THE INFLUENCE OF OCEANOGRAPHIC CONDITIONS AND CULTURE METHODS ON THE DYNAMICS OF MUSSEL FARMING IN SALDANHA BAY, SOUTH AFRICA.

THESIS

Submitted in fulfilment of the

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by

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To my family
for giving life to my ambitions.

TABLE OF CONTENTS

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ABSTRACT

The principal aim of this study was to establish the biological and environmental parameters governing the successful and sustainable cultivation of mussels in Saldanha Bay. The environmental study investigated seston, chlorophyll-a and particulate organic matter (POM) levels, water temperature dissolved oxygen and salinity levels in the bay and water flow in and around the rafts. The biological part of the study investigated the efficiency of food extraction, growth rates, mussel condition, fouling and production and yield on a rope, raft and farm scale.

Saldanha Bay is well suited for the culture of mussels, particularly *Mytilus galloprovincialis* and *Choromytilus meridionalis*. Water temperature and salinity in Saldanha Bay were found to be near optimal for mussel culture. POM and chlorophyll-a levels were found to be high due to primary production resulting from the nutrient rich upwelled water outside Saldanha Bay. The mean levels of chlorophyll-a (8,6μg/l) represent 6%, by mass, of the total POM. On a bay scale the POM remained above the mussels maximum requirements (pseudofaeces threshold) during the study period. Mussels showed a preference for the phytoplankton portion of the POM. Approximately 40% of the chlorophyll-a was extracted from the water by the mussel farm. The efficiency of food extraction increased with mussel age. Rafts with seed mussels younger than 2 months, 3 to 4 months, 5 to 6 months and older than 6 months extracted 32%, 55%, 85% and 92% of the available chlorophyll-a respectively. An increase of rope spacing on the rafts resulted in 37% more chlorophyll-a and 30% more particle volume reaching the lee of the raft. Ambient water currents in the bay show flow rates of up to 22cm per second. However, on entering a raft with a rope spacing of 60cm, the water flow is attenuated by 90%. Increasing the rope spacing to 90cm resulted in a water flow attenuation of 72%. The increase in rope spacing ensures that the mussels in the centre of the raft are feeding on food levels close to, or above, the pseudofaeces level. Mussel growth rate at a rope spacing of 90cm is significantly improved as a result of the increased food delivery. There are other factors, however that effect mussel growth. Growth rates were found to be better in

summer than in winter. The reduced winter growth rate is possibly due to competition with the maturing fouling organisms which settle in mid to late summer. Fouling by mussel spat and *Ciona intestinalis* is seasonal, occurring from December to May. *C.intestinalis* is prevalent in the centre of the farm and rafts as low energy waters are preferred by this species. Mussel spat settles mainly on the periphery of the farm and the rafts. Competition with fouling organisms reduces growth and increases mortality of the cultured mussels.

Results indicate that the present spacing of rafts, (1 raft per hectare) is adequate under existing conditions. Any new farms should maintain batches of 50 rafts with channels between them to ensure water current penetration into the furthest reaches of the farm. Rope spacing on the rafts should be increased to between 60cm and 90cm. Mussel density should be regulated according to mussel size and fouling should be controlled to maintain yields.

CHAPTER 1.

GENERAL INTRODUCTION

Mussels have been cultivated on poles in France since the thirteenth century (Mason 1976). It was during the eighteenth and nineteenth century however, that mussel cultivation started in earnest (Smaal 1991). Today mussels of the family Mytilidae are farmed commercially on a worldwide basis (Hickman 1992). In 1992 world production exceeded 1,08 million tonnes (F.A.O. 1994). The principal species, *Mytilus edulis*, is cultivated mainly on the western and northern coasts of the European continent along with *Mytilus galloprovincialis*. *Mytilus galloprovincialis* is, however, the main species cultured in Mediterranean waters (Chew 1989, Hickman 1992, Loo & Rosenberg 1983, F.A.O. 1989). Mussel farming is also practised in the USSR, North and South America, China, the Australasia region and South Africa (Sukhotin & Kulakowski 1992, Chew 1992, Zhang 1984, Chew 1989, Hickman 1992, Chaparro 1989, Jenkins 1985, F.A.O. 1989, Hecht & Britz 1992). More than half of the worlds annual mussel production consists of *Mytilus edulis* (49%) and *Mytilus galloprovincialis* (11%) (F.A.O. 1994). Twenty seven mytilid mussel species are found on the South African coast (Kilburn & Rippey 1982). *Mytilus galloprovincialis* has the greatest farming potential along with two indigenous species, *Choromytilus meridionalis* and *Perna perna*. *M.galloprovincialis* was unintentionally introduced to South African waters in the 1970s (Grant *et al.* 1984). Although the ranges of *C.meridionalis* and *M.galloprovincialis* extend from East London to Namibia (van Erkom Schurink & Griffiths 1990) the highest densities are found from Cape Agulhas to Namibia (Grant *et al.* 1984). *P.perna* is found from Angola to Mozambique, but excluding the region of maximum upwelling from Cape Town to Walvis Bay (Grant *et al.* 1984).

South Africa has a coast line of approximately 3000km. It is a high energy coastline with few protected bays, thus, there are only a limited number of

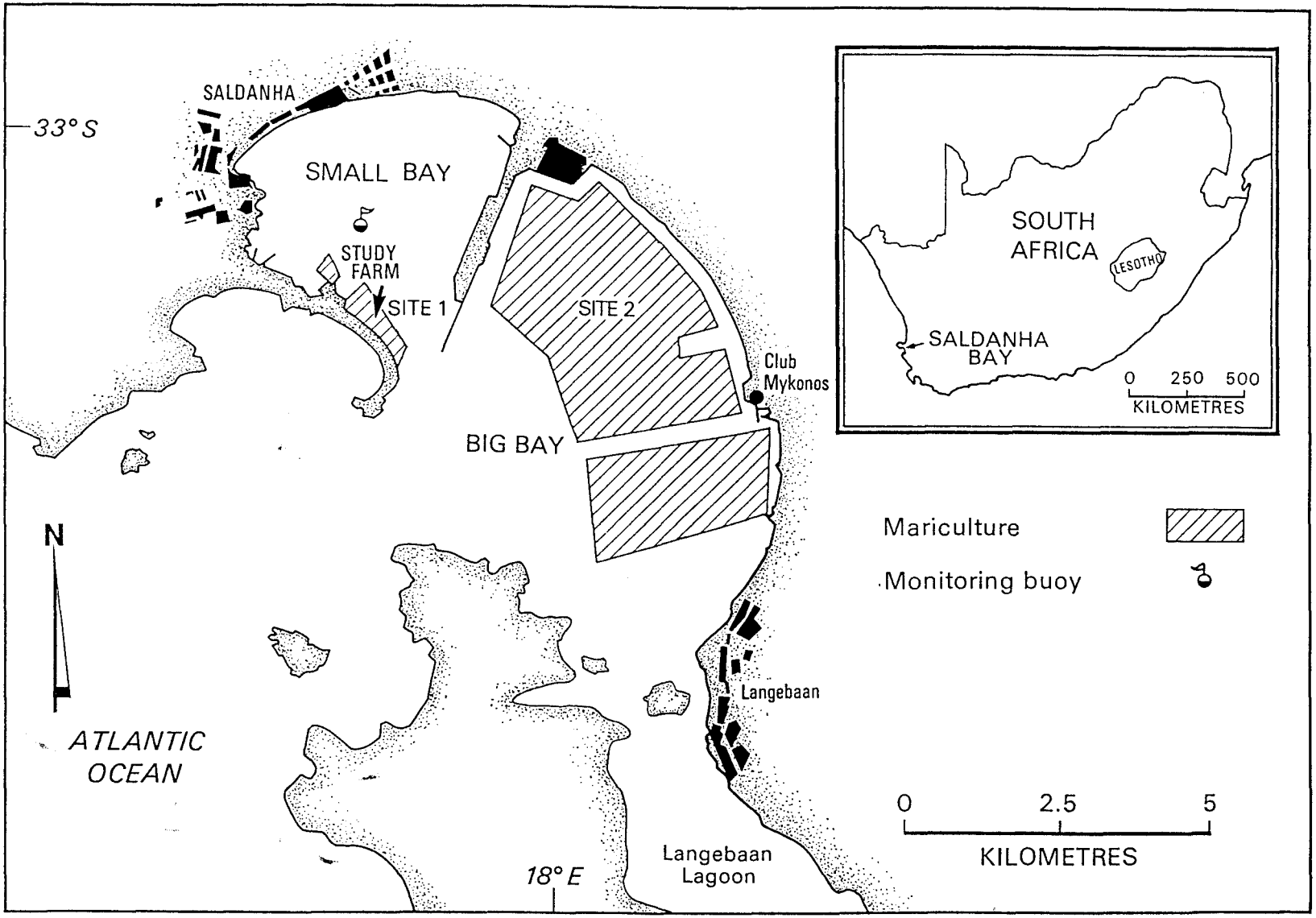


Figure 1.1. Map of Saldanha Bay showing the position of the monitoring buoy and mussel farming areas, 1 in Small Bay and 2 in Big bay.

mariculture sites. Of the few natural bays and inlets that are available, Saldanha Bay (33°03'S, 17°58'E) on the west coast, is the largest (Figure 1.1) and most suitable mariculture site in South Africa.

The water of Saldanha Bay is highly productive as it is situated within the southern Benguela upwelling zone (Monteiro & Brundrit 1990). This upwelling zone extends along the African west coast between 17 and 35°S (Gilchrist 1902). Upwelling in winter occurs in pulses at intervals of approximately 20 days while the summer upwelling pulses occur at intervals of approximately 10 days (Tyson 1986, Jury *et al* 1990). These pulses are related to large scale atmospheric Rossby wave structures (Tyson 1986, Jury *et al* 1990).

In 1975, Saldanha Bay was effectively split into two unequal parts (Figure 1.2) when a jetty was constructed for the loading and exporting of iron ore. The area north west of the ore jetty is known as "Small Bay" and the area to the south east "Big Bay" (Monteiro *et al.* 1990). Two sites have been reserved for mariculture in Saldanha Bay. The first site (Site 1 in Small Bay, Figure 1.1) is in a protected area in the lee of a causeway that was constructed between Marcus Island in the mouth of the Bay and the northern isthmus. Site 1 is approximately 85 hectares in extent (pers.obs). The causeway has had two major effects, it has reduced the wave energy entering Small Bay, and in conjunction with the ore jetty, it has modified the water current patterns for both Big Bay and Small Bay. The second site (Site 2 in Big Bay, Figure 1.1) extends from the south side of the ore jetty to a short distance from the mouth of Langebaan Lagoon (Atlas Sea Farms, pers. comm.). This site is approximately 1600 hectares in size.

In Site 1, which is in a low wave energy area, two different sizes of raft are used for mussel farming. Both consist of wooden lattices supported by hollow asbestos cement floats (1.3m in diameter). The smaller rafts are 15m X 11m supporting 19 beams, 60cm apart. Each beam supports 17 ropes, i.e. 323 ropes per raft.

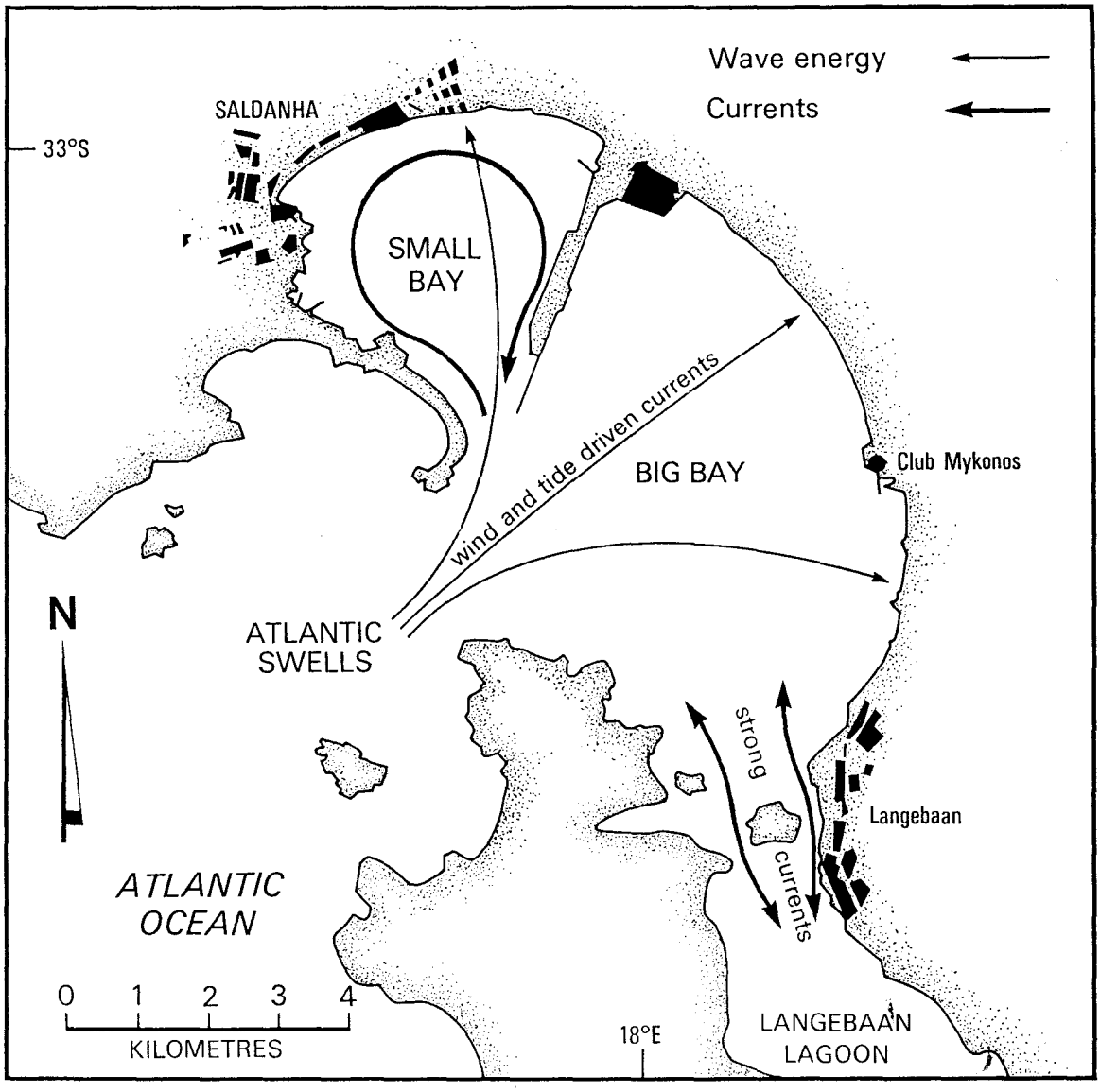


Figure 1.2. Map of Saldanha Bay showing the general currents and extent of exposure to wave energy in Small Bay and Big Bay. (Adapted from CSIR, (EMATEK) EIA report.

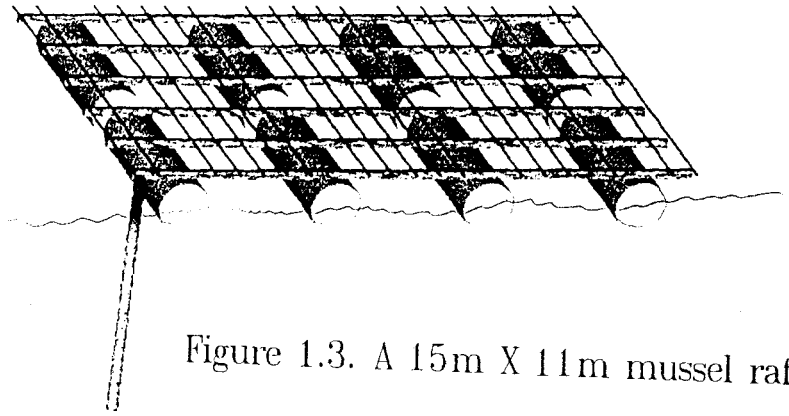


Figure 1.3. A 15m X 11m mussel raft with 6m rope.

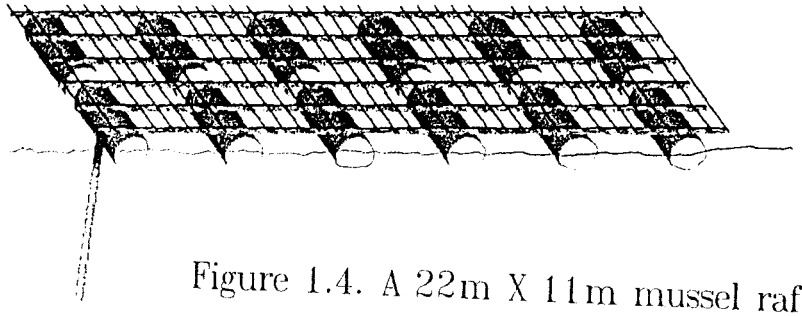


Figure 1.4. A 22m X 11m mussel raft with 6m rope.

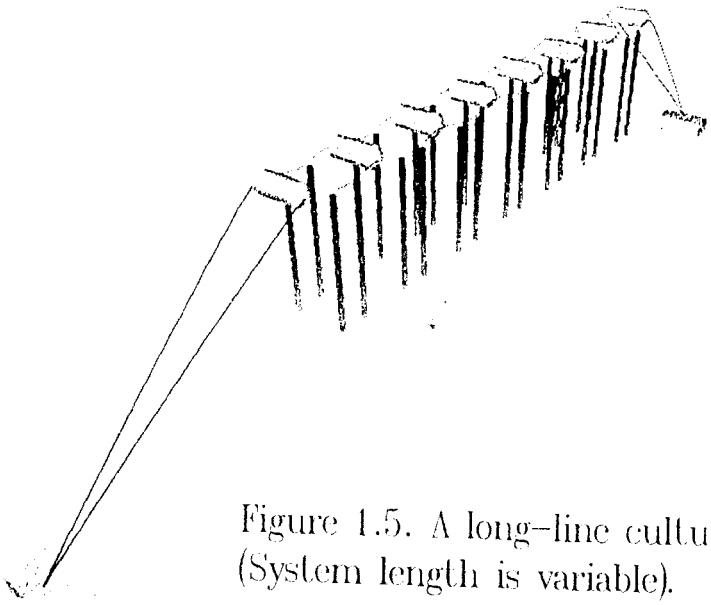


Figure 1.5. A long–line culture system with 6m ropes. (System length is variable).

The ropes are spaced at 60cm (or 90cm during this study) intervals and are suspended to a depth of approximately 6m (Figure 1.3). Approximately every 50cm down the rope a 30cm wooden peg, 3 to 4cm in diameter, is inserted through the rope to prevent the mussels from dislodging and sloughing off. The larger rafts are 22m X 11m with 29 cross beams with 17 ropes each, ie 493 ropes per raft (Figure 1.4). On both of these rafts the rope distribution density is approximately 2 ropes m^{-2}

Site 2 (Figures 1.1 & 1.2) is subjected to greater wave energy levels. Six metre swells occur every year and swells of 10m occur at least once every 5 years (Saldanha Bay Port Control pers. comm.). Such intense wave action would destroy the smaller rafts used in Site 1. A larger more swell-resistant raft (30m X 18m), which has two floats extending the full length of the raft, is currently been tested in this area. There will be approximately 1000 ropes on this large raft. The New Zealand long line culture system is also currently being tested in Saldanha Bay. The system consists of floats supporting two parallel ropes, horizontal with the water surface, from which the mussel ropes are suspended (Figure 1.5). The major problem associated with long lines is sloughing of the mussels during rough weather. An increase in the number of pegs per rope and partial submergence of the floats could possibly alleviate this problem to a degree. Tests are currently being undertaken to assess the viability of this system for mussel culture or for the collection of mussel spat.

Starting in 1985 the mussel industry in Saldanha Bay grew rapidly, producing over 2000 tonnes after only five years (Hecht & Britz 1992). In 1993, 25% of the rafts in Site 2, were destroyed by storms. Since then recovery has been slow as raft design is being reconsidered to suit the high energy conditions. In 1994, marketable mussel yield exceeded 2500 tonnes (Sea Harvest Corporation, Lusitania Sea Products & Atlas Sea Farms, pers.comm). Mussels are harvested throughout the year except during a three-week period in early summer when the

mussels have a low flesh condition brought on by spawning. Toxic red tides also occasionally encroach into Saldanha Bay stopping production for several days. On average, each raft is harvested twice a year, as the seed mussels require five to seven months to reach harvestable size (>65mm shell length). A total biomass of approximately 60 to 200 tonnes is harvested from each raft every year yielding between 30 and 100 tonnes of marketable mussels per year depending on raft size, season and degree of fouling by mussel spat and *Ciona intestinalis* (Chordata, Urochordata). In reality each raft yields between 30 and 70 tonnes of marketable mussels per annum.

Currently the Spanish mussel, *Mytilus galloprovincialis*, is the most important species in South Africa contributing approximately 70% - 80% of total production. The indigenous species *Choromytilus meridionalis*, constitutes the remaining 20% - 30% (pers. obs.). *C.meridionalis* is not highly regarded by the market as the brown flesh of the female is considered unsightly. *M. galloprovincialis*, which has an orange coloured female, and a greater flesh yield (van Erkom Schurink & Griffiths 1993), is the preferred species of the consumer. *Perna perna* is not a competitive culture species in the colder waters of the west coast. It has potential for cultivation on the warmer subtropical east coast of South Africa (van Erkom Schurink & Griffiths 1993). *M.galloprovincialis* is well suited to the conditions of the South African coastline and has become the most dominant mussel in the south western Cape (van Erkom Schurink & Griffiths 1992). It would appear also that *M.galloprovincialis* grows better under local conditions than in its natural area of occurrence (van Erkom Schurink & Griffiths 1992).

This study focuses mainly on *Mytilus galloprovincialis* and, to a lesser extent on the indigenous black mussel *Choromytilus meridionalis*.

The principal objective of this study was to establish the biological and environmental parameters governing the successful and sustainable farming of

mussels in Saldanha Bay. The environmental and oceanographic conditions are dealt with in Chapters 2 and 3. These chapters investigate water temperature, oxygen, chlorophyll *a* and particulate organic matter levels and raft scale water currents. The biological aspects are considered in three chapters. The first of these chapters discusses food availability and removal by mussels of these particles by the mussels on a rope, raft and farm scale. The following chapter discusses seasonal variation of mussel growth, condition and production in relation to whole rafts, the position of mussels on a raft and the raft design. The third biological chapter studies the effect of fouling organisms such as mussel spat and *C.intestinalis* on the mussels. A synthesis of the various chapters concludes this study. This study is part of a broader programme, which examined the currents on the outer shelf and in the Bay, productivity, nutrient cycling, water chemistry and temperature with the overall aim of determining the optimal carrying capacity for mussel farming in Saldanha Bay.

CHAPTER 2
THE OCEANOGRAPHIC AND ENVIRONMENTAL CONDITIONS IN SALDANHA BAY.

INTRODUCTION

Saldanha Bay on the west coast of South Africa is situated within the Benguela upwelling system. The Benguela current, its associated upwelling system and biomass are comprehensively described by Field & Greenwood 1975, Velimirov *et al.* 1977, Andrews & Hutchings 1980, Field *et al.*1980, Griffiths 1981, Jarman & Carter 1981, Newell 1981, Carter 1982, Wulff & Field 1983, Shannon 1985, Chapman & Shannon 1985, Shannon & Pillar 1986 and Shannon *et al.* 1990. Given that the productivity within Saldanha Bay is largely driven by the interaction of oceanic and environmental conditions and events outside and inside Saldanha Bay, it was considered vital to provide a brief overview of these conditions to ensure clarity in later chapters.

Cycles in synoptic weather induce pulses of upwelling and downwelling on the west coast (Jury *et al.* 1990). Upwelled water is cold and nutrient rich (Jarman & Carter 1981) and enters the Bay under tidal or wind forcing conditions (Monteiro & Brundrit 1990, Weeks *et al.* 1991a). An influx of warm water results in low chlorophyll *a* concentrations due to low nutrient levels in the warm water (Monteiro & Brundrit 1990). However, red tides may be introduced under the same conditions resulting in peaks of chlorophyll *a* (Pitcher, Sea Fisheries Research Institute pers.comm.) The warm water may sit above the colder water, unless mixed by wind, and may have a lower residence time than the colder bottom water (Monteiro & Brundrit 1990). It is likely that wind and tidally driven bay scale cycles take place adding to the complexity of the system.

This chapter is intended only to provide a brief overview of the oceanographic and environmental conditions of the water body in which the mussels are cultured, with emphasis on chlorophyll *a*, particulate organic matter, temperature and dissolved oxygen. As this system is so complex it is beyond the scope of this study to enter into the finer details of the oceanographic functioning of the Bay.

METHODS

The methods used to estimate chlorophyll *a* and particulate organic matter (POM) concentrations were those of Parsons, Maita and Lalli (1984).

A navigational buoy in the centre of Small Bay was selected as a monitoring site from which water samples were collected once a day from July 1993 to December 1994. Water samples of two litres each were collected simultaneously using a Niskin Bottle from 2m, 6m and 10m depth on a daily basis. Each sample was fractionated into three sub-samples. They were filtered using Whatman GFF filters. This filter retains particles above 2μm in size. One sample of 250ml was filtered for total chlorophyll *a*. Another sample of 250ml was pre-filtered through a 10μm excluder and filtered to establish the portion of chlorophyll *a* and phaeopigments between 2μm and 10μm. A sample of 1l was filtered for P.O.M.. After filtration the filter papers were stored in a light free container at -25^{0}C.

The filtered chlorophyll *a* sample was homogenized and placed in a centrifuge tube with 8ml of 90% acetone solution and allowed to stand for 12 hours in a dark refrigerator. The tubes were then centrifuged for 10 - 15 minutes at 5000 r.p.m.. The supernatant was then placed in a calibrated fluorometer. Once the fluorescence reading was recorded, two drops of a 10% HCl solution were added to establish the phaeopigment proportion of the sample.

The chlorophyll *a* content was then calculated according to the equation:

mg chlorophyll *a* / m^3 = F_D x (R_b - R_a) x v/V

Where R_a = the fluorometer reading before acidification
R_b = the fluorometer reading after acidification.
F_D = is a factor for the door setting
v = the volume of acetone extract in ml
V = the volume of sea water in litres.

Phaeopigments were determined as follows:

mg phaeopigment / m^3 = F^D x ((2.2 x R^a)- R^b) x v/V

The P.O.M. filters were dried at 90°C for 12 hours, weighed and then ashed at 495°C for three hours and then weighed again. The difference in weight provides the amount of P.O.M. in one litre of water.

