

A review of food availability, sea water characteristics and bivalve growth performance at coastal culture sites in temperate and warm temperate regions of the world

Sidney A. Saxby



Department of Fisheries
Government of Western Australia



Fish for the future

Fisheries Research Division
WA Marine Research Laboratories
PO Box 20 NORTH BEACH
Western Australia 6920

Fisheries Research Report

Titles in the fisheries research series contain technical and scientific information that represents an important contribution to existing knowledge, but which may not be suitable for publication in national or international scientific journals.

Fisheries Research Reports may be cited as full publications. The full citation is: Saxby, S. A. *A review of food availability, sea water characteristics and bivalve growth performance at coastal culture sites in temperate and warm temperate regions of the world*, Fisheries Research Report No. 132, Department of Fisheries, Western Australia, 42p.

Numbers 1-80 in this series were issued as Reports. Numbers 81-82 were issued as Fisheries Reports, and from number 83 the series has been issued under the current title.

Enquiries

Department of Fisheries

3rd floor SGIO Atrium

168-170 St George's Terrace

PERTH WA 6000

Telephone (08) 9482 7333

Facsimile (08) 9482 7389

Website: <http://www.wa.gov.au/westfish/res>



An electronic copy of this report will be available at the above website where parts may be shown in colour where this is thought to improve clarity.

Fisheries research in Western Australia

The Fisheries Research Division of the Department of Fisheries is based at the Western Australian Marine Research Laboratories, P.O. Box 20, North Beach (Perth), Western Australia, 6920. The Marine Research Laboratories serve as the centre for fisheries research in the State of Western Australia.

Research programs conducted by the Fisheries Research Division and laboratories investigate basic fish biology, stock identity and levels, population dynamics, environmental factors, and other factors related to commercial fisheries, recreational fisheries and aquaculture. The Fisheries Research Division also maintains the State data base of catch and effort fisheries statistics.

The primary function of the Fisheries Research Division is to provide scientific advice to government in the formulation of management policies for developing and sustaining Western Australian fisheries.

Contents

	Page
Abstract	1
1.0 Introduction	4
2.0 Marlborough, New Zealand	5
2.1 Pelorus Sound.....	5
3.0 British Columbia, Canada	8
4.0 Galicia, N.W. Spain	10
4.1 Ria de Arousa	10
5.0 Mediterranean Region	14
5.1 Gulf of Castellammare	14
6.0 Seto Inland Sea, Japan	17
7.0 Saldanha Bay, South West Africa	19
8.0 Eastern Scheldt Estuary, SW Netherlands	22
9.0 North Inlet, South Carolina, USA	23
10.0 Marine Lochs, Scotland	24
11.0 Hvalfjordur, Iceland	25
12.0 Tasmania, Australia.	26
12.1 Computer model	27
12.2 Environmental variables.....	27
12.3 Primary productivity and production between sites.....	29
12.4 Predictive modelling.....	30
12.5 Summary outcomes	31
13.0 South Australia, Australia	32
13.1 Coffin Bay, Eyre Peninsula	32
13.2 Ceduna	35
14.0 Summary and Recommendations - Food Availability and Water Conditions	36
15.0 Acknowledgments	40
16.0 References	40

A review of food availability, sea water characteristics and bivalve growth performance at coastal culture sites in temperate and warm temperate regions of the world

Sidney A. Saxby
Western Australian Marine Research Laboratories
PO Box 20, North Beach WA 6920

Abstract

The suitability of a coastal area for bivalve farming, as well as the density at which bivalves can be farmed in that area, is limited by the available food supply and other environmental variables. In this review, a range of successful and marginal bivalve growing areas in temperate and warm temperate coastal areas around the world are characterised. These include areas of high food and nutrient levels, such as Saldanha Bay in South Africa, and the Seto Inland Sea, Japan, through to more oligotrophic areas, typified by parts of the South Australian coastline and the Mediterranean sea. The latter areas are likely to be most similar to prospective sites that may be available in southernWestern Australia.

Environmental data collected at monthly or bimonthly intervals from commercial bivalve sites, and experimental sites, throughout the world, over periods extending from one to four years, reveals erratic but generally high phytoplankton levels at most sites. The presence of adequate particulate food is the consistent stimulus for good growth or condition of bivalves at most of these localities. Water temperature, current speed, water depth, nutrient levels and salinity also affect growth and condition, influencing both bivalve physiology and food availability.

*Phytoplankton levels, measured as chlorophyll a (Chl a) concentrations, varied predominantly between 1 and 10 mg/m³ at sites where bivalve growth did not appear to be greatly restricted by food availability, for example, around Vancouver Island, British Columbia, Saldanha Bay, South Africa, Tasmania, Australia, the Seto Inland Sea, Japan, and the Ria de Arousa, Spain. Where food supplies and/or nutrients were adequate, increased water temperature was associated with improved growth and condition and increased phytoplankton abundance. At these sites, water temperatures between 10 and 18°C promoted good mussel (*Mytilus edulis*, *M. galloprovincialis*) growth, while Pacific oysters (*Crassostrea gigas*) appeared to grow well between 12 and 25°C.*

*Salinity studies from 12 sites in Pelorus-Kenepuru Sound, Marlborough, New Zealand, showed that reduced salinity correlated with improved mussel (*Perna canaliculus*) condition index ($CI = 100 \times \text{steamed meat weight} \div [\text{live weight} - \text{shell weight}]$), higher nutrient levels, higher Chl a and larger quantities of particulates. These correlations revealed the input of nutrient- and organic particulate-rich fresh water into the system, promoting phytoplankton growth and food availability. Salinities consistently ranged from 29-35‰ with no noted adverse effects upon growth, condition or survival. In contrast, prolonged salinity levels below 20‰ in the*

presence of abundant food, at inner regions of estuaries in British Columbia, Canada, caused restrictions in Pacific oyster growth, as measured by whole weight, shell weight, shell height and dry meat weight. Condition (dry meat weight/shell weight) remained as high as in oysters from the most productive sites, but growth was greatly restricted. Prolonged exposure to low salinity may have depressed all growth parameters in these oysters through reduced mineral availability and stress-induced depressions of metabolic activity. Oysters at 4 sites within Coffin Bay, South Australia, experienced salinities between 36 and 45‰ over a 5 month summer - winter trial period. Chl a levels were similar among sites, and, at levels between 0.5 and 1.5 mg/m³, appeared adequate to sustain growth. Temperatures were also satisfactory, decreasing from 23 to 13° C. However, tissue and shell growth were greatly restricted at the two sites which had salinities predominantly above 40‰, while growth appeared more normal at the other two sites, where salinities lay mostly between 36 and 40‰. Unfortunately, high salinity was not established in this study as the cause of, or a contributing factor to, depressed growth. Further laboratory investigations were needed to determine local oyster salinity tolerances. Controlled growth trials at the high salinities encountered in the bay would have established if high salinity caused observed effects upon the oysters. Measurements of phytoplankton availability, which combine water flow and phytoplankton content, were also needed. These would have established if food was depleted at the farm sites where growth was arrested.

Increased salinity and reduced temperature with depth (haloclines and thermoclines) in the outer regions of Pelorus Sound and in Saldanha Bay, correlated with increased Chl a abundance, reflecting the subsurface inputs (advection) of nutrient-rich oceanic bottom water, arising from wind-driven upwelling. These inputs were seen as the main source of nutrients at both sites, stimulating subsurface phytoplankton blooms. Saldanha Bay also received inputs of phytoplankton-rich oceanic surface water, from the highly-productive Banguela upwelling system, through wind-forcing. The high productivity of Pipeclay Lagoon, Tasmania was also due to the levels of phytoplankton in surface waters, combined with the rapid tidal flushing rate of this shallow embayment.

The effects of stocking density (rope spacing) upon water flow rates through ropes were examined in Saldanha Bay. In this region, alternating longshore winds create most of the weak, intermittent current flow in the embayment. Even though this site shows a great abundance of phytoplankton, and mussels are harvested twice yearly, ropes at 60 cm spacings drastically reduced current flow, and consequently food supply was restricted in the centre of rafts. A 50% increase in rope spacing substantially lifted rope yields, mussel sizes and growth rates, especially in the centre of rafts. Yields improved overall by 10%, and the growth period was reduced by two weeks.

Concerns held by oyster growers and government authorities about the impact, on existing farms, of new leases and enlarged farms in productive oyster localities in Tasmania, led to an extensive ongoing study of water conditions, oyster clearance rates, phytoplankton levels and regeneration rates in major Tasmanian farming estuaries and embayments. Preliminary modelling of the effects of higher oyster farm stocking rates, in contrasting extremes of light, water dispersion and phytoplankton replacement by advection and regeneration, was undertaken for Pittwater. The region is a shallow marine embayment with very uniform vertical conditions of food availability, nutrient levels, salinity and temperature. Little input of fresh water and nutrient from terrigenous sources occurs, especially in summer. The model was able to predict that, in stable summer conditions with increased stocking rates on existing farms, or increases in number of farm leases, peak oyster feeding

rates in Pittwater would seriously deplete food resources. As a result, growth and condition of oysters would be compromised, and the viability of existing and proposed sites affected. Other sites in Tasmania are yet to be modelled, and data are still being gathered. Monthly Chl a readings were consistently above 1 mg/m³ at all sites while annual averages were above 2 mg/m³. Phytoplankton blooms predominantly resulted from input of terrigenous nutrient following rainfall. Temperatures ranged between 7°C and 20°C, and salinities were predominantly between 30 ‰ and 35‰.

Since water conditions and food availability fluctuate widely in coastal environments, sampling the various parameters accurately and representatively can be impracticable. Food availability and water conditions also interact in complex ways in their effects upon bivalve growth performance, and complete analysis of these effects has, in some of the studies, not occurred. Hence, the environmental data gathered may have been too limited or may not, in some studies, have correlated strongly with growth performance. Nevertheless, data made available from these studies do give useful, general indications of environmental conditions under which bivalve growth will support commercial exploitation.

In common with other productive sites around the world, existing commercial sites in Australasia have shown generally high phytoplankton levels combined with seasonal blooms, in favourable water conditions. It is logical that a potential Australian farm site would need patterns of phytoplankton levels, food availability and sea water conditions similar to, or better than, those reported at existing commercial sites.

Using the existing sites as a guide, a potential bivalve site in Western Australia may need:

- monthly Chl a levels consistently in excess of 1 mg/m³,*
- a mean annual Chl a reading between 2 and 3 mg/m³,*
- water temperatures ranging between 7 and 25°C ,*
- adequate water exchange and current flow,*
- sheltered conditions,*
- a regular marine or terrestrial source of dissolved nutrient or particulate food,*
- a range of salinity, and a temporal salinity regime, that does not put the animals under prolonged periods of physiological stress (perhaps 20‰ to 40‰ for C. gigas).*

Under such conditions, bivalve growth may be commercially exploitable, and a bivalve industry may be both viable and sustainable. Stocking at lower densities than those seen at existing commercial sites may allow farming to occur in areas where the above conditions of food availability cannot be met.

1.0 Introduction

This review was undertaken because of commercial interest in farming of bivalves in temperate and warm temperate coastal and estuarine waters of Western Australia. The relatively low nutrient levels and hence low phytoplankton content of much of the coastal waters of this state may be a limiting factor for bivalve farming. Pearce *et al.* (2000) have reviewed chlorophyll *a* concentrations for many of these coastal areas. Chlorophyll *a* concentration is a measure of the amount of phytoplankton in the water. Phytoplankton are the principal food source for sedentary bivalves. However, the chlorophyll *a* content of water alone may not be sufficient to indicate site suitability for bivalve farming. Other environmental factors have been identified as major determinants in the productivity of commercial bivalve growing areas in temperate and warm temperate waters throughout the world. In this review, a study of the range of influences upon bivalve growth and condition in each of the areas is undertaken to build a broad picture of the environmental characteristics of successful bivalve farms. This information may provide a guide to the selection of suitable sites and the method of cultivation of bivalves in coastal regions of southern Western Australia.

Sedentary bivalve molluscs are able to tolerate the wide range of water conditions which commonly occur in their natural estuarine or coastal habitats, however, their growth rates and flesh condition are strongly influenced by these fluctuations in environmental conditions. Temperature, salinity, particulate matter, food availability, current speed and water depth have been examined in multiple- and single-locality studies, and have been found to exert varying degrees of influence upon their growth and condition (Brown and Hartwick, 1988a; 1988b; Hickman *et al.*, 1991; Thorarinsdottir, 1994; Pérez-Camacho *et al.*, 1995; Stirling and Okumus 1995; Fernandez-Reiriz *et al.*, 1996; Sara and Mazzola, 1997). These studies of Pacific oysters (*Crassostrea gigas*), blue mussel varieties (*Mytilus edulis*, *M. edulis galloprovincialis*), scallops (*Pecten maximus* and *Chlamys islandica*) and New Zealand mussels (*Perna canaliculus*) indicate that substantial variability in bivalve growth rates can occur even within a single estuary or embayment, and that the relationship between growth or flesh condition and environmental parameters is complex. This reflects the wide range and rapid fluctuation that can occur in environmental variables within an area. Consequently, there is difficulty in obtaining representative environmental data to correlate with growth. In most of the sites studied, environmental data indicate that increased temperature and food availability may have the strongest positive influence on bivalve growth and condition (Hickman *et al.*, 1991; Thorarinsdottir, 1994; Stirling and Okumus, 1995; Sara and Mazzola, 1997). Prolonged exposure to low salinity may restrict shell and tissue growth, even though high nutrient levels in these water conditions promote phytoplankton growth (Brown and Hartwick, 1988a). While shell growth is slow, flesh condition may remain unaffected by low salinity (Brown and Hartwick, 1988b; Hickman *et al.*, 1991). Adequate vertical mixing and current flow can promote food availability, nutrient and water exchange rates (Heasman *et al.*, 1998; Boyd *et al.*, 1998; Gibbs *et al.*, 1992) while correct rope spacing is very important in maintaining food availability and therefore growth rates of mussels suspended in rafts (Boyd *et al.*, 1998).

As mentioned earlier, the food of bivalves is predominantly phytoplankton, which are single-celled or linked aggregations of autotrophic cells. Since the photosynthetic pigment chlorophyll *a* is present in all autotrophs, levels of phytoplankton at bivalve culture sites can be directly correlated with the amount of chlorophyll *a* extracted from site water samples. A sea water sample is filtered to remove particulates above a defined mesh size, say 50 µm, and the phytoplanktonic pigment, chlorophyll *a*, is extracted from the suspensions in the

filtrate, using acetone. Chlorophyll *a* concentration is determined by the difference of absorption at 665 nm of an acidified and non-acidified sample (which corrects for absorption of phaeopigments) (Hickman *et al.*, 1991). As this is a single, “instantaneous” measurement, phytoplankton levels may be converted to phytoplankton availability, by introducing such factors as tidal current flow and depth readings in sample localities. Researchers have found that high phytoplankton levels are a stimulant to improving growth and meat condition of bivalves (Brown and Hartwick, 1987a; 1987b; Sara and Mazzola, 1997; Heasman *et al.*, 1998), but these animals are also able to derive nourishment from other particulate organic matter (Hickman *et al.*, 1991; Pérez-Camacho *et al.*, 1995).

In selecting sites for bivalve culture, determinations of food abundance, current speed, mixing rates, temperature and salinity variations over an extended period of time would appear essential. It is likely that these environmental parameters will need to be similar to those of existing commercial bivalve culture sites, for any new venture to be viable.

