Hill *et al.*, 1996) and the possibility of using animal scarring as a measure of fishing intensity (Brand and Hawkins, 1996; Kaiser, 1996b).

One of the biggest problems with regard to scallop dredging is that the greatest abundance of scallops are often associated with sandy and muddy sediments. These types of seabed contain rich infaunal communities and a large biomass of structural epifauna, such as hydroids and byozoans which provide vital settlement substrata for juvenile scallops (Kaiser *et al.*, 1998a). Dredging has a serious effect on these communities and it has been demonstrated that in the Irish Sea, community structure has changed considerably over a 40 year period (Hill *et al.*, 1999). Often the biggest problem in determining the amount of change is a lack of suitable unfished areas (controls) to use in a comparative analysis (Kaiser, 1998). This problem can be partially overcome by setting up areas closed to fishing (Brand and Hawkins, 1996; Tuck *et al.*, 1998) but this requires suitable regulation and a considerable amount of time for the area to return to a natural state.

The overall aims of this work were to estimate the annual mortality due to dredging of discarded crabs and scallops on the fishing grounds studied. Therefore the aims of each part of this study were to:

- identify the composition of by-catch from commercial dredges on fishing grounds in Guernsey;
- assess the abundance and damage to the commercially important by-catch species;
- assess which factors were most important in causing damage;
- investigate survival of the discarded by-catch;
- calculate the overall mortality for each species of commercially important by-catch.

5.2 Methods

The approach adopted in this study was to obtain data onboard a commercial vessel during normal fishing activity. Therefore the samples obtained would suffer the same physical stress as by-catch caught under normal conditions. As crabs and shellfish form an important part of the Guernsey fishing industry, the main aim of this work was to assess the mortality of the commercially important by-catch so less effort was applied to the other benthic species. Also, individuals caught in the fishing gear may not have been killed instantly so more accurate estimates of mortality were calculated by assessing the survival of damaged by-catch returned to the sea.

5.2.1 **Relative abundance of catch and by-catch**

This study was carried out on a commercial scallop dredger, the MFV '*Rosie J*', during normal fishing trips. This is a 9m vessel that tows three standard scallop dredges, ¾m wide with a spring loaded tooth bar, on either side of the boat. As the vessel was not hired for the survey the skipper decided all aspects of the trip, such as the fishing ground, length and direction of tow, speed of boat and the gear used. However, this meant that the sampling reflected local fishing practices better than a research vessel survey. It was assumed that the skipper did not alter his activities due to the presence of the investigator.

Before fishing commenced, the dimensions of the gear being used were measured and recorded. The length, time and track of each tow were recorded using a handheld GPS (Garmin 45XL). These were downloaded to a PC for later analysis. On hauling the dredges the far left one was selected and the contents were emptied onto the deck, separate from the remaining catch. All the species in the sample were identified and counted, including the number of stones.

Relative species abundance was calculated using the CPUE equation (Eq.2.2, Chapter 2), where results were expressed in numbers of individuals of each species per metre per hour. However, this assumed that gear efficiency remained constant for each of the species caught in the dredge. Even if this was not the case, the results still give important information about the relative abundance of different species in the catch. This enables by-catch comparisons to be made between grounds.

5.2.2 Assessment of damage to by-catch

All the individuals of each species in the sample collected from each tow were assessed for damage. A damage score of 1 to 4 was then assigned to each individual after a visual inspection (Brand and Hawkins, 1996) (Table 5.1). Mean damage scores were then calculated for each species on all the fishing grounds studied.

Table 5.1: Damage scores for species caught in a scallop dredge (from Brand & Hawkins, 1996)

Score	1	2	3	4
Crabs	Undamaged	Legs missing / small carapace cracks	Major carapace crack	Crushed / dead
Starfish	Undamaged	Arms missing	'Worn' and arms missing / minor disc damage	Major disc damage / dead
Urchins	Undamaged	<50% spine lost	>50% spine loss/major cracks	Crushed / dead
Whelks	Undamaged	Edge of shell chipped	Shell cracked / punctured	Crushed / dead
Bivalves	Undamaged	Edge of shell chipped	Hinge broken	Crushed / dead
Hermits	Undamaged	Out of shell and intact	Out of shell and damaged	Crushed / dead

5.2.3 Mortality of discarded by-catch

The immediate mortality of the by-catch can be calculated from the number of individuals with damage score 4. However, it was also important to try and estimate the additional numbers that will die, due to being caught in the dredge, after being discarded. This method was used to estimate the percentage of each damage score that will die up to a week after being returned sea. This study investigated the survival of the undersized commercially important by-catch (*C. pagarus*, *M. squinado* and *P. maximus*).

The samples were obtained from commercial dredges as in the previous method. Individuals which had sustained different levels of damage (score of 1 to 3 only) were selected from the sample and transferred to containers of seawater with a through flow system. In order to keep the treatment of the sample as close to normal fishing conditions as possible, the individuals were not transferred to the seawater until the remaining catch had been sorted. Therefore the sample would suffer similar stress (e.g. desiccation) to the discarded by-catch.

On returning to port, the samples were measured and aged (not crabs) then transferred to small storage pots (45cm by 30cm by 20cm). The crabs were placed in individual pots whereas up to five scallops were stored in each pot. The pots were tied together (~1m apart) and weighted down at either end with a marker buoy to the surface. The lines of pots were kept in Havelet Bay (~12m deep) as it is relatively sheltered and situated next to the harbour for easy access in most weather. The samples were assessed daily for seven days and the number of dead were recorded then removed from the pots. As a control, scallops caught by divers and crabs caught in pots were kept under the same conditions to see if the experimental treatment had an effect on undamaged samples.

The total percentage mortality of each species suffering each damage score was calculated for all the samples in the storage pots. These figures were then used to calculate the percentage of discarded by-catch that suffered minor damage yet would still die due to scallop dredging. The total mortality of each by-catch species was expressed as both percentage mortality of each species CPUE and as the number of individuals killed per 100 scallops in the catch.

5.3 Results

5.3.1 Relative abundance of catch and by-catch

The type and abundance of by-catch vary on different fishing grounds and can make up a large proportion of the total catch. Table 5.2 gives a list of the common benthic megafaunal species found in the dredge samples from each fishing ground. The difference between the communities found in the dredge by-catch on the fishing grounds was analysed using the Bray-Curtis similarity index method in PRIMER (Plymouth Routines In Multivariate Ecological Research, PML). The results showed that all four grounds had a similar composition of species as they were not sub-divided into groups until at least 80% similarity (Figure 5.1). From there, the grounds were grouped as a pair with Tautenay and Long Bank in one, and Gaudine and des Ormes in the other. Therefore there was unlikely to be any significant difference in terms of by-catch between grounds.

Generally the larger species (scallops, crabs & starfish) were found on all the grounds studied, probably because they were capable of being caught in the dredge and occurred in sufficient abundance. The smaller species caught only on some grounds either do not occur on all grounds or occur at too low an abundance to be caught in the dredge or found in the entire catch. As the dredges used were standard commercial ones, they were designed to allow undersized scallops and small by-catch to pass through (i.e. teeth widely spaced and large belly rings).

Figure 5.2 shows the catch per unit effort of common by-catch species on the four fishing grounds studied. The CPUE of the undersized *P. maximus* was fairly constant across all the grounds, whereas for most other common species CPUE varied widely. For example, *M. squinado*, which was the most common species of by-catch on the Tautenay ground, were rarely caught at des Ormes. Some species were also absent from certain grounds yet common on others (e.g. *Marthasterias glacialis*). This pattern has also been observed in the Isle of Man where each fishing ground was characterised by a unique suite of species, although a few species occurred commonly (Hill *et al.*, 1996).

Table 5.2: Benthic megafaunal species found in scallop dredge samples from Guernsey fishing grounds.

Species	Tautenay	Gaudine	Long Bank	des Ormes
Paguridae	+	+	+	+
Galathea spp.		+		
Maja squinado	+	+	+	+
Cancer pagarus	+	+	+	+
Crepidula fornicata	+	+	+	+
Buccinum undatum	+	+	+	+
Glycymeris glycymeris		+		+
Aequipecten opercularis	+	+	+	+
Pecten maximus	+	+	+	+
Laevicardium crassum		+		
Sepia officinalis	+	+	+	
Crossaster papposus		+		
Asterias rubens	+	+	+	+
Marthasterias glacialis	+	+		+
Echinus esculentus	+	+	+	+
Raja spp.	+			
Pleuronectes platessa	+			
Solea solea	+	+		+

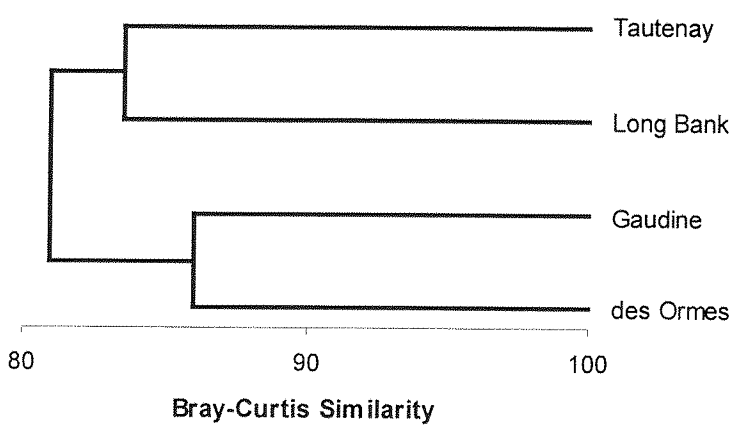


Figure 5.1: Multivariate analysis of scallop dredge by-catch on four dredge fished grounds around Guernsey.

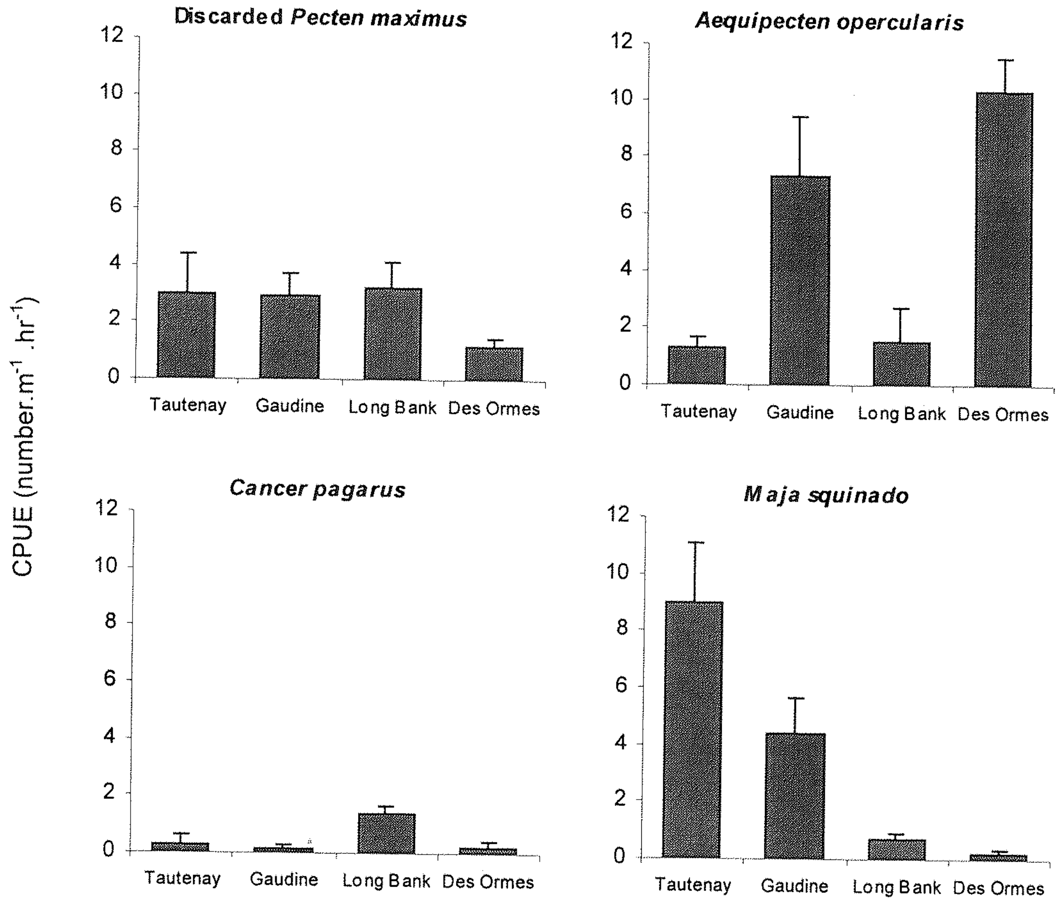


Figure 5.2: Relative abundance (+/- standard error) of scallop dredge by-catch on four fishing grounds around Guernsey.

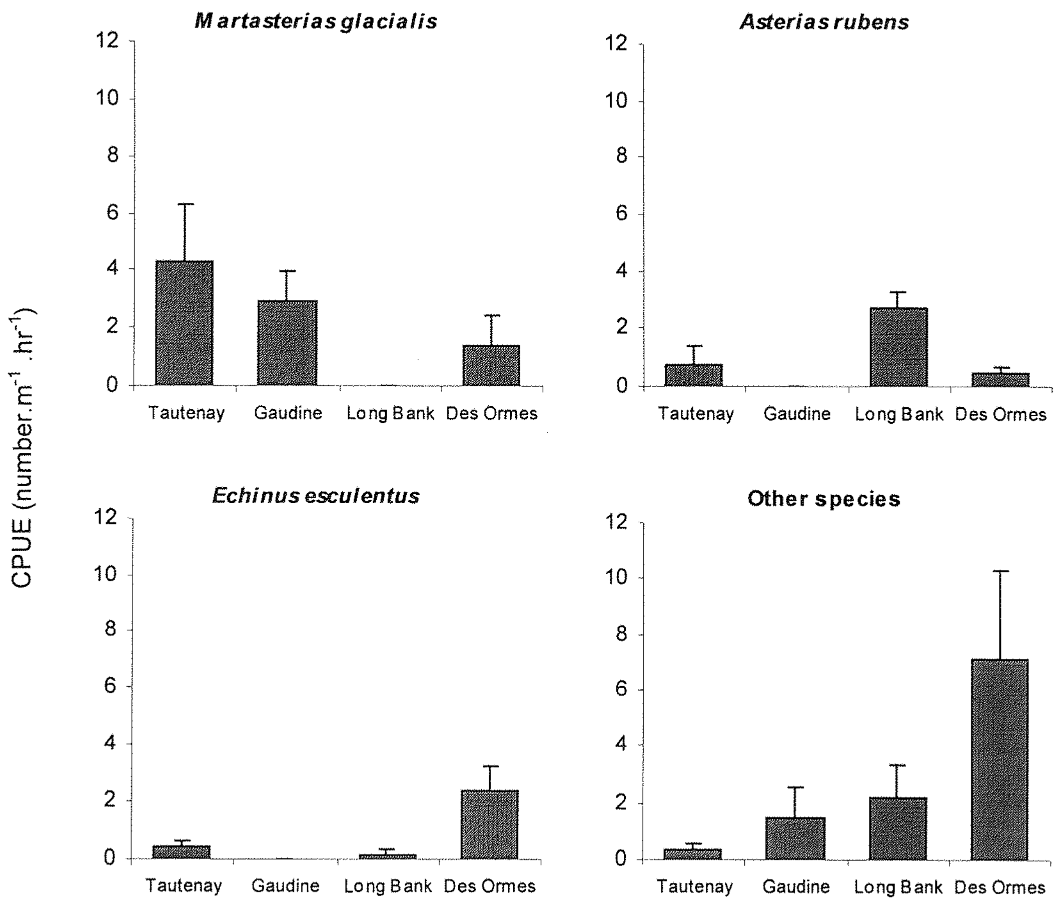


Figure 5.2 (cont.): Relative abundance (+/- standard error) of scallop dredge by-catch on four fishing grounds around Guernsey.

5.3.2 Damage to by-catch

The percentage of individuals suffering each damage score were calculated from the samples from the commercial dredge. The results are separated into commercially important by-catch (Figure 5.3) and other by-catch species (Figure 5.4). The highest percentage of individuals of all the species studied suffered no visible damage (damage score 1). The percentage of other damage scores (2 to 4) were approximately equal (~10%) for most species except the starfish. These suffered a high percentage of damage score 2 (~35%) due to them commonly losing arms in the dredges. *Pecten maximus* appeared to be the most resilient to damage in the scallop dredges whereas *Asterias rubens* was more susceptible as it had the lowest percentage of undamaged individuals. However, it was difficult to compare the percentage of each damage score for different species as they were assessed using different criteria for each group studied (see Table 5.1).

Of the commercially important by-catch, *M. squinado* appeared more susceptible to damage than the other two species mainly due to its low percentage of undamaged individuals. The spider crab is probably less robust than *C. pagarus* as it has longer legs which it can not tuck in, leaving them more exposed to damage.

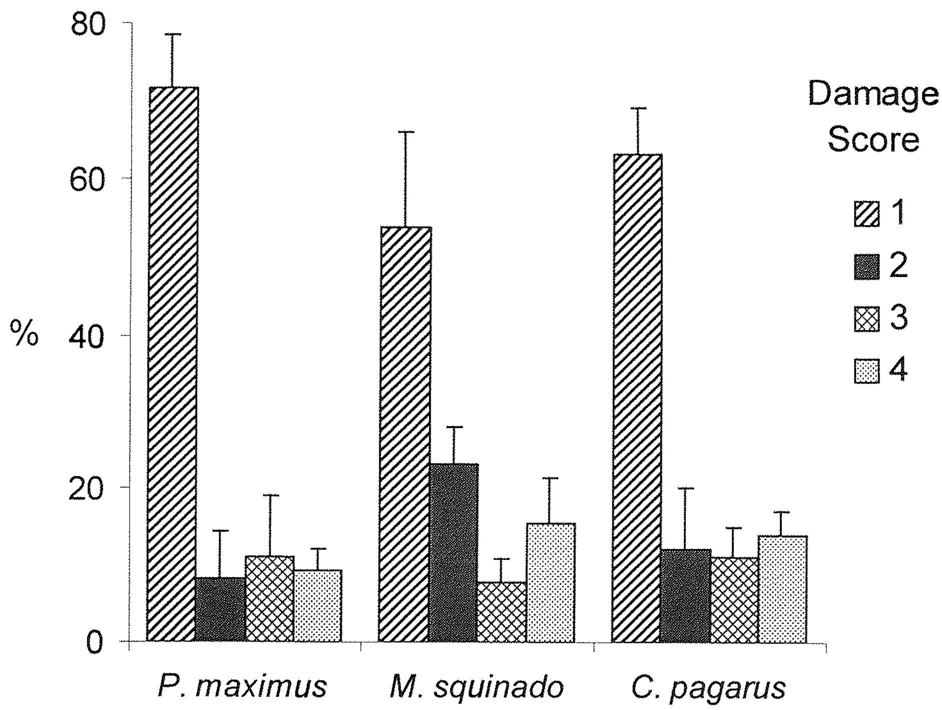


Figure 5.3: Mean percentage of individuals suffering damage of each score for all fishing grounds studied in Guernsey. Error bars show standard error.

