AN ESTIMATION OF THE CARRYING CAPACITY OF A COMMERCIAL MUSSEL FARM IN NEWFOUNDLAND

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by

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Abstract

The mussel industry in Newfoundland began in the early 1980's, with the number of farms increasing rapidly over the next ten years. By the early 1990's some of the farms had grown quite large, in excess of 100 hectares, and the industry was becoming concerned about the carrying capacity of some sites.

This project was initiated to evaluate the carrying capacity of a commercial mussel farm, owned and operated by Atlantic Ocean Farms Ltd., in Fortune Harbour, Newfoundland. The site operators noted it was taking longer to obtain a market size mussel than it had in previous years.

Over the two year study period, 1994-1996, mussels suspended at 2 m and 15 m and at opposite ends of the site were significantly different in shell length, dry tissue weight, dry shell weight and, in those near the surface, in condition.

Chlorophyll-*a*, temperature, and salinity at 2 m were not significantly different at either location although both salinity and temperature at 2 m were significantly different than at 15 m. The site had a low current speed, <2 cm/s, low tidal flushing, and less than optimal chlorophyll-*a* concentrations with an annual mean of 1.6 μg/L.

There were three different carrying capacity models used to determine an appropriate stocking density for the site: tidal volume method, food depletion approach, and food demand versus food supply. The stocking density present on the site, 65 x 10^6 mussels in 1995, was more than two times the suggested stocking density based of these models.

It is recommended the operators reduce density of mussels on the site and stock at a rate of approximately 14,000 socks annually or 35 x 10^6 mussels (132 socks per hectare or 33 x10^4 mussels per hectare).

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Introduction

1.1 The Newfoundland Mussel Aquaculture Industry

The mussel aquaculture industry in Newfoundland commenced in the late 1970's, although there was an industry utilising wild mussels for several years prior to this. In the 1960's there were three commercial mussel canning operations in Newfoundland. The operations harvested mussels from wild beds, but eventually closed due to unreliable supply and competition from other protein sources (Sutterlin et al., 1981).

Inconsistent supply prompted research toward the development of a blue mussel aquaculture industry. Studies were initiated by the Marine Science Research Laboratory of Memorial University in the 1970's with a research site established at Garden Cove, Placentia Bay, in 1976. Various types of equipment and site configurations were evaluated including; rafts and the Japanese long-line for suspending mussels, net arrays and ropes for collecting and growing the seed (Sutterlin et al., 1981). This research eventually lead to the establishment of the Province's first commercial mussel farm at Winter Tickle, Notre Dame Bay. The first gear was deployed in 1981 to culture *Mytilus edulis* L. using Japanese long-line technology similar to that in use today. Subsequent analysis revealed the industry was not producing pure *M. edulis* but rather a mixture of *M. edulis* and *Mytilus trossulus* (Bates and Innes, 1995).

By 1994, the mussel culture industry had expanded to 58 licenced sites, employing 160 persons with sales of 399 mt of product valued at $878,000 (DFA, 1994). There were sites being evaluated or established in many of the bays around the Province although most of the activity was focused in Notre Dame Bay.

The industry had developed such that some mussel sites were covering areas in excess of 100 ha. Aquaculturists were working to maximise the production obtained from leases and reduce costs. Mechanisation was gaining importance on the farm with most businesses obtaining larger, more powerful boats fitted with hydraulic lifts. The

level of farm expansion was a concern to the industry as there was limited information on carrying capacity, and whether the wild food supply could support the growth rates of mussels held at high densities.

There was also limited information to assist growers predict the growth of bivalves under field conditions, yet maximising growth is one of the main objectives of mussel culture (Mallet and Myrand, 1995). Growth information allows farmers to control density, reduce mortality, and increase size, offering economic projections and stability to the industry (Mallet and Carver, 1991).

1.2 Project Rationale

The research site used for this project was established by Atlantic Ocean Farms Limited in 1983. The site was developed over an extended period and used for both collecting seed and grow-out. Seed collection was quite good in the early years but as the stocking density increased volume of seed obtained dropped significantly (J. Ward, Atlantic Ocean Farms, pers. comm.). To ensure that adequate seed was available to meet company objectives, seed was also obtained from a number of other sources including wild beds on the South Coast, salmonid aquaculture grow-out cages in the Bay D'Espoir region, and other seed collection sites throughout the Province.

In addition to a reduction in seed collected, site operators also noted that the time required to obtain a market size mussel appeared to be getting longer (J. Ward, pers. comm.). There was uncertainty as to whether the extended grow-out period required to obtain mussel market size was related to unfavorable environmental conditions or if the company had stocked the site to a level that could not be sustained by the wild food supply. As a result of the concern about reduced growth rates, this research project was initiated to gain a better understanding of the environmental conditions of the site and the variables that influence mussel growth. The study was designed with the prediction that if the site was overstocked and mussels at the entrance to the site would have first access

to food on an incoming tide, then the food would be depleted as it moved through the site and mussels farthest from the entrance would consequently grow at a reduced rate and be in poorer condition. If food was not limiting, then the mussels at both ends of the lease would grow equally well.

1.3 Mussel Growth

Growth of mussels is generally measured by the change in shell length or tissue weight over time (Seed, 1976; Seed and Suchanek, 1992; Mallet and Myrand, 1995). It represents the integrated physiological and biochemical response of the organism to environmental conditions (Riisgård and Randløv, 1981). Growth results when energy acquisition is in excess of energy expenditure. If on the other hand, energy intake is less than expenditure, "negative growth" occurs and endogenous reserves of energy must be utilised to maintain the body in a viable condition (maintenance metabolism) (Bayne and Newell, 1983).

Various environmental factors influence growth rate in *Mytilus spp.*, and in temperate waters shell growth is rapid during the spring and summer, and slow or absent during colder months (Seed, 1976). Flesh weight, by contrast, exhibits pronounced seasonal peaks associated with the annual reproductive cycle (Mallet and Myrand, 1995). Thus the pattern of growth in temperate water populations consists of alternating increments in shell length during the spring and summer and flesh weight during winter (Seed and Suchanek, 1992). Some of the factors that influence the growth in bivalves include water temperature (Mallet and Carver, 1989; Mallet and Carver, 1993; Grant, 1996; Nielsen, 1988; Kautsky, 1982; Seed, 1976; Almada-Villela et al.,1982; Incze et. al., 1980), salinity (Seed, 1976; Kautsky, 1982; Almada-Villela, 1984), food quality and quantity (Seed, 1976; Widdows et al., 1979; Kautsky, 1982; Fréchette and Bourget, 1985a; Page and Hubbard, 1987; Newell et al., 1998), current speed (Rosenberg and Loo, 1983; Rheault and Rice, 1996), seed source (Mallet et al., 1987b; Camacho et al., 1995).

density of animals (Maximovich et al., 1996; Heasman et al., 1998), and biofouling (Grant et al., 1998).

Food

Mussels are active suspension feeders which filter suspended particulate matter, seston, from the water. Seston is composed of non-viable material such as particles of silt, clay, and detritus, and viable material such as bacteria, phytoplankton, and invertebrate eggs and larvae, i.e. particles ranging in size from less than 1 μm to greater than 1 mm. Widdows, Fieth and Worrall (1979) found that filtration rate was a unimodal function in relation to wild seston concentration (dry weight per litre), and that optimum seston concentration increased with increasing animal size.

Seston quality has been extensively investigated in response to mussel feeding. *Mytilus edulis* is considered to be an indiscriminate active suspension feeder (Ward and Targett, 1989), where the filtration rate is not normally stimulated by ectocrine compounds associated with phytoplankton exudates.

Food is probably the single most important factor influencing growth rate of mussels worldwide (Seed, 1976; Page and Hubbard, 1987; Seed and Suchanek, 1992; Mallet and Myrand, 1995; Campbell and Newell, 1998). If food is scarce, growth is retarded regardless of all other conditions (Seed, 1976). Food limitation, in the dynamic environment of a mussel culture system, may result from either quantitative or qualitative depletion of the food source, which may be a reduction in total particulate matter availability, or a change in ratios of phytoplankton to detritus, or organics to inorganics (Hickman, 1992).

Food availability has a greater effect on growth of *M. edulis* than temperature variability (Page and Hubbard, 1987) and may influence the growth rate of mussels at different sites independently of differences in water temperature.

Fréchette and Bourget (1985b) found that growth of *Mytilus edulis* was

significantly depressed at the sediment-water interface compared with growth 1.0 m above the mussel bed. Growth differences resulted from vertical depletion of food, which was attributable to the feeding activity of the mussels themselves.

In a study of the winter growth of *M. edulis* in Nova Scotia, Mallet et al. (1987b) found that shell growth was not food-limited at ice-covered sites but that tissue growth was food limited. They suggested that the development of the spring plankton bloom may be necessary to provide sufficient food for substantial tissue growth.

Reduced growth in response to limited food has been demonstrated in bivalve species other than mussels. The growth response of the eastern oyster, *Crassostrea virginica*, and the bay scallop, *Argopecten irradians irradians*, to varying degrees of food limitation has been attributed to dense assemblages of shellfish that rapidly deplete ambient food concentration under conditions of low current speed, resulting in measurable effects on growth and condition index (Rheault and Rice, 1996).

Depth

Food density may increase with depth as phytoplankton blooms sink. Dabinett and Clemens (1997) reported an increase in food levels (chlorophyll-*a* concentrations) of 12% at depths of 7-12 m compared to 2-7 m, while temperature decreased by 24% at the greater depths at eight Newfoundland mussel farms. They suggested that growers should experiment by lowering mussel socks to deeper water to utilise the increased food resource, which would more than offset the temperature effect.

The growth rate of *M. edulis* was higher at a depth of 9 m than at depths of 2 m and 18 m at Santa Barbara, California (Page and Hubbard, 1987). Differences in mussel growth rate with depth were not associated with water temperature, since water temperature decreased with depth. This study may not be indicative of what might be expected in Newfoundland waters as the low temperature experienced at 18 m was 9°C off California, while in Newfoundland at similar depths temperatures can reach –2°C.

Temperature

Temperature has been widely acknowledged as an important factor in influencing growth in mussels, with optimum growth occurring at temperatures between 10°C and 20°C (Seed, 1976). In Atlantic Canada, cultured mussels are often exposed to temperatures ranging from -2°C to more than 25°C. Shell growth in all size classes of mussels is much reduced at low temperatures, i.e., when the temperature drops below 0°C, whereas the highest growth rates are typically observed after the spring bloom but before spawning (Mallet and Myrand, 1995).

Almada-Villela et al. (1982) studied the shell growth of *M. edulis* at 16 different temperatures and found that growth increased logarithmically between 3 and 20°C but above 20°C the growth rate declined sharply. Further, at lower temperatures (3°C and 5°C) growth rates were constant but very low.

In a study on the growth of raft-cultured mussels, *M. edulis*, at spring temperatures (12-20°C) and autumn temperatures (8-20°C) in Norway, Nielsen (1988) reported the acute response to temperature exposure is an increase in shell length with temperature. He found that in acclimated mussels the rate of increase in length decreased with increasing temperature. Maximum shell-length growth was recorded at the lowest experimental temperatures, i.e., 8°C in autumn and 12°C in spring.

A relationship between growth and temperature is clearly demonstrated when shell length is plotted against age in day degrees (Seed and Suchanek, 1992). However, growth rates expressed in these terms are not always consistent, which suggests that factors other than temperature (e.g., food supply) are probably involved (Kautsky, 1982; Thompson, 1984b).

Salinity

Brackish estuaries and lagoons are known to be suitable for mussel growth but

this probably reflects increased food levels in these environments rather than any beneficial effects of reduced salinity (Seed, 1976; Seed and Suchanek, 1992). *Mytilus edulis* can survive considerably reduced salinities and this frequently provides substantial protection against less tolerant predators, but at concentrations below 20 ‰ there is a detrimental effect on growth (Almada-Villela, 1984).

The effect of salinity on mussels has been studied most frequently in the Baltic Sea as *Mytilus edulis* represent one of the few marine species that have managed to adapt to the reduced salinities found in that environment (Kautsky, 1982). Shell growth rates were reduced in the wild population due to intraspecific competition where the main abiotic factor was found to be salinity (Kautsky, 1982).

Current Speed

Bivalve molluscs are generally active suspension feeders, yet few authors have investigated the effect of velocity on mussel filtration/feeding or growth rates (Wildish and Kristmanson, 1997). Seston quantity available for mussels is a function of both concentration of seston particles and flow or velocity. Measurements of blue mussel filtration rates as a function of velocity in the range of 6-38 cm/s (at constant seston concentration of 10^4 algal cells/mL) indicated that filtration rates were inversely proportional to velocity. Growth experiments with blue mussels over a velocity range of 0.1 - 3.89 cm/s showed that growth was asymptotic with respect to velocity and that up to approximately 2 cm/s growth increased with velocity. Examination of individual growth rates showed that upstream mussels grew better than downstream ones at flows < 2 cm/s, but at > 2 cm/s there was no significant difference between upstream and downstream individual mussel growth. The authors also stated that if seston concentration was increased or mussel density reduced, quite different growth results would be expected (Wildish and Kristmanson, 1997). The suggestion by Bayne et al. (1976) that the relationships among velocity, filtration rates, seston concentration and respiration in

mussels need to be elucidated has not yet been followed (Wildish and Kristmanson, 1997).

Camacho et al. (1995) reported that chlorophyll-*a* content of the water was a secondary factor explaining growth variation compared to the major effect of actual phytoplankton availability, as determined by the current speed.

Fréchette and Bourget (1985a) measured fluctuations and vertical gradients of particulate organic matter concentrations over an intertidal mussel bed over fortnightly tidal cycles. Their data indicated that food is often depleted immediately above mussel populations, and that water movement is critical in determining food availability for suspension feeders.

1.4 Mussel Growth on Aquaculture Sites

It is ironic that the decreased growth rate of mussels, normally associated with dense culture, is one of the most poorly documented aspects of culture environments (Newell, 1990). Maximovich et al. (1996) determined and modeled growth and mortality at commercial mussel farms in the White Sea. They reported very slow growth rates as a result of a short growing season, 3 months, and that annual length increments of mussels and reducing numbers of mussels were a function of their initial length and the density of animals on the artificial substrate.

Heasman et al. (1998) studied growth rates at a raft culture system of mussels, *Mytilus galloprovincialis*, in Saldanha Bay, South Africa. They reported reduced growth rates associated with food depletion and that food depletion through the raft increased with the age of mussels suspended from it. Further, decreased rope spacing resulted in increased feeding and greater retardation of water exchange, which enhanced the food depletion rate.

In Ria de Arosa (Galicia, Spain), experiments directly on mussel (*Mytilus galloprovincialis*) culture rafts under wild conditions of food availability demonstrated

that scope for growth (SFG) measured at the front of the raft was consistently higher than at the back (Navarro et al., 1991) and confirmed empirical evidence on growth rates. The clear difference between SFG values measured at the front and back of the raft was partially explained by persistent differences in food availability. Furthermore, these rafts were moored to a single point and permanently oriented toward the current, so that mussels near the point of attachment (front) always encountered food first, resulting in consistent differences in growth rates within a single raft.

In Atlantic Canada, Mallet and Carver (1993) investigated growth and survival of three size groups of mytilid mussels from a commercial aquaculture farm located near Lunenberg, Nova Scotia. They reported low growth rates from November to February, but an increase in shell growth in March, with some of the smallest mussels exhibiting the highest growth rates. There was no attempt to show how growth rates were affected by densities of animals present in an active mussel aquaculture operation.

Condition Indices

In overstocked sites, condition index is a useful measure of nutritive stress. Condition indices relate the amount of flesh to quantity of shell and have been used extensively for many years in scientific research, the commercial fishery and aquaculture (Seed and Suchanek, 1992). In aquaculture, condition indices serve two purposes, economic (to designate the quality of a marketed product, e.g., the steamed meat yield) or ecophysiological-to characterize the apparent health of a stock or to summarise the physiological activity of animals under given environmental conditions (Crosby and Gale, 1990).

These indices may be used to follow seasonal changes in gross nutrient reserves or indicate differences in commercial quality (meat yield) of bivalve populations (Lucas and Beninger, 1985; Crosby and Gale, 1990). In a study by Rheault and Rice (1996), both oysters and scallops responded to decreasing downstream food availability with

similar declines in incremental growth as well as condition index. Furthermore, condition index was shown to be the most sensitive of the indices to changes in ration downstream and is the preferred method of assessing health of a population.