Total seston was established during one experimental period in February 1995. GFF filter papers were dried at 90°C for 12 hours and weighed. Then one litre of water, collected from 2m depth near the rafts, was filtered through the filter paper. The paper was dried for 12 hours at 90°C, weighed, ashed at 450°C for 3 hours and re-weighed. This provides the total seston, the organic component and the inorganic component.

The percent, by mass, of chlorophyll *a* related organic matter in the seston was derived by multiplying the chlorophyll *a* levels by 34.8 (after Cushing 1957).

Temperature measurements were recorded by a thermistor chain placed on the monitoring buoy and serviced by EMATEK (C.S.I.R.). Thermistors were placed every 1m down the chain to a depth of 10m. Data were logged every 30 minutes from November 1993 to January 1995 excluding periodic logger malfunctions.

Dissolved oxygen and salinity data were also provided by EMATEK (C.S.I.R.) using a Y.S.I. at 2m below the surface and another at 2m above the Bay floor (10m), at the monitoring station.

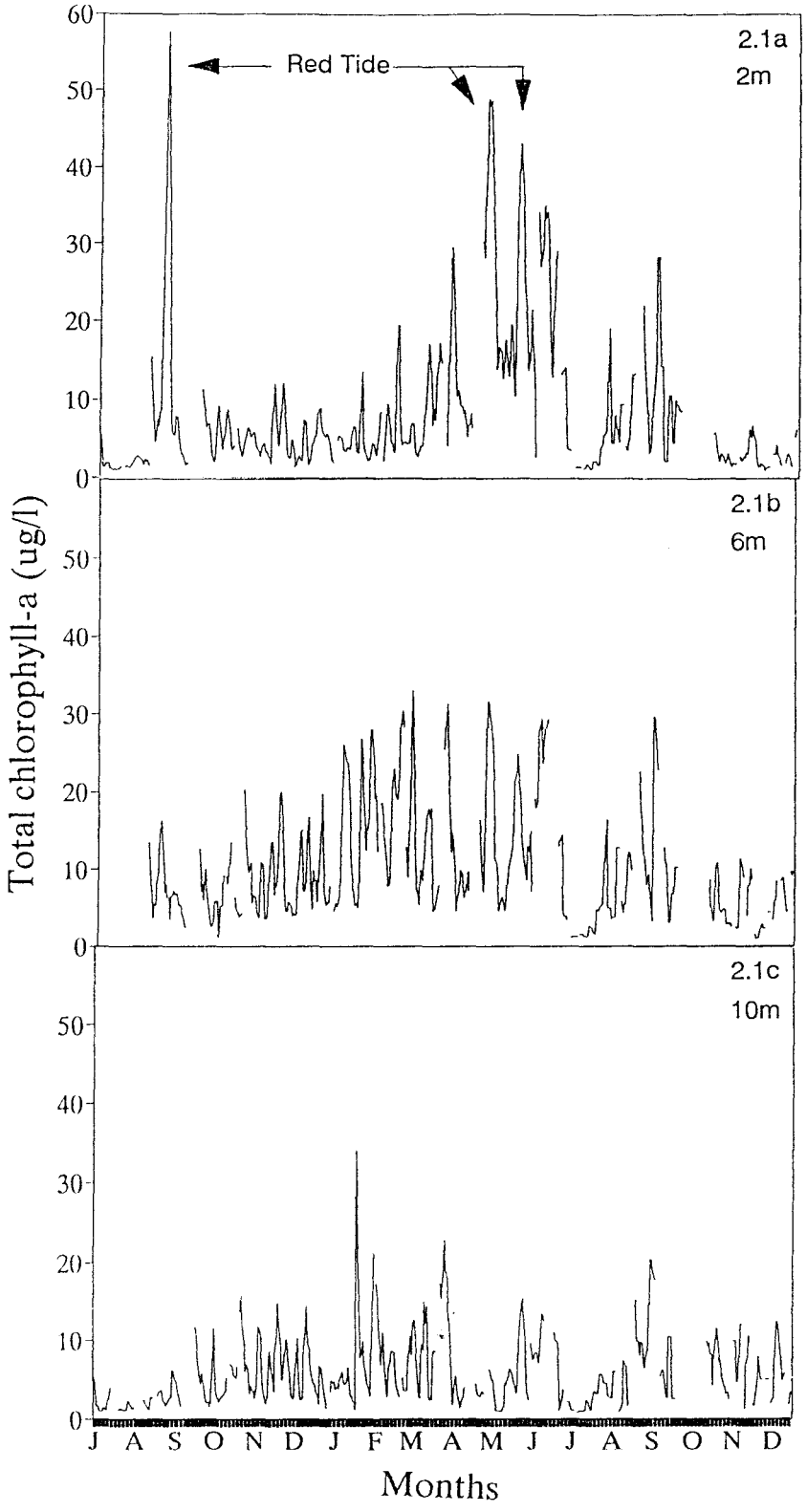
RESULTS

The chlorophyll *a* levels fluctuated daily and seasonally. Figures 2.1a, 2.1b and 2.1c show the daily fluctuations of the total chlorophyll *a* levels at 2m, 6m and 10m. Table 2.1 shows the means of the chlorophyll *a* levels. The mean chlorophyll *a* levels at 10m were lower than at 2m or 6m. The highest values were found in the late summer and early winter. Peaks of up to 58μg/l were recorded in surface waters under red tide conditions. The chlorophyll *a* levels of phytoplankton between 2μm and 10μm are lowest at 10m (Table 2.1). The levels at 6m, were marginally higher than at 2m, as is the case with the total chlorophyll *a*. Chlorophyll *a* derived from phytoplankton of between 2μm and 10μm in size represents between 13% and 18% of the total chlorophyll *a*.

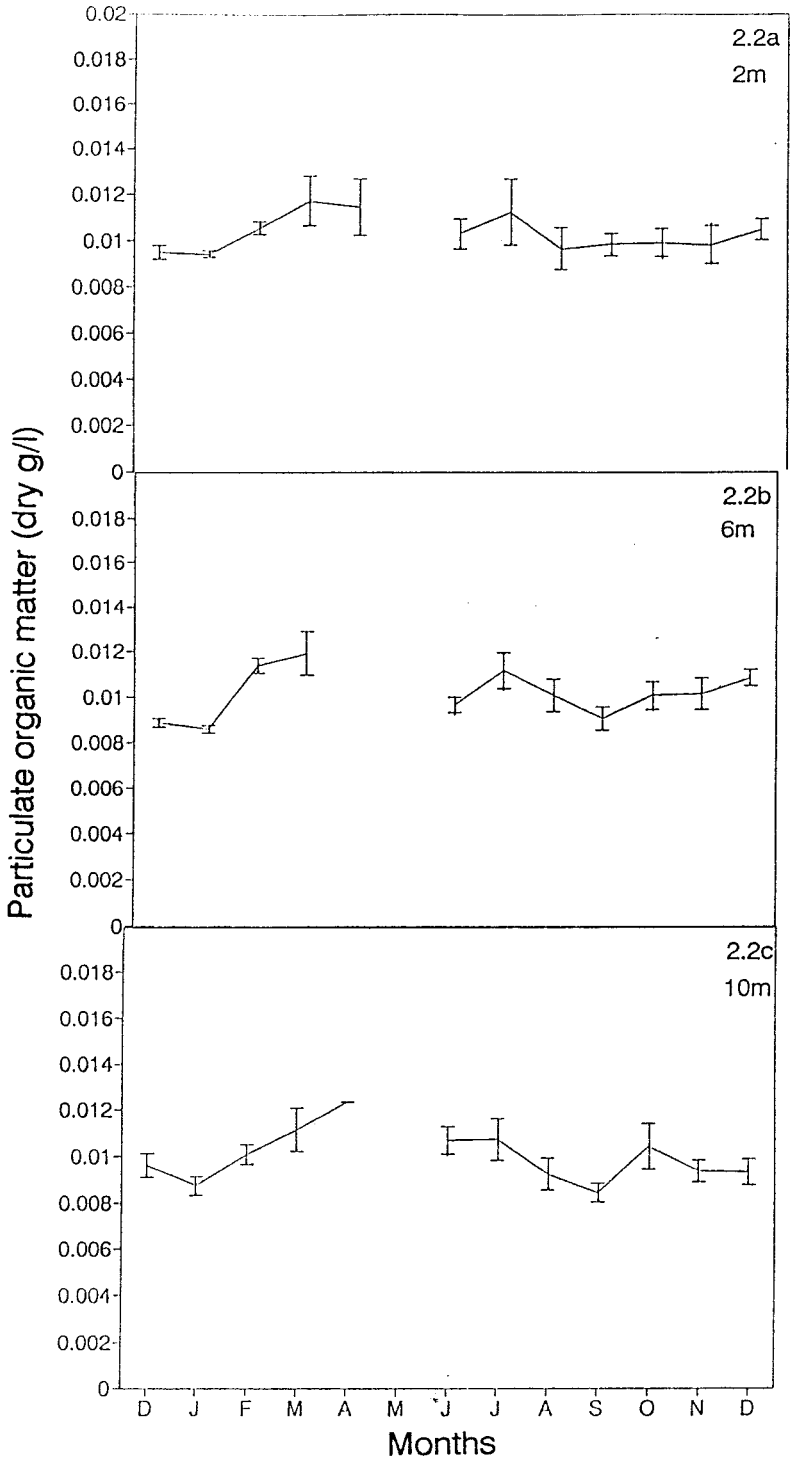
Table 2.1 Mean chlorophyll *a* values from December 1993 to December 1994 taken at 2m, 6m and 10m at the monitoring station. The values are in μg/l. <10μm refers to phytoplankton between 2μm and 10μm in size.

	2m (x ± SD)	6m (x ± SD)	10m (x ± SD)
Total Chlorophyll *a*	9.02 (10.83)	10.83 (8.43)	6.00 (5.25)
Sampling days	370	314	306
<10μm Chlorophyll *a*	1.67 (3.47)	1.85 (1.75)	0.81 (1.14)
Sampling days	351	294	306

The particulate organic matter (P.O.M.) from 2m, 6m and 10m taken at the monitoring buoy is shown in Figures 2.2a, 2.2b & 2.2c. The variation in P.O.M. was not significant and no distinct seasonal trends were apparent. There was also little variation in P.O.M. with depth (Table 2.2).



Figures 2.1a, 2.1b, & 2.1c. Chlorophyll–a from 2m, 6m and 10m depth at the monitoring buoy from July 1993 to December 1994.



Figures 2.2a, 2.2b, & 2.2c. Particulate Organic Matter (P.O.M.) at 2m 6m and 10m atthe monitoring buoy from December 1993 to December 1994. (Vertical bars = Standard deviation)

Table 2.2 Particulate organic matter (P.O.M.) values from July 1993 to December 1994 taken at 2m, 6m and 10m at the monitoring station. The values are in mg/l.

	2m (x ± SD)	6m (x ± SD)	10m (x ± SD)
P.O.M. values	10,27 (1,86)	10,22 (1,64)	9,88 (1,64)
n	109	94	96

The mean percent of P.O.M. in the seston was 25.08% (Table 2.3). The mean percent of chlorophyll *a*, by mass, of the P.O.M. was 5.89%. The maximum values never exceeded 10%.

Table 2.3 Total seston in the water body at the monitoring station during February 1995. Percent dry organic matter and percent chlorophyll *a* in dry organic matter, by mass, in seston. Std dev = Standard deviation. n = 11.

	Mean	Std. Dev.	Minimum	Maximum
Seston, mg/l	31.10	7.10	20.00	47.00
% organic matter in seston	25.08	6.17	20.31	69.49
% chlorophyll *a* in organic matter	5.89	2.18	2.85	9.75

Water temperature was found to vary seasonally and with depth (Figure 2.3) and although not shown, it also varies at the event and synoptic scale. The mean summer water temperature varied by up to 6°C between 1m and 10m. As shown in Figure 2.3, the water was stratified during the summer period. The mean winter temperature varied by less than 1°C.

The mean dissolved oxygen levels in the surface water of the Bay did not drop to levels that would stress mussels (Figure 2.4). Mean oxygen levels at 10m however, showed low levels in late summer.

Mean salinity levels varied from 33.15ppt to 34.97ppt with depth and over all seasons.

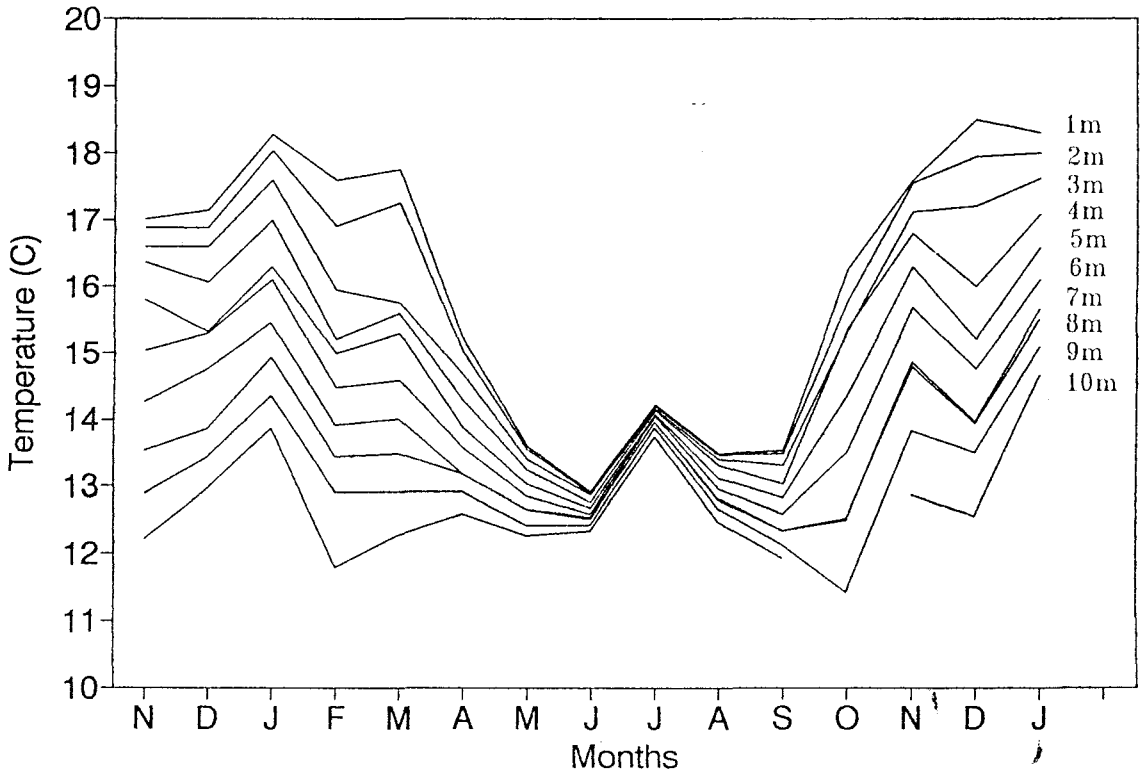


Figure 2.3. Monthly means of water temperature at the monitoring bouy at 1m to 10m depth from November 1993 to January 1995. (C.S.I.R. thermistor chain).

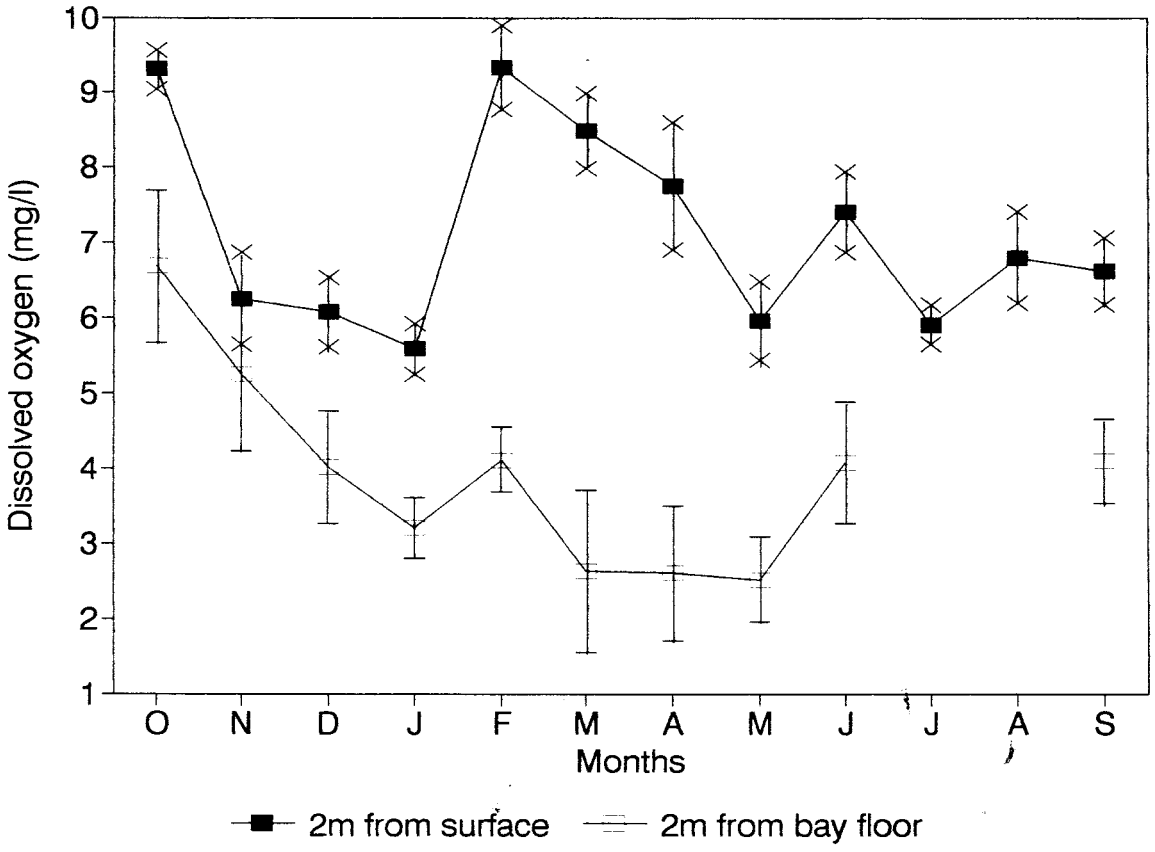


Figure 2.4. The monthly mean dissolved oxygen 2m below the surface and 2m above the bay floor at the monitoring buoy (depth at buoy = 12m). (C.S.I.R. Y.S.I. data). (Vertical bars = Standard variation).

DISCUSSION

Chlorophyll *a* and P.O.M. concentrations in Saldanha Bay have previously been described by Monteiro and Brundrit (1990). In that study, samples were taken periodically over five years in Small and Big Bay. They found that concentrations of chlorophyll *a* ranged from 5μg.l^{-1} to 35μg.l^{-1}, although the average concentration was found to range from 5μg.l^{-1} to 15μg.l^{-1}. This was similar to the findings of this study. Monteiro & Brundrit (1990) found that Big Bay and Small Bay have very similar patterns in peak concentrations of chlorophyll *a*. Chlorophyll *a* peaks in September and during the period March to June were associated with red tides. In most instances the ciliate involved was the non-toxic *Mesodinium rubrum* and the dinoflagellate *Ceratium furca*. On some occasions the non-toxic dinoflagellate *Gymnodinium splendens* and the toxic dinoflagellates, *Alexandruim catenella* and *Dinophysis acuminata*, penetrated the mouth of the Bay. However they seldom penetrated far into the Bay in significant densities.

The relationship between the temperature of the water, the nitrate concentrations and timing of upwelling events are important factors affecting the chlorophyll *a* concentrations (Monteiro & Brundrit 1990). To a certain degree this is determined by wind direction and speed and the residence time of the water in the Bay (Shannon & Stander 1977). The high chlorophyll *a* levels in Saldanha Bay reflect the bay's association with the rich upwelling system on the west coast (see Shannon *et al.* 1990). Although the chlorophyll *a* component of the POM is relatively high compared to other systems, the very low percent of chlorophyll *a*, by mass, in the organic component of the seston reflects a high detrital load. This is also shown in the low seasonal variation in the P.O.M.. However, there is a seasonal variation in the chlorophyll *a* levels indicating that the chlorophyll *a* does not greatly affect P.O.M. levels.

Water temperature showed a distinct summer stratification with a well defined thermocline between 2m and 6m. Diving observations at the thermocline showed that the mixing of the nutrient rich cold water with the warmer nutrient poor surface water results in a zone of production. However, C^{14} estimates of

production in this region show that this is not common as a result of reduced light penetration (Pitcher, Sea Fisheries Research Institute, pers.comm.)

Dissolved oxygen levels show variation between 2m below the surface and 2m above the Bay floor. However, there was no distinct seasonal pattern except for a tendency of reduced variation between the two levels in the winter months. From these results it is suggested that the dissolved oxygen levels reflect a combination of internal Bay cycling and external upwelling events.

CHAPTER 3

WATER CURRENTS IN AND AROUND THE MUSSEL RAFTS.

INTRODUCTION

Successful mussel farming requires, among other things, an understanding of the hydrodynamic regimes of the water body in and around the farm, and the outside forces governing them. Saldanha Bay can be divided into three discrete areas: Small Bay; Big bay and Langebaan Lagoon in the southern part of the Bay (Figure 1.2). Weeks *et al.* (1991a) reported that wind was the dominant factor determining the speed and direction of the surface water in Saldanha Bay. However, the southern end of Big Bay was also influenced by the tidal pulses of Langebaan lagoon. Weeks *et al* (1991a) report that summer stratification results in wind driven surface currents and tidally driven bottom layers. In winter the bay water was well mixed and tidal influences become more dominant under low wind conditions. However, under strong NNE winds during winter, wind forcing again becomes the dominant force (Weeks *et al.* 1991b). Typical current speeds in Small Bay and Big Bay range from 5 - 20cm/s (Shannon & Stander 1977, this study).

Except for short calm periods during spring and autumn the bay was subject to winds ranging from 5 to 45 knots with a high of 98 knots. Bilski (1995) found that winds over 10m/s dominated the tides over the whole of Saldanha Bay. Winds of 5-10m/s dominated tides except in the mouth of Small Bay and winds lighter than 5m/s dominated tides only in Small Bay. Introduction of upwelled water into the bay was controlled by wind generated surface currents, the mechanism of which is described by Monteiro and Brundrit (1990). The windfield and other forces also generated a "tensioning and relaxing" of the water in the bay (G. Brundrit, University of Cape Town, pers.comm).

The methods of determining current flow were established during late 1993 to mid 1994. The emphasis in this chapter is placed on the experimental period in August 1994 when the results display a variety of the general water current trends found in and around the mussel rafts in Saldanha Bay. Results from other periods are included where applicable.

The objective of this study was to determine the water current movement on a farm and raft scale in order to provide the necessary background for understanding food extraction studies, variable growth rates, fouling settlement and the influence of raft design. A comparison of ambient flow through the farm relative to the flow through the rafts with pre-harvest 60cm and 90cm spaced ropes was carried out. The flow pattern around and under a raft were also investigated.

METHODS

Water flow was assessed through the mussel farm, which had a raft density of approximately one raft per hectare of surface water. The rafts were either 11m by 11m or 11m by 22m in size. The depth of water at the farm was 10m at its shallowest point close to the causeway and 18m at its deepest point near the channel.

Farm scale

Standard tetrahedral drogues, developed by Boyd (Sea Fisheries Research Institute, see Figure 3.1) and also used by Bikski (1995) were placed in and around the mussel farm at depths ranging from 2m to 8m. The distance and direction moved by the drogue was measured periodically with a hand held range finder and compass.

A Valeport water current metre with 1cm/s sensitivity giving water speed and direction of flow was used when assessing the ambient water current adjacent to

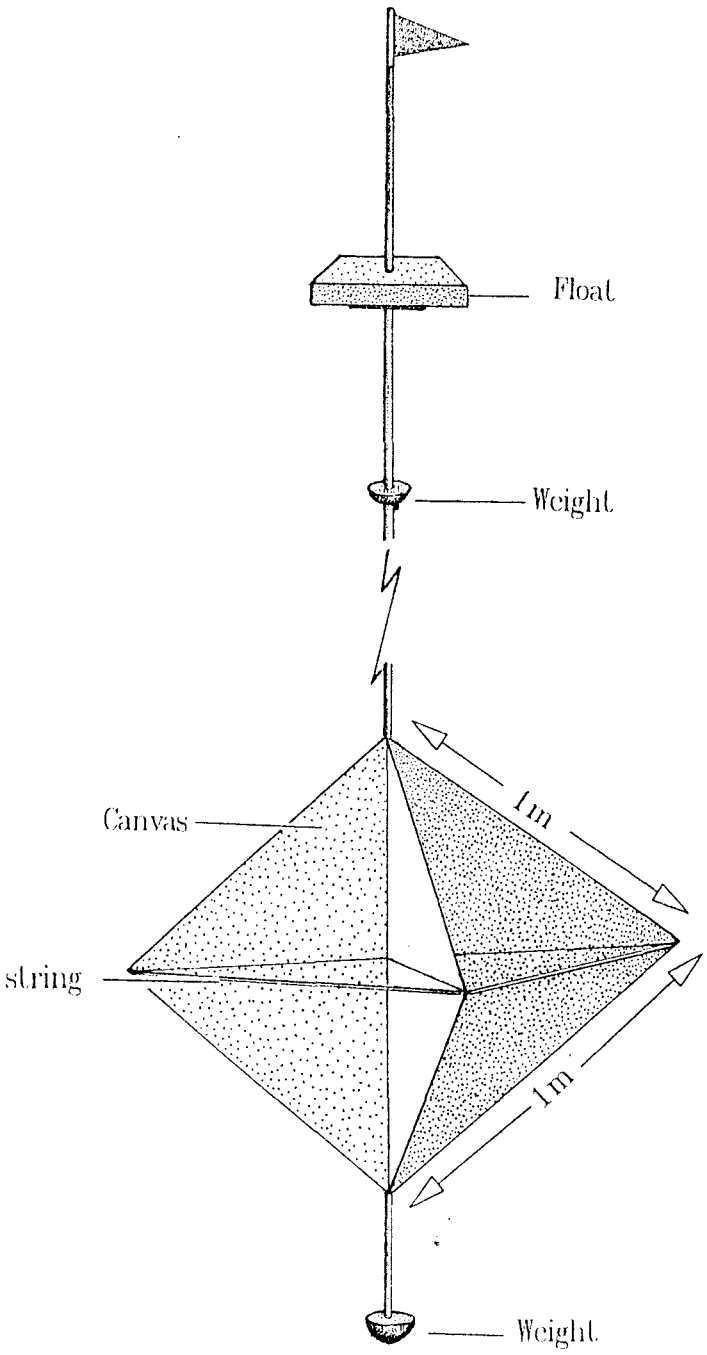


Figure 3.1. The drogue used to establish water currents around the rafts.

the raft. The current meter was set up to indicate the average current speed and direction every 5 minutes.