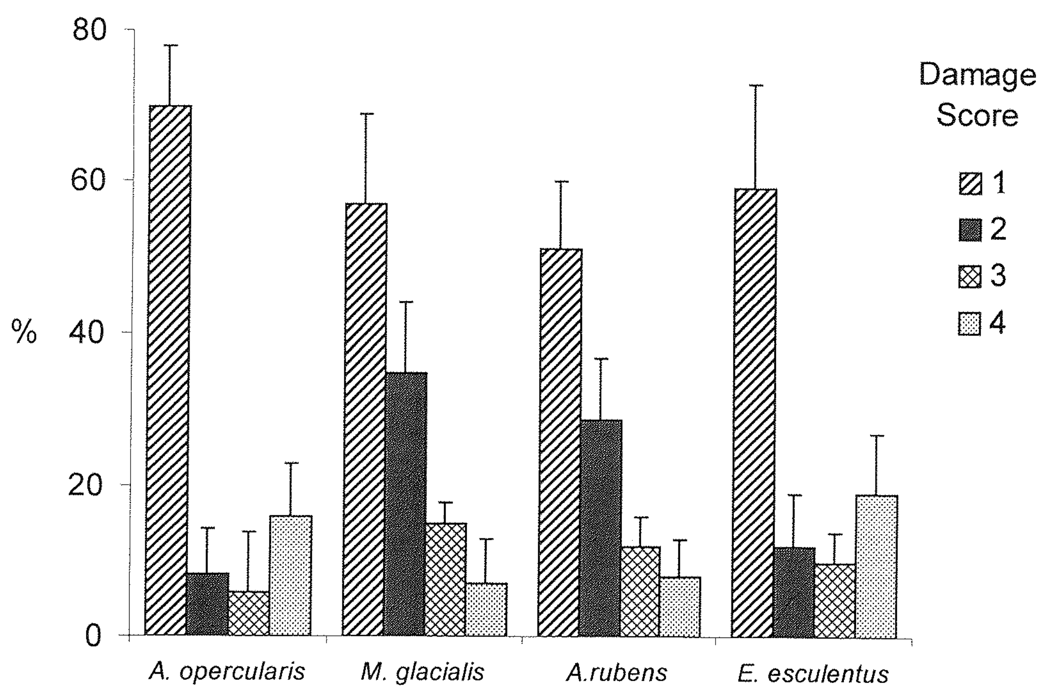


Figure 5.4: Damage to other species of by-catch species caught in the scallop dredge (percentage of individuals suffering each damage score). Error bars show standard error.

5.3.3 **Causes of damage**

The amount of damage to the by-catch could be affected by a number of different factors, therefore possible causes were tested against mortality of the scallop by-catch. The percentage mortality of scallops was plotted against the duration and length of tow and the number of stones in the dredge (Figure 5.5). The data from each day were pooled to get sufficient sample sizes and data from all grounds studied were used together. A Pearson product moment correlation coefficient was calculated for the data to test for correlation between the variables. There was no correlation between duration of tow ($r = 0.00$) or length of tow ($r = -0.04$, p is NS) and the mortality of scallops in the sample. However, there was a significant strong, positive correlation between mortality and the number of stones in the sample ($r = 0.73$, $p < 0.01$).

As mortality of scallops was correlated with the number of stones in the dredge and not the duration or length of each tow, the amount of mortality on different fishing grounds was tested using a one way ANOVA. The results showed that there was no significant difference in mortality between the four fishing grounds studied ($F_{3,24} = 0.282$, p is NS). The lack of a significant difference in mortality between fishing grounds may be due to variation in the bottom type found within each fishing ground.

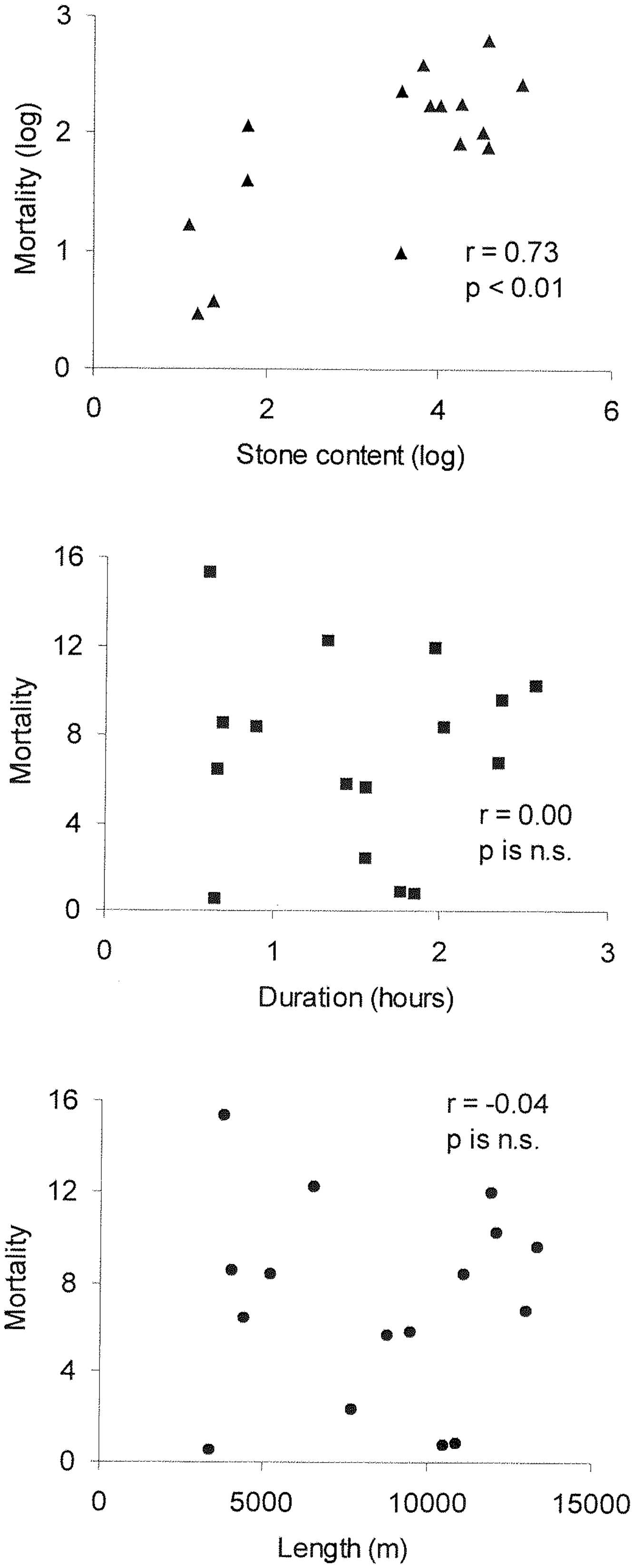


Figure 5.5: Mortality (% of scallops killed per tow) correlated with the number of stones, duration and length of tow.

5.3.4 **Survival of discards**

The survival experiments generally confirmed the initial assessment of damage to the samples of by-catch. The percentage mortalities for each by-catch species with different damage scores are shown in Figure 5.6. Individuals with a damage score of 3 died in at least 80% of cases. However, those suffering damage scores 1 & 2 resulted in much lower mortalities of less than 40%. All the controls (diver caught scallops and crabs caught in pots) survived as expected, indicating that the experimental conditions had not caused the mortality of the dredge by-catch.

Individuals that suffered mortality in the storage pots tended to die within the first few days. This trend was more apparent for both species of crab than for the scallop, some of which were only dead after seven days. This emphasises the importance of studying these species over a longer period than that used in some earlier studies (Kaiser and Spencer, 1995; Brand and Hawkins, 1996).

The results for the three species studied do show some differences. *M. squinado* has the highest mortality for all three damage scores, while *P. maximus* suffers the lowest. Also, the mortality of *M.squinado* was more than twice that of the other species at the damage score of 2. Therefore, spider crabs were not only more likely to suffer more severe damage in the dredges, but were also more likely to die from their injuries. There was also an apparent difference in the survival of different damage scores for the three species. Mortality of crabs increases in stages with damage score, whereas for *P. maximus* there was a clear divide between score 2 and 3. Scallops with a damage score of 2 or less nearly always survived whereas those with score 3 or more suffered almost 100% mortality. Crabs with an intermediate amount of damage suffered a moderate mortality, between 5% and 40%.

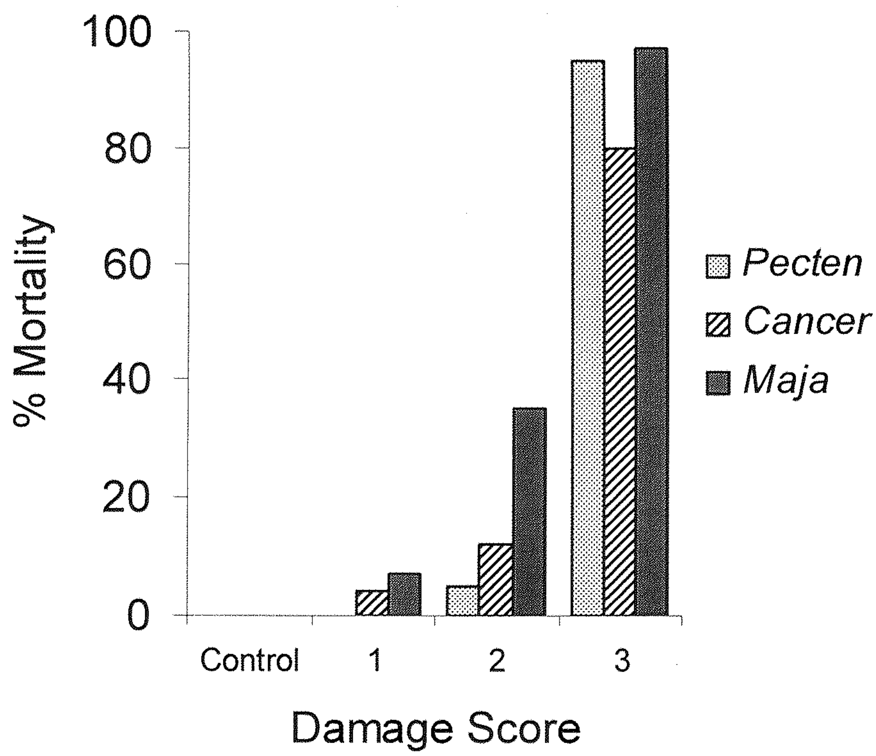


Figure 5.6: Mortality of by-catch species with different damage scores kept in storage pots for 1 week. Controls were undamaged individuals caught by divers or in crab pots. (N was approximately 20 individuals of each species for each damage score).

5.3.5 **Mortality on fishing grounds**

The mortality of discarded, commercially important by-catch was expressed using two different methods. Figure 5.7 shows the CPUE for each species broken down into the proportion which was kept as the catch, the by-catch which was discarded alive and the by-catch which was either dead or will die as a result of being caught in a scallop dredge. This final section was calculated from the results of the survival experiment which enabled the mortality of damaged individuals returned to the sea to be estimated. As CPUE does not account for the catchability of the different species (which varies), these results do not allow a comparison to be made between species.

Of the species studied, *P. maximus* has the highest CPUE, followed by *M. squinado* then *C. pagarus*. However, the proportion of the catch which was discarded due to being undersized was much smaller for the scallop than the two species of crab. Indeed, in some cases virtually all the crabs caught were undersize. Most of the crabs caught end up as discarded by-catch with approximately 30% of these suffering mortality. This figure was lower for the discarded scallops (~20%) as they were more resistant to damage from the dredges. Both species of crab had a high variability in CPUE on the different fishing grounds, *M. squinado* being more abundant at Tautenay, while *C. pagarus* was most abundant on the Long Bank.

The mortality of discarded by-catch was also expressed as the number of individuals killed per 100 scallops in the catch (Figure 5.8). These values were calculated as they could be extrapolated to give annual mortality of discarded by-catch if the annual scallop landings for the fishing grounds were known. The results show that *M. squinado* had a highly variable rate of mortality, suffering the largest mortality of all three species on the Tautenay ground, yet the lowest mortality at des Ormes. *C. pagarus* generally has a very low rate of mortality of below one individual killed per 100 scallops. Variation in mortality could be due to either a difference in the efficiency of the dredge at catching these two species or an actual difference in abundance on the fishing grounds. The low mortality of *P. maximus* was mainly due to the small size of the scallop by-catch, but also to its resistance to damage in the dredges.

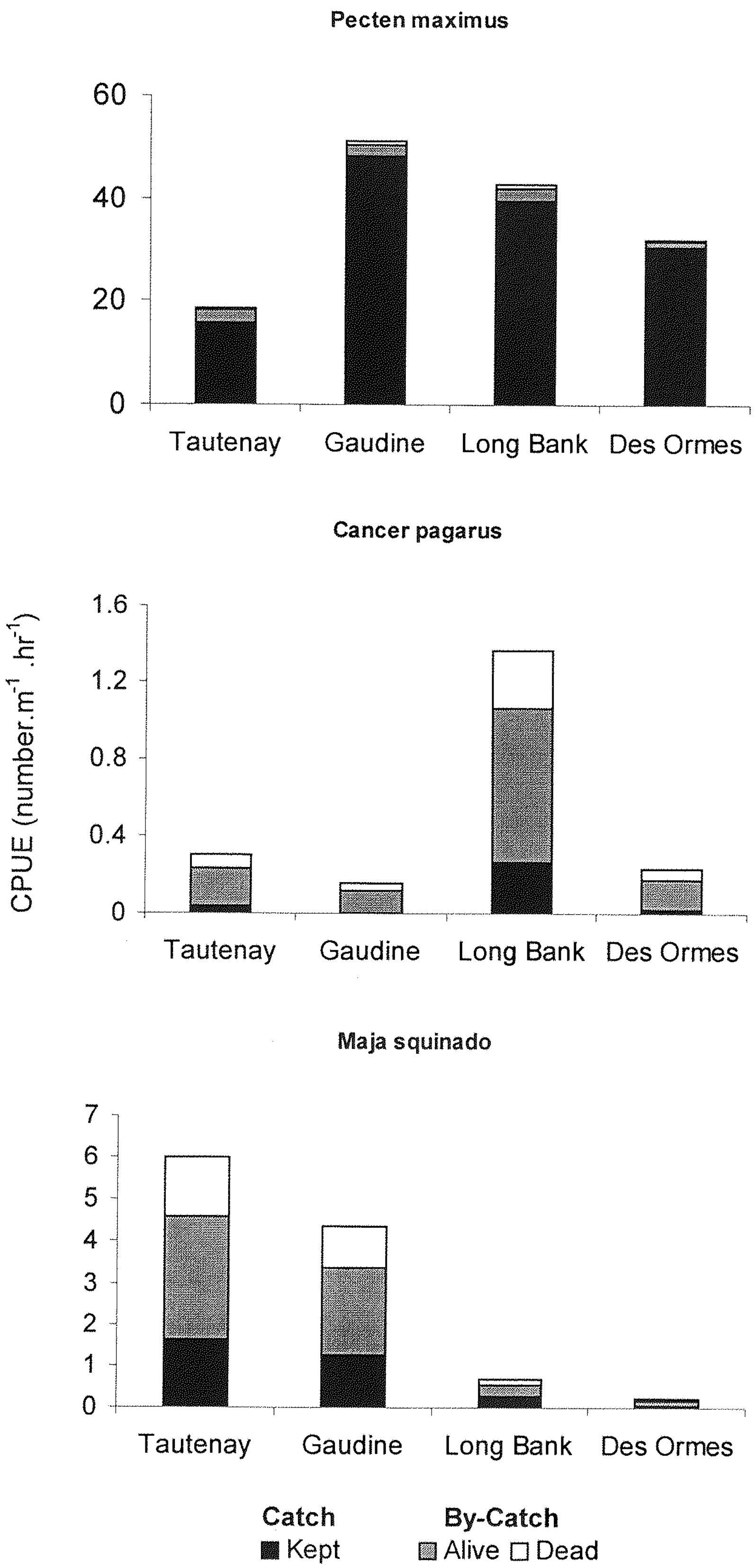


Figure 5.7: CPUE for *P. maximus*, *C. pagarus* and *M. squinado* on four dredge fished grounds. Also shown is the proportion of by-catch killed by dredging and that which was returned alive.

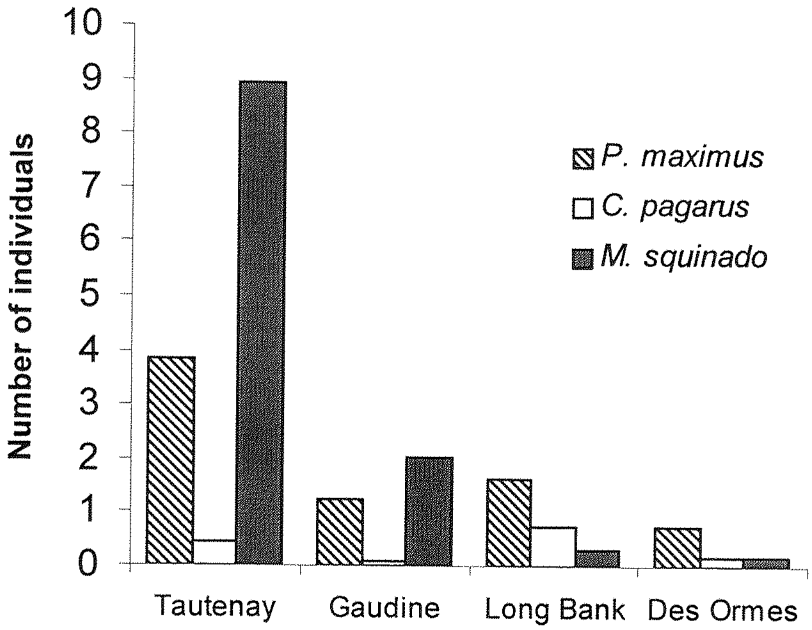


Figure 5.8: Number of commercially important, discarded by-catch species killed per 100 scallops caught on the four fishing grounds studied.

5.4 Discussion

The size and composition of the scallop dredge by-catch was highly variable between the different fishing grounds. Similar variation over a relatively small spatial scale has also been found in other fisheries, such as the Manx scallop fishery (Brand and Hawkins, 1996; Hill *et al.*, 1996) and the North Sea beam trawl fishery (Philippart, 1998). This variation could be due to the effects fishing can have on the marine ecosystem (see Jennings and Kaiser, 1998 for review), as fishing intensity often varies between grounds.

Benthic fishing can have both long term and short term effects on megafaunal communities. In the short term, mobile predators (such as crabs and fish) are known to rapidly migrate into areas recently disturbed by fishing to feed on individuals damaged by the fishing gear (Ramsey *et al.*, 1996; Kaiser *et al.*, 1998b). Therefore these scavenging species will occur more commonly in the fishing gear if the area is fished again in a short space of time. This may help explain the high numbers of *M. squinado* caught at Tautenay, as this is an inshore ground that may be more regularly fished. However, the abundance of spider crabs on this ground could also be due to the inshore migration of this species during the summer months when they group together to breed and moult (Meyer, 1998). This effect may be increased in these results as most of the dredge work was carried out between May and September. Sampling at other times of year may show that the composition of by-catch varies temporally as well as spatially.

Longer term effects of demersal fishing are generally due to the large scale removal of megafaunal animals from the seabed (Hill *et al.*, 1996; Kaiser, 1996a). This results in a decrease in abundance of relatively slow moving megafauna, such as starfish and sea urchins (Kaiser *et al.*, 1998b), as they are easily damaged or killed in the fishing gear. The difference in abundance of *Asterias rubens* on Guernsey fishing grounds could be explained by the intensity of fishing. The highest abundance of this slow moving susceptible species occurred on the offshore Long Bank ground, which may result from a lower fishing intensity. Indeed, Kaiser, (1996b) found that a strong correlation between fishing intensity and arm loss in *A. rubens* in different areas of the Irish Sea.

