ENVIRONMENTAL FACTORS INFLUENCING THE GROWTH AND SURVIVAL OF JUVENILE SEA SCALLOPS, Placopecten magellanicus (GMELIN, 1791)

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BRUNO FRENETTE

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BY

BRUNO FRENETTE

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ABSTRACT

In southeastern New Brunswick, located along the Northumberland Strait, shellfish aquaculturists are interested in the option of cultivating sea scallops, *Placopecten magellanicus,* in shallow water embayments, along with oysters and or mussels. However, sea scallops are not naturally found in the shallow waters of southeastern New Brunswick and environmental conditions at these sites may not be suitable for their culture. The objectives of this study were to investigate the potential for scallop culture in these environments. Laboratory studies were undertaken using two size classes of juvenile scallops (10.0-20.0 mm and 20.1-35.0 mm shell height) to determine their salinity and temperature tolerances. Results indicated that 100% survival was found in salinities ≥ 25 ppt, and temperatures $\leq 18°C$. The health status of the surviving juvenile scallops was assessed by measuring clearance and ingestion rates, oxygen consumption and secretion of stress related enzymes. The highest indicators for these physiological parameters were observed at 13°C at ambient salinity which was above 30 ppt.

Field studies were undertaken using the same size classes to examine scallop growth and survival and environmental parameters in four bays, ranging in minimum depth from 3–7 m, in southeastern New Brunswick which are characterized by heavy freshwater inflow during spring and high temperatures ($\geq 20°C$) in summer. The scallops held in Bouctouche Bay had the highest survival after 13 months, 84.3% for small juveniles and 88.1% for large juveniles. Lowest percent survival values (0.0 %) were

observed in Little Shemogue Bay, Richibucto Bay (sites 2 and 3). The growth rate for small juvenile scallops was the highest in Richibucto Bay (site 1) and Bouctouche Bay (0.061 mm/d ± 0.006 and 0.057 mm/d ± 0.001, respectively). Whereas, for large juvenile scallops the highest growth rate was recorded in Cocagne Bay (0.075 mm/d ± 0.008).

Overall, based on growth, survival and environmental parameters (mainly salinity), Bouctouche Bay has the best potential of the sites tested for the development of a sea scallop aquaculture site. It is concluded that sea scallop aquaculture farming has a limited future in the region of southeastern New Brunswick. It may be possible, however, at some sites in which the environmental parameters are found to meet criteria that are proposed in this study.

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General Introduction

1.1 Rationale

In southeastern New Brunswick, located along the Northumberland Strait, shellfish aquaculturists are interested in the option of cultivating sea scallops, *Placopecten magellanicus* (Gmelin, 1791), in shallow water embayments, in order to diversify their oyster and/or mussel operations. However, the sea scallop is not naturally found in the shallow near shore waters of southeastern New Brunswick and environmental conditions at these sites may not be suitable to the sea scallop. Hence, slow growth and high mortality may be observed (Frishman et al. 1980; Wildish et al. 1988). All environments are somewhat variable and uncertain (Real 1980); however, in the case of shallow water embayments, or estuaries, environmental parameters can undergo rapid or large changes of temperature, salinity or other factors (for example turbidity), which may be detrimental to scallop survival.

1.2 Distribution Range

The sea scallop has a geographical range extending from the Gulf of St. Lawrence to Cape Hatteras, North Carolina (MacKenzie 1979; Abbott and Morris 1995). Sea scallops are subtidal bivalves that prefer a sand-gravel or gravel-pebble substrate, although aggregations are occasionally found on sand-mud or rocky bottoms (Couturier et al. 1995). Sea scallops are usually found at depths ranging from about 15 to 100 m (Naidu et al. 1989); however, in some areas they have been found in shallow water just below low tide (Read 1967). Scallop fishing logbooks from 2002 showed that in the

Northumberland Strait there are three major areas with natural scallop beds ranging in depth from 12–45 m (Department of Fisheries and Oceans, 2003 unpublished data).

1.3 Fishery Overview

The sea scallop has been commercially fished off the Atlantic coast since the late 1800's or early 1900's (Lanteigne and Davidson 1991; Naidu 1991). The scallop beds off the shore of Digby, Nova Scotia were discovered in 1920 and the fishery then expanded rapidly into the Bay of Fundy. In the 1930's, other important scallop beds were discovered on Georges Bank, which is divided between Canada and the US. Today that area is still considered the world's largest producer of wild scallops (Naidu 1991). Total commercial sea scallop (Canada and US) landings have been variable and peaked at 26,671 metric tonnes (mt of meat) in 1978, declined to 9,781 mt in 1984, increased to 22,831 mt in 1991, down to 9,822 mt in 1995, but back up to 21,283 mt in 2001 (Northeast Fisheries Science Center 1997; Statistics Canada 2002). The cyclical variation in catches is attributed to hydrographical, tidal or climatological conditions (Black et al. 1993). Despite these natural occurrences, the combined harvest from Digby and Georges Bank scallop grounds have accounted for more than 80 percent of the total annual Canadian landings of scallops over the past three decades (Naidu 1991).

In comparison, the scallop fishery in the southern Gulf of St. Lawrence recorded peak landings in 1956 (117 mt of meat) and 1957 (115 mt), followed by a low point in 1960 (6 mt). The fishery peaked again to its highest level in 1970 (697 mt). After the 1970's, landings have levelled off varying between 161 mt to 364 mt annually (Lanteigne

and Davidson 1991). The most recent landing recorded was in 2002 at 102 mt of meat, of which 41 mt came from the Northumberland Strait (Department of Fisheries and Oceans, 2003 unpublished data). In the southern Gulf of St. Lawrence, including the Northumberland Strait, the scallop fishery has been characterized by large fluctuations in fishing effort and landings, which have been controlled mainly by socio-economic factors. The scallop fishery in the area is considered a supplementary fishery to the lobster fishery, with its seasons and regulations often established around lobster fishing activities (Lanteigne and Davidson 1992).

The main market for Canadian scallop landings is the United States where the value is between $10–20/kg for adductor muscle meats depending on the supply and demand (Couturier et al. 1995). The variability in catch levels of wild stock, the high value of scallop meat and its well-known biology make the sea scallop an ideal candidate for culturing. Therefore, interest has widened in Atlantic Canada to investigate the possibility of farming the sea scallop (Naidu and Cahill 1986; Young-Lai and Aiken 1986; Tremblay 1988; Wildish et al. 1988; Dadswell and Parsons 1991; Kleinman et al. 1996b).

1.4 Aquaculture Overview

Japan was the first nation to cultivate the scallop, *Patinopecten yessoensis*, on a large scale (Imai 1982; Ventilla 1982; Aoyama 1989; Hardy 1991; Ito 1991). Scallop aquaculture is presently practised to various degrees in many other countries including Australia (Gwyther et al. 1991; O'Connor and Heasman 1998), Chile (Navarro Piquimil

et al. 1991; Navarro and Gonzalez 1998), China (Pillay 1990), France (Ansell et al. 1991), Great Britain (Mason 1983; Ansell et al. 1991), Mexico (Singnoret-Brailovsky et al. 1996; Maeda-Martinez et al. 1997; Maeda-Martinez et al. 2000), New Zealand (Bull 1991), Norway (Andersen and Naas 1993), and the United States (Castagna 1975; Morgan et al. 1980; Pillay 1990). In Atlantic Canada, several scallop aquaculture sites have been developed and are still evolving and being evaluated for their economical feasibility (Frishman et al. 1980; Naidu et al. 1989; Parsons and Dadswell 1992; Couturier et al. 1995; Kleinman et al. 1996b; Penney and Mills 1996; Penney and Mills 2000). In 2001, Canada's total aquaculture production was 128 metric tonnes (120 mt from British Columbia and 8 mt from Nova Scotia) with a total Canadian value of $788,000 (Statistics Canada 2002).

1.5 Culture Techniques

Three basic culture methods are used for scallops: suspended, off-bottom and bottom culture (Imai 1982; Naidu et al. 1989; Ansell et al. 1991; Hardy 1991; Couturier et al. 1995). In suspended culture, scallops are grown in cages (pearl nets, pocket nets, lantern nets, plastic trays) or ear-hung individually in the water column (Mason 1983; Paul 1987; Barnabé 1990; Pillay 1990; Gwyther et al. 1991; Navaro Piquimil et al. 1991; Parsons and Dadswell 1994). Whatever the type of suspended culture gear that is chosen, they are attached on longlines and secured with bottom weights and floating buoys. In off-bottom culture (Ventilla 1982; Aoyama 1989; Bull 1991; Ito 1991), spat are placed in oyster bags (Vexar™ bags) and stacked in iron mesh cages or on metal tables (Hardy

1991). They are then placed on the sea bottom and marked with a floating buoy. In bottom culture, the spat can also be used for enhancement, commonly known as seeding, on commercial trawling grounds to be later harvested (Morgan et al. 1980; MacDonald 1986; Wildish et al. 1988; Cliche and Giguère 1998).

1.6 Scallop Growth and Survival

In the wild, growth of the scallop varies considerably from one bed to another, depending on local environmental conditions (MacDonald and Thompson 1988). Commercial size (> 80 mm) is usually reached between three and five years of age (Black et al. 1993). In Passamaquoddy Bay, NB (depths of 4–10 m), and Mahone Bay, NS (depths of 5–15 m), cultivated scallops in suspension can reach a commercial size (90 mm shell height, 15 g meat) in 33 to 36 months and in some cases, spat collected from an early cohort can be grown to market-size in 25 to 27 months (Dadswell and Parsons 1992). In Notre Dame Bay, Newfoundland (3-m below the water surface), it usually takes 2 years for sea scallops held in pearl nets to reach the shell height size of 50–70 mm (MacDonald 1986; Penney and Mills 1996). The growth of sea scallops in the field in other locations along the Atlantic coast, including Newfoundland, and in the Bay of Fundy are well documented (MacDonald and Thompson 1985; MacDonald and Thompson 1986; Wildish et al. 1988; Parsons and Dadswell 1992; Gaudet 1994; Parsons and Dadswell 1994; Grecian et al. 2000).

Many factors affect the survival of cultivated scallops; such as extreme temperatures (Dickie 1958), suboptimal salinity conditions (Ledwell 1995, Bergman et al.

1996), water turbidity (Young-Lai and Aiken 1986), and stocking density (Parsons and Dadswell 1992). Wildish et al. (1988) believe that a realistic survival rate in commercial grow-out is 75–95% per year excluding the possibility of predator mortality. However, for the aquaculture industry to be economically viable the number should be > 80% (Penney and Mills 2000). Dadswell and Parsons (1991) showed that the survival of sea scallops in suspension (pearl nets) in Passamaquoddy Bay, NB stocked at optimum density ranged from 74.3% to 92.5% between sampling periods (3–8 months), with an overall survival of 76.8% after one year. Penney and Mills (2000) conducted pilot-scale culture trials in Notre Dame Bay, NL with 1-year-old sea scallops using pearl nets of varying mesh size with the same starting density. They concluded that survival was significantly related to initial stocking density, culling and seed grading but not to net mesh size. In comparison, Grecian et al. (2003) compared two stocking densities of nursery-sized spat in collector bags. Neither growth rate nor recovery were significantly different for the two densities (2,600 and 5,200 spat/collector bag) tested.

1.7 Estuaries

Embayments located along the southeastern coast of New Brunswick often have more estuarine conditions than the Bay of Fundy, Nova Scotia, or Newfoundland. Estuaries are highly productive in part due to tidal flushing and land runoff bringing in nutrients. Also, vertical mixing between freshwater and saltwater occurs in the estuary, so that nutrients are circulated throughout the water column (Ketchum 1983). However, there is also inflowing waters from rivers and marshes that carry nutrients into the estuary

that stimulates an increase in phytoplankton production, which is regulated by internal nutrient cycling (Ketchum 1983). This internal cycling involves excretion of mineralized nutrients by herbivorous zooplankton, and release of nutrients remineralized by invertebrates of the bottom sediments, by the mixing of sediments, and by steady-state exchanges between nutrients present in the particulate and dissolved phases (Smayda 1983).

In estuaries, salinity is highly variable spatially and temporally. Salinity is affected by freshwater currents mixing with ocean tides, which vary with seasonal and other environmental factors (e.g., rainfall, wind, etc.) (Dyer 1973; Ketchum 1983; Smayda 1983). As well, salinity varies vertically and horizontally, often within one tidal cycle. Salinity concentration may be the same from top to bottom, or it may be completely stratified, with a layer of freshwater on top and a layer of dense saline water on the bottom (Dyer 1988; Stigebrandt 1988; Wilson 1988). Salinity is homogeneous when currents, particularly eddy currents, are strong enough to mix the water from top to bottom (Ketchum 1983). Estuaries along the eastern coast of New Brunswick are relatively well mixed and show little salinity stratification in the water column. In most cases, the vertical gradient is less than 0.2 ppt/m for the entire water column (St-Hilaire et al. 1997).

In general, the climatic and geographic conditions of embayments along the Atlantic coast favour the cultivation of several types of cold-water marine organisms, especially in the Bay of Fundy and along the coast of Newfoundland and Nova Scotia. The water temperature ranges from –0.7°C in winter to 13°C in summer in most areas; however, it can reach up to 20°C in some locations (Boghen 1995). Embayments along

the eastern coast of New Brunswick contrast sharply to the Bay of Fundy and along the coast of Newfoundland and Nova Scotia. Embayments on the eastern coast of New Brunswick are characterized by shallow water (on average < 10 m), and are subject to a temperature regime varying from below 0°C in winter to above 23°C in summer (Boghen 1995).

1.8 Objectives

This study was undertaken to examine the environmental factors influencing the growth and survival of juvenile sea scallops and to determine the salinity and temperature tolerance limits of sea scallops. This study was conducted in two parts: a laboratory experiment (chapter two) and a field-based experiment (chapter three).

In chapter two the main objective was to determine the salinity-temperature tolerance of juvenile sea scallops under controlled conditions. The purpose of this experiment was to simulate typical estuary-like conditions of southeastern New Brunswick and to determine the survival of sea scallops at various temperatures and salinities. Changes in metabolism such as clearance rate, ingestion rate, oxygen consumption and induction of stress were also measured.

The objective of chapter three was to determine the biological feasibility of culturing juvenile sea scallops held in wire mesh cages in shallow water embayments in southeastern New Brunswick in a 13-month grow-out experiment. The survival and growth rate of sea scallops in off-bottom culture and the relation to environmental parameters under which they were grown were examined.

Chapter Two

Salinity-Temperature Tolerance of Juvenile Sea Scallops, *Placopecten magellanicus*

2.1 Introduction

The most economical and successful way of farming sea scallops to date has been in suspended or off-bottom culture in coastal embayments (Dadswell and Parsons 1991; Couturier et al. 1995; Kleinman et al. 1996b). Such sites on the Atlantic Canadian coast are sheltered land-bound bays and inlets associated with calm water. However, in southeastern New Brunswick, the bays are shallower and have freshwater run-off in spring that will affect the salinity resulting in estuarine conditions. Shallow water embayments can also experience high water temperatures in the summer. Interest in the possibilities of scallop aquaculture makes it necessary to better understand the salinity and temperature tolerance of scallop species (Kirk 1979; Hardy 1991).

Salinity and temperature are important physical factors confronting a marine organism in its environment, and the biological effects of these factors are usually correlated (Kinne 1971; Boghen 1989; O'Connor and Heasman 1998). Optimal survival for adult scallops occurs at salinities found in regular seawater (30–32 ppt) (MacKenzie 1979) with a lower lethal threshold of 16.5 ppt (Chiasson 1952; Ledwell 1995; Bergman et al. 1996). Best growth is reported to be within a temperature range of 10–15°C and wide fluctuations will determine their survival (Young-Lai and Aiken 1986; Stewart and Arnold 1994). Earlier studies showed that, at ambient salinity, water temperatures over 23.5°C are lethal to sea scallops and temperatures between 21°C and 23.5°C for an extended period can be a direct cause of mortality (Dickie 1958; Stewart and Arnold 1994).

Previous works have also shown that changes in water temperature and salinity can affect pectinidae physiological activities such as clearance rate, ingestion rate and oxygen uptake (Kirby-Smith 1970; Shumway 1977a, 1977b; MacDonald and Thompson 1986; Shumway et al. 1988; Bricelj and Shumway 1991; Navarro and Gonzalez 1998; Cranford 1999; Sicard et al. 1999). Exposure to lower salinities is an important contributing factor of stress that can result in a reduction in growth rates. Lower growth rates are due to the physiological adjustments that the scallops undergo to survive under stressful conditions (Shumway 1977a, 1977b; Navarro and Gonzalez 1998). High temperatures in shallow waters during summer season are another stressful physiological factor that can affect feeding and oxygen consumption (MacDonald and Thompson 1986; Shumway et al. 1988; Cranford 1999).

In comparison to sea scallops, there are other molluscs that survive better in shallow water embayments. For example, blue mussels (*Mytilus edulis*), eastern oysters (*Crassostrea virginica*) and bay scallops (*Argopecten irradians*) are naturally found in shallow embayments and are adapted to high temperatures and salinity fluctuations. As well, both blue mussels and eastern oysters have shells that seal tighter than sea scallops, which enables them to withstand salinity and oxygen fluctuations. On the other hand, sea scallops are a more oceanic species, which are found in deeper water and are adapted to more stable environmental conditions. However, sea scallops are an economically important marine species and as a result, there is interest in studying their potential for aquaculture development in southeastern New Brunswick. Therefore, it necessary to better understand the salinity and temperature tolerance of this scallop species.

The main objective of this study was to determine the salinity-temperature tolerance of juvenile sea scallops under controlled laboratory conditions. Due to the combination of the shallowness and the freshwater inflow in estuary embayments of southeastern New Brunswick, warm water temperatures and low salinities are expected. In this experiment estuarine conditions were mimicked to determine the survival rate of sea scallops at different combinations of water temperatures and salinities. To assess the health status of surviving scallops, the following metabolic processes were measured: clearance rate, ingestion rate and oxygen consumption. In addition, mucus samples were extracted from the gills to measure potential stress enzymes as indicators of environmental stress.

2.2 Materials and Methods

2.2.1 Study Site and Spat Origin

This experiment was carried out from February to the end of June 1999 at the Ocean Sciences Centre (OSC), Memorial University in Logy Bay, NL. Initial shell height of juvenile sea scallops, i.e., maximum distance between the dorsal (hinge) and ventral margins (Figure 1), was recorded to the nearest 0.01 mm using an electronic calliper (Mitutoyo Corporation™). This resulted in the scallops being divided into two size-classes for the experiment: small juveniles (10.0–20.0 mm, mean = 17.86 mm in shell height) and large juveniles (20.1–35.0 mm, mean = 25.09 mm in shell height). The

scallops were shipped, by airplane, two weeks prior to the start of the experiment in coolers (3°C ± 1°C) from a commercial wild spat collection site in Arichat, NS.

2.2.2 Salinity-Temperature Bioassay

A total of 2,000 scallops, 1,000 of each size class was first placed in holding tanks at ambient salinity (ranging from 30–32 ppt) and at ambient temperatures (ranging from 2–3°C). The scallops were acclimated to experimental temperatures at a rate of 1°C / day for trials at 3, 8, 13, 18 and 23°C (Figure 2). Scallops were acclimated because studies have found that sudden changes in the environmental or rearing conditions can decrease survival and growth (Thompson 1984; Cranford and Grant 1990; Côté et al. 1993; Christophersen 2000; Christophersen and Magnesen 2001). For example, Hall (1999) observed that in sea scallops 15–21 days were required for membrane fluidity to adjust to a temperature decrease from 15°C to 5°C.

Salinities for the experiment were 5, 10, 15, 20, 25, and 30 ppt. A separate bioassay of the six salinities was conducted over 240-h for each temperature trial. The experiment was carried out using plastic trays measuring 17 x 25 x 9 cm deep containing 2-L of static water (Bergman et al. 1996). For each temperature trial ran separately, there were triplicate trays for each salinity and each size-class with 10 scallops/tray. Thus, there was a total of 18 trays/size-class for each temperature trial (Figure 2). Each tray was supplied with an air stone giving gentle aeration. Salinities were adjusted by diluting seawater with distilled water. The water was completely changed in all trays every 48-h (Ledwell 1995). All trays were held in a water bath to maintain a constant temperature

(Figure 2). All treatments were randomly assigned to a tray and scallops were haphazardly assigned to a tray.

Scallop mortality was monitored at time periods of 1, 2, 6, 12, and 24-h and then every 24-h afterwards for a total of 10-d (240-h). Death was determined using the criteria of a gaping shell with no response from mantle or adductor muscle prodding using a pipette (Ledwell 1995) or complete mantle retraction. Observations were also recorded on the number of scallops attached with byssal threads, number of scallops with their foot extended, and number of scallops starting to gape and retract their mantle.

2.2.3 Metabolic Measurements

Scallops remaining alive at the end of each salinity (15 ppt, 20 ppt, 25 ppt, 30 ppt, and ambient salinity) and temperature (3°C, 8°C, 13°C, 18°C, and 23°C) bioassay were used to determine the metabolic measurements: clearance rate, ingestion rate and oxygen consumption, and mucus extraction for stress enzyme indicators. Before each metabolic measurement, the shell height (Figure 1) of all small and large juvenile scallops was measured. The dry tissue weight for each individual scallop was also determined for the oxygen consumption calculations following the trials.

2.2.3.1 Clearance Rate and Ingestion Rate

Clearance rate (mL/h/animal) is defined as the volume of water cleared of suspended particles greater than 2-μm in diameter per unit time per animal (Coughlan

1969). Ingestion rate (cells/scallop/h) is defined as the number of suspended particles greater than 2-μm in diameter removed per animal per unit time (Hollett 1989).

Scallops were maintained in their original trays, at the same experimental salinities and temperatures. A control tray (no scallops) of the same water volume and conditions was also added. Each tray of scallops and the controls had static water and were gently aerated with an air stone. Cultured microalgae, type *Isochrysis galbana* (clone T-ISO), were added to each tray at a concentration of 20,000 cells/mL.

An initial sample was immediately taken by sampling ~ 30–50 mL of the mixture in each tray. Subsequent samplings were taken from each tray every 30-min, for a total of 90-min. If the algae cell density dropped below 20% of the original concentration in the trays, it was readjusted to the initial density (P. Dabinett, pers. comm.). A Coulter® Multisizer II was used to determine cell counts.

Clearance rates were determined using the following equation from Coughlan (1969):

$$F = ((M*t^{-1} * \ln C_o/C_t) - (M*t^{-1} * \ln C_o'/C_t')) * n^{-1}$$ where:

F = clearance rate (mL/h/animal)

M = volume of water with suspended algae (mL)

C_o = initial particle concentration (cells/mL)

C_t = concentration at time t (cells/mL)

t = time (h)

C_o' = initial concentration control chamber (cells/mL)

C_t' = concentration at time t in control chamber (cells/mL)

n = number of animals per tank

Ingestion rate was determined using the following equation from Hollett (1989):

$IR = (C_i - C_f)\ V * t^{-1} * n^{-1}$ where:

IR = ingestion rate (cells/scallop/h)

C_I = initial cell concentration (cells/mL)

C_f = final cell concentration (cells/mL)

V = volume of seawater (mL)

t = time (h)

n = number of scallops

There were some mortalities in the small and large juvenile scallops after the 10-day experiments and before the clearance rate and ingestion rate were conducted. For the exact number of scallops analyzed see Appendix 1. Upon the completion of clearance and ingestion rate analyses, scallops were individually placed in respiration chambers to measure the rate of oxygen consumption.

2.2.3.2 Oxygen Consumption

Oxygen consumption (mL/h) is defined as the estimated rate of decrease of the volume of oxygen inside a respiration chamber per unit of time. At the different salinities and for each temperature trial, five animals from each size class were randomly selected or if less than five animals survived, all remaining survivors were used to measure their oxygen consumption. All scallops were individually placed in an airtight cylindrical chamber (volume = 0.380 L) with aerated seawater of the same water condition (salinity + temperature) in which they were tested. Each chamber had a magnetic stirring bar

turning gently and freely under a perforated glass plate. The scallop was then placed on top of the perforated glass plate (Figure 3). The temperature was maintained by placing each cylindrical chamber in a Neslab™ unit. The Neslab unit can hold up to four cylindrical chambers sitting on their own magnetic stirrer. At the top of each chamber, an oxygen probe was attached and connected to the oxygen meter unit (OM200™ Oxyprobe) (Figure 3). These probes had been acclimatised to the same salinity and temperature with aerated seawater 24-h prior to commencing the trial. Air bubbles floating at the surface were eliminated to prevent uncontrollable fluctuations in recording respiration data.

For every set of respiration readings, a control chamber, with no scallops, was prepared at the same water conditions (salinity and temperature). At the beginning of the respiration reading and for every chamber, the oxygen meter unit(s) was set at an oxygen span of 166 (mm of Hg) for each probe of each machine.

The respiration measurements took 30-min to 2-h depending upon the water temperature and the size of the animal. The oxygen concentration was never allowed to drop below 75% saturation. The oxygen meter unit was connected to a computer that recorded the oxygen concentration data every 15-s and stored the information on a disk.