The purpose of this report is to describe trophic and physico-chemical culture conditions at existing and experimental bivalve sites in different regions, with a view to providing reference information concerning the suitability of future sites for bivalve culture. Environmental conditions and details of research findings at various bivalve sites will be described, and a summary of conditions tabulated for between-site comparisons of environmental parameters and growth. Conclusions will suggest environmental parameters which may be required if an Australian bivalve site is to be sufficiently productive for commercial farming.

2.0 Marlborough, New Zealand

2.1 Pelorus Sound

Hickman *et al.* (1991) determined the monthly condition index ($CI = 100 \times \text{steamed meat weight} \div [\text{live weight} - \text{shell weight}]$) of green-lipped New Zealand mussels from 12 commercial longline sites in the Marlborough Sounds of New Zealand. The sites had variable current flows, degree of exposure and geographical position (inner, middle or outer region of the sound). Over two years, 6 of the 12 stations were sampled every two months for water salinity, total particulate matter, Chl *a* and particulate carbon. Chl *a* varied considerably between sites, with the most seaward sites generally having the lower values (Fig 1). Seasonal patterns in Chl *a* across the whole area and within regions were not evident. Values ranged between 0.3 and 3.2 mg/m³, with the highest values (above 2.0 mg/m³) restricted to the inner region of the sounds. Particulate carbon concentration was generally in the range 50-400 mg/m³, with higher levels only at the inner stations (up to 700 mg/m³). Salinity varied from 29-34 ‰ typically increasing between the inner and middle regions, and remaining steady in the outer regions, while water temperature variations showed a similar trend, being higher toward the inner stations in the summer and lower in the winter.

Condition index showed an annual cycle (high in autumn, winter and spring and low in summer) which varied from year to year, and a distinctive regional pattern of lowest in the most seaward positions and highest toward the upper reaches of the sound. Environmental data paralleled the condition index data by showing gradients along the length of the sounds, but large anomalies from regional patterns resulted from differing localised environmental conditions, arising in embayments away from the main channel. Very little variation in

CI occurred between exposed and sheltered sites and the exposure ratings did not prove an adequate predictor of mussel condition, when compared with salinity, Chl *a* or particulate carbon. Over the whole area, temperature and salinity were more strongly correlated with CI than food availability (Chl *a*, carbon and particulates). However, at lower ambient food levels, changes in CI strongly correlated with changes in particulate carbon, and slightly less strongly with Chl *a*. Above a food (particulate carbon) threshold of 200 mg C/m³, CI became more affected by temperature and salinity variations than by availability of food.

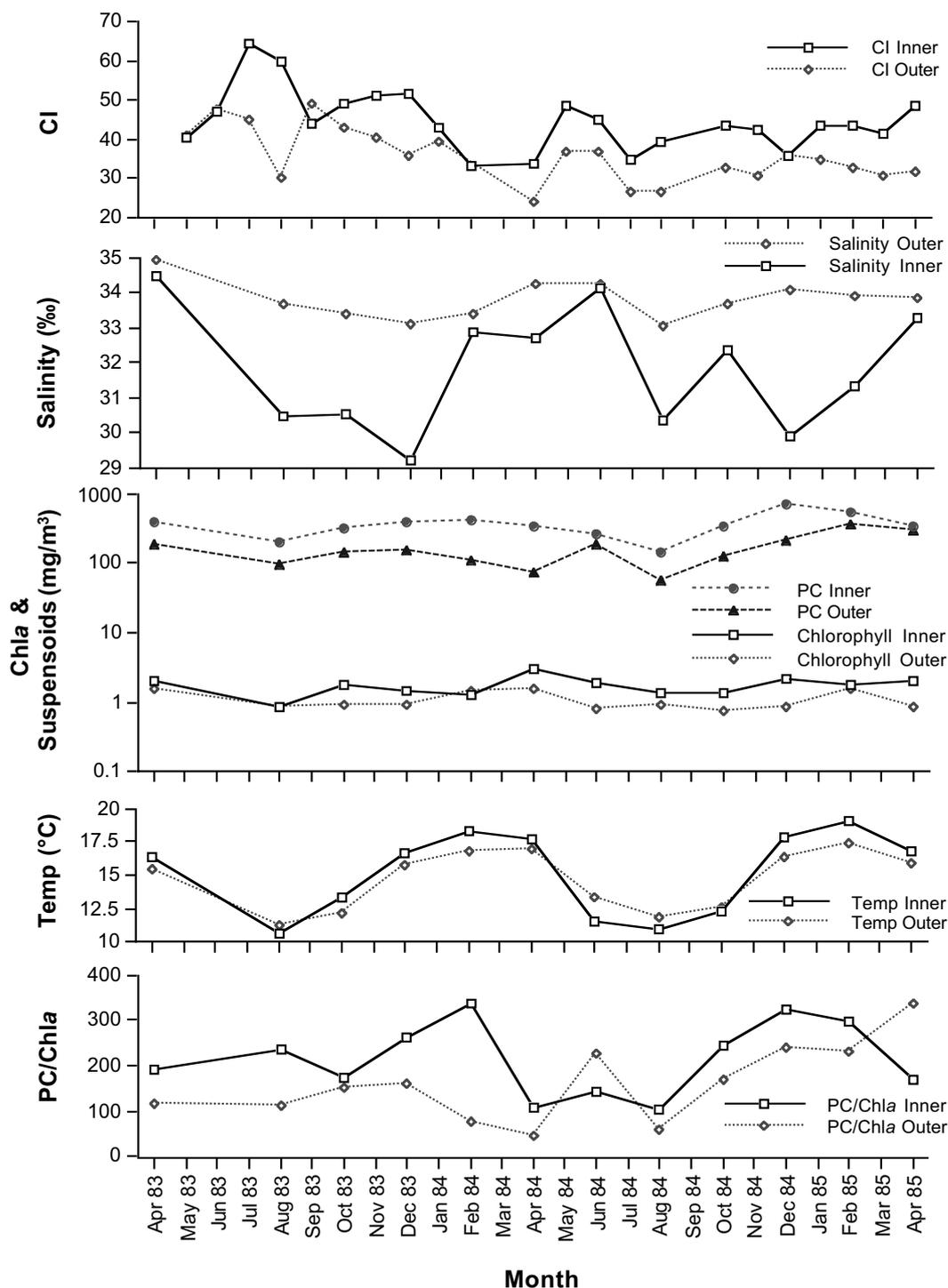


Figure 1. Mean monthly readings of condition index, salinity, temperature, Chl *a*, particulate carbon (PC) and PC/Chl *a* ratio from an inner (I) and outer (O) mussel site of the Marlborough sounds in New Zealand, from Hickman *et al.* (1991).

Individually, none of the environmental variables correlated strongly with CI, and Chl *a* showed the poorest correlation of all (Table 1). Stepwise discriminant analysis, however, suggested that changes in salinity and available food (as particulate carbon) were primary factors controlling high and low CI of the mussels. Analysis of monthly data revealed that 88% of the low CI observations were associated with high salinity, while 54% of the high CI observations were associated with low salinity. If Chl *a* concentration was included, 82% of the low CI group was associated with a high salinity : low chlorophyll regime, while 62% of the high CI group were associated with a low salinity : high chlorophyll regime. There were marked cross-correlations between temperature, salinity and food resource indicators which prevented a clear identification of a single environmental factor determining CI. There was a relatively strong correlation between particulate organic carbon and Chl *a* ($r = 0.521$).

Table 1. Correlation matrix (*r* values) for environmental variables and two mussel variables at 12 locations in the Marlborough Sounds (from Hickman *et al.*, 1991).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Salinity (1)	1.000							
Temperature (2)	0.075	1.000						
Chlorophyll <i>a</i> (3)	-0.105	0.438	1.000					
Particulate Carbon (4)	-0.277	0.569	0.521	1.000				
Particulate Inorganic Matter (5)	-0.442	0.369	0.325	0.311	1.000			
PC : TPM (6)	0.104	-0.194	-0.187	-0.152	-0.388	1.000		
Mussel Length (7)	0.021	-0.142	-0.171	-0.161	-0.125	0.091	1.000	
Condition Index (8)	-0.260	-0.217	-0.050	0.199	-0.076	0.177	-0.003	1.000

While phytoplankton has been identified elsewhere as the principal food source of farmed mussels (Smaal and van Stralen, 1990; Heasman *et al.*, 1998), supplementation by detrital organic matter appears to be very important in the Marlborough sounds, as evidenced by the better correlation in this study of CI to particulate carbon than to Chl *a*. This study, however, was limited in its suitability for analysing the causes of variation in CI. Condition index provides an integrated measure of feeding and associated metabolic activity of mussels, over a long period of time, while the environmental data represent short-term or instantaneous measurements of several factors, each showing a different degree of temporal variability. The authors pointed to the need to increase the frequency of site sampling, and to determine the degree of on-site variability in abiotic and food factors, including determinations of current flow and phytoplankton availability around ropes, in order to more clearly define the causes of variation in condition index in the Marlborough Sounds.

A later study (Gibbs *et al.*, 1992) determined the availability of chlorophyll *a* and nutrients in the same region, by examining on-site nutrient and Chl *a* flux from surface to bottom, and between sites in the sounds. Large nutrient and Chl *a* variability was evident in Pelorus Sound, resulting from the complex hydrodynamic regime operating on three major nutrient sources: sediment remineralisation, advection from the ocean and river inflows. Short temporal changes (minutes to hours) in nutrient and Chl *a* were caused by tides, while long-term changes (days to months) were associated with floodwater, retention times in the system and oceanic exchange. High nitrogen concentrations and Chl *a* abundance in the inner sounds were associated with rainfall, while the highest levels in the seaward (outer) region were associated with sediment remineralisation, oceanic exchange and seasonal variations in oceanic waters in Cook Strait. Some flushing effects were evident with high

rainfall events, where nutrients and phytoplankton were almost completely removed from the system. Lowest nutrient and Chl *a* levels occurred in summer, associated with the lowest rainfall, and low nutrient levels evident in Cook Strait sea water. In localised embayments, separated from the main water flow, accumulation of N in the bottom water layers resulted in high concentrations of Chl *a*, coinciding with the halocline, which was below the levels of mussel farms. However, periodic internal waves of the halocline may have moved the phytoplankton-rich high salinity water up to the levels of the mussel farms on occasion. Table 2 presents mean suspended and Chl *a* levels over the study period.

Table 2. Means and ranges (in parentheses) of suspensoids (in mg/m³) measured in Pelorus Sound, Jan. 1984 - Apr. 1985 (from Gibbs *et al.*, 1992).

Region	Suspended Solids	Chlorophyll <i>a</i>	PC	PN	PP
Inner	1139 (372-3630)	1.81 (0.6-6.0)	327 (46-1472)	33.1 (14.4-71.4)	5.3 (1.4-19.7)
Middle	1002 (196-6320)	1.39 (0.16-4.4)	247 (67-600)	24.3 (4.5-79.2)	3.9 (0.8-28.1)
Outer	778 (129-2310)	1.31 (0.13-4.7)	213 (43-529)	21.4 (6.5-73)	2.5 (1.1-8.2)

PC = Particulate Carbon PN = Particulate Nitrogen PP = Particulate Phosphorus

3.0 British Columbia, Canada

Growth, condition indices and survival of Pacific oysters (*Crassostrea gigas*) at 10 locations were determined over a 14 month period (Brown and Hartwick, 1988a, 1988b). Locations were selected along the coastline of mainland British Columbia and Vancouver Island, in existing oyster culture areas as well as areas where environmental conditions or conflicting coastal developments restricted commercial bivalve culture. Monthly monitoring of experimental sites occurred between June, 1984 and August, 1985, except in January, 1985. At each site, two age classes of cultchless oysters from the same seedstock were placed in separate 5-tier lantern nets. Age classes (Year 0 and Year 1) had initial shell heights of 21.6 mm and 45.2 mm. Approximately 165 oysters were spread evenly among the lantern tiers. Nets were submerged continuously at a depth of 1 m, extending down to 5 m.

Growth was highly variable between sites for both year classes. Final mean shell height ranged from 57 mm to 100 mm for year 0, and 69 mm to 109 mm for year 1 oysters. Sites were divided into low, medium and high growth groups on the basis of shell height growth curves. Measurements of growth in dry meat weight followed the same growth group pattern. When allometric growth regressions were fitted to shell height and dry meat weight data, oysters from the high growth sites had allometry not significantly different from those at low growth sites.

Between sites, water temperatures ranged from summer maxima of 17 to 21.6°C, to winter minima between 2.5 and 7°C. Salinity fluctuated seasonally, as well as varying greatly between sites. Sites adjacent to local rivers had reduced salinity, and prolonged periods of salinity below 20 ‰, especially in the spring-summer period (April - August 1985). Compared with the other bivalve sites in this report, salinities across all sites were low (usually 20 - 30 ‰). Phytoplankton blooms occurred in autumn and spring at most sites, with highest mean monthly Chl *a* readings around September and October. Peak monthly Chl *a* levels coincided with low salinity readings, indicating higher nutrient input from increased spring and autumn runoff. Temperature, salinity and Chl *a* monthly means were

Table 3. Environmental cumulative day-data and means, with summary of comparisons of regressions of fitted to site-specific absolute and allometric growth data for Pacific oysters *Crassostrea gigas* at ten sites in British Columbia, Canada between July, 1984 and August, 1985 (from Brown and Hartwick, 1988a).

	Environmental Data			SH	WW	Growth Data			SWvsDMW
	DD Md	DS Ms	DC Mc			SW	DMW (1984)	DMW (1985)	
Trevenen Bay	5101 13.1	11735 30.2	1990 5.12	H	H	H	H	H	H (1)
Okeover Inlet	5550 14.3	10810 27.7	1464 3.76	H	H	H (1)	H(1,2)	H	H(2)
Lemmens Inlet 1	5192 13.3	9063 23.3	2910 7.48	H	H	H(1,2)	H(1,2)	H	H
Lemmens Inlet 2	5066 13.0	9205 23.6	3645 9.37	H	H	H(1,2)	H(1,2)	H	H
Departure Bay	5029 12.9	8872 22.8	1273 3.27	M	H	H(2)	H(2)	M	M
Saanich (1 m)	5263 13.5	9919 25.4	1243 3.19	M	M	H(2)	M	M	M(2)
Saanich (5 m)	5073 13.0	10498 26.98	1353 3.47	M	M	H(2)	H(2)	M	M(1,2)
Bowen Island	4710 12.1	6841 17.6	2224 5.72	M	M	M	H(2)	M	M(2)
West Vancouver	4742 12.2	7502 19.3	3088 7.94	L	L	L	L	L	H
Keats Island	5411 13.9	6802 17.5	1329 3.41	L	L	L	L	L	H

High (H), medium (M) and low (L) growth groups indicate sites with significantly different growth ($p < 0.05$). Numbers in parentheses indicate significant growth differences between some sites within growth groups. For example, shell weight growth for Departure Bay was significantly different from Trevenen Bay and Okeover Inlet but not Lemmens Inlet sites, while Trevenen Bay, Okeover inlet and Lemmens Inlet sites had similar growth.