5.4.1 Mortality of commercially important by-catch

The results of the impact of scallop dredging from this study were particularly relevant to the fishery in Guernsey as all the samples were collected on a commercial scallop dredger during normal fishing activity. This eliminates some of the assumptions made in other studies where research vessels were used. In these cases the estimates of mortality would not necessarily represent those of the commercial fleet if the fishing performance (e.g. towing speed, gear efficiency, etc) of the research vessel differed greatly to that of the fleet (Hill *et al.*, 1996). However, it was still assumed that the vessel used was representative of other commercial vessels exploiting Guernsey fishing grounds and that fishing activity was not influenced or affected by the presence of the investigator.

Mortality of by-catch was probably underestimated as this study did not take into account species that came into contact with the dredge, yet failed to be retained by it. The damage to species left in the dredge track would need to be assessed in order to estimate fully the mortality due to scallop dredging. Another reason values may have been underestimated was due to the method used to assess long term mortality of non-fatally injured by-catch. The experimental samples were only studied in the storage pots for a week where they were protected from predation. If the damaged individuals had been returned to the seabed, they may have suffered higher mortality. Contact with the dredge may make them more susceptible to predation, disease or reduce their survivorship and fecundity. For example, if a crab lost one of its chela it would be at a disadvantage when defending itself or feeding. However, mortalities due to these factors will be small in comparison to the large numbers killed as a direct result of scallop dredging.

The monitoring of damaged organisms in storage pots enabled the damage scoring system to be verified and also allowed longer term mortality to be assessed. These results showed that the system of scoring individuals based on externally visible damage agreed fairly consistently with the mortality suffered. This subsequent mortality was taken into account in order to obtain a more complete estimate of total mortality. Similar assessments of survival of by-catch have been conducted with samples from beam trawls (Kaiser and Spencer, 1995) as well as scallop dredges

(Brand and Hawkins, 1996). However, these values were not taken into account by Hill *et al.*(1996) when assessing the number of by-catch animals killed annually on Manx scallop fishing grounds.

When investigating the effect of fishing on the marine benthos, the amount of natural disturbance from storms and strong tidal currents must also be considered. These form a background level of natural disturbance which may in some cases mask the potentially damaging effect of physical disturbance from demersal fishing gears. Also, since fishermen tend to concentrate their effort on certain areas of the seabed which produce the best catches (Rijnsdorp *et al.*, 1991), the additive effect of numerous small scale disturbances should be taken into account (Kaiser, 1996a). Following on from this, it also indicates that relatively stable environments with little natural disturbance from storms or currents are at a greater risk from physical disturbance by fishing (Jennings and Kaiser, 1998). Therefore, although this study has shown that the observed side effects of fishing were generally quite small, they may have a more damaging additive effect. The higher levels of natural disturbance in Guernsey waters, when compared with a sea loch for example, will also help hide the impacts of demersal fishing.

A further problem with studies like these was that some areas of seabed, especially those close inshore, have been subject to disturbance from demersal fishing for a considerable length of time (e.g. scallop dredging off the Isle of Man has been important for almost 60 years, Brand *et al.*, 1991a). This meant it was often difficult to find undisturbed areas with which to compare areas that are currently heavily fished, thus further masking the effect. A comparison between historical data collected prior to large scale fishing and samples collected from a currently fished ground would help demonstrate the size of the effect (Hill *et al.*, 1999), but the original data is rarely available.

As scallop dredging has increased the mortality of commercially important by-catch for at least 20 years in Guernsey, it is probably not having a detrimental effect on these crab stocks. However, it must be considered that any additional mortality caused to commercial fish stocks will not only reduce the potential yield from the fishery but must also be taken into account when carrying out stock assessments. Increased mortality due to scallop dredging would become more of a problem if the crabs (*M. squinado* and *C. pagarus*) started to suffer overfishing, or if there was a boom in the scallop dredge fishery leading to much larger mortalities of the commercially important by-catch.

6. Assessment of Scallop Stocks in Guernsey Waters

6.1 Introduction

Assessment of the scallop stocks in Guernsey is necessary in order to apply appropriate management measures as in any fishery (Cushing, 1968; Pitcher and Hart, 1982; Cushing, 1995). Traditionally conventional fishery models have been used although these often present problems when applying them to shellfish fisheries as they tend to break the 'dynamic-pool' assumptions (Caddy, 1989). These assume that the stock is homogeneous, whereas shellfish tend to be patchily distributed with small scale spatial variation in recruitment, growth and mortality as well as temporal fluctuations in recruitment. Despite these problems, such models have been successfully used to manage shellfish fisheries by accounting for the variability in the input parameters (Dao *et al.*, 1975; Sinclair *et al.*, 1985; Bannister, 1986; Caddy, 1989).

Stock assessment of this kind has been carried out on many *Pecten maximus* fisheries, for example in the Isle of Man (Murphy and Brand, 1987; Allison, 1993), Scotland (Mason *et al.*, 1991) and Brittany (Dao *et al.*, 1975) as well as other scallop fisheries throughout the world. Examples of these come from *Placopecten magellanicus* in Canada (Caddy, 1975) and *Amusium japonicum balloti* in Australia (Dredge, 1985; Dredge, 1988).

The overall aim of this chapter was to assess the current state of the scallop fisheries in Guernsey using yield per recruit (Y/R) analysis. The effectiveness of the current management measures and the suitability of any changes could then also be assessed. Although some of the input parameters, such as growth (see Chapter 3) have already been calculated, others still needed to be estimated. Recruitment ogives were calculated for all the grounds studied. These were used to estimate the proportion of each age class that had recruited to the fishery and was therefore susceptible to fishing mortality. Estimates of mortality, both fishing (F) and natural (M), were calculated for each fishing ground using a selection of methods. The range of likely values can then be input into the Y/R analysis to assess the scallop stocks on each of the grounds studied and explore management options. Comparisons with similar situations to Guernsey (i.e. the Isle of Man) were also made.

6.2 Methods

6.2.1 Recruitment ogives

Recruitment ogives show what proportion of each year class in the samples has recruited to the fishery (i.e. scallops which have reached MLS). These were calculated for all the grounds studied using the samples collected by divers and dredges in 1997, 1998 and 1999. The divers, who normally only bring legal size scallops to the surface, were asked to collect undersized ones as well, in order to get a good estimate of recruitment from the younger age classes. Age classes were considered to have recruited to the fishery if more than 50% had reached MLS (100mm in length).

6.2.2 Mortality rates of Guernsey scallops

The mortality rates of scallops on Guernsey fishing grounds were calculated using three different methods. Firstly, rates of instantaneous total mortality (Z) were calculated for each ground for the years between successive samples, from the declining abundance of each age class (Gulland, 1977; Gulland, 1983). A regression of the declining rate of tag returns also provided an estimate of Z which could be split into fishing mortality (F) and natural mortality (M) (Beverton and Holt, 1957). Finally, published empirical relationships (Taylor, 1960; Rikhter and Efanov, 1976; Hoening, 1983; Gunderson and Dygert, 1988) between mortality and growth parameters and other factors were also used to calculate values of Z and M for comparison with the other methods. The different estimates of mortality were used to establish a range of values to use in the stock assessment equations (see 6.2.3).

Instantaneous total mortality

Survival rates (S) were first estimated for each age class from the actual density of scallops on the fishing ground (see Chapter 2). These were calculated from one sampling period to the next so they represent annual rates. Sampling was carried out over three years so survival was estimated for two annual periods from May 1997 to

1998 (S_1) and 1998 to 1999 (S_2). As scallops had aged one year between samples, changes in abundance of each cohort (or successive year classes) were considered. Therefore, the survival rates of each cohort were calculated as follows:

$$S = \frac{N_{a+1}}{N_a} \qquad \text{Eq. 6.1}$$

Where:

N_a = Abundance of year class a scallops in first sample

N_{a+1} = Abundance of year class $a+1$ scallops in second sample

Hence Z can be estimated for each cohort:

$$Z = -\ln(S) \qquad \text{Eq. 6.2}$$

To calculate an annual rate of total mortality all the cohorts needed to be included together. The method used by Heinke (1913) produces a weighted least-squares estimate of the geometric mean Z (Gulland, 1983). This method was favoured as it gives more weight to the values from more abundant age groups where a change in abundance from one year to the next is likely to represent a real change on the ground. As only exploited age classes needed to be considered, values of '*a*' of 3 and 4 were used as these were the age classes which were considered to have recruited to the fishery on different grounds (see 6.3.1). As age at recruitment varied from year to year on some grounds, both values of 'a' were used throughout. Thus annual rates of Z were calculated as follows:

$$\text{Heinke's Z} = -\ln\left(\frac{N_{\mathrm{a}+1} + N_{\mathrm{b}+1} \ldots N_{i+1}}{N_{\mathrm{a}} + N_{\mathrm{b}} \ldots N_i}\right) \qquad \text{Eq. 6.3}$$

Where: a, b … *i* are the ages of the different cohorts at the first sample

N is the abundance of scallops as in Eq. 6.1 above

The maximum value of 'i' used in the calculations was 9 as scallops older than 10 rarely occurred and were grouped together in the 10+ category. Two estimates of Z were calculated, one for a = 3 and the other for a = 4.

Tag returns

Although the tagging experiment was not specifically designed to estimate mortality, the results could be used to estimate values of F, M and Z on the diver fishing grounds. The methods used to tag and release scallops are detailed in Chapter 2. Although the tagging was carried out in April 1997, undersized scallops were used, so the first tagged ones were not caught until September 1997 when they reached landable size. This was assumed to be the release date of commercially sized scallops so there were two annual periods of returns between September 1997 and September 1999. Mortality was calculated by plotting the log of recaptures in each year against time and fitting a straight line. However, as there were only two years worth of data, the method used was not strictly valid, but still provided an estimate of the different types of mortality. Mortality can be calculated from the declining rate of tag returns using the following equation (Beverton and Holt, 1957):

$$\ln(R_t) = \ln(R_0) - Zt \qquad \text{Eq. 6.4}$$

where: R_t = number of recaptures in the period t

R_0 = number of tag releases

Therefore, plotting the log of recaptures each against time in years will give two points from the tag return data. The slope of the line joining these two points will give an estimate of Z. Furthermore, estimates of F and M can be calculated from Z, the number of tagged scallops (T) and the value of R at the time of release (R_{tt}) using the following equations (Gulland, 1983; Allison, 1993):

$$F = \frac{Ze^{(R_{tt} - Zt)}}{T(1 - e^{-Zt})} \qquad \text{Eq. 6.5}$$

$$M = Z - F \qquad \text{Eq. 6.6}$$

However, the number of tagged scallops released (T) needed to be corrected for tag loss using the data on the return of double tagged scallops (Seber, 1982; Murphy, 1986). The probabilities were calculated as follows:

$$P_d = \frac{R_v}{(R_v + R_{dv})} \qquad \text{Eq. 6.7}$$

$$P_v = \frac{R_d}{(R_d + R_{dv})} \qquad \text{Eq. 6.8}$$

$$P_{dv} = P_d P_v \qquad \text{Eq. 6.9}$$

where: P_d = probability of losing the dorsal tag
P_v = probability of losing the ventral tag
P_{dv} = probability of losing both tags
N_d = number recaptured with dorsal tag only
N_v = number recaptured with ventral tag only
N_{dv} = number recaptured with both tags

The corrected numbers were calculated for both the single and double tagged individuals to give a total number of tagged scallops released. This value was used to calculate F from equation 6.5.

Empirical methods

Estimates of the mortality (both M and Z) of a fished population can also be derived from growth parameters and other factors related to the fishery. Some of these empirical relationships from the published literature have been calculated from fish stocks and although their validity for shellfish is questionable (especially with respect to the relative size of the gonad), they have been successfully applied to scallop fisheries (Caddy, 1989; Allison, 1993). The following equations (Eq. 6.10 to 6.13) were calculated using MS Excel to estimate mortality on the fishing grounds studied.

$$M = \frac{2.996}{0.95L_{\infty}} \quad \text{(Taylor, 1960)} \quad \text{Eq. 6.10}$$

$$M = 0.03 + 1.68(WGSI) \quad \text{(Gunderson and Dygert, 1988)} \quad \text{Eq. 6.11}$$

$$M = \frac{1.521}{(t_{m50})^{0.720} - 0.155} \quad \text{(Rikhter and Efanov, 1976)} \quad \text{Eq. 6.12}$$

$$\ln(Z) = 1.23 - 0.832(\ln(t_{\max})) \quad \text{(Hoening, 1983)} \quad \text{Eq. 6.13}$$

Where:

M = instantaneous rate of natural mortality
Z = instantaneous rate of total mortality
L_{∞} = asymptotic length (in cm)
t_{m50} = age at 50% sexual maturity (months)
$t_{\max}$ = age of oldest fish in sample (years)
$WGSI = \frac{\text{wet wt. gonad}}{\text{total wet wt.}}$ = Wet weight gonadosomatic index

The growth and life history parameters required for these equations were either calculated in Chapter 3 or from the data collected for this work. Mortality was estimated for each separate ground where suitable data was available. However, as seasonal cycles were only studied on the inshore diver fished grounds, only one estimate of mortality was calculated for those methods that require these parameters (Eq. 6.11 & 6.12). Other empirical estimates have also been applied to scallop fisheries but the ones shown gave more realistic values for this fishery.

6.2.3 **Yield per recruit and biomass per recruit**

Analysis of yield per recruit (Y/R) and spawning stock biomass per recruit (SSB/R) was carried out on scallop populations in Guernsey waters. The equations used were part of the CEFAS 'FishLab' Excel add-in, which were of the form of the Thompson-Bell formulation of the yield equation (Thompson and Bell, 1934; Pitcher and Hart, 1982).

$$\text{Y/R} = \sum_i \left[1 - \exp^{-Z_i} \frac{F_i}{Z_i} \overline{W_i} \right] \qquad \text{Eq. 6.14}$$

$$\text{SSB/R} = \sum_i \left\{ \exp\left[-\sum_i Z_i \right] \overline{W_i} \right\} \qquad \text{Eq. 6.15}$$

The required input values for the equations were the natural mortality (M), fishing mortality (F) and weight at age. The calculation of SSB/R also required maturity at age and the proportion of mortality, both F and M, which took place before the spawning season. As fishing takes place all year round and spawning occurs in July, it was assumed that half the fishing mortality occurred before spawning. Half of the natural mortality was also assumed to occur before spawning. A range of values were tested in the equations and were found to have no effect on the positions of different curves relative to one another, although Y/R and SSB/R did vary slightly. Y/R and SSB/R were calculated using MS Excel for a range of values of F from 0 to 2, to allow a curve to be plotted. F_{max} and $F_{0.1}$ were also calculated for each situation where the stock assessment equations were used.

Natural mortality at age was assumed to be constant for all age classes and was estimated at 0.2 from the results of the previous sections. However, different values of M from 0.15 to 0.25 were also tested in the equations to see what effect a small variation in M had on the stock assessments (see values used in other studies, in Table 6.6). The fishing mortality at age was the proportion of each age class that had recruited to the fishery and acted as a multiplier on different values of F input into the equations. These were calculated from the length at age data from Chapter 3. Thus age classes which had fully recruited to the fishery suffered the total fishing mortality, whereas those which had only partially recruited suffered a relative proportion of the fishing mortality. Age classes that had not recruited to the fishery suffered no fishing mortality, so it was assumed there was no indirect or incidental fishing mortality.

Weights at age were only available from the monthly gonad analysis samples collected on the Harbour fishing ground. These were calculated by fitting a von Bertalanffy growth function to yield weight at age data. Yield weight (adductor muscle + gonad) was used rather than overall weight as this was the harvestable weight of the scallops and was therefore more directly related to the fishery. Values of weight at age were calculated from the growth curve rather than using empirical data, as the curve gave a good fit and smoothed out any irregularities in the stock assessment equations. Maturity at age was calculated for the same samples and represented the proportion of each age class which had reached sexual maturity (Mason's 1958 stage II or greater). As weight and maturity at age data were only available for the Harbour fishing ground, a comparison between grounds was not directly possible. However, as growth was found to vary between grounds, with the Harbour having the lowest and des Ormes having the greatest growth rate, estimates of weight and maturity at age were calculated in order to compare the two extremes in Guernsey. A length-weight relationship was calculated for the available data on the Harbour ground. This was used to calculate weight at age from the von Bertalanffy growth curve for the des Ormes ground. Maturity at age was assumed to be the same as for the Harbour fishing ground.

The effect of increasing minimum landing size from 100mm to 105, 110 and 115 mm in length was investigated for the Harbour ground. This was input into the stock assessment equations by recalculating the recruitment ogives for the different minimum landing sizes. No reduction in landing size was considered as Guernsey already uses the EEC minimum legal landing size for scallops. The increase to 110mm in length was particularly relevant as this is the current legal size in Jersey and is widely used elsewhere (e.g. Irish Sea, Eastern English Channel and Scotland).

6.3 Results

6.3.1 Recruitment ogives and maturity at age

Table 6.1 shows the recruitment ogives for different areas calculated from annual samples collected from the fishery. Overall, scallops were considered to have recruited to the fishery by age four on all the grounds in each year studied. Also none of the two year old age class had recruited, whereas all the six year old age classes had. However, there was variation in the first age class recruited between grounds and years. In 1997 and 1998 the number of grounds recruited by age three or four were approximately equal but in 1999, six out of the seven grounds had the three year old age class recruited to the fishery.

Recruitment ogives showing the proportion of each age class recruited to the fishery were calculated for sizes of first capture ranging from 100mm to 115mm on the Harbour ground (Table 6.2). Increases in size at first capture result in recruitment to the fishery being delayed to the older age classes and a more drawn out recruitment in that at 115mm MLS, the 9 year old age class was the first to be 100% recruited. These values have been used in the stock recruitment equations to assess the effects of increasing minimum legal landing size (see 6.3.3).

Table 6.1: Recruitment ogives for scallop samples from Guernsey fishing grounds. Values show percentage of each year class that had recruited to the fishery. Year classes which were considered to have recruited to the fishery (>50% greater than MLS) are shown in bold.

		Age						
Year	**Site**	**2**	**3**	**4**	**5**	**6**	**7**	**N**
1997	Petite Canupe	0	**57**	100	100	100	100	342
	Platte	0	34	**82**	97	100	100	162
	Harbour	0	**64**	97	100	100	100	230
	Pipe	0	**79**	100	100	100	100	274
	Anfre	0	32	**95**	93	100	100	259
	Tautenay	0	40	**89**	100	100	100	231
	Long Bank	0	26	**75**	100	100	100	173
	Gaudine	-	-	-	-	-	-	-
	Des Ormes	-	-	-	-	-	-	-
1998	PC	0	**84**	96	100	100	100	293
	Platte	-	-	-	-	-	-	-
	Harbour	0	**70**	85	98	100	100	217
	Pipe	0	**62**	91	100	100	100	192
	Anfre	0	45	**100**	100	100	100	178
	Tautenay	0	**67**	94	90	100	100	138
	Long Bank	0	20	**69**	86	100	100	249
	Gaudine	0	34	**98**	94	100	100	217
	Des Ormes	-	-	-	-	-	-	-
1999	Petite Canupe	0	**76**	100	98	100	100	206
	Platte	-	-	-	-	-	-	-
	Harbour	0	**73**	98	100	100	100	167
	Pipe	0	**89**	94	95	100	100	238
	Anfre	0	**92**	98	100	100	100	124
	Tautenay	-	-	-	-	-	-	-
	Long Bank	0	**53**	79	100	100	100	289
	Gaudine	0	45	**88**	94	100	100	107
	Des Ormes	0	**69**	100	100	100	100	262

Table 6.2: Recruitment, maturity and weight at age population parameters for input into the stock assessment equations. The columns headed 100mm to 115mm represent the proportion of each age class recruited to the fishery assuming different minimum landing sizes. Weight at age is the weight of gonad + adductor muscle.