Oxygen concentration rates were calculated using the following equation:

$R = m * C * V$ where:

R = respiration rate (L/h)

m = slope of the respirometry reading (mm Hg/h)

C = conversion factor for converting mm Hg to oxygen solubility in mL/L based upon salinity and temperature

V = volume of the respiration measurement chamber (L)

Considering that there was a small number of scallops analyzed, the oxygen consumption data for small and large juveniles were combined (see Appendix 1 for the exact numbers of scallops). They were then standardized to 0.1 g using the procedures from Widdows (1985).

2.2.3.3 Stress Enzyme Indicators

Specific activities of enzymes were measured as indicators of stress by the scallops. The three tests conducted were the alkaline phosphatase assay (pmol/min/mg protein), azocasein hydrolysis assay (Mean OD/H/mg protein), and lysozyme assay (units/mg of protein). At the end of the experiments (temperature-salinity bioassay, clearance rate, ingestion rate, and oxygen consumption), mucus from the gills of the live scallops was sampled. A buffered seawater solution was prepared using filtered seawater (filtered at 0.35 μm), which was buffered with ammonium bicarbonate (0.79 g/100 mL). The buffered seawater was then flushed through the gills of each animal using a plastic pipette. Five millilitres of buffered solution was used for the small juveniles and 10 mL for the large juveniles. For each scallop, the buffered-mucus mixture was placed in a small plastic vial, frozen (–70°C) and shipped (coolers with ice) to the Institute for Marine Biosciences, National Research Council, Halifax, NS for analysis using the methodology of Ross et al. (2000) (Appendix 2).

Unfortunately, due to time and labour, the 3°C temperature trial was the only bioassay that the specific activities of the three enzymes were measured at the five

remaining salinities (15 ppt to ambient salinity) for both small and large juveniles. Measurements, only on small juveniles, at temperature trials > 3°C were randomly selected at 15 and 30 ppt at 8°C, 15 and 30 ppt at 13°C, 20 and 30 ppt at 18°C, and 25 ppt and ambient salinity at 23°C. Only the specific activities of alkaline phosphatase and lysozyme were measured at conditions > 3°C.

2.2.4 Data Analysis

The median lethal concentration (LC_{50}), lethal concentration for 50 percent of the individuals, which is used in most fields of biological testing was calculated (Sprague 1973). Probit analysis (SPSS, 10.0© for Windows©) was used to calculate the LC_{50} water salinity exposure for each time interval and the LC_{50} for each time interval for lethal water temperature.

The data of the metabolic measurements were analysed with a two-way analysis of variance (ANOVA) by using the General Linear Model (SPSS, 10.0© for Windows©). For small and large juveniles, a two-way ANOVA was performed to simultaneously test the significance of each of the experimental factors (salinities and temperatures) for the metabolic measurements – clearance rate, ingestion rate, and stress enzyme indicators. For oxygen consumption (mL/h), the only difference was that small and large juveniles were combined. Significant differences among treatments were assessed by using Tukey's HSD, set at a 0.05 alpha level (Appendices 3 to 5).

2.3 Results

2.3.1 Salinity-Temperature Bioassay

The survival after 240-h in test salinities at different temperatures was 100% in small and large juvenile scallops held at a salinity of 25 ppt or higher and at temperatures of 18°C or lower (Figures 4a and 4b). Both size classes of scallops had a lower tolerance to decreasing salinity at increasing temperatures and increasing time exposure (Figures 5a and 5b). At the lowest salinities (5 ppt and 10 ppt) and at all water temperatures, the scallops started to die within the first hours of observation (Tables 1 to 5). At 5 and 10 ppt, all scallops were dead in 96-h at 3°C, 48-h at 8°C, 24-h at 13°C, 48-h at 18°C, and 12-h at 23°C.

Scallop mortality for the first four temperatures (3°C, 8°C, 13°C and 18°C) and in both size classes was similar for the ten-day trial (Figures 5a and 5b). However, for both size classes, the mortality at 23°C was consistently higher than other temperatures. For the large juvenile scallops at 23°C, mortality increased rapidly after 24-h and the mortality increased rapidly in small juvenile scallops after 144-h. At 96-h, for the five respective temperatures (3 to 23°C), the median lethal salinities (LC_{50}'s) were 13, 13, 13, 14.3 and 22.3 ppt and 13, 13, 13, 14.6 and 20.3 ppt for small and large scallops, respectively (Figures 5a and 5b).

For small juveniles (Figure 6a), 100% mortality was observed after 6-h at 5 ppt and after 72-h at 10 ppt. At 96-h, the LC_{50} was 18.9°C at 15 ppt and 21.5C at 20 ppt. The median lethal temperature was at 168-h for 25 ppt (22.7°C) and 30 ppt (23.0°C). At

240-h, the median lethal temperatures dropped gradually to 12.1°C at 15 ppt; 18.7°C at 20 ppt; 22.1°C at 25 ppt; and 20.5°C at 30 ppt. For large juveniles (Figure 6b), there was 100% mortality after 6-h at 5 ppt and after 48-h at 10 ppt. At 96-h, the LC_{50} was 18.6°C at 15 ppt. The median lethal temperature was at 120-h for 20 ppt (22.4°C) and 25 ppt (23.0°C), and at 168-h for 30 ppt (22.9°C). At 240-h, the median lethal temperatures dropped gradually to 13.1°C at 15 ppt and 21.9°C at 30 ppt.

Scallops exhibited shell gaping with mantle retraction at low salinities (5 ppt, 10 ppt, and 15 ppt) combined with slow responses to repeated probing just before dying when the scallops were subjected to temperature trials of 18°C or lower (Tables 1 to 4). At 23°C, at these same low salinities, death was more rapid, with no response by scallops to repeated probing or immediate shell-closure and almost no prior shell gaping and mantle retraction (Table 5). Another notable observation was that some scallops underwent a clapping action when they were immediately exposed to abrupt changes in salinity; from the holding tank (ambient seawater) to the low experimental salinities (< 20 ppt). At all water temperature trials and at higher salinities (25 ppt and 30 ppt), juvenile scallops were byssally attached. They did not form byssal threads when held in salinities of $\leq$ 15 ppt. At a salinity of 20 ppt, absence of byssal attachment was only seen at lower temperatures (3°C and 8°C). Juvenile scallops only extended their foot at salinities of 15 ppt and 20 ppt for all water temperatures and had a poor response to repeated probing. This observation decreased with increasing temperatures.

2.3.2 Clearance and Ingestion Rate

Clearance rate (F) of small and large juvenile scallops increased with increasing salinity and was maximized at experimental temperatures ranging from 8 to 18°C (Figures 7a and 7b). There were significant differences in clearance rate among temperatures for small juveniles (ANOVA; $F = 5.07$, $P = 0.001$) and large juveniles (ANOVA; $F = 20.79$, $P < 0.001$). Clearance rate was also significantly different among salinities for small juveniles (ANOVA; $F = 2.56$, $P = 0.043$) and large juveniles (ANOVA; $F = 9.65$, $P < 0.001$). Clearance rate was the highest at ambient salinity (32 ppt) and a temperature of 13°C, for both small (0.35 ± 0.01 L/scallop/h) and large (0.56 ± 0.10 L/scallop/h) juveniles. Clearance rate was also the highest at 13°C for small and large juveniles at salinities of 20, 25, and 30 ppt. Whereas, the highest clearance rate recorded for both sizes of juveniles at 15 ppt was at an experimental temperature of 8°C.

Ingestion rate (IR) also increased with increasing salinity and was maximized at temperatures of 8 to 18°C (Figures 8a and 8b). There were significant differences in ingestion rate among temperatures for small juveniles (ANOVA; $F = 5.02$, $P = 0.001$) and large juveniles (ANOVA; $F = 11.15$, $P < 0.001$). Ingestion rate was also significantly different among salinities for small juveniles (ANOVA; $F = 2.54$, $P = 0.045$) and large juveniles (ANOVA; $F = 13.73$, $P < 0.001$). IR was the highest at ambient salinity and a temperature of 13°C, for both small ($3.5 \times 10^6 \pm 0.31 \times 10^6$ cells/scallop/h) and large ($3.9 \times 10^6 \pm 0.48 \times 10^6$ cells/scallop/h) juveniles. IR was also the highest at 13°C for small and large juveniles at salinities of 20, 25, and 30 ppt, whereas, small and large juveniles at 15 ppt had the highest IR when the experimental temperature was at 8°C.

For F and IR of small and large juveniles, the means for groups (temperatures and salinities) in homogenous subsets are compared using the Tukey's HSD at $\alpha = 0.05$. The results are shown in Appendix 3.

2.3.3 Oxygen Consumption

Oxygen consumption (VO_2) increased with an increase in salinity at the experimental temperatures of 13°C and 23°C for a standardized scallop of 0.1 g dry tissue weight (Figure 9). There were significant differences in VO_2 among temperatures (ANOVA; $F = 9.64$, $P < 0.001$), yet no significant differences were reported among salinities (ANOVA; $F = 2.15$, $P = 0.078$). The highest overall oxygen uptake (0.458 ± 0.037 mL/h) was at 13°C and at ambient salinity conditions. Oxygen consumption of juveniles was also the highest at 13°C for the water salinities of 30 ppt (0.19 ± 0.015 mL/h) and 15 ppt (0.29 ± 0.094 mL/h), in comparison to the other temperature trials. At 20 ppt (0.305 ± 0.095 mL/h) and 25 ppt (0.368 ± 0.064 mL/h) the highest VO_2 was recorded at the 18°C temperature trial. At a temperature of 23°C, there were results of VO_2 only at the three highest experimental salinities.

The means for groups (temperatures and salinities) in homogenous subsets were compared using the Tukey's HSD at $\alpha = 0.05$, for oxygen consumption of juvenile scallops standardized to 0.1 g. The results are shown in Appendix 4.

2.3.4 Stress Enzyme Indicators

Alkaline phosphatase specific activities for small and large juveniles were higher at lower salinities and lower temperatures (Table 6). There were no significant differences found between small and large juveniles (ANOVA; $F = 0.02$, $P = 0.185$). At 3°C alkaline phosphatase specific activities were not significantly different among salinities in small juveniles (ANOVA; $F = 0.94$, $P = 0.435$) but were significantly different among salinities in large juveniles (ANOVA; $F = 3.31$, $P = 0.031$). Moreover, for small juveniles, there were no significant differences in alkaline phosphatase specific activities between the 3°C temperature trial and the rest of the temperatures tested (ANOVA; $F = 3.14$, $P = 0.179$). For small juveniles, the highest alkaline phosphatase specific activity (4.52 ± 1.73 pmol/min/mg protein) was recorded at 8°C and 15 ppt. For large juveniles, the highest alkaline phosphatase specific activity (3.84 ± 1.71 pmol/min/mg protein) was recorded at 3°C and 20 ppt. For the rest of the small juveniles, at the 13°C and the 18°C temperature trials, the specific activity decreased with an increase in salinity, and at 23°C the specific activity increased with increasing salinity.

At the water temperature of 3°C, the azocasein hydrolysis specific activities were higher when the scallops were at lower salinities (15 ppt and 20 ppt) (Table 7). There were no significant differences between small and large juveniles (ANOVA; $F = 0.03$, $P = 0.864$). At 3°C, the azocasein hydrolysis specific activities among salinities were significantly different in small (ANOVA; $F = 3.06$, $P = 0.040$) and large (ANOVA; $F = 6.31$, $P = 0.001$) juveniles. The highest azocasein hydrolysis specific activities were both

at 3°C and 20 ppt for small (0.85 ± 0.04 mean OD/H/mg protein) and large juveniles (0.94 ± 0.09 mean OD/H/mg protein). There were no results for azocasein hydrolysis specific activities at temperature trials > 3°C.

The specific activities of lysozyme were much higher at the coldest water temperature (3°C) for scallops at all remaining salinities (Table 8). There were significant differences between small and large juveniles (ANOVA; $F = 1.69$, $P = 0.009$). At 3°C the specific activities of lysozyme were significantly different among salinities in small juveniles (ANOVA; $F = 6.89$, $P = 0.001$) and were also significantly different among salinities in large juveniles (ANOVA; $F = 38.40$, $P < 0.001$). As well, for small juveniles, the specific activities of lysozyme at the 3°C temperature trial were significantly different with lysozyme concentrations at the rest of the temperatures tested (ANOVA; $F = 23.22$, $P < 0.001$). The highest specific activities of lysozyme were both at 3°C and 20 ppt for small (49.67 ± 10.65 units/mg protein) and large juveniles (44.32 ± 5.62 units/mg protein). Concentrations were much lower at temperature trials ≥ 8°C ranging from 0.052 ± 0.029 to 0.178 ± 0.059 units/mg protein.

For the specific activities of the three stress enzyme indicators at 3°C (small and large juveniles), the means for groups (temperatures and salinities) in homogenous subsets were compared using the Tukey's HSD at $\alpha = 0.05$. The results are shown in Appendix 5.

2.4 Discussion

2.4.1 Salinity-Temperature Bioassay

This experiment showed that during a ten-day exposure period, juvenile scallops had 100% survival and typical behavioural responses at a salinity ≥ 25 ppt and a temperature ≤ 18°C. This information is useful because Penney and Mills (2000) state that for the aquaculture industry to be economically viable the survival should be > 80%.

In this experiment, *Placopecten magellanicus* died within the first few hours at low salinities (5 ppt and 10 ppt) and were less tolerant to salinity at increasing temperatures. Bergman et al. (1996) had similar findings in which salinities of 16 ppt and below were lethal for juvenile sea scallops and catatonic shock was observed in the 18 ppt and 21 ppt groups. The same authors also concluded that a long-term exposure limit of approximately 18 ppt as well as a short-term exposure limit of 13.5 ppt would result in mortality. Ledwell (1995) exposed adult sea scallops to different salinities (15, 20 and 25 ppt) at two temperatures (0°C and 10°C). One hundred percent mortality was observed at day 9 in scallops at 15 and 20 ppt in 0°C and at 48-h in 10°C in 15 ppt. High mortality at low salinities also occurs in other scallop species. Paul (1980) determined that after a 24-h exposure, depending upon the temperature and the size of the queen scallop, *Chlamys opercularis,* salinities ranging from 16 to 28 ppt were lethal. Mortality also increased at the highest experimental temperature, 20°C (± 2°C), and spat appeared to have a slightly greater tolerance than larger individuals. Tettelbach et al. (1985)

documented a mass mortality of the bay scallop (*Argopecten irradians*) following severe spring rainstorms. They found that the only time when bay scallop mortality appeared to result from low salinity-related effects was when the salinity reached a low of 12.2 ppt. The indirect effect of the reduced salinities, whereby scallops gaped widely and were more susceptible to predatory attacks, apparently contributed to mortality in the wild scallop population.

This study found that the critical point for temperature tolerance for juvenile sea scallops was at 23°C. This result is supported by other studies. For example, Dickie (1958) found for adult sea scallops, that water temperatures over 23.5°C caused large-scale mortalities in a wild population. Temperatures over 21°C also may have sub-lethal effects under certain circumstances (Dickie 1958; Potter et al. 1997). For adult sea scallops, Potter et al. (1997) found higher exfoliation rates of the epithelial cells at the highest experimental temperature (21.0°C) than rates recorded at 8.5°C and 14.7°C. Potter et al. (1997) also noticed some damage to the gill, mantle, and gonad when scallops were exposed to 14.7°C and 21.0°C for a total of 8-d.

In this study, the behavioural responses for both size classes of juvenile sea scallops at decreasing salinities and increasing temperatures with increasing time exposure were consistent with the mortality patterns of scallops in other studies. Foot extension and the poor response to repeated probing at salinities of 15 and 20 ppt was similar to the behaviour of adult sea scallops in Ledwell (1995). These behaviours suggested that the animal was experiencing severe stress due to low salinities. However, when scallops byssally attach, this is believed to be an indication of optimal conditions. Paul (1980) found that the highest rate of byssal attachment in the queen scallop

(*Chlamys opercularis*) spat occurred at 18°C and that attachment was 100% after 24-h in 30 ppt at 15°C and 20°C. In this study, sea scallop spat also had the highest rate of byssal attachment at 18°C; however 100% attachment after 24-h in 30 ppt occurred at a lower temperature (8°C). Duggan (1975) found that when subjected to abrupt salinity changes, the initial response of the bay scallop (*Argopecten irradians*), in all size groups, usually followed one of two patterns: shell gaping coupled with rapid adduction and swimming, or immediate shell-closure. In the present study, similar observations were observed with juvenile sea scallops. However, scallop swimming was limited probably because of the high density of animals per tray (10 spat in 2 L of water). Such behaviour in the wild could lead juvenile scallops to being subjected to depredation (Ledwell 1995). In a farming habitat, culture cages would protect them from any predators, yet they would be vulnerable to any environmental changes.

2.4.2 Clearance and Ingestion Rate

Scallop clearance rates (F) and ingestion rates (IR) had a similar pattern in their response to temperature and salinity. Ward et al. (1992) and Sicard et al. (1999) found that when clearance rate increased so did ingestion rate and conversely, when clearance rate decreased so did ingestion rate. In this study, there were significant differences among all the temperatures and salinities for both small and large juvenile sea scallops. Thus, as salinity increased so did F and IR, resulting in the highest readings at ambient salinity. Whereas, for temperature, F and IR were highest at 13°C and the lowest concentrations were recorded at 3°C and 23°C.

The optimum water condition (ambient salinity at 13°C) had the best feeding rate for *Placopecten magellanicus* in the present study and was similar to other studies. Kleinman et al. (1996a) compared, in the laboratory, the growth rate of juvenile sea scallops at a temperature regime of 7 to 13°C to a lower temperature regime of 4 to 7°C, and found that the scallops had significantly better growth at 7 to 13°C and were in better physiological condition. Adult *Placopecten magellanicus* were studied (135–155 mm shell height) at two different depths (10 and 30 m) in Sunnyside, Newfoundland, and the highest clearance rate was recorded in September when the water temperature was the warmest (10 m = 12°C and 30 m = 8°C) (MacDonald and Thompson 1986). The clearance rate of *Argopecten purpuratus* was higher at 30 and 27 ppt at a temperature of 12°C, decreasing significantly at lower salinities (≤ 24 ppt) (Navarro and Gonzalez 1998). Overall, for ideal F and IR readings, experimental temperatures should range from 8 to 18°C (Figures 7a and 7b, Figures 8a and 8b).

High clearance and ingestion rates are indicators of healthy scallops, showing better growth. However, besides salinity and temperature, clearance and ingestion rates are also affected by the quality and amount of food supply available, which is in a constant state of fluctuation in coastal and shelf environments as particle types and concentrations are affected by a range of natural and human-induced processes. For example, Cranford et al. (1998) found that resuspension of bottom materials during a storm resulted in large changes in the amount and nutritional quality of seston. It was concluded that the overall reduction in ingestion rates after the storm resulted from decreased food availability.

2.4.3 Oxygen Consumption

Oxygen consumption is an important metabolic measurement because high oxygen consumption may indicate that a scallop is under stress due to metabolic activity related to stress. In this study, the highest VO_2 was recorded at ambient salinity at 13°C (0.1 g sea scallop). The results also showed that there was a significant difference among temperatures but not among salinities.

Salinity results showed that at ambient salinity oxygen consumption was 0.46 ± 0.04 mL/h (13°C), decreased to 0.19 ± 0.02 mL/h (13°C) at 30 ppt, and increased again to 0.37 ± 0.03 mL/h (13°C) at 25 ppt. It is possible that the results are not consistent in regards to salinity because of the low number of scallops tested (see Appendix 1 for exact numbers tested). However, the overall pattern, when all the salinities are considered, indicated that the higher the salinity, the higher the oxygen consumption. In contrast, according to Navarro and Gonzalez (1998), the oxygen consumption of *Argopecten purpuratus* (1 g dry tissue weight) increased with decreasing salinity from 30 ppt (0.54 mL/h) to 24 ppt (0.84 mL/h) at a water temperature of 12°C.

In regards to temperature, the highest oxygen consumption was recorded at 13°C for all the salinities tested (15 ppt to ambient). Thus, regardless of the salinity, when the temperature was at 13°C, high oxygen consumption values were recorded. This implies that temperature may have a larger impact on oxygen consumption than salinity (Appendix 4). Other studies also indicate that high oxygen consumption is recorded in the range of 13°C. For example, Shumway et al. (1988) who studied adult *Placopecten magellanicus* in Maine found that in July 1985 the oxygen consumption was 0.84 ± 0.053

mL/h at 17°C (early July) and 0.84 ± 0.04 mL/h at 19°C (late July). However the highest oxygen consumption was recorded in May of the same year with a reading of 0.862 ± 0.062 mL/h at 11°C. MacDonald and Thompson (1986) found that the oxygen consumption rates for *Placopecten magellanicus* sampled from Sunnyside, NL (10 m and 31 m) were highest when the temperature ranged from 7°C to 12°C.

2.4.4 Stress Enzyme Indicators

Marine animals respond to salinity changes by trying to protect themselves from direct contact with a changing environment by secreting mucus (Kinne 1971). The alkaline phosphatase assay, azocasein hydrolysis assay, and lysozyme assay examine the specific activities of enzymes found in the mucus secreted from the gills of the sea scallops which can be used to possibly indicate the amount of stress that a scallop is experiencing.

In this study, the alkaline phosphatase specific activity was higher when salinity and temperatures were low. As well, there was a high concentration at 23°C with lower concentrations at 13°C and 18°C. For azocasein hydrolysis specific activity there was a significant difference among salinities for small and large juveniles at 3°C (Appendix 5). Thus, salinity seems to be important in regards to stress levels of sea scallops. In regards to temperature, it is very difficult to make comparisons with the small amount of data collected. Most of the data were collected at 3°C, therefore it is difficult to have conclusive data on ideal environmental conditions (13°C based on F, IR) for sea scallops.

However, the overall pattern indicated that the scallops are under more stress at extremes of low and high temperatures and were least stressed at 13°C and 18°C.

Other studies also confirm that the presence of alkaline phosphatase and lysozyme activities in the mucus secretion of marine animals is a good indicator of stress levels. Iger and Abraham (1997) reported that a number of stressors including acidity, thermal elevation, polluted water and distilled water resulted in increases in the number of alkaline phosphatase-positive Rodlet cells in the skin of rainbow trout. In a study by Brun et al. (2000), it was shown that when the Eastern oyster (*Crassostrea virginica*) is infected with the turbellarian *Urastoma cyprinae* it will secrete a mucus that contains a multitude of active components, including hemolysins, lysozymes, agglutinins, lectins, and proteases. Those active components are thought to have important roles in host defense mechanisms of vertebrates and invertebrates (Cornick and Stewart 1968; Ingram 1980; Ellis 1981; Hjelmeland et al. 1983; Fisher and DiNuzzo 1991; Alexander and Ingram 1992; Canicatti et al. 1992; Fisher 1992).

2.5 Conclusion

The purpose of this experiment was to simulate typical estuary-like conditions of southeastern New Brunswick and to determine the survival and behavioural responses of juvenile sea scallops at various temperatures and salinities. Thus, the salinity-temperature tolerance of juvenile sea scallops under controlled laboratory conditions was studied. As well, changes in metabolism such as clearance rate, ingestion rate, oxygen consumption,

and induction of stress were also measured to assess the health of the scallops at experimental temperatures and salinities.

In conclusion, this laboratory study showed that in order to have 100% survival, the water conditions should be ≥ 25 ppt and ≤ 18°C. These results are in agreement with previous studies (Dickie 1958; Ledwell 1995; Bergman et al. 1996). Also, optimum water conditions for the best feeding rate (clearance and ingestion) of *Placopecten magellanicus* would be at ambient salinity at a temperature a 13°C. Thus, a site with water conditions of ≥ 25 ppt and a range of 8–18°C would be most suitable. Scallops can live in lower temperatures and still survive, but growth rate would be lower. Basically, high temperatures and low salinities in a marine environment are stressful conditions for *Placopecten magellanicus*. This is important to consider when aquaculturists are selecting a site for sea scallop aquaculture.

While water temperature and salinity are probably the most important factors to consider when selecting a site, there are other environmental parameters that will also affect the success of an aquaculture farm. In the next section, six sites will be evaluated for their feasibility as possible sea scallop aquaculture sites.

Chapter Three

Growth and Survival of Juvenile Sea Scallops (*Placopecten magellanicus*) in Shallow Water Embayments of Southeastern New Brunswick

3.1 Introduction

Existing oyster (*Crassostrea virginica*) and/or mussel (*Mytilus edulis*) growers in southeastern New Brunswick want to diversify their operations by introducing the sea scallop to their aquaculture sites. Those aquaculture leases are located in shallow water estuaries; whereas wild scallop beds are located in deeper water in the Northumberland Strait. In estuaries, sea scallops held in culture may have to cope with many environmental parameters that are not optimal for growth and survival. The most important physical factors are salinity and temperature (Kinne 1971; MacDonald and Thompson 1985, 1986; Bricelj and Shumway 1991; Thompson and MacDonald 1991). For example, heavy freshwater inflow during spring season, when rivers and streams are discharging their peak loads, can affect the growth and survival of the sea scallops (Robinson et al. 1981; Bergman et al. 1996). As well, a lack of depth in the coastal lease sites along southeastern New Brunswick can result in high temperatures during the summer season. Thus, having knowledge of site characteristics is crucial for the survival and growth of sea scallops.