In Pelorus and Kenepuru Sounds, New Zealand, Hickman et al. (1991) monitored mussel condition at 12 commercial farms for a two-year period in response to industry concerns that food limitation, due to overstocking, was causing a decline in condition. They reported that environmental data paralleled the condition data by showing gradients along the length of the sound. A study by Heasman et al. (1998), with raft-cultured mussels, *Mytilus galloprovincialis*, reported that condition at the center of the rafts tended to be lower than at either end.

To date there is no information available on the downstream condition of mussels on bivalve farms in Atlantic Canada.

1.5 Biomass

There are ongoing studies to determine the optimum stocking density for shellfish farms in Newfoundland (C. Couturier, Marine Institute of Memorial University of Newfoundland, pers. comm.), yet there has been very little estimation or record keeping to determine the biomass of animals present on an operating site. The biomass at a farm is continually changing as seed is transferred both to and from a site, and as animals grow, spawn, die, and as product is harvested.

For a site owner, the focus is usually on the number of socks or collectors in the water and the total quantity available for harvest at present or in the near future. Scant attention is focused on carrying capacity and total biomass of all year classes.

1.6 Carrying Capacity

The concept of carrying capacity, originating from population ecology, has been

used in bivalve aquaculture as culture operations rely on wild seston as the source of food for the farmed bivalves. Considering a culture site or shellfish farm as an ecosystem, the carrying capacity can be defined as the maximum standing stock that can be supported by a given ecosystem for a given time. Mathematically, the carrying capacity, K, is a term in the equation that describes the logistic or "S" shaped growth curve, where the change in population size, N, over time, T, is given by

$$dN/dT = r(1 - N/K)N$$

where r is the rate of increase and K is the maximum population size (Errington, 1934; Odum, 1953 cited in Smaal et al., 1998). At an aquaculture site, carrying capacity for exploitation may be defined as the standing stock at which the annual production of a marketable cohort is maximised (Bacher et al., 1998). Here, the concept of an annual yield has been introduced. A basic rule of exploitation is that maximum yield is obtained from populations at less than maximum density (Krebs, 1972, cited in Smaal et al., 1998). Thus exploitation carrying capacity may be defined as the stock size at which maximum yield is achieved from a marketable cohort. If economic considerations are included, where the goal is to maximise return on investment, rather than maximise yield of marketable product, then the economic carrying capacity may differ from the exploitation carrying capacity (Smaal et al., 1998), but no examples using this definition were found in the literature.

Some definitions refer specifically to growth rate, for example "Carrying capacity is the stocking density at which production levels are maximised without negatively affecting growth rates" (Carver and Mallet, 1990) or "Carrying capacity is the change in growth trajectory for individual animals as a function of stocking density (Grant et al., 1998), who in the same report, also propose another definition in ecological terms "the maximum flux of mussel carbon biomass that can be derived from phytoplankton".

The possible consequences of overstocking a site include reduced growth rate,

increased mortality, negative effects of biodeposition on the benthos, slow recovery of meat yields after spawning and susceptibility to disease (Grant et al., 1998), so a reasonable estimate of carrying capacity is a very useful measure for shellfish aquaculture production. Reports of carrying capacity estimations for shellfish farms using suspended-culture systems date from the early 1980's (Incze et al., 1980; Incze et al., 1981) and the growth of the shellfish culture industry world-wide has facilitated numerous investigations since that time. These investigations generally focus on food quantity, quality, and other seston characteristics, supply and demand, feeding physiology, and physical factors such as temperature, depth, water flow dynamics, with all parameters integrated over annual cycles. Some of the more complex models (e.g., MUSMOD®, Campbell and Newell 1998) require over 50 initial input parameters and forcing functions. There have also been attempts to estimate carrying capacity from relatively few basic inputs (e.g. Carver and Mallet 1990, Grant and Bacher 1998, Grant 1999). These latter examples are potentially useful in site assessments where resources do not permit major studies involving many collaborators.

Carrying capacity studies may be categorised from a trophic level perspective as either "top down" or "bottom up" (Grant et al., 1998). The top down approach is based on an existing mussel yield, and estimates the phytoplankton food supply consumed (Incze and Lutz, 1980; Incze et al., 1981; Rosenberg and Loo, 1983). The bottom up approach measures phytoplankton production and water exchange and calculates the potential production of mussels based on principles of energy flow (Rodhouse and Roden, 1987; Raillard and Menesguen, 1994; Dowd, 1997). The latter approach may be broadened into a whole ecosystem study to include other potential competitors or phytoplankton sinks. For example, with raft culture of *Mytilus galloprovincialis* in the Benguela system of S.E. Africa, the total primary production was partitioned 21% to mussels, 7% to biofouling organisms, 24% to zooplankton, and 41% to suspension feeding benthic organisms, leaving 8% as a surplus (Grant et al., 1998).

Minimum requirements for modelling bivalve carrying capacity are summarised

by Small et al. (1998), who present a brief synthesis of the results of an EU-sponsored "Carrying Capacity workshop" (TROPHEE) held in October 1996 at Plymouth (UK) (Bayne, 1998; Grant and Bacher, 1998). Common features for carrying capacity models include feeding physiology and scope for growth (the energy from ingested ration available for growth remaining after respiratory, excretory, and faecal losses), spawning, and mortality. Recruitment and competition with other suspension feeders has been included in some studies. Food supply is calculated from primary production, and sometimes resuspension, with the former requiring measures of nutrient availability, light attenuation, and temperature; food delivery also requires hydrodynamic submodeling

Precise minimum requirements for determining carrying capacity differ depending on the scale of the study, i.e., local or ecosystem (Smaal et al., 1998). The local scale model can be used for site selection and density optimisation, and is nested within an ecosystem scale model. Local scale models include variables such as water velocity gradients, advection, resuspension, suspended particulate matter (SPM), chlorophyll-*a* concentration, suspended detritus, temperature, season, salinity, oxygen concentration, shell length, dry weight, filtration, ingestion, absorption, respiration, excretion, storage, gametogenesis, seed stocking, cohort size and age, mortality, harvesting, and total stock size. Ecosystem scale models require, in addition, variables related to primary production, such as the supply of limiting nutrient, mineralisation, competition for resources, and an accounting of energy flow to the various trophic levels and populations in the ecosystem.

From a practical perspective, relatively simple approaches to the determination of exploitation carrying capacity are preferred, providing the outcomes are accurate enough to predict the harvest within commercially acceptable ranges of variability. In Atlantic Canada, two such approaches show promise, those of Carver and Mallet (1990) and Grant and Bacher (1998).

In the study by Grant and Bacher (1998), a model of feeding behaviour using simple formulations of the energy budget (statistical model) was adequate to simulate

growth, which was measured at a Nova Scotian grow-out site to validate model predictions. The energy budget was formulated in terms of ingestion, POM, and absorption efficiency, and respiratory costs were estimated from literature values. The authors found that this model satisfactorily predicted growth in environments where seston values were not extreme (e.g. high turbidity). They also applied sensitivity analysis to critical variables related to absorption efficiency to identify the more significant variables in terms of accuracy of the output of the model. The model indicated that seston depletion caused a relatively steep reduction in growth rate. The growth penalty resulted in a greater variance, 46%, (expressed as coefficient of variation (CV)) in the harvestable meat weight (Grant, 1999), compared with the CV of 23% resulting from variation in initial stocking seed size.

Since uniform harvest size is a desirable outcome from a farming perspective, optimal production strategies should minimise variation due to seston depletion from possible overstocking. Furthermore, CV, which is easy to determine, may be a very useful indicator of site potential.

Two methods for estimating carrying capacity or stocking density for bivalves (mussels and scallops) in coastal inlets have been described by Carver and Mallet (1990, 1996), a tidal exchange model and a food depletion model. In the tidal exchange model, food supply is calculated from measurements of tidal exchange and POM, and food demand estimated from grazing experiments performed in the field. Food supply divided by food demand was used as an estimate of carrying capacity and calculated at weekly intervals giving a range of values varying seasonally.

The food depletion model estimates carrying capacity based on the rate at which food is depleted as it moves through a site. Estimates of current flow, food quantity and filtration rates are required, together with a critical threshold value for seston depletion used to identify the maximum stock size or carrying capacity that can be recommended without adversely affecting growth rates. Primary production values are not required for these two models.

The tidal exchange model has been applied to several sites in Newfoundland (Dabinett and Clemens, 1993; Lawrence, 1996), but the predicted carrying capacities have not yet been verified by actual production statistics.

1.7 Study Outline and Objectives

This study originated in 1994 when the operators of a mussel farm at Fortune Harbour, Notre Dame Bay, Newfoundland (a long, narrow closed embayment) reported that growth rates of mussels on the site were dropping, resulting in a longer time to reach harvestable size, 24 months from 1987-1993, and 30-36 months in 1994 depending on location within the site (Lawrence, 1996). The causes could have been due to inter-annual environmental variation or stocking density in excess of carrying capacity.

The site management provided data on location and density of long-lines over the lease, approximate numbers and locations of the cohorts of three year classes representing newly stocked year 1 seed, year two and year three mussels and annual harvest biomass.

The objectives of this study were to investigate the carrying capacity of the site, and the relative food requirements of each year class of mussels to provide information for management decisions.

Specifically the aims were:

1. To describe the site in general hydrodynamic terms relevant to factors affecting food supply.

2. To measure mussel growth and condition indices at each end of the site, termed the entrance and the end, and at two depths representing the range of temperature regimes present.

3. To collect or assemble available data in terms of TPM, POM, PIM, chlorophyll-*a*, temperature, salinity, year class structure, harvest volume, and mortality relevant to carrying capacity determination.

4. To determine if there is a downstream depletion of food on an operating mussel culture site.

5. To determine how much mussel production can be supported by the food supply and tidal volume.

6. To make predictions useful for sustainable production and site management.

2. Materials and Methods

2.1 Study Site

The commercial mussel farm (49°52′N, 55°27′W) used for this research project (Figure 1) is located on the northeast coast of Newfoundland approximately 70 km north of the Trans-Canada highway on route 352. The site, referred to as Northwest Arm, is adjacent to the community of Fortune Harbour, Notre Dame Bay. The site is leased and licenced to Atlantic Ocean Farms Limited, which also operates a mussel processing plant in Fortune Harbour. The site is largely enclosed by land, with two narrow entrances at the south (400 m wide) and southeast (100 m wide) ends of the site. The southeast opening is very shallow (2 m) and only navigable at high tide. The licenced area of the site totals 87 hectares (J. Ward, pers. comm.), although this does not include some of the shallower areas that are unsuitable for aquaculture. The total surface area of Northwest Arm is calculated to be 106 hectares.

2.2 Environmental Monitoring

A conductivity, temperature, depth meter (CTD, Seabird Electronics Inc., Washington, USA) was used to measure the various environmental variables of the water column at different times throughout the two-year study period. The recordings occurred at various times of day and different stages in the tidal cycle. The meter was equipped with a fluorometer to measure chlorophyll-*a* concentration. CTD data was processed using Surfer (Win 32) software, version 6.01 (Golden Software Inc. Colorado, USA. 1995).

Values for total particulate matter (TPM) and particulate organic matter (POM)

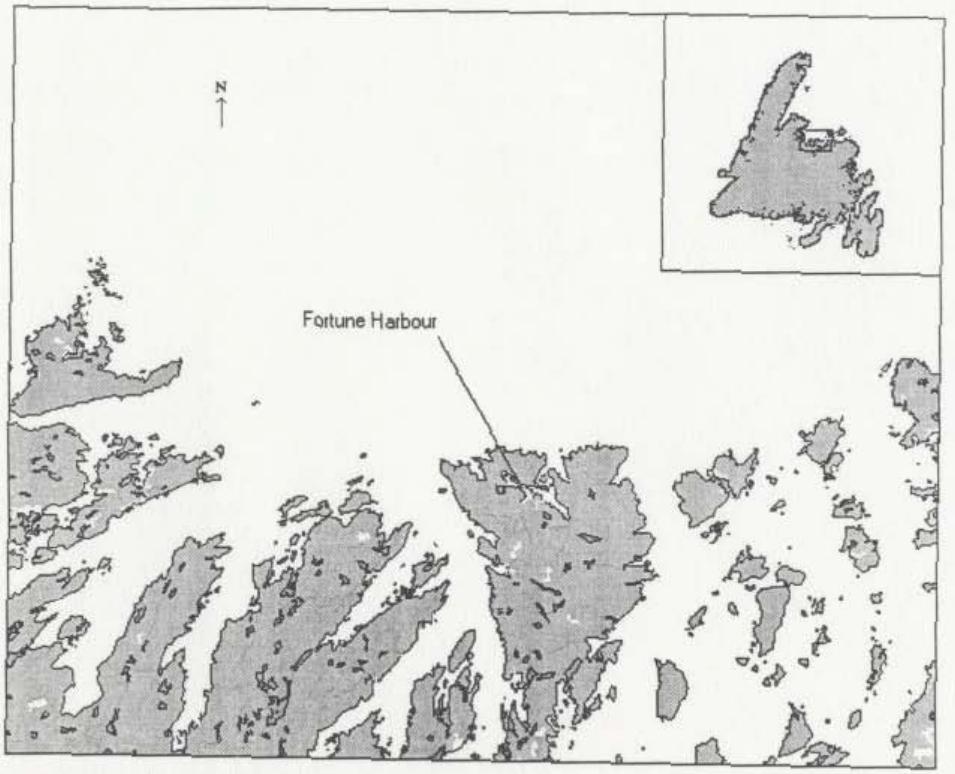

Figure 1: Location of study site, 49°52´N, 55°27´W, at Fortune Harbour, Notre Dame Bay, Newfoundland.

were obtained for this site covering the study period from published technical reports (Dabinett and Clemens, 1997; Clemens et al., 2000).

To provide a long-term measure of temperature, thermographs (HOBO® - Temp, Temperature Logger, Onset Computer Corporation, Pocasset, MA, USA) were attached to the main lines at 2 m and 15 m at both ends of the site. These thermographs were set to record temperature every 5 h.

To obtain measurements of current speed in the vicinity of experimental gear, a current meter (Interocean Systems, Inc. Model S4) was deployed at each end of the site for 24-hours on November 8-9, 1999 and November 16-17, 1999. The deployments were timed to coincide with the neap tides and spring tides for the period. Meters were secured

by a concrete weight lowered to the ocean bottom and held buoyant by a subsurface float tied one metre above the current meter. The current meters were set at three metres below the surface, adjacent to the site of the experimental socks.

2.3 Mussel Growth

Two long-lines, one at the southern entrance to the site and one at the northern end (Figure 2), were installed in October 1994. Mussel socks (24), 3 m in length, were suspended from each of these lines. The 24 socks included 12 socks of seed taken from a site adjacent to Random Island, Trinity Bay (mean shell length 3.27 cm), and 12 socks of seed originating from Roti Bay, Bay D'Espoir (mean shell length 1.44 cm), on the South Coast. Six socks were suspended starting at 2 m below the surface and 6 suspended at 15 m from the surface. To determine if there was a difference in the growth, the socks were filled to a density of 500 seed per metre and attached at intervals of 0.5 m along the mainline. The Random Island seed was taken from collectors in an aquaculture site in Long Harbour, Random Island, Trinity Bay, which is situated on the north end of the island. The Roti Bay seed came from Atlantic salmon cages used in the aquaculture industry in Bay D'Espoir. The long-lines were suspended using 41 cm floats, 1 for every 3 socks. Although, two seed sources were used in the study there was no comparison of growth based on seed source completed as the Random Island seed was much larger at the beginning of the experiment.