DD day.degrees DS day.salinity DC day.Chl *a* SH Shell height WW whole weight SW shell weight
DMW (1984),(1985) dry meat weight in summer (1984) and winter sections(1985) of the growth period
SWvsDMW Allometric growth, shell weight vs dry meat weight
Md mean temperature °C Ms mean salinity (‰) Mc mean Chl *a* (mg/m³)

converted to cumulative day.degrees, day.salinity and day.Chl *a* values, by multiplying average readings between two visits, or two monthly means, by the number of days separating the visits. Table 3 summarises growth and environmental data from the ten sites. In high growth sites, oysters had greatest increases in shell heights and whole weights, attributed to high phytoplankton availability and suitable salinity and temperature regimes. At medium growth sites, shell height and dry meat weight was less than at high growth sites, but whole weight and shell weight was not restricted. Temperature and salinity were suitable, but food availability may have been restricted. Growth in all body variables was reduced at low growth sites, because periods of high food availability coincided with prolonged, sub-optimal salinity conditions (< 20 ‰). Prolonged exposure to low salinity may have depressed both shell and meat growth in oysters through reduced mineral availability and stress-induced depressions of metabolic activity.

Volumetric condition index (dry meat weight/internal volume, VCI) and dry weight (dry meat weight/dry shell weight, DWCI) condition indices were regarded as within the normal

range for Pacific oysters in this region, and higher overall than oysters cultured elsewhere. Volumetric condition index correlation coefficients ranked monthly whole weight, water temperature, salinity and Chl *a* in decreasing order as factors contributing to variance in VCI data. Variables significantly correlated with DWCI, in decreasing order of importance were: water temperature, salinity and Chl *a* concentration. Salinity was negatively correlated with DWCI and VCI (Table 4). The authors concluded that DWCI was a better index for evaluating the physiological status of oysters, with seasonal fluctuations of this index following trends in water temperature, salinity and food availability. A considerable amount of the total variance in both condition indices was not attributed to the environmental factors mentioned, and the authors indicated that they may have been affected by gonadal maturation and spawning.

Slow growing oysters from low salinity sites (<20 ‰) had DWCI equivalent to those of fastest-growing oysters at high salinity sites with abundant food supply, illustrating the reduction in all growth parameters in low salinity water. Chl *a* levels at low salinity sites fluctuated more than at high salinity sites, with average levels generally higher than the more saline sites.

Table 4. Significant partial correlation coefficients of volumetric condition index and dry weight condition index against environmental factors and monthly Pacific oyster (*Crassostrea gigas*) weight (from Brown and Hartwick, 1988b)

	Temperature	Salinity	Chlorophyll <i>a</i>	Wet Weight
VCI	0.336	-0.277	0.141	0.502
DWCI	0.519	-0.236	0.141	

Most oyster mortalities occurred in the initial 2-3 months, with year 0 oysters showing lower survival rates. Differences in survival between sites were not significant. Inner-facing surfaces of dead oysters from low salinity sites had patches of extreme shell thinness and blistering, thought to be due to lack of minerals and environmental stress.

Growth rates of Pacific oysters at the better British Columbia commercial sites (80 mm/yr) are equivalent to oysters in Hinase waters, Tasmania, and Galician rias (Table 17). In contrast, growth at the low-salinity trial sites was very slow (10 mm/yr). Although chlorophyll levels at the trial sites were comparable to other very productive sites worldwide, prolonged exposure to low salinity (< 20 ‰) has restricted both shell and tissue growth of Pacific oysters.

4.0 Galicia, N.W. Spain

4.1 Ría de Arousa

Pérez-Camacho *et al.* (1995) investigated the influence of seed source, cultivation site and phytoplankton availability (measured as Chl *a*) upon the growth and CI of *Mytilus edulis galloprovincialis* within the Ría de Arousa in Galicia, north western Spain. Mussel seed, obtained from the intertidal zone or from collector ropes, was cultivated for three months on ropes suspended from three rafts located at three different sites within the estuary.

Phytoplankton availability at each of the sites was markedly different (Table 5). Seed stock originating from two intertidal zones (Stocks A and B) had lower growth rates than the collector rope stock (C), probably because of the better initial condition and previous adaptation of the seed originating from the collector rope. Phytoplankton availability (as grams Chl *a*/rope/hour) at the cultivation sites was measured by water Chl *a* content and current flow:

$$F = \text{Chl } a \times f \div N,$$

where F is grams of chlorophyll *a* per rope per hour, Chl *a* is grams of chlorophyll *a* per cubic metre, and N is the number of ropes per metre, and f is the current flow in cubic metres per hour.

Table 5. Current speed, water flow, chlorophyll *a* content, phytoplankton availability and mussel growth of stocks derived from intertidal zones (A and B) and rope culture (C) at the three mussel sites (1, 2 and 3) within the Ría de Arousa, Spain (from Camacho *et al.*, 1995).

	Site 1			Site 2			Site 3		
Current (min., max.) (cm/s)	1.81 (0, 12.45)			2.99 (0, 23.5)			3.04 (0, 30.7)		
Water flow (m ³ /raft/h)	14 661			24 219			24 264		
Chl <i>a</i> (mg/m ³)	4.2 ± 1.22			3.1 ± 1.88			4.4 ± 1.61		
Phytoplankton availability (g Chl <i>a</i> /hr/rope)	0.123			0.15			0.216		

Stock source	Site 1			Site 2			Site 3		
	A	B	C	A	B	C	A	B	C
Shell length increase (mm)	20	19	25	21	18	25	21	20	32
Live weight increase (g)	2.5	3	6.5	2.8	2.5	7	3	4	10.5

Condition Index	Beginning of Trial		End of Trial	
	Stock A	15		22
Stock B	16.5		22.5	
Stock C	19.5		23	
Site 1	16		24.5	
Site 2	16.5		16.5	
Site 3	16.3		27	

Growth of stock from the two intertidal zones showed no significant differences across all sites. However, superior growth performance came from the collector rope seed (stock C) at all sites, with growth greatest at the oceanic site (site 3). This was directly related to the greater availability of phytoplankton. Growth of collector rope seed at the other two sites was not significantly different, despite almost 20% lower phytoplankton availability at site 1. Although particulate carbon was not measured in this study, the authors indicated that presence of detritus at site 1 may have been high, since it was the most landward station of the three, and thus a higher contribution to the food of the mussels may have been derived from this source.

There were significant differences between the condition index of the seed stock collected from each intertidal site (A and B) and the collector rope stock (C) at the beginning of the experiment, with stock A having the lowest CI and stock C having the highest CI. At the end of three months, no significant differences in CI between stocks were evident, therefore the readings of each stock type in each locality were pooled. However, the condition index for all mussels at each locality, which were not significantly different at the beginning of the trial, showed significant improvement at sites 1 and 3, and remained the same at site 2. Once again, the authors pointed to greater availability of phytoplankton at site 3 and a possible supplementary food source from seston at site 1 for the improvements in condition of the mussels at these sites. Over the ninety days of the experiment (April-July, spring-summer growing season), mussels grew at a rate of 6.3 - 11 mm/month, at an initial rope density of 2000/m. Water conditions at all sites were similar; mean temperature ranged between 13 and 17°C, while salinity remained at 34-35 ‰ (Table 17).

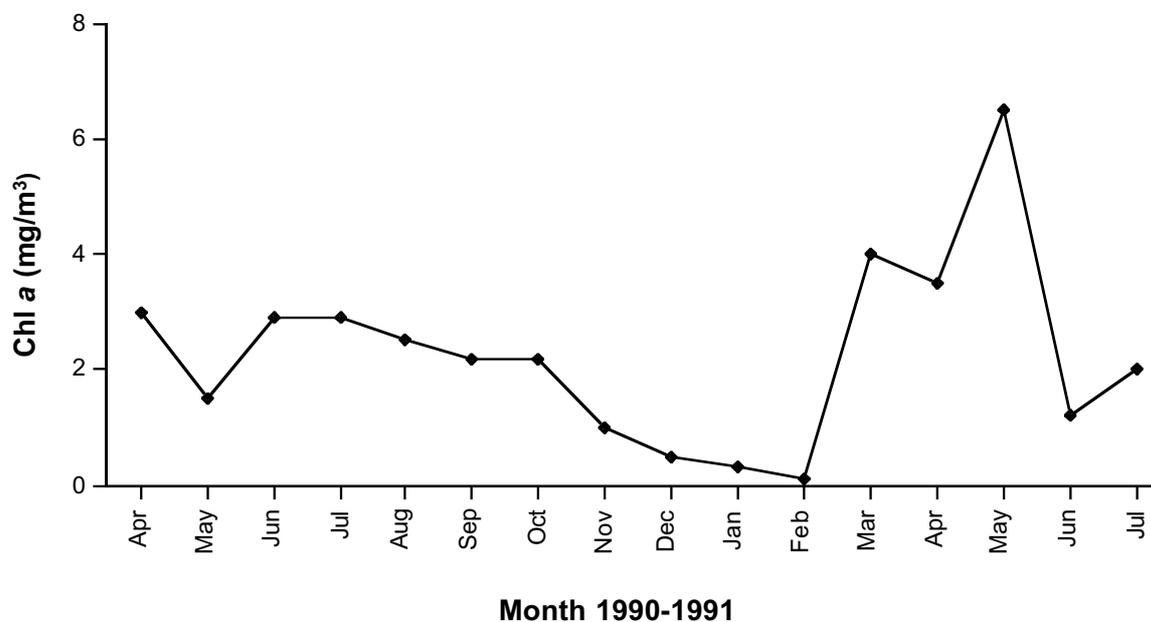


Figure 2. Mean monthly readings of Chl *a* in the Ria de Arousa (from Pazos *et al.*, 1996).

Pazos *et al.* (1996) studied scallops (*Pecten maximus*), cultured by the ear-hanging technique, in the Ria de Arousa and examined their reproductive cycle, in relation to water temperatures and Chl *a* readings. Temperatures ranged between 11 and 21°C, mean monthly Chl *a* values are shown in Fig 2. Spawning appeared to be stimulated by temperatures above 16°C in spring/summer (May-July) and the presence of a phytoplankton bloom in winter (Feb - March), when temperatures were 12 - 13°C. Seston levels varied on a seasonal basis, with high levels of PIM during winter, while POM remained relatively stable around 2 mg/m³.

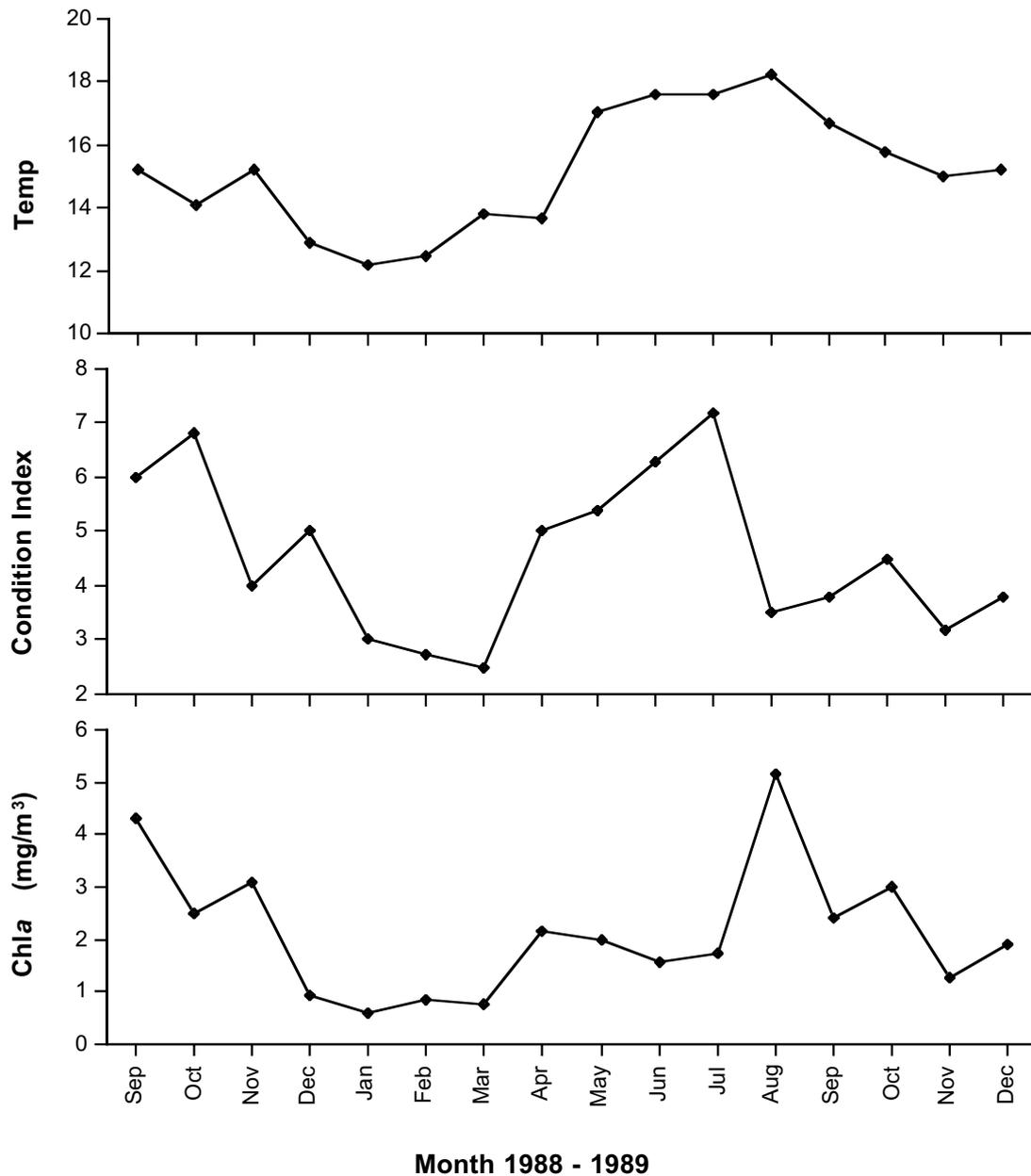


Figure 3. Mean monthly water temperatures and chlorophyll a readings, with oyster condition indices in El Grove, Ría de Arousa, Galicia, in 1988-89 (from Ruiz *et al.*, 1992).

Ruiz *et al.* (1992) examined the effect of temperature, salinity and Chl *a* upon the condition, reproductive activity and biochemical composition of Pacific oysters, *C. gigas* in suspended culture in El Grove, Ria de Arousa, Galicia, over 16 months. Two spawning periods (June/July and October) were evident from histological studies. The first spawning event took place as a result of water temperatures, while the second appeared to coincide with a major phytoplankton bloom. Data for temperature, Chl *a* variations and oyster condition for the period Sept 1988 to Dec 1989 are presented in Figure 3. Condition index was determined as [mean ash-free dry weight/mean dry shell weight] x 100

A Kendall matrix revealed that temperature correlated significantly with Chl *a*, meat dry weight, condition index and maturity index (arithmetic mean of individual gametogenic development) of oysters at this site. Chl *a* correlated significantly with the maturity index of

the oysters. The correlations and the spawning of oysters at temperatures below 16°C supported the authors hypothesis that spawning in *C. gigas* may be induced by phytoplanktonic blooms as well as temperature.