By choosing an adequate site for culture with high food availability and protection from predators (cages), scallop growth can be faster in culture than in the wild (MacDonald and Thompson 1985, 1986; Barber and Blake 1991; Claereboudt et al. 1994a; Emerson et al. 1994; Gaudet 1994). Barber and Blake (1991) reported that a lack of food at greater depths (170–180 m) resulted in a lower adductor muscle size and glycogen content and in addition, a reduction in fecundity. In shallower water (13–20 m) the growth of the muscle and gonad was superior. The timing of spat deployment can

also affect scallop growth. Growth rates of cultured *Placopecten magellanicus* are highest in the summer and lowest in the winter (Dadswell and Parsons 1991, 1992; Côté et al. 1993; Kleinman et al. 1996b; Parsons et al. 2002) and show no increase during the autumn bloom compared with summer (Emerson et al. 1994). Grecian et al. (2003) found that the highest growth rates and retrieval of nursery-sized scallops were observed during August and early September when the nursery site water column was characterized by high food densities, high temperature and low sea star settlement. Thus, spat deployed during optimal food density and temperatures have higher growth rates and survival (Dadswell and Parsons 1992; Couturier et al. 1995).

Sea scallops, like oysters and mussels, are active suspension feeders ingesting phytoplankton, small zooplankton, spores, and detrital particles (Posgay 1963; Shumway et al. 1987; Cranford and Grant 1990). However, there are differences in feeding ability and food sources among scallops, mussels, and oysters. Many suspension-feeding bivalves have the capacity to enhance the quality of particles consumed by rejecting particles of lower nutritive value as pseudofeces. However, selection efficiencies vary widely among bivalves (Kiørboe and Mhølenberg 1981). For example, indirect evidence of fine particle selection has been observed for the American oyster (*Crassostrea virginica*) feeding on mixed suspensions of silt and algae (Newell and Jordan 1983). As well, Pierson (1983) documented that bay scallops (*Argopecten irradians*) will ingest virtually all diatoms *Phaeodactylum tricornutum* Bohlin (clone Phaeo). Shumway et al. (1985) showed that in monospecific cultures, sea scallops would preferentially reject the same diatom in mixed-cell suspensions and that cryptophytes are a preferred alga in mixed diets and are related to growth in sea scallops (Shumway et al. 1985, Parrish et al.

1995). It is expected that scallops exposed to a higher quality diet allowing adaptation to declining conditions would perform better than scallops exposed to a lower quality diet (Shumway et al. 1997).

Many studies have shown that scallop growth rates vary markedly among culture sites and depths (MacDonald and Thompson 1986; Dadswell and Parsons 1992; Emerson et al. 1994; Gaudet 1994; Kleinman et al. 1996b). Differences in scallop growth are usually attributed to variations in the local water temperature and the concentration of suspended particulate organic matter (Brannen 1940; MacDonald and Thompson 1985; Wilson 1987; Grant and Cranford 1991; Andersen and Naas 1993; Kleinman et al. 1996b; MacDonald et al. 1998). MacDonald and Thompson (1985) found that shell growth was higher under favourable conditions of food and temperature, and that this was site specific.

When culturing scallops, there will be fouling on the culture gear. The amount and type of fouling will be determined by location, depth, strength of the water current or water mixing, and turbidity. Sources of turbidity include phytoplankton, organic matter, presence of humic substances, and inorganic materials such as suspended clay and silt (Almazan and Boyd 1978). Besides, fouling and turbidity, it is also important to examine if the seston concentration is high at a site, as well as chlorophyll-a concentrations and the composition of the benthic sediment. When there is a large amount of water mixing, the sediment grain size can affect the concentration of turbidity and seston, this in turn, can affect feeding quality which can affect growth. For example, according to Cranford (1994), sea scallops are highly sensitive to the presence of low concentrations (< 10 mg/L) of suspended clay leading to adverse effects on feeding rate and the low ability to

selectively reject fine inorganic particles prior to ingestion. Larger inorganic particles appear to have less impact on sea scallop growth owing to a greater capacity to maintain high filtration rates while rejecting these particles as pseudofeces. Thus, if a site has a large amount of clay particles this could affect scallop feeding when the sediment is disturbed due to natural or human-induced processes.

The main objective of this study was to determine the biological feasibility of culturing. The influences of environmental, physical, and biological factors were examined.

3.2 Materials and Methods

3.2.1 Study Sites and Spat Origin

The four aquaculturists who participated in this project are currently growing mussels and/or oysters. The names of the four participants, the species they are culturing, and the location of their sites are listed in Table 9. All study sites were estuaries and were located along the Northumberland Strait in southeastern New Brunswick (Figure 10). A brief general overview of each bay: Bouctouche, Cocagne, Little Shemogue, and Richibucto (sites 1, 2 and 3) is presented in Table 10. The approximate area (km^2) for each bay was calculated and listed in Table 10 (for an example of the calculation used see Appendix 6).

The spat (10,000 including 15% to replace mortality due to transportation stress) were obtained from a commercial wild collection site in Arichat, NS (spawned in autumn

1997). A health check of a sample of scallop spat was conducted by Dr. Sharon McGladdery's laboratory, Department of Fisheries and Oceans (Moncton, NB), prior to the transfer of scallop spat to the Northumberland Strait.

3.2.2 Experimental Design

The experimental design involved placing two size classes of scallops, small juveniles (10.0–20.0 mm, mean = 17.67 mm in shell height) and large juveniles (20.1–35.0 mm, mean = 25.15 mm in shell height), at each study site. In collaboration with the corresponding aquaculturist, each size class of scallops was placed in duplicate cages at the deepest location at each test site. At the study sites in Cocagne Bay, Little Shemogue Bay, Richibucto Bay (sites 2 and 3) two wire-mesh cages (600 mm X 920 mm and 48 mm aqua-mesh size across) each containing four Vexar™ bags (790 mm X 510 mm and 9 mm mesh size across) were suspended 0.5 m from the bottom (Figure 11a). In Bouctouche Bay the wire mesh cages with the Vexar™ bags and in Richibucto Bay (site no.1) only the Vexar™ bags were attached on a metal table also 0.5 m from the bottom (Figure 11b). Each Vexar™ bag for each size group contained 100 juvenile scallops. The aquaculturists provided the anchors, lines, buoys, labour, and boats.

3.2.3 Growth and Survival

The shell height of juveniles, i.e., maximum distance between the dorsal (hinge) and ventral margins (Figure 1), of 100 small juvenile scallops and 100 large juvenile

scallops, was recorded to the nearest 0.01 mm using an electronic calliper (Mitutoyo Corporation™). These measurements were used as a representation of the entire population. Additionally, a separate sample of 100 scallops was also randomly selected for each size class for shell heights and soft tissue body weights. Individual tissue weights (gonad, meat, and viscera combined) were recorded after drying at 90°C for 48-h. At each biological sampling date, a sample of 20 scallops for each size class at each study site was retained for the same initial morphological measurements.

Small and large juvenile scallops were then placed at the appropriate study sites (in October 1998). During the summer of 1999, biological samples (growth rate and survival) on the two sizes of juvenile scallops were taken and environmental parameters (see below) were monitored for all six sites. It is important to note that, the accessibility to each aquaculture site depended upon the availability of the aquaculturists, thus the cultivated scallops from different sites had different biological sampling frequencies (Appendix 7). The study sites were covered with ice from December to March annually, therefore no sampling of environmental conditions nor scallop growth and survival could be undertaken. At each sampling date, 30 scallops were randomly selected from each bag, from each study site, and for each size group for shell height measurements. The final sampling was completed in October/November 1999. The growth rate (GR) of the scallops was calculated as follows:

$$GR = (H_2 - H_1) / t$$

where H_2 is final shell height in millimetres, H_1 is initial shell height and t is total elapsed time in days.

The survival (%) between sampling dates was calculated as the number of living scallops divided by the number of living scallops from the previous sampling date minus any scallops that were removed for morphological measurements multiplied by one hundred. The survival (%) at the end of the 13-month grow-out period is equal to the initial number of scallops (n = 100 per culture bag) minus the total number of dead scallops at each sampling date.

3.2.4 Fouling

Observations of fouling (type and amount) on the culture cages were also recorded at the same time as the biological sampling. The three types of fouling recorded were: blue mussel spat (*Mytilus edulis*), barnacles (*Balanus balanoides*), and eelgrass (*Zostera marina*). The amount of fouling was an approximate percentage of covering on the cages based upon visual observation.

3.2.5 Environmental Parameters

The following environmental parameters were monitored at high or rising tide for each study site: salinity, temperature, seston, chlorophyll-a and turbidity. A benthic sediment composition sample was taken at each site at the beginning of the study to measure the sediment grain size. When water samples were required to measure environmental parameters, they were collected at the same depth as the juveniles, using a submersible pump. A sample of water (2,000 mL in a transparent plastic bottle) was

collected at each study site and was then transported in a cooler to the laboratory to be filtered for seston. Another sample of water (1,000 mL in an opaque plastic bottle) was collected at each study site. To preserve the existing algae, a couple of drops of $MgCO_3$ were added to the samples and were transported in a cooler to the laboratory to be filtered for chlorophyll-a.

3.2.5.1 Salinity

The salinity, in parts per thousand (ppt), was determined on site using a hand-held refractometer (Shilac© Pur-1410).

3.2.5.2 Temperature

A temperature recorder (Vemco™ Temperature Logger, Minilog-TR: cylindrical shape, 94 mm in length and 21 mm wide) was utilised to collect temperature data. The device was programmed to take a temperature reading every hour and was then securely attached to one selected Vexar™ bag at every site. The temperature data (± 0.1°C) were recorded from June 1998 to late November 1999.

3.2.5.3 Seston

Seston is the total suspended particulate matter (TPM), which is composed of the particulate organic matter (POM), and the particulate inorganic matter (PIM). The

methods and equations utilized were taken from Wetzel and Likens (1979) and Newell (1982) (Appendix 8).

3.2.5.4 Chlorophyll-a

Chlorophyll-a was determined using the standard methods and equation from Strickland and Parsons (1968) (Appendix 9).

3.2.5.5 Turbidity

A secchi disk, 30 cm in diameter, with a 1.5 kg weight attached to a rope line graduated in metres was lowered at each study site near the cages. The lowest depth (m) at which the black and white of the disk could be distinguished was recorded as the secchi disk visibility (SDV). The SDV is a good indicator for phytoplankton concentration, which is commonly used by aquaculture pond managers (Jamu et al. 1999). Thus, secchi disk depth is primarily used as an indicator of algal abundance and general lake productivity. However, organic matter, colour of humic substances and inorganic materials like suspended clay may also be significant sources of turbidity.

The unit of measurement to express turbidity was in metres and considered to be the overall light extinction coefficient (k_t). The k_t was estimated from the SDV measurements using the Poole and Atkins (1929) equation:

$k_t = 1.7 / SDV$

3.2.5.6 Benthic Sediment Composition

In summer 1998, bottom samples were collected from each of the six study sites by using the Heavyweight Deep Water Bottom Dredge® (stainless steel, 11.3 kg in weight, effective sampling area of 91.44 cm^2). Samples were brought to the laboratory to be dried. Granulometric sizings were then conducted using the methods from Bellair and Pomerol (1984) (Appendix 10).

3.2.6 Data Analysis

The Chi-square test ($\alpha = 0.05$), using Microsoft Excel XP©, was used to verify if growth rate and survival were dependent on the size class of juveniles and the site of culture. After having their overall growth rate calculated, each size class of juveniles were placed into four different growth groups in mm/day, which allowed the calculation of the Chi-square test. The growth groups were <0.047 mm/d; 0.047– 0.062 mm/d; 0.063–0.078 mm/d; and >0.079 mm/d (Appendix 11). The number of scallops found in each group was used for the observed values. The expected, or predicted, values for the survival were 100% based upon the shortness of the study. The observed values were the actual total number of living scallops minus the number of dead animals per duplicate cages at the end of the study.

Values for dry tissue weight (W_{dt}) and shell height (S_h) for small and large juveniles at each test site, from the initial sampling (n = 100) until after the biological samplings (n = 20) were fitted to the power curve regression equation

$$\text{Log } W_{dt} = a + b \log S_h$$

where W_{dt} is in grams and S_h is in millimetres and a and b are fitted parameters, the slope and intercept were then presented in a summary table (Table 11). The regression parameters (slope and intercept) were compared by means of an analysis of covariance (ANCOVA, $\alpha = 0.05$) by using SPSS 10.0© for Windows©. The factor "weight" was the dependent variable and the factor "height" was the covariate. When the ANCOVA results showed significant differences among sampling dates, a parameter estimates table was then calculated. The final sampling date was used as the reference date. The results in the parameter estimates table identified more specifically which sampling dates were different from the others.

To compare the environmental parameters (salinity, temperature, chlorophyll-a, turbidity, PIM, and POM) among culture sites, the analysis of covariance (ANCOVA, $\alpha = 0.05$) was used. The different environmental parameters were the dependent variables. The factor "day" was a continuous factor and was identified as a covariate. When the ANCOVA results showed significant differences among sites and the specific environmental parameter being evaluated (e.g., salinity), a parameter estimates table was then calculated. Little Shemogue Bay was used as the reference site, yet, any site could have been chosen. The results in the parameter estimates table identified more

specifically which sites were different from the others in regards to the parameter being analysed.

3.3 Results

3.3.1 Growth and Survival

The shell height (mm) for small and large juvenile scallops was measured at each sampling date for the six study sites during October 1998 to November 1999 and the growth rate (mm/d) was calculated (Tables 12 and 13). Growth rate of scallops were significantly different among sites (Chi-square test; $P < 0.001$) and between size classes (Chi-square test; $P < 0.001$). The small juveniles at Richibucto Bay (site 1) had the best growth rate (0.061 ± 0.006 mm/d), followed by Bouctouche Bay (0.057 ± 0.001 mm/d) and Cocagne Bay (0.049 ± 0.002 mm/d). For large juveniles, the best growth rate was at Cocagne Bay (0.075 ± 0.008 mm/d) followed by Bouctouche Bay (0.053 ± 0.003 mm/d) and Richibucto Bay (site 1) (0.049 ± 0.008 mm/d). The large juveniles in Richibucto Bay (site 3) were all dead at the first sampling date (August 23, 1999).

The average survival (%) for small and large juvenile scallops was calculated at each sampling date for the six study sites during October 1998 to November 1999 and the survival (%) was calculated at the end of the 13-month grow-out (Tables 12 and 13). At the end of the 13-month study period, surviving scallops were only found in Bouctouche Bay, Richibucto Bay (site 1) and Cocagne Bay. There were no significance differences in

survival between small and large juveniles within each study site: Bouctouche Bay (Chi-square test; $P = 0.24$), Cocagne Bay (Chi-square test; $P = 0.22$), and Richibucto Bay (site 1) (Chi-square test; $P = 0.689$). The survival of both of the size classes among the three sites was significantly different from each other (Chi-square test; $P < 0.001$). For both size classes, the scallops held in Bouctouche Bay had the highest overall survival (small: 84.2 ± 3.86%, large: 88.1 ± 14.42%); followed by Richibucto Bay (site 1) (small: 53.0 ± 0.22%, large: 52.0 ± 0.22%); and Cocagne Bay (small: 41.0 ± 4.51%, large: 37.4 ± 13.88%). Scallops held in Richibucto Bay (sites 2 and 3) and Little Shemogue Bay were all dead before September 1999 (11 months of grow-out). The survival for small juveniles in Cocagne Bay decreased from 98% to 47% during the period of July to October (9–12 months of grow-out). For large juveniles in Cocagne Bay, at the first sampling date in September there was 50% survival, of which 76% survived for another month, resulting in a final survival rate of 37%.

The shell height vs. dry tissue weight power curve relation of small and large juveniles from the initial sampling to the biological sampling dates was regressed to determine the slope and intercept (Table 11). All study sites had significant differences between regression parameters (slope and intercept) for small and large juveniles from the initial sampling date and sampling date 1 (ANCOVA; $P < 0.001$) with the exception of large juveniles at Richibucto Bay (site 2) (ANCOVA; $F = 0.50$, $P = 0.479$). Only 17 small juveniles and 20 large juveniles were left in Little Shemogue Bay for sampling date 1 and no data were available for sampling date 1 for small and large juveniles at Richibucto Bay (site 3). The parameter estimates table, using the final sampling date as

the reference, showed that there was no significant difference found between sampling date 1 and sampling date 2 in small juveniles at Bouctouche Bay ($P = 0.76$) and Cocagne Bay ($P = 0.38$). There was also no significant difference found between sampling date 1 and sampling date 2 in large juveniles at Cocagne Bay ($P = 0.10$).

3.3.2 Fouling

A general observation of the type and the amount (%) of fouling on the culture cages was recorded at the same time as the biological sampling at all study sites. The three types of fouling recorded were: blue mussel spat (*Mytilus edulis*), barnacles (*Balanus balanoides*), and eelgrass (*Zostera marina*) (Table 14). The culture cages in Little Shemogue Bay were the ones with the highest amount of fouling; the cages in Richibucto Bay (site 1) had the lowest amount with only traces of dead algae.

3.3.3 Environmental Parameters

3.3.3.1 Salinity

Salinity readings at the six study sites were taken from October 1st to November 25th, 1998 and from July 2nd to November 15th, 1999 (Figures 12a to 12f). Giving the amount of sampling at each site, Bouctouche Bay had the highest average salinity concentration reaching 30 ppt several times in the summer and the autumn. Richibucto

Bay (site 3) recorded the lowest average salinity; its overall average value was 20.8 ± 2.1 ppt.

The ANCOVA results showed that there was a significant difference between the sites and salinity (ANCOVA; $F = 50.96$, $P < 0.001$). The parameter estimates table, using Little Shemogue Bay as the reference site, showed that Bouctouche Bay ($P < 0.001$) and Richibucto Bay (site 3) ($P < 0.001$) were significantly different in salinity from the reference site.

3.3.3.2 Temperature

Water temperature (°C) at the six study sites was recorded every hour from early October 1998 to late November 1999 (Figures 13a to 13f). The mean daily and monthly temperatures for every site for the 13-month study period were calculated (Table 15). It was found that Little Shemogue Bay and Bouctouche Bay both had the highest overall water temperature during the study. Whereas, Richibucto Bay (site 1) was the only one that did not have a monthly average water temperature > 20°C during the months of July and August 1999 (Table 15). Also, Richibucto Bay (site 1) was the only site that did not have one day with average temperatures over 23.5°C and also had the least number of days (10) with average temperatures over 21°C. The ANCOVA results showed that there was a significant difference between the sites and temperature (ANCOVA; $F = 88.40$, $P < 0.001$). The parameter estimates table, using Little Shemogue Bay as the reference site, showed that all of the sites were significantly different in temperature from the reference site ($P < 0.001$) except for Bouctouche Bay ($P = 0.094$).

The temperature data were further sorted into four categories to analyze the number of consecutive days that the water temperature was in a specific temperature range. The four categories were: 1) between 10°C–15°C, best growth range (Young-Lai and Aiken 1986), 2) 13°C ± 1°C, optimum conditions for F and IR (results in chapter 2), 3) over 21°C, the stress boundary, and 4) over 23.5°C, the lethal boundary (Dickie 1958). This breakdown of data allowed for observation of specific water temperature conditions at the six sites considered important for the scallop culture (Table 16). The results showed that Little Shemogue Bay had the highest number of consecutive days (n = 39) with a water temperature between 10°C–15°C. Richibucto Bay (sites 2 and 3) both had the most consecutive days (n = 20) with temperatures ranging from 13°C ± 1°C. Richibucto Bay (site 2) had the highest number of consecutive days (n = 44) over 21°C. Whereas, Little Shemogue Bay had the most number of consecutive days (n = 4) with a water temperature over 23.5°C.

3.3.3.3 Seston

Water seston (TPM), as well as POM and PIM, concentrations in mg/L at the six study sites were taken from November 3rd to November 25th 1998 and from July 2nd to November 14th 1999 (Figures 14a to 14f). During the 13-month study, based upon the data collected, Richibucto Bay (site 2) revealed the highest overall average in TPM (37.27 ± 18.83 mg/L) and POM (6.45 ± 4.01mg/L), the highest overall average PIM was found in Cocagne Bay (31.74 ± 12.19 mg/L). The lowest overall average of TPM (19.78 ± 3.72 mg/L), POM (1.91 ± 0.54 mg/L) and PIM (17.87 ± 3.37 mg/L) were all found in

Richibucto Bay (site 1). In general, when combining all six study sites, there was more suspended particulate matter during the autumn months (October-November) than the summer months (July-September). The average POM and PIM, respectively, were 4.28 ± 1.96 mg/L and 36.11 ± 14.78 mg/L during autumn 1998, and 5.15 ± 3.46 mg/L and 29.76 ± 12.65 mg/L during autumn 1999. During the summer 1999 the average POM and PIM was 2.18 ± 1.33 mg/L and 23.56 ± 12.34 mg/L, respectively.

The ANCOVA results showed that there was a significant difference between the sites and particulate organic matter (POM) (ANCOVA; $F = 2.80$, $P = 0.032$). The parameter estimates table, using Little Shemogue Bay as the reference site, showed that Richibucto Bay (site 2) ($P = 0.030$) was the only site that was significantly higher in POM concentrations from the reference site. The results also showed that there was no significant difference between the sites and particulate inorganic matter (PIM) (ANCOVA; $F = 1.45$, $P = 0.233$). There was also no significant difference between the sites and total particulate matter (TPM) (ANCOVA; $F = 1.78$, $P = 0.144$).

3.3.3.4 Chlorophyll-a

Chlorophyll-a concentrations in µg/L at the six study sites were taken from November 18th to November 25th 1998 and from July 2nd to November 14th 1999 (Figures 15a to 15f). During this period, giving the amount of sampling, Cocagne Bay recorded the highest overall average chlorophyll-a concentration (7.5 ± 2.2 µg/L). The lowest overall average of chlorophyll-a (2.8 ± 1.1 µg/L) was found in Richibucto Bay (site 1). In general, when combining all six study sites, there were higher chlorophyll-a

concentrations in the water during the summer months (July-September) than the autumn months (October-November). The average chlorophyll-a was 5.8 ± 2.1 μg/L during summer 1999. The average chlorophyll-a concentrations during the autumn 1998 (5.0 ± 0.40 μg/L) and autumn 1999 (5.2 ± 1.41 μg/L) were lower.

The ANCOVA results showed that there was a significant difference between the sites and chlorophyll-a concentrations (ANCOVA; $F = 3.88$, $P = 0.008$). The parameter estimates table, using Little Shemogue Bay as the reference site, showed that Richibucto Bay (site 1) ($P = 0.012$), Richibucto Bay (site 2) ($P = 0.042$) and Richibucto Bay (site 3) ($P = 0.023$) were significantly lower in chlorophyll-a concentrations during the study period from the reference site.

3.3.3.5 Turbidity

Water turbidity, i.e., the overall light extinction coefficient, at the six study sites was taken from October 1st to November 25th 1998 and from July 16thto November 14th 1999 (Figures 16a to 16f). Based upon the data collected, Little Shemogue Bay was found to have the highest overall water turbidity (average = 1.79 ± 1.08 m). The lowest overall water turbidity (average = 0.69 ± 0.19 m) was found in Richibucto Bay (site 1). In general, when combining all six study sites, the water turbidity was higher during the autumn months (October-November) than the summer months (July-September). The average water turbidity was 1.37 ± 0.60 m during autumn 1998 and 1.18 ± 0.33 m during autumn 1999. The average water turbidity was lower during summer 1999 (1.04 ± 0.68 m).

The ANCOVA results showed that there were no significant differences between the sites and turbidity (ANCOVA; $F = 1.65$, $P = 0.197$).

3.3.3.6 Benthic Sediment Composition

The granulometric sizing of the bottom samples collected from the six study sites is presented as the benthic sediment composition measurements (Figures 17a to 17f). For the sites of Cocagne Bay and Richibucto Bay (site 1), the majority of the sediment was retained on the 0.1 mm sieve. In Bouctouche Bay, the majority of the sediment was retained on the 0.25 mm sieve. Richibucto Bay (site 2), Richibucto Bay (site 3) and Little Shemogue Bay had the largest sediment particles, the majority of which were retained on the 0.5 mm sieve. Those same three sites had the highest amount of sediment particles in the smallest category size (< 0.05 mm). Almost 20% of their sediment sample was under 0.05 mm, which is in the category of silt (0.002 to 0.06 mm) and clay (less than 0.002 mm) in particle size.

3.4 Discussion

3.4.1 Growth and Survival

The growth of sea scallops along the Atlantic coast, including Newfoundland, and in the Bay of Fundy has been well documented (MacDonald and Thompson 1985; MacDonald and Thompson 1986; Wildish et al. 1988; Parsons and Dadswell 1992; Gaudet 1994; Parsons and Dadswell 1994). Previous studies have shown that scallop growth rates vary markedly among culture sites and depths. Differences are usually attributed to variations in the local water temperature and concentration of suspended particulate organic matter, upon which scallops feed (MacDonald and Thompson 1985, 1986; Wilson 1987; Barber and Blake 1991; Anderson and Naas 1993; Emerson et al. 1994; Gaudet 1994; Kleinman et al. 1996b).