Mussels were sampled six (6) times between October 1994 and October 1996. During each sampling mussels were collected from the top, middle, and bottom of each of 3 socks of the different seed sources and depths. Each sock was treated as a separate sample and mussels from different parts of the sock were pooled and thirty (30)

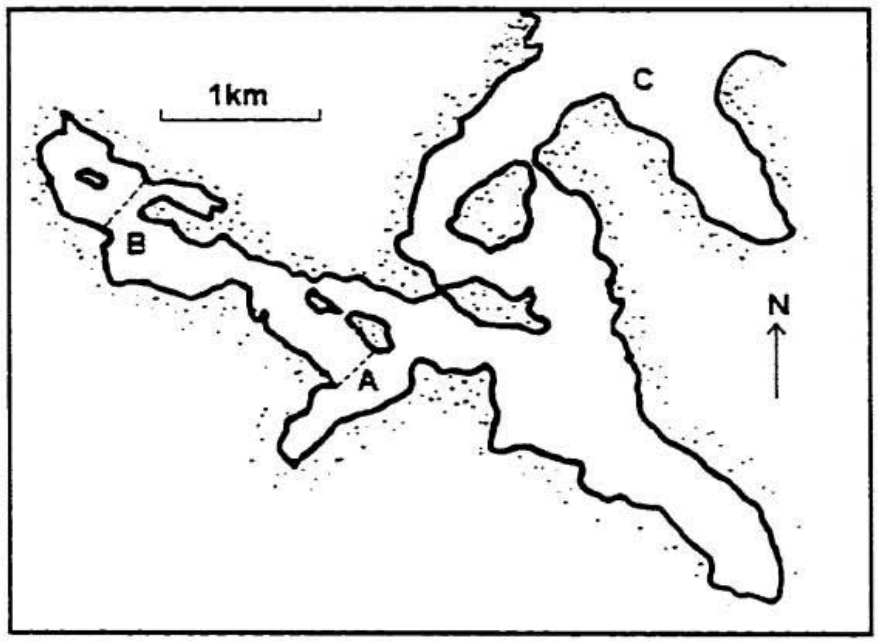

Figure 2: Location of the sampling stations at Fortune Harbour. A = the entrance to the site, B = the end of the site, C = the entrance to the open ocean.

animals were haphazardly removed for analysis. Individual mussel shell length (L), width (W), and height (H) were recorded to the nearest 0.01 mm using calipers.

Condition Index

The mean wet weight of mussels of each size/year class was determined for use in biomass calculations. Adductor muscles were cut and animals were placed with their ventral edges on tissue paper to allow intervalvar water to drain. Tissues were then dissected and placed in a pre-weighed aluminum pan for drying. Both valves were placed together in a pan separate from the tissue. Pans were dried at 70°C until constant weight, which was measured to the nearest 0.0001 g.

Condition Index (CI) was calculated using a formula described by Walne and

Mann (1975) such that CI is a ratio of tissue dry weight (Wt) and the dry weight of the shell (Ws), as follows:

$$CI = (Wt/Ws) \times 100$$

Coefficient of Variation - Dry Tissue Weight

Using dry tissue weights obtained for calculation of the condition index, the coefficient of variation for mussel dry tissue weight was calculated using the formula:

$$\text{Coefficient of Variation (CV)} = (\text{Standard Deviation} / \text{Mean}) \times 100$$

2.4 Biomass

Calculation of biomass was done using a combination of data obtained from company records, data collected through the course of this project, and statistics submitted to the Department of Fisheries and Aquaculture as part of the annual licence renewal. This information was used to determine location and biomass of the three year classes (year 1, year 2, year 3 cohorts) present during the autumn of each year throughout the project period.

Number of Socks and Collectors Deployed each Year

The site operators provided a record of the location of all deployments and retrievals of socks and collectors. Information was recorded by line number and corresponded to a line number on a master chart maintained by the company (Figure 3). This information was used to determine location and number of collectors and socks of

each year class present on the site at any given time.

Average Yield per Sock

The site operator deployed socks that were 3 m long and filled at a mean density of 760 mussels per metre. From historical production figures obtained from the Department of Fisheries and Aquaculture, and number of socks harvested from company records, the average yield per sock was calculated as follows:

Annual production (kg) / number socks harvested = yield per sock (kg)

The estimate of the yield per sock was then increased by 25% to account for the standard overpack of each shipment at the processing facility to account for weight loss that occurs during transit to market. The processing facility does not get compensated for this volume of product and it is not routinely reported as production. In calculations of biomass for this study this extra weight was included.

Number of Mussels in a Sock

The initial stocking density of the sock was approximately 830 animals per metre in a 3.3 m sock for the aquaculture operation (J. Ward, pers. comm). Using the average yield per sock for this company, as stated above, the number of mussels in a sock at harvest was calculated. Further, the number of mussels in a sock 12 mo after installation was calculated as follows:

No. at 12 mo = No. at 24 mo + (initial density-24 mo density/24x12)

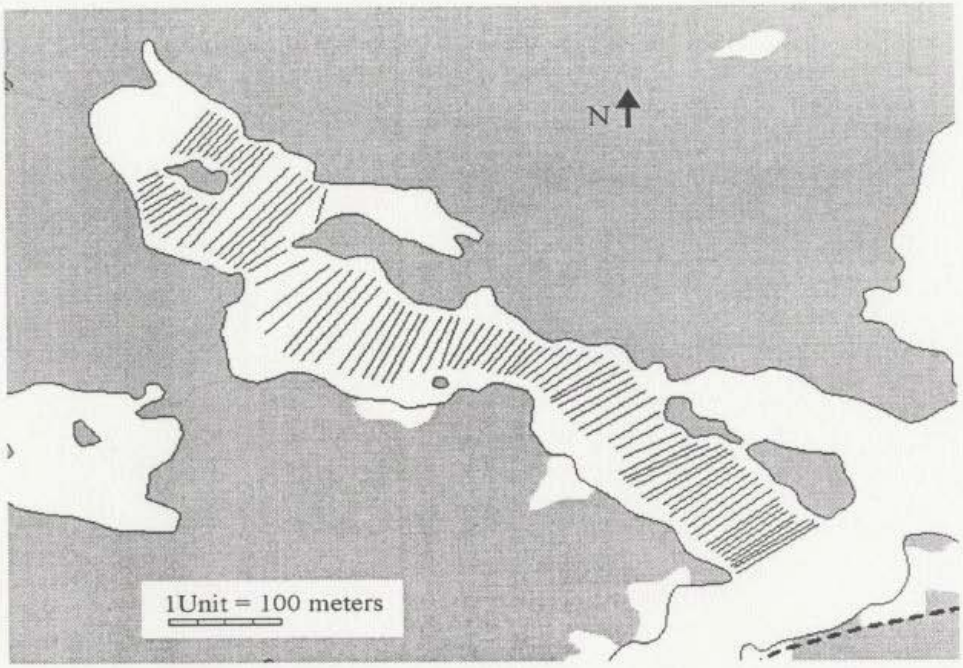

Figure 3: Location of 92 long-lines on the commercial mussel farm. On these lines were collectors and socks of three different year classes of mussel.

The reduction in number over time represents losses due to mortality, predation, and falling off the socks.

Biomass Calculation

Total mussel biomass present on the site is the sum of the biomass of each of the three year classes. Using the following formula, each cohort biomass present on the site at a fixed time during the autumn of each year was calculated:

Biomass of cohort = no. socks of this cohort x no. mussels per sock x average mussels weight

2.5 Carrying Capacity

To evaluate the carrying capacity of the site, three different modeling techniques were used, the first two being the tidal volume approach and the food depletion approach described by Mallet and Carver (1995b). The food depletion method is a modification of one method used by Rosenberg and Loo (1983). The third technique assesses carrying capacity by calculating the ratio of food demand to food supply (Carver and Mallet, 1990).

Tidal Volume Method

The tidal volume method assesses carrying capacity on the basis of tidal volume of water entering the site and ability of mussels, based on filtration rates, to deplete the food supply in the incoming water. The method assumes a complete exchange the tidal volume on each cycle and therefore a replenishment of the food supply. It addition it is assumed there is no primary production of food within the site.

The volume of water entering the site was calculated using a 1:25,000 scale chart, LC4520, published by the Canadian Hydrographic Service, Minister of Fisheries and Oceans Canada. Tidal height records were determined using data from the Canadian Tide and Current Tables (1994-1996), Atlantic Coast and Bay of Fundy. Tidal heights were determined for the reference port St. John's and then corrected for the site using the closest secondary port, Exploits Upper Harbour.

Using the scale of the map, the area (km^2) covered by the entire map was calculated. The page was then weighed and the area covered by the aquaculture site was cut out and weighed. The area of the site was then calculated as follows:

Area of the site (km^2) = (weight of site/weight of entire map) x area of map

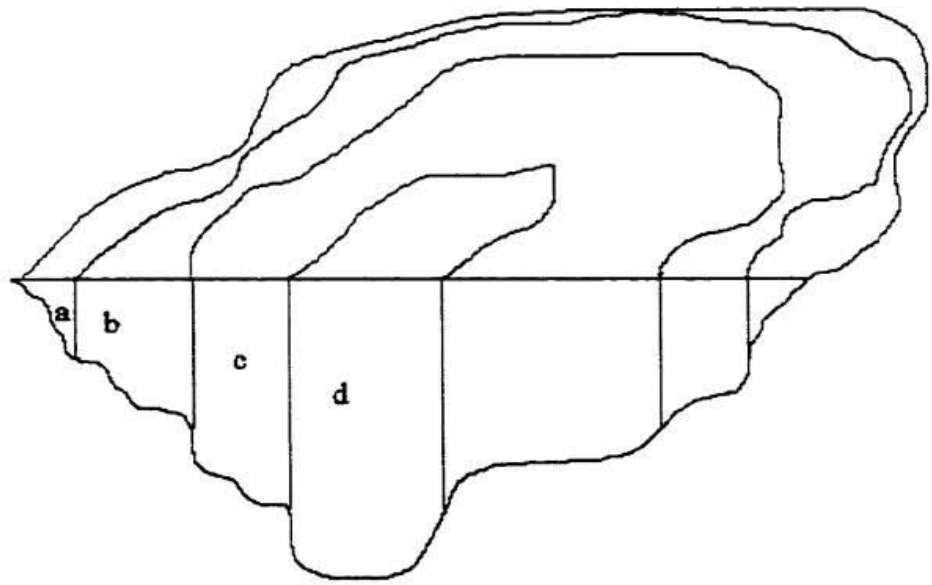

Figure 4: A cross section of a site to illustrate how it was subdivided for the purpose of calculating volume of water in the site. Each symbol, a-d, represents a 2 fathom depth contour. The volume in each section was calculated separately.

The site was cut out of the chart by depth contours at 2 fathom intervals (Figure 4), as chart depths were recorded in fathoms, and the area of each contour determined as a proportion of the entire site on the basis of its weight versus weight of the entire area covered by the site. The surface area of each contour was multiplied by the mean depth of each contour to determine volume. Volumes were then summed to give total volume of the site at mean low tide.

The tidal range during a spring tide and a mean tide were determined from tide tables. The volume of water added to the site during both tidal periods was estimated by multiplying the tidal range values by the total area of the site.

Using the tidal volumes, the length of time it takes to exchange the entire volume of the site (tidal exchange coefficient (T)) and the percentage of the site that is exchanged (dilution factor (D)) during each tidal cycle were calculated as follows:

$$T = ((v+p)/p)xt$$

where v= low tide volume, p= intertidal volume, t= tidal period and,

$$D = p/(v+p)$$

The proportion of incoming water filtered by an increasing density of mussels was determined using the mean tidal volumes and published filtration rates for this species. Filtration rates were obtained from literature values reported for mussels under ambient Newfoundland conditions-year 1 mussels from Mooney (2000) and market size (year 3) mussels from Thompson (1984). The filtration rate of year 2 mussels was estimated using dry tissue weight from this study and dry tissue weight and filtration rates from literature values using the allometric equation relating filtration (F) to weight (W), $F= aW^b$, and plotting log F against log W.

Filtration rates were converted to m^3/mussel/tidal cycle. The volume of water filtered during a tidal cycle was calculated by multiplying the filtration rate by the density of mussels on site. The percentage of the incoming water that was filtered during a tidal cycle was calculated for various mussel densities.

Food Depletion Approach

The food depletion method of assessing carrying capacity, estimates the decline in food concentration as water passes through site, using estimates of flow rates, food concentration, and filtration rates. Stocking density is assessed assuming food levels (expressed as carbon) not be allowed to decline below the critical minimum value required to support growth, the minimum carbon requirement. This method assumes that

all mussels at the entrance to the site have first access to food on an incoming tide and consequently that the food level is reduced as water moves through the site at a measured current speed, and food is progressively depleted.

To calculate densities of mussels filtering the incoming water, the site was divided into groups of ten lines beginning at the entrance to the site. On the basis of standard management practice for this site (J. Ward, pers. comm.), the following assumptions were used:

- socks were set 0.5 m apart
- each sock was 3.3 m long
- the longlines were set 29 m apart

The number of mussels in a newly seeded year 1 sock, 2 year sock and 3 year sock were 2500, 1550, and 600, respectively based on calculations in the biomass section described above.

The number of mussels present in each group of 10 lines was calculated by multiplying the number of socks of each year class by the density of mussels in a sock of each respective year class. The average depth and distance across the site within each group of 10 lines was estimated from the hydrographic chart. The number of mussels per m^3 within the group of 10 lines was calculated as follows:

No. = No. per group of lines / longline spacing / length of the longlines / average depth

The mean food density on the incoming tide, measured as both chlorophyll-*a* concentration and particulate organic matter (POM), was expressed as carbon using conversion factors. For chlorophyll-*a*, a C:chl-*a* ratio of 40 was used. This value is within the range of ratios reported by Widdows et al. (1979), Cloern et. al. (1995), and

Gallegos and Vant (1996) at 21.5 to 46.6 mg C / (mg chl-*a*), 27 to 33 mg C / (mg chl-*a*), and 54 mg C / (mg chl-*a*), respectively. Ratios within the range described by Gallegos and Vant (1996) are considered to be typical of healthy, nutrient-sufficient phytoplankton.

To convert POM to particulate organic carbon (POC), a ratio of 1:0.38 was used, obtained from Grant and Bacher (1998) for a Nova Scotia mussel farm site, and detrital POC = total POC - chl-*a* C.

To estimate the rate of depletion of food (C) as it passes through the site, the following formula was used (Carver and Mallet, 1996):

$C(x) = C(\text{initial}) \times e^{(-fx/u)}$

C(x) = Carbon concentration (μg/g/h)

C(initial) = Carbon entering the site (μg/g/h)

f = food demand (filtration rate (m^3/h x density (mussels/m^3))

u = flow rate (m/h) through the site

The minimum carbon requirement for mussels was calculated using a formula from Lucas et al. (1987) as follows:

CR (μg/g/h) = O_2 consumption (μg/g/h) x 12 μg C x 22.4 μL O_2 x AE/100

Where AE = Absorption Efficiency

CR = Carbon Requirement

Data for O_2 consumption and AE were taken from Thompson (1984a) for a population of mussels at Bellevue, Trinity Bay, Newfoundland.

Food Demand versus Food Supply

The third method of assessing carrying capacity determines stocking density based on the ratio of food supply in relation to food demand. This method is as described by Carver and Mallet (1990) with a modification of the parameter to assess the ration. In the present study, food was measured both in terms of seston chlorophyll-*a* concentration (CTD data) and as seston particulate organic matter (POM).

Food supply (FS) was calculated as follows:

FS= weekly tidal volume (Vt) (m^3) x Chl-*a* concentration converted to mg/L or POM

where Vt = no. of hours in a week / length of a tidal cycle x mean tidal volume
The mean tidal volume was as described above for the tidal volume approach to assessing carrying capacity.

Food demand (FD) (mg/wk) per kg of fresh weight of mussels was calculated as follows:

FD = filtration rate (L/wk) x no. of mussels/kg x Chl-*a* (mg/L) or POM

The number of mussel in a kg is calculated as per the formula in the biomass section and based on a 6.35 cm mussel, which is the desirable size for a market mussel (J. Ward, pers. comm.).

The carrying capacity (CC) was calculated as follows:

CC (kg/ha)= FS (mg/wk) / FD (mg/wk/kg) / area of the site (ha)

The area of the site was as calculated in the tidal volume method of assessing carrying capacity described above.

2.6 Data Analysis

Paired Student's t-tests were performed on the data for chlorophyll-*a* concentrations, temperature, and salinity to identify differences at 2 m and 15 m, and at opposite ends of the site. These tests were performed using Jandel Corporation SigmaPlot for Windows Version 3.06.

Two-way analysis of variance (ANOVA) was used to test effects of date and location, and effects of date and depth, on the dependent variables: dry shell length, dry shell weight, dry tissue weight, and condition index. As the condition index data was expressed as percentage values, an arc-sin square root transformation was completed prior to the ANOVA. The two-way analyses of variance were carried out using SPSS for Windows Version 10.0.