Raft scale

The raft current was assessed by suspending a slightly negatively buoyant, 100ml, laterally compressed bottle in between the ropes of the raft, with a fluorescent nylon monofilament line. The direction was determined with a compass and the distance measured manually. A new deployment was made every ten minutes. The line from the bottle to the float was observed continuously and immediately freed if it snagged the mussels. The ambient water movement around the raft was tracked using drogues, either those used in the raft or the tetrahedral, and/or by way of a current meter placed in the incoming current. Water under the raft was tracked using a diver and dye. The dye was released, observed and timed relative to the water speed and direction between the rafts.

Water current speed relative to rope spacing was tested using an ANOVA. However, due to unequal variance in the data set, tests for significance could not be carried out.

RESULTS

Water movement through the farm at a depth of 2m and 8m showed differences in both magnitude and direction. The water at 2m generally flowed faster than at 8m (Figure 3.2). Figures 3.3, 3.4 and 3.5 compare ambient water flow at 2m with the simultaneous water flow through rafts at 2m. Figures 3.3, 3.4 and 3.5 show water flow direction and magnitude at 5 minute intervals outside the raft and every 10 minutes within the rafts. Figure 3.3 illustrates the change from a northerly flow to a southerly flow. However, after 3hrs 40mins the flow alternated north and south every 20mins. Figure 3.4 initially shows an hourly fluctuation which becomes predominantly southerly. Ambient water flow in Figure 3.5 also shows an extended period of southerly flow, i.e. cross shelf flow.

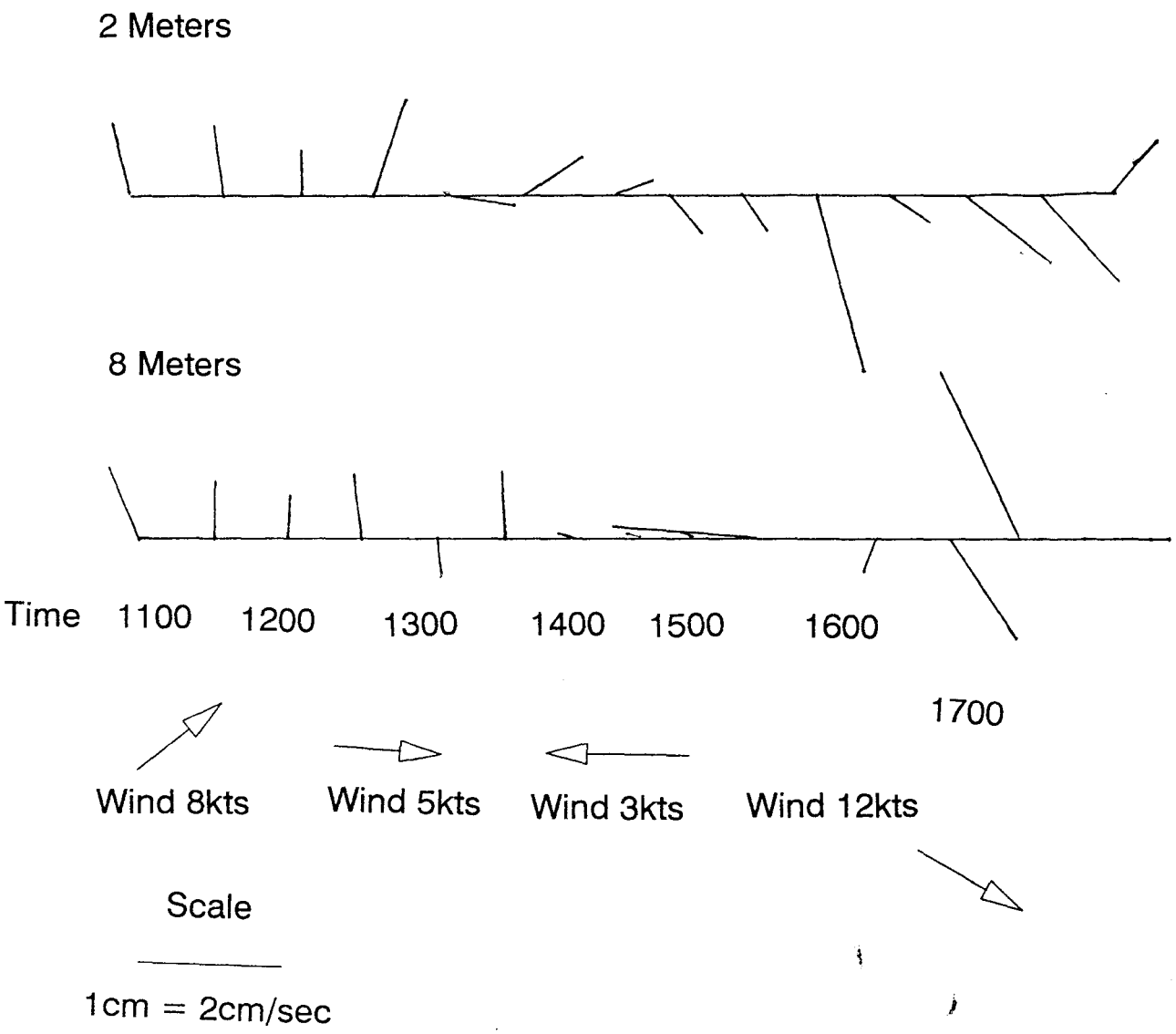


Figure 3.2. Water currents in the farm at 2m and 8m.

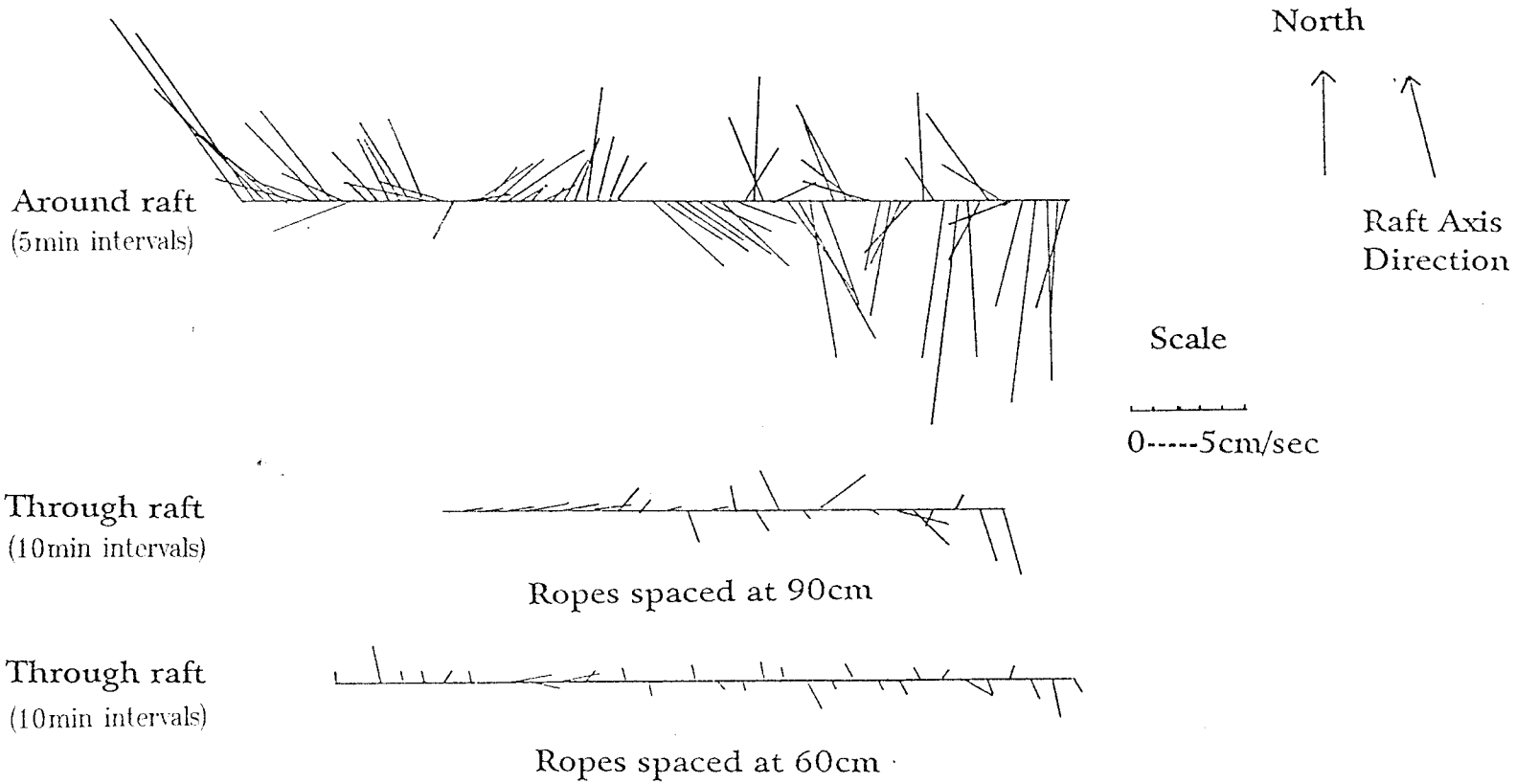


Figure 3.3. The speed and direction of water currents taken simultaneously around the rafts and through rafts with 90cm rope spacing and 60cm rope spacing during August 1994.

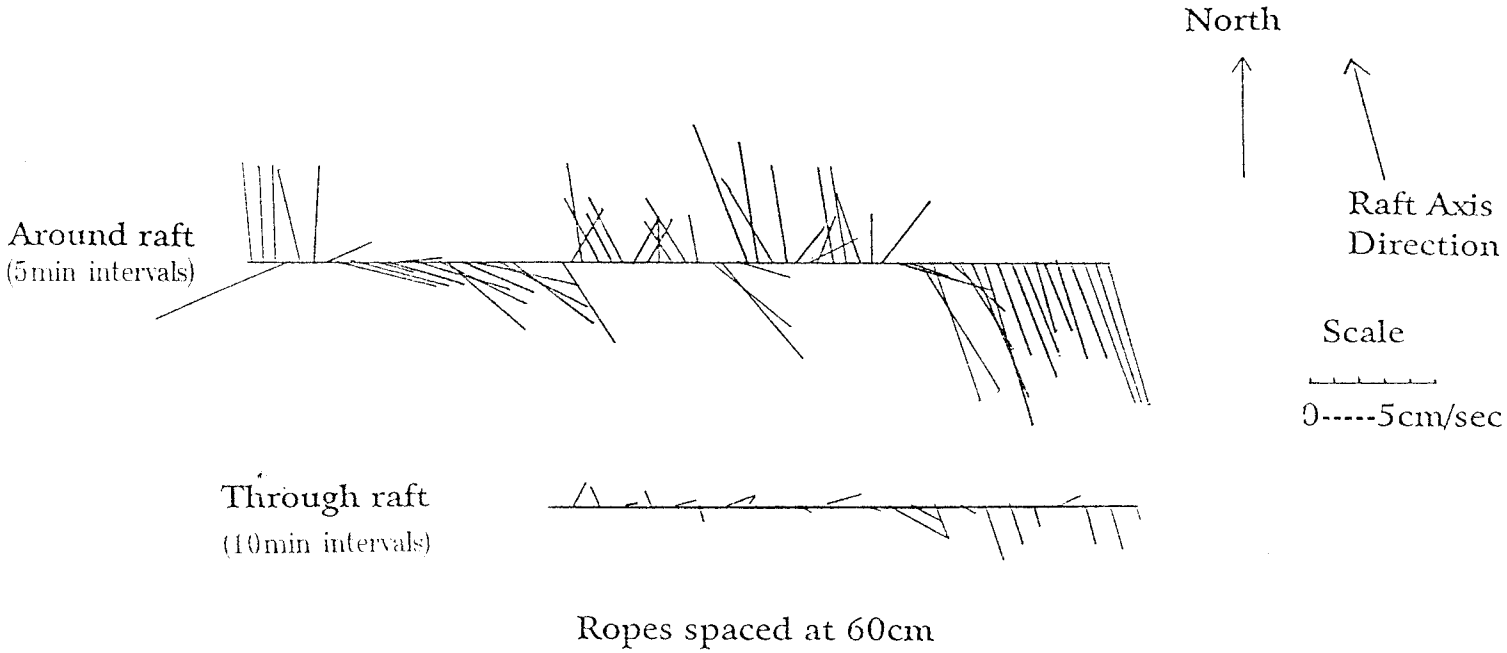


Figure 3.4. The speed and direction of water currents taken simultaneously around the rafts and through a raft with 60cm spaced ropes in August 1994.

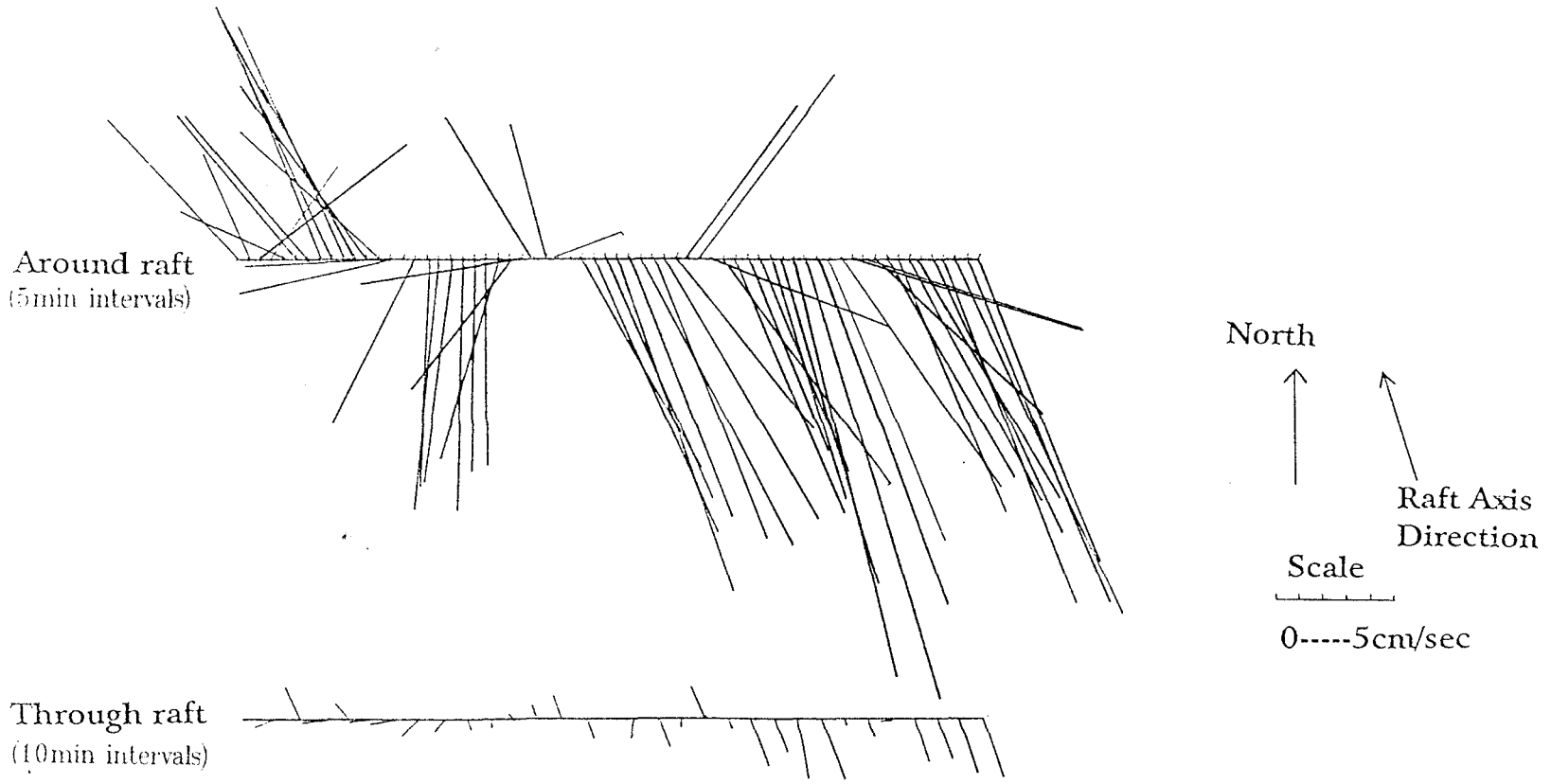


Figure 3.5. The speed and direction of water currents taken simultaneously around the rafts and through a raft with ropes spaced at 60cm on the 9 August 1994.

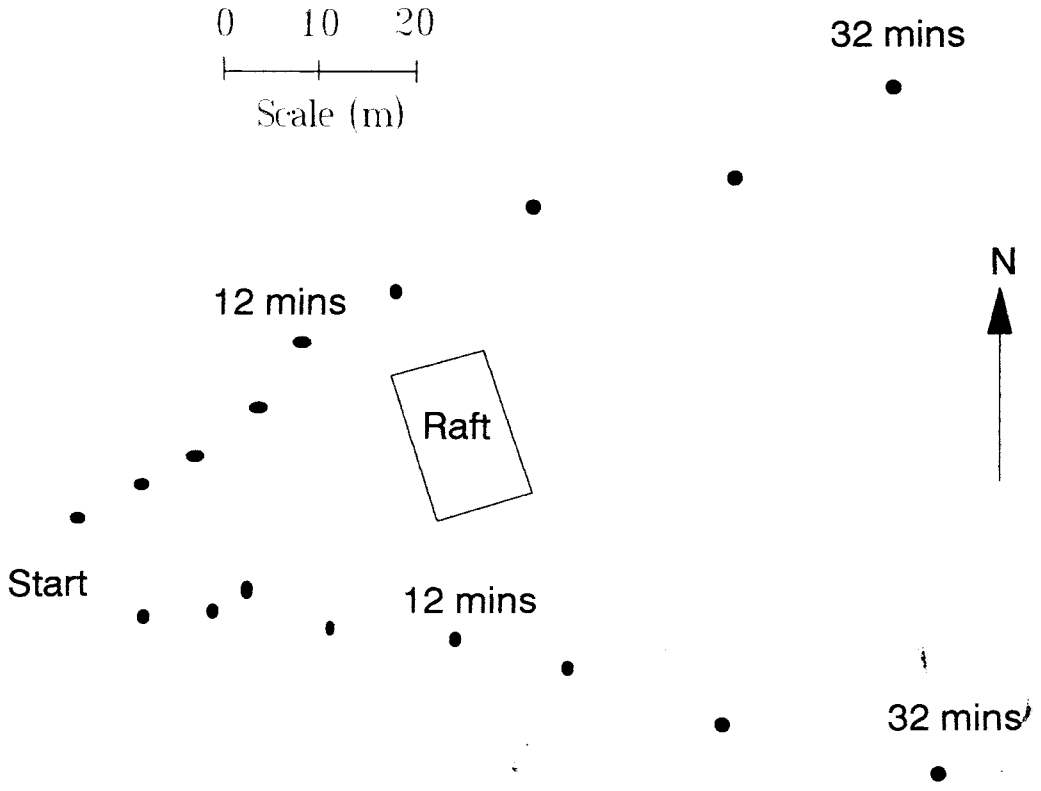


Figure 3.6. Spatial separation of 2m drogues around a mussel raft with time.

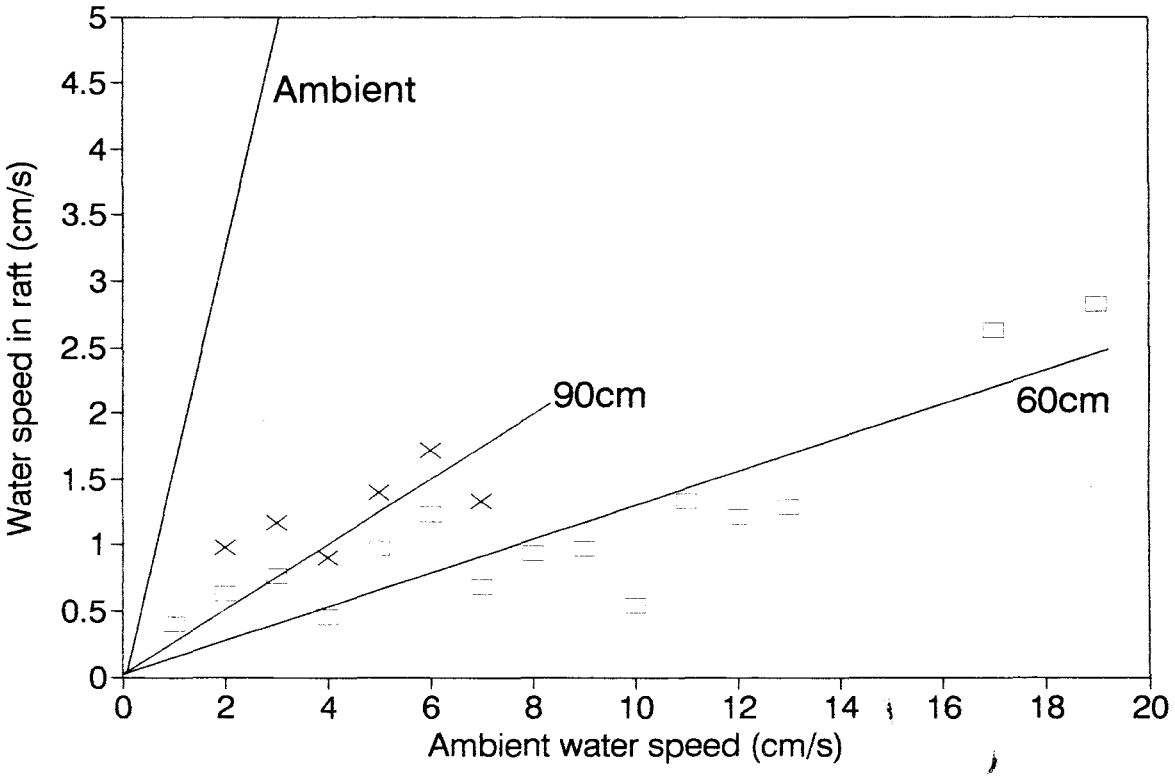


Figure 3.7. The mean ambient water flow and mean water flow through mussel rafts with 60cm (□) and 90cm (×) rope spacings.
(Standard deviations omitted for clarity.)

Two trials measuring water flow under the rafts were undertaken. However, they did not to be differ from the ambient flow. An earlier experiment had shown clearly that the water flow on approaching a raft deviated around it (Figure 3.6). Water flow through a raft was thus often not parallel to the ambient flow in the same time period. Generally, the flow in the raft was perpendicular to the longitudinal axis of the raft or parallel to the raft axis even if the ambient flow was at an angle to these axes. Water flow rate through the raft clearly increased if the ambient flow was along these axes. However, this could not be quantified due to the interference of mussel ropes with drifters. The flow rate increases in the raft if the rope spacing was increased from 60cm to 90cm (Table 3.1 & Figure 3.7).

Table 3.1 Water flow in the farm and the simultaneous water flow through rafts with 60cm and 90cm rope spacing. Percent attenuation represents the reduction of flow rate in the raft. Ropes on the raft were six months old.

Rope spacing	Mean ambient water flow (Std Dev)	Mean internal water flow (Std Dev)	Percent attenuation
60cm	7.40 (3.26)	0.91 (0.60)	91.04
n	140	58	
90cm	3.85 (1.51)	1.09 (0.69)	71.79
n	139	49	

DISCUSSION

The ambient water flow direction and speed, as shown in Figure 3.2, varied with depth. Sampling at 30 minute intervals, however, did not highlight the high degree of water speed and direction fluctuation as seen in Figures 3.3, 3.4 and 3.5. Therefore although the earlier experiments were useful, a better indication of short term variability was derived from the latter experiments when sampling was done at greater frequency.

The experiments with the 90cm rope spacing shows a bias toward slow currents compared to the 60cm rope spaced experiments as no fast ambient water flow was experienced when rafts with 90cm rope spacing were being tested. However, the trends of increased flow through the 90cm spaced raft still follow (Figure 3.7).

An increase of the ambient current speed did not have a proportional increase in internal flow rate. Theoretically the attenuation would increase to a maximum.

The ambient water direction varied according to wind direction and strength, the tidal influences and the Bay resonance. This had a profound influence on water current speed through the mussel farm and rafts. Waite (1989), as reported in Gibbs *et al.* (1991) estimated that a farm attenuated water flow by approximately 70%. The farm scale attenuation in this study was uncertain as the water flow never remained constant in magnitude or direction long enough to determine it with confidence.

Although water was seen to diverge around mussel rafts (Figure 3.6), with a boundary layer at the periphery of the raft, the water that penetrated the raft flowed down the channels between the ropes. Younger rafts have less resistance to the water as the ropes are only 15cm in diameter. However 5 to 7 month old seed ropes, on which most of the water current studies were done, may have diameters of 45cm to 55cm, therefore on a 60cm ropes spaced raft the water channels between ropes are reduced to 5cm. On the other hand a 90cm rope spaced raft with a 55cm diameter rope would have a water channel of 35cm between ropes which would allow for better water flow. It was found that if the water current approaches the rafts perpendicular to the edges, the water flow through the raft was enhanced. The flow rate between the 60cm spaced ropes and the 90cm spaced ropes, under these circumstances, was substantially improved. The mussel rafts with 60cm rope spacing attenuated the water flow within the raft by 91%, whereas the rafts with 90cm rope spacing attenuated the water flow by only 72%. However, if the water current comes from an angle to the perpendicular, the water attenuation within the raft was greater. The settlement of fouling organisms would probably add to the attenuation. Rapid directional changes of the ambient flow also resulted in a lag response of the water flow in the raft. This resulted in little movement of the water in the raft.

Water flow under the raft showed no attenuation when compared to the ambient water flow. This was contrary to Gibbs *et al.* (1991) who found an increase in the water flow immediately under the raft, presumably caused by water being forced

around the raft. Under such conditions growth should be increased around the periphery of the raft, however, this was not the case (Chapter 5).

CONCLUSION

Water flow appeared to be influenced by the wind, the tidal phases, the Bay resonance and the degree of farm exposure (pers.obs.). Water current speed in the mussel farm ranges from 0m/s to 20cm/s (Figure 3.5). The orientation of mussel rafts in relation to the water current direction was an important factor regulating water flow within the raft. This effect was enhanced by increased rope spacing and reduced by rope age and fouling. Due to the large variance in current speeds the difference between the water flow in a 60cm rope spaced raft and at 90cm rope spacing could not be tested for significance. The trends, however, suggest that a raft with 90cm rope spacing has a greater through flow of water than a raft with 60cm rope spacing. Although the results shown in Figure 3.7 are in linear form, the internal water flow will ultimately reach a maximum level (above the range of this graph) and level out. Water flow was not markedly retarded under the mussel rafts on a farm scale. The direction of water flow showed a large fluctuation, seldom flowing in one direction for more than two hours at the study site, therefore if simple wind/tide current models are to be used they may be inadequate for modelling the dynamics of the study farm.