In this study, the success of cultured scallops was also related to the cage locations and depths. The scallops that were held deeper in the estuary and closer to the opening to the sea, which corresponded to higher salinities and slightly lower temperatures, had better growth and survival. Richibucto Bay (site 1) had the highest growth for small juvenile scallops and Cocagne Bay had the highest growth for large juvenile scallops. The scallops at site 1 (15 m) in Richibucto Bay had a good growth rate even though they were exposed to the lowest suspended particulate organic matter. This was the deepest study site and the overall temperature was slightly lower during warm days (Table 11) and the salinity variation during rainfall was not as great as compared to the other study sites. Kleinman et al. (1996b) also observed similar results, they found that juvenile sea

scallops that were monitored had a higher growth rate when cultured at the bottom (up to 9 m in depth) than those cultured in suspension (6 m).

In this study, small juveniles grew faster than large juveniles except for those held in Cocagne Bay and Richibucto Bay (site 2). These observations are consistent with Penney and Mills (1996). They found that their small grade spat (15.3 mm, mean SH) grew faster (0.093 mm/day). Their large grade spat (22.5 mm, mean SH) grew slower at an average of 0.077 mm/day, which is comparable to the overall growth rate of large juveniles (0.075 mm/day) held in Cocagne Bay in this study. The results of this study are also comparable to the same age scallops grown in pearl nets using the weir stakes method (Wildish et al. 1988). The overall growth rate (mm/d) of small and large juvenile sea scallops at all sites of this study were considerably lower than sea scallops cultured in commercial farming sites, for example, Passamaquoddy Bay, NB (Wildish et al. 1988; Dadswell and Parsons 1991, 1992), Mahone Bay, NS (Dadswell and Parsons 1991) and Notre Dame Bay, NL (Penney and Mills 1996). Scallops at these sites have a better growth rate in mm/d for the same age scallop because these sites also have wild scallop populations and they have lower, more optimal temperatures, greater depths, and a constant ambient salinity.

The weight–height relationship of scallops over a time period is another way of looking at relative changes in growth. Generally, a positive growth in a population will have larger and/or heavier individuals over time. This was the case in this study. From the initial sample to the first sampling date a high positive growth was observed. For the six test sites the time period between initial sampling and the first sampling ranged from 9 to 13-months. The grow-out time between the first and second sampling date was only 1

to 3-months. Thus, there was a higher significant growth observed from the initial to the first sampling date. The results of this study for small juvenile scallops are in agreement with the results in Parsons and Dadswell (1992). For aquaculturists the weight-height relationship is also useful to determine the performance of their sites of culture.

Of the six sites studied, only three had surviving scallops after 13 months. They were Bouctouche Bay, Richibucto Bay (site 1), and Cocagne Bay. Of the three sites, Bouctouche Bay had the highest survival. As well, there was no significant difference in survival between small (10–20 mm) and large (20–35 mm) juvenile sea scallops within each study site. Penney and Mills (1996) noted the opposite observation. Under ideal conditions, in Notre Dame Bay on the northeast coast of Newfoundland where sites of commercial scallop farms are found, the large grade scallop spat (22.5 mm, mean SH) showed higher survival than the small grade spat (15.3 mm, mean SH).

One important observation was that scallops that were not sampled during the summer, which were at Bouctouche Bay and Richibucto Bay (site 1), had better survival. The survival in Bouctouche Bay for small (84.3%) and large (88.1%) juveniles was higher than the survival of long line intermediate culture (pearl nets) of same age juvenile sea scallops in other studies (Wildish et al. 1988; Dadswell and Parsons 1991). The survival in Richibucto Bay (site 1) for small (53.0%) and large (52.0%) juveniles is comparable to the survival of pearl net culture (weir stakes) of same age juvenile sea scallops in Wildish et al. (1988). This suggests that scallops should not be brought to the surface during warm summer months, which may result in a higher survival. If it is absolutely necessary to handle the scallops, steps should be taken to reduce stress-related deaths caused by handling animals at high water temperatures or exposure to air and

drying during measurements (Grieshaber and Gäde 1977; Wildish et al. 1988; Minchin et al. 2000).

3.4.2 Fouling

Fouling organisms that are a concern to shellfish aquaculture are mainly filter-feeding organisms (e.g., tunicates, barnacles, mussels) that are feeding on the same resources as the cultured species. In this study fouling organisms were mostly *Mytilus edulis* (spat), *Balanus balanoides*, and *Zostera marina* (Table 10). Even though eelgrass is not a filter feeder they were a fouling organism, taking into consideration the amount growing on the cages, which was up to 50% coverage on the study cages in Richibucto Bay (site 2). There was also heavy fouling of blue mussel spat on the culture cages in Little Shemogue Bay. This type of fouling may affect the current velocity through culture gear reducing the volume of water and available food and in turn affecting the growth and survival of scallops. The reduction of the water flow through the culture gear reduces the growth rate of the sea scallop (Claereboudt et al. 1994a). Thus, growth can be hindered if the fouling community either blocks off water flow through the nets or competes with scallops for food or space resources. The degree of fouling, or at least composition of the fouling organisms, can be controlled by changing the time of net deployment (Parsons and Dadswell 1994). For example, Wildish et al. (1988) showed that there was considerable net fouling during peak months of September/ October and that fouling still occurred over winter but it was less severe.

Claereboudt et al. (1994b) concluded that at a strong current site, tissue masses were greater for scallops inside than outside pearl nets. In high-energy environments where growth can be limited because high current velocities inhibit feeding, scallops grow better inside enclosures because of the reduction in current velocity caused by the enclosures. Thus, bays thought to be unsuitable for scallop growth because of high current velocities may actually be suitable when the mesh size of the cages, or bags, and the incidence and the type of fouling in the area are considered (Devaraj and Parsons 1997).

A further observation was noted among the study sites for food concentration: the deepest site (site 1 in Richibucto Bay) had the lowest particulate organic matter and the lowest chlorophyll-a concentration, yet, it had the highest growth rate for small juvenile scallops. As well, no fouling organisms like mussels and barnacles were present on the study cages at that site. Thus, the amount of fouling may have a larger influence on growth rate than the particulate organic matter and chlorophyll-a concentrations. Claereboudt et al. (1994a) found that the total biomass of fouling organisms decreased with increasing depth, which would confirm the observations in this study. When fouling organisms result in competition with sea scallop farming, the result will be lower productivity. This reduction in productivity will generally translate itself into an economic loss for the aquaculturists.

3.4.3 Environmental Parameters

3.4.3.1 Salinity

Based upon the data collected, all the sites in this study were above the recommended salinity (≥ 25 ppt) during summer and autumn 1999. No salinity data were collected during the spring and winter due to ice cover, however, during the spring season, the rivers and streams are discharging their freshwater peak loads. In Richibucto Bay the maximum discharge from tributaries is usually reached in April with a mean of 91.5 m^3/s (St-Hilaire et al. 1997) and growers indicated that the water salinity typically drops below 12 ppt at many sites in the estuary during spring season (M. Daigle, pers. comm.). Bergman et al. (1996) found that salinities of 16 ppt and below were lethal for sea scallops and that a short-term exposure limit of 13.5 ppt would result in mortality. In Chapter 2, juvenile sea scallops were dying within the first few hours at low salinities (5 ppt and 10 ppt) and were less tolerant to low salinities at increasing temperatures. Furthermore, it was observed that 100% of the scallops survived in waters with salinities of 25 ppt to ambient salinity. Thus, in springtime, the estuaries of the present study would be stressful for scallop survival and growth. The high mortality in sites 2 and 3 of Richibucto Bay and in Little Shemogue Bay was most likely caused by the low salinity in the springtime. A small amount of growth (0.004 ± 0.003 mm/d) had been observed on the large juveniles cultured at site 3 Richibucto Bay indicating that they probably all died within the first six to seven months of the grow-out, which coincided with spring 1999.

In comparison, giving the amount of sampling, Bouctouche Bay recorded the highest average salinity and also the highest survival.

3.4.3.2 Temperature

According to Boghen (1989) the embayments along the southeastern coast of New Brunswick are subject to a temperature regime varying from below 0°C in winter to above 23°C in summer. The temperature data collected on all sites during this study had a similar range. Chapter 2 showed that in a ten-day laboratory experiment, 100% survival was observed in juvenile scallops held in waters with a temperature of ≤ 18°C.

The critical point for temperature tolerance for the scallops in this study was at 23°C. Dickie (1958) found similar results for adult sea scallops, where water temperatures over 23.5°C caused large-scale mortalities in a wild population. Temperatures over 21°C also may have sub-lethal effects under certain circumstances (Dickie 1958; Potter et al. 1997). In this study, site 1 in Richibucto Bay (15 m of depth) was the only site that recorded average monthly temperatures < 20°C during the warmest months. However, a total of 10 days was recorded > 21 °C at that site. All the other culture sites had monthly averages over sub-lethal temperatures (> 21°C) during July and August 1999. Little Shemogue Bay and Bouctouche Bay both had the highest overall water temperatures during this study. However, the scallops held in Bouctouche Bay had the highest overall survival, > 84% for small juveniles and > 88% for large juveniles. The only culture cages that were not hauled to the surface for biological sampling during the

warm days were the ones held in Bouctouche Bay and Richibucto Bay. The growers at these sites refused to handle the animals in the summer when the water in the bay was too warm. The elimination of these operations most likely reduced the amount of stress on the scallops and therefore influenced survival. In Cocagne Bay there were biological samplings done on the scallops during the months of July and September. In addition, the survival of the small juveniles went down from 98% in July 1999 to an overall survival of 41% in October 1999. Juvenile scallops may have been subjected to a short-term (~1-h) exposure to temperatures of over the lethal limit during those manipulations. In general, according to most of the earlier studies, the temperatures recorded in all the culture sites during summer 1999 should have resulted in lower survival in this study. However, when subjected to sub-lethal or even potentially lethal temperatures, scallops in the wild may still survive. Stevenson (1934) subjected wild adult sea scallops from L'Etang Harbour, near Passamaquoddy Bay, to high water temperatures. He found that the lowest temperature in which death took place was at 29.3°C (after 48 hours), whereas the highest temperature from the effects of which a scallop managed to recover was at 30.7°C. In these conditions, the scallop is very weak and vulnerable to predators. This is why, in this study, avoiding manipulation during warm summer months, added with the protection from the cages, enhanced the survival of the sea scallops.

In regards to optimum water temperature conditions, the best temperature range for the growth of sea scallops is 10–15°C (Young-Lai and Aiken 1986) and the optimum for feeding is in the temperature range of 13°C ± 1°C (MacDonald and Thompson 1986; Chapter 2). In this study, the number of consecutive days that the preferred temperatures were recorded at each site was similar (Table 16). Pilditch and Grant (1999) studied the

effect of temperature fluctuations and food supply on the growth and metabolism of juvenile sea scallops. They subjected juvenile scallops to a constant temperature (10°C) and 8 day cycles (6–15°C). They concluded that there was no difference in growth between temperature treatments and found very low mortality. However, higher growth was observed in the higher food treatments and better growth in soft tissue (excluding the adductor muscle) was found in the fluctuating temperature treatment. Thus, the numbers of days with optimal temperatures for growth may represent an important factor to consider as recommended by MacDonald and Thompson (1985) and Chouinard and Mladenov (1991).

3.4.3.3 Seston

In this study, based upon the data collected, Richibucto Bay (site 2) recorded the highest TPM and POM. However, the effect of high organic matter cannot be compared to overall growth rate because the scallops at this site did not survive for the 13-month study due to other environmental factors. The lowest TPM, POM, and PIM in this study were found in Richibucto Bay (site 1). Regardless, the scallops survived the 13 months and still had sufficient growth rates.

A high particulate organic matter (POM) in the water is an index of more food availability for the scallops, which will potentially lead to higher growth rates. In the sea scallop diet, the type of food particle such as phytoplankton, macrophyte detritus, and organic matter resuspended from sediments are a major component of the variance in food quality (Grant and Cranford 1991). MacDonald et al. (1998) observed that the

absorption efficiency of sea scallops increased with increasing seston quality, but was independent of seston concentration. MacDonald et al. (1998) found that the absorption efficiency of sea scallops was independent of concentration and quality of suspended particles, and increased as the organic fraction of the seston increased. Ward et al. (1992) suggested that chemical cues from phytoplankton are important factors that allow scallops to adjust feeding rates. The seston (total particulate) of all sites studied by MacDonald and Thompson (1985) was consistently between 5 and 10 mg/L and up to 16 mg/L during the spring bloom. According to Claereboudt et al. (1994a), at 9-m at Gascons, Qc., the seston (total particulate) from July to October ranged from 9.1 to 31.2 mg/L. The total particulate during this 13-month study was much higher, ranging between 10 and 60 mg/L, which was mostly composed of inorganic matter. However, the organic matter present was most likely higher in this thesis than in other studies because the research was conducted in estuaries which naturally have high food productivity in part due to tidal flushing bringing in nutrients (Ketchum 1983).

Results from field and laboratory studies by Cranford (1994) indicate that sea scallops can regulate feeding activity (filtration rate and efficiency and pre-ingestive particle selection) in response to short- and long-term changes in food supply. Also, many suspension-feeding bivalves have the capacity to enhance the quality of particles consumed by rejecting particles of lower nutritive value as pseudofeces. However, there may be a threshold of particle concentration at which selection begins to operate with efficiency (Newell et al. 1989). This threshold may correspond to the threshold for formation of pseudofaeces (Palmer and Williams 1980). General findings of indirect quantitative particle selection studies (Newell and Jordan 1983; Shumway et al. 1985;

Shumway and Cucci 1987; Newell et al. 1989), suggest that when a variety of particle types (approximately 10 μm) are available above a threshold concentration, negative selection may be dominant, i.e., all but a limited number of "undesired" (toxic or inorganic) particles are ingested. Particles in the "undesired" category are rejected with an increasing degree of efficiency as total particle concentration increases (Beninger 1991). As mentioned in the introduction, sea scallops are highly sensitive to the presence of low concentrations (< 10 mg/L) of suspended clay leading to adverse effects on feeding rate and the low ability to selectively reject fine inorganic particles prior to ingestion (Cranford 1994). Larger inorganic particles appear to have less impact on sea scallop growth owing to a greater capacity to maintain high filtration rates while rejecting these particles as pseudofeces. Thus, seston is important to consider for growth rates at a site. However it is a parameter that must be used as a comparison among sites along with the consideration of other environmental parameters.

3.4.3.4 Chlorophyll-a

Chlorophyll-a was measured to estimate the abundance of phytoplankton in the water. Phytoplankton is a major component of particulate organic matter (POM) and is an important part of the scallop's diet. Giving the amount of sampling, this study showed that during the autumn seasons of 1998 and 1999, the particulate organic matter was higher in all sites but more for the sites that were located further upstream in the riverine system. However, some of those sites also had low chlorophyll-a concentrations. For

example, site 2 in Richibucto Bay (4 m) had the highest overall average particulate organic matter but was one of the lowest in chlorophyll-a concentrations. Whereas, Little Shemogue Bay (average depth of 3.2 m) had one of the highest overall particulate organic matter concentrations and also one of the highest overall chlorophyll-a concentration averages. Consequently, the amount and type of riverine plankton was probably different among these sites. According to Hellings et al. (1999) riverine plankton and terrestrial detritus are two major sources of particulate organic matter (POM). Also, eelgrass detritus will contribute to the seston and POM concentration. As a result, rather than improving the energy budget as suggested by Emerson et al. (1994), the high concentrations of seston near the bottom inhibits growth, probably due to the high concentration of inorganic matter. In general, water mixing is more active during the autumn as a result of seasonal storms and water turn-overs (Ketchum 1983). This was reflected in this study, the seston concentration and the water turbidity were higher during autumn 1998 and autumn 1999. On the other hand, the chlorophyll-a concentrations were higher during the summer of 1999, when there were longer daylight hours, less runoff, and less wind.

In this study, Cocagne Bay had the highest chlorophyll-a concentrations and Richibucto Bay (site 1) had the lowest chlorophyll-a concentrations. Richibucto Bay (site 1) had the lowest concentration, because it was also the deepest site (15 m) and there was less light reaching the test site. Overall, chlorophyll-a is an important indicator of organic matter available for scallop feeding and will help determine whether or not a site may be suitable for scallop farming. However, this information will only be one factor of many when examining the advantages of a site.

3.4.3.5 Turbidity

Turbidity caused by a large volume of suspended sediment will reduce light penetration, thereby suppressing photosynthetic activity of phytoplankton, algae, and macrophytes. As well, stream-carried suspended inorganic particles add to the water turbidity (Almazan and Boyd 1978) and can cause mortality in sea scallops (Larsen and Lee 1978; Cranford et al. 1998). Scallop spat are highly susceptible to siltation (Dickie and Medcof 1956). For example, silt in suspension can cause mortality, in part through the clogging of cilia on the gills, which reduces oxygen consumption and will lead to eventual suffocation (Larsen and Lee 1978). As well, Young-Lai and Aiken (1986) report that bottom resuspension of silt can cause mortality in sea scallops at the juvenile stage.

In this study, giving the amount of sampling, Little Shemogue Bay had the highest turbidity and Richibucto Bay (site 1) the lowest turbidity. Little Shemogue Bay also had one of the highest total particulate matter concentrations, mostly inorganic, which would mean that there was a high amount of suspended particles. Whereas, Richibucto Bay (site 1) had the lowest turbidity due to the depth of the test site (15 m) and the low amount of light. Overall, turbidity is an important element of a site because suspended particles can suppress photosynthetic activity thereby reducing food production, as well the cilia of the scallop gills can become clogged with suspended particles. Thus, turbidity needs to be evaluated at a site before establishing an aquaculture operation.

3.4.3.6 Benthic Sediment Composition

Benthic sediment composition assesses the size of the sediment found at the bottom of a test site. This study showed that Richibucto (sites 2 and 3) and Little Shemogue Bay have mostly large sediment (> 0.5 mm); however, these three sites also contained the highest amount of the smallest particles measured (< 0.05 mm). It is these very small sediment particles that are of greatest concern to the survival of sea scallops. These three sites all had no surviving scallops at the end of the 13-month study and were all located close to where a river enters into the bay. Thus, as the rivers approach the sea, besides bringing freshwater downstream, small sediments like silt (0.002 to 0.06 mm) and, or clay (less than 0.002 mm) are carried into the estuary environment. Cranford (1994) discovered that adult sea scallops had a low tolerance to suspended clay sediment (bentonite). Overall, the high water turbidity, PIM (particulate inorganic matter), and the small size of bottom sediment compositions (silt and, or clay) may have contributed greatly to scallop mortality in sites 2 and 3 of Richibucto Bay and in Little Shemogue Bay during this study.

3.5 Conclusion

The objective of this field study was to determine the biological feasibility of culturing juvenile sea scallops held in wire mesh cages in shallow water embayments in southeastern New Brunswick in a 13-month grow-out experiment. The survival and

growth rate of sea scallops in off-bottom culture and the relation to environmental parameters under which they were grown were examined.

In conclusion, giving the amount of environmental sampling, Bouctouche Bay appeared to be the best location of the six test sites to establish a sea scallop aquaculture farm. The survival at Bouctouche Bay was > 84% for small juveniles and > 88% for large juveniles. Of the six sites tested, only 3 had living scallops at the end of the 13-month study. It is likely that the main reason that the scallops at Richibucto Bay (sites 2 and 3) and Little Shemogue Bay did not survive was because of low salinities in the spring time from freshwater run-off. In comparison, the other three sites were not as influenced by freshwater sources. For example, Bouctouche Bay had the highest mean salinity of all six sites and very little influence from Bouctouche River. However, at the same time, Bouctouche Bay had the highest mean water temperature. In regards to growth rates, Richibucto Bay (site 1) and Cocagne Bay had the highest growth rates for small and large juvenile scallops, respectively. However, Bouctouche Bay still had acceptable growth rates.

Besides salinity and temperature, it is also important to realize that other environmental parameters such as seston, chlorophyll-a, turbidity, and sediment composition can influence the survival and growth of sea scallops. For example, the three sites that had no surviving scallops also had the smallest sediment particles (< 0.05 mm), which can be stressful to scallops. In this study the scallops were able to tolerate the stress and survive the summer months in Bouctouche Bay, along with the added protection of the cages. However, it is also important to note that Bouctouche Bay and

Richibucto Bay were the only sites without summer sampling. This may have had an influence on survival and also indicates that handling of scallops is an important consideration. For example, Cocagne Bay had 98% survival in July 1999, which dropped to 41% by October 1999. It would be interesting to assess the effect of summer sampling in Cocagne Bay to determine whether or not survival may be higher. Overall, the results determine that further study of Bouctouche Bay and possibly Cocagne Bay and Richibucto Bay (site 1) as possible aquaculture sites for sea scallops is justified.

Chapter Four

General Conclusion

4.1 Conclusion

To conclude this thesis, the laboratory and field studies combined, have shown that site selection characteristics, especially sources of freshwater input and expected summer temperatures, need to be determined prior to establishing scallop aquaculture sites in shallow coastal waters. The laboratory study in Chapter 2 showed that water temperature and salinity were important factors in scallop survival. It was shown that in order to have 100% survival, the water conditions should be $\geq$ 25 ppt and $\leq$ 18°C. Also, optimum water conditions for the best feeding rate (clearance and ingestion) of *Placopecten magellanicus* would be at ambient salinity at the temperature of 13°C.

In Chapter 3 six potential sea scallop aquaculture sites were assessed for their biological feasibility as acceptable sites. It was found that Bouctouche Bay had the best survival and Richibucto Bay (site 1) had the best growth rates. However, giving the amount of sampling, it was interesting that Bouctouche Bay had the highest mean salinity of all six sites, but also had to highest mean water temperature. This may indicate that salinity has a larger influence on scallop survival, and also that scallops are possibly able to recover from the stress of high temperatures. Also, the handling of scallops during the summer is an important factor that may have a negative influence on survival.

In general, it is essential to have high survival (> 80%, Penney and Mills 2000) and adequate growth rates. The goal of a commercial aquaculture enterprise is to produce the maximum amount of high quality product in a short time with minimum expense. Overall, the ideal site for sea scallop cultures would have high salinities (ideally $\geq$ 25

ppt), moderate temperatures (≤ 18°C), low turbidity and PIM, high chlorophyll-a and POM, and low amounts of small sized bottom sediments. As well, it is recommended to leave the cages at the bottom during the warmer summer months.

Based upon these recommendations, clearly a number of sites commercially used for oysters in the Northumberland Strait are not suitable for sea scallop culture. However, Bouctouche Bay and possibly Cocagne Bay and Richibucto Bay (site 1) have potential as aquaculture sites for sea scallops. This study has contributed to a better understanding of sea scallop farming in shallow water bays (estuaries), which may lead to the study of other bays or coastal areas in the region. The aquaculture industry for sea scallops in Atlantic Canada still has room for improvement and it would be beneficial to develop this field in southeastern New Brunswick.

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TABLES

Table 1. Mortality and behavioural responses of small and large juvenile scallops at 3°C at different salinities over a 10-d time period (3 rep. of 10 scallops/tray); a (# with shell gaping and retracted mantle); b (# with extended foot); c (# attached with byssal threads); and d (total # of scallops dead after each time period).

Small Juveniles		**Time (hrs)**												
Temp (°C)	**Salinity (ppt)**	**1**	**6**	**12**	**24**	**48**	**72**	**96**	**120**	**144**	**168**	**192**	**216**	**240**
3	**5**	2[a]	2[a]	29/30[d]	30/30[d]									
	10			4/30[d]	13/30[d]	18/30[d]	22/30[d]	30/30[d]						
	15								2[b]		5[b]		1/30[d] 4[b]	7/30[d]
	20									1[c]		1/30[d]	2/30[d] 1[b]	
	25	25[c]	25[c]	25[c]	24[c]	22[c]	24[c]	24[c]	22[c]	21[c]	25[c]	22[c]	25[c]	25[c]
	30	28[c]	28[c]	27[c]	27[c]	27[c]	28[c]	27[c]	27[c]	27[c]	28[c]	28[c]	28[c]	28[c]
Large Juveniles		**Time (hrs)**												
Temp (°C)	**Salinity (ppt)**	**1**	**6**	**12**	**24**	**48**	**72**	**96**	**120**	**144**	**168**	**192**	**216**	**240**
3	**5**	2[a]	2[a]	30/30[d]										
	10			4/30[d]	21/30[d]	26/30[d] 1[b]	29/30[d] 1[b]	30/30[d]						
	15										3[b]			2/30[d]
	20								1[b]	1[b]		1/30[d] 1[b]	2/30[d]	4/30[d]
	25	26[c]	26[c]	26[c]	27[c]	26[c]	26[c]	27[c]	28[c]	28[c]	25[c]	26[c]	27[c]	27[c]
	30	28[c]	28[c]	29[c]	28[c]	28[c]	28[c]	28[c]	28[c]	28[c]	29[c]	29[c]	30[c]	30[c]

Table 2. Mortality and behavioural responses of small and large juvenile scallops at 8°C at different salinities over a 10-d time period (3 rep. of 10 scallops/tray); a (# with shell gaping and retracted mantle); b (# with extended foot); c (# attached with byssal threads); and d (total # of scallops dead after each time period).