3. Results

3.1 Environmental Variables

Food

The chlorophyll-*a* concentrations at 2 m depth were not significantly different at the entrance to the site compared with the end of the site (t-test, d.f. = 21, t-value = -0.259, p=0.798). The recorded values at the entrance ranged from 4.50 µg/L in May 1995, to 0.60 µg/L in May 1996, with a mean of 1.59 µg/L. The values at the end of the site ranged from 4.20 µg/L in May 1995, to 0.80 µg/L in September 1994, with a mean of 1.62 µg/L. Each end of the site had higher chlorophyll-*a* levels in the spring of 1995 than in the spring of 1996 (Figure 5a).

The chlorophyll-*a* concentration at 2 m compared to 15 m showed no significant difference (t-test, d.f. = 20, t-value = 0.093, p=0.926). At 15 m the values ranged from 3.50 µg/L in August 1996, to 0.50 µg/L from April-June 1995, with a mean of 1.63 µg/L over the two year period. The chlorophyll-*a* concentration at 15 m indicated increased food levels during the July-September period in both observed years, unlike the concentration at 2 m, which did not show increased levels in 1996 (Figure 5b).

Temperature

Water temperatures at both stations were not significantly different (t-test, d.f. = 64, t-value = 0.81, p=0.418). The temperature ranged from a low of -1.5°C during the winter-spring 1995 and 1996 to a high of 17-18°C during August 1996. The temperature during the summer of 1996 was approximately 6°C higher than in the summer of 1995 (Figure 6).

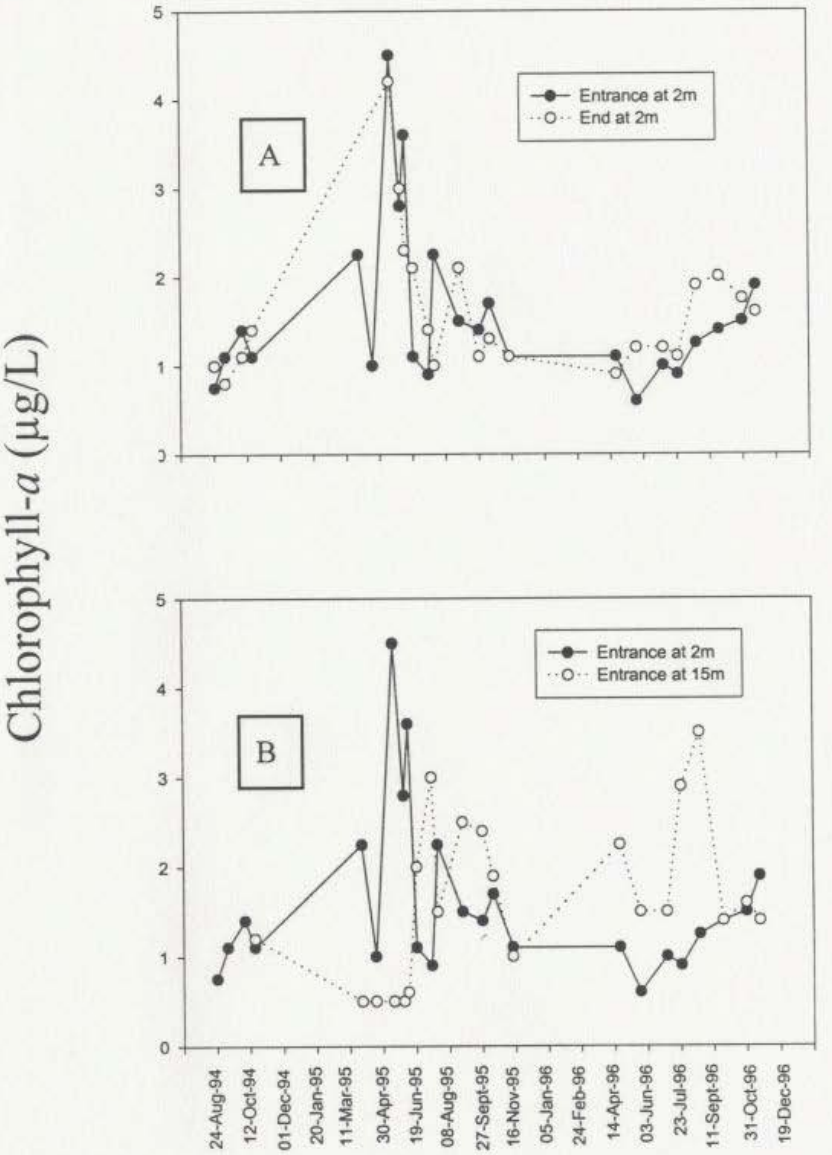

Figure 5: Chlorophyll-*a* concentrations at Fortune Harbour. A = Chlorophyll-*a* concentrations at 2 m from surface at opposite ends of the site. B = Chlorophyll-*a* levels at 2 m and 15 m, from the surface at the entrance to the site.

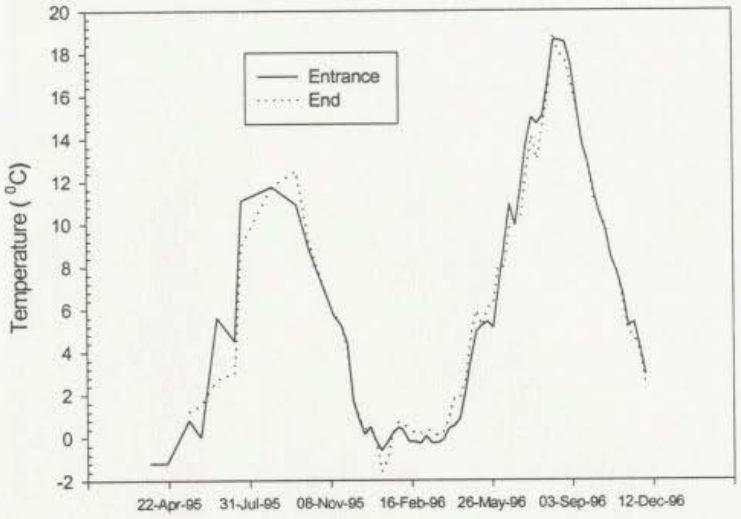

Figure 6: Fortune Harbour: Temperature at opposite ends of the site as recorded by Hobo® Temperature Logger thermographs attached to the mainline at a depth of 2 m.

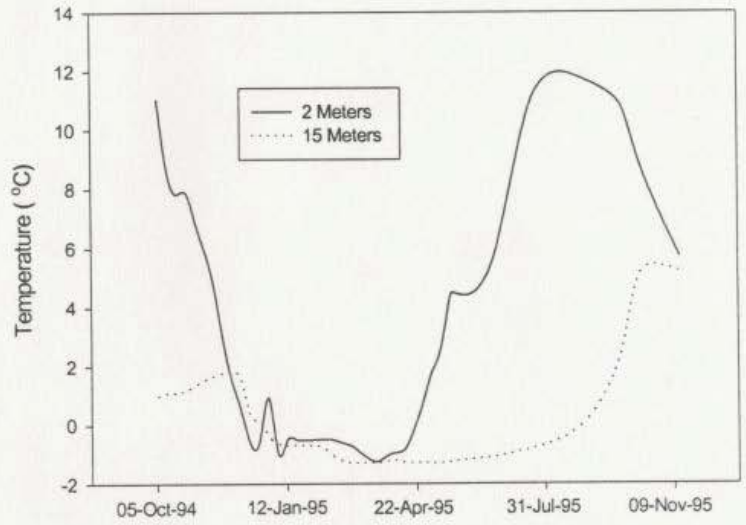

Figure 7: Fortune Harbour: Temperature at 2 m and 15 m recorded by Hobo® Temperature Logger thermographs.

There was a significant difference between temperature at the two depths (2 m and 15 m) (t-test, d.f. = 39, t-value = 4.88, p=0.00001). While the peak temperature at 2 m reached 12°C, the peak temperature at 15 m reached only 5°C and remained below 0°C for 7 mo of the year (Figure 7).

Salinity

The salinities at opposite ends of the site were not significantly different (t-test, d.f. = 16, t-value = -0.717, p=0.483). The level remained consistent at 30 $^{o}/_{oo}$ throughout the two-year period with the exception of the spring of 1995 when it dropped to 18 $^{o}/_{oo}$ for a short period at both ends of the site (Figure 8).

The salinity at 15 m did not drop to the lower values experienced near surface during the spring of 1995. Throughout the two-year period, the salinity remained consistently higher at depth than at surface, at approximately 32 $^{o}/_{oo}$. The salinity at the two depths was significantly different (t-test, d.f. = 19, t-value = -3.569, p=0.002) (Figure 9).

Current Speed

Current speed at the entrance was approximately one-half the speed at the end of the site during both periods (Table 1). There was an increase in current speed at both locations when measured during the spring tide with the increase at the end of the site being higher than that at the entrance.

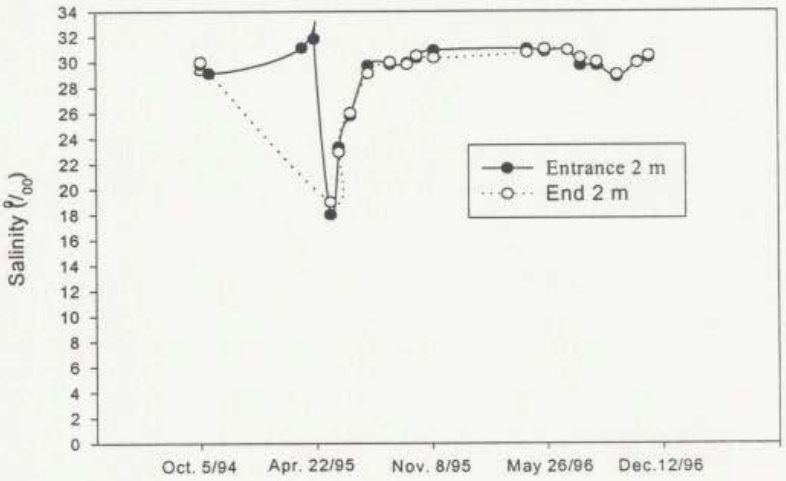

Figure 8: Fortune Harbour: Salinity at 2 m from the surface at opposite ends of the site.

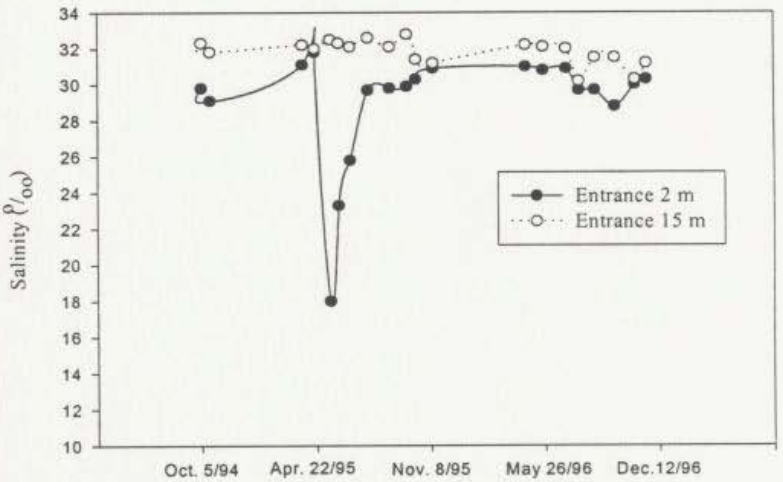

Figure 9: Fortune Harbour: Salinity at the entrance to the site at 2 m and 15 m.

Table 1: Fortune Harbour: Current speed at opposite ends of the site during neap and spring tides. Current speed was measured with a current meter deployed for 24- hour periods.

Location	Spring tide current speed (cm/s)	Neap Tide current speed (cm/s)
Entrance	1.16	0.96
End	2.64	1.74

The calculated flow rates for the site indicated that the flow at the entrance was higher than at the end of the site (Table 2). The flow rates ranged from 0.3 cm/s at lines 71-80 to 4.9 cm/s at lines 31-40, where the cross sectional area was very low in comparison to both ends of the site. The calculated flow rate at the entrance was approximately five times higher than at the end.

Table 2: Fortune Harbour: Estimated flow rates for each group of ten lines progressing through the site starting at the entrance. Tidal volume was calculated from tidal height, whereas added tidal volume was the water passing through that section on a rising tide.

Line numbers	Mean width (m)	Mean depth (m)	Area (km^2)	Mean tide (m)	Tide volume (10^4 m^3)	Added tidal volume (10^4 m^3)	Net tidal volume (10^4 m^3)	Cross section area (m^2)	Flow rate (cm/s)
1 to 10	368	13.72	0.097	0.92	8.90	90.85	99.76	5049	0.86
11 to 20	303	8.23	0.096	0.92	8.81	82.04	90.85	2492	1.59
21 to 30	408	6.22	0.099	0.92	9.09	72.95	82.04	2539	1.40
31 to 40	211	5.46	0.067	0.92	6.18	66.77	72.95	1152	2.75
41 to 50	342	7.92	0.104	0.92	9.54	57.23	66.77	2707	1.07
51 to 60	447	19.44	0.145	0.92	13.35	43.87	57.23	8688	0.29
61 to 70	355	16.03	0.174	0.92	15.98	27.89	43.87	5692	0.33
71 to 80	487	14.16	0.104	0.92	9.54	18.35	27.89	6895	0.18
81 to 92	381	8.41	0.200	0.92	18.35	0.00	18.35	3203	0.25

3.2 Mussel Growth

Shell length

A two-way analysis of variance (ANOVA) was used to test the effects of date and location in the site on the shell length of mussels. The analysis revealed that date ($F = 188.66$, d.f. = 4, 660, $P = <0.001$), and location ($F = 9.956$, d.f. = 1, 660, $P = 0.002$) (Table 3) both had a significant effect on the shell length. The shell length of mussels suspended at the entrance to the site increased from 3.20 cm to 5.33 cm while those at the end of the site reached 5.11 cm during the two-year study period (Figure 10).

Table 3: ANOVA showing a significant difference in mussel shell length at opposite ends of the site over time.

Source	Type III Sum	df	Mean	F	Sig.
Corrected Model	377.920 [a]	9	41.991	96.671	<.001
Intercept	5400.549	1	5400.549	2433.082	<.001
Date	327.789	4	81.947	188.658	<.001
Location	4.324	1	4.324	9.956	.002
Date * Location	.213	3	7.112E-02	.164	.921
Error	282.774	651	.434		
Total	14644.814	661			
Corrected Total	660.694	660			

a. R Squared = .572 (Adjusted R Squared = .566)

Shell Length and Depth

The mussels suspended at 15 m were observed for a 12-mo period. During this time shell length increased from 1.44 cm to 1.68 cm while those at 2 m increased from 1.44 cm to 3.25 cm (Figure 11). A two-way analysis of variance (ANOVA) to test

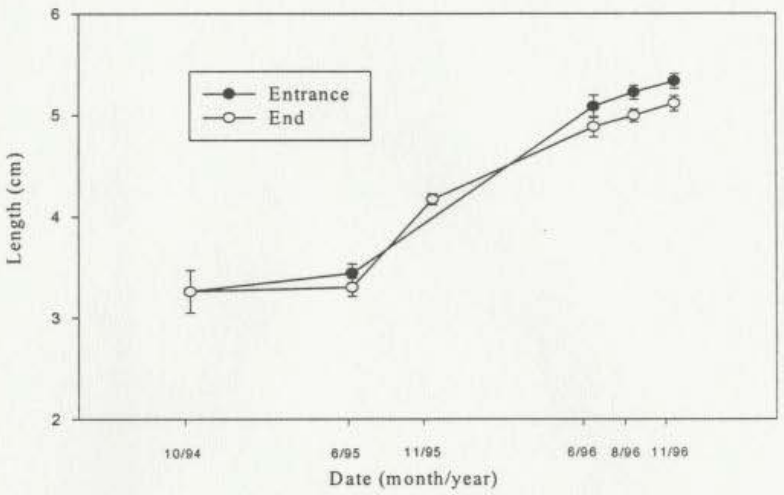

Figure 10: Shell length of mussels that were suspended 2 m from the surface at opposite ends of the site. (Mean±SE)

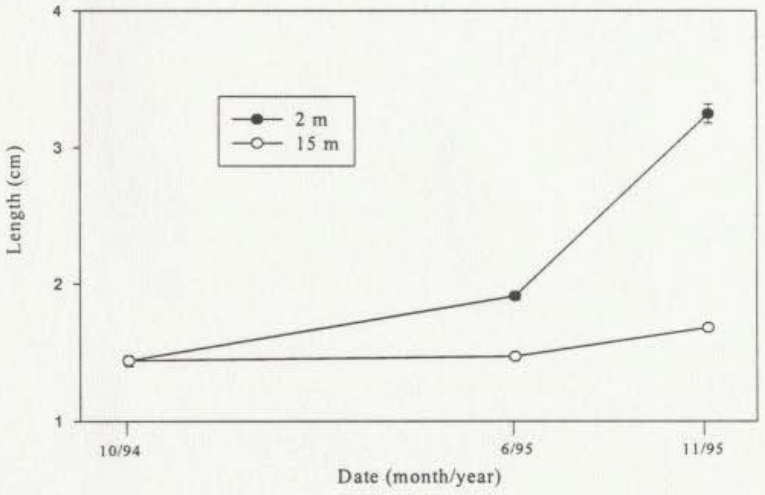

Figure 11: Shell length of mussels suspended at 2 m and 15 m over a one year period. (Mean±SE)

the effects of date and depth on the shell length of mussels revealed that both date (F = 293.99, d.f. = 2, 349, P =<.001) and depth (F = 697.11, d.f. = 1, 349, P =<.001) (Table 4) had a significant effect on the shell length.