CHAPTER 4
FEEDING AND FOOD EXTRACTION

INTRODUCTION

The interaction between the hydrodynamics of bivalves and the hydromechanical principles of food extraction (in relation to the availability and utilisation of food particles) by mussels, is complex and a continuing source of debate (Gosling 1992). An understanding of these interactions is, however, necessary for the maintenance of sustainable mussel farming.

Feeding and food utilisation are regulated and influenced by many factors. These include: mussel density (Hughes & Griffiths 1988), mussel size (Jørgensen 1976), the degree of interspecific competition (Jørgensen 1976), temperature (Schulte 1975, Jørgensen 1976, van Erkom Schurink & Griffiths 1992), food concentration (Foster-Smith 1975, Bayne *et al.* 1987, Bayne *et al.* 1989, Riisgård 1991, Bayne *et al.* 1993), food composition (Strømgren & Cary 1984, Ward & Targett 1989, Fidelgo *et al.* 1994), salinity (Bøhle 1972, Almada-Villela 1984), light intensity (Strømgren 1976, Nielsen & Strømgren 1985), water circulation and speed (Walne 1972, van Erkom Schurink & Griffiths 1993) and silt loading (Theisen 1977, van Erkom Schurink & Griffiths 1993).

Mytilid bivalves obtain their food by trapping particles on the gill (ctenidia) filaments. This is achieved by ciliary pumping of water through the gills during respiration. Cilia also sort and transport food particles from the gill filaments to the mouth. The fact that the gill surface area exceeds that required for respiration alone, suggests that the gills are primarily adapted for feeding (Jones *et al.* 1992). Three types of cilia are used by *Mytilus edulis* during feeding. These are the frontal, latero-frontal and lateral cilia (Silvester & Sleigh 1984). There is a fourth type, which connects the gill filaments and maintains the distance between them, known as the inter-filamental ciliary junctions. These can be used to adjust the distance between the filaments (Jones *et al.* 1992). The gill filaments and the cilia effectively provide two sieves of equal surface area (Morton 1981), although the sieves have different "mesh" sizes (Vahl 1972). The first sieve collects particles over 5μm in size and the second collects particles between 2 and 5μm (Vahl

1972). Therefore, in theory, no particle below 2μm will be retained. However bacteria as small as 0.524μm can be retained, although not efficiently in *M.edulis* (Lucas *et al.* 1987).

It has been found that an increasing proportion of the particles between 2μm and 4μm, and 100% of the particles above 4μm, are retained by *M.edulis* (Lucas *et al.* 1987). The food is trapped in the latero-frontal cilia, transferred to the food grooves at the apex of the gill and moved towards the mouth by the frontal cilia on a mucous string (Silvester & Sleigh 1984). If food particles are too large, or in excess of the digestive ability, the labial palps select out the excess food into a mucus ribbon, called pseudofaeces, which is ejected through the exhalant vent (Thompson & Bayne 1974, Widdows *et al.* 1979, Smaal 1991). The labial palps also select out inorganic particles thereby increasing the organic content of the diet (Bayne *et al.* 1989).

Filtration and ingestion rates, gut passage time, assimilation and absorbtion of food particles are all interrelated. Mytilid mussels have a broad feeding spectrum (Jϕrgensen *et al.* 1981, Beninger *et al.* 1993) and appear to be able to modulate their biochemistry, physiology and morphology in response to environmental changes (Hawkins & Bayne 1992). This modulation enhances the organic component in the gut and maximises nutrient absorption. In view of the variable conditions within a mussel rope and raft, the ability of mussels to modulate and adapt to changing conditions is important. The position of a mussel on a rope or raft will dictate the type and concentrations of food available to that mussel. The density of the mussels also dictates the gape of the valves, affecting the physical aspects of filter feeding.

This study was undertaken to determine particle extraction on three scales: by a rope of mussels, a raft of mussels and by the farm as a whole. It was also decided to establish whether the availability of particles to the mussels on a rope and a raft as a whole has a direct effect on growth and production. The proportion of particles extracted by the mussels in relation to total availability was also determined. This provided the information upon which raft and farm stocking densities can be calculated.

METHODS

Food availability in Small Bay was established by sampling water at 1m, 6m and 10m depths at the monitoring buoy located in the centre of Small Bay. The water was analyzed for chlorophyll *a*, phaeopigments, particulate organic matter (P.O.M.) and inorganic matter (Chapter 2). The buoy was anchored in such a place that it was sufficiently close to the farm to give a reasonable indication of food supply, but far enough from the rafts to avoid their effects.

To establish the reduction of food density at a farm scale, two methods were used. The first method involved taking water samples, at a depth of 2m, at six stations 250m apart, starting 100m in front of the farm, down the longitudinal axis of the farm and ending approximately 100m out the other end of the farm, providing the spatial variability (line a, Figure 4.1). The second involved following drogues through the mussel farm and taking water samples periodically. In this way the same body of water was followed and sampled providing the temporal variability. However, this was unsuccessful as the variation in water current direction and magnitude (Chapter 3) generally resulted in the drogue not travelling through the entire farm (line b & c, Figure 4.1).

The mean chlorophyll *a* levels relative to the distance into the rafts were tested using an ANOVA. Tukey's test was used to establish the difference between means.

The extraction of particles on a raft scale was determined by collecting water samples from the incoming water before it reached the raft and at equidistant points (4 metres apart) along the median axis of the raft at a depth of 2m ($n = 51$ rafts, 171 samples). If possible, water samples were collected from rafts with 60cm and 90cm rope spacing simultaneously or taken from a range of rafts of different ages. Water samples were collected periodically from July 1993 to December 1994. The rafts had seed ropes ranging in age from one month to seven months.

The effects of distance into the rafts on mean chlorophyll *a* levels were tested

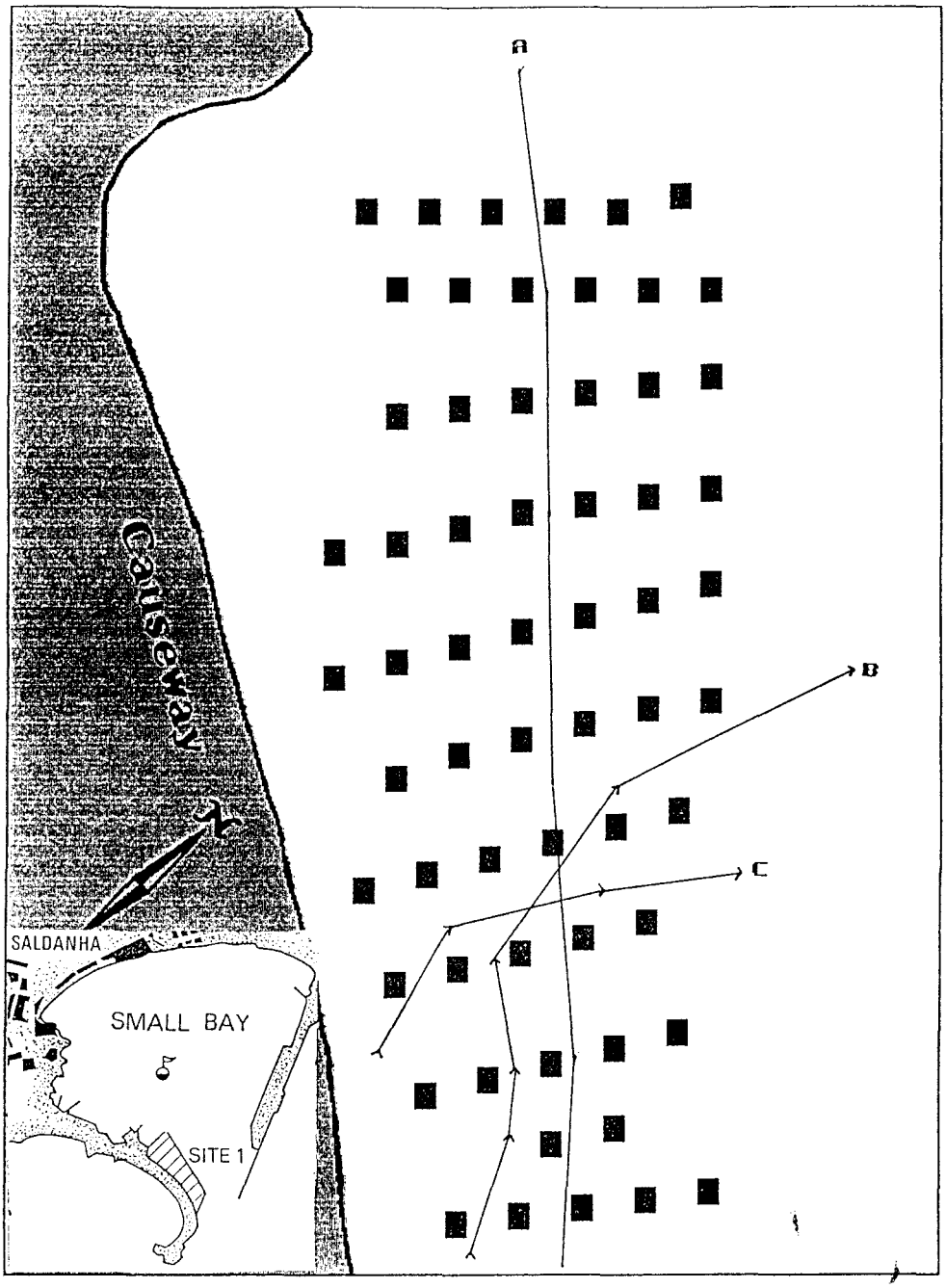


Figure 4.1. The transect through the mussel farm (line a) and drogue movement at 2m in the farm (line b & c).

using an ANOVA. Tukey's test was used to establish the difference between means.

Rope scale particle extraction was investigated on two rafts, with six month old seed ropes (n = 6). The extraction of particles by mussels on a rope scale was determined by pushing a 6mm diameter tube 10cm into the mussel mass on the rope, and drawing a 50ml sample of water. Another water sample was taken at the outer perimeter of the mussels, and then 5cm, 15cm, 25cm and 35cm away from the perimeter of the mussel mass of the rope. This was achieved by using an array of syringes set into a piece of wood. The syringe holding apparatus was taken down the rope by a diver and placed perpendicular to the incoming current next to the rope. The tube for taking the water sample inside the mussel mass was inserted, followed by a waiting period of a few minutes to allow conditions to re-establish themselves before the water samples were taken. The samples were taken from two ropes on the side of the raft facing the incoming current, two ropes in the raft centre and two ropes on the leeward side of the raft.

All the water samples were filtered, using Whatman GFF 2μm filters, to determine the total chlorophyll *a* and phaeopigment content of the water. In addition, some of the water samples were tested for total seston, inorganic fraction, P.O.M. fraction and volume and number of particles. The specific methods have been described in Chapter 2.

RESULTS

Farm Scale

The total seston concentration available to the mussel farm and the percentage of organic matter in the seston are shown in Table 4.1. Seston, POM and chlorophyll *a* on the farm scale were sampled eleven times. To establish the chlorophyll *a* portion of the POM by mass, the chlorophyll *a* values were multiplied by a factor of 34.8, which is the conversion factor of chlorophyll *a* to dry organic matter (Cushing 1957). The chlorophyll *a* portion of the organic matter, is shown as a percent of the total organic matter in the seston in Table 4.1.

Table 4.1 The total seston available to the mussel farm, the percentage by mass of dry organic matter in the seston and chlorophyll *a* organic biomass as a percent of the organic portion. Std. Dev. = Standard deviation. N = 11.

	Mean (Std dev)	Minimum	Maximum
Seston, g/l	0.0311 (0.0071)	0.0200	0.0470
% organic matter in seston	25.08 (6.17)	20.31	69.49
% Chlorophyll *a* in organic matter	5.89 (2.18)	2.85	9.75

Table 4.1 shows that the mean organic component of the seston is only 25.08%, by mass, and that non-chlorophyll *a* detritus represents over 90% of the organic component in the water. It is unknown how this ratio compares with other environments.

Only one experiment determining seston, POM, particle volume and chlorophyll *a* was carried out (Table 4.2). The mean seston level during this particular experiment was close to the pseudofaeces threshold. The pseudofaeces threshold is the point where the mussel filters more particles from the water than it can consume (see pseudofaeces section later in this chapter). There was a substantial variation in the particle volume and chlorophyll *a* in the water column as it passed through the mussel farm which may be due to natural heterogeneity in the plankton concentrations in the water. Inconsistent water currents may affect this through introduction of water that has not yet passed through the rafts (Chapter 3). A significant difference ($P<0.05$) between the chlorophyll *a* levels from the front of the farm to the back of the farm (Figure 4.2) was found.

Table 4.2 The extraction of seston, particle volume, P.O.M. and chlorophyll *a*, at 2m depth, in the water from the Bay passing through the mussel farm (58 rafts) taken during a period of constant water flow. Current direction within the farm was from South (S) to North (N). n = 1.

Direction/ Distance (m)	Seston g per litre	Particle Volume $\mu m \times 10^6$ / ml	P.O.M. g per litre	Chlorophyll *a* μg per litre
S 0	0.0412	5.834	0.00906	16.99
↓ 250	0.03808	3.57	0.00792	11.73
↓ 500	0.04102	5.497	0.00838	12.21
↓ 750	0.0324	3.65	0.00596	8.86
↓ 1000	0.036	4.264	0.00662	8.38
N 1250	0.0306	3.137	0.00520	8.62

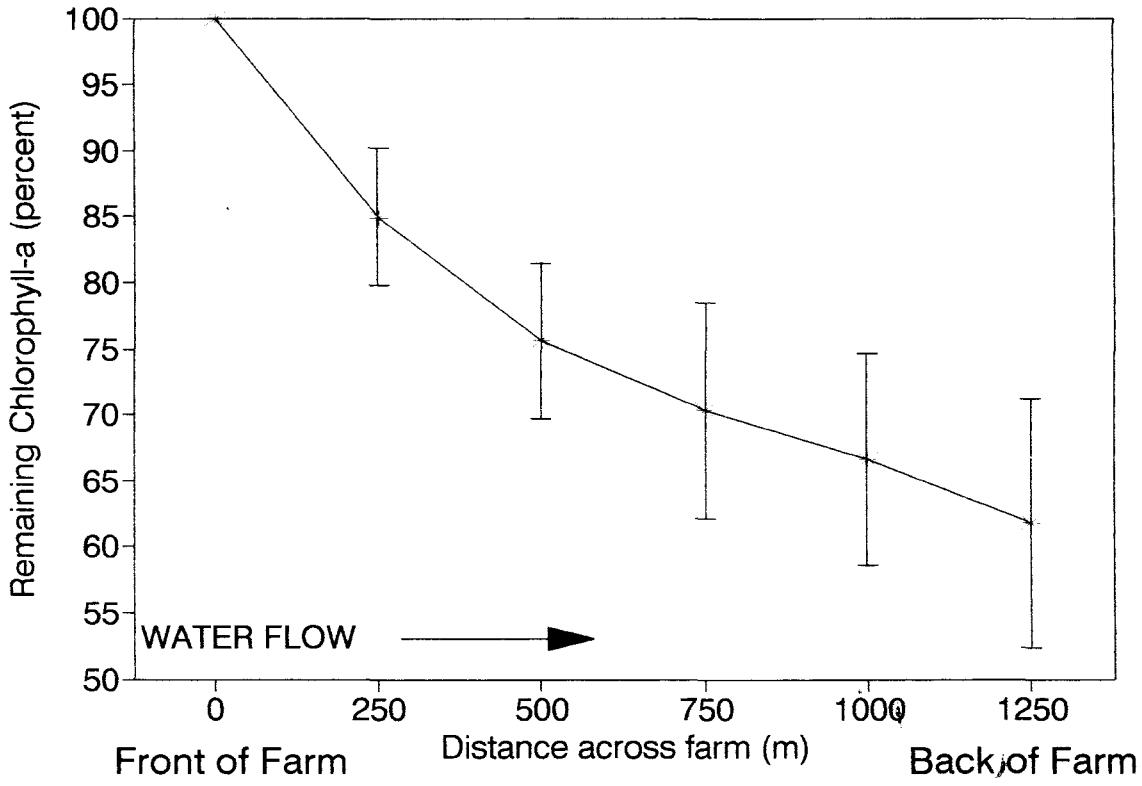


Figure 4.2. The percent chlorophyll–a extracted from the water passing through the mussel farm. (Vertical bars = Standard Deviation). n = 5 for each point.

Raft Scale

The rafts within the farm contain mussel ropes of various ages. The average age at any one time usually varies by between three and four months. The total seston, particulate organic matter (P.O.M.), phaeopigments and inorganic content of the water body, showed irregular extraction patterns through the rafts. However, the percentage of particle volume and total chlorophyll *a* extracted showed a significant positive correlation ($P<0.05$) $r = 0.88$ (Figure 4.3). Particle volume and chlorophyll *a* may increase at the leeward side of the raft due to, faecal matter, particles produced by the raft and matter introduced through water eddies. An increase in phaeopigment levels was also shown on the leeward side of the raft due to the faecal matter in the water.

Figure 4.4 shows a typical example of the particle volume and sizes extracted from the water, after travelling through a raft with six month old mussel ropes. Several experiments of this type showed similar results. The bars represent the total particulate matter prior to entering a mussel raft, the darkened area within the graph represents the particles extracted. Not all the particles between 4μm and 75μm in size were removed by the mussels, although particles above 75μm were extracted with almost 100% efficiency.

The quantity of chlorophyll *a* extracted by a raft, increases with the age of the mussel ropes suspended from it and with decreasing rope spacing (Table 4.3 & Figures 4.5 and 4.6a, 4.6b, 4.6c & 4.6d).

Seed ropes that had been in the water for less than two months extracted significantly less ($P<0.05$) chlorophyll-a than ropes that had spent between three and four months in the water. These in turn, extract significantly less ($P<0.05$) chlorophyll *a* than ropes that have been in the water for six months or longer (Figure 4.6a, 4.6b, 4.6c & 4.6d).

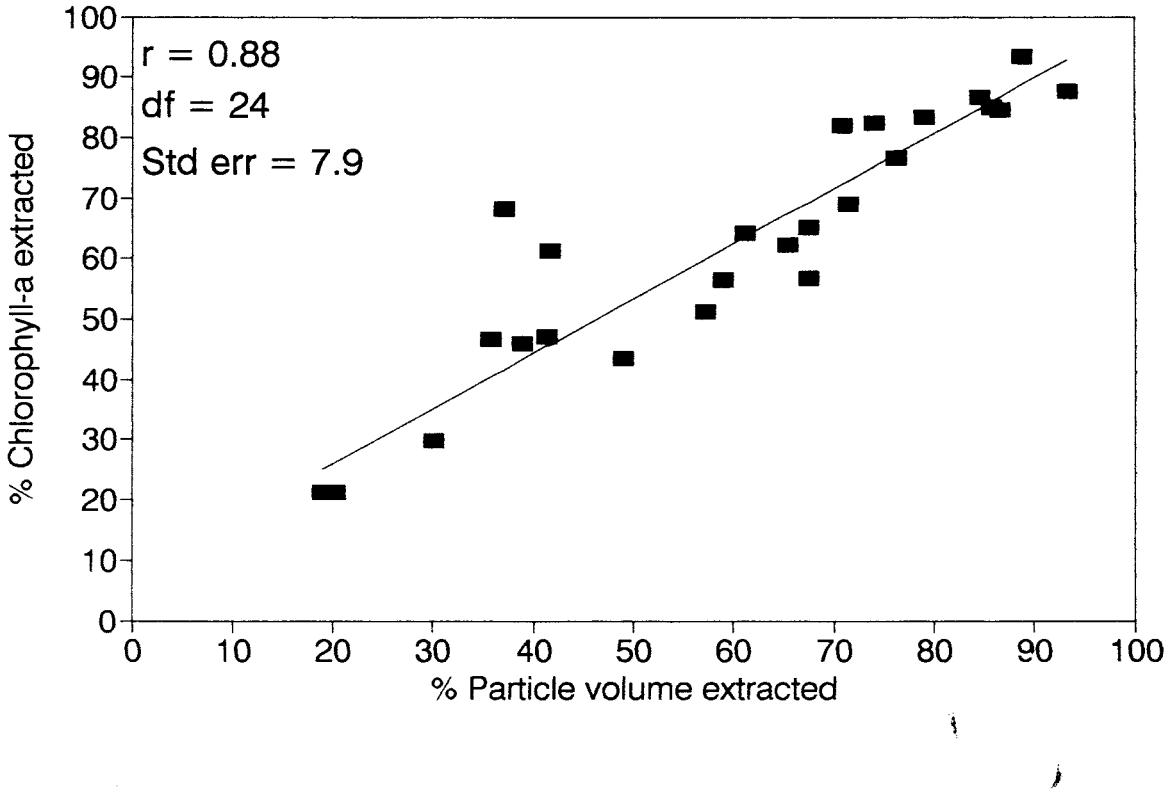


Figure 1.3. The relationship between the particle volume extracted and chlorophyll–a extracted from the water passing through mussel rafts.

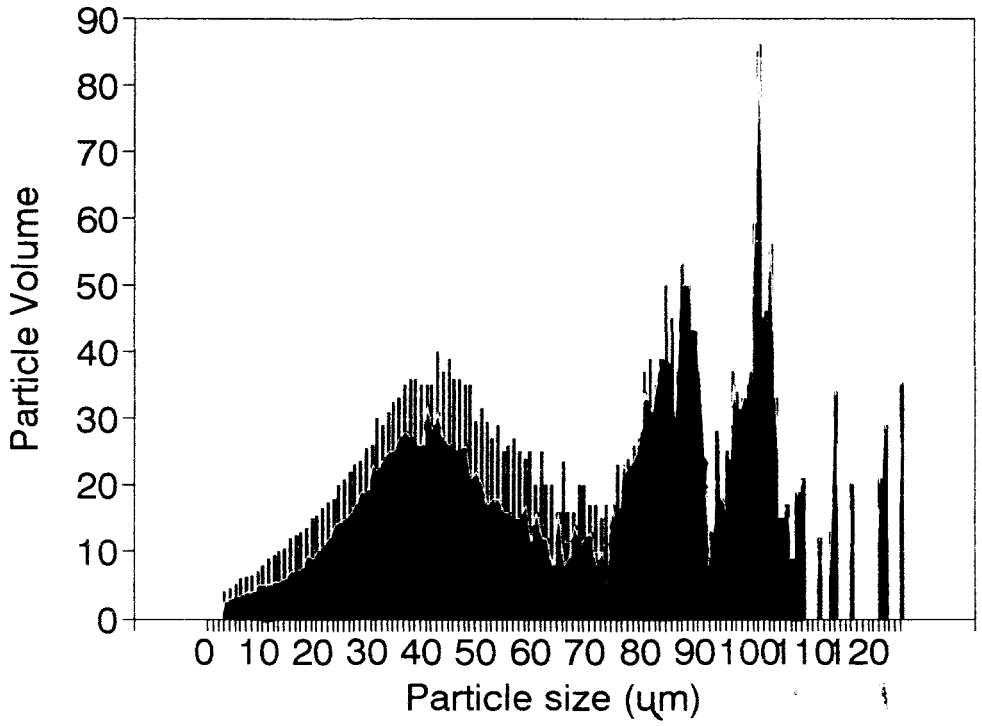


Figure 4.4. The size distribution of particles entering and leaving the raft. Particles below the white line have been extracted. n = 1.

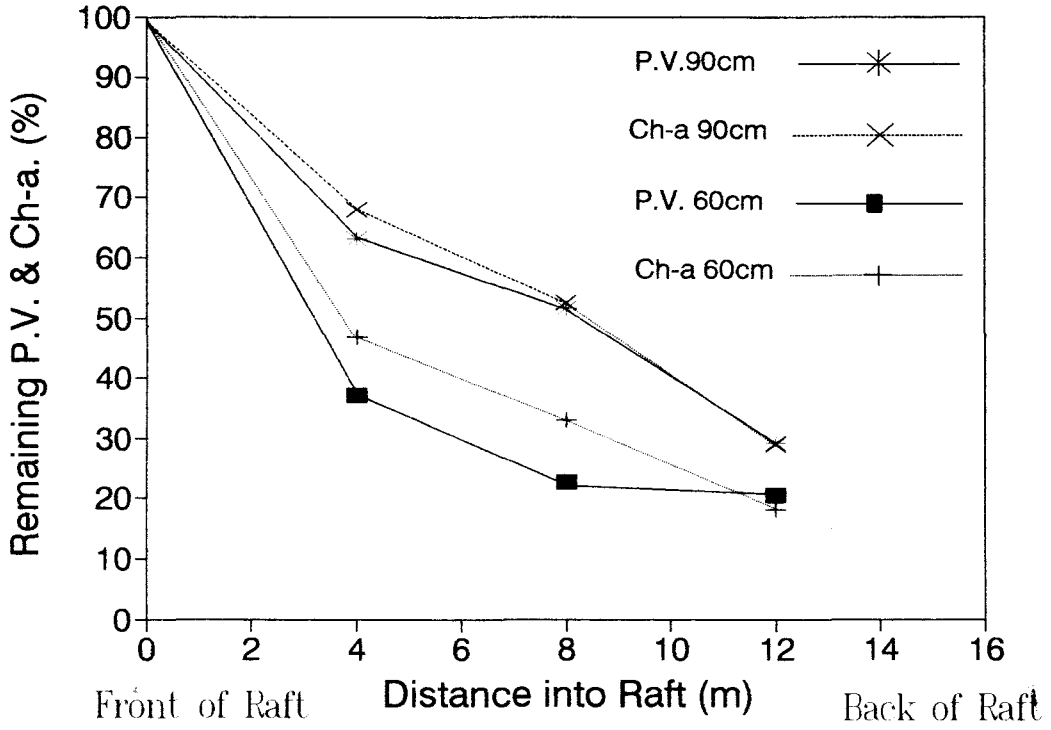


Figure 4.5. Particle volume and chlorophyll-a extraction by six month old seed ropes on rafts with 60cm and 90cm rope spacing. P.V. = particle volume. Ch-a = Chlorophyll-a. (n = 6). (Standard Deviation omitted for clarity).