	Harbour						des Ormes	
Age	100mm	105mm	110mm	115mm	Maturity	Weight	100mm	Weight (g)
0	0	0	0	0	0	0.0	0	0.0
1	0	0	0	0	0.25	10.0	0	6.6
2	0	0	0	0	0.95	22.1	0	18.8
3	0.32	0.26	0.03	0	1	29.5	0.69	27.6
4	0.97	0.81	0.48	0.26	1	33.2	1	33.4
5	1	0.97	0.84	0.58	1	34.9	1	37.0
6	1	1	0.87	0.77	1	35.6	1	39.2
7	1	1	1	0.90	1	35.9	1	40.6
8	1	1	1	0.96	1	36.1	1	41.5
9	1	1	1	1	1	36.1	1	42.0
10	1	1	1	1	1	36.1	1	42.3

6.3.2 Estimates of mortality rates

Mortality rate estimates were calculated using a variety of methods in order to understand the range of mortality on the different fishing grounds. Some of these methods were applied to all the fishing grounds whereas others were only applicable on the inshore diver ground where the tagging experiment and reproductive studies were carried out. The first method was based on the annual decline in density of each cohort, so it could be used on most of the fishing grounds with data from more than one year.

Table 6.3 shows the density of each age class in consecutive years for the grounds where data were available. The change in density of each cohort from one year to the next gives the survival rate (S) from which annual mortality (Z) was calculated. On most grounds, survival rate and mortality were calculated for two annual periods: 1997 to 1998 (S_1 & Z_1) and 1998 to 1999 (S_2 & Z_2). For some cohorts, especially the younger ones, mortality estimates were negative, indicating that the density had increased. As the samples were collected from commercial fishermen this could be due to the cohort not being fully recruited to the fishery at the start of each annual period. This also occurred on the Anfre ground for the first annual period where all the cohorts had negative mortality, which was due to a very high overall density estimate in 1998. To try to smooth out these irregularities the geometric mean of Z was calculated for all exploited year classes assuming a recruitment age of three and four (Heinke's $Z_{a=3}$ & $Z_{a=4}$ respectively) (Heinke, 1913).

Heinke estimates of Z showed greatest variability between years on single grounds rather than between grounds. Generally Z was greater for the second annual period which was due to the overall high densities of scallops found during 1998 as a result of good recruitment in 1995. Estimates of Z on the dredged grounds were less variable than the diver fished grounds and were generally lower than expected (~0.3). However, the high densities found during 1998 resulted in lower than expected estimates of mortality in the first year and much higher than expected values in the second annual period on the diver fished grounds.

Table 6.3: Survival (S) and mortality (M) rates of commercial sized scallops calculated from density at age values (scallop.100m^{-2}) for Guernsey fishing grounds. S_1 and Z_1 refer to the annual period between sampling from May 1997 to May 1998, and S_2 and Z_2 refer to the same period from May 1998 to May 1999. Heinke's $Z_{a=3}$ was the annual mortality assuming 3 year olds had recruited to the fishery, whereas $Z_{a=4}$ assumed that only the 4 year olds were considered to have recruited to the fishery.

Harbour

	Density (scallops.100m^{-2})						
Age	**1997**	**1998**	**1999**	S_1	S_2	Z_1	Z_2
3	1.31	2.10	1.43				
4	2.05	1.87	1.27	1.42	0.61	-0.35	0.50
5	1.00	1.17	0.48	0.57	0.26	0.56	1.36
6	0.74	1.31	0.29	1.31	0.25	-0.27	1.40
7	1.00	0.47	0.13	0.64	0.10	0.45	2.33
8	0	0.42	0.06	0.42	0.14	0.86	1.99
9	0	0.09	0.13		0.30		1.19
10+	0	0	0		0		
					Heinke's $Z_{a=3}$	**0.14**	**1.15**
					Heinke's $Z_{a=4}$	**0.32**	**1.59**

Pipe

	Density (scallops.100m^{-2})						
Age	**1997**	**1998**	**1999**	S_1	S_2	Z_1	Z_2
3	0.60	1.84	1.22				
4	0.69	1.17	0.54	1.95	0.29	-0.67	1.23
5	0.43	0.53	0.16	0.77	0.14	0.26	1.99
6	0.42	0.37	0.02	0.87	0.04	0.14	3.29
7	0.49	0.47	0.06	1.11	0.16	-0.10	1.83
8	0.07	0.08	0.02	0.17	0.04	1.76	3.16
9	0.02	0.06	0.04	0.85	0.48	0.16	0.74
10+	0	0	0				
					Heinke's $Z_{a=3}$	**0.01**	**1.69**
					Heinke's $Z_{a=4}$	**0.33**	**2.19**

Table 6.3 (cont.)

Petite Canupe

	Density (scallops.100m^{-2})						
Age	**1997**	**1998**	**1999**	**S_1**	**S_2**	**Z_1**	**Z_2**
3	0.57	3.33	1.42				
4	0.62	1.55	1.17	2.70	0.35	-0.99	1.05
5	0.35	0.71	0.34	1.14	0.22	-0.13	1.52
6	0.46	0.52	0.29	1.48	0.41	-0.39	0.89
7	0.88	0.56	0.11	1.21	0.21	-0.19	1.55
8	0.17	0.95	0.07	1.09	0.13	-0.08	2.07
9	0.04	0	0.04		0.04		3.17
10+	0.04	0	0				
					Heinke's $Z_{a=3}$	**-0.33**	**1.33**
					Heinke's $Z_{a=4}$	**-0.08**	**1.61**

Anfre

	Density (scallops.100m^{-2})						
Age	**1997**	**1998**	**1999**	**S_1**	**S_2**	**Z_1**	**Z_2**
3	0.87	3.75	1.78				
4	0.71	2.09	1.11	2.39	0.29	-0.87	1.22
5	0.62	1.75	1.07	2.46	0.51	-0.90	0.67
6	0.53	1.67	0.36	2.70	0.20	-0.99	1.60
7	0.76	0.75	0.24	1.42	0.14	-0.35	1.95
8	0.07	1.17	0.04	1.53	0.05	-0.43	2.95
9	0	0.17	0.12	2.31	0.10	-0.84	2.29
10+	0	0	0.04		0.24		1.44
					Heinke's $Z_{a=3}$	**-0.76**	**1.34**
					Heinke's $Z_{a=4}$	**-0.72**	**1.41**

Table 6.3 (cont.)

Long Bank

Age	Density (scallops.100m^{-2}) 1997	1998	1999	S_1	S_2	Z_1	Z_2
3	0.62	1.03	0.80				
4	0.72	0.65	0.75	1.04	0.73	-0.04	0.32
5	0.62	0.75	0.40	1.04	0.61	-0.04	0.49
6	0.59	0.51	0.45	0.82	0.60	0.19	0.51
7	0.53	0.41	0.32	0.70	0.62	0.36	0.47
8	0.13	0.45	0.11	0.85	0.26	0.17	1.35
9	0.03	0.14	0	1.04	0	-0.04	
10+	0.07	0.03	0.03	1.04	0.19	-0.04	1.64
				Heinke's $Z_{a=3}$		**0.10**	**0.65**
				Heinke's $Z_{a=4}$		**0.14**	**0.80**

Gaudine

Age	Density (scallops.100m^{-2}) 1997	1998	1999	S_1	S_2	Z_1	Z_2
3		0.40	0.90				
4		0.51	0.93		2.32		-0.84
5		0.44	0.45		0.89		0.12
6		0.31	0.30		0.69		0.37
7		0.24	0.27		0.86		0.15
8		0.30	0.09		0.37		1.00
9		0.07	0.03		0.10		2.29
10+		0.03	0.06		0.86		0.15
				Heinke's $Z_{a=3}$			**0.06**
				Heinke's $Z_{a=4}$			**0.44**

Table 6.3 (cont.)

Tautenay

	Density (scallops.100m^{-2})						
Age	**1997**	**1998**	**1999**	**S_1**	**S_2**	**Z_1**	**Z_2**
3	0.31	0.70					
4	0.25	0.35		1.10		-0.10	
5	0.23	0.19		0.76		0.28	
6	0.20	0.21		0.92		0.08	
7	0.30	0.17		0.86		0.15	
8	0.15	0.23		0.75		0.29	
9	0.03	0.02		0.12		2.16	
10+	0	0.03		1.38		-0.32	
					Heinke's $Z_{a=3}$	**0.21**	
					Heinke's $Z_{a=4}$	**0.31**	

To try to avoid the problem of the high densities in 1998, new Heinke estimates of Z were calculated for the two year period between the 1997 samples and 1999 samples. Mortality was calculated in a similar way as before (Eq. 6.3), except that as it was over two years the age classes in 1997 were compared with those two years older in 1999, so that the same cohort was studied. Also, the result needed to be divided by two to give annual mortality. Therefore:

$$\text{Heinke's } Z = -\left(\frac{1}{2}\right) \times \ln\left(\frac{N_{a+2} + N_{b+2} \ldots N_{i+2}}{N_a + N_b \ldots N_i}\right) \qquad \text{Eq. 6.16}$$

Where: a, b … *i* are the ages of the different cohorts at the first sample

N is the abundance of scallops as in Eq. 6.1 above

These estimates of Z not only smooth out variation between cohorts but also the annual variation in density found on some grounds (Table 6.4). These values were closer to those expected and showed up some possible differences in fishing effort, in that the inshore diver grounds at the Harbour and Pipe had higher mortalities than further offshore at Petite Canupe. Total mortality was also found to be greater on the diver grounds than the dredge fished ground.

Table 6.4: Estimates of mortality (Z) calculated between 1997 and 1999. Heinke's $Z_{a=3}$ was annual mortality assuming the 3 year olds had recruited to the fishery, whereas $Z_{a=4}$ assumed that only the 4 year olds were considered to have recruited to the fishery.

Site	Heinke $Z_{a=3}$	Heinke $Z_{a=4}$
Harbour	0.86	1.03
Pipe	1.10	1.36
Petite Canupe	0.64	0.79
Anfre	0.33	0.61
Long Bank	0.45	0.53

Further estimates of mortality were also calculated for the Harbour fishing ground from the declining rate of tag returns (Table 6.5). This method also allowed total mortality (Z) to be split into fishing mortality (F) and natural mortality (M). The tagging experiment was fairly successful as not only was tag loss relatively low (~20%), but returns were also very high. Total mortality was similar to that calculated using the method above and natural mortality was in the range found for other *P. maximus* fisheries (Table 6.6) (see Orensanz *et al.*, 1991 for review). Although these estimates were calculated after only two years of tag returns they still provide a good comparison with other methods used to estimate mortality.

Table 6.5: Results of mortality estimated from the tagging experiment on the inshore diver fished grounds.

Number of scallops marked		542
Number marked corrected for tag loss		428
Recaptures in 1998		184
Recaptures in 1999		80
Slope of line = $-Z_t$		-0.833
Log_e of corrected tag releases = R_{tt}		6.047
	Z	**0.83**
	F	**0.64**
	M	**0.19**

Table 6.6: Values of natural mortality (M) that have either been estimated (E) using a variety of methods or used (U) to assess scallop stocks in different fisheries. *These values of M include incidental fishing mortality caused by dredge damage, so the true value of M should be lower (Brand *et al.*, 1991a).

M	Area	Estimated/Used	Source
0.30	Hollyhead Hbr.	E	(Baird, 1966)
0.16	N. Irish Sea	E	(Gruffydd, 1974)
0.11	England/Wales	E	(Franklin *et al.*, 1980b)
0.15	SW Scotland	U	(Mason *et al.*, 1980)
0.39*	N. Irish Sea	E	(Murphy, 1986)
0.15	N. Irish Sea	U	(Murphy and Brand, 1987)
0.61*	N. Irish Sea	E	(Brand *et al.*, 1991a)
0.15	N. Irish Sea	U	(Allison, 1993)

Finally, mortality was also estimated using empirical relationships from the published literature (Table 6.7). Three of these equations were used to estimate natural mortality but only one of them (Eq. 6.10) could be applied to all the fishing grounds as data on reproduction was only available from the Harbour ground. The estimates of natural mortality were slightly higher than found in studies of other fisheries, but total mortality was lower (Brand *et al.*, 1991a; Orensanz *et al.*, 1991). This meant that F, which was calculated by subtracting M from Z, was much lower than expected. Therefore, although these estimates from empirical relationships were a useful indicator of relative differences between scallop fisheries, they do not provide suitably accurate estimates of mortality that can be used for stock assessment. This was most likely due to them being derived from other species of fish and shellfish and not specifically from *P. maximus*.

Table 6.7: Results of calculations of mortality (both M and Z) on Guernsey fishing grounds using published empirical relationships.

			M			Z	F
Area	L_∞	t_{max}	**Taylor**	**Gunderson & Dygert**	**Rikhter**	**Hoening**	**(Z-M)**
Harbour	12.60	8	0.25	0.25	0.17	0.61	0.36
Pipe	12.94	8.6	0.24	-	-	0.57	0.33
Petite Canupe	13.39	10	0.24	-	-	0.50	0.26
Anfre	12.76	8	0.25	-	-	0.61	0.36
Long Bank	13.66	9	0.23	-	-	0.55	0.32
Gaudine	13.27	9.4	0.24	-	-	0.53	0.29
Tautenay	12.81	9.8	0.25	-	-	0.51	0.26
des Ormes	14.44	11.4	0.22	-	-	0.45	0.23

6.3.3 Yield and spawning stock biomass per recruit

Assessment of the scallop stocks in Guernsey was carried out on one of the grounds studied (the Harbour) as this was where most data on mortality and recruitment was collected. Yield per recruit (Y/R) and spawning stock biomass per recruit (SSB/R) were first calculated for three different values of M from 0.15 to 0.25

(Figure 6.1). For the range of values of F studied (0 to 2), the lowest value of M resulted in the highest Y/R and SSB/R and conversely the highest value of M gave the highest Y/R and SSB/R. The F_{max} values (the fishing mortality which results in the maximum yield) were calculated for Y/R curves but all of them resulted in unrealistic values greater than 10. A value of M of 0.2 was used in the remaining stock assessments, as this was roughly the mean of all the estimates from the different methods used. This value was thought to be more accurate for Guernsey populations than the value of 0.15 used in the Isle of Man (Murphy, 1986; Murphy and Brand, 1987; Brand *et al.*, 1991a; Allison, 1993), as predation by crabs and starfish may have been higher. This may be due to the abundance of two large species of crab (*Maja squinado* and *Cancer pagurus*) in Guernsey waters, the first of which is not found in the Irish Sea.

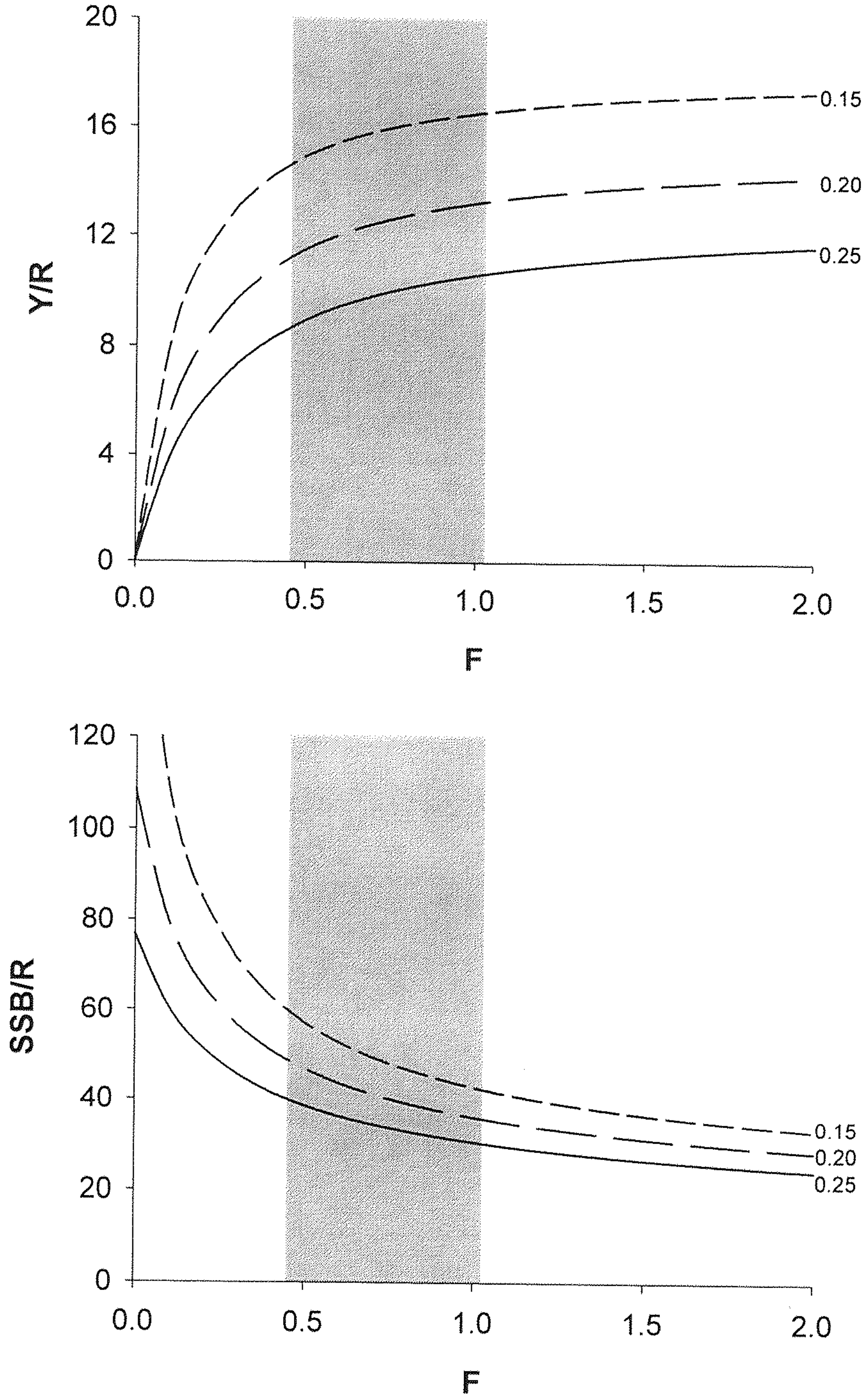


Figure 6.1: Yield per recruit and spawning stock biomass per recruit (grams per recruit) for the Harbour fishing ground. The three lines show the effect of different values of M (0.15, 0.20 & 0.25) on the equations. The shaded box shows the estimated range of current fishing mortality (F).