Table 4: ANOVA showing a significant difference in mussel shell length at 2 m and 15 m over time.

Source	Type III Sum	df	Mean	F	Sig.
Corrected Model	131.318[a]	4	32.829	294.005	<.001
Intercept	673.197	1	673.197	6028.829	<.001
Date	65.656	2	32.828	293.994	<.001
Depth	77.841	1	77.841	697.110	<.001
Date * Depth	27.573	1	27.573	246.934	<.001
Error	38.524	345	.112		
Total	1509.506	350			
Corrected Total	169.842	349			

a. R Squared = .773 (Adjusted R Squared =.771)

Dry Shell Weight

The dry shell weight of mussels at 2 m was consistently higher at the entrance to the site than mussels at the end of the site (Figure 12). In addition, the ratio of dry shell weight to length was consistently higher at the entrance to the site (Table 5b). A two-way analysis of variance (ANOVA) was used to test the effects of date and location in the site on the dry shell weight of the mussels. The analyses revealed that both date (F = 35.66, d.f. = 4, 606, P =<.001), and location (F = 19.69, d.f. = 1, 606, P =<.001) (Table 5a) had a significant effect on the dry shell weight.

Table 5a: ANOVA showing a significant difference in dry shell weight at opposite ends of the site over time.

Source	Type III Sum	df	Mean	F	Sig.
Corrected Model	622.316 *	9	69.146	27.564	<.001
Intercept	1619.746	1	1619.746	645.678	<.001
Date	357.890	4	89.473	35.666	<.001
Location	49.386	1	49.386	19.687	<.001
Date * Location	12.188	3	4.063	1.619	.184
Error	1497.633	597	2.509		
Total	7460.672	607			
Corrected Total	2119.950	606			

a. R Squared = .294 (Adjusted R Squared = .283)

Table 5b: Ratio of dry shell weight to length of mussels suspended 2 m from surface at opposite ends of the site.

	Ratio of dry shell weight/length	
	Entrance	End
October 1994	0.25	0.25
June 1995	0.47	0.45
June 1996	0.58	0.48
August 1996	0.69	0.55
October 1996	0.84	0.65

Dry Shell Weight and Depth

The dry shell weight of mussels suspended at 15 m was found to be lower than mussels at 2 m after 8 mo on the site (Figure 13). A two-way analysis of variance (ANOVA) to test the effects of date and depth on the dry shell weight of the mussels revealed that both date ($F = 16.98$, d.f. = 2, 235, $P = <.001$) and depth ($F = 55.48$, d.f. = 1,

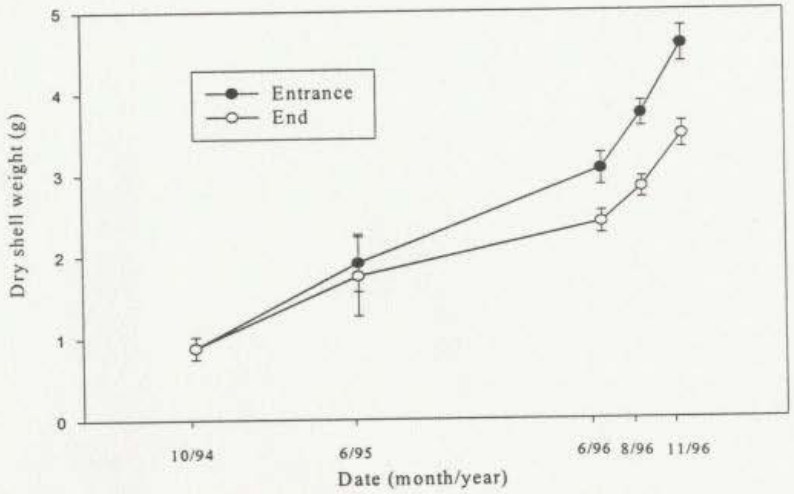

Figure 12: Dry shell weight of mussels suspended at 2 m at opposite ends of the site. (Mean±SE)

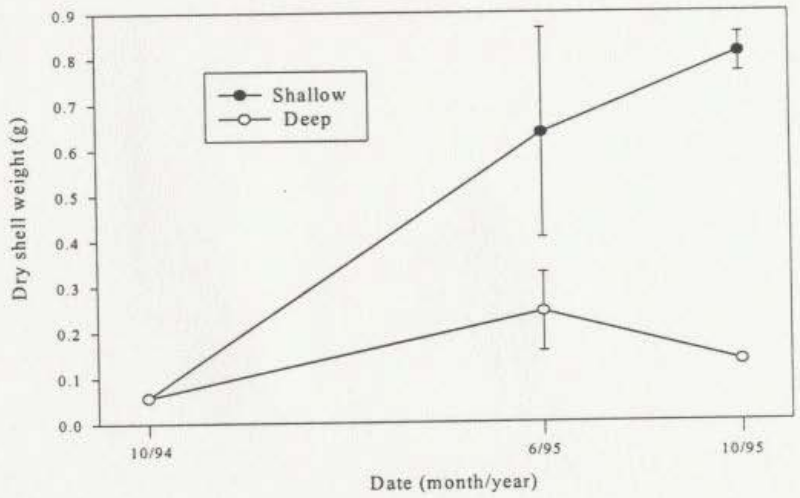

Figure 13: Dry shell weight of mussels suspended at 2 m and 15 m over a one year period. (Mean±SE)

235, P = <.001) (Table 6) had a significant effect on the dry shell weight.

Table 6: ANOVA showing a significant difference in dry shell weight at 2 m and 15 m over time.

Source	Type III Sum	df	Mean	F	Sig.
Corrected Model	20.440 [a]	4	5.110	25.135	<.001
Intercept	13.420	1	13.420	66.007	<.001
Date	11.279	1	11.279	55.477	<.001
Depth	6.906	2	3.453	16.983	<.001
Date * Depth	1.455	1	1.455	7.155	.008
Error	46.964	231	.203		
Total	99.982	236			
Corrected Total	67.405	235			

a. R Squared = .303 (Adjusted R Squared = .291)

Dry Tissue Weight

The dry tissue weight of mussels suspended at 2 m was consistently higher at the entrance to the site than at the end (Figure 14). The highest observed weights were in June and November 1996. A two-way analysis of variance (ANOVA) was used to test the effects of date and location in the site on the dry tissue weight of the mussels. The analyses revealed that both date (F = 22.06, d.f. = 4, 603, P = <.001), and location (F = 44.53, d.f. = 1, 603, P = <.001) (Table 7) had a significant effect on the dry tissue weight.

Dry Tissue Weight and Depth

The dry tissue weight of mussels suspended 15 m from the surface was 0.01 g at the beginning of this project and reached a high of 0.05 g one year later. The maximum

was considerably lower than that of mussels suspended 2 m from the surface, which reached 0.18 g over the same time period (Figure 15). A two-way analysis of variance (ANOVA) to test the effects of date and depth on the dry tissue weight of the mussels revealed that both date ($F = 13.87$, d.f. = 2, 235, $P = <.001$) and depth ($F = 46.21$, d.f. = 1, 235, $P = <.001$) (Table 8) had a significant effect on the dry tissue weight.

Table 7: ANOVA showing a significant difference in dry tissue weight at opposite ends of the site over time.

Source	Type III Sum	df	Mean	F	Sig.
Corrected Model	17.414 *	9	1.935	21.683	<.001
Intercept	54.553	1	54.553	611.321	<.001
Date	7.877	4	1.969	22.067	<.001
Location	3.974	1	3.974	44.535	<.001
Date * Location	1.534	3	.511	5.729	.001
Error	53.007	594	8924E-02		
Total	216.987	604			
Corrected Total	70.421	603			

a. R Squared = .247 (Adjusted R Squared = .236)

Table 8: ANOVA showing a significant difference in dry tissue weight at 2 m and 15 m over time.

Source	Type III Sum	df	Mean	F	Sig.
Corrected Model	1.024 *	4	.256	16.585	<.001
Intercept	.792	1	.792	51.261	<.001
Date	.428	2	.214	13.870	<.001
Depth	.713	1	.713	46.207	<.001
Date * Depth	4.572E-03	1	4.572E-03	.296	.587
Error	3.567	231	1.544E-02		
Total	6.619	236			
Corrected Total	4.591	235			

a. R Squared = .223 (Adjusted R Squared = .210)

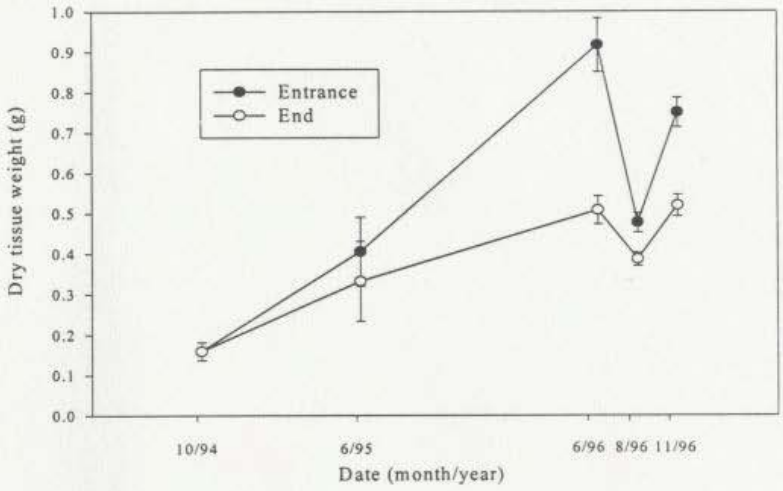

Figure 14: Dry soft tissue weight of mussels suspended at 2 m at opposite ends of the site. (Mean±SE)

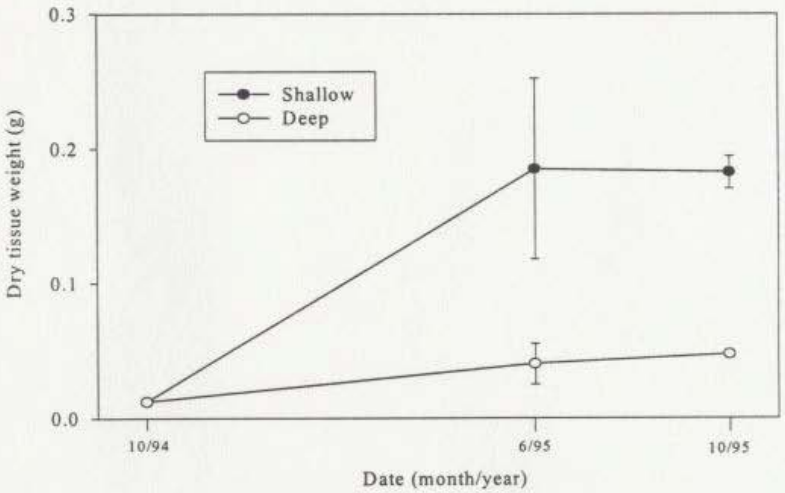

Figure 15: Dry soft tissue weight of mussels suspended at 2 m and 15 m from surface, at the end of the site, over a one year period. (Mean±SE)

Condition Index

A two-way ANOVA testing the effects of date and location in the site on the condition of the mussels was performed. Date ($F = 168.80$, d.f. = 4, 603, $P = <.001$) and location in the site ($F = 54.37$, d.f. = 1, 603, $P = <.001$) were both found to significantly effect the condition (Table 9). The condition index was consistently higher at the entrance to the site than at the end, with the exception of August, 1996. On that date the mussels were also found to have their lowest condition in the time series (Figure 16).

Table 9: ANOVA showing a significant difference in the condition index at opposite ends of the site over time.

Source	Type III Sum	df	Mean	F	Sig.
Corrected Model	1.546 [a]	9	0.172	82.803	<.001
Intercept	55.079	1	55.079	26552.159	<.001
Date	1.401	4	0.350	168.804	<.001
Location	0.113	1	0.113	54.374	<.001
Date * Location	0.178	3	5.945	28.661	<.001
Error	1.232	594	2.074		
Total	111.606	604			
Corrected Total	2.778	603			

a. R Squared = .556 (Adjusted R Squared =.550)

Condition and Depth

The mussels suspended at 15 m were in lower condition than those at 2 m, in the early summer of 1995, but by autumn the reverse had occurred, and the those at depth were in the best condition (Figure 17). A two-way analysis of variance (ANOVA) to test the effects of date and depth on the condition of the mussels revealed that date ($F = 13.33$.

d.f. = 2, 235, P = <.001) had a significant effect on condition but that depth (F = 0.367, d.f. = 1, 235, P = .545) did not have a significant effect (Table 10).

Table 10: ANOVA showing no significant difference in condition indices at 2 m and 15 m.

Source	Type III Sum	df	Mean	F	Sig.
Corrected Model	1.379[a]	4	0.345	44.287	<.001
Intercept	41.042	1	41.042	1540.347	<.001
Date	0.203	2	0.101	12.412	<.001
Depth	2.778	1	2.788	.096	.756
Date * Depth	0.957	1	0.957	121.402	<.001
Error	1.756	231	7.603		
Total	72.284	236			
Corrected Total	3.135	235			

a. R Squared = .440 (Adjusted R Squared = .430)

Coefficient of Variation

The coefficient of variation of mussel dry tissue weight, calculated for the seed initially placed at 2 m, was found to be 60%. After two years the coefficient of variation of mussels on the three socks at the entrance to the site ranged from 39% to 48% with a mean of 46% for all animals at the station. The three socks at the end of the site had a coefficient of variation ranging from 44% to 49% and a mean of 48% for all animals at the station. The coefficient of variation of mussels held at opposite ends of the site for two years was not found to be significantly different (t-test, d.f. = 4, t-value = -0.36, p=0.560).