Small Juveniles		**Time (hrs)**												
Temp (°C)	**Salinity (ppt)**	**1**	**6**	**12**	**24**	**48**	**72**	**96**	**120**	**144**	**168**	**192**	**216**	**240**
8	**5**	29[a]	27/30[d]	30/30[d]										
	10	13[a]	21[a]	5/30[d]	18/30[d]	30/30[d]								
	15				1[b]	1[b]				1/30[d]			2/30[d]	5/30[d]
	20	1[b]	2[b]	4[b]	2[b]		1[b]				1[b]	1[b]		
	25	1[b] 27[c]	2[b] 27[c]	30[c]	30[c]	30[c]	29[c]	29[c]	30[c]	30[c]	30[c]	30[c]	30[c]	30[c]
	30	26[c]	26[c]	30[c]	1[b] 30[c]	28[c]	30[c]	30[c]	30[c]	30[c]	30[c]	30[c]	30[c]	30[c]
Large Juveniles		**Time (hrs)**												
Temp (°C)	**Salinity (ppt)**	**1**	**6**	**12**	**24**	**48**	**72**	**96**	**120**	**144**	**168**	**192**	**216**	**240**
8	**5**	18[a]	30/30[d]											
	10	3[a]	10[a]	4/30[d]	21/30[d]	30/30[d]								
	15					2[b]	1[b]						1/30[d]	8/30[d]
	20	4[b]	4[b]		4[b]		3[b]	1[b]			1[b]	1[b]	1[b]	1[b]
	25	1[b] 26[c]	1[b] 26[c]	2[b] 29[c]	29[c]	29[c]	29[c]	28[c]	29[c]	29[c]	29[c]	29[c]	29[c]	29[c]
	30	2[b] 27[c]	2[b] 27[c]	29[c]	30[c]	30[c]	29[c]	30[c]	30[c]	30[c]	30[c]	30[c]	30[c]	30[c]

Table 3. Mortality and behavioural responses of small and large juvenile scallops at 13°C at different salinities over a 10-d time period (3 rep. of 10 scallops/tray); a (# with shell gaping and retracted mantle); b (# with extended foot); c (# attached with byssal threads); and d (total # of scallops dead after each time period).

Small Juveniles		**Time (hrs)**												
Temp (°C)	**Salinity (ppt)**	**1**	**6**	**12**	**24**	**48**	**72**	**96**	**120**	**144**	**168**	**192**	**216**	**240**
13	**5**	17/30[d] 13[a]	25/30[d] 1[a]	30/30[d]										
	10	16[a]	4/30[d] 15[a]	24/30[d]	30/30[d]									
	15				1[b]	1[b]	3[b]	4[b]	2/30[d]	1[b]	4/30[d]	6/30[d]		
	20			1[b]	7[c]	8[c]	15[c]	15[c]	15[c]	2/30[d] 16[c]	3[c]	3/30[d] 8[c]	10[c]	4/30[d] 13[c]
	25		17[c]	25[c]	27[c]	27[c]	27[c]	27[c]	30[c]	30[c]	30[c]	30[c]	30[c]	29[c]
	30		17[c]	24[c]	26[c]	26[c]	29[c]	29[c]	29[c]	30[c]	30[c]	30[c]	30[c]	30[c]
Large Juveniles		**Time (hrs)**												
Temp (°C)	**Salinity (ppt)**	**1**	**6**	**12**	**24**	**48**	**72**	**96**	**120**	**144**	**168**	**192**	**216**	**240**
13	**5**	24/30[d] 6[a]	30/30[d]											
	10	2/30[d] 28[a]	7/30[d] 21[a]	23/30[d] 4[a]	30/30[d]									
	15		1[a]		1[b]	1[b]	1[b]	2[b]	1/30[d] 1[b]	3/30[d]	1[b]	1[b]		5/30[d]
	20		1[a]	1[b]	4[b]	1[b] 6[c]	8[c]	8[c]	8[c]	13[c]	4[c]	1/30[d] 8[c]	11[c]	2/30[d] 18[c]
	25		22[c]	28[c]	28[c]	28[c]	25[c]	22[c]	1[b] 29[c]	28[c]	28[c]	1/30[d] 1[b], 28[c]	24[c]	2/30[d] 27[c]
	30		17[c]	23[c]	29[c]	29[c]	29[c]	29[c]	29[c]	1/30[d] 29[c]	29[c]	28[c]	27[c]	29[c]

Table 4. Mortality and behavioural responses of small and large juvenile scallops at 18°C at different salinities over a 10-d time period (3 rep. of 10 scallops/tray); a (# with shell gaping and retracted mantle); b (# with extended foot); c (# attached with byssal threads); and d (total # of scallops dead after each time period).

Small Juveniles		**Time (hrs)**												
Temp (°C)	**Salinity (ppt)**	**1**	**6**	**12**	**24**	**48**	**72**	**96**	**120**	**144**	**168**	**192**	**216**	**240**
18	**5**	10/30[d] 1[a]	21/30[d] 1[a]	30/30[d]										
	10	2/30[d] 8[a]	12/30[d]	16/30[d]	26/30[d]	30/30[d]								
	15	7[a]	7[a]	4[a]	1/30[d] 3[a], 1[b]	6/30[d]	9/30[d]	2[a]	17/30[d]	23/30[d]	25/30[d]	26/30[d]	29/30[d]	30/30[d]
	20	1[b]	1[b] 2[c]			15[c]	21[c]	26[c]	20[c]	20[c]	1/30[d] 18[c]	2/30[d] 21[c]	3/30[d] 21[c]	5/30[d] 14[c]
	25	1[b] 14[c]	27[c]	28[c]	29[c]	29[c]	30 [c]	29[c]	30[c]	30[c]	30[c]	30[c]	28[c]	27[c]
	30	20[c]	27[c]	28[c]	27[c]	29[c]	27[c]	29[c]	26[c]	27[c]	30[c]	29[c]	30[c]	26[c]
Large Juveniles		**Time (hrs)**												
Temp (°C)	**Salinity (ppt)**	**1**	**6**	**12**	**24**	**48**	**72**	**96**	**120**	**144**	**168**	**192**	**216**	**240**
18	**5**	15/30[d] 10[a]	30/30[d]											
	10	2/30[d] 18[a]	19/30[d]	29/30[d]	30/30[d]									
	15	4[a]		1[a]	1/30[d]	2[a]	8/30[d] 1[a]	11/30[d]	17/30[d]	20/30[d] 2[a]	24/30[d]	27/30[d]		28/30[d]
	20		4[b] 9[c]	10[c]	10[c]	13[c]	1/30[d] 24[c]	25[c]	21[c]	2/30[d] 20[c]	20[c]	24[c]	25[c]	25[c]
	25	4[b] 16[c]	28[c]	1[b] 28[c]	28[c]	30[c]	29[c]	30[c]	30[c]	30[c]	30[c]	30[c]	29[c]	30[c]
	30	2[b] 24[c]	30[c]	30[c]	28[c]	28[c]	30[c]	30[c]	30[c]	30[c]	29[c]	28[c]	28[c]	28[c]

Table 5. Mortality and behavioural responses of small and large juvenile scallops at 23°C at different salinities over a 10-d time period (3 rep. of 10 scallops/tray); a (# with shell gaping and retracted mantle); b (# with extended foot); c (# attached with byssal threads); and d (total # of scallops dead after each time period).

Small Juveniles		**Time (hrs)**												
Temp (°C)	**Salinity (ppt)**	**1**	**6**	**12**	**24**	**48**	**72**	**96**	**120**	**144**	**168**	**192**	**216**	**240**
23	**5**	30/30[d]												
	10	17/30[d]	30/30[d]											
	15			21/30[d]	29/30[d]	30/30[d]								
	20				4/30[d]	15/30[d]	24/30[d]	25/30[d] 1[c]	29/30[d]	30/30[d]				
	25	2[c]	11[c]	18[c]	15[c]	2/30[d] 26[c]	3/30[d] 26[c]	4/30[d] 23[c]	6/30[d] 18[c]	14/30[d] 14[c]	17/30[d] 12[c]	18/30[d] 8[c]	20/30[d] 6[c]	21/30[d] 6[c]
	30	11[c]	2[c]	1[c]	18[c]	29[c]	29[c]	29[c]	29[c]	1/30[d] 21[c]	15/30[d] 2[c]	22/30[d]	25/30[d]	29/30[d]
Large Juveniles		**Time (hrs)**												
Temp (°C)	**Salinity (ppt)**	**1**	**6**	**12**	**24**	**48**	**72**	**96**	**120**	**144**	**168**	**192**	**216**	**240**
23	**5**	30/30[d]												
	10	8/30[d] 19[a]	22/30[d]	30/30[d]										
	15	15[a]	12[a]	4/30[d]	6/30[d]	22/30[d]	30/30[d]							
	20	5[a]	2[b]			2/30[d]	7/30[d]	10/30[d] 3[c]	18/30[d]	26/30[d]	28/30[d]		29/30[d]	
	25	1[b] 5[c]	11[c]	19[c]	20[c]	25[c]	1/30[d] 20[c]	5/30[d] 13[c]	15/30[d] 1[b] 5[c]	20/30[d] 7[c]	21/30[d] 6[c]	22/30[d] 2[c]	24/30[d]	25/30[d]
	30	22[c]	22[c]	28[c]	29[c]	29[c]	28[c]	23[c]	15[c]	8/30[d] 13[c]	17/30[d] 8[c]	2[c]	19/30[d] 1[c]	21/30[d]

Table 6. Alkaline phosphatase specific activities (pmol/min/mg protein ± SE) in mucus secretion of live juvenile scallops, small (S) and large (L), after 240-h versus the temperature trials for all remaining experimental salinities. The number of scallops analyzed = n.

	3°C	8°C	13°C	18°C	23°C
15 ppt					
S	1.07 ± 0.48 n = 9	4.52 ± 1.73 n = 8	0.54 ± 0.13 n = 8	n.d.	n.d.
L	1.09 ± 0.26 n = 10	n.d.	n.d.	n.d.	n.d.
20 ppt					
S	1.96 ± 0.73 n = 9	n.d.	n.d.	0.71 ± 0.23 n = 10	n.d.
L	3.84 ± 1.71 n = 10	n.d.	n.d.	n.d.	n.d.
25 ppt					
S	1.99 ± 1.71 n = 8	n.d.	n.d.	n.d.	1.64 ± 0.34 n = 6
L	0.25 ± 0.07 n = 8	n.d.	n.d.	n.d.	n.d.
30 ppt					
S	0.23 ± 0.03 n = 10	0.05 ± 0.03 n = 8	0.30 ± 0.13 n = 10	0.64 ± 0.21 n = 10	n.d.
L	0.45 ± 0.09 n = 10	n.d.	n.d.	n.d.	n.d.
Ambient salinity					
S	n.d.	n.d.	n.d.	n.d.	2.39 ± 0.68 n = 9
L	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. Not Determined

Table 7. Azocasein hydrolysis specific activities (Mean OD/H/mg protein ± SE) in mucus secretion of live juvenile scallops, small (S) and large (L), after 240-h versus the temperature trials for all remaining experimental salinities. The number of scallops analyzed = n.

	3°C	8°C	13°C	18°C	23°C
15 ppt					
S	0.76 ± 0.02 n = 9	n.d.	n.d.	n.d.	n.d.
L	0.83 ± 0.03 n = 10	n.d.	n.d.	n.d.	n.d.
20 ppt					
S	0.83 ± 0.04 n = 9	n.d.	n.d.	n.d.	n.d.
L	0.94 ± 0.08 n = 10	n.d.	n.d.	n.d.	n.d.
25 ppt					
S	0.77 ± 0.04 n = 8	n.d.	n.d.	n.d.	n.d.
L	0.69 ± 0.03 n = 8	n.d.	n.d.	n.d.	n.d.
30 ppt					
S	0.72 ± 0.03 n = 10	n.d.	n.d.	n.d.	n.d.
L	0.67 ± 0.03 n = 10	n.d.	n.d.	n.d.	n.d.
Ambient salinity					
S	n.d.	n.d.	n.d.	n.d.	n.d.
L	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. Not Determined

Table 8. The specific activities of lysozyme concentration (units/mg protein ± SE) in mucus secretion of live juvenile scallops, small (S) and large (L), after 240-h versus the temperature trials for all remaining experimental salinities. The number of scallops analyzed = n.

	3°C	8°C	13°C	18°C	23°C
15 ppt					
S	30.17 ± 8.49 n = 9	0.18 ± 0.06 n = 8	0.13 ± 0.05 n = 8	n.d.	n.d.
L	9.12 ± 1.92 n = 10	n.d.	n.d.	n.d.	n.d.
20 ppt					
S	49.67 ± 10.65 n = 9	n.d.	n.d.	0.07 ± 0.06 n = 10	n.d.
L	4.32 ± 5.62 n = 10	n.d.	n.d.	n.d.	n.d.
25 ppt					
S	18.72 ± 1.78 n = 8	n.d.	n.d.	n.d.	0.17 ± 0.03 n = 6
L	6.57 ± 0.70 n = 8	n.d.	n.d.	n.d.	n.d.
30 ppt					
S	6.85 ± 2.08 n = 10	0.11 ± 0.06 n = 8	0.08 ± 0.03 n = 10	0.11 ± 0.06 n = 10	n.d.
L	4.48 ± 1.17 n = 10	n.d.	n.d.	n.d.	n.d.
Ambient salinity					
S	n.d.	n.d.	n.d.	n.d.	0.05 ± 0.03 n = 9
L	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. Not Determined

Table 9. Names of the four aquaculturists, the species they are culturing, and the locations of their sites.

Name	Species Cultured	Location	Study Site (longitude and latitude)
Donald Jaillet	*Crassostrea virginica*	Bouctouche Bay, NB	46° 27' 48" N 64° 38' 65" W
Jean Gallant	*Crassostrea virginica*	Cocagne Bay, NB	46° 20' 47" N 64° 34' 39" W
Maurice Daigle	*Crassostrea virginica* and *Mytilus edulis*	Richibucto Bay, NB	Site 1 46° 41' 35" N 64° 51' 11" W Site 2 46° 42' 24" N 64° 51' 47" W Site 3 46° 43' 37" N 64° 52' 70" W
Steven Pauley	*Crassostrea virginica*	Little Shemogue Bay, NB	46° 11' 03" N 64° 04' 72" W

Table 10. Brief description of each bay in southeastern NB where experiments were conducted.

Bay	Description
Bouctouche	-*26.40 km^2, large opening to the sea -Small amount of freshwater influence from Bouctouche River -Muddy but compact bottom -Max. depth at low tide = 7 m
Cocagne	-*12.15 km^2, two openings to the sea with island in the middle -Small amount of freshwater influence from Cocagne River -Sandy bottom with eel grass -Max. depth at low tide = 4 m
Little Shemogue	-*4.49 km^2, large opening to the sea -Large amount of freshwater influence from Little Shemogue River -Soft muddy bottom -Max. depth at low tide = 3.2 m
Richibucto	-*26.19 km^2, narrow opening to the sea -Freshwater influence from three major rivers: (Richibouctou, Little Aldouane, and St. Charles) -Max. depth at low tide = 15 m
-Study site no. 1	-Located in the middle of the bay, the closest to the opening to the sea -Freshwater influence from Richibouctou River -Depth of 15 m at low tide -Hard sandy bottom
-Study site no. 2	-Located 2 km upstream -Freshwater influence from Little Aldouane River, and St. Charles River -Depth of 4 m at low tide -Hard sandy bottom with eel grass
-Study site no. 3	-Located another 2 km upstream -Fresh water influence from Aldouane River and St. Charles River -Depth of 4.5 m at low tide -Soft muddy bottom with eel grass

* See Appendix 6 for area calculations.

Table 11. Summary table of power curve regression equations of dry tissue weight (W_{dt}) and shell height (S_h) for small and large juveniles at the six study sites. Equations with different superscript are significantly different (ANCOVA, $P < 0.001$) and equations with the same superscript are not significantly different (ANCOVA, $P > 0.05$). Sampling dates (T0, T1, T2) are presented in appendix 7.

	Equation	r^2	n
Bouctouche Bay			
Small			
T0	$\text{Log } W_{dt} = 3.27 \times \log S_h - 6.01^{*}$	0.51	100
T1	$\text{Log } W_{dt} = 2.84 \times \log S_h - 4.97^{**}$	0.83	20
T2	$\text{Log } W_{dt} = 1.52 \times \log S_h - 2.87^{**}$	0.25	20
Large			
T0	$\text{Log } W_{dt} = 3.19 \times \log S_h - 5.78^{*}$	0.25	100
T1	$\text{Log } W_{dt} = 2.39 \times \log S_h - 4.11^{**}$	0.70	20
T2	$\text{Log } W_{dt} = 1.48 \times \log S_h - 2.73^{**}$	0.09	20
Cocagne Bay			
Small			
T0	$\text{Log } W_{dt} = 3.27 \times \log S_h - 6.01^{*}$	0.51	100
T1	$\text{Log } W_{dt} = 3.35 \times \log S_h - 5.71^{**}$	0.74	20
T2	$\text{Log } W_{dt} = 2.49 \times \log S_h - 4.34^{**}$	0.17	20
Large			
T0	$\text{Log } W_{dt} = 3.19 \times \log S_h - 5.78^{*}$	0.25	100
T1	$\text{Log } W_{dt} = 2.29 \times \log S_h - 3.89^{**}$	0.43	20
T2	$\text{Log } W_{dt} = 2.98 \times \log S_h - 5.14^{**}$	0.26	20
Richibucto Bay (Site 1)			
Small			
T0	$\text{Log } W_{dt} = 3.27 \times \log S_h - 6.01^{*}$	0.51	100
T1	$\text{Log } W_{dt} = 3.71 \times \log S_h - 6.17^{**}$	0.55	20
T2	n.d.	n.d.	n.d.
Large			
T0	$\text{Log } W_{dt} = 3.19 \times \log S_h - 5.78^{*}$	0.25	100
T1	$\text{Log } W_{dt} = 3.18 \times \log S_h - 5.45^{**}$	0.64	20
T2	n.d.	n.d.	n.d.

n.d. Not Determined

Table 11. Continued

	Equation	r^2	*n*
Richibucto Bay (Site 2)			
Small			
T0	Log W_{dt} = 3.27 × log S_h - 6.01*	0.51	100
T1	Log W_{dt} = 3.55 × log S_h - 6.12**	0.89	20
T2	n.d.	n.d.	n.d.
Large			
T0	Log W_{dt} = 3.27 × log S_h - 6.01*	0.25	100
T1	Log W_{dt} = 3.81 × log S_h - 6.65*	0.87	20
T2	n.d.	n.d.	n.d.
Richibucto Bay (Site 3)			
Small			
T0	Log W_{dt} = 3.27 × log S_h - 6.01	0.51	100
T1	n.d.	n.d.	n.d.
T2	n.d.	n.d.	n.d.
Large			
T0	Log W_{dt} = 3.27 × log S_h - 6.01	0.25	100
T1	n.d.	n.d.	n.d.
T2	n.d.	n.d.	n.d.
Little Shemogue Bay			
Small			
T0	Log W_{dt} = 3.27 × log S_h - 6.01*	0.51	100
T1	Log W_{dt} = 3.41 × log S_h - 5.77**	0.85	17
T2	n.d.	n.d	n.d.
Large			
T0	Log W_{dt} = 3.27 × log S_h - 6.01*	0.25	100
T1	Log W_{dt} = 3.53 × log S_h - 5.95**	0.62	20
T2	n.d.	n.d.	n.d.

n.d. Not Determined

Table 12. Daily mean water temperature (T), mean shell height (SH ± SD) and survival (S) for each sampling date, and overall growth rate and survival of small juvenile scallops (n = 2 replicates of 4×100 scallops per culture site).

		Site																	
		Bouctouche Bay			**Cocagne Bay**			**Richibucto Bay (site 1)**			**Richibucto Bay (site 2)**			**Richibucto Bay (site 3)**			**Little Shemogue Bay**		
Date	Grow-out (mths)	T (°C)	SH (mm)	S (%)	T (°C)	SH (mm)	S (%)	T (°C)	SH (mm)	S (%)	T (°C)	SH (mm)	S (%)	T (°C)	SH (mm)	S (%)	T (°C)	SH (mm)	S (%)
Oct 98	Initial	6.81	18.1 ± 3.1	100	8.84	18.9 ± 1.6	100	-	18.9 ± 2.3	100	-	16.8 ± 2.7	100	-	17.7 ± 2.7	100	-	16.9 ± 1.7	100
July 99	9	-	-	-	22.87	36.7 ± 1.7	98	-	-	-	-	-	-	-	-	-	22.39	28.4 ± 2.7	5
Aug 99	10	-	-	-	-	-	-	-	-	-	20.07	24.6 ± 4.2	21	22.62	23.9 ± 2.6	3		All dead	0
Sept 99	11	-	-	-	21.25	36.7 ± 1.7	88	-	-	-		All Dead	0		All dead	0			
Oct 99	12	9.52	41.0 ± 2.8	86	8.03	36.7 ± 2.1	47	-	-	-									
Nov 99	13	2.55	40.3 ± 2.9	84				1.26	43.0 ± 4.1	53									
Total days of culture		387			358			396			304			286			266		
Overall growth rate (mm/d ± SD)		0.057 ± 0.001			0.049 ± 0.002			0.061 ± 0.006			0.026 ± 0.002			0.022 ± 0.005			0.043 ± 0.0004		
Overall survival (% ± SD)		84.25 ± 3.86			41.00 ± 4.51			53.00 ± 0.22			0			0			0		

Table 13. Daily mean water temperature (T), mean shell height (SH± SD) and survival (S) for each sampling date, and overall growth rate and survival of large juvenile scallops (n = 2 replicates of 4×100 scallops per culture site).

		Site																	
		Bouctouche Bay			**Cocagne Bay**			**Richibucto Bay (site 1)**			**Richibucto Bay (site 2)**			**Richibucto Bay (site 3)**			**Little Shemogue Bay**		
Date	Grow-out (mths)	T (°C)	SH (mm)	S (%)	T (°C)	SH (mm)	S (%)	T (°C)	SH (mm)	S (%)	T (°C)	SH (mm)	S (%)	T (°C)	SH (mm)	S (%)	T (°C)	SH (mm)	S (%)
Oct 98	Initial	6.81	24.6 ± 1.7	100	8.84	25.8 ± 1.4	100	-	24.8 ± 1.5	100	-	25.0 ± 1.6	100	-	24.8 ± 1.7	100	-	25.6 ± 1.5	100
July 99	9	-	-	-	22.87	-	-	-	-	-	-	-	-	-	-	-	22.39	36.0 ± 3.2	11
Aug 99	10	-	-	-	-	-	-	-	-	-	20.07	33.3 ± 3.3	37	22.62	*25.8 ± 1.9	0		All dead	0
Sept 99	11	-	-	-	21.25	54.6 ± 3.6	50	-	-	-		All dead	0		All dead				
Oct 99	12	9.52	45.0 ± 3.1	95	8.03	52.6 ± 4.0	76	-	-	-									
Nov 99	13	2.55	45.1 ± 2.9	88				1.26	44.3 ± 3.7	52									
Total days of culture		387			358			396			286			286			266		
Overall growth rate (mm/d ± SD)		0.053 ± 0.003			0.075 ± 0.008			0.049 ± 0.008			0.029 ± 0.005			-			0.039 ± 0.004		
Overall survival (% ± SD)		88.13 ± 14.42			37.38 ± 13.88			52.00 ± 0.22			0			0			0		

* All dead at the first sampling date (08/23/99), mean shell height calculated from the size of the remaining shells.

Table 14. General observations on the type and visible amount (%) of fouling covering the culture cages recorded at the same time as biological sampling at all study sites.

	Bouctouche Bay	Cocagne Bay	Richibucto Bay (site 1)	Richibucto Bay (site 2)	Richibucto Bay (site 3)	Little Shemogue Bay
Jul. 1999	n.s.	*Zostera marina* (30%) *Balanus balanoides* (5%)	n.s.	n.s.	n.s.	*Mytilus edulis* spat (80%) *Balanus balanoides* (10%)
Aug. 1999	n.s.	n.s.	n.s.	*Zostera marina* (50%)	*Zostera marina* (40%)	n.s.
Sept. 1999	n.s.	*Zostera marina* (30%) *Balanus balanoides* (5%)	n.s.	n.s.	n.s.	n.s.
Oct. 1999	Dead algae (30%)	*Zostera marina* (30%) *Balanus balanoides* (5%)	n.s.	n.s.	n.s.	n.s.
Nov. 1999	Dead algae (30%)	n.s.	Nil	n.s.	n.s.	n.s.

n.s. Not Sampled

Table 15. Monthly mean water temperatures (°C ± SD) at the six study sites for the 13-month grow-out period.