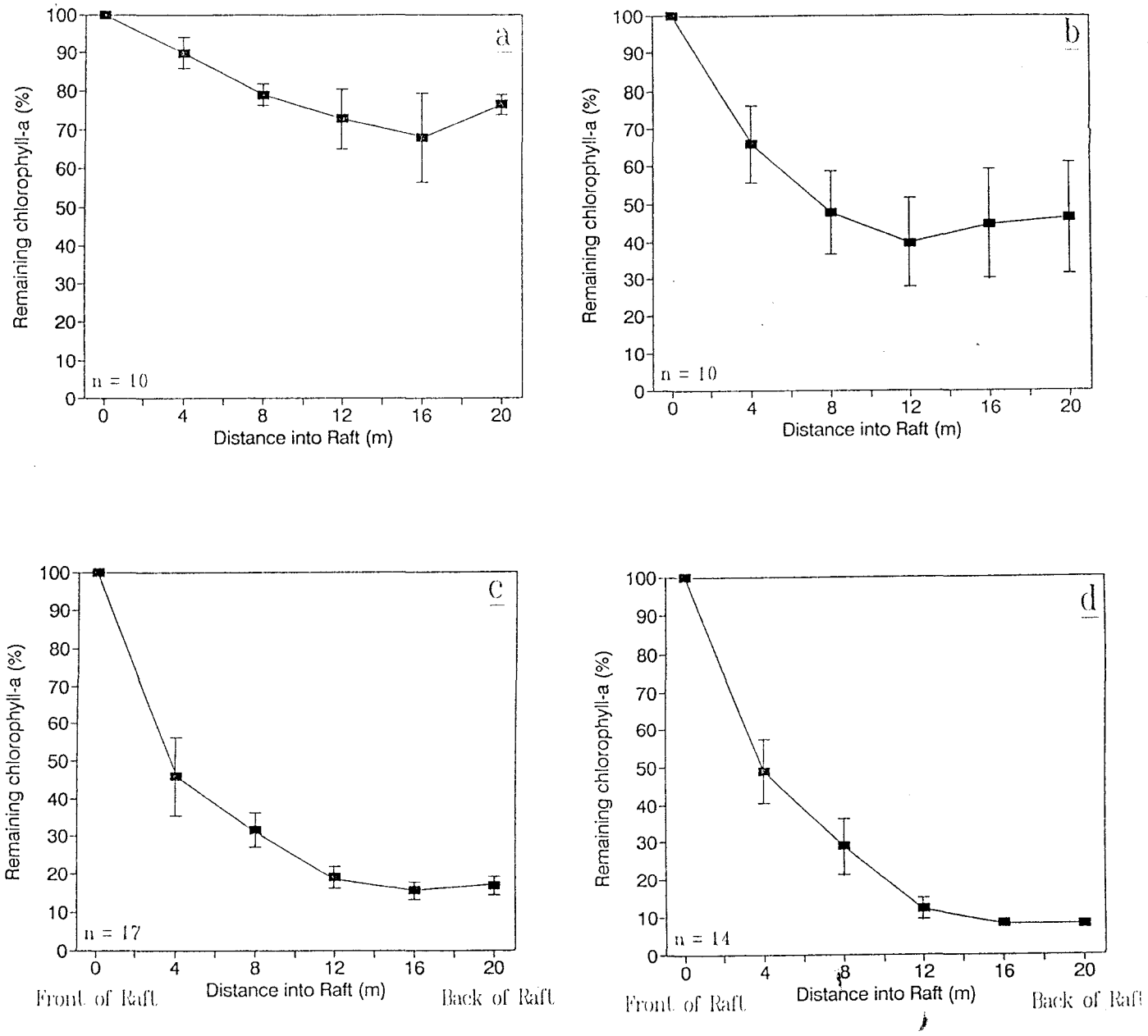


Figure 4.6a, 4.6b, 4.6c & 4.6d. The percentage of chlorophyll–a extracted from the water passing through the rafts with mussels of different ages. Rope spacing = 60cm.
(Vertical bars = Standard deviation)
a = ropes less than 2 months old.
b = ropes 3 & 4 months old.
c = ropes 5 & 6 months old.
d = ropes over 6 months old.

Table 4.3 The percent chlorophyll *a* remaining in the water at 2m depth at a distance of 4m, 8m, 12m, 16m and 22m from the leading edge of the raft. Means and standard deviations are shown in Figures 4.6a, 4.6b, 4.6c & 4.6d. Ropes were spaced at 60cm.

Distance into Raft Age of seed rope		4M	8M	12M	16M	22M
2 Months	Mean	89.86	78.96	72.78	67.88	76.33
	S.D.	(8.22)	(5.43)	(15.40)	(22.86)	(5.25)
	n	10	9	9	5	3
3 and 4 Months	Mean	65.87	47.73	39.69	44.69	46.33
	S.D.	(20.44)	(21.90)	(23.57)	(28.94)	(29.60)
	n	10	10	10	6	6
5 and 6 Months	Mean	45.91	31.73	19.15	15.43	16.8
	S.D.	(20.7)	(9.15)	(5.68)	(4.89)	(4.86)
	n	17	16	9	5	5
Over 6 months	Mean	48.94	28.86	12.28	8.28	8.08
	S.D.	(16.84)	(15.04)	(5.4)	(1.54)	(0.08)
	n	14	11	11	3	2

Significantly greater proportions of particle volume and chlorophyll *a* were extracted by a raft with 60cm rope spacings than those with 90cm rope spacing (Tables 4.4a & 4.4b and 4.5a & 4.5b).

Table 4.4a The percent chlorophyll *a* remaining in the water on passing through mussel rafts with 60cm and 90cm rope spacing. Different superscripts indicate significant differences at $P<0.05$. The statistical results are shown in Table 4.4b.

	Chlorophyll *a* remaining at 4m (x ± SD)	Chlorophyll *a* remaining at 8m (x ± SD)	Chlorophyll *a* remaining at 12m (x ± SD)
60cm rope spacing	46.75^{b} (15.74)	33.02^{b} (16.02)	18.27^{c} (14.16)
90cm rope spacing	67.94^{a} (32.22)	52.57^{ab} (15.14)	29.02^{b} (2.88)

Table 4.4b A multiple analysis of variance test on the amount of chlorophyll *a* remaining in a mussel raft in relation to the distance the water has travelled into the raft, ie from the raft edge facing the current, 4m, 8m and 11m into the raft, and the distance between the rope centres (60cm and 90cm). ns = non-significant. * = significant ($P<0.05$). Homogeneity of variances was tested using Bartletts test.

Source of variance	d.f.	F-Ratio	Sig. level
Distance	2	7.580	0.0111*
Spaces	1	8.832	0.0013*
Dist / space	2	0.217	0.8062 ns

Table 4.5a The percent particle volume remaining in the water on passing through mussel rafts with 60cm and 90cm spaced ropes. Different superscripts indicate significant differences at $P<0.05$. The statistical results are shown in Table 4.5b.

	Particle volume remaining at 4m (x ± SD)	Particle volume remaining at 8m (x ± SD)	Particle volume remaining at 12m (x ± SD)
60cm rope spacing (Std dev)	37.16^{b} (15.72)	22.74^{b} (16.01)	20.44^{c} (12.8)
90cm rope spacing (Std dev)	63.115^{a} (16.02)	51.485^{ab} (15.13)	29.147^{b} (2.87)

Table 4.5b A multiple analysis of variance test on the Particle Volume remaining in a mussel raft in relation to the distance the water has travelled into the raft, ie from the edge facing the current, 4m, 8m and 11m into the raft, and the distance between the rope centres (60cm and 90cm). ns = non-significant. * = significant ($P<0.05$). Homogeneity of variances was tested using Bartletts test.

Source of variance	d.f.	F-Ratio	Sig. level
Distance	2	10.999	0.029*
Spaces	1	4.962	0.0157*
Dist \ spaces	2	0.781	0.8062 ns

Rope Scale

As shown in Table 4.7, the mussels on the ropes facing the incoming current on a raft have substantially more chlorophyll *a* and particle volume available to them

than the mussels in the middle or on the leeward side of the raft. There was a significantly greater volume of particles inside the mussels on a rope than on the outside, presumably due to particle build up through lack of flushing. The greatest reduction of particle volume occurs at the rope surface.

Chlorophyll *a* levels appear generally to be minimal at, or near to, the rope surface. However the trend is not clear. Phaeopigments have high values in and around the mussel ropes in comparison to the average values found in Saldanha Bay, probably due to breaking down faecal matter. Ropes facing the incoming current have very high values within the rope. The middle of the raft has the lowest phaeopigment values. The phaeopigment values decrease with distance from the rope (Table 4.7).

Pseudofaeces

The threshold at which *Mytilus galloprovincialis* produces pseudofaeces in Saldanha Bay was not determined. However, at no time did the mean particulate organic matter level, at the monitoring station, drop below pseudofaeces threshold levels as reported in the literature for *Mytilus edulis* which is closely related (Table 4.6, Figure 4.7).

Table 4.6 The pseudofaeces threshold levels found by various authors. The thresholds are in mg/l of particulate organic matter (P.O.M.) or total seston.

Mussel size	Pseudofaeces Threshold	Seston or P.O.M.	Source
1.7cm	2.6mg/l	seston	Widdows *et al.* 1979
3.5cm	4.3mg/l	seston	" " " "
5.5cm	4.6mg/l	seston	" " " "
7cm	5.0mg/l	seston	" " " "
2,5cm	1.3mg/l	P.O.M.	Bayne *et al.* 1989
4cm - 5cm	2.98mg/l - 3.41mg/l	P.O.M.	Bayne *et al.* 1993

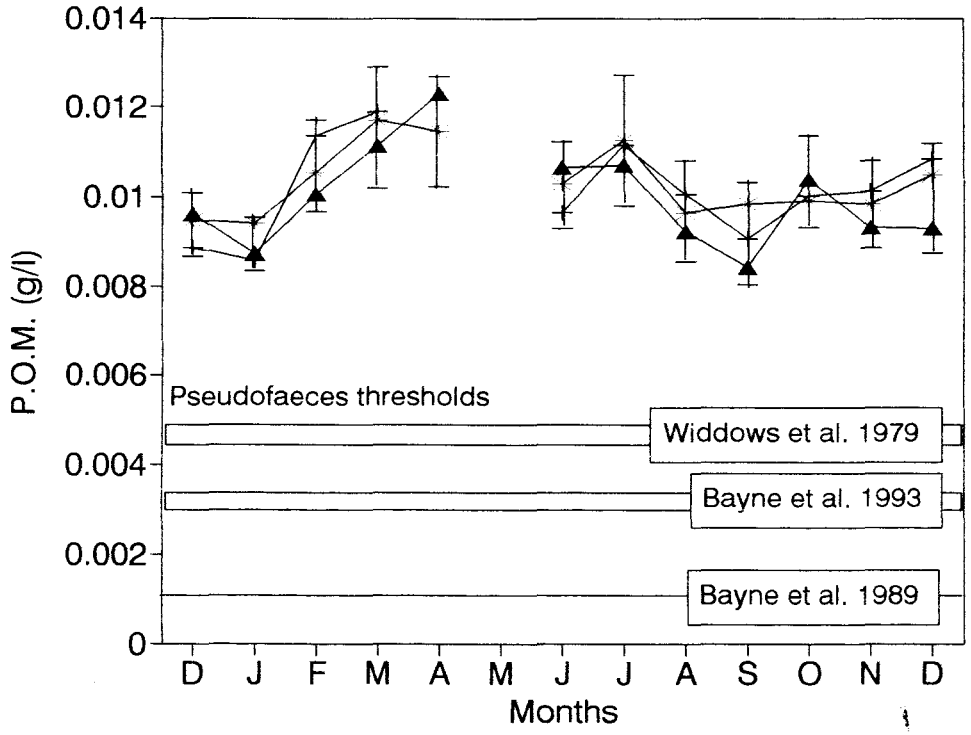


Figure 4.7. Mean particulate organic matter (P.O.M.) at the monitoring buoy. Pseudofaeces thresholds are levels of P.O.M. and seston above which pseudofaeces production is induced. (see Table 4.7) (Vertical bars = Standard deviation).

Table 4.7 The mean chlorophyll *a*, particle volume and phaeopigment found inside, at the edge and at various distances from a 6 month old rope of mussels. Ropes were sampled from the side of the raft facing the incoming water current (raft front), from the middle of the raft and from the leeward side of the raft. N = 2 for each position. Standard deviation is shown in brackets.

Distance	Chlorophyll *a* (μg/l)			Particle Volume (μg x 10^6 / ml)			Phaeopigment (μg/l)		
	Front of Raft	Middle of Raft	Back of Raft	Front of Raft	Middle of Raft	Back of Raft	Front of Raft	Middle of Raft	Back of Raft
10cm into rope	5.47 (0.68)	1.41 (0.15)	1.21 (0.54)	22.125 (7.25)	5.886 (1.16)	4.190 (1.86)	213.5 (32.5)	34.84 (5.11)	31.46 (6.23)
Rope surface	3.90 (3.33)	0.82 (0.51)	1.00 (0.33)	4.314 (0.595)	1.522 (0.655)	1.687 (0.40)	8.76 (2.98)	4.98 (0.74)	12.19 (8.82)
5cm	3.25 (1.51)	1.64 (1.26)	0.73 (0.48)	5.407 (1.16)	1.952 (0.59)	0.901 (0.14)	8.23 (3.93)	2.61 (2.21)	3.47 (0.67)
15cm	5.33 (4.44)	1.49 (0.96)	1.24 (0.72)	5.959 (0.64)	1.701 (0.70)	1.192 (0.16)	5.69 (2.03)	2.21 (0.86)	2.66 (0.61)
25cm	4.72 (2.65)	1.31 (0.93)	0.32 (0.10)	6.757 (0.58)	1.872 (0.995)	1.223 (0.31)	3.83 (1.71)	0.86 (0.42)	1.15 (0.63)
35cm	4.04 (2.11)	1.55 (1.18)	0.56 (0.26)	7.064 (0.05)	2.113 (0.12)	1.32 (0.16)	2.89 (0.80)	1.97 (0.56)	3.45 (2.36)

DISCUSSION

Mussels constitute the largest filter feeding biomass on the mussel rafts in Small Bay (pers.obs.) and, except for *Ciona intestinalis* (See Chapter 5), the effects of other organisms on food particle extraction are considered to be minimal.

From a physical perspective, feeding in mussels is influenced by the hydrodynamics and hydromechanics within the mantle cavity. Simultaneously, however, the biochemical and physiological responses to environmental change appear to act homeostaticaly in an attempt to maximise performance and net energy gain (Hawkins & Bayne 1992). Absorption efficiency, filtration rates, respiration and excretion rates all vary with food concentrations (van Erkom Schurink & Griffiths 1992). Similarly, filtration rates and pseudofaeces production are affected by a number of factors which vary relative to the position of the mussels on the raft. For example, filtration rates will improve with increasing water flow (Walne 1972b) and reduced light intensity (Nielsen and Strømgren 1985).

Mytilus edulis has been shown to reduce filtration rates and shell gape in high concentrations of phytoplankton, thereby possibly reducing its growth potential (Schulte 1975, Widdows *et al.* 1979, Riisgård 1991). However, it is suggested that the reduction of pseudofaeces production as a result of the reduced gape may be an energy saving. Therefore, the growth potential may not decrease despite a reduced gape. However, there is no convincing evidence of this.

Some factors which affect filtration rates, however, vary in intensity according to the scale on which it is acting, i.e. from farm to raft and rope scale.

Farm Scale

There is a large variation in the quantity of food taken out of the water as it passes through the mussel farm. Work done by Dr G.Pitcher of the Sea Fisheries Research Institute (1995 unpublished) revealed that there are patches of phytoplankton across the bay. Therefore due to the variation of particle volume and chlorophyll-a in the water entering the farm, it is virtually impossible to determine the exact

percentage extracted by the farm. When current drogues indicated that water currents were consistent, there was a significant difference ($P < 0.05$) between the chlorophyll *a* in the incoming water at the front of the farm and outgoing water on the leeward side of the farm (Figure 4.2). Generally, however, the water current flow is inconsistent in direction and magnitude (Chapter 3), resulting in "new" water being injected into the farm introducing pockets of chlorophyll *a*. Such replenishment would minimise the importance of chlorophyll *a* reduction by the farm, however, the important point is that the farm is capable of significantly reducing ambient food concentrations. It is unlikely, however, that the present farm has a significant effect on the Bay scale food availability. It remains to be seen what impact a larger farm would have on Bay scale food availability.

Temperature may also have an effect on filtration rates on a farm scale (Newell & Branch 1980, Carver & Mallet 1990, van Erkom Schurink & Griffiths 1992). However, it is unlikely that this contributed to the variation of food extracted through the farm. The vertical water temperature variation in Saldanha Bay is within the range found to have least effect on absorption rates (van Erkom Schurink & Griffiths 1992) or filtration and metabolic rates (Walne 1972, Schulte 1975, Widdows 1978). Temperature can therefore be discounted as a regulating factor in this instance. This is supported by the finding that there was no substantial seasonal trend in percentage of particles extracted. Seasonal variation in food uptake may also be influenced by phytoplankton type. Pre-ingestive chemical cues from microalgae can influence mussel feeding behaviour, selection of food particles and ingestion rates (Ward & Targett 1989). However although there are seasonal changes in phytoplankton (Pitcher, Sea Fisheries Research Institute, pers.comm.) the low percentage of phytoplankton, by mass, of the organic portion of the seston makes it unlikely that this effect is important (Chapter 2). Furthermore, food extraction studies were carried out over several seasons and were found to be similar over all the seasons (Figures 4.6a, 4.6b, 4.6c & 4.6d).

With the present stocking densities of rafts in the study farm it is highly unlikely that the available seston ever dropped to below the pseudofaeces threshold level

on the farm scale. Samples taken from the monitoring buoy show organic loadings in the water which were well above the pseudofaeces threshold (Figure 4.7).

Raft Scale

In Spain, a 528m² raft with 80 tonnes of mussels was found to reduce the P.O.M. by 24% and the chlorophyll *a* by 36% between the incoming and out going water (Navarro *et al.* 1991). The rafts at Saldanha Bay, which are about half the size (242m²), and hold approximately 50 to 100 tonnes of production mussels, settled seed and *Ciona intestinalis*, extract approximately 79% of the P.O.M. and up to 96% of the chlorophyll *a* in the water. This may be a function of the higher biomass on the rafts or the reduced water flow through the rafts in Saldanha Bay. Unfortunately, inconsistent water flow rates, in both speed and direction, make the estimation of food removal as a function of water current impossible in Saldanha Bay. Camacho *et al.* (1991) found that a raft extracted 30% of the carbon fraction and 60% of the chlorophyll *a* contained in the P.O.M.. This suggests a preference by the mussels for the phytoplankton over the other P.O.M. constituents.

Water entering the front of the raft has a high seston load, therefore, the mussels at the front of the raft are subjected to food saturation. However, if the current changes, as it does, they would be in the leeward side of the raft and have 80% to 90% less food. In instances when the mussels are facing the incoming current, it is suggested that they would adopt a strategy of particle selectivity, excluding a portion of the inorganic component and large particles as pseudofaeces, and selecting phytoplankton. This is done with the labial palps at the mouth (Theisen, 1977, Kiørboe *et al.* 1980, Theisen 1982, Essink *et al.* 1986) and by increasing or reducing the valve gape to extend or retract the mantle varying the food intake (Jørgensen *et al.* 1988). The seston load entering the raft (see Table 4.2) would exceed the pseudofaeces threshold of the mussel (Foster-Smith 1975, Widdows *et al.* 1979, Kiørboe *et al.* 1980, Bayne *et al.* 1989, Bayne *et al.* 1993).

In instances where the mussels are on the leeward side of the raft, the feeding strategy would theoretically be very different. The ventilation period would increase, as would filtration rates, no pseudofaeces would be produced, gut passage time would be increased and assimilation and absorption efficiency would

improve (Bayne *et al.* 1989, Bayne *et al.* 1993). It is also suggested that mucus secretion may increase (Beninger *et al.* 1993) and the inter-gill filament ostia may be reduced in size, through the voluntary contraction of the ciliary junctions (Jørgensen *et al.* 1988, Jones *et al.* 1992). This would enable the feeding mechanisms to capture smaller particles, such as bacteria (Lucas *et al.* 1987), which are not captured by upstream mussels. Field observations showed that pseudofaeces and faecal pellets are excluded at the mantle or rejected by contracting the posterior adductor muscle. Therefore, pseudofaecal matter and intestinal faecal matter are not a source of food to the mussels in low food situations.

Because of the extraction of preferred food particles at the leading edge of the raft the mussels deeper into the raft effectively have to process a totally different seston. At 4m into the raft, with 60cm rope spacing, the water has a 56% lower chlorophyll *a* concentration and 63% lower particle volume level, than the water at the front of the raft (Table 4.5a). Increasing the rope spacing from 60cm to 90cm significantly increased the particle volume penetrating the raft (Figure 4.5). This resulted in up to 30% more food reaching the centre of the raft and 10% more food reaching the leeward side of the raft.

The percentage of particle volume extracted by a raft with a 60cm rope spacing (Figure 4.5) would indicate that portions of the raft are functioning below the pseudofaeces threshold. The higher percentage of particle volume in a 90cm spaced rope would indicate that a much smaller proportion of the raft is functioning under the pseudofaeces threshold. This is reflected in better mussel growth rates on rafts with ropes spaced at 90cm apart in comparison with those with 60cm rope spacing (See Chapter 5). The proportion of the raft that is below the pseudofaeces level will be determined by the degree of fouling, water current speed and the direction of the current flow.

Mussels in the raft centre are consistently subjected to low food situations. This is reflected by a lower condition index, although growth in length is not significantly affected (Chapter 5). The food extracted by mussels in the centre of the raft would consist of smaller particles ignored by upstream mussels, such as bacteria, which may be generated within the raft. Another possible food source in

the centre of the raft is dissolved organic material (D.O.M.), which is reported to represent 13% to 40% of the requirements for growth and reproduction (Hawkins & Bayne 1992).

Rope Scale

Indications are that a large volume of faeces is not flushed out from between the mussels on a rope. This is reflected by the very high phaeopigment (decomposed chlorophyll *a*) level and high particle volume level (Table 4.7). Although the chlorophyll *a* levels inside the rope are relatively high in comparison to the water outside the rope, it is probable that most of the chlorophyll *a* originates from the faeces and is therefore not available to the mussels. This is quite possible as some algal cells are rejected by the mussel because of size, shape and chemical cues (Ward & Targett 1989) while others survive the digestive process. The high levels of phaeopigments at the rope facing the incoming current would also indicate high pseudofaeces production. The mussels inside the rope are therefore subject to much lower food availability. Observations have shown that where mussels are totally encompassed by naturally settled spat and/or *Ciona intestinalis*, mortalities occur at the rope centre. The dissolved oxygen levels inside the rope never differed by more than 0.3mg/l to levels on the outside of the rope. This would suggest that the mussels at the centre of the rope starved to death and were not asphyxiated.

CONCLUSION

Mytilid bivalves have a complex mucociliary mechanism which is used in the capture and transport of particles to the mouth. The mechanism enables the mussel to retain bacteria, phytoplankton and detritus and selectively sort them at the mouth. The movement of food particles through the digestive tract can be increased or decreased, depending on food type, size and density. Mussels in Small Bay are subjected to large variations in food type (i.e chlorphyll *a* / P.O.M.), density and sizes as well as temperature (through a fluctuating thermocline depth) and oxygen fluctuations. The wide range of particles available to the mussels varies through the mussel raft. However the growth results from a 60cm rope spaced raft indicate that although there is sufficient food for growth an increase in rope spacing will optimise growth. An increase in rope spacing increases the particle delivery to the mussels in the centre of the raft. Although the condition index of mussels, in the centre of the rafts is lower than the periphery, growth is not limited.

CHAPTER 5
GROWTH, PRODUCTION AND CONDITION

INTRODUCTION

The growth rate of mussels in Saldanha Bay is among the highest in the world (Table 5.1). To optimise this rate and thereby economic yields, an understanding of the variables affecting mussel growth is imperative. However, mussel growth is dependant on many factors, for example: size and age (Mallet & Carver 1993), stocking density (Hughes & Griffiths 1988), the extent of fouling (Seed & Suchanek 1992), light intensity (Nielsen & Strömgren 1985), food quality and availability (Newell *et al.* 1989), degree of cohort mixing (Seed & Suchanek 1992), temperature (Almalda Villela *et al.* 1982, Loo & Rosenberg 1983, van Erkom Schurink & Griffiths 1992), salinity (Seed & Suchanek 1992), as well as other environmental and culture conditions (Figueras 1989) and genotype (Strømgren & Nielsen 1989, Seed & Suchanek 1992). In general, it would appear that temperature, salinity, food availability, density and farming methods are the five main regulators of mussel growth. Due to the unique environmental conditions it is unlikely that salinity, temperature or food availability would have a growth regulating effect in Saldanha Bay (see Chapters 4 & 5).

This study was undertaken to determine the growth rate of mussels in Saldanha Bay in relation to density on the ropes, rope spacing, their relative position on the ropes and on the rafts and secondly, to identify those factors which control the rate of growth, condition, production and yield. Unfortunately the variability in water current speed and direction (see Chapter 3) makes it very difficult to relate the mussel growth to food availability.

Table 5.1 The growth rates of mussels at various localities around the world.

Country	Species	Size	Time (months)	Reference
Norway	*Mytilus edulis*	46mm	36	Wallace 1983
White Sea	*M.edulis*	65mm	48	Sukhotin & Kulakowski 1992
Netherlands	*M.edulis*	65mm	36	Thompson 1984

Table 5.1 (continued)

Country	Species	Size	Time (Months)	Reference
Canada	*Mytilus edulis*	55mm	18-24	Muise 1990
Sweden	*M.edulis*	60mm	18	Loo & Rosenberg 1983
U.S.A.	*M.edulis*	50mm	15	Lutz 1980
China	*M.edulis*	80mm	12	Nie 1991, Zhang 1984
Spain	*M.galloprovincialis*	80mm	12	Figueras 1989
South Africa	*M.galloprovincialis*	75mm	11-13	This study
India	*Perna viridis*	93mm	12	Parulekar *et al.* 1982
Tahiti	*P.viridis*	90mm	10	Coeroli *et al.* 1984
Philippines	*P.viridis*	100mm	10	Rosell 1991
New Zealand	*P.canaliculus*	115mm	10	Hickman 1991

METHODS

Spat is defined here as naturally settled mussels. Seed is defined as mussels bound onto ropes.