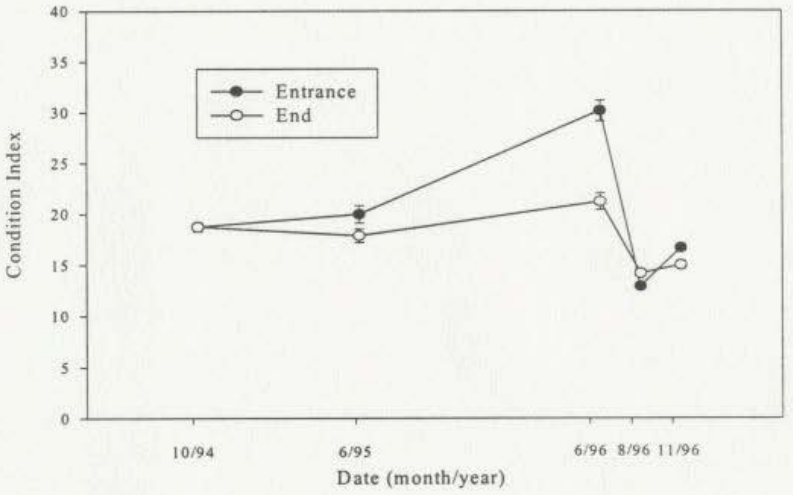

Figure 16: Condition of mussels suspended at 2 m at opposite ends of the site. Condition Index = dry tissue weight/ dry shell weight x 100. (Mean±SE)

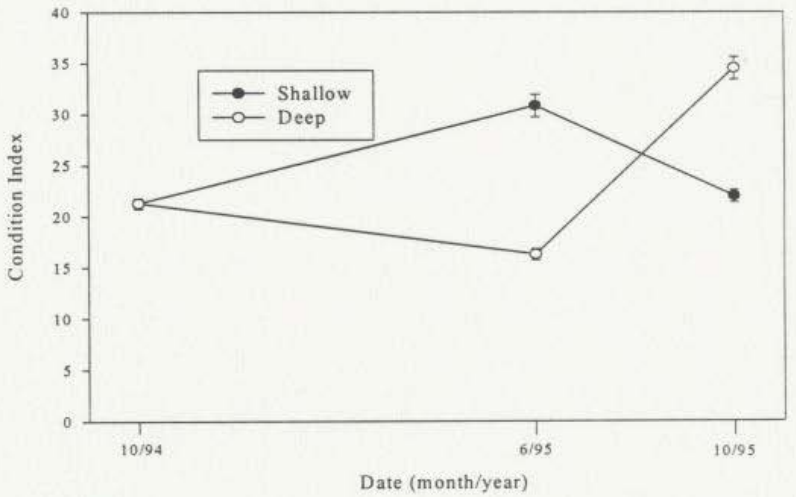

Figure 17: Condition of mussels suspended at 2 m and 15 m. Condition Index = dry tissue weight/ dry shell weight x 100. (Mean±SE)

3.3 Biomass

The number of mussels in a sock was initially 2,500, decreasing to 1,550 after one year and 600 by the end of year 2 due to natural mortality and mussels falling off the sock. Mussel loss was not attributed to competition for space or food with other fouling organisms. The was an occasional star fish present but few tunicates, hydroids, or secondarily set mussels. The individual live weights of year 1, year 2, and year 3 cohorts were 8.55 g (117 mussels/kg), 10.1 g (98 mussels/kg), and 12.5 g (80 mussels/kg), respectively.

An analysis of the biomass data for 1994 revealed that most of the animals were concentrated in two areas of the site, the first 400 m and a section 1400 m-2500 m from the entrance (Figure 18). Placing socks in these areas is a consistent practice in the operation of this site where socks were installed during the period 1993-1996 (Figure 19). The biomass of these two sections accounted for 71% of the total biomass present. These areas also corresponded with the deepest locations within the arm (Figure 20).

The peak biomass for the entire site during the study period was 6×10^5 kg in 1995 but decreased the following year as relatively few socks were added (Table 11), product was harvested, and natural mortality occurred. The peak biomass of year 1 socks occurred in 1994, while year 2 socks peaked in 1995, and year three socks peaked in 1996 (Figure 21).

Table 11: The number of socks added, socks removed, and weight harvested each year during the study period.

	Socks added	Socks harvested	Socks remaining	Harvested weight (kg)
1993	15,145	0	0	0
1994	15,234	2,541	27,838	40,000
1995	12,069	9,875	30,032	68,040
1996	610	2,779	27,863	24,800

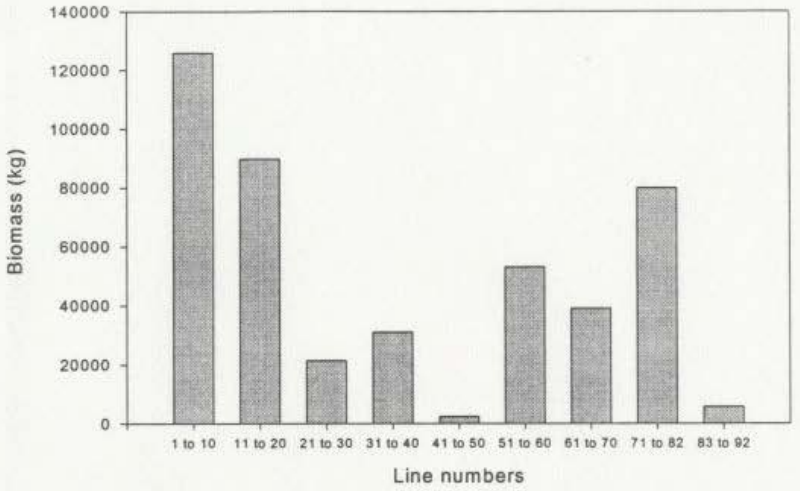

Figure 18: Fortune Harbour: Location and biomass in the autumn of 1994 within each group of 10 lines. Lines are numbered beginning at the entrance and proceeding to the end.

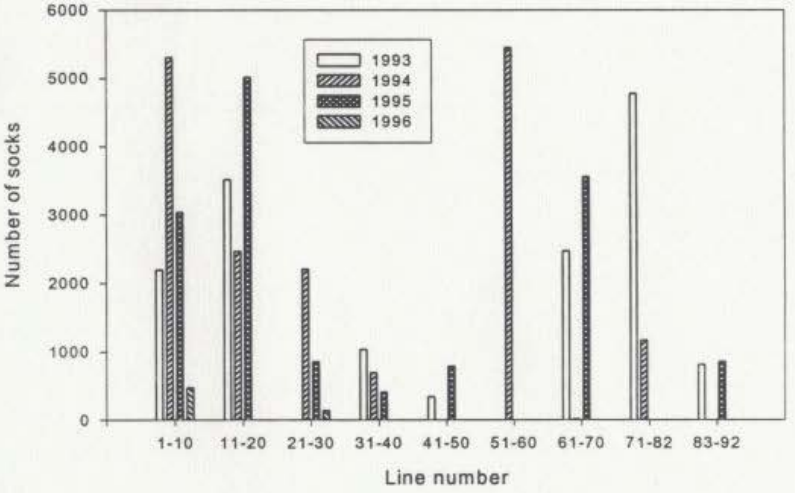

Figure 19: Fortune Harbour: Number of socks added during the years 1993-1996 within each group of ten lines. Lines are numbered beginning at the entrance to the site and proceeding to the end.

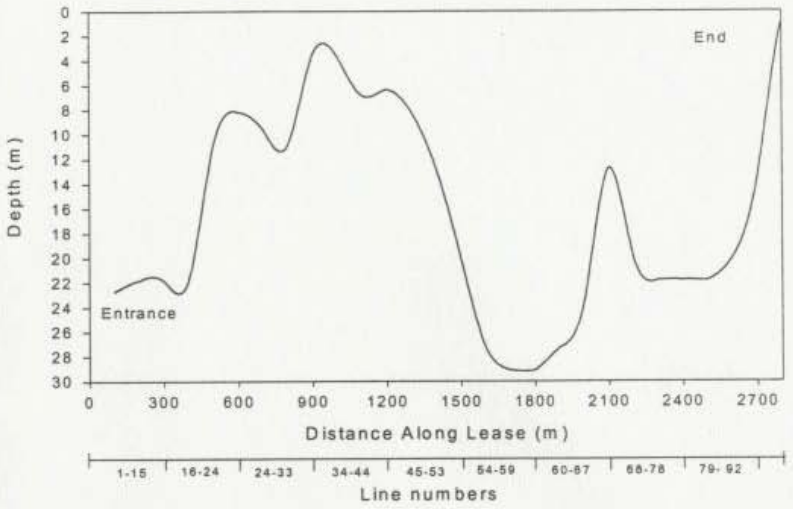

Figure 20: Fortune Harbour: Depth profile through the centre of the site beginning at the entrance and the corresponding long-lines within each 300 m section.

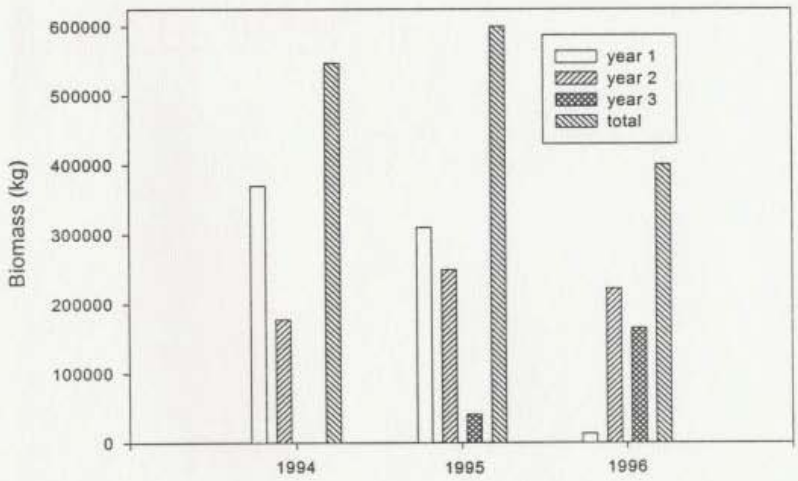

Figure 21: Biomass of mussels on the site in Fortune Harbour, Newfoundland from 1994 to 1996. Year 1 is the biomass of newly socked mussels, year 2 and 3 represent the biomass of older year classes.

3.4 Production Capacity

Tidal Volume Method

The volume of water in the site is shown in table 12. The low tide volume is the volume of water in the site when the tide is low, spring tide volume and mean tide volume are the amounts of water added during the respective tidal periods. During a spring tide there is 60% more water added to the site than is added during a mean tide.

The length of time it takes to exchange the entire volume of water in the site was calculated for a spring tidal period and a mean tidal period. On a spring tide it would take 91 h or 7.3 tidal cycles with 14% of the site being exchanged on each tide, while during a mean tidal period it would take 139 h or 11.1 tidal cycles with 9% being exchanged during each tidal period (Table 13).

Table 12: Summary of volume of water in the Fortune Harbour site at low tide, volume added during a spring tide and volume added during a mean tidal cycle. Volume was determined by calculating the volume of water in each 2 fathom depth contour. Tide heights used in the calculation were taken from the Canadian Tide Tables.

Contour Depth (fathoms)	Contour Depth (m)	Area (km^2)	%	Low Tide Volume (10^4 m^3)	Spring Tide (m)	Spring Tide Volume (10^4 m^3)	Mean Tide (m)	Mean Tide Volume (10^4 m^3)
1	1.82	0.40	38	73.53	1.49	60.20	0.92	37.17
3	5.46	0.11	10	59.51	1.49	16.24	0.92	10.03
5	9.1	0.17	16	155.61	1.49	25.48	0.92	15.73
7	12.74	0.14	13	173.26	1.49	20.26	0.92	12.51
9	16.38	0.04	4	72.07	1.49	6.56	0.92	4.05
11	20.02	0.11	10	212.21	1.49	15.79	0.92	9.75
13	23.66	0.05	4	108.84	1.49	6.85	0.92	4.23
15	27.3	0.05	5	139.23	1.49	7.60	0.92	4.69
Totals		**1.07**	**100**	**994.27**		**158.98**		**98.16**

Table 13: Summary of tidal exchange coefficient and dilution during both spring tide and mean tide. Exchange coefficient is the length of time it takes to exchange entire volume of water in the site. Dilution is an estimate of the proportion of the volume that is renewed at each tidal cycle.

	Spring tide			Mean tide		
Low tide volume (m^3)	Spring tidal volume (10^4 m^3)	Exchange coefficient (hr)	Dilution %	Mean tidal volume (10^4 m^3)	Exchange coefficient (hr)	Dilution %
994.27	158.9	94	14	98.2	139	9

Estimates of mean tidal volume (Table 12) and filtration rates for the year classes of mussels present each year were used to determine the volume of water filtered during each tidal cycle (Table 14). Filtration rate was calculated on the basis of the proportion of each year class present on the site and the filtration rate for the year class. For newly socked mussels with a mean soft tissue dry weight of 0.161 g the filtration rate was 1.12 L/h. After one year in the sock, mean soft tissue dry weight was 0.45 g and the filtration rate used was 1.65 L/h, and after two years in the sock, mean soft tissue dry weight was 0.749 g and the filtration rate used was 1.91 L/h. The mean filtration rates for 1994, 1995, and 1996 were 1.27 L/h, 1.36 L/h, and 1.72 L/h, respectively (Appendix 1). The results showed that in 1995 the mussels present were capable of filtering close to 100% of the water that actually entered the site during a tidal cycle. The mussels present in 1996 would filter the least amount of the tidal water as there were many fewer mussels on site.

Food Depletion Method

The depletion of food, as measured by chlorophyll-*a* concentrations (chl-*a*) and particulate organic matter (POM) converted to carbon, as tidal water moves through the site beginning at the entrance is plotted in figure 22. Using chlorophyll-*a* levels

Table 14: Volume of water filtered during a mean tidal cycle by the mussels present on the Fortune Harbour site during the study period, 1994-1996. The number of mussels present on the site during each year is a sum of the number present in each of the year classes.

	Year Class	Number of mussels on site (10^6)	Filtration rate (L/h)	Volume filtered per tidal cycle ($m^3 \times 10^6$)	% of mean Tidal volume filtered
1994	year 1	46	1.12	0.64	91
	year 2	14	1.65	0.25	
1995	year 1	36	1.12	0.51	98
	year 2	24	1.65	0.38	
	year 3	3	1.91	0.07	
1996	year 1	2	1.12	0.03	80
	year 2	22	1.65	0.46	
	year 3	12	1.91	0.29	

converted to carbon, the modelling indicated the incoming food would be depleted to a level insufficient to sustain respiration in mussels, as indicated by the dashed line in figure 22. after the tidal water has progressed 300-600 m into the site. This is the equivalent to the distance covered by 15-24 lines. The results are similar for each of the study years , 1994-1996, with the levels in all years falling below the minimum required.

Converting carbon from POM levels provided a different outcome. The POM levels indicated that there was a much higher initial carbon level in the incoming tidal water and the amount depleted in either of the study years did not reduce the carbon level below the level determined as the minimum for respiration. The largest reduction occurred in 1995 which is the year in which the largest biomass was present on the site.

Minimum Carbon Requirement

The minimum carbon required to sustain respiration in mussels was calculated to be 57 µg/g/h (Table 15). This is the mean of the values calculated for each month. There were

periods throughout the year when mussels required much more food than others, with the range being from 20 µg/g/h to 115 µg/g/h.

Table 15: Calculations of the minimum carbon required for respiration in mussels using values for absorption efficiency and oxygen consumption from Thompson (1984).

	Oxygen µg/g/h	Absorption Efficiency (%)	Minimum Carbon Requirement µg C/g/h
November	250	54	72.32
December	100	56	30.00
March	170	49	44.63
April	200	23	24.64
June	230	39	48.05
July	440	49	115.50
September	250	40	53.57
October	270	75	108.48
December	130	30	20.89
January	160	53	45.43
Mean		**46.8**	57
sd		**14.6**	32.9

Food Demand and Food Supply

Estimates of the carrying capacity of the site were made on the basis of food supply and food demand (Table 16). On the basis of filtration rates of the different year classes of mussels present on the site in 1996, the aquaculture site in Fortune Harbour was estimated to have a capacity to produce 490 x 10^3 kg. The highest projected capacity, 552 x 10^3 kg, was based on 1994 filtration rates. On a per hectare basis the estimates range from 4.63 x 10^3 kg to 5.21 x 10^3 kg.

The estimates of carrying capacity did not change whether chl-*a* or POM levels were used in the calculation of food supply and food demand. The estimates were a ratio of filtration rate to tidal volume expressed in terms of mass of mussels.

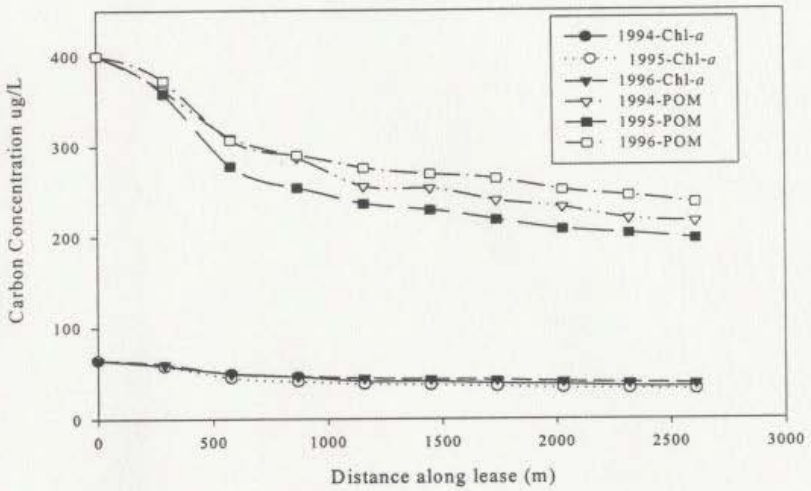

Figure 22: Decline in carbon levels as tidal water moves through the Fortune Harbour site from the entrance with decline calculated based on the densities of animals encountered during each year and their filtration rates. Carbon is based on chlorophyll-*a* (chl-*a*) x 40 and particulate organic matter (POM) x 0.38. The dashed line represents the minimum carbon requirement for mussels at a mean filtration rate of 1.36 L/h (57 µg/h/1.36 L/h = 41 µg/L).