Date	Bouctouche Bay	Cocagne Bay	Richibucto Bay (site1)	Richibucto Bay (site2)	Richibucto Bay (site3)	Little Shemogue Bay
October 1998	7.38 ± 1.69	8.50 ± 0.99	n.d.	n.d.	n.d.	n.d.
November 1998	3.76 ± 2.83	4.11 ± 2.24	4.78 ± 1.53	3.89 ± 1.86	4.58 ± 1.69	3.74 ± 1.92
December 1998	-0.94 ± 0.73	-0.25 ± 1.17	0.64 ± 1.52	-0.11 ± 1.24	0.19 ± 1.29	0.18 ± 1.37
January 1999	-1.58 ± 0.12	-1.05 ± 0.32	-1.27 ± 0.16	-1.20 ± 0.26	-1.08 ± 0.21	-0.72 ± 0.34
February 1999	-1.41 ± 0.16	-0.93 ± 0.33	-1.19 ± 0.11	-1.06 ± 0.18	-0.97 ± 0.13	-0.85 ± 0.09
March 1999	-1.12 ± 0.27	-0.61 ± 0.30	-0.98 ± 0.30	-0.85 ± 0.29	-0.77 ± 0.23	-0.53 ± 0.38
April 1999	1.26 ± 2.23	2.71 ± 2.45	2.37 ± 1.82	2.90 ± 2.49	2.40 ± 2.04	3.02 ± 1.99
May 1999	10.67 ± 2.74	8.71 ± 2.64	7.75 ± 2.41	10.28 ± 3.01	9.37 ± 2.96	10.67 ± 2.75
June 1999	17.98 ± 2.37	19.89 ± 0.72	13.91 ± 2.88	16.65 ± 3.07	16.73 ± 3.27	18.13 ± 2.32
July 1999	20.47 ± 1.45	21.54 ± 1.01	18.68 ± 2.23	20.25 ± 2.13	20.91 ± 1.95	21.21 ± 1.32
August 1999	20.83 ± 1.65	20.64 ± 0.98	19.24 ± 1.43	21.26 ± 1.37	21.52 ± 1.40	21.27 ± 2.37
September 1999	20.07 ± 2.30	19.68 ± 1.67	18.61 ± 1.75	19.45 ± 2.18	19.20 ± 1.87	17.26 ± 2.43
October 1999	11.12 ± 3.28	16.39 ± 0.77	10.45 ± 3.38	11.14 ± 2.92	10.96 ± 2.96	10.71 ± 2.58
November 1999	6.11 ± 1.86	n.d.	5.09 ± 2.59	6.27 ± 2.21	6.12 ± 2.33	6.91 ± 1.45

n.d. Not Determined

Table 16. The number of days that the average temperature, in degrees Celsius (°C), was at temperature ranges of 10°C–15°C (best growth range, Young-Lai and Aiken 1986); 13°C ± 1°C (optimum condition for F and IR– Results in Chap. 2); over 21°C; and over 23.5°C (the sub-lethal boundary and the lethal boundary, Dickie 1958) during the 13-month study period (from the last week of October 1998 to the first week of November 1999).

Site	10°C–15°C	13°C ± 1°C	> 21°C	> 23.5°C
Bouctouche Bay	28	14	40	3
Cocagne Bay**	28	14	37	2
Richibucto Bay (site 1)*	32	16	10	0
Richibucto Bay (site 2)*	36	20	44	2
Richibucto Bay (site 3)*	36	20	38	3
Little Shemogue Bay*	39	19	38	4

* No temperature data for October 1998.
** No temperature data for November 1999.

FIGURES

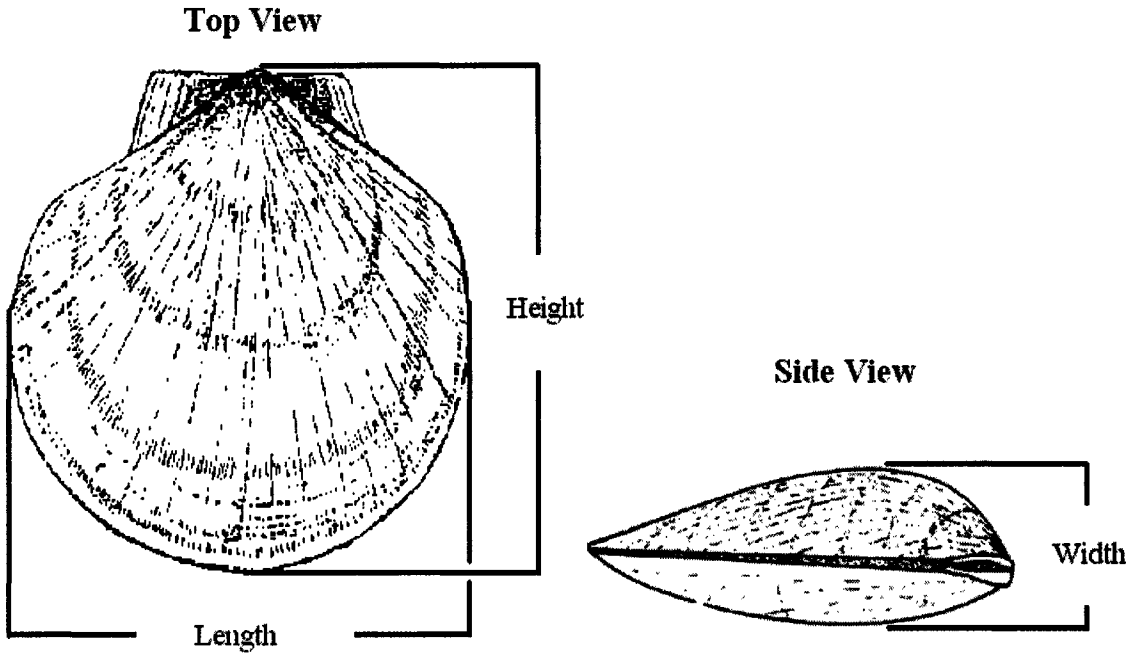


Figure 1. Sea scallop, *Placopecten magellanicus*, shell height, length, and width (Wildish et al. 1988).

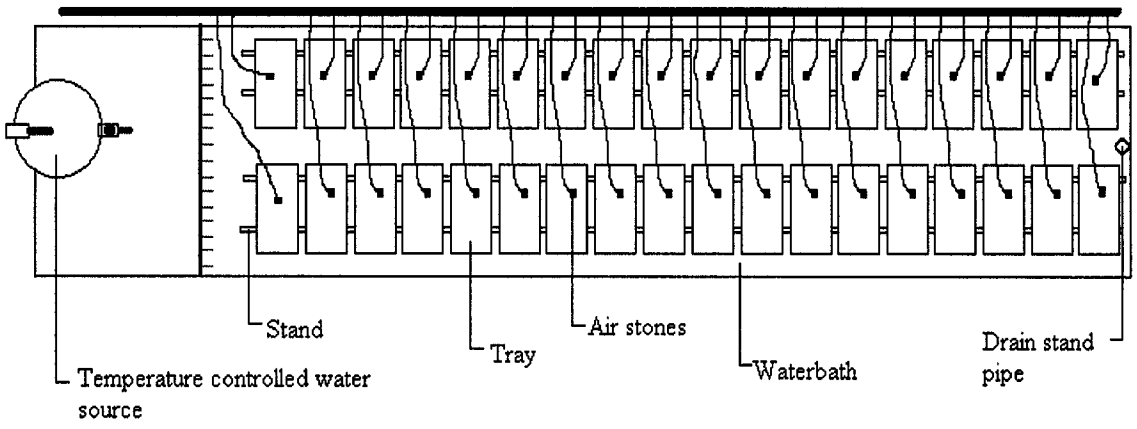


Figure 2. Experimental set-up of the salinity-temperature bioassay.

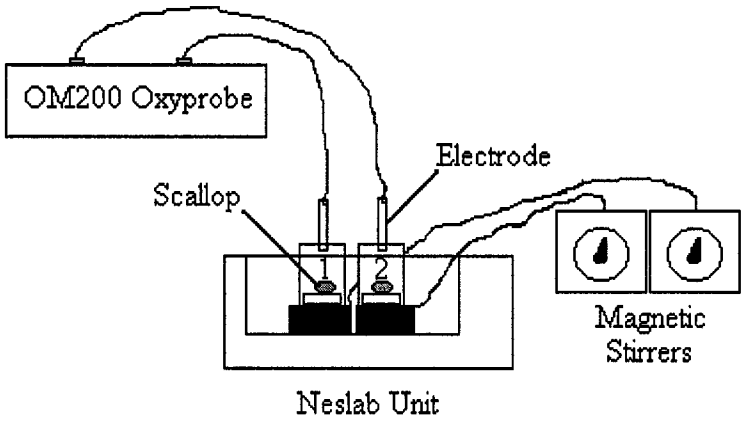
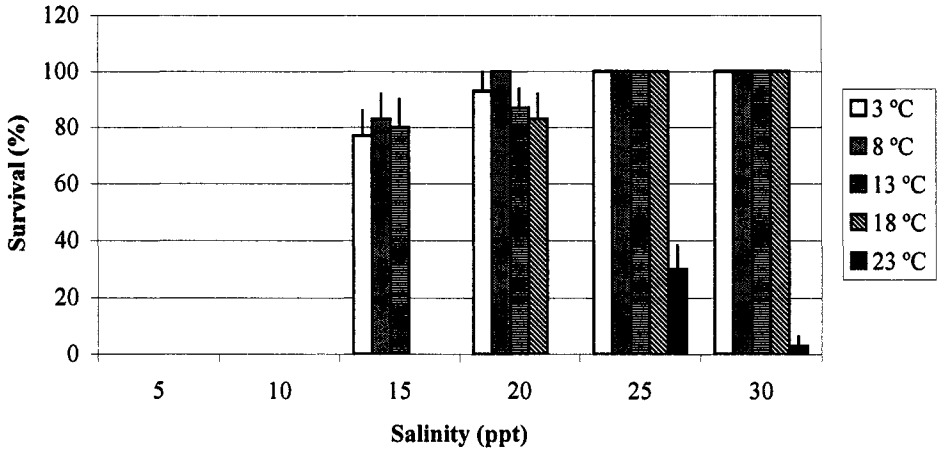


Figure 3. Set-up for oxygen consumption trials.

(A)



(B)

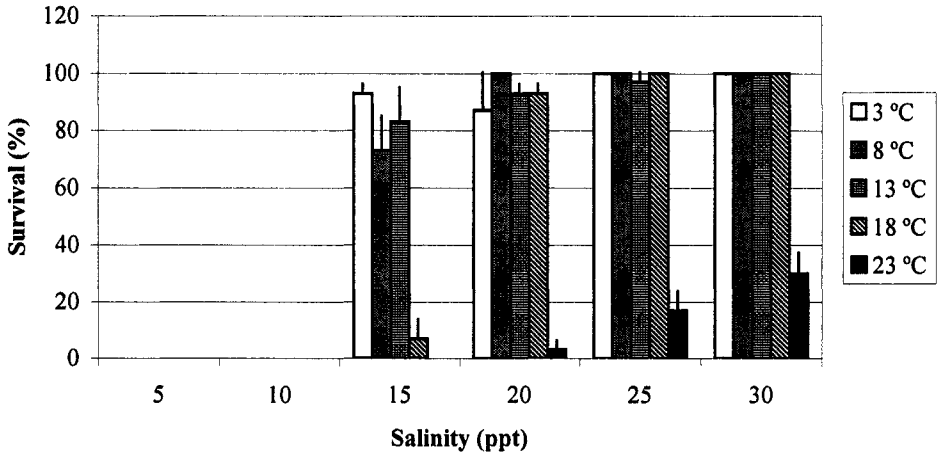


Figure 4. Percent survival of scallops after 240-h in test salinities at different acclimatized temperatures (n = 3 replicates of 10 scallops per treatment); A) small juvenile scallops; B) large juvenile scallops. Vertical bars are + SE.

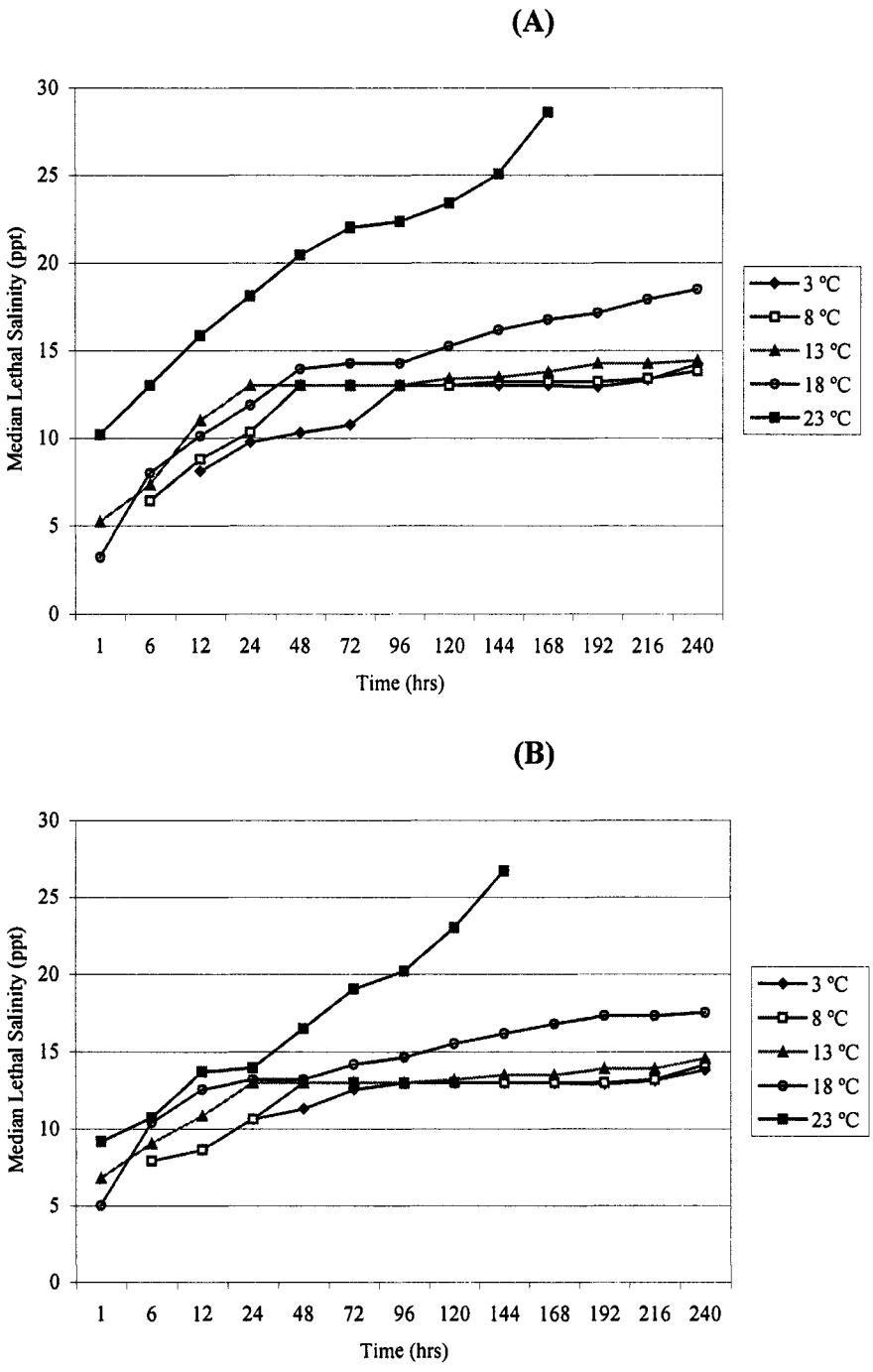
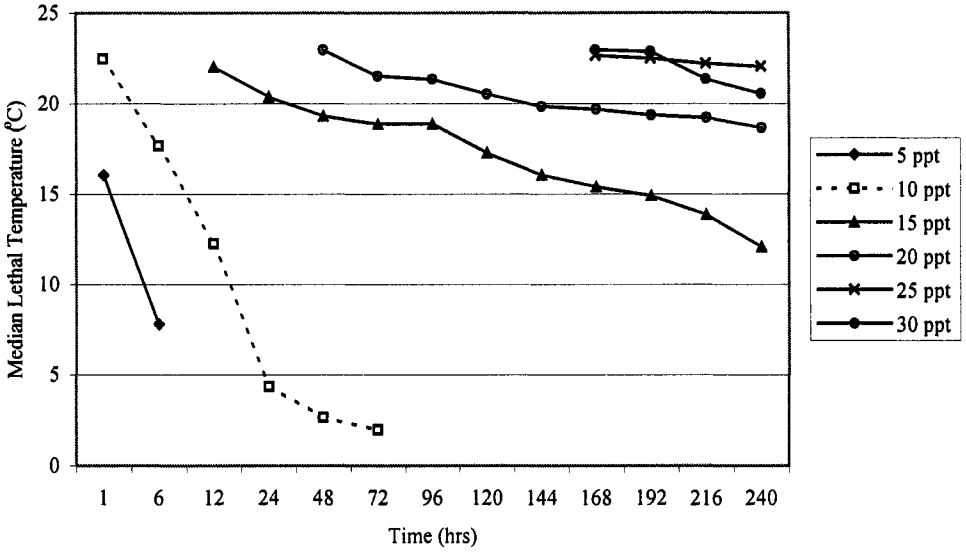


Figure 5. Median lethal salinities in scallops exposed to five experimental temperatures after 240-h (n = 3 replicates of 10 scallops per treatment); A) small juvenile scallops; B) large juvenile scallops.

(A)



(B)

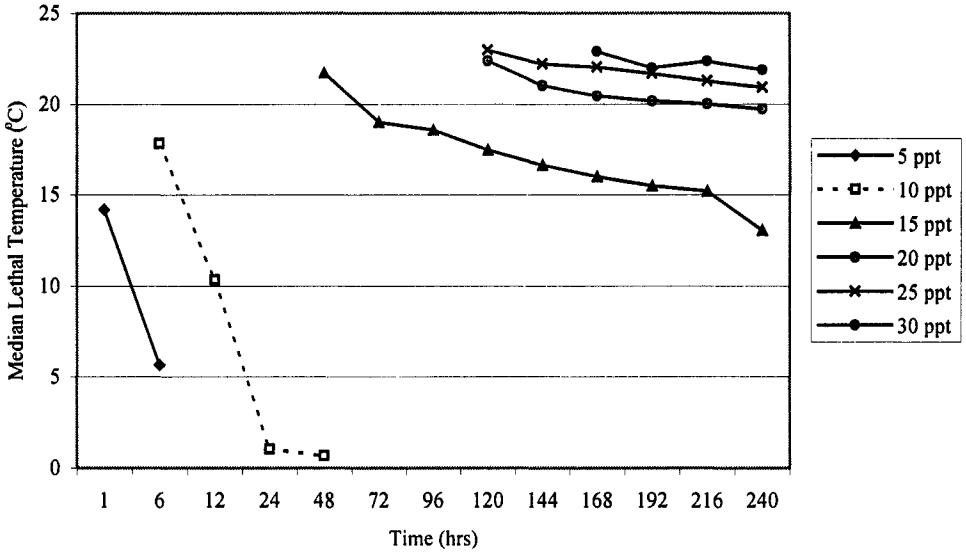
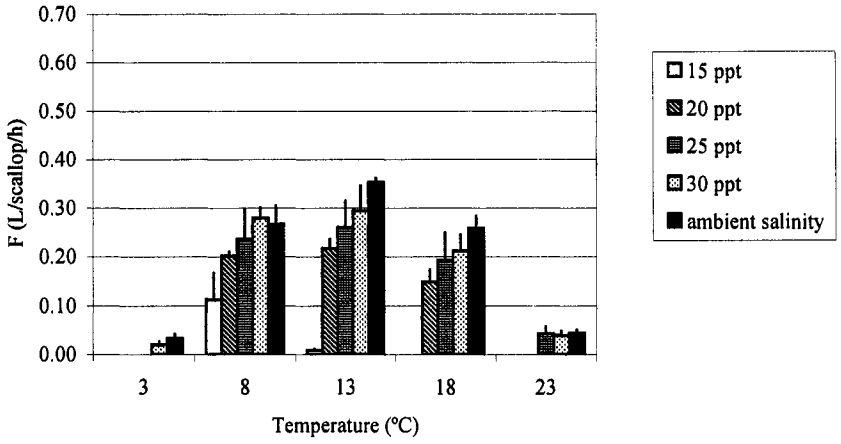


Figure 6. Median lethal temperatures in scallops exposed to six experimental salinities over 240-h (n = 3 replicates of 10 scallops per treatment); A) small juvenile scallops; B) large juvenile scallops.

(A)



(B)

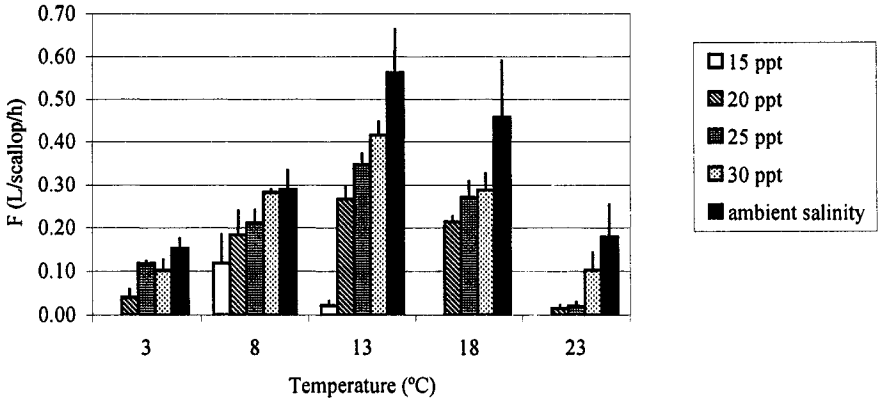
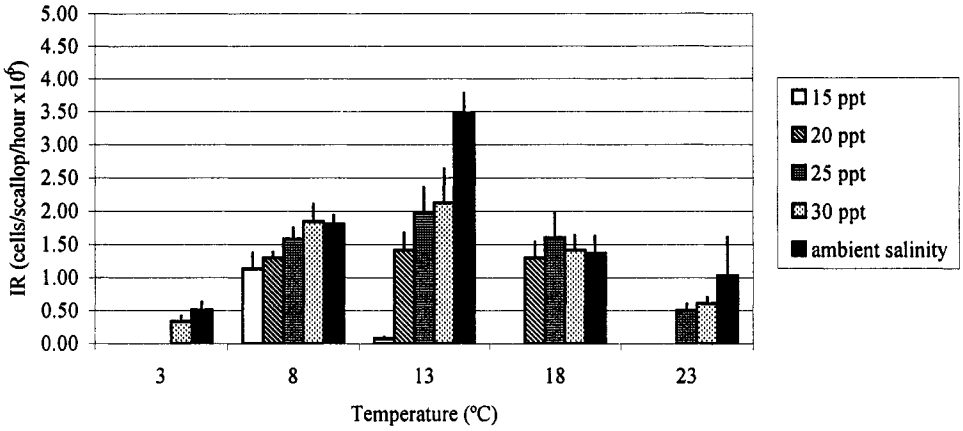


Figure 7. Clearance rate (F) at experimental temperatures and salinities (n = see Appendix 1); A) small juvenile scallops; B) large juvenile scallops. Vertical bars are + SE.

(A)



(B)

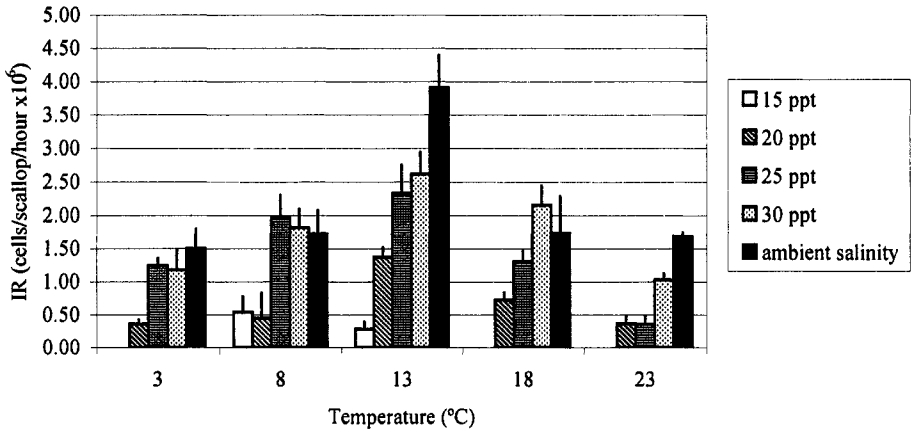


Figure 8. Ingestion rate (IR) at experimental temperatures and salinities (n = see Appendix 1); A) small juvenile scallops; B) large juvenile scallops. Vertical bars are + SE.

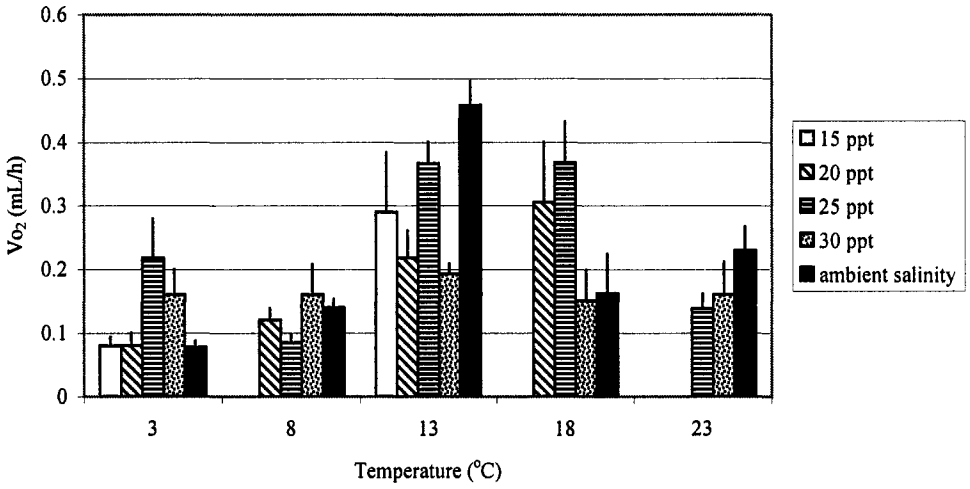


Figure 9. Oxygen consumption (VO_2) for juvenile scallops, small and large combined and standardized to 0.1 g at experimental temperatures and salinities (n = see Appendix 1). Vertical bars are + SE.