Three methods were used to estimate mussel growth rates. The first method was by measuring engraved mussels. Seed mussels were collected and each mussel engraved with a number using a standard jewellery engraver. There are three layers that make up a mussel shell, the outer periostracum layer, the middle prismatic layer and the inner nacreous layer (Seed & Suchanek 1992). The outer periostracum layer and the middle prismatic layer of the mussel shell were grooved with the engraver but the inner nacreous layer was not damaged. The engraved numbers on the mussels were initially painted with fluorescent red paint and then with fluorescent green paint. The mussels were then bound onto ropes, at three depths, at just below the surface, at three metres and at the bottom of the rope at approximately six metres depth. Two plastic plates were fixed to the ropes above and below each position, to mark the position of the marked mussels. There were 90 mussels between each pair of plates, i.e. a total of 270 engraved mussels per rope. The ropes were tied to rafts A & B (see Figure 5.1). Two ropes were

placed at each end and two in the middle. However, this method was only used once as the paint attracted predators (*Octopus vulgaris*) resulting in the loss of a large proportion of the marked mussels. The assumption was made that engraving the mussel did not affect the growth rate. The "marked mussel" growth trial lasted seven months with measurements of mussel lengths made after six weeks and every month thereafter. At each interval 10 mussels were removed, measured and discarded as the stress of removal may have affected the growth rate. The data for this duplicate trial was treated with caution as one raft sank and the data-set was not complete and the other raft broke free, was damaged and repositioned after a storm. Therefore, the data were only used for comparative purposes (Trial 1, Table 5.3).

The second method involved grading seed mussels to within 5mm shell length (SL) of each other and seeding entire ropes with the graded mussels. The mussels were bound onto ropes using a cotton stocking in the same way and same density as under commercial conditions. i.e. approximately 1500 mussels per 6m rope. The same numbers of ropes were placed on two rafts in a similar fashion as for the first method. This experiment was run only once over a six month period after which the mussels were measured. The data were not used for total growth analysis, for reasons see results section of this chapter.

The third method was to measure the shell length of 1000 seed mussels (0.1mm accuracy) and bind these onto seed ropes. Eight ropes were seeded in this way and placed centrally down the long axis of the raft. A sample of mussels (n = ± 25) was collected every month from the top and bottom of each rope at either end and in the middle of the raft and measured. In total, eight growth trials were undertaken using this method. Six of the trials took place on two adjacent rafts. Raft C, which had a 60cm rope spacing and raft D which had a 90cm rope spacing (Figure 5.1), i.e. three trials on each raft. Two trials took place from September 1993 to March 1994, two from March 1994 to September 1994 and the last two from October 1994 to March 1995. In Table 5.2 & 5.3 these trials are referred to as trials 2 to 7. The remaining two trials were carried out on rafts (E & F, Figure 5.1) from April to September 1994. However these rafts broke free during a storm and were repositioned. As a result the data derived from these trials were only included in the "total raft" growth analysis. They are referred to as Trials 8 & 9 in Table 5.3.

Newly settled cohorts were ignored and only the seed mussels bound onto the ropes were collected and measured. Some error may have been introduced toward the end of the growth trial as those mussels which grew very slowly could have been considered as part of the newly settled cohort and consequently disregarded. Fortunately, observations showed that these very slow growing mussels represent only a very small proportion of the population.

The effect of rope spacing (ie. the distance between ropes on the raft) on mussel growth and total raft production was also tested. Based on mussel growth rate the production of rafts with different rope spacing was also calculated. Production is defined here as the total mass of mussels, (of any size), harvested from a rope or a raft, after a period of time. Production was calculated for two adjacent rafts. On one of the rafts the ropes were spaced at 60cm and on the other the ropes were spaced at 90cm intervals. One rope from each end and one from the centre of each raft were sampled. Mussels were sampled and measured, from the top (metre one) and bottom (metre six) of the ropes on a monthly basis. To calculate production the mussels were size graded and weighed at harvesting. Adjacent rafts were chosen on the assumption that food availability would be less variable than if the rafts were far apart in the farm.

Seed mussels are bound onto the ropes by hand, resulting in unequal densities and variation in biomass along the length of the rope and between ropes. The average seed number per rope is 250 mussels per metre. Unequal densities may have affected growth although, given the total number of mussels measured on a monthly basis (n = 300) the error in the results would have been minimised.

The seed that settled on the ropes during the growth trial was used in subsequent growth trials. In this way the growth trials were conducted with seed of known age.

Mussel condition was determined on a monthly basis as described by Crosby & Laurence (1990). Mussels between 65mm and 85mm SL, were scrubbed and placed in fresh water. This effects the instantaneous closing of the two valves avoiding intake of water. The mussel was then put into a container completely full of water and the overflow was collected and measured. The flesh was then extracted, dried for 48 hours at 80°C and weighed. The dry mass of mussel flesh

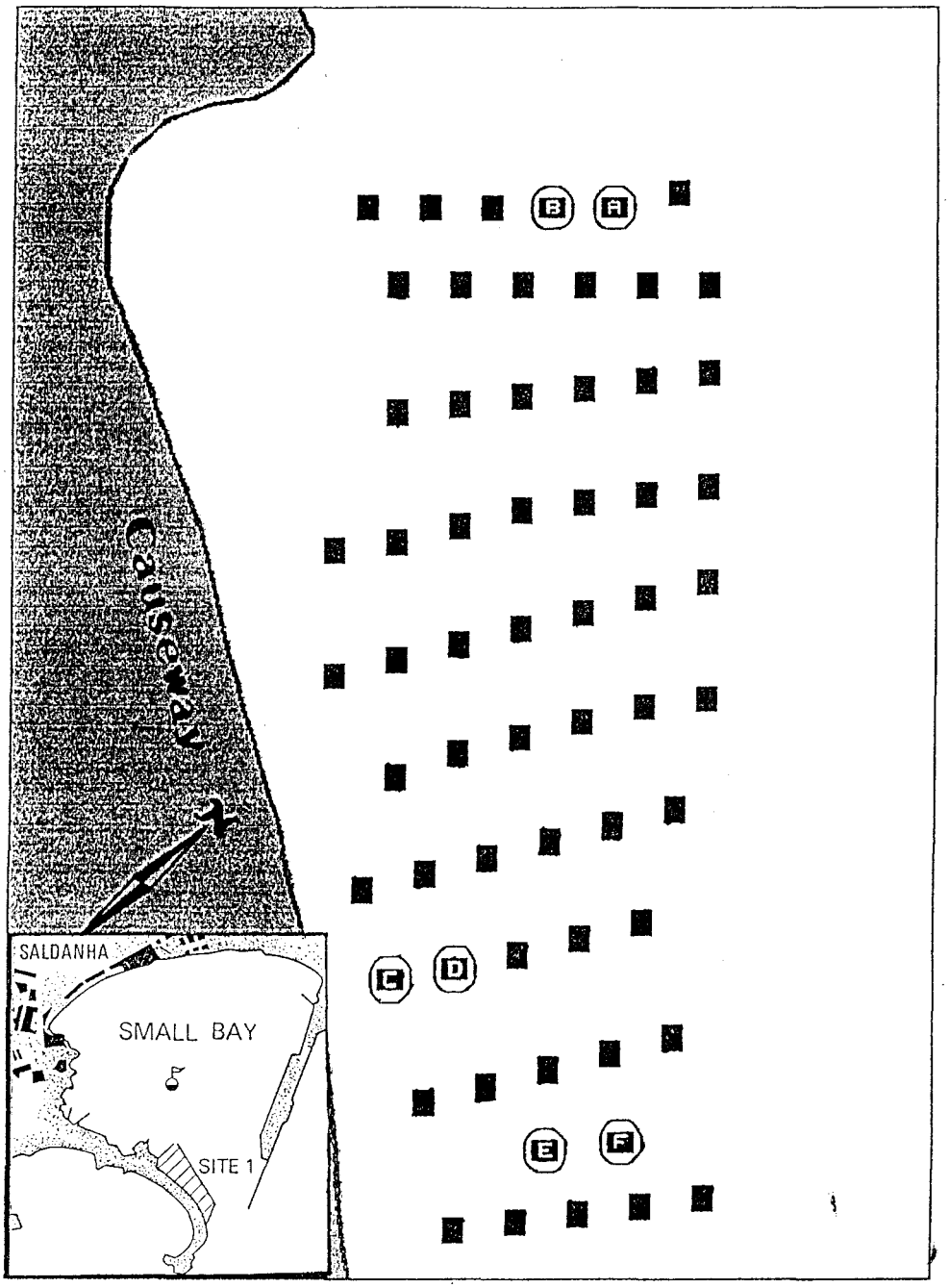


Figure 5.1. An enlarged view of Site 1 (see inset) showing the rafts used for growth trials.

was then divided by the volume of the mussel to give an index of condition, according to the equation:

$$\text{Condition Index} = \frac{\text{Mass of dry flesh (g) X 100}}{\text{Volume of the mussel (ml)}}$$

Biomass, production and yield were established by harvesting a number of randomly selected ropes down the centre of the longitudinal axis of the raft. Biomass is defined here as the total live mass, including mussels and fouling organisms, on the rope, raft or farm at any time. Yield is defined as the production minus the initial seed and unmarketable mussel mass. Marketable yield is defined here as the marketable mussel mass. Ropes were kept separate from one another. The total biomass of each rope was weighed (without the rope) and put through a declumper. The declumper and the automatic grading machine separated the mussels into small seed (≈10-25mm), large seed (≈25-65mm), small (≈65-75mm), medium (≈75-83mm) and large (≈ >83mm) mussels. The individual categories were then weighed.

Growth checks on seed mussels (Seed & Suchanek 1992) were treated with caution. A naturally settled mussel of up to 40mm will have a smooth shell, i.e. no growth checks, providing no major stress factor stopped growth. A bound seed mussel will have a growth check induced from the stress of declumping and exposure to air for an extended period. However, any major environmental stress which was sufficient to slow or stop growth will also induce a growth check line. Therefore the growth check line was used as a supportive indicator and not a true indicator of growth rate.

Mussels normally show a sigmoidal growth pattern however the growth trials were run during the linear phase of growth and therefore growth was best modeled using the linear regression model $Y = a + bx$, where a is the intercept point on the Y axis and B is the slope of the line. Slopes of the regression models for shell length as a function of time were compared using an F-test, based on the analysis of covariance, (ANCOVA), i.e test for the equality of slopes (Zar 1981). Tests for significance between slopes were calculated for trials 1 to 9. The slopes for growth of the mussels at the top (metre one) and bottom (metre 6) of the trial ropes on each end and the middle of the rafts used in trials 1 to 7 were also calculated.

Tukey's test was employed to test for differences between the means at an error probability of $p<0.05$.

RESULTS

Due to predation losses and storm damage, growth rate calculations for marked mussels are only based on data from one raft (Trial 1, Table 5.3).

Due to the high mortality and low production rates observed for the graded mussels the second method of assessing growth was deemed to be unsuitable and the data for this trial were not used to estimate growth rate. The data were, however, used to highlight production problems (Table 5.6).

The third method of assessing growth rates (Trials 2 to 9) provided the most consistent and reliable data. The growth trials for trials 2 to 7 are shown in Figures 5.2a & 5.2b. Slopes of the regression models of growth rate as a function of time for trials 2 to 9 are shown in Figure 5.3a & 5.3b and Table 5.3. The slopes of the regression models of growth rates as a function of time at the top (metre one) and bottom (metre 6) of sample ropes for trials 2 to 7 are presented in Table 5.2.

The mussels on the rafts with 90cm rope spacing showed a trend of better growth over mussels on 60cm spaced ropes during summer and winter growth trials (Figure 5.3a & 5.3b, Table 5.3). However, some effect, possibly fouling (Chapter 6), masked the trend in the 1994 winter period and the 1994/1995 summer period (Table 5.3).

Overall, there was greater variation among the growth rates of mussels on rafts with 60cm ropes than on rafts with 90cm spaced ropes (Figure 5.2a & 5.2b). Growth rate was also affected by the position of mussels on the ropes (i.e. either top or bottom) and also by the position of the ropes on the raft. However, there was no consistent trend of better growth in any one position within seasons. The winter growth rate was significantly slower than the summer growth rate, irrespective of rope spacing.

The mussels at the top of the centre rope in the raft with the 90cm rope spacing showed significantly better growth than the mussels at the same position in the

rafts with 60cm rope spacing during summer. However, rope spacing had no significant effect on the growth during winter (Table 5.2).

Table 5.2 Slopes of the regression equations for shell length as a function of time for different positions on a raft. i.e. South end, Centre & North end and top and bottom of each rope. Growth trials took place over summer and winter periods on rafts with different rope separation (60cm or 90cm). Different superscripts indicate statistical differences at $P<0.05$. Sum = Summer. Win = Winter.

Date Rope Spacing Season	93/94 60cm Sum	93/94 90cm Sum	94/95 60cm Sum	94/95 90cm Sum	94 60cm Win	94 90cm Win
South top	1.94^{c}	1.98^{c}	1.8^{d}	2.18^{b}	1.38^{f}	1.36^{f}
South bottom	1.97^{c}	1.92^{c}	1.67^{e}	2.23^{b}	1.32^{f}	1.25^{f}
Centre top	1.97^{c}	2.34^{a}	1.63^{e}	2.12^{b}	1.38^{f}	1.39^{f}
Centre bottom	2.02^{c}	1.94^{c}	2.07^{bc}	2.20^{b}	1.38^{f}	1.28^{fg}
North top	1.99^{c}	2.35^{a}	2.12^{b}	1.96^{c}	1.26^{g}	1.17^{g}
North bottom	2.22^{b}	2.39^{a}	2.19^{b}	1.96^{c}	Storm damage	1.47^{f}

Table 5.3 Slopes of the regression equations for shell length as a function of time for different rafts over two summer periods, and two winter periods and different rope spacing (60cm or 90cm). Different superscripts indicate significant differences at $P<0.05$.

Raft Number	Season	Rope spacing (cm)	r	Regression slope
Trial 1	Winter 1993	60	0.82	1.05^{d}
Trial 2	Summer 1993/4	90	0.87	2.11^{a}
Trial 3	Summer 1994/5	90	0.78	1.95^{b}
Trial 4	Summer 1993/4	60	0.80	1.91^{b}
Trial 5	Summer 1994/5	60	0.83	1.85^{b}
Trial 6	Winter 1993	90	0.80	1.46^{c}
Trial 7	Winter 1994	90	0.81	1.37^{cd}
Trial 8	Winter 1993	60	0.82	1.32^{d}
Trial 9	Winter 1994	60	0.78	1.29^{d}

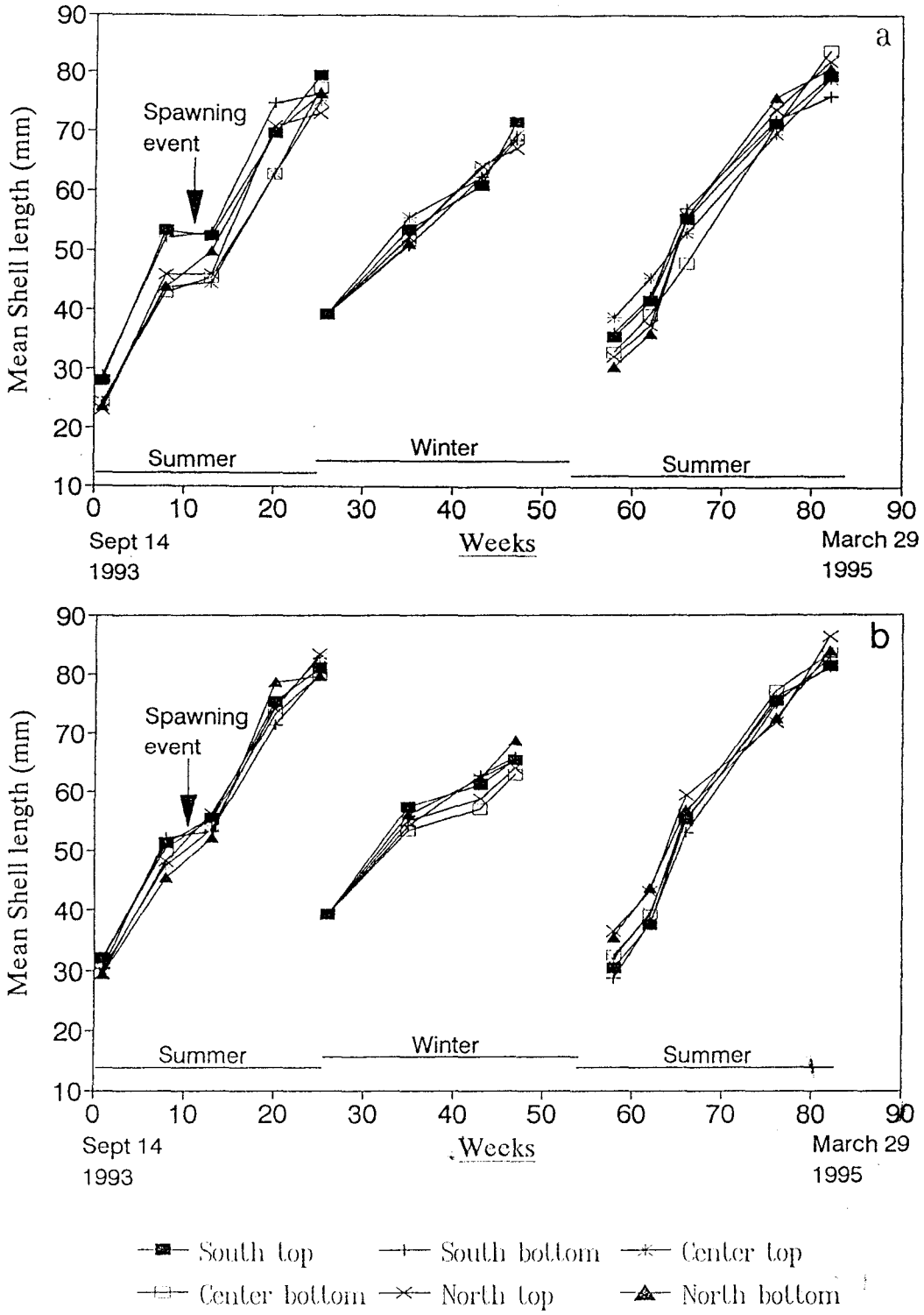


Figure 5.2a & 5.2b. The Summer and Winter growth of mussels on rafts with 60cm (a) and 90cm (b) rope spacings. Standard deviations omitted for clarity.

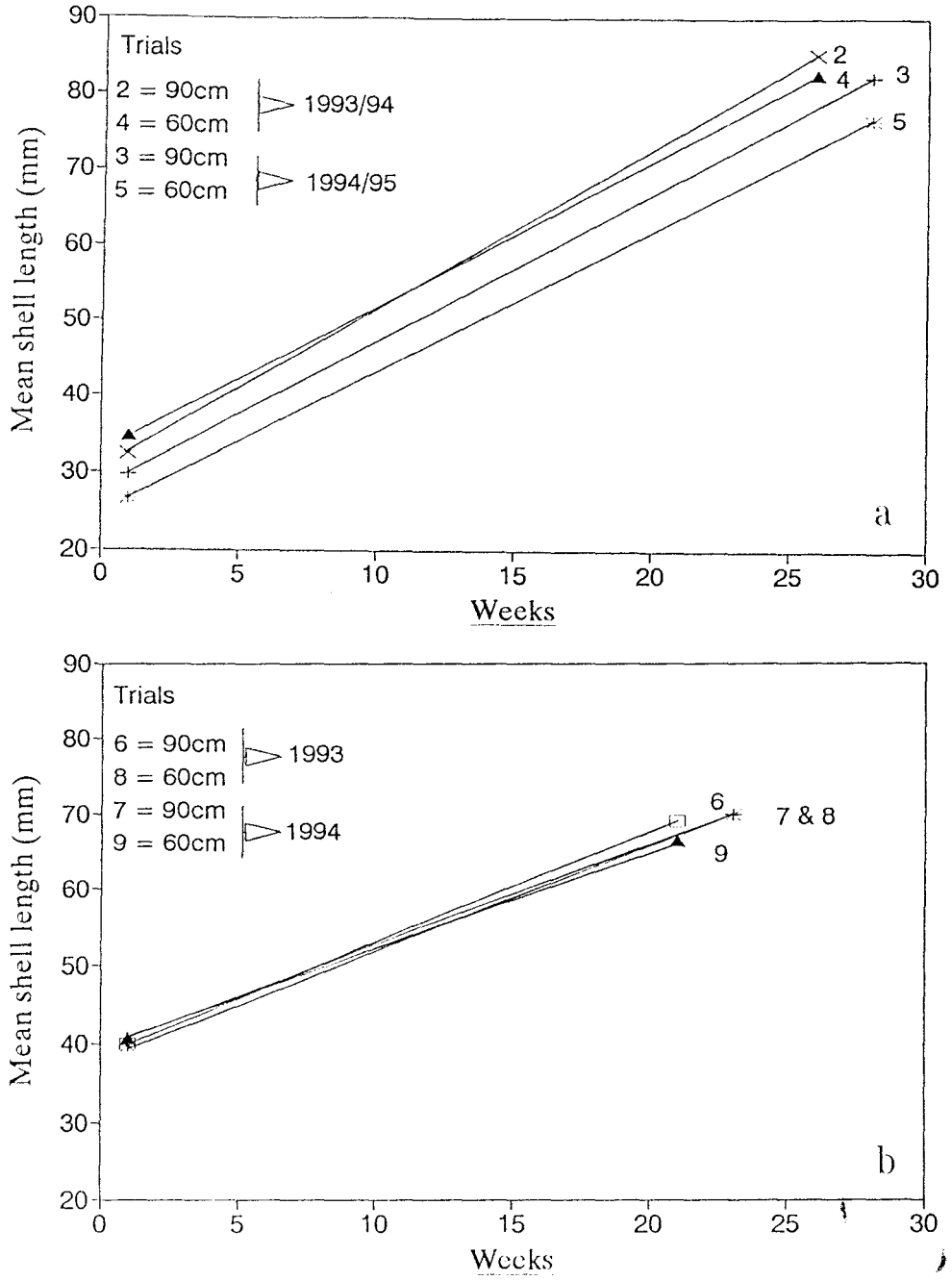


Figure 5.3a & 5.3b. Summer (a) and Winter (b) growth rates of mussels at 60cm and 90cm rope spacing in Saldanha Bay. Growth trials took place between 14 September 1993 and 29 March 1995.

Condition

The condition of mussels varied seasonally irrespective of rope spacing. The seasonal variation was clearly a consequence of mass spawning in October / November each year (Figure 5.4). The spawning event in October / November 1994 was of longer duration than the event in October 1993. At the time of writing, the 1995 spawning event had been delayed. During the spawning events the mean condition index of the mussels decreased by up to 54%. The high standard deviation around the monthly condition indices is possibly related to trickle spawning (i.e. individual mussels spawning throughout the year (Figure 5.4).

Production and Yield

Total production of a rope was found to vary with season, and the position of the rope on a particular raft, and rope spacing. Fouling significantly affected production (Chapter 6). The production and yield of rafts with 90cm rope spacing were higher than for rafts with 60cm rope spacing (Table 5.4). Under conditions of severe fouling the yield of large mussels is significantly ($P<0.05$) reduced and the yield of small mussels significantly ($P<0.05$) increased (Table 5.5).

Figure 5.5 shows the monthly percent marketable yield of mussels on the entire farm as a percent of production. Yield was lower from mid June to October. This coincided with the growout period of naturally settled mussel spat and *Ciona intestinalis* settlement on the ropes. Fouling decreases marketable yield on all ropes irrespective of spacing.

Table 5.6 shows the production and yield of ropes that were seeded with mixed cohorts and graded seed mussel of similar size. While the production in total mass was very similar there were marked differences in the marketable yield of medium and large size mussels. Those ropes seeded with mixed seed consistently yielded a significantly ($P<0.05$) higher mass of marketable mussels than the ropes prepared with graded seed. On unfouled ropes there was a significantly ($P<0.05$) higher yield of large mussels on 90cm spaced ropes in comparison to 60cm spaced ropes (Table 5.4).

Table 5.4 Production, yield and marketable yield (in kilograms) of ropes on two unfouled rafts with different rope spacing. The trial extended from September 1993 to March 1994. n = 16

	60cm rope spacing (x ± SD)	90cm rope spacing (x ± SD)
Total production	273.87 (35.89)	326.89 (48.99)
Initial seed mass	20.21 (6.13)	20.21 (6.13)
Total Yield	251.66 (29.76)	306.68 (42.86)
Settled seed	123.89 (20.77)	139.78 (24.84)
Marketable Yield	80.87 (9.52)	116.76 (10.93)
Small	18.43 (8.89)	16.12 (4.71)
Medium	39.04 (15.79)	51.33 (10.52)
Large	23.4 (3.88)	49.31 (17.55)

Small = ≈ 65 - 75mm mussels
Medium = ≈ 76 - 83mm mussels
Large = ≈ >83mm mussels
Marketable yield = total yield of small, medium and large mussels.

Table 5.5 Production, yield and marketable yield (in kilograms) of ropes from two severely fouled rafts with different rope spacing. The trial extended from October 1994 to March 1995. n = 16.

	60cm rope spacing (x ± SD)	90cm rope spacing (x ± SD)
Total Production	215.54 (53.16)	225.74 (29.81)
Initial seed mass	20.21 (6.13)	20.12 (6.13)
Total Yield	195.33 (47.03)	205.62 (23.68)
Settled seed	76.14 (23.37)	75.51 (14.07)
Marketable Yield	91.01 (9.74)	88.96 (8.61)
Small	42.88 (10.05)	42.79 (5.38)
Medium	35.79 (14.80)	42.38 (18.30)
Large	12.34 (4.36)	3.79 (2.16)

Small = ≈ 65 - 75mm mussels
Medium = ≈ 76 - 83mm mussels
Large = ≈ >83mm mussels
Marketable yield = total yield of small, medium and large mussels.