Table 16: Estimates of carrying capacity of the aquaculture site in Fortune Harbour on the basis of food supplied to the site and demand by mussels present during each of the years 1994-1996. Food supply and food demand have been calculated based on available food as measured by mean annual chlorophyll-*a* levels and mean annual particulate organic matter levels.

	Tidal volume ($m^3 \times 10^6$ per wk)	Chl-*a* (mg/L.)	POM (mg/L.)	Food Supply (mg $\times 10^6$ per wk)	Filtration Rate (L/hr)	Ration (mg/d)	Demand per kg mussels (mg /wk)	Carry Capacity (kg mussels $\times 10^1$)	Production per hectare (kg $\times 10^1$)
1994	13.19		1.05	13.84	1.27	32,000	25.09	552.0	5.21
1995	13.19		1.05	13.84	1.36	34,270	25.91	534.5	5.04
1996	13.19		1.05	13.84	1.72	43,340	28.22	490.8	4.63
1994	13.19	1,600		21.10	1.27	48,760	38.23	552.0	5.21
1995	13.19	1,600		21.10	1.36	52,220	39.48	534.5	5.04
1996	13.19	1,600		21.10	1.72	66,040	43.00	490.8	4.63

4. Discussion

4.1 Environmental Parameters

Food

The aquaculture site in Fortune Harbour, a semi enclosed inlet, is like most in Newfoundland, where the tendency has been to develop sites in estuaries, bays, lagoons, or basins characterised by narrow entrances and relatively low water renewal. Given the tendency to increase stocking density every year, it is inevitable that food limitations will occur (Mallet and Myrand, 1995), yet food supply is probably the most important single factor in determining growth rate (Seed, 1976). There are several studies that report localised and downstream food depletion associated with bivalve aquaculture, in particular the raft culture of mussels (Navarro et al., 1991; Heasman et al., 1998).

The present study measured chlorophyll-*a* as an indicator of food levels at opposite ends of a site, which was an active mussel farm. There was no indication of a decline in food as water passed through the site (Figure 5). The chlorophyll-*a* concentrations at 2 m at both ends of the lease and at 15 m varied throughout the two-year study period, and peaked at different times at the stations, but the mean levels at each station were the same. This is not indicative of a site that is overstocked. If there were an excess number of mussels filtering the incoming water, a downstream depletion of the chl-*a* levels would be expected.

The chl-*a* levels at this site were lower than those reported for Spain, South Africa, and Maine but within the ranges reported for California, the Netherlands, and New Zealand (Table 17), which is one of the larger mussel producing nations in the world. A report by Clemens et al. (2000) of the chl-*a* levels at 14 mussel producing sites around Newfoundland, including Fortune Harbour, shows the levels reported at the study

site are typical of Newfoundland mussel farms, with an annual range of 0.5 µg/L to 10 µg/L with means less than 2 µg/L.

The primary productivity (the growth of phytoplankton in the site) was not measured in this study and therefore there is no indication of the contribution it may be making to the production of mussels on the site. The chlorophyll-*a* concentrations were measured at both ends of the site but if localised depletions were being supplemented by primary productivity this would not be detected.

Table 17: Chlorophyll-*a* concentrations reported for different mussel producing areas.

Author	Location	Chlorophyll-*a* levels (µg/L)		
		low	mean	high
Page and Hubbard (1987)	California	0.5		3.0
Smaal and Van Stralen (1990)	Netherlands	0.8	1.3	1.8
Camacho et al. (1995)	Spain	3.1		4.4
Hickman et al. (1991)	New Zealand	0.3		3.2
Grant et al. (1998)	South Africa	5.0		50.0
Newell et al. (1998)	Maine		3.1	

The particulate organic matter (POM) for this site, as reported by Clemens et al. (2000) (Appendix 2), indicates that the levels at this site during the study period (mean 1.05 mg/L) are similar to those reported for Nova Scotia at 1-2 mg/L (Mallet and Carver, 1987), and the U.K. at 1.1 mg/L (Widdows et al., 1979), higher than those in Spain at 0.62 mg/L (Navarro et al., 1991) but lower than at a site in Maine, 2.7 mg/L (Newell et al., 1998). A level of 1 mg/L is not considered abnormally low for this region as values less than 1 mg/L are common along the Atlantic Coast of Nova Scotia (Mallet and Carver, 1987). The percentage of POM in relation to the total particulate matter (TPM) for this site is 56%, which is higher than levels reported for Spain, 49% (Navarro et al.,

1991), Nova Scotia, 33-55% (Carver and Mallet, 1990), and the U.K., 25% (Widdows et al., 1979), and indicates a higher energy value (quality) of the suspended material. An increase in the inorganic sediment load would be expected to cause a dilution of the organic fraction and thereby reduce the quality (Mallet and Myrand, 1995).

Temperature

Temperature is widely acknowledged as an important factor in controlling growth with optimum growth occurring between 10-20°C (Seed, 1976). Nielson (1988) reported that length-growth rate increases with temperature but that there is an abrupt decline at the highest temperature (>17°C in spring and > 15-16°C in autumn). A similar finding was reported by Almada-Villela et al. (1982), but with the threshold occurring at 20°C, beyond which growth declined sharply. While it is reported that growth is slow at lower temperatures, 3°C to 5°C (Almada-Villela et al., 1982), Mallet and Carver (1993) found that in Nova Scotia the resumption of shell growth in spring coincides with the transition in water temperature from <0°C to >0°C. In other words, there appears to be a threshold effect where mussels show little growth at temperatures below 0°C, regardless of the food availability. However, given sufficient food significant growth may be obtained at temperatures from 0°C to 5°C.

In the present study, temperature was monitored at the sampling stations to determine if differences could explain any observed differences in growth rates. The temperatures at opposite ends of the lease at 2 m from the surface were not significantly different and therefore could not have accounted for growth differences (Figure 6). The temperature at 15 m was substantially lower than that near the surface for most of the year (Figure 7), with the exception of brief periods during the winter of 1995. Given that the temperature at 15 m remained below 0°C from December, 1994 to August, 1995

and did not exceed 2°C until September, 1995 a lower growth rate would be expected regardless of the amount of food available.

Salinity

The salinities at the site were recorded to determine if there were differences at the stations that may explain any observed growth differences in the mussels. The results indicated that the levels experienced by the mussels were well within the tolerance range for this species. Mallet and Myrand (1995) state that acceptable growth rates are recorded at salinities above 18 ‰, with an optimum at 26 ‰ .

The salinity at both ends of the lease were not found to be significantly different and therefore would not contribute to any observed differences in growth (Figure 8). The salinity at 15 m was significantly different than that at 2 m but both were well within the range reported for this species and therefore would not be expected to impact on growth (Figure 9).

Current Speed

The measured current speeds at the entrance to the Fortune Harbour site were lower than at the end of the site during both the spring tidal period and the neap tidal period (Table 1). This may have been a result of the locations at which the current meters were installed. At the end of the site approximately 200 m seaward of the meter location the site narrows from 500 m to 210 m, and then widens once again beyond the narrows. This is likely causing a funnelling effect with current speed increasing as the tidal volume passes through this narrow section.

The current speeds, calculated on the basis of tidal volume and the cross sectional area that the water must pass through, predicted the exact opposite with higher current

speeds at the entrance to the site (Table 2). The effect of the narrowing is negated at the end of the site as it is just a small portion of a larger area when calculating the cross sectional area and the surface area covered by each group of ten lines. The accuracy of this method of determining current speeds will increase with more frequent on-site measurements of the tidal height. The method depends heavily on the volume of water added during tidal cycles and the cross sectional area through which it must pass. If the actual tidal height of a mean tide was 1.2 m. instead of 0.92 m. the calculated flow through lines 1-10 would increase from 1.56 cm/s to 2.04 cm/s. Even with increased tidal height the calculated flow at the end of the site still would only reach 0.59 cm/s.

Regardless of which current speeds are considered accurate, they are at the low end of the range normally reported for mussel aquaculture sites. Hickman (1992) reports current speeds for typical sites range from 2 cm/s to 10 cm/s. Current speeds at three raft culture sites in Spain had mean measurements of 1.81 cm/s, 2.99 cm/s, and 3.04 cm/s with peak current speeds as high as 30.7 cm/s (Camacho et al., 1995).

4.2 Mussel Growth

Shell Length

The statistical analysis of the effects of date and location in the site on shell length showed that both had a significant effect (Table 3). The effect of date was expected as mussels grew during the study period. The fact that location had a significant effect indicates mussels grew at different rates at opposite ends of the site. After two years the difference in mean shell length was 0.22 cm (Figure 10). This difference cannot be explained by differences in temperature, salinity, or food levels as none were significantly different. There was a difference in current speeds, and higher current speeds can increase the rate of supply of food to mussels (Hickman, 1992). In

this case there was no clear indication that current speed may be impacting growth as the higher current speeds were measured at the end of the site and the calculated current speeds for the end of the site were so low that an even larger difference in shell length would have been expected between the two stations.

From an aquaculture perspective the actual differences in the shell length were so small, 0.22 cm, that it would not impact the operation of the farm. It would take a few extra months for the mussels at the end of the lease to reach market size, and harvesting occurs over extended periods anyway. The site operator could simply start the harvest using the larger product and utilise the mussels farther in the site at a later date.

Shell Length and Depth

An analysis of the effects of growing mussels at depth, 15 m versus 2 m from surface shows that depth has a significant effect on the shell length (Table 4). Over a one year period mussels held lower in the water column only increased in length by 0.44 cm (Figure 11), despite having access to the same food supply as those held near surface, as indicated by chlorophyll-*a* levels. The difference in growth rates is attributed to different temperatures mussels were exposed to. As already discussed, the temperature at the two depths was significantly different.

These findings suggest that caution must be exercised when growers experiment with lowering animals into deeper water as suggested by Dabinett and Clemens (1993). They report finding higher levels of chl-*a* deeper in the water column, accompanied by slightly lower temperatures. Further they suggest that by lowering mussel socks animals could access additional food and the benefit may outweigh the cost of being at a lower temperature. The result would be increased growth. This concept is still worthy of further investigation. In the present experiment animals were lowered to 15 m, which in this case resulted in very low temperatures and no increase in food availability. Future

experiments should explore depths in between, to see if there are zones where the temperature differential was not as extreme and there may be higher food levels as suggested by previous studies.

Dry Shell Weight

The dry shell weights at opposite ends of the site were significantly different (Table 5a). When the ratios of shell weights to shell lengths were compared it revealed that shells at the entrance to the site were thickening at a greater rate (Table 5b). A similar observation was made by Mallet and Carver (1993), who noted that shell weight to length ratio increased in winter when linear shell growth was at its lowest. They suggest that shells of mussels tend to thicken, rather than lengthen, during this period. The present study suggests that rates of shell thickening may differ at different locations within a site as well as at different times of the year (Figure 12).

Dry Shell Weight and Depth

The influence of depth on dry shell weight was significant (Table 6). Figure 13 showed the change in shell weight of mussels after one year in the sock. From figure 13 it appears animals at depth actually lost shell weight between June 1995 and October 1995. This is likely a result of sampling artifact, as the standard error bar indicated the mean shell weight at depth in June 1995 could be much lower and similar to the weight measured in October 1995.

Dry Tissue Weight

The dry tissue weight of mussels suspended at opposite ends of the site was significantly different (Table 7) over time and on the basis of location in the site. In fact each time measured the animals at the entrance to the site consistently had more soft tissue (Figure 14). The differences in soft tissue at opposite ends of the site cannot be attributed to a lack of food at the station at the end of the site. For the period June 1996-August 1996 there was more dry soft tissue in mussels at the entrance, yet during this same interval there was consistently more food, as indicated by chl-*a* levels (Figure 5). There was considerable variation in dry tissue weights throughout the year with apparent losses during some intervals. This is consistent with findings in other studies (Mallet et al., 1987b; Mallet and Carver, 1993).

A substantial tissue weight gain occurs during the spring bloom and losses occur during spawning and during periods of low temperature and low food levels (Mallet and Myrand, 1995). This could explain some of the differences in tissue weight observed. For example, during June 1996 there was an 80% higher tissue weight in mussels at the entrance to the lease, it is possible the mussels at the end of the lease had already spawned. This would not explain differences observed in August and September when recovery at both stations should be occurring.

Dry Tissue Weight and Depth

The dry tissue weights of mussels held at 15 m from surface were significantly different than those held at 2 m (Table 8). This is a function of the change in size of mussels as time progressed. As previously stated, mussels at depth grew very little and the difference in animal size at the two depths, as measured by length, after a year was

substantial. Such a difference in animal size would result in differences in dry tissue weight seen in Figure 15, regardless of spawning events.

Condition Index

There are a number of methods of measuring condition indices in bivalves reported in the literature (Baird, 1958; Gabbott and Walker, 1971; Lucas and Beninger, 1985; Crosby and Gale, 1990; Rainer and Mann, 1992) with some debate as to which is the most appropriate. The three most common, use dry tissue weight as the numerator and divide by either internal shell cavity volume, internal shell cavity capacity, or dry shell weight. Rainer and Mann (1992) concluded that all three are useful indices of nutritive stress. The authors state that the requirement of any static condition index is to provide a stable denominator to compare with a sensitive numerator. In this instance shell weight is as useful as cavity volume. Both are considered to increase over time as mussels grows but neither will decrease in value, with the exception of possible minor weight loss due to abrasion or boring organisms. Therefore, the method of Walne and Mann (1975) was used.

The condition of animals at both ends of the site was found to be significantly different by both date and position (Table 9). To be significantly different over time is expected as the calculation uses dry tissue weight as the numerator, which will vary depending on the time of the year as discussed above.

To be significantly different on the basis of location in the site suggests the animals have a physiologically different status. The mussels at the entrance to the site were in better condition, and of better quality from a production perspective, at all times except August 1996 (Figure 16). The poorer condition on this date was a result of the 50% reduction in dry tissue weight that occurred at the entrance to the site following the June 1996 measurement. During this same period the dry tissue weight at the end of the

site only dropped by 20%. This indicated that a much larger spawning event occurred at the end of the lease. Just three months later the animals at the entrance had once again surpassed the animals at the end of the lease and were in better condition.

From an aquaculture perspective these differences in the amount of soft tissue are important. Growers are paid for mussels that are of sufficient market size but if the mussels weigh less, i.e., it takes more mussels to make up a kilogram, the growers financial return will obviously be lower. In many cases the condition, meat yield, must meet minimum standards before the processing plant will accept the product.

The condition index calculated for this site are within the range of those for other mussel culture sites in Newfoundland. Clemens et al.,(2000) reported on the condition of mussels at five sites around the island using the same method of calculating condition indices as used in this study. The levels ranged from 10 to 35 with all sites showing seasonal patterns.

Condition Index and Depth

There was a significant difference in the condition of mussels held at depth when compared to those near the surface (Table 10). Mussels near the surface were of higher quality in June 1995 while in October those at depth had a higher condition index. Mallet and Myrand (1995) state the during periods of low temperature and poor food levels mussels rely on their energy reserves to meet their metabolic requirements. In this case mussels at depth were in very cold water for most of the year (Figure 7), the consequence being less soft tissue in relation to their shell (Figure 17). By autumn the water temperature had increased to 5°C and animals had continued to increase their soft tissue and had not spawned. The animals at surface had spawned during the summer and their proportion of soft tissue to shell was less than at depth after spawning.

The practice of lowering mussels into deeper colder water to inhibit spawning had been used by the operators of this site in the past (J. Ward, pers. comm.). They had lowered marketable mussels below the thermocline to allow them access to better quality product later in the season when mussels on most sites had spawned. The difficulty with this technique was when mussels were raised for harvesting or when they were exposed to higher temperatures in the processing plant or during shipping they would spawn.