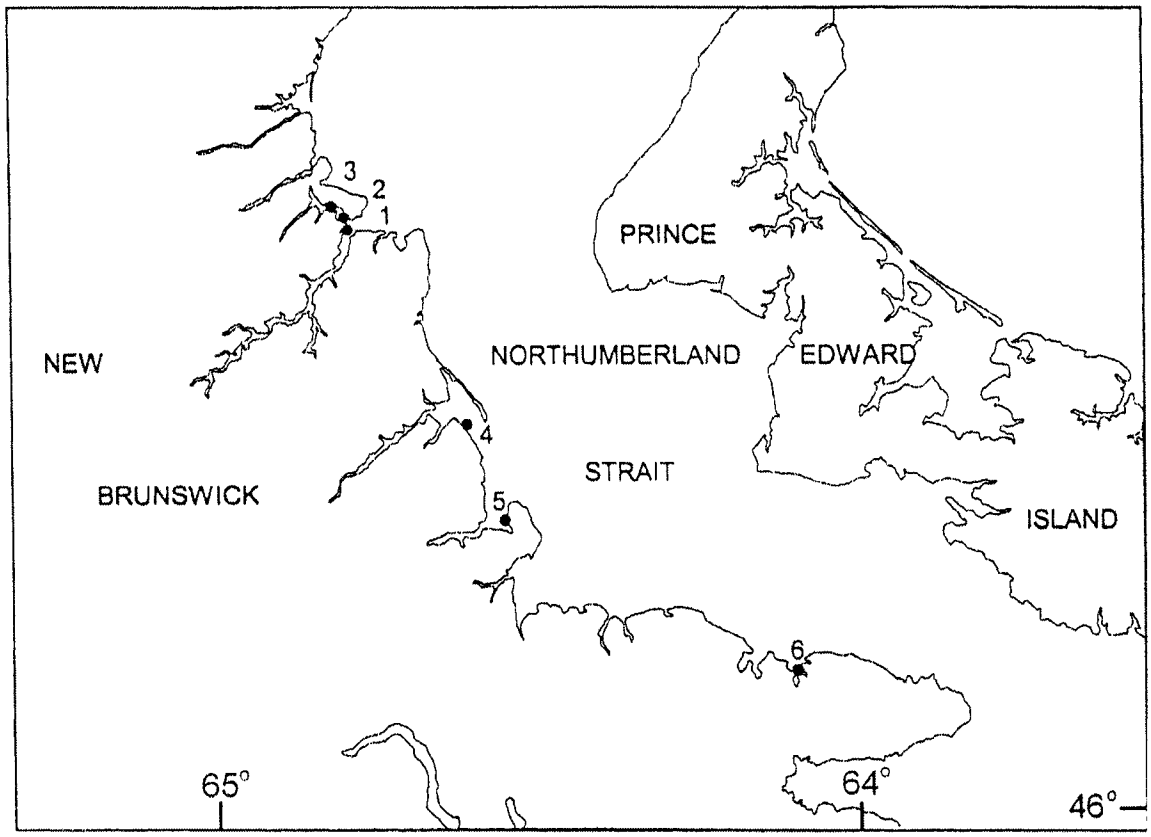


Figure 10. Location of the study sites along the Northumberland Strait
1) Richibucto Bay site 1; 2) Richibucto Bay site 2; 3) Richibucto Bay site 3;
4) Bouctouche Bay; 5) Cocagne Bay; 6) Little Shemogue Bay.

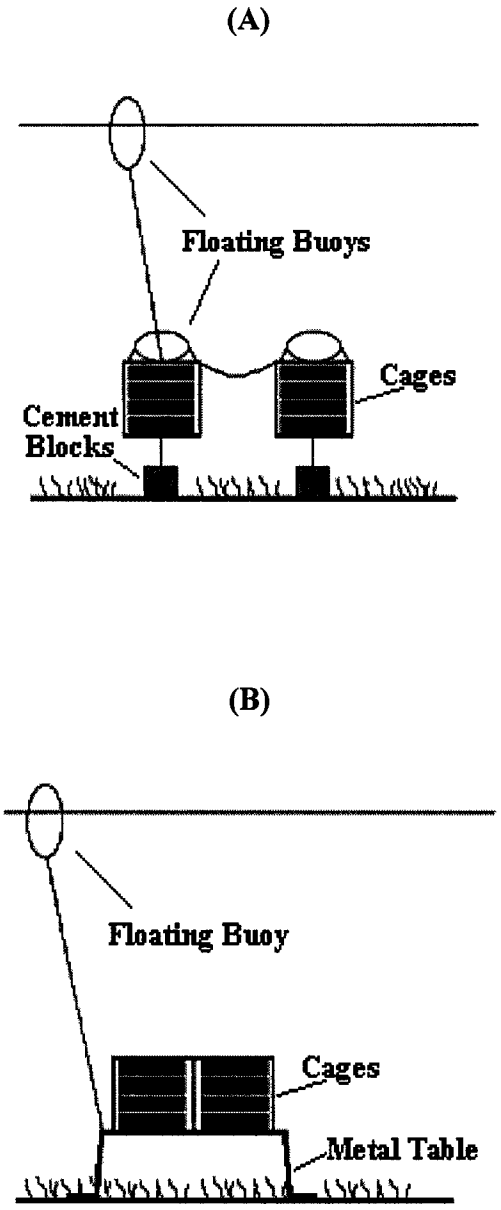


Figure 11. Experimental set-up of the field-based culture study; A) in Cocagne Bay, Little Semogue Bay, and Richibucto Bay (sites no. 2 and 3); B) in Bouctouche Bay and Richibucto Bay (site no. 1).

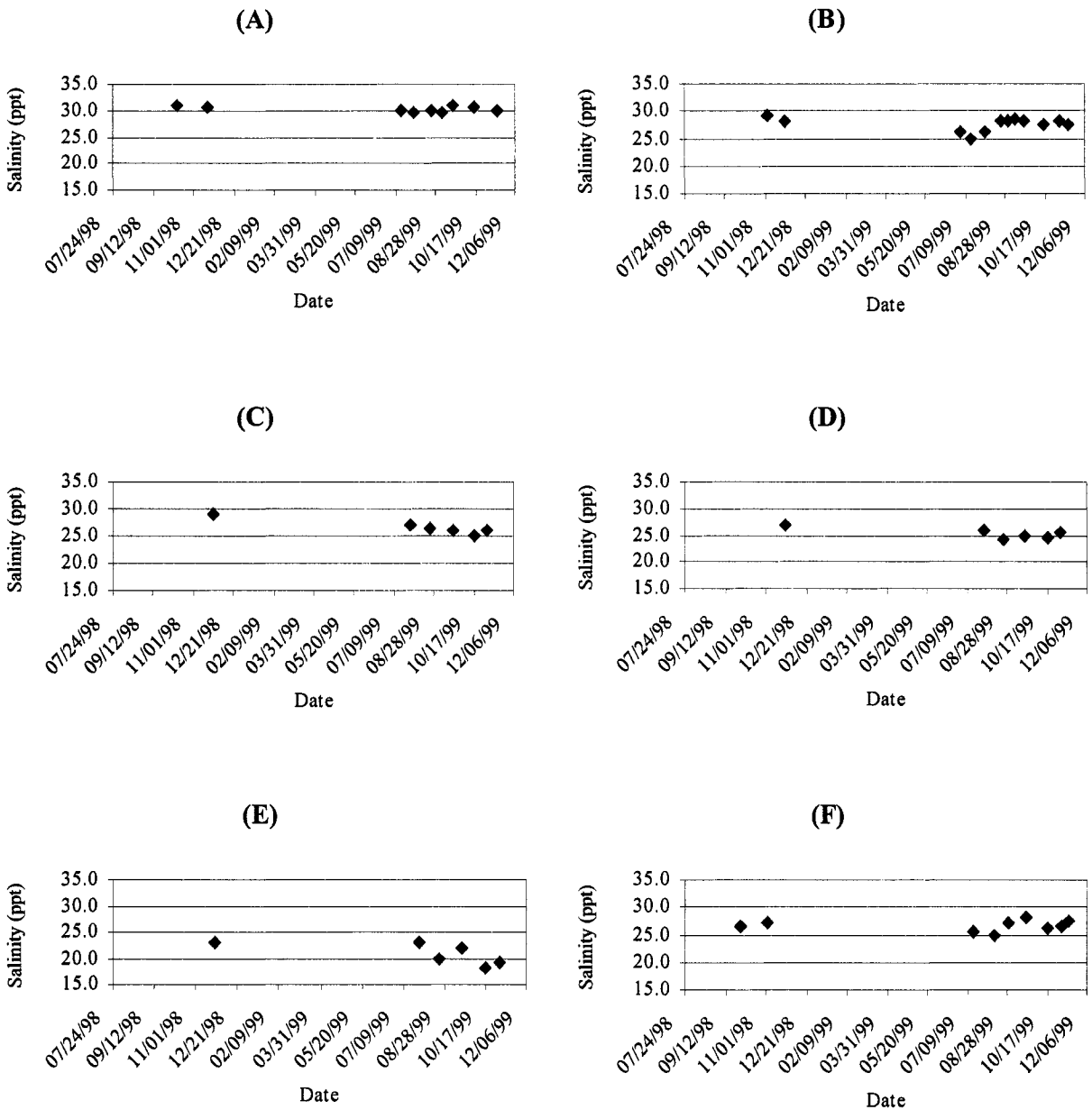


Figure 12. Salinity levels (ppt) for all six sites during the study period (Jul. 98–Dec. 99) (mm/dd/yy); A) Bouctouche Bay; B) Cocagne Bay; C) Richibucto Bay (site 1); D) Richibucto Bay (site 2); E) Richibucto Bay (site3); F) Little Shemogue Bay.

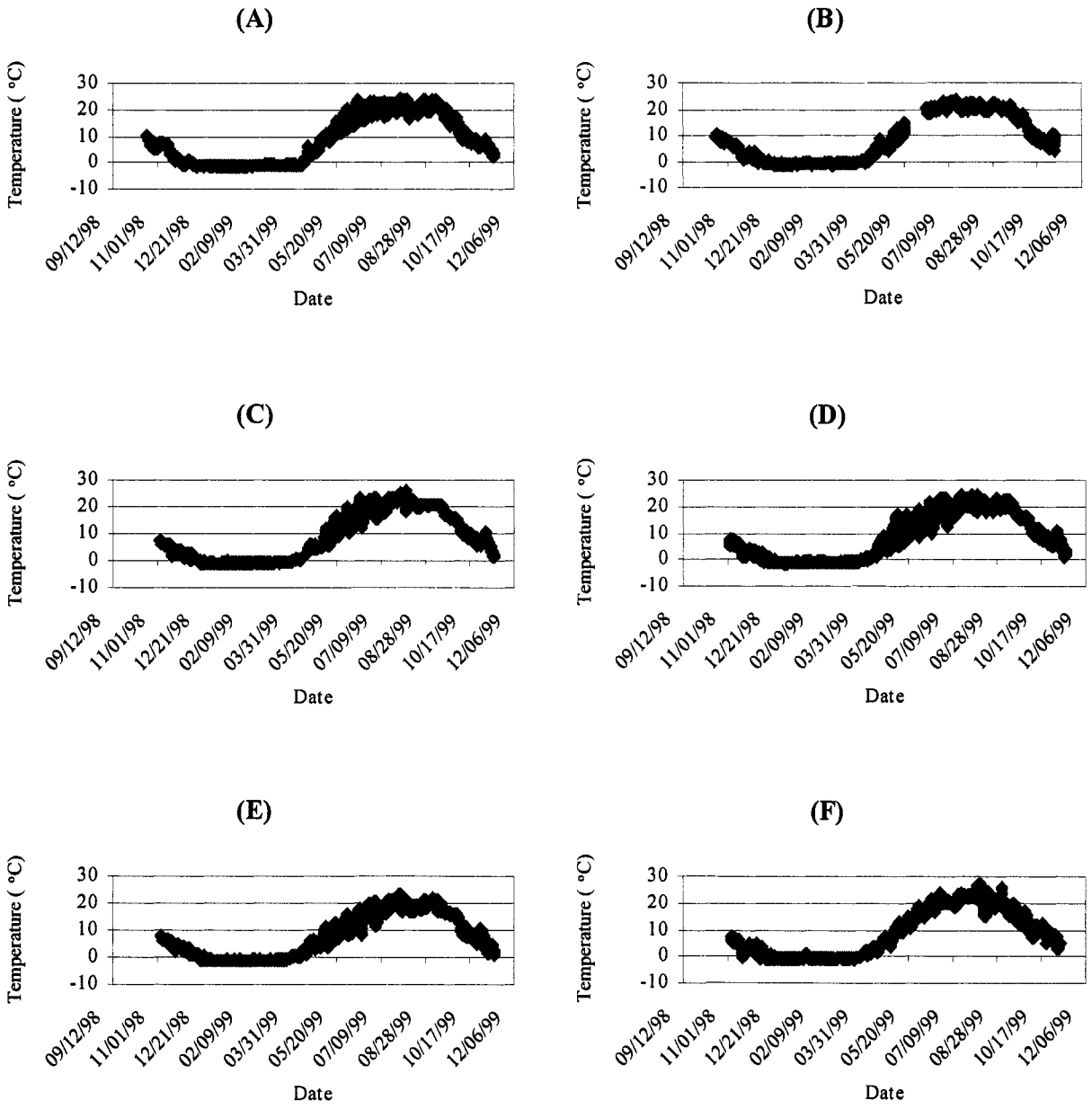


Figure 13. Water temperature (°C) for all six sites during the study period (Jul. 98–Dec. 99) (mm/dd/yy); A) Bouctouche Bay; B) Cocagne Bay; C) Richibucto Bay (site 1); D) Richibucto Bay (site 2); E) Richibucto Bay (site 3); F) Little Shemogue Bay.

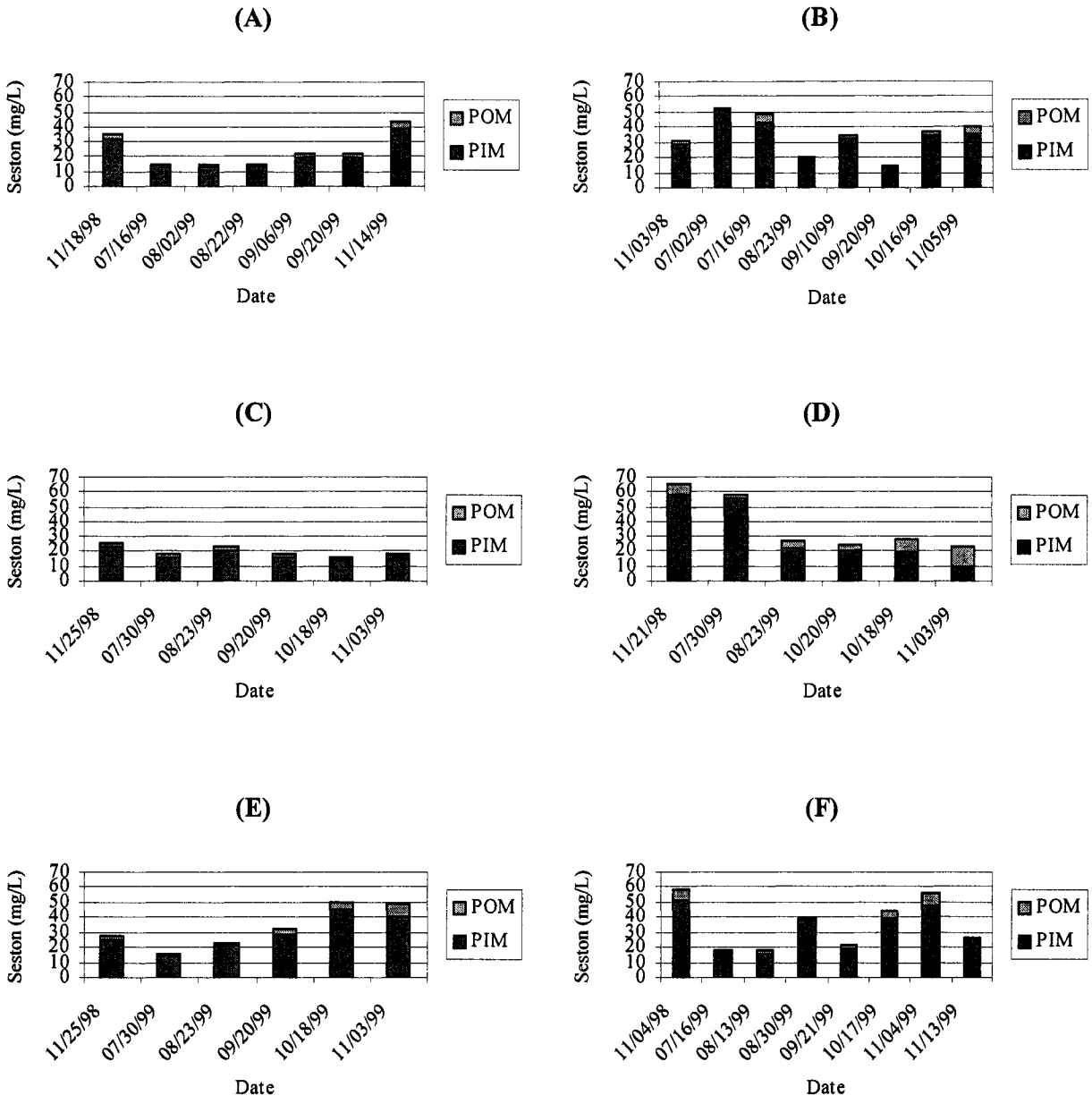


Figure 14. Water seston (POM and PIM) concentrations in mg/L for all six sites during the study period (Jul. 98–Dec. 99) (mm/dd/yy); A) Bouctouche Bay; B) Cocagne Bay; C) Richibucto Bay (site 1); D) Richibucto Bay (site 2); E) Richibucto Bay (site 3); F) Little Shemogue Bay.

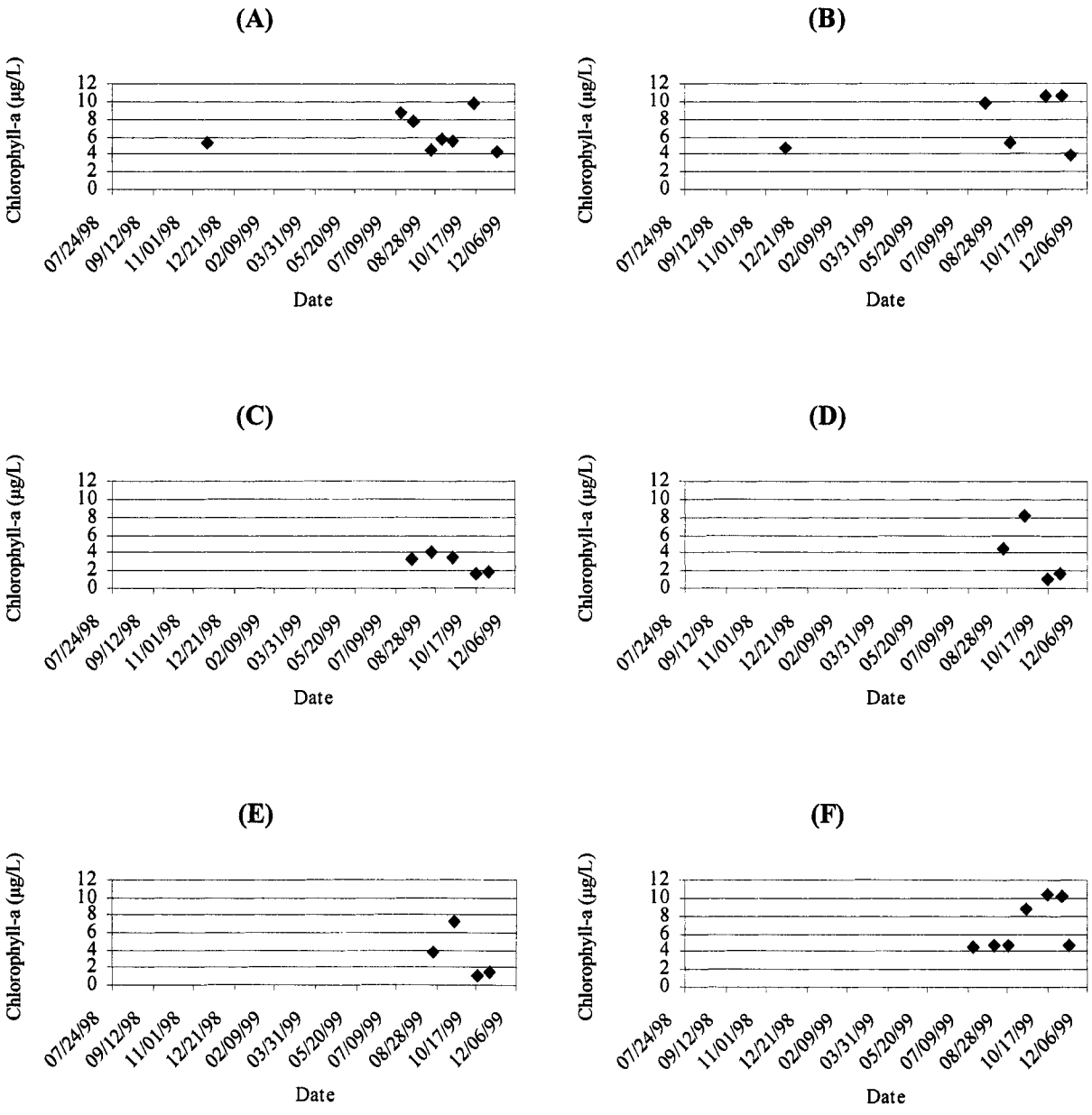


Figure 15. Chlorophyll-a concentration in µg/L for all six sites during the study period (Jul. 98–Dec. 99) (mm/dd/yy); A) Bouctouche Bay; B) Cocagne Bay; C) Richibucto Bay (site 1); D) Richibucto Bay (site 2); E) Richibucto Bay (site 3); F) Little Shemogue Bay.

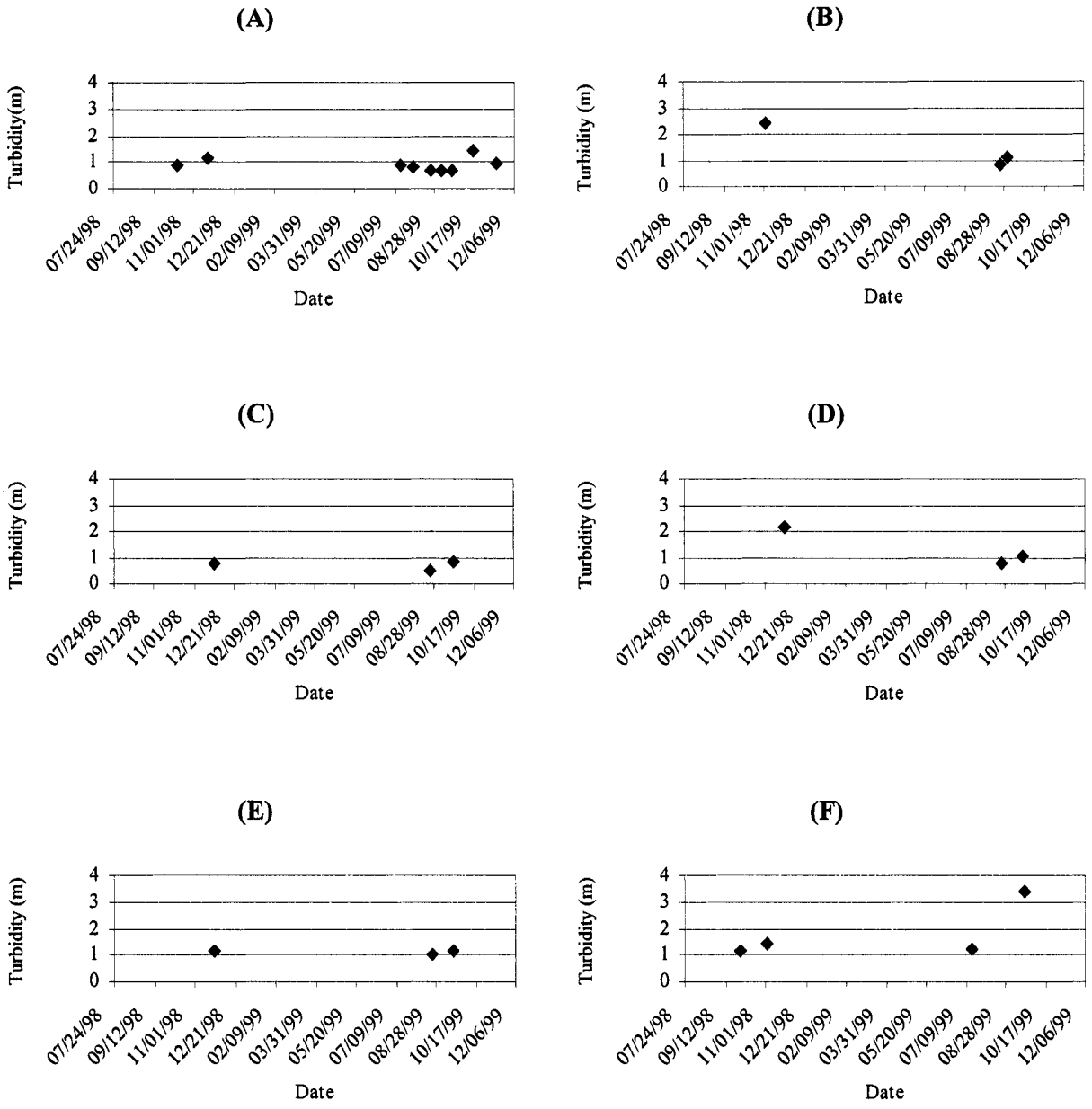


Figure 16. Water turbidity measured by the overall light extinction coefficient (k_t) in meters for all six sites during time the study period (Jul. 98–Dec. 99) (mm/dd/yy); A) Bouctouche Bay; B) Cocagne Bay; C) Richibucto Bay (site 1); D) Richibucto Bay (site 2); E) Richibucto Bay (site 3); F) Little Shemogue Bay.