Figure 6.2 shows the effect of changing length of first capture (or minimum legal landing size) on Y/R and SSB/R on the Harbour ground. Increasing MLS from the current 100mm to 105mm has very little effect on either Y/R or SSB/R. However, further increases to 110mm (as is the case in Jersey) or 115mm results in progressively lower Y/R at the range of values of F studied. Conversely SSB/R increases with length of first capture, as fishing will have a less effect on the scallop stocks.

Although sufficient data were not available for all the fishing grounds studied, an assessment of the stocks was carried out on two of the grounds, the Harbour and des Ormes, to compare the two extremes found in the growth parameters (Figure 6.3). The Harbour had the lowest growth rate found and des Ormes the highest. The analysis of Y/R showed a higher yield at des Ormes compared with the Harbour although the curves were of the same shape and did not reach a maximum within the range of reasonable fishing mortalities studied. Between the values of fishing mortality from 0.5 to 2, yield was approximately 4g per recruit higher at des Ormes. However, SSB/R was virtually identical on the two grounds, only differing at the lower end of fishing mortalities studied. This may have been partly due to using the same data on maturity at age and the length-weight relationship, which were both derived for the Harbour ground.

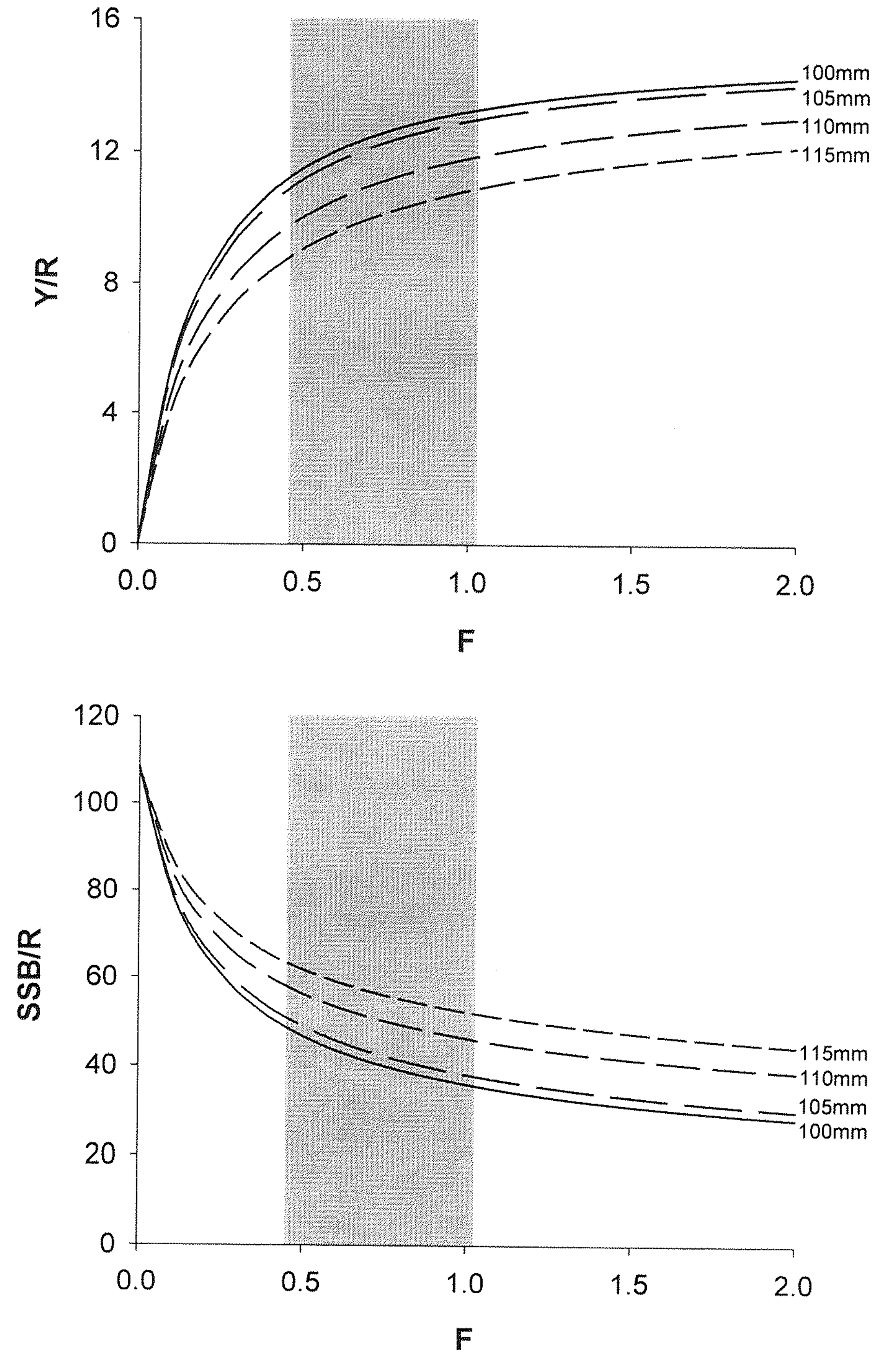


Figure 6.2: Yield per recruit and spawning stock biomass per recruit (grams per recruit) calculated for the Harbour fishing ground (M = 0.2). The four different lines show the effect of increasing the minimum landing size from 100mm to 105mm, 110mm & 115mm in length. The shaded box shows the estimated range of current fishing mortality (F).

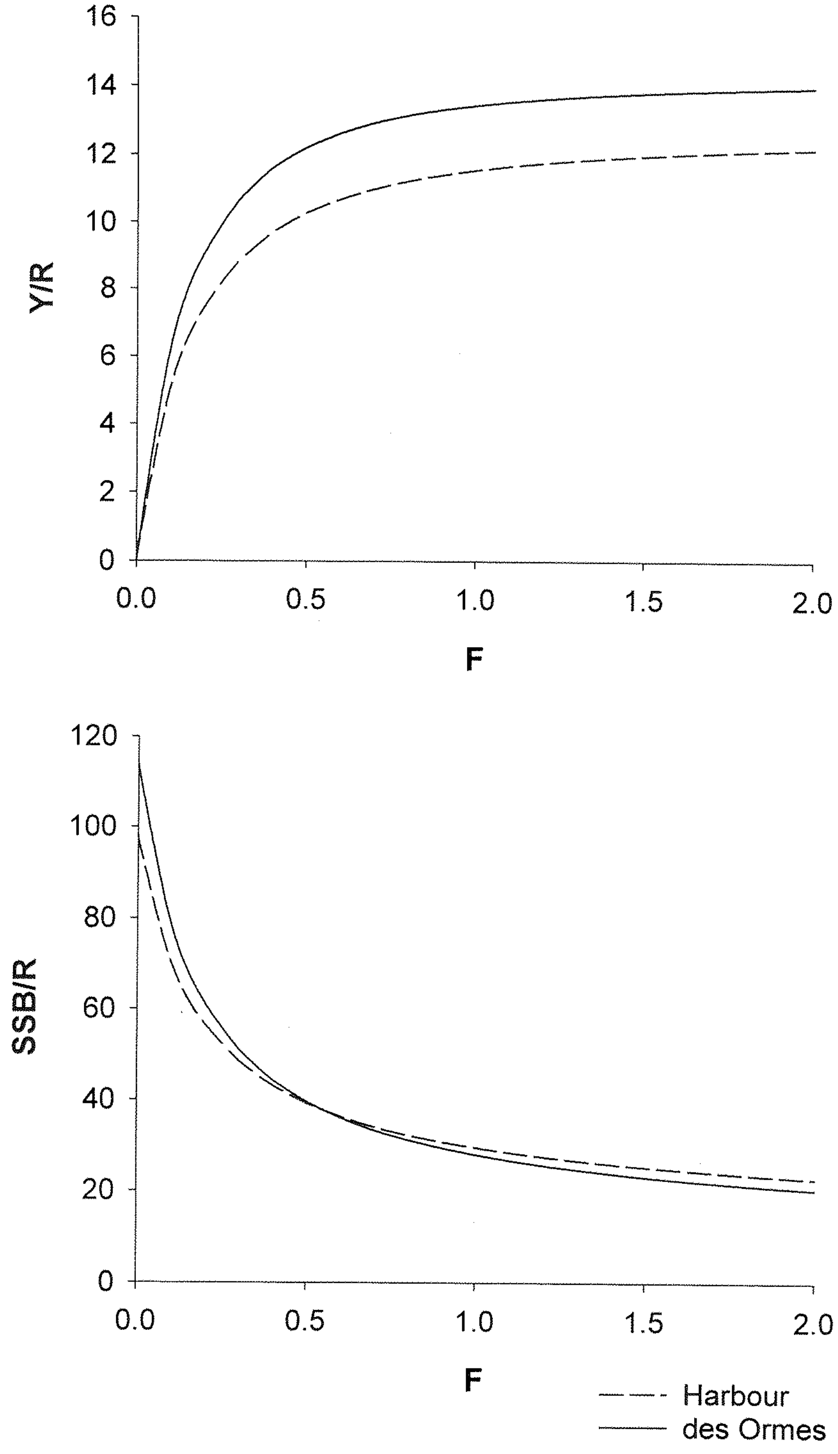


Figure 6.3: Yield per recruit and spawning stock biomass per recruit (grams per recruit) for two different grounds (M = 0.2). These represent the grounds with the highest (des Ormes) and lowest (Harbour) growth rates studied.

6.4 Discussion

The main limitation of this work was in estimating both natural and fishing mortality. Although a variety of methods were used to estimate mortality on the Harbour fishing ground, comparatively little information was available for the other grounds studied. The main method used, that of calculating mortality from the declining abundance of successive age classes, was highly dependent on accurate estimates of density which fluctuated widely over the diver fished grounds. However, despite these problems plausible values of Z from 0.33 to 1.1 for the dive fishery and 0.31 to 0.8 for the dredge fishery, were obtained after ignoring outlying values.

Also, although the tagging study on the Harbour ground did provide good estimates of F and M, the experiment was not specifically designed for this purpose, so assumptions on release date had to be made as only undersized scallops were tagged. The theoretical release date when the tagged scallops were open to exploitation from the fishery would have been different for each individual scallop, as they would reach legal size at different times. If legal sized scallops had been tagged, too many would have been caught in the first few months after release to have been any use in studying growth rates or mortality. A very large number of scallops would have needed to be tagged in order to get a good estimate of mortality, but the resources were simply not available. Another problem with estimating mortality from the tag data was that there was only two years of return data available. Finally, the published empirical relationships used gave reasonable estimates of M and Z, although some other relationships that were calculated from fish stocks gave unrealistic values. This was most likely due to the difference in relative size of the gonad to overall body weight between fish and shellfish. The gonad of *P. maximus* makes up a much greater proportion of the body weight than the gonad of pelagic fish.

The assessments of Y/R and SSB/R relied on information about maturity and weight at age, which was only available for the Harbour fishing ground. Due to the wealth of information for this ground the stock assessments should be very reliable. However, as all the necessary information was not available for the other fishing grounds, the assessment of these grounds was less reliable and therefore Y/R and

SSB/R were only assessed on the Long Bank ground. This was where growth and recruitment differed most to the Harbour ground. Therefore the two extremes of the situations found on Guernsey fishing grounds have been presented.

6.4.1 Mortality and stock assessment on Guernsey fishing grounds

The values of mortality calculated for the Guernsey fishing grounds were of a similar order of magnitude to those found in other fisheries (see Orensanz *et al.*, 1991 for review). The estimate of natural mortality (M) used for stock assessment was 0.2 which was slightly higher than the 0.15 used in similar studies in the North Irish Sea (Murphy, 1986; Murphy and Brand, 1987; Allison, 1993) and Scotland (Mason *et al.*, 1980) (see Table 6.6). However, estimates of M derived from the different methods all indicated that this higher value should be used. Also, the effect of indirect fishing mortality would normally be included in estimates of M derived from a tagging study (Brand, 1991), but here this would be negligible as tagging was only used in the dive fishery. The divers were unlikely to cause a significant amount of incidental mortality as they generally only collected a few scallops which were undersized, these being returned to the sea as soon as they were measured on deck. In a dredge fishery there is likely to be a significant amount of mortality caused by damage from the scallop dredges (see Chapter 5 for examples).

Total mortality (Z) calculated from the decline in abundance of cohorts of scallops varied greatly between the diver fished grounds. This was probably due to large variations in the calculated density as the method used only covered relatively small areas of seabed, so fluctuations due to the patchiness of scallops were not evened out. This would not happen to such an extent in the dredge fishery as larger areas of the seabed were sampled. Mortality was generally greater on the diver fished grounds, which gives an indication of the intensity of this fishing method. Total mortality was also relatively low on the dredged grounds compared with other similar fisheries (Gruffydd, 1972; Bannister, 1986; Mason *et al.*, 1991; Brand and Murphy, 1992). This may be due to the small number of boats exploiting these grounds although some of them were regularly fished (e.g. Tautenay).

Assessment of the scallop stocks in terms of Y/R and SSB/R resulted in curves of similar shape for the different grounds and management options modelled. This indicates that within the range of likely values of F, the scallop stocks were not subject to overfishing. Also, error in estimating the parameters of fishing and natural mortality does not effect the trends found for the range of values used. Reducing fishing effort would result in increases in the spawning stock but with corresponding reduction in yield. In some cases where F was already quite low, an increase in fishing effort could occur to gain a greater yield without having a damaging effect on the spawning stock. These options will be considered in further detail with regard to the different possible management measures (see below).

6.4.2 Management recommendations based on stock assessment

The analysis of management recommendations for scallop fisheries in Guernsey has been based on the stock assessments from the Harbour fishing ground due to the limitations in the available information for other grounds (see above). The most suitable method for managing the fishery following this sort of assessment is to alter minimum landing size as the effects on Y/R and SSB/R can be easily modelled. The other management option is to alter F, either letting it increase to get a better yield or reducing it to prevent overfishing and maintain a sustainable stock. However, fishing mortality can only be indirectly controlled by altering fishing intensity (e.g. by introducing licences, closed seasons etc) and it is more difficult to predict the direct effect of these measures on the scallop stocks.

Although there appears to be no problem with the scallop stocks in the current situation, it was worth assessing the impact of the available management strategies. Therefore the following management options have been considered (Gulland, 1983; Allison, 1993):

- Maintaining F at its current level and increasing MLS
- Maintaining MLS at its current size and altering F
- Increasing MLS and altering F

Increases in F were assessed by considering the value of F_{max}, whereas $F_{0.1}$ was used to assess decreases in F. However, as all the curves reached an asymptote resulting in very high values of F_{max}, attempts to cause F to move towards F_{max} will always result in a decline in Y/R and SSB/R. As the estimates of current values of F on the Harbour fishing ground were quite variable, a range of values from 0.41 to 1.03 were used. The effects of the available management options are summarised in Table 6.8.

Table 6.8: Percentage change in Y/R and SSB/R from the current situation after considering various management options for the Harbour fishing ground. A range of estimated current values of F were used (from 0.41 to 1.03) to assess the effect of the management options. The possibilities were to increase minimum landing size (MLS) while maintaining F at its current level or aiming for $F_{0.1}$.

		MLS			
		100mm	**105mm**	**110mm**	**115mm**
Maintain current F	**Y/R**	0	-3 to -2	-13 to -11	-22 to -18
	SSB/R	0	4 to 6	18 to 29	29 to 46
	$F_{0.1}$	0.4	0.41	0.44	0.47
Aim for $F_{0.1}$	**Y/R**	-1 to -19	0 to -19	2 to -19	5 to -18
	SSB/R	1 to 43	0 to 40	-2 to 27	-3 to 21

Increasing MLS whilst maintaining fishing mortality at its current level will result in decreases in Y/R and increases in SSB/R. The changes will be very small if MLS is changed to 105mm (<6%), yet much greater at 115mm (up to 46%). Percentage change in SSB/R is greater than Y/R for all the different management options considered. Reducing fishing intensity from the current rate to $F_{0.1}$ (0.4) and maintaining the current MLS will result in Y/R dropping by up to 20% and SSB/R increasing by up to 43% depending on the estimate of current F. The larger estimates of fishing mortality result in the greater changes in yield and stock from the current situation as they differ most from the calculated $F_{0.1}$ values.

Attempts to alter fishing mortality to the $F_{0.1}$ level will generally require fishing effort to be reduced. However, for the two larger minimum landing sizes, fishing intensity would need to be increased as the lowest estimates of current fishing effort (0.41) were less than the calculated values of $F_{0.1}$ (0.44 and 0.47) in these cases. The result of both increasing MLS and altering F was generally a reduction in yield by up to 20% and an increase in SSB/R up to 43% greater than the current situation. For the two cases where aiming for $F_{0.1}$ actually results in an increase in fishing effort (MLS of 110mm and 115mm at the lowest estimate of current fishing mortality of 0.41), this gives slight increases in Y/R (<5%) and decreases in SSB/R (<3%). Also the range of different estimates of F gave virtually no difference in yield with increasing MLS, whereas changes in SSB/R were up to twice as great at 100mm compared with a 115mm legal size.

From the available information there was no evidence to suggest that the current management of the scallop fishery in Guernsey should be altered. However, although this work only strictly applies to the Harbour ground, the situation appears to be similar throughout the Guernsey fishery. Further work on mortality rates should be carried out on the other fishing grounds, as well as regular monitoring, in order to identify any potential problems before they become too severe.

7. General Discussion

The overall aim of this work was to assess the state of scallop fisheries in Guernsey, which required various parameters regarding the biology and exploitation of *Pecten maximus* to be calculated for the local fishery. Although a large amount of research has been done on *P. maximus* and its fisheries (see Shumway, 1991 for review), there was considerable variation in growth, reproduction and exploitation between locations. Therefore this work has aimed to fill a gap in the knowledge of *P. maximus* fisheries in Guernsey and provide useful information and recommendations for local fisheries managers. As the results of this work have been discussed in detail at the end of the respective chapters this discussion will cover the limitations and generality of this study. It will also cover the management options and recommendations to the fisheries managers in more detail and the necessity for further work and continued monitoring.

7.1 Limitations

The main limitations with this study have resulted from the work being completed remotely from laboratory facilities and with relatively few resources. Hence, virtually all the fieldwork and sample collection was done on commercial fishing boats during normal fishing activity. Although this meant that areas could not be objectively sampled, the results were more directly related to the fishery than research vessel surveys. It also resulted in the more popular fishing grounds being easily identified and sampled in more detail. However, the disadvantage of this type of work was that the fishermen's behaviour (i.e. grounds fished) could have been influenced by my presence on board. Ideally this work would have been improved if it had been possible to back up the results by doing a combination of sampling on a research vessel (not available in Guernsey) and a commercial boat engaged in normal fishing activity. Indeed this would have made it possible to obtain comparative estimates of density and CPUE for areas that were not normally fished.

The more experimental work, such as the studies of spat settlement, mortality of by-catch and tagged scallops relied heavily on the use of private boats and the States of Guernsey fisheries protection vessel. The lack of available manpower and time meant that all these experiments could not be carried out to the size or extent that was hoped. To be able to carry out a sufficiently large tagging experiment to estimate mortalities on all the fishing grounds would have required a team of people, a fishing boat dedicated to the experiment and sufficient funds to pay for the returned, tagged scallops. As these were not available the resulting experiment was done on the inshore diver fished grounds and was not ideally suited to estimating mortality.