4.2 Ria Sada

In a study of mussels (*Mytilus edulis galloprovincialis*) cultured in two adjacent zones of the Ria Sada (Galicia), Fernandez-Reiriz *et al.* (1996) found a close correlation between chlorophyll *a* abundance and growth of mussels. Both mussel sites were on the seaward verge of the southern edge of the Ria Sada, and 3.2 km apart. Mussels were cultured from seed size to “first split” (initial mean size 28 mm, reaching 42 mm at the inner site) over the winter period, November 1992 to April 1993. Mussels exhibited faster growth in the inner zone site, which had consistently higher Chl *a* levels throughout the year. Mean annual Chl *a* values were 1.763 mg/m³ and 1.066 mg/m³ for each site, while the ranges were from 0 to 2.5 mg/m³ at the outer site and 0 to 8 mg/m³ at the inner site. No measurements were made of suspended particulates, salinity or current flow at the sites. Growth rates for the mussels, measured as allometric growth rates (Y = dry meat weight, X = size) were:

$$Y = 0.00264 X^{3.062} \text{ (} r = 0.996, p < 0.0001, n = 10 \text{) at the inner site}$$

$$Y = 0.00668 X^{2.782} \text{ (} r = 0.998, p < 0.0001, n = 10 \text{) at the outer site}$$

5.0 Mediterranean Region

5.1 Gulf of Castellammare

Crassostrea gigas, cultured experimentally on longlines in the Gulf of Castellammare (Northern Sicily) at depths of 7 and 13 m, grew at similar allometric rates in almost identical phytoplankton concentrations (Sarà and Mazzola, 1997). The lower oysters were slightly faster growing (not significantly), and the authors linked slightly better growth at greater depth to the greater abundance of particulate organic matter (POM) available (Table 6). The allometric growth rates[§] were very similar at -7 and -13m:

$$Y = 7.54 \times 10^{-6} X^{2.45} \text{ (} r = 0.96, p < 0.01, n = 652 \text{) at -7 m}$$

$$Y = 7.54 \times 10^{-6} X^{2.48} \text{ (} r = 0.96, p < 0.01, n = 692 \text{) at -13 m}$$

≈ From the stated means and s.d. (Table 6), it is difficult to agree with the authors' calculations of a P (probability) of 0.005 that the two POM means are similar. As well, the significance levels of differences in pH, DO, temperature and Chl *a* /POM between -7m and -13m seem incorrect. However, the data were not normal, and matrices of data were transformed using Spearman Ranks.

§ Published equations were $DW = -11.80SL^{2.45}$, and $DW = -11.80SL^{2.48}$, coefficients in the text were derived from the published graph by interpolation.

The low chlorophyll values (0.04 and 0.05 mg/m³ at each depth) and small proportion of Chl *a* to POM (less than 3% over the year) of the area characterised the gulf as oligotrophic. Significant differences in POM and POM energy content between the two depths were reported to have reached their greatest magnitude during late summer and early autumn, but tabulated monthly values showed little consistent variation between the two depths. The authors reported visual sightings of a greater turbidity at -13 m, and an increase in water POM gross energy (GE) content at this level, which appear to indicate a greater availability of non-phytoplanktonic POM at the -13 m level during the winter. Although the authors have indicated that there were differences in the water parameters at the two levels, their tabulated data do not reflect this. Similarly, growth at the two levels appear almost identical. Figure 4 displays the mean monthly Chl *a*, POM GE and temperature data for the two depths.

Table 6. Mean (\pm s.d.) physico-chemical and trophic parameters and the significance levels of *U*-tests between the means for each depth (from Sarà and Mazzola, 1997).

	-7 Metres	-13 Metres	P
Temperature (°C)	19.81 \pm 4.67	18.03 \pm 3.03	0.01
Salinity (‰)	37.5 \pm 1.11	37.8 \pm 0.20	0.28
DO (% sat)	85.67 \pm 12.78	89.33 \pm 9.33	0.009
pH	8.31 \pm 0.11	8.32 \pm 0.11	0.06
Chl <i>a</i> (mg/m ³)	0.05 \pm 0.01	0.04 \pm 0.01	0.40
Phaeopigments (mg/m ³)	0.02 \pm 0.01	0.02 \pm 0.01	0.80
Carbohydrate* (mg/m ³)	188 \pm 216	141 \pm 133	0.51
Protein* (mg/m ³)	76 \pm 34	80 \pm 43	0.85
Lipid* (mg/m ³)	81 \pm 87	111 \pm 130	0.95
POM (mg/m ³)	344 \pm 201	334 \pm 228	0.005
POM gross energy (kJ/g)	5.97 \pm 1.29	6.13 \pm 0.80	0.02
Chl <i>a</i> /POM index	1.43 \pm 0.74	1.21 \pm 0.76	0.87

* particulate nutrient composition

A subsequent study by Sarà *et al.* (1998) of mussels (*Mytilus galloprovincialis*) on longlines in the same area was carried out over the period, May 1994 to April 1995. Juvenile mussels grew approximately 30 mm in the year (11.2 to ~40 mm), while sub-adults in the same culture conditions grew about 20 mm, to market size (~40 mm to \geq 60 mm). Chl *a* ranged between 0.03 and 0.08 mg/m³, with a mean of 0.05 mg/m³ during the period. Daily specific growth rates were determined over periods of a month in summer and 2 months in winter. Many unpredictable daily specific growth rate fluctuations (in both length and weight) of both juvenile and sub-adult populations occurred over the trial period, but lowest overall growth rates were evident during the summer/autumn (Fig 5). Mussel flesh condition reduced (and hence daily SGR's, based on mean ash-free dry weight, were negative) during these periods where food availability, or proportion of food to suspended inorganic sediment were lowest, and may have been related on one occasion to a spawning event in the adult population. The authors noted that this region may be able to support growth of mussels, but that recruitment did not occur, probably because of the area's oligotrophic nature. They proposed that the site could support longline culture of mussels, transferred from other culture sites.

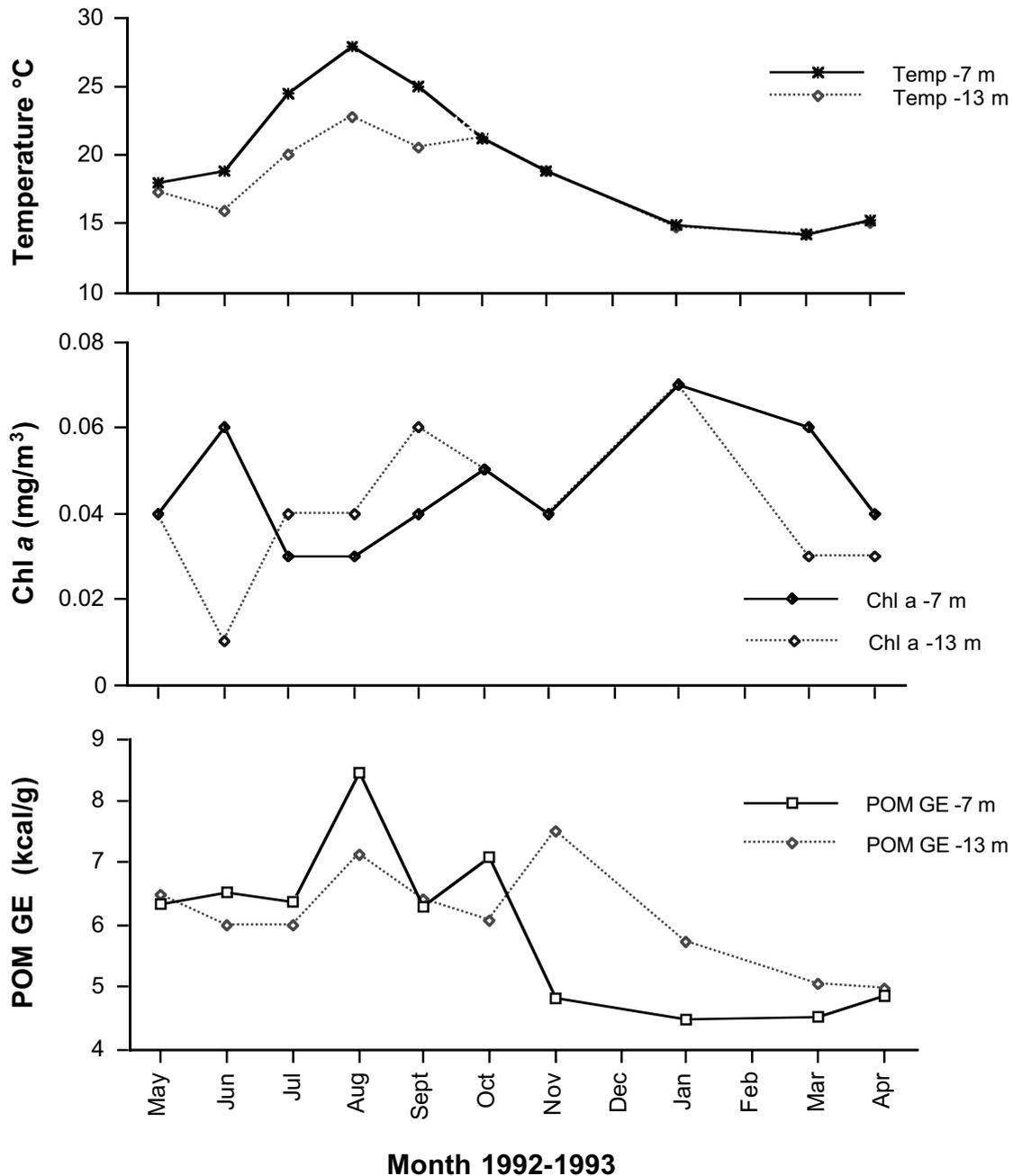


Figure 4. Mean monthly temperature, particulate organic matter gross energy (POM GE) and chlorophyll a readings at depths of 7 and 13 m in the Gulf of Castellammare (from Sarà and Mazzola, 1997).

Physico-chemical conditions in the Gulf of Castellammare appear to be suitable for oyster growth, but the limited availability of labile particulates and low Chl *a*, in comparison with other European, Japanese and New Zealand sites (which generally average above 1 mg/m³), do not indicate that this is a productive bivalve culture region. Oysters and mussels grew a total of ~30 mm over a year, but with frequent losses in mussel flesh condition (Sarà *et al.*, 1998) and very limited oyster growth (from 12 to 16 mm) in the autumn-summer period (May-Nov) (Sarà and Mazzola, 1997). Oysters grew from 16 to 42 mm, and mussels had more months of rapid growth and improving flesh condition, in the winter/spring months (Nov-Apr).

Very low food availability probably caused the restriction in growth rates during summer months. If low summer Chl *a* and POM combined with low water dispersion (as indicated by the recorded permanent summer thermocline at 10 m depth in the Gulf of Castellammare) are a feature of this oligotrophic region, it would have very limited capacity to support the development of commercial bivalve culture. For instance, Crawford *et al.* (1996), in modelling the impact of high and low stocking rates on farm sites in Pittwater, Tasmania, illustrated that in stable summer conditions of low water exchange (low dispersion), high grazing rates and high light/temperatures, large depletions in food supply would occur around the present farm sites (Table 15). If large depletions of food are likely in and around the Tasmanian farm sites with stable summer weather conditions, and mean annual Chl *a* readings ten to one hundred times those of the Mediterranean site, they are very likely to occur with oysters and mussels at commercial stocking densities in the Gulf of Castellammare.

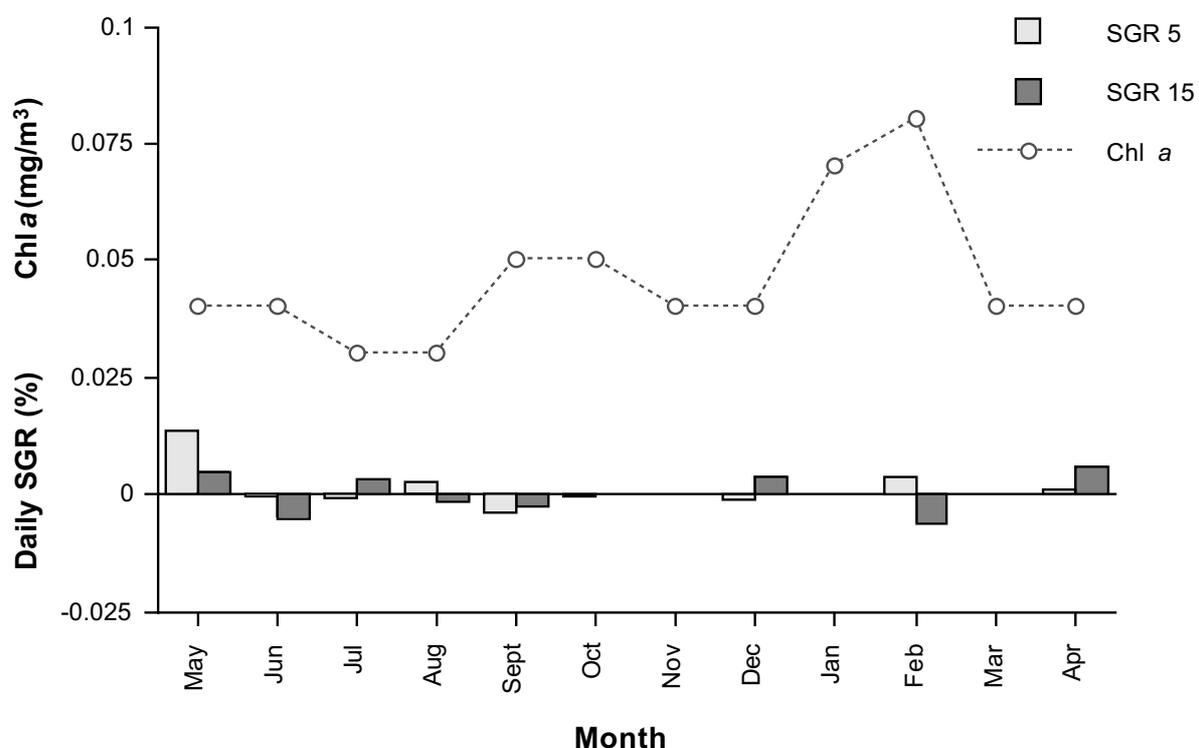


Figure 5. Daily specific growth rates of Pacific oysters (*Crassostrea gigas*) at depths of 5 and 15 metres, and water chlorophyll levels in the Gulf of Castellammare, Sicily (from Sarà *et al.*, 1998).

6.0 Seto Inland Sea, Japan

A large proportion of Japanese mariculture of bivalves (90% of the Okayama Prefecture production since 1950) is centred around the Seto Inland Sea, and Kobayashi *et al.* (1997) have developed a model for the growth of *C. gigas* in this area. As part of their research, readings of the temperature, salinity and Chl *a* content of the waters in the Hinase region were made. Figure 6 displays the average monthly readings of four experimental areas in Hinase waters between May 1990 and January, 1991.