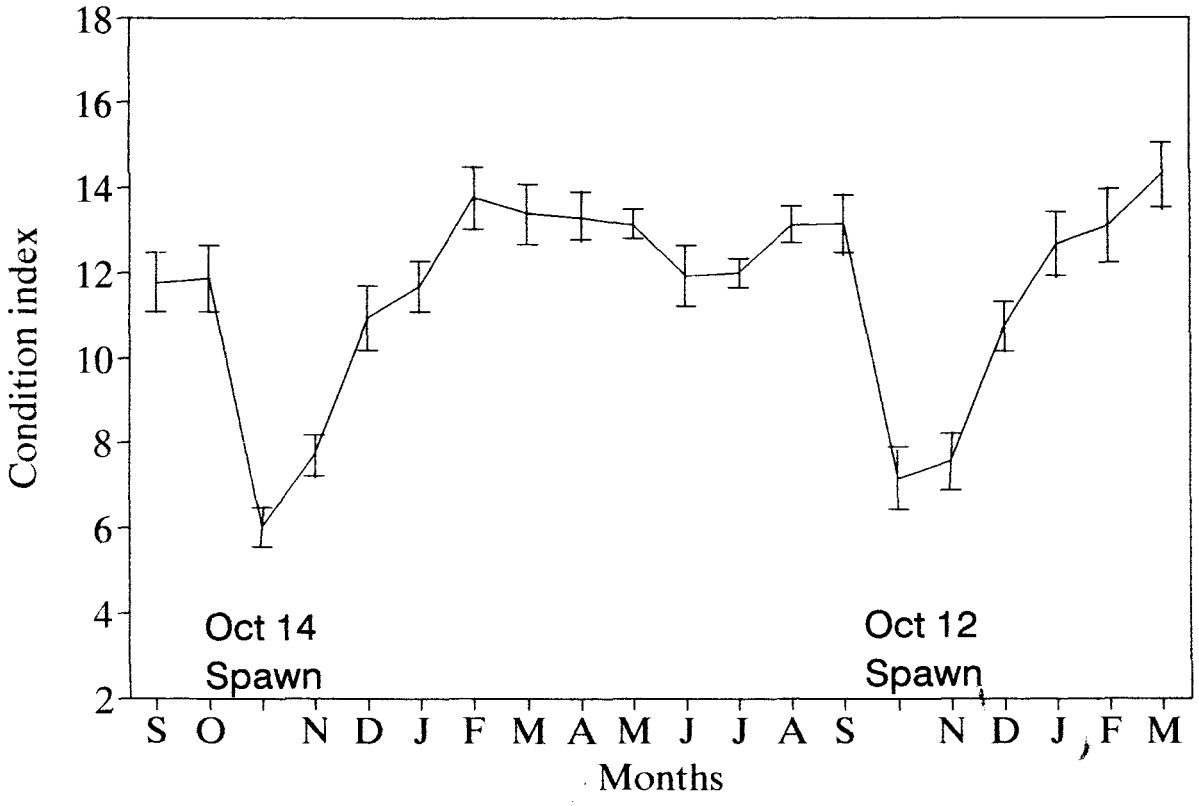


Figure 5.4. The condition index of mussels in Saldanha Bay from September 1993 to March 1995. The two annual synchronised spawning events are seen in October / November each year. (Vertical bars = Standard Deviation).

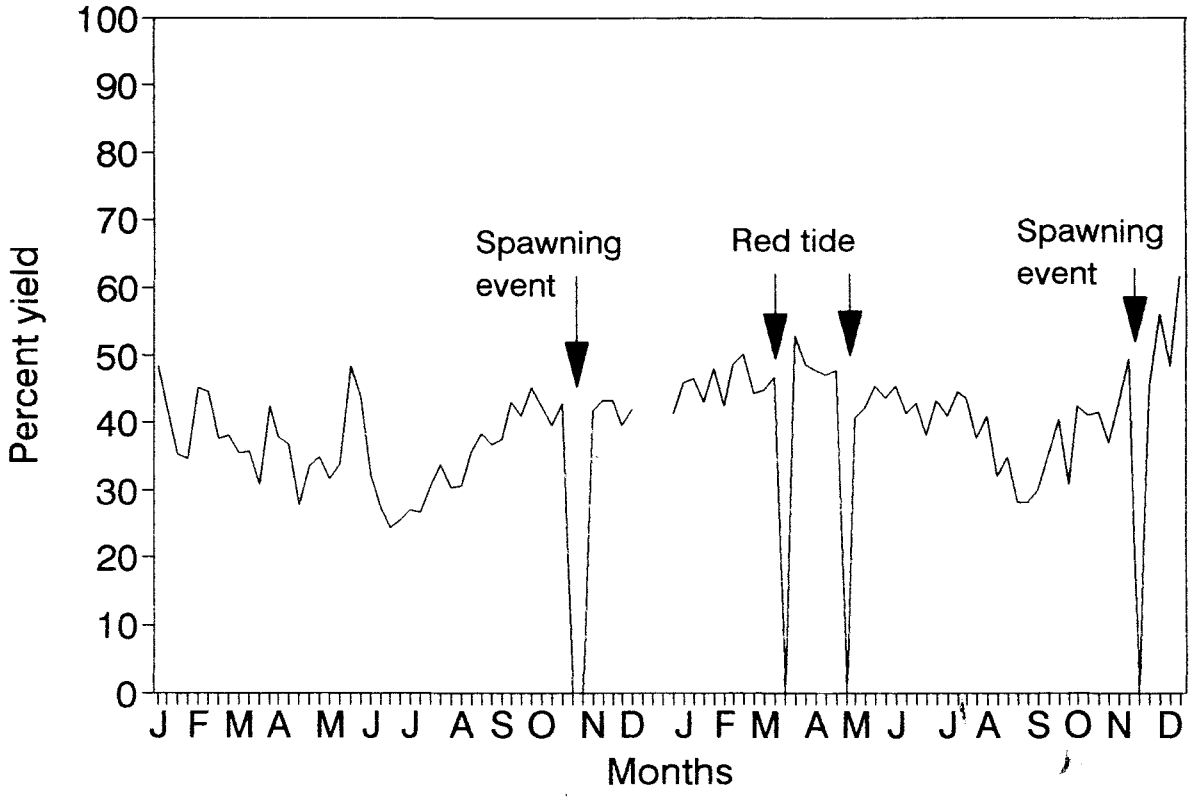


Figure 5.5. Yield of marketable mussels as a percentage of the total production on the farm fron January 1993 to December 1994.

Table 5.6 Production, yield and marketable yield (in kilograms) on ropes prepared with mixed and graded seed. The trial took place from April 1994 to September 1994. n = 14

	Mixed seed (x ± SD)	Graded seed (x ± SD)
Total Production	74.99 (24.98)	76.9 (17.22)
Initial seed mass	20.21 (6.13)	20.21 (6.13)
Total Yield	50.01 (18.85)	72.19 (11.09)
Settled seed	13.5 (10.09)	16.5 (4.76)
Marketable Yield	30.5 (7.72)	17.24 (2.90)
Small	5.4 (1.52)	5.5 (0.55)
Medium	13.5 (2.94)	8.15 (0.86)
Large	11.6 (3.26)	3.59 (1.24)

Small = ≈ 65 - 75mm mussels
Medium = ≈ 76 - 83mm mussels
Large = ≈ >83mm mussels
Marketable yield = total yield of small, medium and large mussels.

DISCUSSION

As pointed out in the introduction to this chapter, mussel growth rates are highly variable and many factors appear to affect growth. In most instances there is one primary and several secondary limiting factors, normally environmental, that affect mussel growth rate. In Saldanha Bay the primary growth and survival inhibiting factors appear to be fouling of ropes by mussel seed settlement and by the sea squirt *Ciona intestinalis* (Chapter 6). Although the effect of fouling on growth and survival was not specifically tested it was nevertheless clear from field observations that a reduction in growth between the first and second year summer growth and between winter and summer growth could probably be attributed to fouling although a specific study is necessary to confirm this beyond doubt.

Rope spacing and mussel seeding densities are also important growth regulators but appear to be secondary in relation to fouling. A greater rope spacing resulted in improved growth rate (Rosenberg & Loo 1983, this study) except when fouling becomes severe. This is due to better water penetration. However, the variability

in current speed and direction results in an unknown quantity of water, and therefore food, being delivered to the raft. Therefore growth was not related to food availability.

Settlement of fouling organisms and sub-optimal stocking density of seed can reduce growth and increase mortality (van Erkom Schurink & Griffiths 1993, pers.obs.). Trevelyan (1991) found that the growth rate of *M.edulis* can vary 10-fold under conditions of heavy mussel spat settlement. The densities of seed mussels and settled spat on the ropes, in Saldanha Bay, were very high from February to August. Densities of up to 3500 mussels (10 to 45mm shell length), were recorded per metre of rope. Generally a density of 200 to 300 mussels (40mm shell length) per metre of rope is considered to be optimal (Jenkins 1985, Figueras 1989). Deliberate overcrowding can however be used as a management tool to reduce growth rates for management purposes (Hickman 1992).

Growth is also affected by the size composition of the mussels bound onto the ropes. In general, slower growth has been recorded when mixed size seed was bound onto ropes (Seed & Suchanek 1992). However, the opposite was found to be the case in Saldanha Bay. The growth trial using graded and ungraded mussel seed showed that the graded mussels grew at a slower rate, and with a lower marketable yield, than mixed cohort mussels. From this study, therefore, it would appear that thinning mussel numbers to acceptable densities of mixed cohort mussels from March to August would ensure that high mussel growth rates are maintained year round. The reduced density would allow ample space for the mussels to gape, which in turn would improve mantle extension and therefore filtration rates (Chapter 4).

Excessive handling of mussel seed, such as during the process of binding new ropes, leads to stress which in turn results in a longer recovery period after being placed back in the water, this decreases growth. During the rebinding process mussels spend extended periods of up to 30 hours out of the water. It has been observed (pers.obs.) that it takes up to two weeks for the rebound mussels to

show any shell growth. This would lead to an appreciable annual loss in terms of marketable yield.

Temperature has been found to be one of the major factors effecting mussel growth (Almalda Villela *et al.* 1982, Loo & Rosenberg 1983, van Erkom Schurink & Griffiths 1992). The water temperature in Saldanha Bay showed a maximum variation of up to 8°C, through upwelling and stratification, on any one day (CSIR data, Chapter 2.). The monthly means, however, show a maximum range of 3.6°C between the top and the bottom of the ropes. Although temperature normally plays an important role in mussel growth rates, the temperature range in Saldanha Bay falls within the zone where the affect would theoretically be negligible (Walne 1972, Schulte 1975, Widdows 1978, Page & Hubbard 1987). It was also shown (Chapter 4) that the temperature range in Saldanha Bay does not appear to affect the feeding rate of mussels.

Food availability and extraction are discussed in Chapter 4. Seed and Suchanek (1992) suggest that food availability is one of the primary factors effecting mussel growth. This was clearly not the case, on a farm scale, in Saldanha Bay where it has been shown (see Chapter 4) that food was always in abundance. On a raft scale however, food is a limiting factor particularly on rafts with 60cm rope spacing. The conclusions about the effect of rope spacing on growth is reinforced by the feeding data in Chapter 4 where rafts with 60cm rope spacing have reduced food availability and larger portions of the raft were below the pseudofaeces threshold than in rafts with 90cm rope spacing.

High light intensities have also been reported to have negative effects on mussel growth rates (Nielsen & Strömgren 1985). This would not appear to be the case in Saldanha Bay. While the top and bottom of the ropes are certainly subjected to different light intensities (although it was not measured) there were no significant differences in growth between mussels at the bottom and the top of the ropes.

Mussel genotype and growth rate appear to be closely linked (Koehn & Gaffney 1984). Genetic influences may account for up to 28% of the variation in growth

and mortality (Hawkins & Bayne 1992). Koehn & Gaffney (1984) showed that greater heterozygosity in mussels led to better growth at more uniform rates. Meat gain can be increased and the growth rate increased by an estimated 24 - 35% per generation through genetic selection (Strömgren & Nielsen 1989). This highlights a problem in the Saldanha Bay culture method as the fast growing mussels are harvested and the slower growing mussels replace them as seed. It is unknown if these mussels supply the spat for the next generation. If so, then the fitness of the mussels in Saldanha Bay will deteriorate over time.

The condition index reflects the flesh content of the mussel. Condition is lost during the synchronised spring spawning event and as a consequence of individual random spawning (trickle spawning). The triggers for spawning are not well understood. However, on two occasions synchronised spawning was preceded by a slight increase in water temperature, and the first strong south westerly winds, with associated wave build up, in summer. The loss of over 50% in the mean condition index in October 1993 and November 1994 clearly reflects synchronised spawning events (Figure 5.4). During the spawning period the growth rate of the mussels, on the ropes spaced at 60cm, was substantially reduced (Figure 5.2a). A gradual decline in condition of the mussels was also recorded over the winter months. It is suggested, since temperature and food availability do not appear to be primary growth limiting factors, that this is a consequence of inter- and intraspecific competition by fouling organisms reducing space and valve gape, thereby physically restricting access to food.

Yield, in terms of mass of marketable mussels in Saldanha Bay, varies from year to year. However, when the ropes remain unfouled, total yield increases with increased rope spacing. The annual decline in marketable yield in winter (from May to August) coincides with the simultaneous growout of settled *Ciona intestinalis* and naturally settled mussel spat (Figure 5.5).

CONCLUSION

Apart from the recovery in condition and growth rate after spawning, it would appear that the growth rate of mussels in Saldanha Bay is affected mainly by the

interaction of rope spacing and competition for space and food through fouling by naturally settled mussel spat and *Ciona intestinalis*. The occurrence of fouling and spat settlement is dealt with in greater detail in the next chapter.

The growth rate of mussels in Saldanha Bay does not appear to be severely affected by abiotic factors mentioned previously. Temperature may contribute to the reduced growth rates in winter, however it is unlikely to be significant. Salinity fluctuations in Saldanha Bay are negligible and would not have a significant effect on mussel growth. There is also no apparent seasonal pollution in Saldanha Bay which might affect mussel growth. Food availability is not a controlling factor on a farm scale as the particulate organic matter levels never drop below the pseudofaeces threshold (See Chapter 4). However, on a raft scale, particularly on 60cm rope spaced rafts, food is a controlling factor. Therefore, the control of the fouling organisms through improved farming methods and the determination of optimal rope spacing will reflect the greatest improvement of mussel production and yield in Saldanha Bay. The densities of seed mussels must be regulated and a minimum space maintained between the periphery of the mussel on each of the ropes.

CHAPTER 6
THE OCCURRENCE OF FOULING ORGANISMS AND IMPLICATIONS FOR THE GROWTH OF MUSSELS.

INTRODUCTION

Fouling is a major universal problem in bivalve culture (Enright 1993). The main fouling organisms in mussel culture are macroalgae (Lutz *et al.* 1991), barnacles (Mook 1981), hydroids (Jenkins 1985), sponges (Mook 1981) ascidians (Figueras 1989, Lutz *et al.* 1991, Szewzyk *et al.* 1991) and settled mussel spat (Figueras 1989, Lutz *et al.* 1991, Enright 1993). Mussel spat is defined here as naturally settled mussels in contrast to seed mussels which are mussels bound onto production ropes.

Ascidians and mussel spat are the two main fouling organisms in Saldanha Bay. There are 84 species of ascidians found on the South African coast, of which approximately half are endemic (Millar 1971). Of these, two are a problem. They are *Pyura stolonifera*, which is found in high wave energy areas and *Ciona intestinalis*, which is found mainly in low energy, darker water (Millar 1971, Branch *et al.*1994). The main fouling species in Small Bay of Saldanha Bay was *C.intestinalis*. Little is known about the biology of this species. The ever increasing number of mussel rafts is obviously providing an ideal habitat for colonisation and propagation of this species. *P.stolonifera* is not a problem in Small Bay but it will in all probability become a problem in the high energy areas in Big Bay.

Algae do not pose a major fouling problem in Saldanha Bay. However, they may become a problem through greater release of nutrients from near by fish factories (P.Monterio, Sea Fisheries Research Institute, pers. comm.). Although there are numerous sponge, hydroid and barnacle species on the mussel rafts they are not an economic threat at this stage.

Although most farmers recognise the potential threat of fouling organisms, little has been done to find methods which would control them cost effectively. There is an urgent need to understand the biology and ecology of *Ciona intestinalis* on mussel rafts. The information would provide the basis for the development of control measures.

The aim of this study was to document the occurrence and intensity of *Ciona*

intestinalis and mussel spat settlement on the mussel rafts in the farm.

METHODS

Sampling took place in May 1994, when *Ciona intestinalis* were abundant and relatively mature. The numerical abundance of *C.intestinalis* was determined by selecting three rafts with 5 - 6 month old seed ropes. One raft was situated on the side closest to the causeway, another was situated on the opposite side of the farm facing the bay and a third was situated in the centre of the farm between the two (Figure 6.1). A rope with 20cm diameter rings spaced at 0m (surface), 1,5m, 3m, 4.5m and 6m, was suspended against the ropes. Each ring had an area of 314.2 cm^2. The sea squirts surrounded by the ring were then counted and recorded. This was done on six ropes across each of the three rafts.

The numerical abundance of mussel spat was also established on the same three rafts mentioned above (Figure 6.1), one day after counting the sea squirts. Random ropes (n = 6) were selected across each of the mussel rafts. A diver stripped off mussels from a 50cm section from the top one metre and from the bottom one metre of each selected culture rope. The collected mussels were divided into 500g groups whereupon each group was separated into production mussels and naturally settled spat. The mussel spat were then counted.

The numerical abundance of *Ciona intestinalis* and mussel spat, in relation to depth and distance into the raft, were each tested using a two-way ANOVA including the test for interactions between depth and distance. Tukeys test was employed to test for differences between means of both depth and distance into the raft at an error probability of 5%.

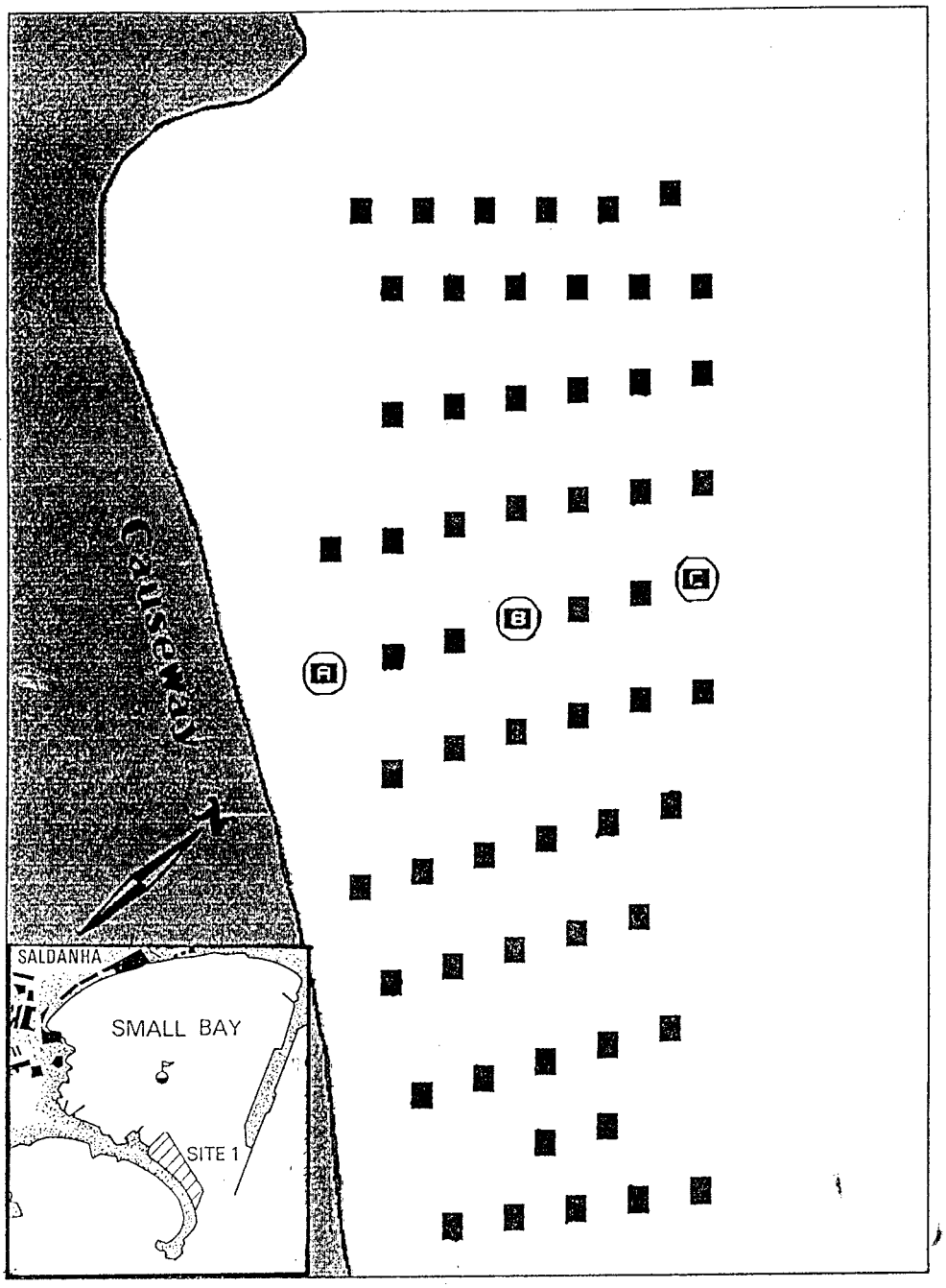


Figure 6.1. An enlarged view of Site 1 (see inset) showing the rafts sampled for mussel spat and Ciona intestinalis.

RESULTS

The main settlement period of *Ciona intestinalis* is from the latter part of December to April/May (pers. obs.). Mussel spat settles all year round although there is a peak in settlement from January to April. The lowest incidence of mussel spat settlement occurs in October to November (pers. obs.).

C.intestinalis was found in significantly ($P<0.05$) greater numbers with increasing depth (Table 6.1 & Figure 6.2). Although it would appear from Table 6.2 that there is a trend of greater density of *C.intestinalis* in the middle of the raft, in comparison to the raft periphery, the differences were not significant.

Significantly ($P<0.05$) more mussel spat is found on the side of the raft facing the mouth of the bay than in the middle of the raft (Table 6.2 & Figure 6.3). In contrast to sea squirt abundance there were significantly ($P<0.05$) fewer mussel spat at the bottom than at the top of the rope (Table 6.1). The raft in the centre of the farm had significantly ($P<0.05$) less mussel spat than the rafts on the periphery of the farm (Table 6.3 & Figure 6.4 & 6.5). The mussel spat on the raft in the centre of the farm was also significantly ($P<0.05$) larger than the spat on the peripheral rafts (Table 6.3 & Figure 6.6 & 6.7).

Table 6.1 The vertical distribution of mussel spat (Spat) and *Ciona intestinalis* (*Ciona*) from the surface (0 to 0.5m) to 6.5m depth on a mussel rope. Spat is measured as the number of spat in a 500g sample of mussels taken from the rope. *C.intestinalis* is expressed in number per m^2. Different superscripts show significant relationships ($P<0.05$).

	surface	1.5m	3m	4.5m	6m
Spat					
Mean	59.89^a	50.05^a	45.5^a	41.5^a	37^b
(Std dev)	(9.45)	(8.38)	(12.94)	(9.03)	(8.19)
Ciona					
Mean	83^a	846^b	1180^b	1641^c	2054^c
(Std dev)	(104)	(221)	(257)	(523)	(495)

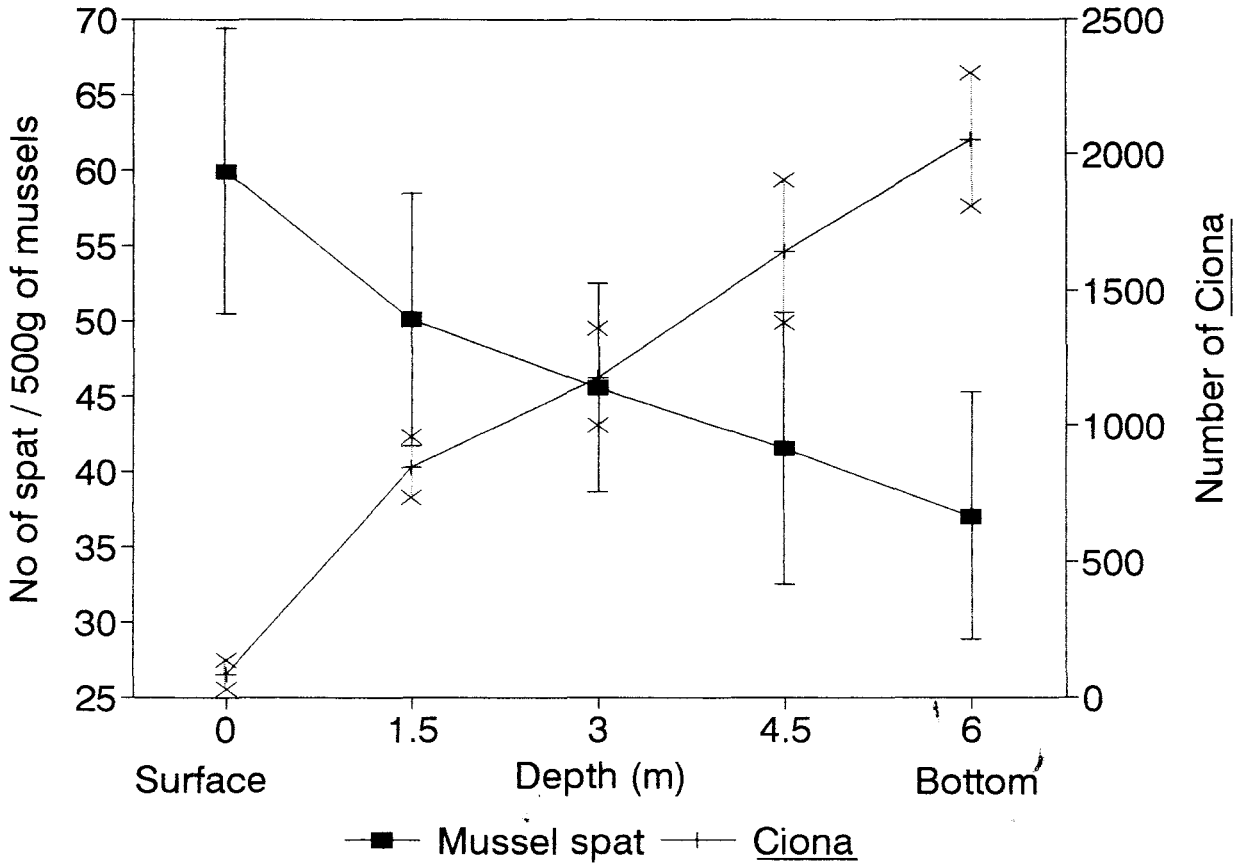


Figure 6.2. The number of spat per 500g of mussels and the number of Ciona intestinalis per m^2 down the mussel ropes. (Vertical bars = Standard deviation).