The experiments on the mortality of by-catch and spat settlement were more limited by the lack of suitable laboratory facilities in Guernsey. Therefore survival of commercially important by-catch was studied in storage pots kept in the sea. Although this meant they were less accessible and therefore checked on a less regular basis, the conditions in the storage pots were more closely related to those experienced by discarded by-catch when compared with samples stored in seawater tanks in the laboratory. As for the settlement study, most of the initial sorting of the bags was done either at sea or in the harbour and samples were frozen before being more carefully analysed in the laboratory in Southampton. Again this was extremely labour intensive and therefore the associated settling community of species was not studied as fully as hoped.

The problems encountered with this work were generally logistical ones, with either bad weather preventing fishing and experimental work, or sampling being limited to grounds that were currently popular with the fishermen. Obviously this was difficult to overcome and often resulted in a variable number of replicate samples from different grounds.

Despite these problems and limitations, this work still provided useful information on the scallop fishery in Guernsey, which would be of benefit in managing the fishery. Details of the biology of *P. maximus* in local waters were studied and compared with results obtained in other fisheries. It was found that there was only one main spawning each year at the end of June and that juvenile scallops became sexually mature at the end of their second year. Local settlement of spat of *P. maximus* was found to be very low, although this was only assessed in one year (1998). The growth rates of Guernsey scallops were comparable to those found in the western English Channel (Franklin and Pickett, 1980; Bannister, 1986; Dare, 1991; Bell *et al*., in press), but reached a smaller maximum size than in the Isle of Man (Mason, 1957; Murphy, 1986; Allison, 1994). The tagging experiment showed that growth rings were found to be laid down annually, although the first growth ring was rarely visible. Scallops were generally recruited to the fishery at age three or four at the latest although there was some variation between the grounds studied. Recruitment was also found to be highly variable with evidence of strong recruitment in some years (e.g. 1990) and the fishery becoming heavily reliant on the recruiting age class at the end of the study.

The study of the effects of scallop dredging on commercially important by-catch showed that although generally relatively small numbers were caught, most of the discarded by-catch would die. Diver fishermen were found to subject themselves to increased risks in the pursuit of greater catches, as they would catch more scallops on deeper dives. The final section of this study aimed to assess the current state of the fishery and the need for further management. Values of natural mortality were obtained that were slightly higher that in other *P. maximus* fisheries (Orensanz *et al.*, 1991) and fishing mortality was thought to be lower (M=0.2, F=0.4 to 1.0).

7.2 Generality of this work

This work on the fished populations in Guernsey was an initial study of a small local fishery. Very little previous work has been done on this fishery and there was no information available on the growth or reproduction on *P. maximus* in local waters. However, there has been a significant amount of research done on *P. maximus* on the south coast of England and in the St. Brieuc Bay on the French coast to the south of the island. Indeed, the growth curves calculated for the Guernsey population were very similar to those found in scallops from the western English Channel (Franklin and Pickett, 1980; Dare, 1991; Chauvaud *et al.*, 1998; Bell *et al.*, in press). Similarity has also been found in the reproductive season as there was one main spawning in the middle of the summer which has also been found in other populations nearby (Dao *et al.*, 1975; Thouzeau and Lehay, 1988; Thouzeau, 1991). This has not been the case in the North Irish Sea where two peaks in spawning have been found in some years (Mason, 1958), whereas in others only one occurs (Allison, 1993; Wanninayake, 1994).

The results of scallop density and CPUE from this study have given estimates of a similar order of magnitude to work done on other *P. maximus* fishing grounds using similar methods (Orensanz *et al.*, 1991). This was the case for fished grounds from Scotland (Mason, 1982) down to the St. Brieuc Bay (Thouzeau, 1991). However, the very dense patches (5-6 m^{-2}) found in the English Channel (Franklin *et al.*, 1980b) did not occur on the Guernsey fishing grounds studied. This was most likely due to unfished grounds being sampled in the English Channel, which was not done in this study.

Compared with fisheries for other species of scallops around the world, densities of scallops on *P. maximus* fishing grounds were generally lower than elsewhere. For example, in the fishery for *Chlamys tehuelcha*, divers choose beds with a density of 40-60 scallops per m^{-2} and moved to other grounds when the density fell below 20 scallops per m^{-2} (Orensanz, 1986). However, this is a much smaller species and would need to be caught in greater numbers to obtain a profitable catch. A scallop similar in size to *P. maximus*, *Placopecten megellanicus*, occurs on the Georges Bank at densities at least 10 times greater than on most *P. maximus* fishing grounds (Caddy, 1975). This area does, however, support a very productive fishery due to the high abundance of large scallops.

Mortality estimates from this study were also similar to those found in other *P. maximus* fisheries as well as other scallop species (Orensanz *et al.*, 1991). The main difference in this work was that natural mortality (M) was generally found to be higher than the value of 0.15 found for other fished populations such as in the North Irish Sea (Murphy, 1986; Murphy and Brand, 1987; Brand and Murphy, 1992; Allison, 1993) and in Scotland (Mason *et al.*, 1980). This may be due to larger numbers of predators in Guernsey, such as the spider crab *Maja squinado* which is not found in the Irish Sea or off Scotland. Therefore a value of M of 0.2 was used in the assessment of the scallop populations in Guernsey. Estimates of fishing mortality (F) were derived from the change in density of cohorts over time and resulted in a wide variation between both years and grounds. This was partly due to variations between age classes as the older ones were fully recruited to the fishery and therefore would suffer higher mortality rates. Indeed natural mortality would also vary between age classes with the younger ones suffering high mortality from predation (Thouzeau and Lehay, 1988) and the older ones dying from disease and other natural causes.

This variability in F may have also been due to variations in the strength of recruitment in different years. If the population were being recruited from a different parent stock then the larvae would need to be carried by currents to the local fishing grounds. This is a likely situation due to the number of scallop populations in the English Channel (Dare *et al.*, 1994a) and the strength of local tidal currents. These currents or the timing of spawning may be altered by variations in the climate resulting in different levels of annual recruitment. Therefore there is a need to investigate water movement and larval behaviour to predict where newly recruited scallops have come from. The use of genetic methods to identify the parent stock would provide confirmation of this important information. Indeed proof that the population is being recruited from outside the local fishing ground would help explain the lack of a stock recruitment relationship which is the case for many other scallop fisheries (Mason, 1983; Sinclair *et al.*, 1985). Recruitment overfishing is also a possibility in low density populations like this (Dredge, 1988), but it is unlikely in the case of the Guernsey fishery.

The assessment of Y/R and SSB/R of Guernsey scallop populations showed that from the information available, the stocks were not subject to overfishing. This was probably due to the low intensity of local fishing as other *P. maximus* fisheries have suffered from declining stocks and yield (e.g. the inshore grounds off the Isle of Man Allison, 1993).

A small island fishing industry like the scallop fishery in Guernsey has benefits as well as problems when compared with larger fisheries such as in the rest of the English Channel. The main benefit is that fishing effort can be more easily controlled, especially if fisheries managers have jurisdiction over their territorial waters, as is the case in Guernsey. This means that non-local boats can be prevented from fishing on inshore grounds where stocks can be preserved for the local fleet. Also, in a small fishery there is less possibility of a large influx of boats if there is a boom in the fishery. Indeed this problem occurred in Cardigan Bay where newly found scallop stocks quickly attracted a large fleet which led to the collapse of the fishery within a couple of years (Bannister, 1986).

One of the problems often associated with a small scale fishery is a lack of research due to its relative unimportance. This preliminary work is required to effectively manage the fishery by applying appropriate restrictions before stocks collapse. This same problem occurs in many new fisheries as fishermen will be attracted in before managers have the chance to carry out research to protect the stock. Indeed it has often been the case that research into a fishery does not take place until stocks are in decline. However, at this late stage there is often very little managers can do apart from closing the fishery (Bannister, 1986). For this reason it is important to do initial baseline research on the species and the fishery before problems from overfishing develop. This is where cost effective research like this is useful as it can be carried out on emerging fisheries and can be used to determine whether more research is required.

7.3 Management options for the Guernsey scallop fishery

The effect of different management options in terms of altering MLS or fishing mortality (F) have been assessed in chapter six. Yield per recruit (Y/R) was calculated rather than total yield as this takes into account the variability in recruitment of scallops to the fishery. If there is a failure in recruitment then the yield from the stock may also crash especially if the fishery is reliant on the recruiting age class (Orensanz, 1986). Therefore the methods used are most applicable to a fishery which is in a steady state, much like the Guernsey scallop industry which has changed little in over 20 years. The weakest links in this analysis were due to imperfections in the information gathered from the fishery, such as the estimates of natural mortality and age at recruitment. Error in these estimations will result in large variations in Y/R and hence a range of values of natural mortality have been used to produce a set of possible curves. Once the yield has been suitably assessed there are further problems to be overcome, as there are many possible methods available to fisheries managers to alter and maintain F at a suitable level for the fishery (see Chapter 1 for review).

As there is currently no regulation of fishing effort of the Guernsey scallop fleet the most practical option in the event of declining stocks would be to increase MLS. This precautionary approach would bring the Guernsey fishery in line with Jersey and would eventually result in only a small decline in yield but a significant increase in the spawning stock. Increasing MLS though would cause a dramatic reduction in yield over the following year, as the inshore fishery is heavily reliant on the recruiting size classes. This increase would mean that scallops that had reached the old MLS of 100mm would require almost another season to grow to 110mm in length. The resulting low yield from the fishery during the change over period could severely effect the livelihood of the fishermen currently involved and they may be forced to leave the industry. Therefore a better solution would be to gradually increase MLS over a two to four year period which would give much smaller initial decline in yield yet the same desired long term increase in SSB/R.

The other main option available to protect the fishery is to reduce the amount of fishing effort and hence lower fishing mortality. A safe option is to reduce fishing mortality to the $F_{0.1}$ level although it is often difficult to determine how much to reduce fishing effort by to get the desired effect on F. There are many possible methods used to control effort although the most widely used involve regulating the size of the fishing gear/boats or imposing a closed season. The latter of these has been successfully used in the Isle of Man (Brand, 1993) and would be the simplest to implement and regulate in the Guernsey fishery.

The most sensible timing for a closed season would be for a relatively short period (2 – 3 months) between May and September as this would protect the stocks during spawning. This would allow the newly recruited three year old scallops a full spawning season before they were susceptible to the fishery. However, this option would cause more problems for the fishermen, especially the divers, as they would be unable to fish for other species during the closed season and would effectively be out of work for this period every year. Therefore a more workable solution would be to introduce rotational closures where certain grounds would be closed to fishing at different times of the year. For example, for the divers the inshore grounds at the Harbour and Pipe could be closed for a few months over the summer and the further offshore grounds at Petite Canupe closed during the winter. This would allow the divers to continue fishing all year yet still protect the stocks on the inshore grounds during spawning and reduce overall effort. However, this option would be more difficult to regulate than the simple closed season although the effect on lowering fishing effort would be similar.

As there currently appears to be no need to reduce fishing effort, an approach to prevent an increase in effort would be a better way to manage the fishery. Therefore the most appropriate option here would be to introduce a limited number of both scallop dive and dredge fishing licences. This would mean that no new fishermen could enter the fishery unless it was shown that the stocks could cope with an increase in effort. The number of licences available would be difficult to determine although all fishermen currently involved in the scallop fishery could be issued with one as their numbers have not varied greatly in recent years. Additional licences could be issued if the yield could be increased without having a damaging effect on the stock. However, the requirement for scallop diver licences in Guernsey has recently been removed although the total number was not limited in the past. Scallop divers require licences in both Sark and Jersey; those for the latter are divided into professional or recreational divers (limited to 24 scallops per day). This would give fisheries managers more control if further regulation is required in the future, without interfering with the livelihood of the current fishermen. Finally, in a licensed fishery, catch quotas could also be used as a further means of regulation although these would require annual surveys in order to estimate stock abundance. However, these would probably be too expensive to carry out on the small scale fishery in Guernsey and quotas would also prove difficult to enforce. At the current state of the fishery this would also be unnecessary.

One final area to be considered in managing the fishery is to actually enhance the productivity of the fishing grounds rather than conserving the stock through restrictive methods. The most common way to achieve this is by restocking the seabed with juvenile scallops either collected from the wild using spat collectors or grown in aquaculture. Indeed, the Department of Fisheries in Jersey restocked some of their inshore grounds in 1997 due to declining catches in these heavily fished areas. This initial restocking has proved successful with the larger individuals reaching minimum size by the end of December 1999 and with no massive losses due to the influx of predators (G. Morell, pers. comm.). The most successful example of restocking scallop beds was done in Mutsu Bay, Japan which resulted in spectacular increases in the settlement rate (Ventilla, 1982). Therefore restocking is probably a viable option to enhance the stocks, especially for the inshore diver fished grounds, although the costs of buying spat would need to be considered.

If restocking is to be carried out the spat are most likely to come from other populations, as collecting locally produced spat was not found to be viable due to low settlement rates. Therefore the genetic consequences of introducing spat from a different population must be carefully considered, as when they reach sexual maturity they will be able to freely interbreed with the local scallop population. For example, a population from further south than Guernsey may have different temperature tolerances and its growing season could be significantly reduced in the colder local waters. This genetic trait could be introduced into the local population and result in scallops reaching the minimum landing size at an older age, which would have a detrimental effect on the fishery. This problem may have already been introduced as scallop grounds in Jersey were reseeded with spat from Mulroy Bay, which have since reached reproductive age. This population is known to have a low genetic diversity and is genetically isolated from other Irish populations (A. Brand, pers. comm.). There is also the possibility that the spat could be diseased or contain parasites which could result in these pests being accidentally introduced (Minchin, 1996). Therefore the safest option would be to reseed grounds using spat artificially produced in aquaculture from locally collected adult scallops.

7.4 Future work

The most important consideration for managing the fishery is to continue monitoring the stocks so that any declines are noticed before recovery becomes impossible. Annual samples of the abundance of age classes in the catch would provide suitable data for managing this small scale fishery. Therefore it is recommended that annual surveys should be done either by chartering a commercial fishing vessel or by carrying out an independent assessment. This information should be combined with detailed landing statistics to provide an overall picture of the current state of the fishery. In the first instance, scallop landing statistics could be compiled from the voluntary logbook scheme which was recently introduced, but in the future it would be better to introduce a logbook more suited to the scallop fishery. This logbook should include information about fishing effort (e.g. number of dives per day or number of hours of dredging) and the locations that were fished, as well as the total catch per day. These logbooks could be introduced to the scallop fishermen on a voluntary basis and eventually made a condition of a scallop fishing licence.

Further analysis of local spat fall would provide useful information on the variability of settlement and could be used to assess the need for reseeding if poor natural recruitment occurs. Continued monitoring of the amount of scallop dredging in local waters should also be done, especially if more boats are attracted to the fishery. This would be beneficial to assess the need to control the amount of seabed fished as dredging can have a detrimental effect on the scallop stocks as well as other commercial fish species and the marine benthos.

Other further work that could be carried out would be to assess the abundance and damage to benthic species not caught in the scallop dredges. This would need to be done by diver surveys of areas of seabed that had recently been fished. This work would help provide an overall estimate of the numbers of by-catch species killed by scallop dredging on local fishing grounds. Diver surveys of both dive and dredge fished areas could be made to assess the impact of scallop dredging as well as provide comparable estimates of scallop density on the major fishing grounds.

References

Acosta, C. P. and Roman, G., (1994). Growth and reproduction in a southern population of scallop *Pecten maximus*. In *9th International Pectinid Workshop* (eds. N. F. Bourne, B. L. Bunting and L. D. Townsend), pp. 119-126. April 22-27, 1993, Nanaimo, B.C., Canada.

Allison, E. H., (1993). The dynamics of exploited populations of scallops (*Pecten maximus* L.) and queens (*Chlamys opercularis* L.) in the North Irish Sea. Phd Thesis, University of Liverpool.

Allison, E. H., (1994). Seasonal growth models for great scallops (*Pecten maximus* (L.)) and queen scallops (*Aequipecten opercularis* (L.)). *Journal of Shellfish Research*, **13**, 555-564.

Allison, E. H. and Brand, A. R., (1995). A mark-recapture experiment on queen scallops, *Aequipecten opercularis*, on North Irish Sea fishing grounds. *Journal of the Marine Biological Association of the United Kingdom*, **75**, 323-335.

Allison, E. H., Wilson, U. A. W. and Brand, A. R., (1994). Age determination and the first growth ring in North Irish Sea populations of the scallop, *Pecten maximus* (L.). *Journal of Molluscan Studies*, **60**, 91-95.

Ansell, A. D., Dao, J. C. and Mason, J., (1991). Three European scallops: *Pecten maximus*, *Chlamys (Aequipecten) opercularis* and *C. (Chlamys) varia*. In *Scallops: biology, ecology and aquaculture* (ed. S. E. Shumway), pp. 715-751. Elsevier, Amsterdam.

Askew, C. G., Dunn, M. R. and Reay, A., (1973). The Fishery for Queen Scallops in Guernsey. Portsmouth Polytechnic Marine Resources Unit.

Aylmer, A., (1998). Hands off those summertime scallops! In *Diver*, vol. Jan 1998, p. 45.

Baird, R. H., (1966). Notes on an escallop (*Pecten maximus*) population in Holyhead Harbour. *Journal of the Marine Biological Association of the United Kingdom*, **46**, 33-47.

Baird, R. H. and Gibson, F. A., (1956). Underwater observations on escallop (*Pecten maximus* L.) beds. *Journal of the Marine Biological Association of the United Kingdom*, **35**, 555-562.

Bannister, R. C. A., (1986). Assessment and population dynamics of commercially exploited shellfish in England and Wales. In *North Pacific Workshop on stock assessment and management of invertebrates*, vol. 92 (eds. G. S. Jamieson and N. Bourne), pp. 182-194.

Barber, B. J. and Blake, N. J., (1991). Reproductive physiology. In *Scallops: biology, ecology and aquaculture* (ed. S. E. Shumway), pp. 377-420. Elsevier, Amsterdam.

Beaumont, A. R. and Barnes, D. A., (1992). Aspects of veliger growth and byssus drifting of the spat of *Pecten maximus* and *Aequipecten* (*Chlamys*) *opercularis*. *ICES Journal of Marine Science*, **49**, 417-423.

Bell, M. C., Palmer, D. W. and Dare, P. J., (in press). Shell growth patterns in *Pecten maximus* L. (Bivalvia: Pectinidae) from the English Channel, Western approaches and Irish Sea.

Beninger, P. G. and Le Pennec, M., (1991). Functional anatomy of scallops. In *Scallops: biology, ecology and aquaculture* (ed. S. E. Shumway), pp. 133-209. Elsevier, Amsterdam.

Beverton, R. J. H. and Holt, S. J., (1957). On the dynamics of exploited fish populations. *Fish. Invest. Minist. Agric. Fish. Food U.K. (Series 2)*, **No.19**, 533pp.

Bourne, N., (1991). Fisheries and aquaculture: west coast of north America. In *Scallops: biology, ecology and aquaculture* (ed. S. E. Shumway), pp. 925-942. Elsevier, Amsterdam.

Brand, A. R., (1976). Pectinid settlement on artificial collectors: initial results of the Wolfson Foundation Scallop Cultivation Project at Port Erin, Isle of Man. In *1st International Pectinid Workshop*, Baltimore, Ireland.

Brand, A. R., (1991). Scallop ecology: distributions and behaviour. In *Scallops: biology, ecology and aquaculture* (ed. S. E. Shumway), pp. 517-584. Elsevier, Amsterdam.

Brand, A. R., (1993). Scallop and queen fisheries - a summary of the current situation (January, 1993). Port Erin Marine Laboratory, University of Liverpool.