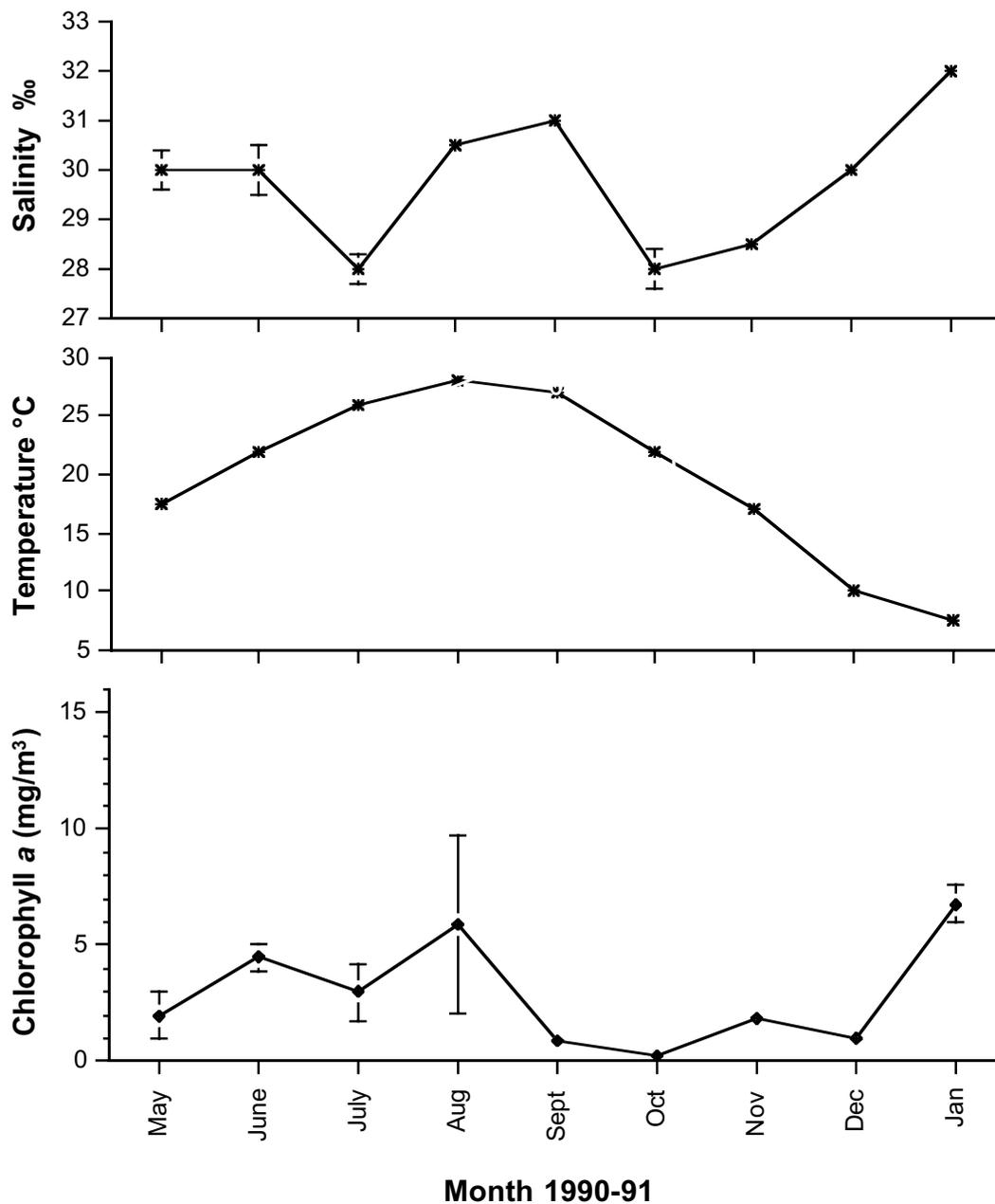


Figure 6. Mean (\pm s.d.) monthly readings of Chl *a*, temperature and salinity for Hinase waters in the Seto Inland Sea, Japan (from Kobayashi *et al.*, 1997).

Shell height and dry flesh weight of oysters were determined, giving an allometric growth rate of:

$$Y = 0.046 X^{2.65}$$

Oysters grew from 27 mm to 93 mm between May 1990 and January 1991, with two thirds of the growth occurring between June and September. Increase in live wet weight was almost linear over that period. Oysters were able to grow a total of 90 mm in an 18 month period (Aug 1990 - Jan 1991), and growth appears to be faster than for *C. gigas* at Tasmanian and Galician sites (Table 17).

While food availability of Hinase waters, as indicated by mean Chl *a* content, is similar to

the mussel and oyster sites in Tasmania, New Zealand and the Ria de Sada, higher summer temperatures, coupled with good summer phytoplankton availability may contribute substantially to more rapid annual growth rates in the Seto Inland Sea.

7.0 Saldanha Bay, South West Africa

Most of the mussel (*Mytilus galloprovincialis*) culture in South Africa occurs in Saldanha Bay, a semi-enclosed embayment on the south west coast. Cold water, nutrients and phytoplankton periodically enter the bay from the highly-productive, wind-driven Banguela upwelling system. Growth rates of mussels in this embayment are extremely rapid; shell lengths increase an average of 1.5 mm/week during autumn/winter, and 2.5 mm/week during spring/summer growth. Rafts supporting ropes at 60-90 cm spacing (approx 1.5 - 2 ropes/m²) produce two harvests a year (Heasman *et al.*, 1998), contributing to an overall annual market production of more than 2500 tonnes from less than 3 ha of rafts (Boyd and Heasman, 1998). In one spring-autumn growing period, mean single rope production from adjacent rafts, with rope spacings at 60 and 90 cm, were 252 kg and 307 kg, respectively, contributing to a small raft (15 x 11 m) marketable production of 26.1 to 28.6 t over the period (Heasman *et al.*, 1998).

Pitcher and Calder (1998) have determined phytoplankton availability throughout the bay, at different depths, and over time. Monthly mean concentrations of Chl *a* were calculated from daily means, derived from water column integrals of Chl *a* at a monitoring buoy, stationed adjacent to mussel rafts (Fig 7). A mean water column Chl *a* reading over the sampling period (winter 1993 - autumn 1995) was determined as 8.62 mg/m³, with a mean daily rate of primary production of 3.4 g C/m²/d (Pitcher and Calder, 1998). A general increase in biomass occurred during the upwelling season, with highest Chl *a* readings at the end of the season. During the September to December period, mean Chl *a* concentrations varied between 4 and 8 mg/m³, and for the upwelling period between January and June, concentrations ranged between 10 and 14 mg/m³. Periodic incursions of nutrient-rich subsurface ocean water caused prominent thermoclines and phytoplanktonic biomass concentrations in the zone of mixing, at depths between 3 and 10 metres (Pitcher and Calder, 1998). High wind energy along the bay, diurnal tidal mixing and barotropic shelf waves passing along the coast, combined to produce highly dynamic water conditions in the bay. Short-term thermoclines were dissipated predominantly by wind, and some tide-forced mixing. Mussels were cultured on a site which is sheltered from the ocean but exposed to prevailing longshore winds. Temperature conditions in the bay appeared ideal for mussel culture. Embayment water (surface water) ranged between 14 and 19°C over the year, while wind-forced oceanic upwellings periodically introduced subsurface water at 10 - 12°C (Pitcher and Calder, 1998).

Subsurface productivity determined from Chl *a* readings at depth often approached the theoretical maximum of 25 mg C/m² during periods of spring blooms of diatoms (Pitcher and Calder, 1998). A measure of the total productivity of the water column down to the 1% light level (photoc depth) was made, using Secchi depths and Chl *a* readings. Productivity readings were undertaken on three alternate days, in winter, spring/summer and autumn, between 1993 and 1995. Table 7 presents a set of Secchi disc depths, integral Chl *a* readings, measures of primary productivity and productivity normalised to biomass, of the water column determined from a station adjacent to the mussel farm.

Table 7. Productivity station photic depth and photic zone integrals of Chl *a*, primary productivity and productivity normalised to biomass, adjacent to a mussel farm in Saldanha Bay, South Africa (from Pitcher and Calder, 1998).

Date	Photic Depth (m)	Integral Chl <i>a</i> (mg/m ²)	Productivity (mg C/m ² /h)	Biomass Productivity (mg C/mg Chl <i>a</i> /h)
July 31, 1993	9.5	10.8	66.3	6.2
Aug 2, 1993	9.5	23.3	106.9	4.6
Aug 4, 1993	6.8	14.9	54.5	3.7
Dec 8, 1993	7.6	60.6	458.2	7.6
Dec 10 1993	7.0	22.0	339.1	15.4
Dec 13, 1993	9.8	38.0	343.7	9.0
Mar 13, 1994	6.2	77.1	427.6	5.6
Mar 15, 1994	8.1	65.7	495.1	7.5
Mar 17, 1994	7.5	104.1	626.6	6.0
Aug 6, 1994	9.2	48.1	183.5	3.8
Aug 8, 1994	12.1	83.2	259.6	3.1
Aug 10, 1994	9.2	161.0	495.9	3.1
Nov 23, 1994	5.4	45.2	285.5	6.3
Nov 28, 1994	6.8	48.4	404.2	8.4
Nov 30, 1994	6.0	60.4	492.8	8.2
Mar 17, 1995	7.5	109.9	237.6	2.2
Mar 19, 1995	7.5	123.5	670.7	5.4
Mar 22, 1995	7.5	94.8	603.9	6.4

Although the waters in Saldanha Bay are extremely productive, and Chl *a* contents are commonly 5 to 10 times higher than other mussel sites around the world, research has shown that the growth of mussels on longlines hung from floating rafts was still limited at high rope density. Wind-forced, variable, surface ambient water flow in the bay (~5 - 20 cm/s, alternating in opposite directions) was greatly reduced between the mussel ropes, particularly between ropes spaced at 60 cm. Simultaneous measurements of fastest ambient and through-rope flow revealed as much as 85% of the flow reduced by the presence of rafts and the 60 cm-spaced ropes, while 90 cm-spaced ropes reduced flow by around 70% (Boyd and Heasman, 1998). Figure 8 shows the derived regressions of current flows through the two rope spaces, compared with the unrestricted ambient flow. Studies of food extraction rates and growth rate of the mussels at the two rope spacings revealed increasing food depletion as mussels grew larger with both spacings, and progressively-greater depletions of food with reduced growth rates on the 60 cm-spaced ropes as the mussels aged, particularly in the centre of the raft. Condition index of mussels in the centres of rafts with 60 cm-spaced ropes was reduced, though not significantly, and mean large mussel (> 83 mm) production on 90 cm-spaced ropes was more than double that of 60 cm-spaced ropes. Improvements in growth rates and medium-large mussel yields at the 90 cm spacing were sufficient to increase production from the rafts by 9%, and to shorten the between-harvest growth periods by 2-4 weeks (Heasman *et al.*, 1998).

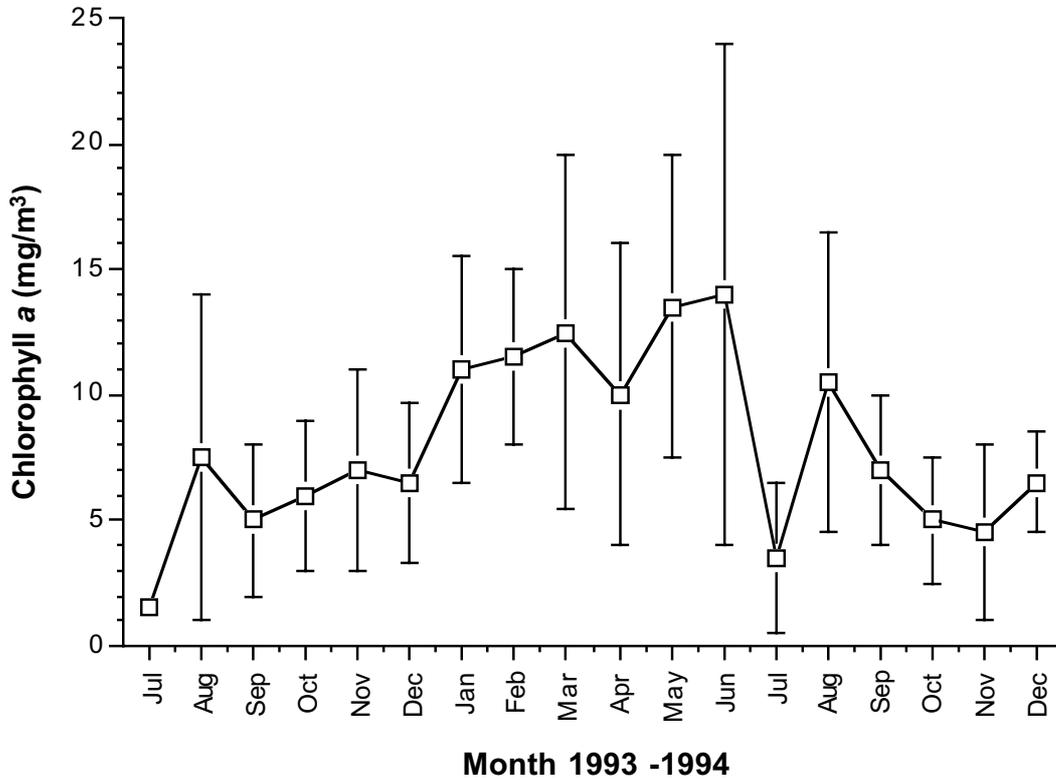


Figure 7. Mean monthly Chl a (1993-1994) calculated from daily means, derived from water column integrals, at the monitoring station adjacent to the mussel farm, Saldanha Bay, South Africa (from Pitcher and Calder, 1998).

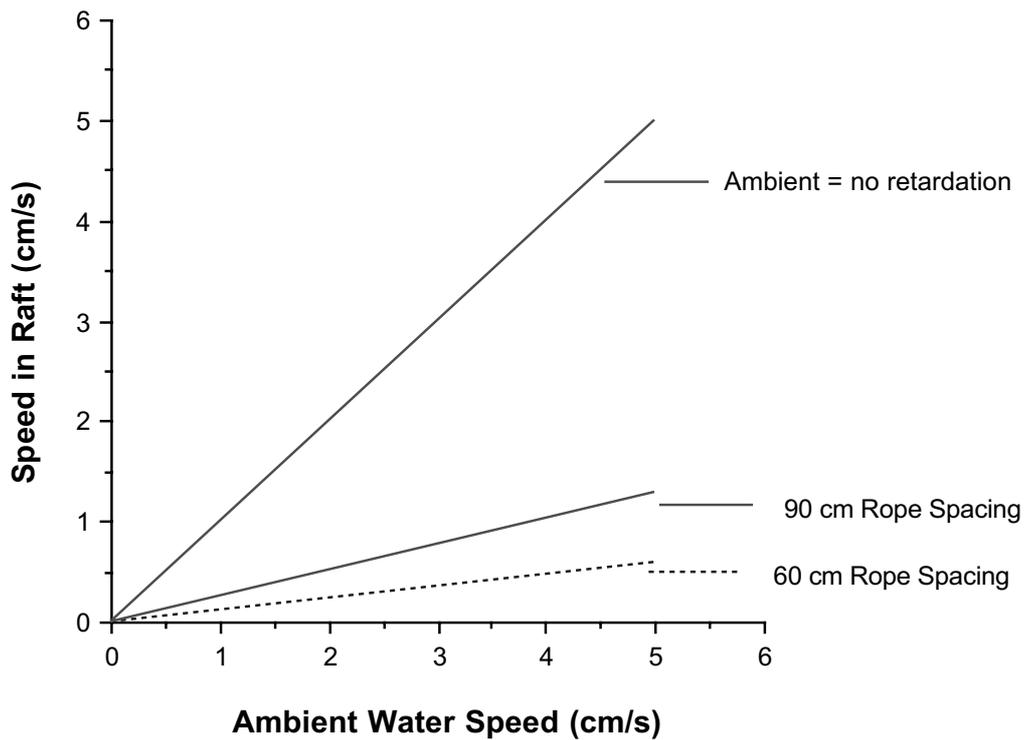


Figure 8. Regressions of current flow data between the 60 and 90 cm-spaced ropes of raft-cultured mussels in Saldanha Bay, South Africa (from Boyd and Heasman, 1998).