Coefficient of Variation

In mussel culture individual mussels are sheltered from flow at sock or long-line scales, and growth may suffer compared to animals exposed to ambient flow and food. This may lead to variance in mussel size. Grant (1999) modelled and measured coefficient of variation for adult mussels (53-57 mm). The author concluded that size variation of seeded mussels is not the sole cause of variation in adults. The seed mussels used by Grant (1999) had a coefficient of variation of approximately 50%, these animals were then used in a model, which predicted a coefficient of variation of 23% in the autumn of the year. The measured coefficient of variation in the autumn was actually 46%. On the basis of what was observed compared to what was predicted by the model, the author states that size variation in seeded mussels is not the sole cause of size variation in adults but rather food depletion also plays a role. The author predicts that a range of 0 to 40% seston depletion will result in a coefficient of variation of meat weight of 46%, further a seston depletion of 10% results in a 25% reduction in peak weight.

In the present study coefficients of variation of the seed (60%) and adults at both ends of the site were in the range measured by Grant (1999), with the entrance at 46% and the end at 48%. These values are consistent with animals experiencing 0-40% seston depletion, as stated above. Using chlorophyll-*a* as an indicator of food concentration,

there were no measured differences in food availability at both ends of the site (Figure 5a) and thus no indication of food depletion.

4.3 Biomass

The biomass on the site was calculated for the autumn of each year with the peak during the study period being in 1995 (Figure 21). The biomass will vary throughout the year as socks are added, product is removed, animals grow and spawn, and natural mortality occurs. The autumn was chosen as this was the time of the year when the best information was available on what occurred throughout the year and on the physiological status of the animals.

The decline in biomass in 1996 was as a result of the site operator's concern about the production capacity of the site (J. Ward pers comm.). They added fewer socks that year and natural mortality of the mussels already present reduced biomass further (Table 11). The tendency of the operators of this site has been to place most of the socks (Figure 19) and therefore the resulting biomass (Figure 18) in two areas, lines 1-20 and lines 50-80. These areas correspond with deeper portions of the site and reduce the risk of socks touching bottom (Figure 20). The consequence of this is an increased density of animals within these sections of lines and increased competition for available food. The remaining sections of the site do contain some socks but are also used for setting collectors for seed acquisition.

The accuracy of the biomass calculation could be increased with a better estimate of density of mussels on a sock after one year in the water. In the present study the number of mussels in a sock after one year was calculated assuming a straight line mortality rate from initial installation to harvest. If increased mortality actually occurs immediately following sock installation or at another time throughout the production period then the biomass associated with one year sock will be affected.

Approximately 10.000 collectors were installed on the site in Fortune Harbour each year. The seed attached to these collectors was not included in biomass calculations as the biomass was calculated just a couple months after these collectors were placed in the water. The seed was small by early autumn, commonly referred to as pepper, and an accurate assessment of the biomass associated with seed was not possible.

4.4 Production Capacity

Tidal Volume Method

The tidal volume method of assessing the status of the site uses the mean filtration rates of the different year classes of mussels to determine how much of the incoming water on a mean tide was filtered. Results suggest that mussels on the site had the ability to filter a volume of water close to the entire volume of the incoming tidal cycle. During 1996, when the site had the lowest biomass during the study period, it was calculated that a volume equivalent to 80% of the water on an mean tide was filtered. This value reached a high of 98% in 1995 when the biomass was at its peak (Table 14). Mussels should not filter more than 50% of the incoming water (Carver and Mallet, 1990), therefore this site had too many mussels present during the period, 1994-1996. If the target is to filter no more than 50% of the tidal volume, the suggested biomass is 23.5 x 10^6 to 33 x 10^6 mussels. This is approximately 50% of the actual biomass present at 60 x 10^6 mussels in 1994, 65 x 10^6 mussels in 1995 to 35 x 10^6 in 1996.

This method of assessment does not consider the amount of food present in the incoming water (Carver and Mallet, 1996). It assumes that a 50% depletion would not result in starvation. If food levels are close to the critical limit, then even a 20% depletion rate may be too high and stocking densities on this site would greatly exceed what could be supported.

The calculation is based on the mussels having access to all the water entering on a tide including what enters along shallow areas of the site where mussels were not suspended. After eliminating these areas from the calculations, the percentage of accessible tidal volume filtered increases and in some cases exceeds the tidal volume.

The accuracy of these calculations could be improved by taking measurements of the tidal range in the site. For this study the tidal range for the low, spring, and neap tides were taken from tide tables. For a mean tide, with a range of 0.92 m, the tidal volume entering the site is 98.16×10^4 m^3 (Table 12). If the tidal range is actually 1.2 m on a mean tide the volume filtered by the mussels present in 1996 drops from 80% to 60%.

The exchange coefficients for the site suggest that the proportion of water in the site that is changed on each tide is quite low. During a mean tide only 9% of water in the site is exchanged and it takes 139 h to exchange the entire volume (Table 13). The amount changed on a spring tide is higher than on a mean tide. The exchange coefficient and the percentage dilution for this site are higher than values calculated for Goose Arm on the West Coast of Newfoundland, which require 61-68 h to exchange the volume of the site with 19-21% exchanged on each tide. Both the study site and Goose Arm have a lower exchange coefficient and higher dilution than values reported for St. Patricks Bay, Notre Dame Bay at 159-290 h, and 4-8% (Carver and Mallet, 1996).

Food Depletion Method

The food depletion method of estimating carrying capacity is based on determining the rate of food depletion as water moves through the site and is filtered by the mussels. The results suggest that on the basis of chlorophyll-*a* converted to carbon, as an indicator of the concentration of food available to the mussels, there was just enough food available to meet the minimum carbon required for respiration but based on

particulate organic matter concentrations, as an indicator of the concentration of food available to the mussels, there is more than necessary (Figure 22).

The minimum carbon required is 57 µg C/g/h (Table 15) or at a filtration rate of 1.36 L/g/h = 42 µgC/g/L. The carbon:chlorophyll ratio is 40, therefore the minimum chlorophyll-*a* concentration is:

$$57\ \mu gC/g/h \times 1/40 = 1.43\ \mu g\ chl\text{-}a\ /g/h$$

From measurements on the site, the average chlorophyll-*a* concentration was 1.6 µg/L. The mean filtration rate in 1995 was 1.36 L/g/h. Therefore, the supply of chlorophyll-*a* was:

$$1.36\ L/g/h \times 1.6\ \mu g/L = 2.18\ \mu g\ chl\text{-}a/g/h$$

There is 2.18 µg chl-*a*/g/h availability and 1.43 µg chl-*a*/g/h required, therefore the is more available then required (1.52 times).

The absorption efficiency for mussels feeding on phytoplankton is reported to be 80% (Grant and Bacher, 1998). This would reduce the supply of food from 2.18 µg chl-*a*/g/h to 1.74 µg chl-*a*/g/h, with the result that only 1.22 times the minimum carbon required by mussels would actually be available.

Using the same approach to assess the site based on particulate organic matter (POM) concentrations, as indicators of food, the result is quite different. The conversion to carbon from POM is POM x 0.38 (Grant and Bacher, 1998). Therefore the minimum POM required for respiration in mussels is:

$$57\ \mu g\ C/g/h \times 1/0.38 = 150\ \mu g\ POM/g/h$$

With a mean reported POM level of 1.05 mg/L (Appendix 2), and the same filtration rate for 1995, 1.36 L/g/h, the supply of food is:

1.36 L/g/h/1.05 mg/L = 1.43 mg POM/g/h

On the basis of POM concentrations there was 9.5 times as much food as is required for mussel respiration (1.43 mg POM/g/h x 1000/150 µg POM/g/h). Grant and Bacher (1998) report an absorption efficiency of 46.8% for POM, which would reduce the food supply to 0.67 mg POM/g/h. This means that instead of there being 9.5 times as much food as is required for mussel respiration there was 4.5 times.

As stated chlorophyll-*a* x 40 = carbon, while carbon x 1/0.38 = POM (algal matter). The mean chlorophyll-*a* concentration was 1.6 µg/L, therefore the algal POM is: 1.6 µg/L x 40 x 1/0.38 = 168 µg/L or 0.168 mg/L. The mean POM concentration on the site was 1.05 mg/L which means the non-algal POM (detrital POM, zooplankton and bacteria (Dame, 1996)), was:

1.05 mg/L-0.168 mg/L= 0.88 mg/L

This level of algal particulate organic matter is considered low. Bayne and Widdows (1978) found that positive growth efficiency was obtained with levels of algal particulate organic matter between 0.2-0.3 mg/L. Widdows et al. (1979) report a positive growth efficiency over 0.28 mg/L of algal particulate organic matter. In small mussels (100 mg dry weight), the maximum growth rate is attained at approximately 0.8 mg dry algal matter per litre (Widdows, 1978).

The particulate organic matter supplied on a 12.5-h tidal cycle is:

mean tidal volume (98.2×10^4 m^3)/12.5 h x 1.05 mg/L = 8.25×10^7 mg/h

The mussel uptake is:

1.36 L/h x 1.05 mg/L POM = 1.43 mg/h

Therefore. 55×10^6 mussels could filter all the particulate organic matter in a tidal cycle.

These calculations are based on mean food concentrations averaged for the year. There are periods. during an algal bloom, when the levels are much greater than the mean and conversely there are times when the concentrations are below the mean. Using an average value does not show what the available food may be in relation to the requirements of the mussel during these periods.

Food Supply and Food Demand

The food supply and food demand approach is a ratio based on the tidal volume and the filtration rate of the mussels present. The results suggest a carrying capacity for the site of 4.600 kg/ha to 5.200 kg/ha (Table 16). This equates to 39×10^6 to 44×10^6 mussels at 80 mussels per kg. If 50% of the tidal volume is filtered. as previously suggested as the maximum. then the suggested number of mussels on the site would be reduced by one-half.

This method of assessing carrying capacity has been used by several authors (Carver and Mallet. 1990; Dabinett and Clemens. 1993; Lawrence. 1996). All the authors have used food concentrations in the calculations. yet the food concentrations have no bearing on the outcome. This method is a ratio of food supply to food demand

with both supply and demand calculated using food concentrations. In the calculations they cancel out and therefore have no impact on the results.

The findings of the present study are within the range reported by these authors. Dabinett and Clemens (1993) suggest a carrying capacity for three sites in Newfoundland and the mean was reported at 5,000 kg/ha, Carver and Mallet (1990) suggest a carrying capacity of 4,000-12,000 kg/ha for a site in Nova Scotia, and Lawrence (1996) suggested 1,500-2,100 kg/ha for the same site as the present study, based on filtering 50% of the tidal volume.

Recommended stocking density

To determine a recommended stocking density some assumptions are necessary. First that mussels only deplete 50% of the available food. Second that mussels confined to the 87 ha leased area, have access to all food entering the entire 106 ha, at some point through a tidal cycle. On this basis the models suggest 19 x 10^6 to 33 x 10^6 mussels can be stocked on the 87 ha leased area before food becomes limiting.

Tidal volume method - 23.5 x 10^6 to 33 x 10^6 mussels
Food depletion method - 55 x 10^6 x 50% = 22.5 x 10^6 mussels
Food supply and food demand method - 19.5 x 10^6 to 20.5 x 10^6 mussels

On this basis it is recommended the site operators aim to have 22 x 10^6 mussels (1 g dry weight) on site and assess the impact of this density. This is less than half the number present on the site at times during the present study.

Using densities of 2,500, 1,550, and 600 mussels for year 1, year 2, and year 3 socks respectively, and dry weights of 0.161 g, 0.45 g, and 0.75 g respectively. This equates to 14,160 socks installed and harvested on an annual basis:

2500 mussels x 0.161 g= 402.5 g/sock (26% of biomass)

1550 mussels x 0.450 g= 697.5 g/sock (45% of biomass)

600 mussels x 0.750 g= 450.0 g/sock (29% of biomass)

22×10^6 mussels x 26% = 5.7×10^6 g of mussels

5.7×10^6 g of mussels/0.161 g/2500 mussels per sock = 14.160 socks per year.

5. Summary

The mussel aquaculture site in Fortune Harbour is characterised by low current speeds, a high exchange coefficient, limited dilution on a tidal cycle, and low chlorophyll-*a* concentrations.

The shell length, dry shell weight, dry tissue weight, and condition of mussels were found to be significantly different at opposite ends of the site despite the fact that the temperature, salinity, and chlorophyll-*a* concentrations at 2 m were not significantly different at the two sampling stations. Growth rates were significantly different in mussels held at depth compared to those near the surface, while the condition of the mussels was not significantly different at the two depths. The animals at depth were in significantly colder water for most of the study period.

Based on chlorophyll-*a* concentrations at opposite ends of the site there is no measurable down stream depletion of food. The food concentrations do not indicate that the densities of mussels present were impacting chlorophyll *a* concentrations moving through the site on a tidal cycle, contrary to what was suggested by the carrying capacity models.

The concentration of chlorophyll-*a* on the site was low in relation to the levels required for respiration and growth in mussels on the site. Particulate organic matter concentrations suggest much higher food levels, although the algal particulate organic matter concentrations were below values required for positive growth.

The biomass present on the site during the study period, 35 x 10^6 to 65 x 10^6 mussels, was twice the suggested level of the carrying capacity models at 19 x 10^6 to 33 x 10^6 mussels. All the analyses were consistent and suggest the site was overstocked.

The suggested stocking density for the 106 ha site is 22 x 10^6 mussels (1 g dry weight). This equates to approximately 14,000 socks installed and 106,000 kg harvested

annually and assumes the mussels, that are confined to the 87 ha leased, will have access to all the food in the site at some point in the tidal cycle.

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Appendix 1: A sample demonstrating how mussel filtration rate grouped by lines and mean filtration rate calculated for 1996. Numbers of socks are separated by year class within each group of lines.

Line number	Number of socks	Number mussels/sock	Number of mussels (10^3)	Volume filtered (l. x 10^3)	Filtration rate by year class (l/h)	Filtration rate per line group (l/h)
1 to 10	470	2,500	1,175	1,316	1.12	1.64
	2,727	1,550	4,226	6,974	1.65	
	3,596	601	2,161	4,127	1.91	
11 to 20	5,013	1,550	7,770	12,820	1.65	1.70
	2,985	601	1,793	3,426	1.91	
21 to 30	140	2,500	350	392	1.12	1.69
	858	1,550	1,329	2,194	1.65	
	1,935	601	1,162	2,221	1.91	
31 to 40	407	1,550	630	1,040	1.65	1.75
	690	601	414	792	1.91	
41 to 50	786	1,550	1,218	2,010	1.65	1.69
	341	601	204	391	1.91	
51 to 60	5,451	601	3,276	6,257	1.91	1.91
61 to 70	3,554	1,550	5,508	9,089	1.65	1.65
	12	601	7	13	1.91	
71 to 82	4,676	601	2,810	5,367	1.91	1.91
83 to 92	854	1,550	1,323	2,184	1.65	1.72
	812	601	488	932	1.91	

Appendix 2: Total particulate matter (TPM), and particulate organic matter (POM) levels reported by Clemens et al. (2000) for 1995 and 1996. Particulate organic carbon (POC) = POM x 0.38 (Grant and Bacher, 1998). (SE=Standard Error)

Date	TPM (mg/L)	TPM SE	POM (mg/L)	POM SE	POC (mg/L)	% Organic	% Organic SE
30-Mar-95	1.95	0.17	0.9	0.13	0.34	45.90	4.40
20-Apr-95	1.35	0.07	0.73	0.09	0.27	53.31	3.75
05-May-95	2.47	0.23	1.47	0.22	0.55	58.46	3.82
18-May-95	1.82	0.14	1.02	0.14	0.38	55.18	3.76
01-Jun-95	1.73	0	1.17	0.12	0.44	67.34	6.74
21-Jun-95	1.82	0.18	0.88	0.14	0.33	47.89	4.72
22-Jul-95	1.78	0.08	0.83	0.2	0.31	47.69	11.95
29-Aug-95	1.67	0.08	1.07	0.1	0.40	63.63	2.72
28-Sep-95	2.32	0.38	1.48	0.21	0.56	64.57	2.02
14-Oct-95	1.45	0.04	1.05	0.1	0.39	72.93	8.46
13-Nov-95	1.75	0.02	0.83	0.03	0.31	47.70	2.16
23-Apr-96	4.15	0.11	1.75	0.04	0.66	42.27	1.93
25-May-96	1.55	0.07	0.75	0.08	0.28	48.73	5.97
03-Jul-96	1.65	0.13	0.97	0.05	0.36	59.58	5.01
01-Oct-96	1.8	0.15	1.17	0.16	0.44	64.03	3.29
20-Nov-96	1.4	0.11	0.78	0.08	0.29	56.77	6.73