Brand, A. R. and Allison, E. H., (1987). The Isle of Man fishery for the queen scallop, *Chlamys opercularis*. In *6th International Pectinid Workshop*, pp. 11, Menai Bridge, Wales.

Brand, A. R. and Allison, E. H., (1994). Estimating abundance on north Irish Sea scallop, *Pecten maximus* (L.), fishing grounds. In *9th International Pectinid Workshop* (eds. N. F. Bourne, B. L. Bunting and L. D. Townsend), pp. 121-130. April 22-27, 1993, Nanaimo, B.C., Canada.

Brand, A. R., Allison, E. H. and Murphy, E. J., (1991a). North Irish Sea scallop fisheries: a review of changes. In *An international compendium of scallop biology and culture* (eds. S. E. Shumway and P. A. Sandifer), pp. 204-218. World Aquaculture Society, Baton Rouge.

Brand, A. R. and Hawkins, S. J., (1996). Assessment of the effects of scallop dredging on benthic communities. Interim Progress Report to MAFF. Port Erin Marine Laboratory, University of Liverpool.

Brand, A. R. and Murphy, E. J., (1992). A tagging study of North Irish Sea scallop (*Pecten maximus*) populations: comparisons of an inshore and an offshore fishing ground. *Journal of Medical and Applied Malacology*, **4**, 153-164.

Brand, A. R., Paul, J. D. and Hoogesteger, J. N., (1980). Spat settlement of the scallops *Chlamys opercularis* (L.) and *Pecten maximus* (L.) on artificial collectors. *Journal of the Marine Biological Association of the United Kingdom*, **60**, 379-390.

Brand, A. R., Wilson, U. A. W., Hawkins, S. J., Allison, E. H. and Duggan, N. A., (1991b). Pectinid fisheries, spat collection, and the potential for stock enhancement in the Isle of Man. In *ICES Symposium on Ecology and Management Aspects of Extensive Mariculture*, pp. 79-86. 20-23 Jun 1989, Nantes (France).

Bricelj, V. M. and Shumway, S., (1991). Physiology: energy acquisition and utilization. In *Scallops: biology, ecology and aquaculture* (ed. S. E. Shumway), pp. 305-346. Elsevier, Amsterdam.

Briggs, R. P., (1991). A study of the Northern Ireland fishery for the escallop *Pecten maximus* (Linnaeus 1758). In *An international compendium of scallop biology and culture* (eds. S. E. Shumway and P. A. Sandifer). World Aquaculture Society, Baton Rouge.

Bruce, J. R., Colman, J. S. and Jones, N. S., (1963). Marine fauna of the Isle of Man. University Press, Liverpool.

Buestel, D., Dao, J. C. and Lemarie, G., (1979). Collection of pectinid spat in Brittany. (Collectes du naissain de pectinides en Bretagne). *Rapport et Procès-Verbaux des Réunions. Conseil International pour l'Exploration de la mer*, **175**, 80-84.

Bull, M. F., (1989). The New Zealand scallop fishery: a brief review of the fishery and its management. In *Proceedings of the Australian Scallop Workshop* (eds. M. C. L. Dredge, W. F. Zacharin and L. M. Joll), pp. 42-50, Hobart, Australia.

Caddy, J. F., (1973). Underwater observations on tracks of dredges and trawls and some effects of dredging on a scallop ground. *Journal of the Fisheries Research Board of Canada*, **30**, 173-180.

Caddy, J. F., (1975). Spatial model for an exploited shellfish population, and its application to the Georges Bank scallop fishery. *Journal of the Fisheries Research Board of Canada*, **32**, 1305-1328.

Caddy, J. F., (1989). A perspective on the population dynamics and assessment of scallop fisheries, with special reference to the sea scallop *Placopecten magellanicus* Gmelin. In *Marine Invertebrate Fisheries: their assessment and management* (ed. J. F. Caddy), pp. 559-589. Wiley.

Carbone, C. and Houston, A. I., (1994). Patterns in the diving behaviour of the pochard, *Aythya ferina*: a test of an optimality model. *Animal Behaviour*, **48**, 457-465.

Cashmore, D., Learmouth, M. M. and MacMillan, J. T., (1998). Improving the efficiency of wild *Pecten maximus* spat collection: potential effects of spat bag design and of species temporarily settling in spat bags. *Aquaculture*, **160**, 273-282.

Chapman, C. J., Mason, J. and Kinnear, J. A. M., (1977). Diving observations on the efficiency of dredges used in the Scottish fishery for the scallop, *Pecten maximus* (L.). Scottish Fisheries Research Report, No. 10.

Chauvaud, L., Thouseau, G. and Grall, J., (1996). Experimental collection of great scallop postlarvae and other benthic species in the Bay of Brest: settlement patterns in relation to spatio-temporal variability of environmental factors. *Aquaculture International*, **4**, 263-288.

Chauvaud, L., Thouzeau, G. and Paulet, Y., (1998). Effects of environmental factors on the daily growth of *Pecten maximus* juveniles in the Bay of Breast (France). *Journal of Experimental Marine Biology and Ecology*, **227**, 83-111.

Cochard, J. C. and Devauchelle, N., (1993). Spawning, fecundity and larval survival and growth in relation to controlling in native and transplanted populations of *Pecten maximus* (L.): evidence for the existence of separate stocks. *Journal of Experimental Marine Biology and Ecology*, **169**, 41-56.

Comely, C. A., (1972). Larval culture of the scallop *Pecten maximus* (L.). *Journal du Conseil International pour l'Exploration de la Mer*, **34**, 365-378.

Connor, P. M., (1978). Seasonal variation in meat yield of scallops (*Pecten maximus*) from the south coast (Newhaven) of England. International Council for the Exploration of the Sea CM 1978/K:8.

Currie, D. R. and Parry, G. D., (1996). Effects of scallop dredging on a soft sediment community: a large-scale experimental study. *Marine Ecology Progress Series*, **134**, 131-150.

Cushing, D. H., (1968). Fisheries Biology. The University of Wisconsin Press, London.

Cushing, D. H., (1995). Population Production and Regulation in the Sea: a Fisheries Perspective. University Press, Cambridge.

Dao, J. C., Laurec, A. and Buestel, D., (1975). Application de la dynamique des populations au gisement de coquilles St. Jacques de la Baie de St. Brieuc. Recherche d'un modele bio-economique. In *Economie et Problemes des Peches Locales, OCDE*, pp. 165-171.

Dare, P. J., (1991). The use of shell microgrowth patterns for determining growth and age in the scallop, *Pecten maximus* (L.). In *8th International Pectinid Workshop*. 22nd-29th May, 1991, Cherbourg, France.

Dare, P. J., Darby, C. D., Durance, J. A. and Palmer, D. W., (1994a). The distribution of scallops, *Pecten maximus*, in the English Channel and Celtic Sea in relation to hydrographic and substrate features affecting larval dispersal and settlement. In *9th International Pectinid Workshop* (eds. N. F. Bourne, B. L. Bunting and L. D. Townsend), pp. 20-27. April 22-27, 1993, Nanaimo, B.C., Canada.

Dare, P. J. and Deith, M. R., (1989). Age determination of scallops, *Pecten maximus* (L.), using stable oxygen isotope analysis, with some implications for fisheries management in British waters. In *7th International Pectinid Workshop*, pp. 15, Portland, Maine, USA.

Dare, P. J. and Deith, M. R., (1991). Age determination of scallops, *Pecten maximus* (Linnaeus, 1758), using stable oxygen isotope analysis, with some implications for fisheries management in British waters. In *An international compendium of scallop biology and culture* (eds. S. E. Shumway and P. A. Sandifer), pp. 118-133. World Aquaculture Society, Baton Rouge.

Dare, P. J., Palmer, D. W., Howell, M. L. and Darby, C. D., (1994b). Experiments to assess the relative dredging performances of research and commercial vessels for estimating the abundance of scallops (*Pecten maximus*) in the western English Channel fishery. Fisheries Research Techical Report, No. 96, MAFF.

de Groot, S. J. and Apeldoorn, J. M., (1971). Some experiments on the influence of the beam-trawl on the bottom fauna. International Council for the Exploration of the Sea CM 1971/B:2.

Devauchelle, N. and Mingant, C., (1991). Review of the reproductive physiology of the scallop, *Pecten maximus*, applicable to intensive aquaculture. *Aquatic Living Resources*, **4**, 41-51.

Dintheer, C., Lemoine, M., Latrouite, D., Berthou, P., Delpech, J. P., Morizur, Y. and Tetard, A., (1995). Les grands metiers de Manche: reflexions et propositions pour la conservation de la ressource et la gestion des pecheries. *La Peche Maritime*, **7488**, 181-195.

Dredge, M. C. L., (1985). Estimates of natural mortality and yield per recruit for *Amusium japonicum balloti* Bernardi (Pectinidae) based on tag recoveries. *Journal of Shellfish Research*, **5**, 103-109.

Dredge, M. C. L., (1988). Recruitment overfishing in a tropical scallop fishery. *Journal of Shellfish Research*, **7**, 223-239.

Dredge, M. C. L., (1994). Modelling management measures in the queensland scallop fishery. *Memoirs of the Queensland Museum*, **36**, 277-282.

Drinkwater, K. F. and Myers, R. A., (1987). Testing predictions of marine fish and shellfish landings from environmental variables. *Canadian Journal of Fisheries and Aquatic Sciences*, **44**, 1568-1573.

Edwards, E., (1995). Europe's shell fisheries. In *World Fishing Industry Review*, pp. 46-48.

Eleftheriou, A. and Robertson, M. R., (1992). The effects of experimental scallop dredging on the fauna and physical environment of a shallow sandy community. *Netherlands Journal of Sea Research*, **30**, 289-299.

Engel, J. and Kvitek, R., (1998). Effects of otter trawling on a benthic community in Monterey Bay National Marine Sanctuary. *Conservation Biology*, **12**, 1204-1214.

Faveris, R. and Lubet, P., (1991). Energetic requirements of the reproductive cycle in the scallop *Pecten maximus* (Linnaus, 1758) in Baie de Seine (Channel). In *World Aquaculture Workshops 1, World Aquaculture Society,* (eds. S. E. Shumway and P. A. Sandifer), pp. 67-73, Baton Rouge, U.S.A.

Fifas, S., Jezequel, M. and Cropp, D. A., (1991). Age composition of catches from the scallop stock (*Pecten maximus*, L.) in the Saint-Bruieuc Bay (English Channel, France). Estimation of variances and bias. Stochastic virtual population analysis. International Council for the Exploration of the Sea, Statutory Meeting 1991/D:28, Ref K.

Franklin, A. and Pickett, G. D., (1980). Shell growth increments in scallops (*Pecten maximus*) from the English Channel. International Council for the Exploration of the Sea CM 1980/K:13.

Franklin, A., Pickett, G. D. and Connor, P. M., (1980a). The scallop (*Pecten maximus*) and its fishery in England and Wales. M.A.F.F Laboratory Leaflet, **51**, 19pp.

Franklin, A., Pickett, G. D., Holme, N. A. and Barrett, R. L., (1980b). Surveying stocks of scallops *Pecten maximus* and queens *Chlamys opercularis* with underwater television. *Journal of the Marine Biological Association of the United Kingdom*, **60**, 181-192.

Fuentes, H. R., (1994). Population and biology of the commercial scallop (*Pecten fumatus*) in Jervis Bay, NSW. *Memoirs of the Queensland Museum*, **36**, 247-259.

Gallucci, V. F. and Quinn, T. J., (1979). Reparameterizing, fitting, and testing a simple growth model. *Transactions of the American Fisheries Society*, **108**, 14-25.

Gibson, F. A., (1956). Escallops (*Pecten maximus* L.) in Irish waters. *Scientific Proceedings of the Royal Dublin Society*, **27**, 253-271.

Gillis, D. M., Pikitch, E. K. and Peterman, R. M., (1995). Dynamic discarding decisions: foraging theory for high-grading in a trawl fishery. *Behavioural Ecology*, **6**, 146-154.

Gruffydd, L. D., (1972). Mortality of scallops on a Manx bed due to fishing. *Journal of the Marine Biological Association of the United Kingdom*, **52**, 449-455.

Gruffydd, L. D., (1974). An estimate of natural mortality in an unfished population of the scallop *Pecten maximus* (L.). *Journal du Conseil International pour l'Exploration de la Mer*, **35**, 209-210.

Gulland, J. A., (1977). Fish Population Dynamics. John Wiley & Sons, Bath.

Gulland, J. A., (1983). Fish Stock Assessment. The Bath Press, Avon.

Gunderson, D. R. and Dygert, P. H., (1988). Reproductive effort as a predictor of natural mortality rate. *Journal du Conseil International pour l'Exploration de la Mer*, **44**, 200-209.

Guo, X., Ford, S. E. and Zhang, F., (1999). Molluscan aquaculture in China. *Journal of Shellfish Research*, **18**, 19-31.

Heinke, F., (1913). Investigations on the Plaice. I. Plaice fishing and protection measures. *Rapport et Proces-Verbaux des Reunions. Conseil International pour l'Exploration de la mer*, **16**, 1-70.

Helyar, M., (1995a). Report of the Guernsey Fishing Industry, 1994. Department of Fisheries, Guernsey.

Helyar, M., (1995b). A survey of Guernsey scallop divers. Department of Fisheries, Guernsey.

Hennessy, T., (1988). BSAC '88 Decompression Tables. The British Sub-Aqua Club.

Hill, A. S., Brand, A. R., Wilson, U. A. W., Veale, L. O. and Hawkins, S. J., (1996). Estimation of by-catch composition and the numbers of by-catch animals killed annually on Manx scallop fishing grounds. In *Aquatic Predators and their Prey* (eds. S. P. R. Greenstreet and M. L. Tasker), pp. 111-115. Fishing News Books, Farnham.

Hill, A. S., Veale, L. O., Pennington, D., Whyte, S. G., Brand, A. R. and Hartnoll, R. G., (1999). Changes in Irish Sea benthos: possible effects of 40 years of dredging. *Estuarine, Coastal and Shelf Science*, **48**, 739-750.

Hoening, J. M., (1983). Empirical use of longevity data to estimate mortality rates. *Fishery Bulletin (USA)*, **81**, 898-903.

Houston, A. I. and Carbone, C., (1992). The optimal allocation of time during the diving cycle. *Behavioral Ecology*, **3**, 255-265.

IFREMER, (1992). La coquille Saint-Jacques (*Pecten maximus*).

Iribarne, O. O., Lasta, M. I., Vacas, H. C., Parma, A. M. and Pascual, M. S., (1991). Assessment of abundance, gear efficiency and disturbance in a scallop dredge fishery: results of a depletion experiment. In *An international compendium of scallop biology and culture* (eds. S. E. Shumway and P. A. Sandifer), pp. 242-248. World Aquaculture Society, Baton Rouge.

Jennings, S. and Kaiser, M. J., (1998). The effects of fishing on marine ecosystems. *Advances in Marine Biology*, **34**, 119 pp.

Joll, L. M., (1989). History, biology & management of Western Australian stocks of the saucer scallop Amusium balloti. In *Proceedings of the Australian Scallop Workshop* (eds. M. C. L. Dredge, W. F. Zacharin and L. M. Joll), pp. 30-41, Hobart, Australia.

Jones, R., (1958). Lee's phenomenon of "apparent change in growth-rate" with particular reference to haddock and plaice. *International Commission for the Northwest Atlantic Fisheries, Special Publication*, **1**, 229-242.

Kaiser, M. J., (1996a). The effects of beam-trawl disturbance on infaunal communities in different habitats. *Journal of Animal Ecology*, **65**, 348-358.

Kaiser, M. J., (1996b). Starfish damage as an indicator of trawling intensity. *Marine Ecology Progress Series*, **134**, 303-307.

Kaiser, M. J., (1998). Significance of bottom-fishing disturbance. *Conservation Biology*, **12**, 1230-1235.

Kaiser, M. J., Armstrong, P. J., Dare, P. J. and Flatt, R. P., (1998a). Benthic communities associated with a heavily fished scallop ground in the English Channel. *Journal of the Marine Biological Association of the United Kingdom*, **78**, 1045-1059.

Kaiser, M. J., Edwards, D. B., Armstrong, P. J., Radford, K., Lough, N. E. L., Flatt, R. P. and Jones, H. D., (1998b). Changes in megafaunal benthic communities in different habitats after trawling disturbance. *ICES Journal of Marine Science*, **55**, 353-361.

Kaiser, M. J., Hill, A. S., Ramsay, K., Spencer, B. E., Brand, A. R., Veale, L. O., Prudden, K., Rees, E. I. S., Munday, B. W., Ball, B. and Hawkins, S. J., (1996). Benthic disturbance by fishing gear in the Irish Sea: a comparison of beam trawling and scallop dredging. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **6**, 269-285.

Kaiser, M. J., Rogers, S. I. and McCandless, D. T., (1994). Improving quatitative surveys of epibenthic communities using a modified 2m beam trawl. *Marine Ecology Progress Series*, **106**, 131-138.

Kaiser, M. J. and Spencer, B. E., (1995). Survival of by-catch from a beam trawl. *Marine Ecology Progress Series*, **126**, 31-38.

Krebs, J. R. and Davies, N. B., (1997). Behavioural Ecology. Blackwell Scientific Publications, Oxford.

Lake, N. C. H., Jones, M. B. and Paul, J. D., (1987). Crab predation on scallop (*Pecten maximus*) and its implication for scallop cultivation. *Journal of the Marine Biological Association of the United Kingdom*, **67**, 55-64.

Lee, H. C., Niu, K. C., Huang, K. L., Tsai, J. D., Shyu, R. K., Shiraki, K., Hong, S. K. and Lin, Y. C., (1994). Diving pattern of fishermen in the Pescadores. *Undersea and Hyperbaric Medicine*, **21**, 145-158.

Lee, R. M., (1912). An investigation into the methods of growth determination in fishes. *Conseil Permanent International pour l'Exploration de la Mer, Publications de Cironstance*, **63**, 35pp.

MacDonald, D. S., Little, M., Eno, N. C. and Hiscock, K., (1996). Disturbance of benthic species by fishing activities: a sensitivity index. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **6**, 257-268.

MacKenzie, C. L. J., Burrell, V. G. J., Rosenfield, A. and Hobart, W. L., (1997). The history, present condition, and future of the molluscan fisheries of north and central America and Europe. *NOAA Technical Report NMFS*, **129**, 85-165.

Margretts, A. R. and Bridger, J. P., (1971). The effects of a beam trawl on the seabed. International Council for the Exploration of the Sea CM 1971/B:9.

Martin, L., (1997). Scuba diving explained: questions and answers on physiology and medical aspects of scuba diving. Best Publishing Company, Flagstaff.

Mason, J., (1957). The age and growth of the scallop, *Pecten maximus* (L.), in Manx waters. *Journal of the Marine Biological Association of the United Kingdom*, **36**, 473-492.

Mason, J., (1958). The breeding of the scallop, *Pecten maximus*, in Manx waters. *Journal of the Marine Biological Association of the United Kingdom*, **37**, 653-671.

Mason, J., (1972). The Scottish fishery for scallops and queens. Scottish Fisheries Information Pamphlet. Marine Laboratory, Aberdeen.

Mason, J., (1978). The Scottish scallop fishery. *Scottish Fisheries Bulletin*, **44**, 38-44.

Mason, J., (1982). Population study; diving, dredging and TV techniques: Comparisons. (*Pecten maximus*). International Council for the Exploration of the Sea CM 1982/K:24.