8.0 Eastern Scheldt Estuary, SW Netherlands

The Eastern Scheldt Estuary is a prolific mussel culture region, with a standing stock of about 4000 t (ash-free d.w.), of which 95% are cultured. Mussels are cultured on bottom plots on the slopes of tidal channels and on intertidal flats, over a total area of 1900 ha (Smaal and van Stralen, 1990). Most of the culture plots are on the western and central parts of the estuary.

Research in the 4 years prior to construction of a storm-surge barrier at the mouth of the estuary showed that mussel condition correlated strongly with average annual primary production, but not with Chl *a* concentrations (Smaal and van Stralen, 1990). Inflow of water from the North Sea appeared to provide additional food for mussels in the western region, contributing to their improved condition and growth, compared with central region mussels. After the barrier was built, no differences were observed between mussels in the western or central part of the estuary. The authors suggested from preliminary evidence that a lack of water exchange between the western region and the North Sea after the barrier had been built would reduce western mussel condition by reducing the import of food, and increasing silt sedimentation.

As part of this study, annual means of Chl *a*, suspended particulate matter (SPM), particulate organic carbon (POC) and primary production (PP) were determined weekly at positions 5 cm above mussel beds, for the western and central parts of the estuary, and they are presented in Table 8.

Table 8. Mean annual suspensoid concentrations in the western (W) and central regions (C) of the Eastern Scheldt estuary, for the years 1981-1984, and 1987 (from Smaal and van Stralen, 1990).

	1981		1982		1983		1984		1987	
	W	C	W	C	W	C	W	C	W	C
SPM (g/m ³)	14.3	16.8	19.0	18.8	26.7	18.2	19.8	12.6	9.1	6.9
POC (g/m ³)	1.1	1.2	1.4	1.2	1.6	1.2	1.4	0.9	0.8	0.7
Chl <i>a</i> (mg/m ³)	5.8	4.7	8.0	7.0	7.5	5.2	6.6	5.1	6.5	5.4
PP (g C /m ² /y)	234	219	466	334	250	201	372	310	371	333

SPM = Suspended particulate matter POC = Particulate organic carbon PP = Primary productivity

Correlation coefficients of mussel condition with primary production and Chl *a* concentration were determined and are presented in Table 9. There was little correlation between Chl *a* and mussel condition at any of the sites. However, the authors emphasised that in years with high primary production, rapid turnover of phytoplankton by filter feeders would make Chl *a* readings much lower than the productivity of the system would suggest. The Chl *a* readings may have reflected the dynamic equilibrium between production and consumption in the areas tested. This view is supported by the evidence from Saldanha Bay, which revealed that Chl *a* concentrations in water passing through mussel rafts were reduced by an average of 80%, with greatest depletions of Chl *a* at positions nearest the ropes (Heasman *et al.*, 1998). A strong correlation existed between the growth of mussels and their condition in both regions of the estuary ($r = 0.89$). Also, significant correlations existed between primary production of each region and mussel condition over the five years of testing, indicating a direct link between primary production and growth.

Table 9. Correlation coefficients of mussel condition with primary production and Chl *a* concentration, at stations in the two regions of the Eastern Scheldt estuary (from Smaal and van Stralen, 1990).

Region/Site	Mussel Condition/ Primary Production	Mussel Condition/ Chlorophyll <i>a</i>
West 1/2	0.95*	0.24
West 3	0.36	0.002
Central 1	0.45	0.29
Central 2	0.91*	0.41
Central 3	0.74	0.27

* = $p < 0.05$

9.0 North Inlet, South Carolina, USA

Dame and Libes (1993) determined the summer nutrient and Chl *a* levels in six tidal creeks draining the same upland area and flowing into North Inlet, South Carolina, before and after removing oyster beds in three of them. Oyster (*Crassostrea virginica*) biomass was calibrated to the volume of water in each creek. Oyster reefs were normalised with a biomass of 250 g dry body/m². Analyses for 30 days prior to the removal of oysters showed the creeks to be biogeochemically similar. Once oysters were removed, readings of environmental parameters were taken daily for 60 consecutive days. After removal of oysters, total nitrogen, ammonium, total phosphorus and total dissolved phosphorus were significantly different between the creeks, while concentrations of other parameters, including Chl *a*, were not. Mean concentrations of environmental parameters are presented in Table 10.

Table 10. Mean concentrations of materials in tidal creeks during pretest (1 June - 30 June, 1989) and experimental manipulation (1 Jul- 30 Aug, 1989), for creeks with and without oysters (from Dame and Libes, 1993). Nutrient units are mg N/m³ and mg P/m³.

Constituent	Pretest	Experiment		
		Oysters	No Oysters	Significant Difference (P<0.05)
Chlorophyll <i>a</i> (mg/m ³)	9.94 ± 0.16	8.30 ± 0.27	8.31 ± 0.29	
Ammonium	1.09 ± 0.07	1.25 ± 0.10	0.90 ± 0.06	*
Nitrite + Nitrate	0.29 ± 0.02	0.37 ± 0.02	0.35 ± 0.02	
Σ Dissolved Nitrogen	55.4 ± 1.68	22.16 ± 0.55	21.78 ± 0.50	
Particulate Nitrogen	38.42 ± 1.75	16.07 ± 0.68	15.27 ± 0.71	
Σ Nitrogen	93.82 ± 30.23	38.22 ± 0.80	36.94 ± 0.77	*
Orthophosphate	0.55 ± 0.01	0.40 ± 0.01	0.39 ± 0.01	
Σ Dissolved Phosphorus	0.44 ± 0.16	0.69 ± 0.03	0.62 ± 0.02	*
Particulate Phosphorus	3.91 ± 0.06	1.08 ± 0.05	1.05 ± 0.05	
Σ Phosphorus	4.25 ± 1.62	1.77 ± 0.06	1.67 ± 0.05	*

The significant differences between the creeks with respect to inorganic nitrogen and phosphorus were interpreted as demonstrating that oyster excretion can, and does, influence the nutrient content of tidal creek water. Growth of phytoplankton in the creek was assumed to be nitrogen-limited, since the N:P ratio was much less than the Redfield-Richards ratio of 16:1 (Howarth, 1988).

The authors postulated that the higher levels of inorganic nutrients in creeks with oysters would have caused an increase in phytoplankton levels, which served as food for the oysters, thereby resulting in an increase in oyster biomass while phytoplankton levels did not change. Thus, the oysters may have acted to hold nutrients in the estuarine environment, by creating a positive feedback loop, where nutrients are cycled between phytoplankton and oysters. Rapid flushing rates would otherwise remove dissolved nutrients from the system within a few days, resulting in nutrient limitations for bivalves in the area.

10.0 Marine Lochs, Scotland

The differences in water conditions and growth and production of mussels (*Mytilus edulis*) were examined over two years (May 1990 - May 1992) in Lochs Leven and Etive (Stirling and Okumus, 1995). Mussels were suspended from longlines attached to rafts, and from salmon cages in each loch. Water temperatures showed a pronounced seasonal cycle, and growth was restricted to the months May to October. Reductions in wet meat weight occurred in all localities during the winter. Mussels lost more weight at the mussel sites than at the salmon farms. Particulate organic matter (POM) and Chl *a* were higher adjacent to salmon farms, POM significantly so in Loch Etive. Slightly higher temperatures and greater phytoplankton availability may have produced significantly greater annual length increases in Loch Etive than for mussels cultured in Loch Leven. Growth at shellfish farms was not consistently lower than growth at salmon farms. A multiple regression analysis of the effects of environmental factors on shell length increment gave significant coefficients for water temperature and Chl *a*, together accounting for 67-88% of the total variance. Non-algal POM had a significant effect upon shell length increments in Loch Etive in 1990-91 only, accounting for 6% of the variance. The differences in performance between salmon and shellfish farms in Loch Etive may have resulted from the utilisation of higher organic matter concentrations at salmon farms. Means for the different sites are presented in Table 11.

Table 11. Means of monthly values of environmental parameters at mussel (M) and salmon (S) sites in Loch Etive (E) and Loch Leven (L), May 1990 - 1992 (from Stirling and Okumus 1995).

	EM	ES1	ES2	LS	LM
Temperature (°C)	10.8	10.9	10.6	10.5	10.5
Salinity (‰)	22.2	22.5	30.8	25.7	28.8
Seston (mg/l)	5.0	6.6	6.9	7.1	7.6
POM (mg/l)	2.2	3.1	3.3	3.3	3.6
Chl <i>a</i> (mg/m ³)	1.78	1.80	1.75	1.10	1.51
POM/Chl <i>a</i>	1236	1722	1886	3000	2384

11.0 Hvalfjordur, Iceland

Thorarinsdottir (1996) examined the gonad development, larval settlement and growth of *M. edulis* in suspended culture in Hvalfjordur during 1986/87. The growth season extended from March to October, with spawnings coinciding with elevated June/July temperatures of 10 -12°C. Gonad redevelopment took place during the winter, under low temperature conditions and lack of phytoplanktonic food. Growth was ~25 mm/y over the two years required for mussels to reach market size. Growth of suspended mussels was more rapid than those in natural mussel beds. Fig 9 displays the temperature and Chl *a* data for the location.

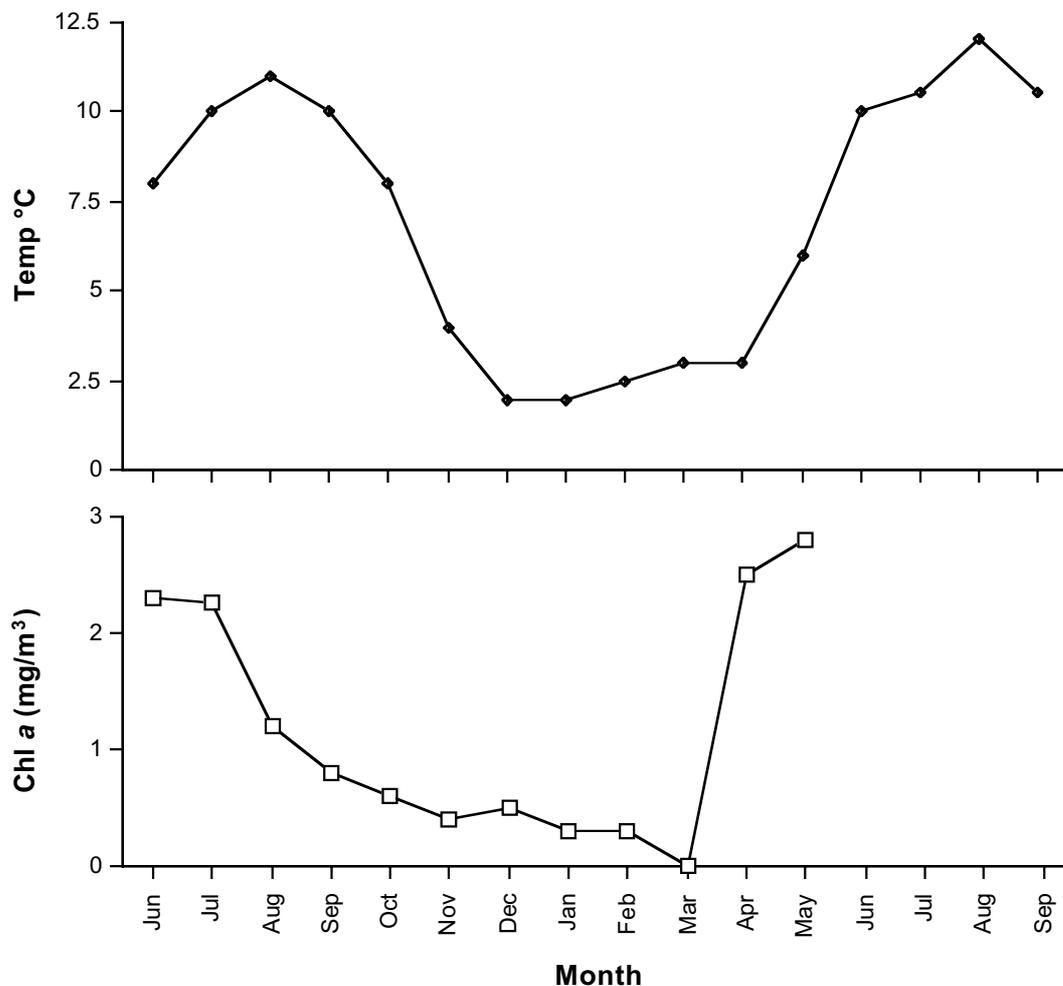


Figure 9. Mean monthly readings of temperature and Chl *a* in Hvalfjordur, south west Iceland (from Trorarinsdottir 1996).

12.0 Tasmania, Australia.

The rapid expansion of intertidal and subtidal Pacific oyster (*C. gigas*) farming in Tasmania in the late 1980s raised concerns from the farming industry that too many oysters were being placed in the same growing areas, and that production levels were not sustainable. At the same time, large numbers of requests for new leases were being submitted to the fisheries

regulating authority. Consequently, there was need for information to determine the maximum sustainable number of farms, and densities of oysters that would maximise sustainable yields from each growing area. In response to this need, Crawford *et al.* (1995) sought to assess oyster production in relation to environmental conditions in five oyster growing areas, Pittwater, Pipeclay Lagoon, Little Swanport, Georges Bay and Simpson's Bay. Some sites were studied in more detail and for longer periods than others.

The factors used in the predictive model to estimate carrying capacities of growing areas were:

- the amount of oyster food available,
- rate of replenishment of the food and
- the quantity of food consumed by the oysters.

Information on environmental parameters which affected the growth rates of oysters, the transport of food and the regeneration rate of oyster food, such as light levels, temperature and nutrient concentrations were also considered important. Data were collected monthly on temperature, salinity, Chl *a*, nitrate/nitrite, silicate and phosphate concentrations at several sites in the growing areas. Water movements were determined for each growing area to provide information on the rate of replenishment of food supplies, and a model was developed to estimate the flow, velocity and flushing rate at different tidal heights. Oyster clearance rates (incorporating rate of food consumption and assimilation efficiency) were investigated at Pipeclay Lagoon and Pittwater. Oysters were placed in grazing chambers adjacent to commercial racks, and feeding rates were determined by the difference between food particles in the influent and the effluent water. Initially, direct cell counts were used, but later in the project, TPM, POM and PIM were determined and POM used to quantify feeding rate.

Formulae used to determine the feeding rate and assimilation efficiency were:

Feeding Rate from cell counts (0.2 - 20 µm)

$$F_eR = V([N^o \text{ cells in} - N^o \text{ cells out}] \div N^o \text{ cells in}),$$

where *N^o cells in* is the number of cells/l in the influent water, *N^o cells out* is the number of cells/l in the effluent water, *V* is the mean flow rate in l/hr and *F_eR* is the feeding rate in cells/hr.

Feeding Rates using POM were calculated using a similar formula,

$$FR = V ([P_{in} - P_{out}] \div P_{in})$$

where *P_{in}* is mean POM concentration (mg/l) of influent water, and *P_{out}* is the mean POM concentration (mg/l) of the effluent water.

Assimilation efficiency (AE),

$$AE = 100([F - E] \div [1-E]F)$$

where *F* = weight POM ÷ weight TPM of food, *E* = weight POM ÷ weight TPM of faeces. Any assimilation or release of dissolved organic matter was not included in the analysis.