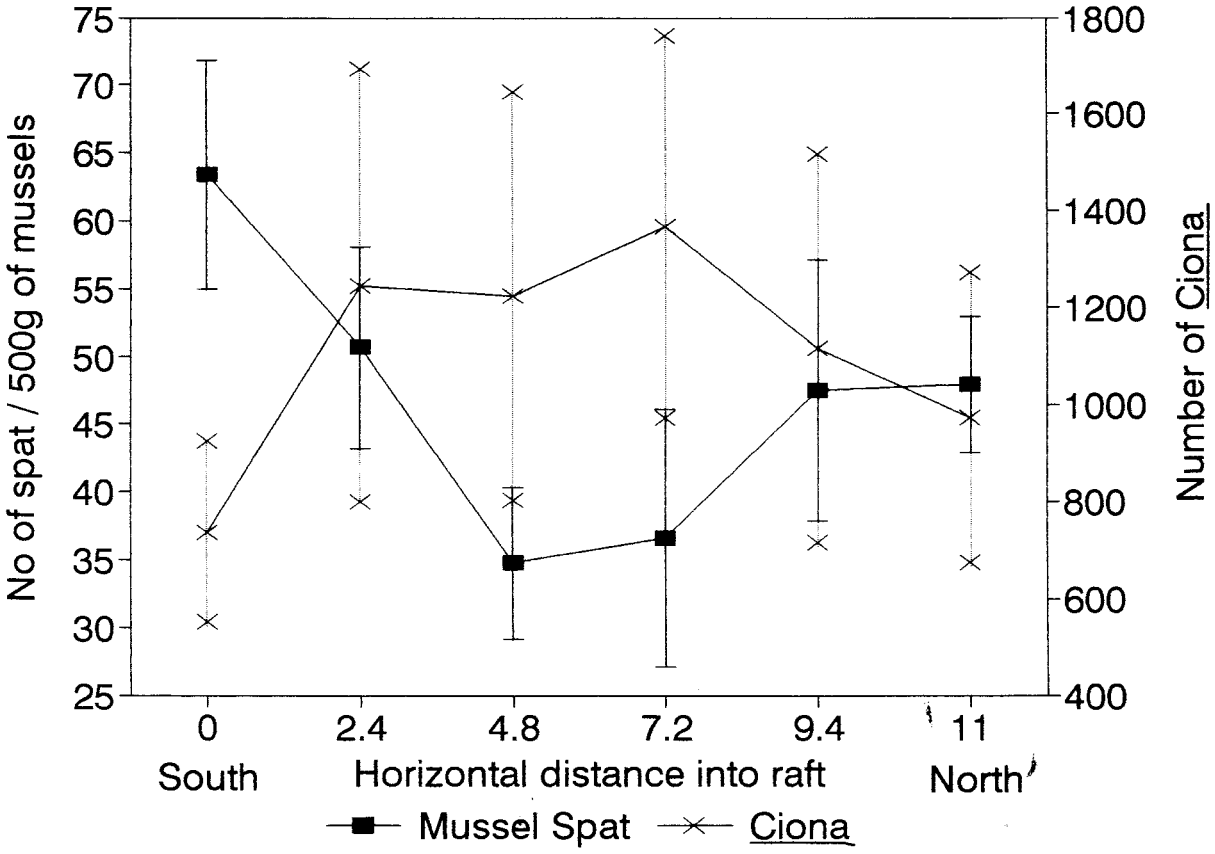


Figure 6.3. The number of mussel spat per 500g of mussels and the number of Ciona intestinalis per m^2 on mussel ropes along the axis of a mussel raft. (Vertical bars = Standard deviation).

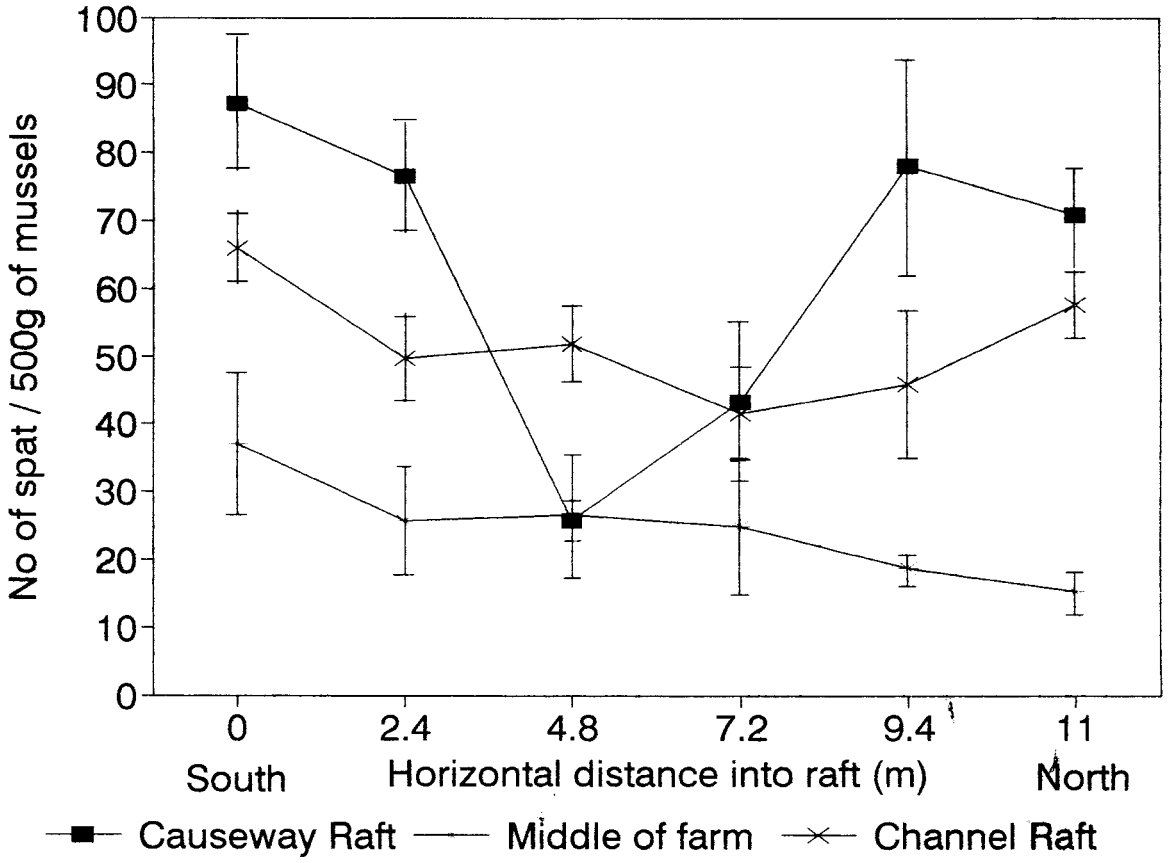


Figure 6.4. The number of mussel spat per 500g of mussels found along the axis of three rafts from different locations on the farm. (Vertical bars = Standard deviation)

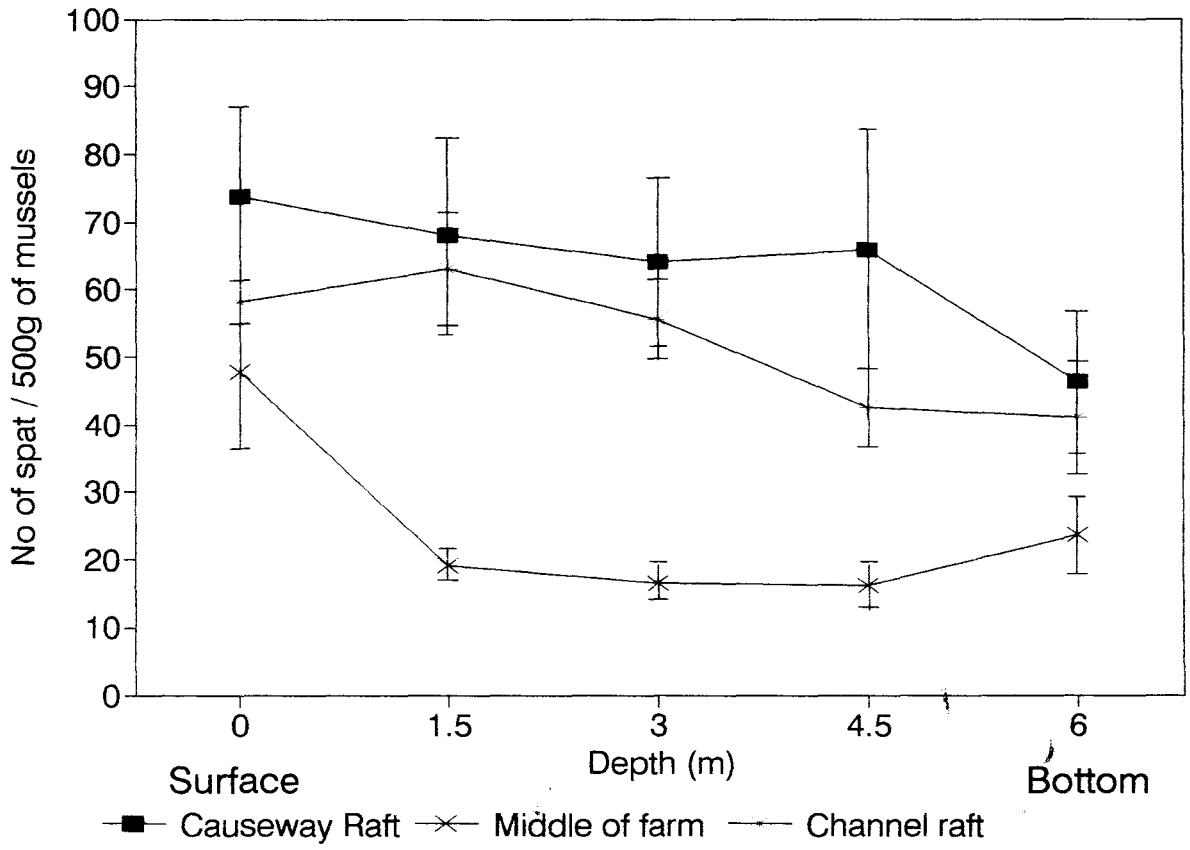


Figure 6.5. The number of mussel spat per 500g of mussels found down mussel ropes from rafts at three different locations on the farm. (Vertical bars = Standard deviation).

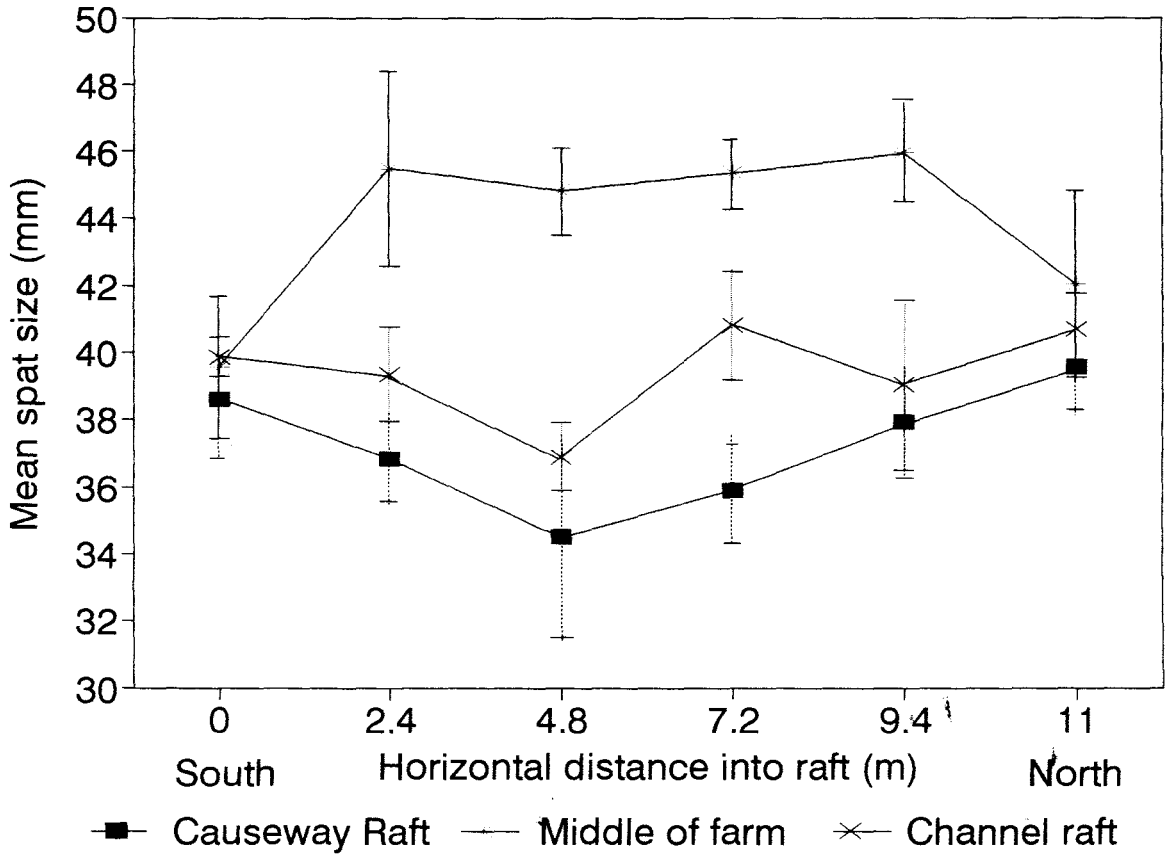


Figure 6.6 Size variation of spat along the axis of three rafts at different locations on the farm. (Vertical bars = Standard variation).

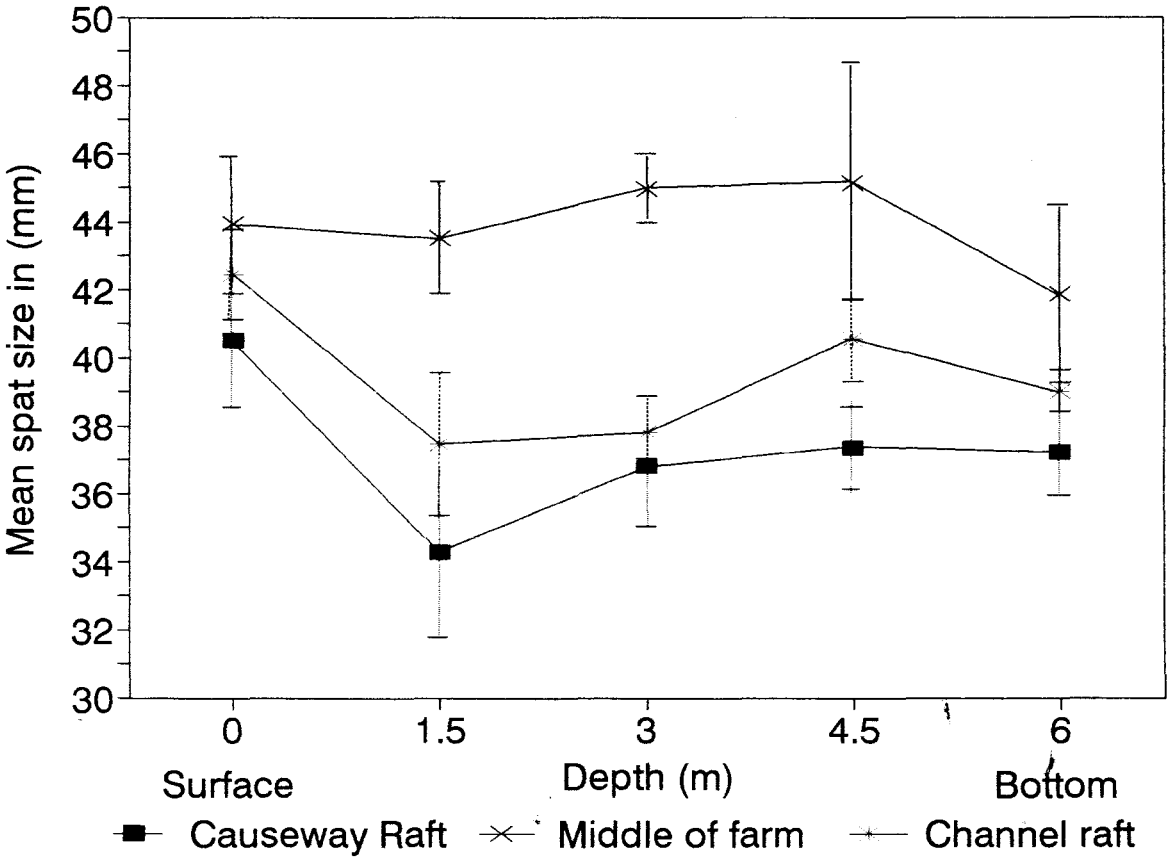


Figure 6.7. Size of mussel spat down the length of ropes on rafts from three different locations. (Vertical bars = Standard deviation)

Table 6.2 The occurrence of mussel spat (Spat) and *Ciona intestinalis* (*Ciona*) Horizontally across a mussel raft from South to north at 2,4m intervals. Spat is measured as the number of spat in a 500g sample of mussels taken from the rope. *C.intestinalis* is measured in number per m^2. Different superscripts show significant differences at $p<0.05$.

	South	2,4m	4,8m	7,2m	9,4m	North
Spat						
Mean	63.40[a]	50.67[a]	34.73[b]	36.60[ab]	47.47[ab]	47.87[a]
(Std dev)	(8.43)	(7.45)	(5.65)	(9.52)	(9.62)	(5.25)
Ciona						
Mean	738[a]	1247[a]	1224[a]	1367[a]	1116[a]	973[a]
(Std dev)	(375)	(982)	(854)	(788)	(802)	(600)

Table 6.3 The statistical relationship of mussel spat number and spat size between the rafts on the periphery of the farm (Causeway raft and Channel raft) and the raft in the middle of the farm (Mid-farm raft).

	Spat Number	Spat Size
Causeway Raft	63.6[a] (29.61)	37.22[a] (4.15)
Channel raft	52.06[a] (15.87)	39.44[a] (3.28)
Mid-farm raft	20.76[b] (18.31)	43.86[b] (4.73)

DISCUSSION

The results reflect Millar's (1971) findings which show a preference of the motile larvae of *Ciona intestinalis* for areas of low energy and low light for colonisation. The origin of the larvae of *C.intestinalis* which settle on the mussel rafts is unknown. Petersen *et al.*(1995) found that mechanisms exist to ensure that the larvae settle close to the adult population. Therefore, it would not be surprising if the mature *C.intestinalis* on the substrate and rafts reseed themselves on an annual basis. The eggs and developing larvae are supported in mucus strings (Svane & Havenhand 1993) and dispersal of the larvae is limited. Havenhand & Svane (1991) also suggest that the number of settled larvae is significantly higher around adults or mimics of adults, however, this is due to hydrodynamic processes and not due to behaviourial characteristics. In Saldanha Bay the sea squirt fouling problem has increased with the increase in the number of rafts (A.Wood, Sea Harvest Corporation). This supports the closed population theory. Although there are periods in Saldanha Bay when very few *C.intestinalis* occur on the ropes, they

are also present on the substratum below the rafts from where settlement could also occur on an annual basis.

Ciona intestinalis shows a preference for low energy areas. This is shown by the increased numbers of *C.intestinalis* at the bottom of the ropes, which are not subjected to wave action. There was also a trend of increasing numbers in the centre of the raft however the variation was large and the differences were not significant. Observations showed that the survival rate of production mussels is reduced with increasing numbers of *C.intestinalis*, which according to Petersen *et al.* (1995) can remain highly competitive at low chlorophyll *a* concentrations of 1,5 to 4μg. Therefore, in the centre of the farm, although the mussels grow at a faster rate, through low spat settlement, the competition for space and food by *C.intestinalis* will lead to higher rates of mortality.

In contrast to the precocial and motile larvae of *Ciona intestinalis* the larvae of mytilid mussels are subject to a series of life history stages, with restricted mobility, prior to settling. Furthermore settlement occurs weeks after the spawn (Lutz & Hidu 1979, Lutz *et al.* 1991, Widdows 1991, Seed & Suchanek 1992). During this period of development the mussel larvae are carried, with limited swimming ability, in the surface water currents. Metamorphosis and settlement occurs on finding a suitable substratum. The period between egg fertilisation and settlement varies according to environmental condition (Lutz *et al.* 1991, Widdows 1991).

In those areas where the mussel spat settlement was high, the spat are small. This is probably a consequence of intraspecific competition which will reduce the growth rate (See Chapter 5) of mussels at high densities (Hughes & Griffiths 1988, Trevelyan 1991). However, if the periphery of the rafts are heavily settled then the mussels in the raft centre are smaller in size as a consequence of less food reaching the raft centre. Therefore, the rafts on the farm periphery have the combined effect of intraspecific competition and reduced food availability which in turn results in a reduction in mussel growth rate. The rafts in the farm centre have less spat settlement and less competition for food and therefore show an increase in size of mussel spat.

Productivity however is not necessarily improved between the centre and the periphery of the farm. The high mussel spat density on the farm periphery results

in smaller spat size. *Ciona intestinalis*, preferring calmer water, increases mussel mortality in the sheltered rafts at the centre of the farm. The area colonised by *C.intestinalis* is increased in the absence of mussel spat as is the area of spat settlement in the absence of *C.intestinalis*. Therefore, as farms increase in size in energy rich areas the peripheral rafts with have a problem predominantly with mussel spat and the interior rafts with *C.intestinalis*. Yield of marketable mussels can only be increased if effective ways are found to control fouling by *C.intestinalis* and mussel spat.

CONCLUSION

Mussel spat fouls the periphery of both the farm and the rafts. Increasing the mussel number through spat settlement reduces the growth rate of mussels (Table 6.6). *Ciona intestinalis* is found mainly in the centre of the farm and rafts where wave energy is reduced. The control of these organisms is imperative for efficient mussel farming to take place.

CHAPTER 7
SUMMARY AND CONCLUSION

The Saldanha Bay system is well suited to raft culture of the Spanish mussel, *Mytilus galloprovincialis*. At present the bay is the centre of mussel farming activity in South Africa with over 2500 tonnes produced in 1994, only nine years after the industry's initiation. The industry is now in the process of modifying its technology and refining existing production systems to meet local conditions after which it should grow rapidly to maturity. The design of the rafts used in Saldanha Bay is modelled on Spanish technology which is more suited for low wave energy conditions. An increase in South Africa's mussel production will require expansion into high wave energy areas, therefore new rafts are being designed and adapted for these high energy areas.

The current culture technique whereby the mussels are bound onto and suspended from ropes (average length 6m) in open water is the most appropriate system for the prevailing environmental conditions. Open water culture of mussels ensures greater food availability than in the traditional way of farming mussels in beds on the substratum. This is reflected by high growth rates and high condition of mussels cultured by this method. The high growth of mussels in Saldanha Bay is, however, principally a consequence of the fact that the bay is situated in an upwelling zone. The cold, nutrient rich upwelled waters promote phytoplankton growth and become productive on warming and with increasing light intensity. This results in a food rich environment and a temperature regime that is within the optimal range for farming *Mytilus galloprovincialis*. Wind and tide are the main driving forces controlling water currents in the bay, which in turn control the delivery of food to the farm and rafts. Wind induced currents are dominant over tide induced currents when the winds are strong particularly in winter when the water column is well mixed. In summer, under stratified conditions, the wind forces generate surface currents with tidal or compensatory deeper currents (Bilski 1995).

It has been shown in this study that food and fouling are primary factors determining the growth rate of mussels on the rafts. Primary production occurs outside the Bay (McQuaid, Rhodes University, pers.comm.), and inside the Bay (Pitcher, Sea Fisheries Research Institute, pers.comm.). This primary production and detritus brought in, or developed in the Bay, resulted in high chlorophyll *a* levels and POM levels being consistently above the pseudofaeces threshold of the

mussels. Water currents, which transport this food to the mussels, reach speeds of up to 20cm/s in Small Bay. However, on entering the rafts, water currents are attenuated by up to 90%. This reduces food delivery into the raft to near or below the pseudofaeces threshold and as a result the growth rate of mussels is reduced. Increasing the rope spacing from 60cm to 90cm reduces the attenuation of water flow to 72%. The increase in water penetration, and therefore the food input into the raft, resulted in a higher mussel growth rate of mussels during all seasons and improvement to the yield in summer months. The quantity of food reaching the centre of the 90cm rope spaced raft was substantially increased and maintained a level slightly below, at, or above the pseudofaeces threshold. Optimal rope spacing appears to be between 60 and 90cm, although this still needs to be determined empirically. Optimal rope spacing will ensure maximum growth and yield. The seeding densities of mussels on the ropes also appear to be critical. High densities of mussels reduce gape and feeding rate causing an increase in competition for food and space.

Apart from the growth limiting factors discussed above, fouling is regarded as the principal growth and yield inhibiting factor. There are two main fouling organisms: *Ciona intestinalis* and mussel spat. Each affects different zones in the rafts, however, both have the effect of reducing growth and yield of marketable mussels. Both organisms show a distinct pattern of settlement on both a farm scale and a raft scale. Mussel spat is transported passively in the surface water currents prior to settling. This results in the greatest numbers of spat settling on the periphery of the farm and of individual rafts. The resultant densities are extremely high and growth rates are reduced. The low energy areas in the centre of the farm, or of a raft, have lower mussel spat settlement but are colonised by *C.intestinalis*. Growth and colonisation by this organism is rapid, resulting in dislodgment and starvation of the production mussels on the ropes. The area settled by *C.intestinalis* will be greater if settlement takes place without competition from spat settlement. This is also the case with mussel spat if *C.intestinalis* is not present.

Therefore, for more successful mussel culture to take place, mussel farms would have to be spaced correctly so that water current speeds are not significantly reduced which impairs food penetration into the farms. As farms develop, the outer rafts may absorb energy and act as mussel spat collectors. On the other hand, the inner rafts will be in an area of reduced energy and so have less mussel spat but be more prone to *C.intestinalis* fouling. Larger wave resistant rafts will be more

susceptible to colonisation by *C.intestinalis* and as farms increase in size, the inner rafts will become increasingly prone to greater *C.intestinalis* settlement. If the *C.intestinalis* and mussel spat can be controlled then the fouling problems fall away. The outer rafts may be expensive energy resistant rafts and can effectively be used for spat collection while the cheaper, low energy inner rafts, which would be relatively free of fouling organisms, could be used as production rafts. Rafts should initially be placed at the present stocking density of approximately one raft of 11m x 22m per hectare of surface area. The rafts should also be orientated so that the prevailing currents enter the rafts perpendicularly as this improves water penetration into the raft. On the rafts themselves the rope spacing should be between 60cm and 90cm to maintain sufficient food penetration into the raft, ensuring maximum growth and yield from each raft. The number of mussels bound onto ropes must be standardised to an optimal density of seed per seed size, per metre of rope. This may possibly be extended to reducing the density of mussels on ropes in the centre of the raft to effect a reduction in competition for food and therefore increasing yield.

FURTHER STUDY

Given that mussels extract food in excess of their metabolic requirements a continuous study of mussel growth and food availability is imperative for sustained growth of the industry.

It is possible that a better insight into the feeding strategy of mussels would be gained by studying the enzymes found in the gut of mussels taken simultaneously from different points of the mussel rafts. This would possibly distinguish the food type being processed at different positions on the ropes and rafts and give some indication on the efficiency of food utilisation. Work on the optimal growth rations required by mussels in Saldanha Bay is necessary not only to maintain growth but also assist in optimal raft design.

The origin and genotypic variation of mussel spat settling on the mussel rafts should be determined, as correct seed management could significantly enhance production. The optimal stocking density of mussels, according to mussel size, on each rope through a mussel raft should be determined as this could reduce mortality, increase mussel gape and increase growth rates.

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