Mason, J., (1983). Scallop and queen fisheries in the British Isles. Fishing News Books, Farnham.

Mason, J., Cook, R. M., Bailey, N. and Fraser, D. I., (1991). An assessment of scallops, *Pecten maximus* (Linnaeus 1758), in Scotland west of Kintyre. In *An international compendium of scallop biology and culture* (eds. S. E. Shumway and P. A. Sandifer), pp. 231-241. World Aquaculture Society, Baton Rouge.

Mason, J., Nicholson, M. D. and Shanks, A. M., (1979). A comparison of exploited populations of the scallop, *Pecten maximus* (L.). *Rapport et Procès-Verbaux des Réunions. Conseil International pour l'Exploration de la mer*, **175**, 114-120.

Mason, J., Shanks, A. M. and Fraser, D. I., (1980). An assessment of scallop, *Pecten maximus* (L.), stocks off southwest Scotland. International Council for the Exploration of the Sea CM 1980/K:27.

McCleery., (1997). Optimal behaviour sequences and decision making. In *Behavioural Ecology* (eds. J. R. Krebs and N. B. Davies). Blackwell Scientific Publications, Oxford.

Meyer, C., (1998). *Maja squinado*, the European spider crab, biology and fishery. http://www2.hawaii.edu./~carlm/spider.html, Jersey.

Millican, P. F., (1997). The hatchery rearing of king scallops (*Pecten maximus*). CEFAS, Lowestoft.

Minchin, D., (1978). The behaviour of young escallops (*Pecten maximus* L. Pectinidae). In *2nd International Pectinid Workshop*, pp. 11. 8-13 May 1978, Brest, France.

Minchin, D., (1992). Biological observations on young scallops, *Pecten maximus*. *Journal of the Marine Biological Association of the United Kingdom*, **72**, 807-819.

Minchin, D., (1996). Management of the introduction and transfer of marine molluscs. *Aquatic Conservation*, **17**, 21-45.

Murphy, E. J., (1986). An investigation of the population dynamics of the exploited scallop, *Pecten maximus* (L.), in the North Irish Sea. Phd Thesis, University of Liverpool.

Murphy, E. J. and Brand, A. R., (1987). Yield per recruit analyses for north Irish Sea scallop (*Pecten maximus*) stocks. In *6th International Pectinid Workshop*, Menai Bridge.

Neville, P. J., (1989). Managemnet of the queensland scallop fishery. In *Proceedings of the Australian Scallop Workshop* (eds. M. C. L. Dredge, W. F. Zacharin and L. M. Joll), pp. 21-29, Hobart, Australia.

O'Boyle, R. N. and Zwanenburg, K., (1996). A comparison of catch and effort-based fisheries management. In *Report of the Second Workshop on Scotia-Fundy Groundfish Management.*, vol. 2100 (eds. D. L. Burke, R. N. O'Boyle, P.

Partington and M. Sinclair), pp. 59-70. Canadian Technical Report of Fisheries and Aquatic Science.

Orensanz, J. M., (1986). Size, environment and density: the regulation of a scallop stock and its management implications. *Canadian Special Publications in Fisheries and Aquatic Science*, **92**, 195-227.

Orensanz, J. M., Parma, A. M. and Iribarne, O. O., (1991). Population dynamics and management of natural stocks. In *Scallops: biology, ecology and aquaculture* (ed. S. E. Shumway), pp. 625-713. Elsevier, Amsterdam.

Palmer, D. W., (1997). Survey of scallop (*Pecten maximus*) stocks in the Western Channel, 1990-96. CEFAS, Lowestoft.

Paquotte, P., (1992). Aquaculture, restocking and stock enhancement as an answer to the scallop fisheries management crisis in the areas of Brest and Saint-Brieuc (Brittany). *Oceanis*, **18**, 456-465.

Paul, J. D., (1978). The biology of the Queen scallop, *Chlamys opercularis* (L.) in relation to its prospective cultivation. Phd Thesis, University of Liverpool.

Paul, J. D., Brand, A. R. and Hoogesteger, J. N., (1981). Experimental cultivation of the scallops *Chlamys opercularis* (L.) and *Pecten maximus* (L.) using naturally produced spat. *Aquaculture*, **24**, 31-44.

Paulet, Y. M., Lucas, A. and Gerard, A., (1988). Reproduction and larval development in two *Pecten maximus* (L.) populations from Brittany. *Journal of Experimental Marine Biology and Ecology*, **119**, 145-156.

Pauly, D. and Munro, J. L., (1984). Once more on the comparison of growth in fish and invertebrates. *Fishbyte*, **2**, 21.

Pawson, M. G., (1995). Biogegraphical identification of English Channel fish and shellfish stocks. Fisheries Research Technical Report, No. 99, MAFF.

Philippart, C. J. M., (1998). Long-term impact of bottom fisheries on several by-catch species of demersal fish and benthic invertebrates in the south-eastern North Sea. *ICES Journal of Marine Science*, **55**, 342-352.

Pickett, G. D., (1977). Artificial collection of pectinid spat: preliminary experiments in start bay, south-west England. International Council for the Exploration of the Sea CM 1977/E:29.

Pickett, G. D., (1978). The scallop. *Underwater World*, November 1978, 14-16.

Pitcher, T. J. and Hart, R. B., (1982). Fisheries Ecology. Croom Helm, London.

Ramsey, K., Kaiser, M. J. and Hughes, R. N., (1996). Changes in hermit crab feeding patterns in response to trawling disturbance. *Marine Ecology Progress Series*, **144**, 63-72.

Rees, H. L. and Dare, P. J., (1993). Sources of mortality and associated life-cycle traits of selected benthic species: a review. Fisheries Research Data Report, No. 33, MAFF.

Rhodes, E. W., (1991). Scallop ecology: distributions and behaviour. In *Fisheries and aquaculture of the Bay Scallop, Agropecten irradians, in the Eastern United States.* (ed. S. E. Shumway), pp. 913-924. Elsevier, Amsterdam.

Rieucau, J., (1980). The exploitation of scallops and queens in the English Channel. (Original Title : L'exploitation de la coquille Saint-Jacques et du vanneau en Manche.). *Pêche Maritimes*, **1224**, 150-158.

Rijnsdorp, A. D., Groot, P. and van Beek, F. A., (1991). Micro distribution of beam trawl effort in the southern North Sea. International Council for the Exploration of the Sea CM 1991/G:49.

Rikhter, V. A. and Efanov, V. N., (1976). On one of the approaches to estimation of the natural mortality of fish populations. Research Document, 76/VI/8, International Commission for Northwest Atlantic Fisheries.

Rolfe, M. S., (1969). The determination of the abundance of escallops and of the efficiency of the Baird escallop dredge. International Council for the Exploration of the Sea CM 1969/K:22.

Rolfe, M. S., (1973). Notes on queen scallops and how to catch them. Shellfish Information Leaflet, No. 27, MAFF.

Roman, G., (1991). Fisheries and Aquaculture: Spain. In *Scallops: biology, ecology and aquaculture* (ed. S. E. Shumway), pp. 753-762. Elsevier, Amsterdam.

Seber, G. A. F., (1982). The estimation of animal abundance and related parameters (2nd Edition). Griffin, London.

Sendall, R., (1997). Sea Fisheries Department Statistical Report. Department of Fisheries, Guernsey.

Shepard, J. G., Pope, J. G. and Cousens, R. D., (1984). Variation in fish stocks and hypotheses concerning their links with climate. *Rapport et Proces-verbaux des Reunions. Conseil International pour l'Exploration de la Mer*, **185**, 255-267.

Shumway, S. E., (1991). Scallops: biology, ecology and aquaculture. In *Developments in Aquaculture and Fisheries Science*, vol. 21, pp. 1095. Elsevier, Amsterdam.

Sinclair, M., Mohn, R. K., Robert, G. and Roddick, D. L., (1985). Considerations for the effective management of Atlantic scallops. *Canadian Technical Report in Fisheries and Aquatic Sciences*, **1382**, 113.

Smith, E. A., (1983). Anthropological applications of optimal foraging theory: a critical review. *Current Anthropology*, **24**, 625-651.

Smith, W. C., (1938). Report of the Manx Sea Fisheries 1935-37. Isle of Man Fisheries Board Publication.

Soemodihardjo, S., (1974). Aspects of the biology of *Chlamys opercularis* (L.) (Bivalvia) with comparative notes on four allied species. Phd Thesis, University of Liverpool.

Stephens, D. W. and Krebs, J. R., (1986). Foraging Theory. University Press, Princetown.

Strange, E. S., (1977). An introduction to commercial fishing gear and methods used in Scotland. *Scottish Fisheries Information Pamphlet*, No. 1, 34pp.

Tang, S. F., (1941). The breeding of the scallop (*Pecten maximus* (L.)) with a note on growth rate. *Proceeding and Transactions of the Liverpool Biological Society*, **54**, 9-28.

Taylor, C. C., (1960). Temperature, growth and mortality - the Pacific cockle. *Journal du Conseil International pour l'Exploration de la Mer*, **26**, 117-124.

Thompson, W. F. and Bell, F. H., (1934). Biological statistics of the Pacific halibut fishery. 2. Effect of changes in intensity upon total yield and yield per unit of gear. *Report of the International Commission for the Pacific Halibut Fishery*, **8**, 49pp.

Thouzeau, G., (1991). Determination of *Pecten maximus* (L.) pre-recruitment in the Bay of Saint-Brieuc: processes regulating the abundance, survival and growth of post-larvae and juveniles. *Aquatic Living Resources*, **4**, 77-99.

Thouzeau, G. and Lehay, D., (1988). Variabilite spation-temporelle de la distribution, de la croissance et de la survie des juveniles de *Pecten maximus* (L.) issus des pontes 1985, en baie de Saint-Brieuc. *Oceanologica Acta*, **11**, 267-283.

Thrush, S. F., Hewitt, J. E., Cummings, V. J. and Dayton, P. K., (1995). The impact of habitat disturbance by scallop dredging on marine benthic communities: what can be predicted from the results of experiments? *Marine Ecology Progress Series*, **129**, 141-150.

Thrush, S. F., Hewitt, J. E., Cummings, V. J., Dayton, P. K., Cryer, M., Turner, S. J., Funnel, G. A., Budd, R. G., Milburn, C. J. and Wilkinson, M. R., (1998). Disturbance of the marine benthic habitat by commercial fishing: impacts at the scale of the fishery. *Ecological Applications*, **8**, 866-879.

Tuck, I. D., Hall, S. J., Robertson, M. R., Armstrong, E. and Basford, D. J., (1998). Effects of physical trawling disturbance in a previously unfished sheltered Scottish sea loch. *Marine Ecology Progress Series*, **162**, 227-242.

Underwood, A. J., Chapman, M. G., Richards, S. A. and Sage, M., (1998). GMAV5 for Windows. Institute of Marine Ecology, Sydney.

Ventilla, R. F., (1982). The scallop industry in Japan. *Advances in Marine Biology*, **20**, 309-382.

von Bertalanffy, L., (1938). A quantitative theory of organic growth (Inquiries on growth laws II). *Human Biology*, **10**, 181-213.

von Bertalanffy, L., (1964). Basic concepts in quantitative biology of metabolism. *Helgolander wiss. Meeresunters*, **9**, 5-37.

Wanninayake, T., (1994). Seasonal cycles of two species of scallop (Bivalvia: Pectinidae) on an inshore and an offshore fishing ground. Phd Thesis, University of Liverpool.

Wilson, U. A. W., (1994). The potential for cultivation and restocking of *Pecten maximus* (L.) and *Aequipecten* (*Chlamys*) *opercularis* (L.) on Manx inshore fishing grounds. Phd Thesis, University of Liverpool.

Zacharin, W., (1989). Scallop fisheries management: the Tasmanian experience. In *Proceedings of the Australian Scallop Workshop* (eds. M. C. L. Dredge, W. F. Zacharin and L. M. Joll), pp. 1-11, Hobart, Australia.

Zacharin, W., (1994). Scallop fisheries in Southern Australia: managing for stock recovery. *Memoirs of the Queensland Museum*, **36**, 241-246.

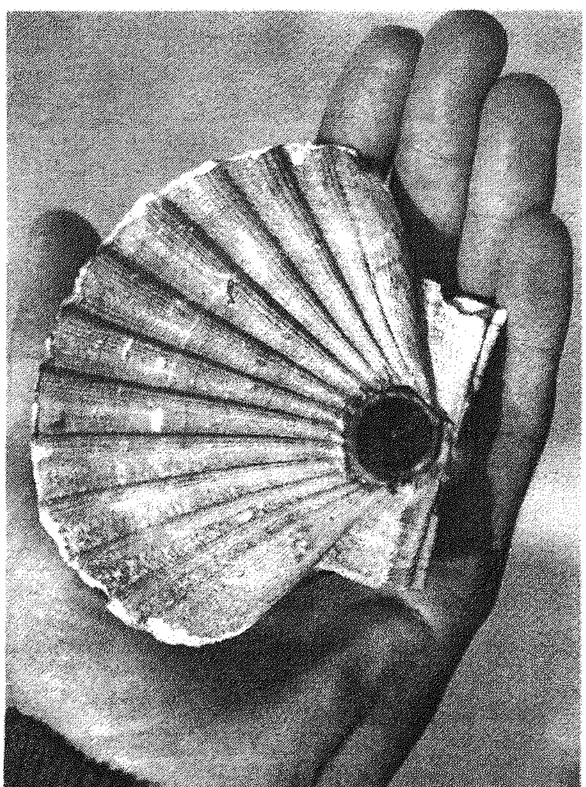
Appendices

Appendix 1: Newspaper article

Newspaper article that appeared in the Guernsey Evening Press (5/5/97) advising scallop divers about tagged scallops.

Keeping £1 tags on scallop population

by Mark Ogier



Wanted (in a year or so's time): tagged scallops. Reward offered. (627/28/97)

DIVERS collecting certain scallops next year could find themselves earning a reward for each of them, thanks to a local student who has started a Ph.D. course looking at the scallop population around the island's coast.

Adam Jory is a student at the University of Southampton, and his research will involve his tagging up to 500 undersize shellfish before releasing them back into the wild.

The various aims of the study of pecten maximus (great scallops) include defining the population, age and size structure of both fished and total populations on various sites, studying the reproductive biology and growth of the scallops, evaluation of the current fishing effort, and an investigation of fishing methods and their effect.

Sea Fisheries officer Steven Ozanne says that research like Adam's is useful to the committee, which does not have the resources to carry it out itself.

The last survey carried out by Sea Fisheries was in 1992, which revealed that 99 tonnes of scallops – worth about £1m. – was caught during the year.

Recently it was suggested that numbers are dropping, but Mr Ozanne says that the population can fluctuate dramatically.

Because Adam wants to tag young scallops, Mr Ozanne says that Sea Fisheries will not object to divers landing enough to help him in his study.

Each scallop will have a small tag glued to its flat side, and will be measured, as well as having a note taken of the date and site where it was collected.

The first tagged scallops should be big enough to be collected for consumption in a year or so, and all those that are handed in to Adam, Sarnia Skin Divers or the Sea Fisheries Committee will earn the collector £1 each.

Of course, it is also important that the collector notes the date and location of his catch.

The reward will be paid by the committee.

But Adam stresses that he does not want any tagged scallops back yet. 'At the moment divers are being asked to leave them alone,' he says.

Appendix 2: Analysis of spat collector contents

Artificial spat collectors were put out to sea in July 1998 and brought in again during October 1998. The aim of this work was to assess the variability in scallop spat settlement around the coasts of Guernsey (See Chapter 3 for methods and results). However, as there was a considerable variety of other species found in the spat collectors, it was decided it would also be interesting to study the associated settled community. The main aim of this appendix was to analyse the contents of the spat collectors and see if the settled communities varied at the different sites around the island.

Methods:

The design of spat collector, deployment sites and methods used to assess the contents of each sample can be found in Chapter 3.

Results & Discussion:

A wide variety of species were found in the spat collectors although not all were transferred to the frozen samples as they could not easily be separated from the mesh without destroying them (e.g. sponges). Table 1 shows the list of species that were identified from the samples although they did not all occur in every sample.

Table 1: List of species (in taxonomic order) which were found in samples taken from artificial spat collectors in Guernsey.

Polychaeta	*Necora puber*	*Akera bullata*
Elminius modestus	*Carcinus maenas*	*Anomia ephippium*
Dynamene sp.	*Endeis spinosa*	*Mytilus edulis*
Other Gammaridea	*Calliostoma zizyphinum*	*Aequipecten opercularis*
Jassa falcata	*Tricolia pullus*	*Pecten maximus*
Phtisica marina	*Rissoa sarsi*	Other Molluscs
Caprella linearis	*Crepidula fornicata*	Ophiuroidea
Palaemon serratus	*Trivia monacha*	*Asterina gibbosa*
Galathea spp.	Nudibranchia	Other Echinoidea
Pisidia longicornis	*Aplysia punctata*	Pisces
Macropodia spp.		

The results of the abundance of different species at each site were analysed using PRIMER (Plymouth Routines In Multivariate Environmental Research, PML) to see if there were any differences between sites (Figure 1).

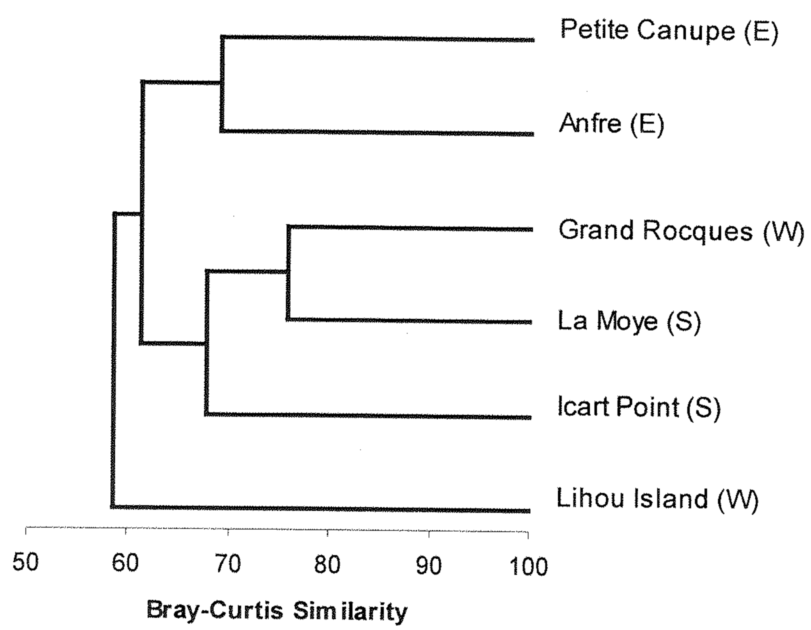


Figure 1: Multivariate analysis of species that were found in samples taken from the artificial spat collectors at six sites around Guernsey. The letters in brackets next to the site names show on which coast (East, South or West) the sites were located.

The results showed that the sites were divided into three groups, with the two sites on the east coast in the first group, the two sites on the south coast and Grand Rocques in the second group and Lihou Island in the third group on its own. The cause of this grouping was most likely due to the variability in numbers of *A. opercularis* as it was most abundant on the east coast sites and only occurred in small numbers at Lihou Island. The Lihou site also had very few other species possibly due to excessive fouling by *Jassa falcata*, which may have prevented other species from settling in the spat collectors.