12.1 Computer model

The EcoS Version 2 hydrodynamic simulation shell (Institute of Marine Environmental Research, Plymouth UK, and UK National Rivers Authority) was used as a basis to develop the computer model. It is a one-dimensional numerical model, where the body of water under study is divided into axial segments of equal length, up to a maximum of 50 segments. All quantities of interest are taken as cross-sectional averages for each segment. Variation of the quantity with depth (cross section of axial segment) is assumed to be non-significant, and measurement of temperature and salinity profiles with depth confirmed this at Pittwater. When the report was written, a preliminary model had only been developed for Pittwater, and data collection at the various sites was continuing. Tidal heights were not consistently recorded due to unreliable data loggers, so the heights for Hobart (~20 km away) were entered into the model.

12.2 Environmental variables

Temperatures showed a typical annual pattern (Fig 10), although summer temperatures in 1993 were higher than the other two years. Salinities in Pittwater were higher than marine levels, especially toward the upper reaches of the estuary, during most of the year. Occasional outflows of fresh water occurred during some winter and spring months over the study period, and salinities were then reduced at the inmost stations.

Chl *a* levels were generally between 1 and 4 mg/m³, apart from a peak in Feb 1992, and summer to winter 1994. The upper reaches of Pittwater tended to have higher Chl *a* levels than the lower estuary and marine station. No trends were evident over time. Nitrate levels were considered to be generally low, ranging below 10 mg/m³ except for peaks at some stations in Aug-Sept 1991 and Feb-Mar 1992. Phosphate levels were between the range 5-15 mg/m³, with no clear patterns or trends between the stations, except that the marine station had higher phosphate readings than all estuarine stations in the first 12 months of the study. Silicate readings varied unpredictably between stations, apart from the fact that the estuarine readings were generally higher than at the marine station.

The other sites in Tasmania showed Chl *a* readings which were similar to Pittwater, with an overall range between 1 and 4 mg/m³, and occasional peaks reaching 7 or 8 mg/m³, usually in the autumn months. No temporal or spatial trends were evident. Salinity at the various sites generally ranged between 30 and 36 ‰, with some highly reduced readings at Little Swanport showing outflows of fresh water over 1 - 3 monthly periods. Salinities in Georges Bay and Little Swanport were greatest at the marine sampling stations and least in the inmost regions of the estuaries, reflecting fresh water inflow, while Pittwater and Pipeclay lagoon had elevated salinities at their inmost sites, indicating substantial water loss through evaporation and low flushing rates. Seasonal trends in temperature in all the locations were evident, ranging between summer-autumn highs of ~18 - 20°C and winter lows of ~6 - 7°C. Georges Bay had a smaller range in temperature (10.2 - 18.5°C) than the other sites, with Pittwater and Pipeclay Lagoon having the greatest range (6.5 - 21°C). Georges Bay also showed the greatest variation in temperatures between sample sites. Nitrate + nitrite concentrations were generally around 10 mg/m³ at all sites, with some irregularly high peaks coinciding with, or immediately preceding high Chl *a* readings.

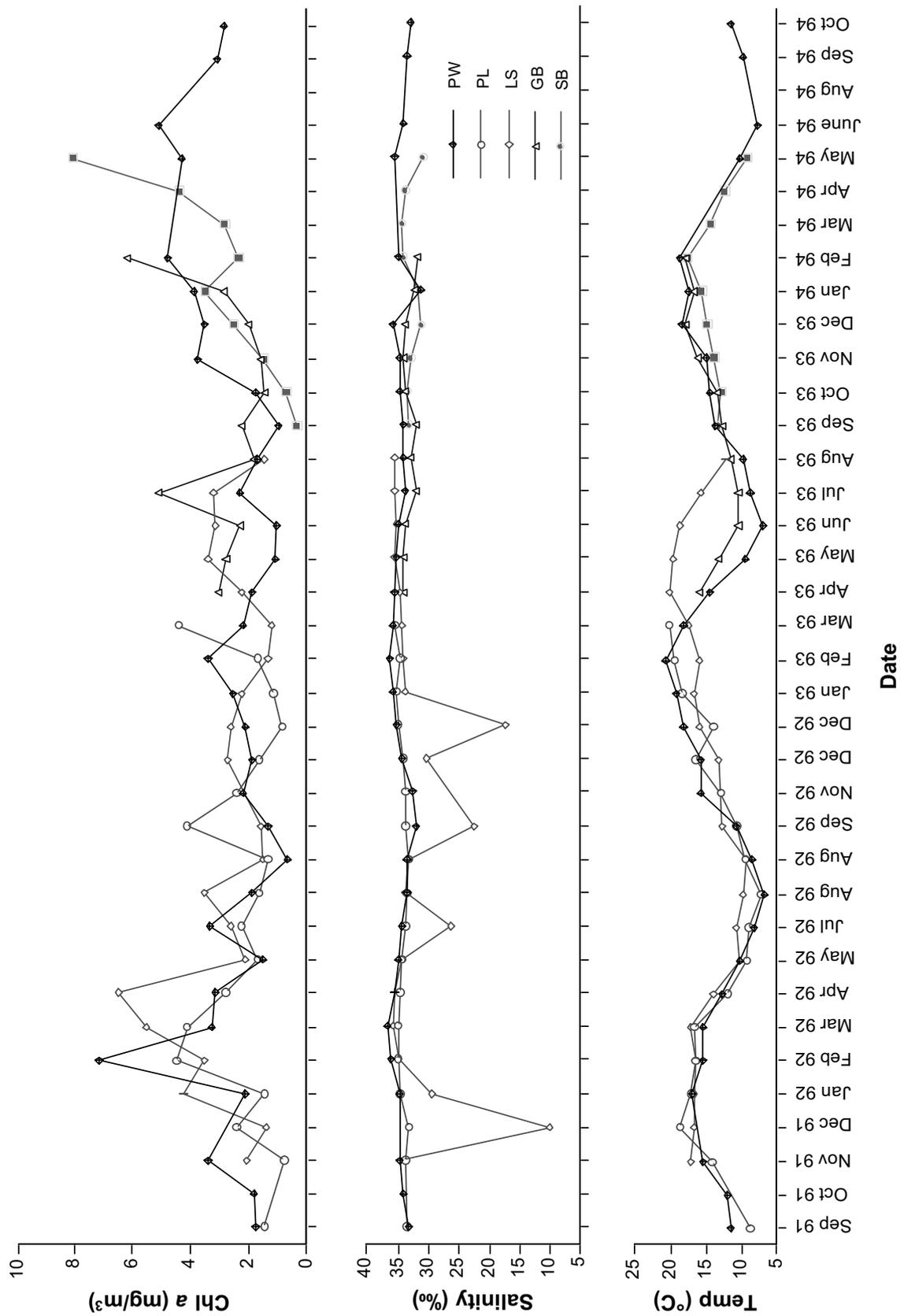


Figure 10. Mean monthly temperature, salinity and chlorophyll a readings from Pittwater (PW), Pipeclay Lagoon (PL), Little Swanport (LS), Georges Bay (GB) and Simpson's Bay (SB). (Data from Crawford *et al.*, 1996)

12.3 Primary productivity and production between sites

As part of the modelling study, measures of primary productivity were determined at two positions (X and Y) in Pittwater and Pipeclay Lagoon, on 5 occasions. Estimations of primary production were made using a light/dark oxygen production method, with the assumption of vertical light and phytoplankton uniformity throughout the water column (maximum depth ~8 metres, oyster sites generally ~ 2 - 4 m). The results are presented in Table 12.

Table 12. Primary production at Pittwater and Pipeclay Lagoon (from Crawford *et al.*, 1996)

Location	Date	Daylight Hours (sunrise-sunset)	Daily Solar Radiation (W/m ²)	Primary Production*	
				Site X	Site Y
Pipeclay	30/1/95	14h 20 mins	25054	205.5	271.0
Lagoon	23/5/95	9 h	14589	136.5	676.7
Pittwater	4/4/95	11 h	19919	243.7	425.1
	24/5/95	9 h	8258	309.8	506.2
	22/6/95	9 h	10316	118.3	348.1

* mg C fixed/m³/day

The allometric relationship for oyster shell length and dry tissue weight for Pipeclay Lagoon oysters was determined as:

$$\ln(L) = 0.39 \times \ln(TW) + 4.00, \quad (r^2 = 0.97), \quad \text{or, in the format of this report,}$$

$$Y = 0.01832 X^{2.564}$$

where L (X) is shell length in mm and TW (Y) is tissue dry weight in g.

This growth rate is slightly less than oysters in Hinase waters, and more rapid than the oysters cultured in the Gulf of Castellammare.

A comparison of the production of oysters from each of the growing areas shows that Pipeclay Lagoon is clearly the most productive of the four developed sites (Table 13), and the authors pointed to its shallowness and rapid flushing rate (1.4 tidal cycles) as the reasons for its high productivity. No nutrient input reaches Pipeclay Lagoon from terrigenous sources, so the high productivity must be due to the rapid flushing rate, and consequent replenishment of available food.

Table 13. Production of oysters from the five growing areas in Tasmania (from Crawford *et al.*, 1996).

	Pittwater	Pipeclay Lagoon	Georges Bay	Little Swanport	Simpson's Bay
Production (x1000 oysters/ha)	52	170	108	43	(site not developed)

12.4 Predictive modelling

In this preliminary form, the ECos model has been useful in estimating carrying capacity in the Pittwater growing area. The results of various simulated conditions derived from the readings taken, have predicted that under summer light conditions, with limited water exchange, no primary production occurring (very low nutrient levels and little oceanic exchange, “uncompensated”) and high stocking densities, the average percentage depletion of food would be around 20%, but that this would rise to as much as 48% on certain days. The greatest segmental food depletion rates were evident from the area of current bivalve leases. On the basis of a threshold for maximum ingestion of 50% of ambient seston concentration, oyster growth may become restricted through lack of food during these summer days, that is, the carrying capacity of the growing area would be exceeded when minimum water dispersion and low nutrient levels are present in the growing area. With compensation in food availability due to primary production on these summer days, segmental depletion rates at high stocking density were reduced to around 10%. A summary of the average percent depletion of food throughout Pittwater in different seasons and with different water dispersion coefficients is given in Table 14. Restrictions in total food supply were calculated as average % depletion, the mean of all average segmental % depletions in the bay over a 30 day period.

Table 14. Summary of average % depletion of food in different seasons, two stocking rates and with different dispersion coefficients in Pittwater Bay (from Crawford *et al.*, 1996)

Season	Dispersion Uncomp. High SR	Av. % Dep. Uncomp. Low SR	Av.% Dep. Comp. High SR	Av % Dep. Comp. Low SR	Av % Dep.
Winter	high	7.93	5.53	3.02	2.05
	low	11.78	8.41	3.41	2.32
Summer	high	14.03	10.13	2.73	1.85
	low	19.76	14.75	2.83	1.92

Av. % Dep. = average % depletion of food reserves throughout the entire bay over 30 days

SR = stocking rate High SR = 30 million oysters Low SR = 20 million oysters

Uncomp. = uncompensated (food not replaced by regeneration and flushing)

Comp. = compensated (food replaced)

High dispersion was modelled as $K = 600 \times U$, and low dispersion as $K = 100 \times U$ where K is the longitudinal dispersion coefficient, and U is the net water velocity. Elevated and reduced grazing rates, determined from the grazing chamber experiments, were set at 0.96 m³/s/million oysters and 0.48 m³/s/million oysters. Incident light levels were set at a winter low of 10 watts/m² and a summer high of 100 watts/m², allowing calculations of total net primary production at various concentrations of Chl *a*. Arbitrary “summer” and “winter” values of Chl *a* were used for each segment, from the values established by sampling in those seasons. Overall clearance rates were determined from the chamber data and from clearance rates of various size ranges of oysters tested elsewhere, combined with the normal size ranges of oysters held in Pittwater during the “summer” and “winter” periods. Average segmental % depletions were determined from the average of food (Chl *a*) reductions in each segment of the bay transect during one 2 hour period. Table 15 presents predictions of food depletions under varying conditions of stocking rate, dispersion, light intensity, grazing rates and compensation through regeneration and flushing.

Table 15. Average % depletion and maximum segmental depletion of high and low stocking rates at Pittwater under high and low conditions of light, grazing rates, and dispersion.

	30 Million Oysters						20 Million Oysters					
	WC			C			WC			C		
	H	L	S	H	L	S	H	L	S	H	L	S
Average % depletion	14.03	11.78	19.76	2.73	3.41	2.83	10.13	8.41	14.75	1.85	2.32	1.92
Std Devⁿ	0.23	0.16	0.28	0.03	0.04	0.02	0.16	0.11	0.20	0.02	0.02	0.02
Maximum %	43.66	38.15	47.73	10.69	11.00	9.58	32.43	28.10	36.69	7.35	7.61	6.60
Segmental Depletion												

H= high light , high dispersion and high grazing rates WC = without compensation
L= low light, low dispersion and low grazing rates C = with compensation
S= summer conditions: high light, low dispersion and high grazing rates

The model has predicted the degree of local (maximum segmental depletion, adjacent to farm) and regional food depletion (average depletion). Since the figures present possible reductions in food availability which may occur over a quite short period of 2 hours, the impact of a number of days of stable weather conditions, low flushing rates and low summer nutrient levels, combined with high feeding levels, upon oyster condition at high stocking rates is likely to be very profound.

12.5 Summary outcomes

The success of the simple hydrodynamic model for the Pittwater growing area was largely dependent upon the vertical uniformity of water conditions in this locality. However, other bivalve sites often have highly-stratified water conditions (Hickman *et al.*, 1991; Gibbs *et al.*, 1992; Boyd and Heasman, 1998) and may not be suitable for the one dimensional ECos model. It is likely that those growing areas in Tasmania which incorporate wide, shallow tidal flats and deeper water channels in estuaries, for example, Georges Bay and Little Swanport, will not fit easily into the ECos model assumptions of vertical uniformity in measured parameters, and that a two-dimensional model may be necessary to more accurately predict carrying capacities in these areas.

The model continues to be refined, through gathering of data on oyster growth rates and stocking density from each of the growing areas. As well, measurements of food availability now include all components of seston. Nutrient levels and Chl *a* data are yet to be integrated into the model. The effects of temperature, food concentration and oyster biomass upon oyster clearance rates need to be further investigated. Finally, account needs to be made of the impact of other filter feeders and zooplankton levels in the oyster growing areas.

The research has shown that a generalised model of the carrying capacity of bivalve sites is feasible, however, detailed site-specific data will be required for each growing area, if the model is to reliably predict the carrying capacity of that area. This is due to the high degree of inter-site variation in the parameters used to construct the model. In particular, detailed

studies of the hydrodynamics of each growing area, and bivalve food availability will be required over a number of years.

The model predicted that average depletions of food available for oysters at high stocking density during summer months in Pittwater would be between 2 and 20%, while winter depletions ranged between 2 and 12% (Table 14). It is likely that the extreme conditions of food depletion would exist for a number of days to weeks in Pittwater, which experiences prolonged periods in late summer, of high light, low wind and low nutrient levels. At high stocking rates or with increases in number of oyster leases in Pittwater, oyster growth may be restricted under these conditions, with consequent effects upon viability of existing and proposed future sites.

In common with other highly productive commercial bivalve sites around the world, Tasmanian sites show consistently good Chl *a* levels, greater than 1 mg/m³, throughout the year, combined with periodic blooms. While water temperatures and primary productivity appear to be lower than Spanish and Japanese sites, growth rates remain acceptable (50-60 mm/y), with harvests of oysters usually during, or after, the second warm season of culture (12 - 18 months old) (Treadwell *et al.*, 1991).