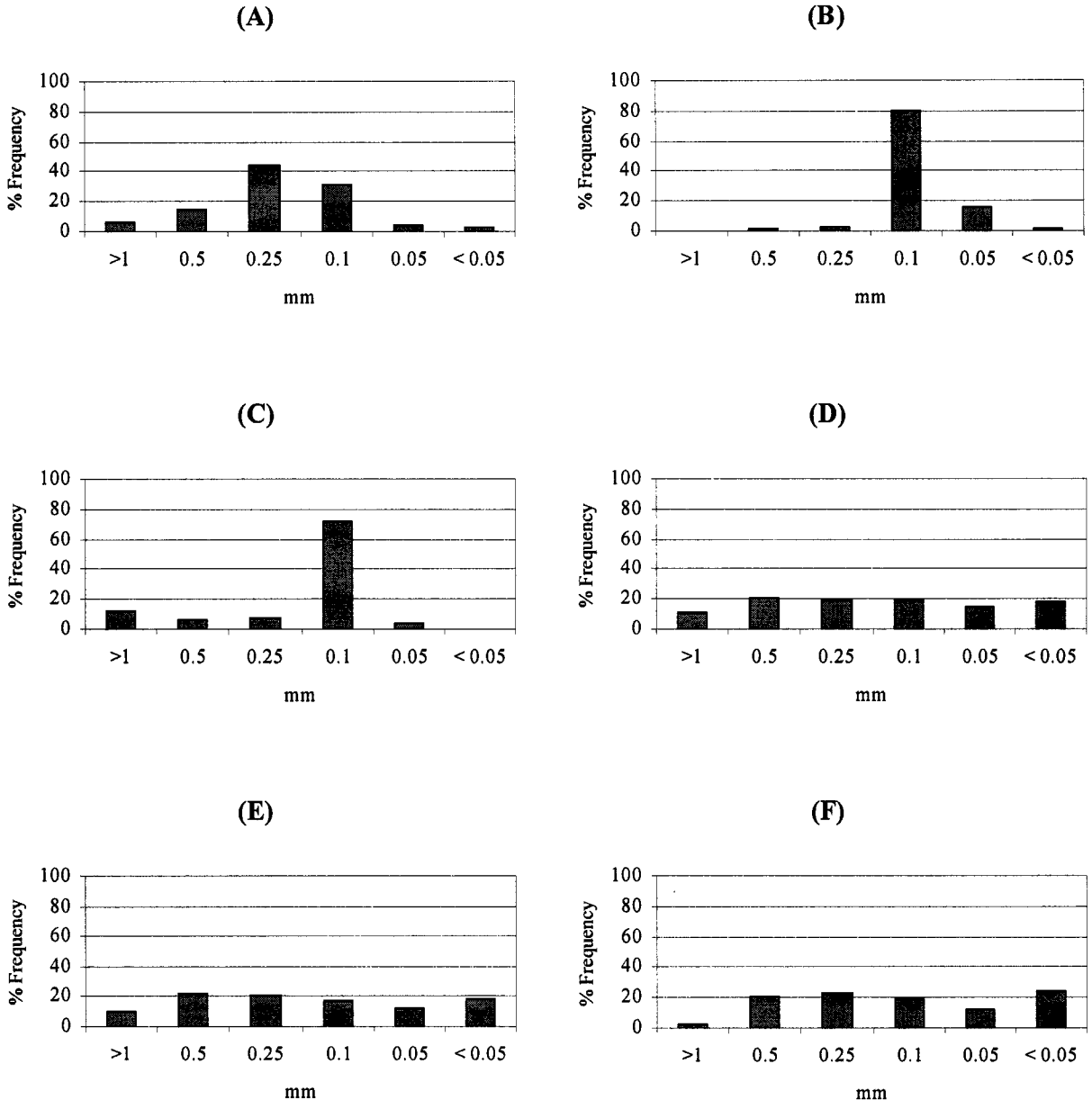


Figure 17. Bottom sediment particle size class distribution in millimeters for all six sites; A) Bouctouche Bay; A) Cocagne Bay; C) Richibucto Bay (site 1); D) Richibucto Bay (site 2); E) Richibucto Bay (site 3); F) Little Shemogue Bay.

APPENDICES

APPENDIX 1

Number of scallops used for metabolic measurements

Number of juvenile scallops used for the clearance and ingestion rates (F and IR), and oxygen consumption (VO_2) after the 240-h bioassays. No living scallops were available at 5 ppt and 10 ppt at all temperature trials after 240-h.

	15 ppt	20 ppt	25 ppt	30 ppt	Ambient salinity
***3 °C**					
F and IR (small)	n.a.	n.a.	n.a.	n.a.	10
F and IR (large)	n.a.	n.a.	n.a.	n.a.	10
VO_2 (0.1g juvenile)	6	8	6	8	8
8 °C					
F and IR (small)	1	20	17	23	10
F and IR (large)	1	20	20	20	10
VO_2 (0.1g juvenile)	n.a.	8	8	8	10
13 °C					
F and IR (small)	10	26	30	30	10
F and IR (large)	16	28	28	29	10
VO_2 (0.1g juvenile)	6	7	7	5	5
18 °C					
F and IR (small)	n.a.	15	19	20	10
F and IR (large)	n.a.	18	20	20	10
VO_2 (0.1g juvenile)	n.a.	9	10	9	8
23 °C					
F and IR (small)	n.a.	n.a.	9	1	10
F and IR (large)	n.a.	n.a.	5	9	10
VO_2 (0.1g juvenile)	n.a.	n.a.	5	5	10

n.a. None available

* Because of the availability of the laboratory equipment (Coulter® Multisizer II) for the 3°C temperature trial, the VO_2 was done first. At all the other temperature trials the F and IR were done before VO_2.

APPENDIX 2

Methodology for Stress Enzymes Analysis

The methodology used at the National Research Council was taken from Ross et al. (2000) and is as follows:

> For alkaline phosphatase assays, mucus samples were incubated with 4 mM *p*-nitrophenyl phosphate in 100 mM ammonium bicarbonate buffer with 1 mM $MgCl_2$, pH 7.8 at 30°C. The increase in OD was measured continuously over 2 to 3 h at 405 nm using a microplate reader. The initial rate of the reaction was used to calculate the activity. One unit (U) of activity was defined as the amount of enzyme required to release 1 μmol of *p*-nitrophenol product in 1 min. The extinction coefficient of *p*-nitrophenol in the microplate wells was experimentally determined.
>
> For the azocasein hydrolysis assay (Charney and Tomarelli 1947), samples were added to azocasein (Sigma, St. Louis, MO; 3.5 mg mL^{-1} dissolved in 100 NH_4HCO_3, pH 7.8) and tubes were placed on a shaker at 30°C for approximately 19 h. The reaction was stopped by adding trichloroacetic acid (4.5 % final concentration), the samples were cooled on ice, centrifuged at 15 000 × g for 5 min and 100 μL of each supernatant was added to 100 μL of 0.5 M NaOH in microplate wells. Optical density (OD) was measured at 450 nm on a Thermomax microplate reader (Molecular Devices, Sunnyvale, CA).
>
> A turbidimetric assay (Shugar 1952) for lysozyme was adapted for continuous monitoring of absorbance in a microplate reader. Mucus samples were lyophilized, resuspended in an equal volume of 40 mM sodium phosphate buffer prior to assay and incubated with lyophilized cells of *Micrococcus lysodeikticus* at 30°C for 1 h. The initial rate of the reaction was used to calculate the activity, with 1 U of activity being defined as the amount of enzyme that catalyzed a decrease in absorbance at 450 nm of 0.001 min^{-1} at 20°C.

APPENDIX 3

Homogeneous subsets for F and IR.

F (small juveniles)

Tukey HSD [a, b, c]

	N	Subset		
SALINITY (ppt)		1	2	3
15	6	60.3041694		
Ambient	15		173.9137550	
20	27		189.0087311	189.0087311
25	33		200.6850359	200.6850359
30	33			291.2959630
Sig.		1.000	.962	.086

Means for groups in homogeneous subsets are displayed. Based on Type I Sum of Squares. The error term is Mean Square (Error) = 12023.591.
a Uses Harmonic Mean Sample Size = 15.107.
b The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.
c Alpha = .05.

Tukey HSD [a, b, c]

	N	Subset	
TEMPERATURE (°C)		1	2
3	6	26.2112305	
23	12	77.8383963	
18	30		204.8431710
8	33		228.2075246
13	33		289.1414685
Sig.		.710	.241

Means for groups in homogeneous subsets are displayed. Based on Type I Sum of Squares. The error term is Mean Square (Error) = 12023.591.
a Uses Harmonic Mean Sample Size = 14.537.
b The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.
c Alpha = .05.

F (large juveniles)

Tukey HSD [a, b, c]

	N	Subset	
SALINITY (ppt)		1	2
15	9	79.9767094	
20	33		227.8771436
25	33		237.8796499
30	36		285.3870873
Ambient	15		323.2818810
Sig.		1.000	.053

Means for groups in homogeneous subsets are displayed. Based on Type I Sum of Squares. The error term is Mean Square (Error) = 11252.770.
a Uses Harmonic Mean Sample Size = 18.786.
b The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.
c Alpha = .05.

Tukey HSD [a, b, c]

	N	Subset	
TEMPERATURE (°C)		1	2
23	15	65.5770405	
3	12	102.2477850	
8	33		271.0896640
13	36		275.3871085
18	30		338.0801361
Sig.		.800	.258

Means for groups in homogeneous subsets are displayed. Based on Type I Sum of Squares. The error term is Mean Square (Error) = 11252.770.
a Uses Harmonic Mean Sample Size = 20.711.
b The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.
c Alpha = .05.

IR (small juveniles)

Tukey HSD [a, b, c]

	N	Subset		
SALINITY (ppt)		1	2	3
15	6	601011.1111111		
20	27	1333485.8612581	1333485.8612581	
25	33	1443581.3852814	1443581.3852814	
Ambient	15		1867467.7777778	1867467.7777778
30	33			2479240.5829388
Sig.		.087	.488	.348

Means for groups in homogeneous subsets are displayed. Based on Type I Sum of Squares. The error term is Mean Square (Error) = 820388578356.566.
a Uses Harmonic Mean Sample Size = 15.107.
b The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.
c Alpha = .05.

Tukey HSD [a, b, c]

	N	Subset		
TEMPERATURE (°C)		1	2	3
3	6	418114.0350877		
23	12	1278597.6190476	1278597.6190476	
18	30		1381216.3227513	
8	33		1721768.6227353	1721768.6227353
13	33			2453594.4444444
Sig.		.086	.680	.197

Means for groups in homogeneous subsets are displayed. Based on Type I Sum of Squares. The error term is Mean Square (Error) = 820388578356.566.
a Uses Harmonic Mean Sample Size = 14.537.
b The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.
c Alpha = .05.

IR (large juveniles)

Tukey HSD [a, b, c]

	N	Subset	
SALINITY (ppt)		1	2
15	9	337155.5555556	
20	33		1554967.1717172
25	33		1669524.6272246
30	36		2152106.0626102
Ambient	15		2218128.8888889
Sig.		1.000	.130

Means for groups in homogeneous subsets are displayed. Based on Type I Sum of Squares. The error term is Mean Square (Error) = 730682292569.264.
a Uses Harmonic Mean Sample Size = 18.786.
b The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.
c Alpha = .05.

Tukey HSD [a, b, c]

	N	Subset		
TEMPERATURE (°C)		1	2	3
23	15	759106.6666667		
3	12	1069534.7222222	1069534.7222222	
18	30		1716065.9259259	1716065.9259259
8	33			2063734.9446849
13	36			2121781.4814815
Sig.		.769	.114	.547

Means for groups in homogeneous subsets are displayed. Based on Type I Sum of Squares. The error term is Mean Square (Error) = 730682292569.264.
a Uses Harmonic Mean Sample Size = 20.711.
b The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.
c Alpha = .05.

APPENDIX 4

Homogeneous subsets for VO_2.

VO_2 (0.1g juvenile)

Tukey HSD[a, b, c]

	N	Subset
SALINITY (ppt)		1
30	33	.1628433
20	33	.1816582
15	12	.1847297
Ambient	41	.1928424
25	34	.2573863
Sig.		.123

Means for groups in homogeneous subsets are displayed. Based on Type I Sum of Squares. The error term is Mean Square(Error) = 2.008E-02.
a Uses Harmonic Mean Sample Size = 25.286.
b The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.
c Alpha = .05.

Tukey HSD[a, b ,c]

	N	Subset		
TEMPERATURE (°C)		1	2	3
3	36	.1202550		
8	31	.1276316		
23	20	.1897103	.1897103	
18	36		.2521855	.2521855
13	30			.3028111
Sig.		.332	.443	.650

Means for groups in homogeneous subsets are displayed. Based on Type I Sum of Squares. The error term is Mean Square(Error) = 2.008E-02.
a Uses Harmonic Mean Sample Size = 29.215.
b The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.
c Alpha = .05.

APPENDIX 5

Homogeneous subsets for the concentrations of the three stress enzyme indicators at 3°C.

Alkaline phosphatase specific activities (small juveniles)

Tukey HSD[a,b,c]

	N	Subset
SALINITY (ppt)		1
30	10	.22960
25	7	.36514
15	7	.54957
20	6	.57050
Sig.		.323

Means for groups in homogeneous subsets are displayed. Based on Type I Sum of Squares. The error term is Mean Square (Error) = .138.
a Uses Harmonic Mean Sample Size = 7.241.
b The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.
c Alpha = .05.

Alkaline phosphatase specific activities (large juveniles)

Tukey HSD[a,b,c]

	N	Subset	
SALINITY (ppt)		1	2
25	8	.31425	
20	5	.35840	
30	10	.45170	.45170
15	9		.86533
Sig.		.815	.059

Means for groups in homogeneous subsets are displayed. Based on Type I Sum of Squares. The error term is Mean Square (Error) = 9.079E-02.
a Uses Harmonic Mean Sample Size = 7.461.
b The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.
c Alpha = .05.

APPENDIX 5 (cont.)

Azocasein hydrolysis specific activities (small juveniles)

Tukey HSD[a, b, c]

	N	Subset	
SALINITY (ppt)		1	2
30	10	.715789	
15	10	.762500	.762500
25	10	.770066	.770066
20	10		.853947
Sig.		.650	.219

Means for groups in homogeneous subsets are displayed. Based on Type I Sum of Squares. The error term is Mean Square (Error) = 1.079E-02.
a Uses Harmonic Mean Sample Size = 10.000.
b Alpha = .05.

Azocasein hydrolysis specific activities (large juveniles)

Tukey HSD[a, b, c]

	N	Subset	
SALINITY (ppt)		1	2
30	10	.669408	
25	10	.686842	
15	10	.830592	.830592
20	10		.939474
Sig.		.131	.439

Means for groups in homogeneous subsets are displayed. Based on Type I Sum of Squares. The error term is Mean Square (Error) = 2.582E-02.
a Uses Harmonic Mean Sample Size = 10.000.
b Alpha = .05.

Specific activities of lysozyme (small juveniles)

Tukey HSD [a, b, c]

	N	Subset	
SALINITY (ppt)		1	2
30	10	6.8450508	
25	10	18.7153803	
15	10	30.1668388	30.1668388
20	10		49.6694174
Sig.		.101	.212

Means for groups in homogeneous subsets are displayed. Based on Type I Sum of Squares. The error term is Mean Square (Error) = 482.595.
a Uses Harmonic Mean Sample Size = 10.000.
b Alpha = .05.

Specific activities of lysozyme (large juveniles)

Tukey HSD [a, b ,c]

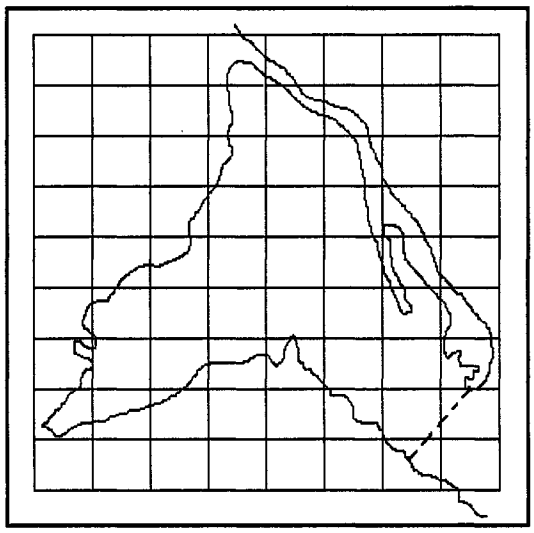
	N	Subset	
SALINITY (ppt)		1	2
30	10	4.4768726	
25	10	6.5699232	
15	10	9.1174920	
20	10		44.3203047
Sig.		.706	1.000

Means for groups in homogeneous subsets are displayed. Based on Type I Sum of Squares. The error term is Mean Square (Error) = 92.964.
a Uses Harmonic Mean Sample Size = 10.000.
b Alpha = .05.

APPENDIX 6

The area of each bay that the experiments were conducted was calculated following the standard methods and equations from Daniel Caissie (Pers. Comm.):

1. Using transparent grid paper, the area of each bay on a map was calculated. An imaginative border was created to close the bay (as shown on diagram).



2. The size of each square was calculated by comparing with the scale of the map.

3. The total amount of squares that appears on each bay was then counted for the total area. For partial squares, anything over half was counted as one and any under a half was ignored.

E.g.: Each square was equal to $800m^2$, in Bouctouche Bay 33 squares were counted.

$33 \times 800m^2 = 26{,}400\ m^2$

$26.40\ km^2$

APPENDIX 7

Sampling Frequency

Site	Scallop Code	Put Out	Initial (T0)	Sampling Date #1 (T1)	Sampling Date #2 (T2)
Bouctouche Bay	S	2 X 4 of 100	10/23/98	10/16/99	11/14/99
	L	2 X 4 of 100	10/23/98	10/16/99	11/14/99
Cocagne Bay	S	2 X 4 of 100	10/23/98	07/16/99	10/16/99
	L	2 X 4 of 100	10/23/98	10/16/99	NA
Richibucto Bay (s-1)	S	2 X 4 of 100	10/23/98	11/23/99	NA
	L	2 X 4 of 100	10/23/98	11/23/99	NA
Richibucto Bay (s-2)	S	2 X 4 of 100	10/23/98	08/23/99	*11/23/99
	L	2 X 4 of 100	10/23/98	08/05/1999	*11/23/99
Richibucto Bay (s-3)	S	2 X 4 of 100	10/23/98	08/23/99	*11/23/99
	L	2 X 4 of 100	10/23/98	08/05/1999	*11/23/99
Little Shemogue Bay	S	2 X 4 of 100	10/23/98	07/16/99	*11/04/99
	L	2 X 4 of 100	10/23/98	07/16/99	*11/04/99

NA: no data available
*: All dead

APPENDIX 8

Methodology for Seston

Seston was determined using the following standard methods and equations from Wetzel and Likens (1979) and Newell (1982):

1- Two litres of sampled water was filtered and retained on to pre-ashed GF/F glass fibre filters (1 litre/filter) at a pressure of less than 13 lb/in^2.

2- At the end of the filtration, the filter was rinsed with approximately 10 mL of ammonium formate (HCO_2NH_4, 3 %). Ammonium formate prevents salt crystallisation.

3- The filter was carefully removed with forceps and individually placed in a numbered aluminium tray.

4- The filters were then dried (60°C for 24-h), weighed, ashed (450°C for 24-h) and re-weighed.

5- The following equations are then used:

$$\text{Total seston weight (mg/L)} = \frac{c - b}{a}$$

$$\text{Inorganic seston weight (mg/L)} = \frac{d - b}{a}$$

Organic seston weight = total seston weight – inorganic seston weight
(mg/L) "ash-free dry weight"

Where:

(a) volume of filtered water (litres)
(b) weight of pre-ash filter before filtration
(c) weight of total seston + filter
(d) weight of inorganic seston + filter

APPENDIX 9

Methodology for Chlorophyll-a

The water collected (1,000 mL) was kept in an opaque bottle to prevent algae proliferation, preserved with a couple of drops of $MgCO_3$, and was transported in a cooler to the laboratory. The following is the standard methods and equation from Strickland and Parsons (1968):

1- Within a few hours of sampling, chlorophyll was filtered onto GF/F glass fibres (0.45 μm in pore size).

2- A couple of drops of $MgCO_3$ were added in the last millilitres of the filtration.

3- The filter was carefully removed with small pliers, folded twice, individually placed in an opaque bottle, clearly labelled (date of sampling, location, volume filtered), and frozen.

4- The filters were analysed after being frozen for 30-d or were analysed the same days of sampling within a maximum waiting time of 8-h.

5- The filters have to be dissolved before the reading of the pigments. In a centrifuge tube, each of the filters were dissolved with 8 mL of acetone 90%, given a strong shake, and refrigerated for 20-h. Afterwards, the tubes were brought to room temperature (2-h).

6- An additional 10 mL of acetone 90% was added to each tube and shaken. They were then ready to be centrifuged for 10-min at 28 000 RPM.

7- The top floating liquid was transferred in to a spectrophotometer cell. The spectrophotometer was calibrated with acetone and six readings (wave lengths) were observed and noted:

750 nm (1)
665 nm (2)
645 nm (3)
630 nm (4)
510 nm (5)
480 nm (6)

8- The different pigments were then calculated using the results found in the six different readings:

mg of pigment/m^3 = C/V

C = concentration
V = volume (1 L)

C (Chl.a) = 15.6(2) – 2.0(3) – 0.8(4)
C (Chl.b) = 25.4(3) – 4.4(2) – 10.3(4)
C (Chl.c) = 109(4) – 12.5 (2) – 28.7(3)
C (Carot.) = 7.6(6) – 1.49(5)

Note: Steps 1 to 5 were done in obscurity to prevent algae proliferation

APPENDIX 10

Methodology for Granulometric Analysis

Granulometric analysis of the bottom samples was conducted using the following methods from Bellair and Pomerol (1984):

1- An amount of 50 to 100 g of dried sample for each study site was utilised.

2- Five sieves were used to separate the sands in five fractions – very coarse, coarse, medium, fine and very fine – respectively retained on the 1 mm, 500 μm, 250 μm, 100 μm and 50 μm. Any particles that passed through the 50 μm were considered as silt and clay.

3- One was placed on top of the other in a decreasing mesh size, the sieves were all shaken together with an electric agitator.

4- The remaining particles on each sieve, including the smaller than 50 μm were carefully brushed off and weighed.

APPENDIX 11

Growth classes in mm/day

With the help of "pivot table" in Microsoft Excel XP©, four different growth classes in mm/day (<0.047; 0.047 – 0.062; 0.063 – 0.078; >0.079) were created.

Total numbers						
	Bouctouche Bay	Cocagne Bay	Richibucto Bay (s-1)	Richibucto Bay (s-2)	Richibucto Bay (s-3)	Little Shemogue Bay
< 0.015				3	37	
0.015 – 0.030				11	73	3
0.031 – 0.046	38	39	41	7	32	23
0.047 – 0.062	260	93	106	1	1	9
0.063 – 0.078	118	5	125			1
0.079 – 0.094	1		15			
> 0.094			3			
	417	137	290	22	143	36

The number of scallops found in each class was used for the observed values in the Chi-square test.

e.g., Bouctouche Bay vs. Cocagne Bay

Observed values			
	Bouctouche Bay	Cocagne Bay	
< 0.047	38	39	77
0.047 – 0.062	260	93	353
0.063 – 0.078	118	5	123
> 0.079	1	0	1
	417	137	554

Predicted values			
	Bouctouche Bay	Cocagne Bay	
< 0.047	57.9584838	19.04152	77
0.047 – 0.062	265.705776	87.29422	353
0.063 – 0.078	92.5830325	30.41697	123
> 0.079	0.75270758	0.247292	1
	417	137	554

P-value = 2.7896^{-12}