13.0 South Australia, Australia

13.1 Coffin Bay, Eyre Peninsula

The Coffin Bay region of the Eyre Peninsula, Australia, has supported Pacific oyster farming since the 1970's. Intertidal culture methods are used. Polyethylene mesh bags for oyster growout are suspended ~1 - 1.5 m above the substrate on wire longlines, which are supported by a post and rail system. Under the normal tidal range of 0.5 m, oysters spend approximately 2-3 h/d exposed to the air.

In a study by Bridger (unpublished honours thesis) of site-related differences in oyster growth and water conditions at four locations, oysters were cultured experimentally for 5 months at two commercial sites (Kellidie and Dutton) and two other unused embayments within Coffin Bay (Longnose and Central). Height and weight of shell, wet and dry meat weight were determined monthly using 60 oysters from each site, along with water conditions and particulate food levels. Current flow at the sites was measured indirectly using rate of solution of calcium sulphate blocks (Table 16). Control blocks from two batches produced for trials 1 and 2 dissolved at different rates in the laboratory. Hence, solution rates in this review have been standardised, as ratios of solution rates of batch controls. Food levels were determined as Chl *a*, direct cell counts, POM and PIM. The author stated that measures of particulate food except for Chl *a* were not used in the analysis of growth, due to high variability. Of the environmental variables measured, Chl *a*, pH, and temperature did not vary significantly between sites (Fig 11). In contrast, salinity values for the four sites differed significantly. The experimental sites (Longnose and Central) experienced salinities predominantly below 40 ‰. The two commercial sites experienced higher salinities, generally above 40 ‰, throughout the sampling period (Fig 12).

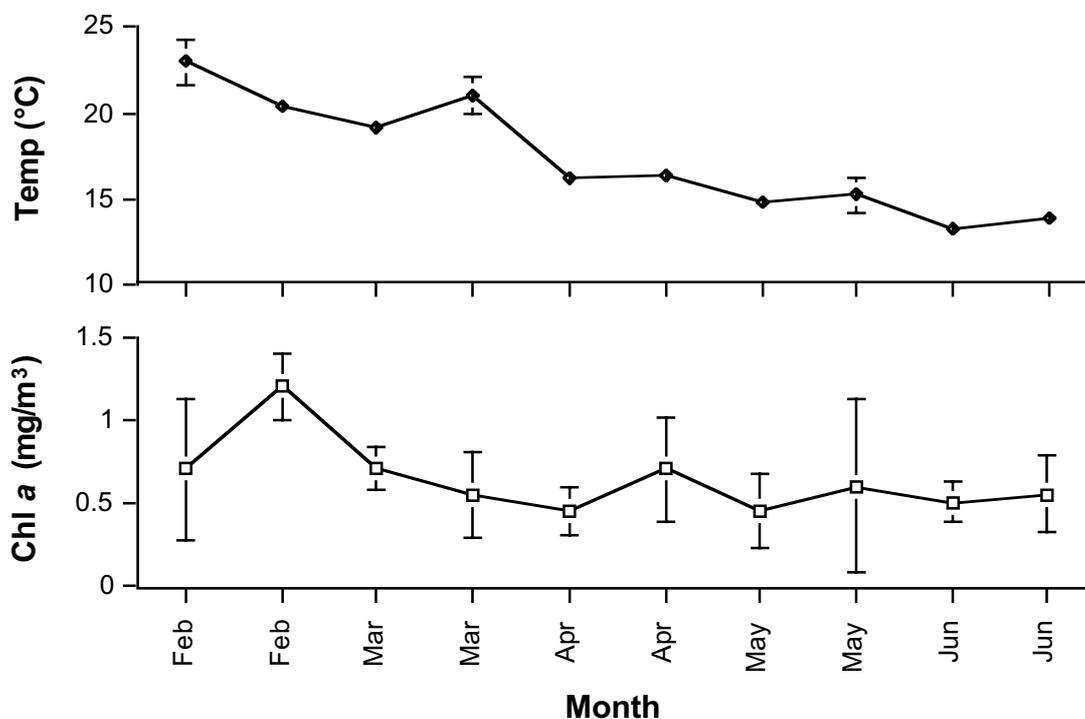


Figure 11. Composite means (\pm sd) of sea water Chl a content and temperature taken half-monthly at the four sites within Coffin Bay, Eyre Peninsula, South Australia. No significant differences were found between sites for these variables (Error bars are s.e., $n = 12$) (from Bridger, unpublished data).

Table 16. Standardised measures of dissolution of calcium sulphate blocks over 12 days, at each of the oyster sites within Coffin Bay, South Australia. Rate of solution of blocks was used as an indication of differences in current flow between sites. Standardised mass loss = mass loss of site block/mass loss of laboratory control (adapted from Bridger, unpublished data).

Site	Standardised Mass Loss (g /g control)	
	Trial 1	Trial 2
Longnose	4.79	4.05
Central	5.04	4.50
Dutton	3.67	2.79
Kellidie	2.36	1.72

Reduced standardised rates of dissolution of blocks at Dutton and Kellidie may indicate lower current flows at these sites, especially at Kellidie. Since controls were tested in a laboratory aquarium, site water conditions without current flow were not used to gain a measurement of control block dissolution rates. Therefore, statistical analyses of these data are inappropriate. As well, current flow was not related to block dissolution rates, or used to determine food availability in this study

Changes in dry meat weight and shell height differed significantly between sites. Oysters at Kellidie did not increase in dry meat weight over the 5 months of the study. Kellidie oysters

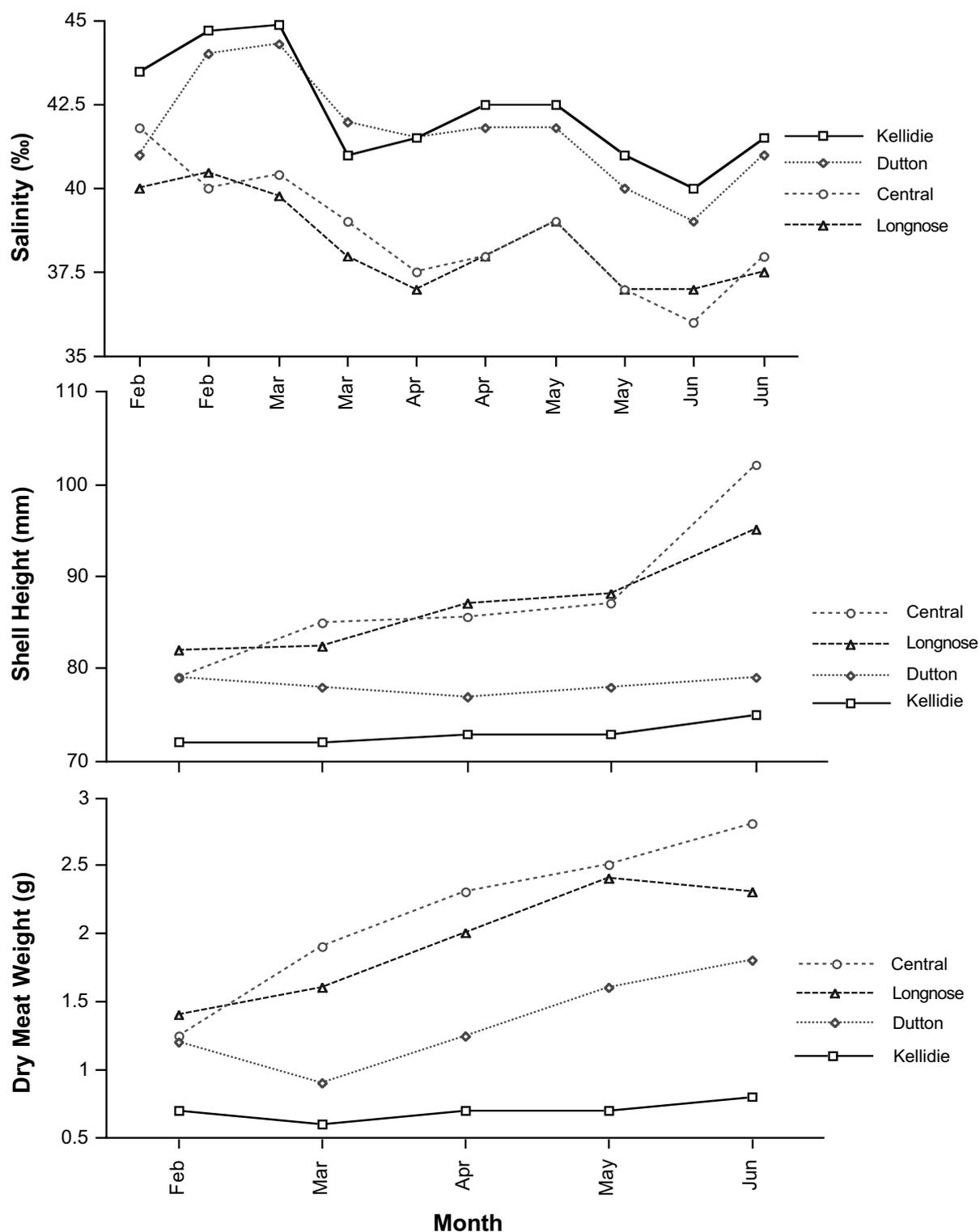


Figure 12. Mean sea water salinity, with oyster shell height and dry meat weight of 60 oysters sampled monthly at the four sites within Coffin Bay in 1996 (from Bridger, unpublished data).

were smaller than oysters at other sites at the beginning of the study. Both Kellidie and Dutton oysters exhibited minimal shell growth, while at the two experimental sites, oysters grew steadily. From March to June, Dutton oysters improved in meat weight but shell length did not increase. During February-March, oysters at Dutton and Kellidie lost condition. Environmental conditions, other than temperature, pH and phytoplankton levels, appeared to severely hinder shell growth at both commercial sites during the majority of the trial period. Differences in salinity and perhaps current flow (Fig 12, Table 16) between sites were detected, and salinity was shown by partial correlation analysis to be the dominant parameter when correlated with dry meat weight ($r = -0.863$, $p < 0.001$). The indication of negative influence of increasing salinity upon oyster growth needs to be further examined, since food availability for oysters (a function of particulate food levels, stocking density and current flow) was not directly measured. The limited data may indicate that oysters at Kellidie and Dutton had restricted growth because of physiological stress, due to salinities which surpassed the animals' ability to acclimate, or some other undetected factor. Additionally, this physiological stress may have been size-related, since Kellidie oysters were most affected. The limit of salinity tolerance for Pacific oysters in this region may have been exceeded, but this inference needs to be supported either by the use of trials of salinity tolerance, or laboratory growth at a range of high salinities.

In conclusion, the data from Coffin Bay do indicate arrested growth in the presence of adequate phytoplankton and high salinity, but the range of site-related environmental and biological factors associated with oyster growth, for example, current flow, food depletion rates in oyster leases (measures of food availability) and oyster size, remain to be evaluated.

13.2 Ceduna

A phytoplankton survey, water Chl *a*, Chl *b* and total organic carbon values were determined at various sampling sites at Ceduna in South Australia, around the localities where *Crassostrea gigas* is farmed (Australian Water Quality Centre, 1996). No bivalve growth parameters were incorporated in this water sampling study. Samples were taken at approximately monthly intervals between October 1995 and May 1996. The data presented in Figure 13 are means (\pm s.e.) of the Chl *a* readings obtained for the six sampling sites at each date.

Mean Chl *a* values ranged between 0.3 and 1.7 mg/m³, similar to Coffin Bay. Total organic carbon levels ranged between 1.1 and 2.3 mg/l. Compared with the New Zealand sites, waters around Ceduna contain less phytoplankton and more organic carbon. This indicates a significant source of particulate food other than phytoplankton at the South Australian site. At the low levels of Chl *a* indicated, this food resource may be very important to oyster productivity.

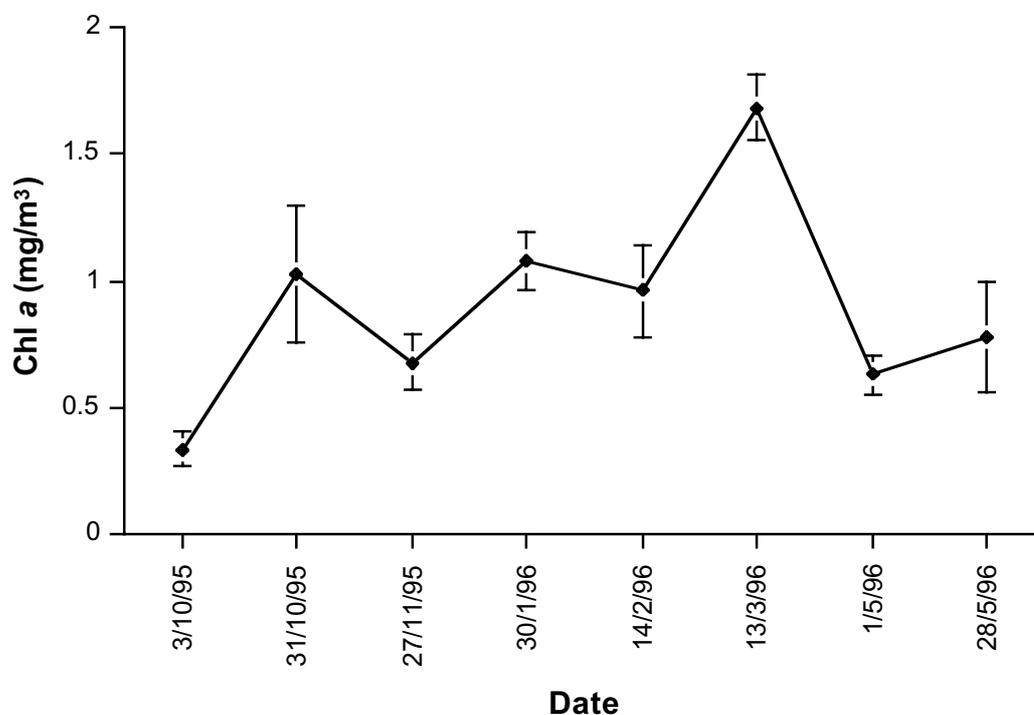


Figure 13. Mean Chl a readings for waters around Ceduna, South Australia, taken at approximately monthly intervals (data from Australian Water Quality Centre, 1996).

14.0 Summary and recommendations - food availability and water conditions

From the broad range of culture conditions reviewed (see site summary, Table 17), temperature and food availability appear to be the major factors affecting growth of bivalves at existing commercial bivalve sites. A combination of very low temperature and low food availability may cause bivalves to lose condition, by decrease in flesh weight during winter. Stable summer conditions of increasing temperature, low food availability, high salinity, low water exchange and low nutrient levels, may also adversely affect the flesh condition and growth of bivalves.

Mean chlorophyll *a* concentrations of the order of 1-10 mg/m³ were predominant at sites where bivalve growth does not appear to be greatly limited by lack of nutrients, for example, British Columbia, Saldanha Bay, Tasmania and the Ria de Arousa. At sites where phytoplankton growth was more nutrient-limited, other particulate organic matter may have made a larger contribution to the growth and condition of bivalves, for example, Pelorus Sound, New Zealand, in the Ria Sada, Galicia, Spain, and in the Gulf of Castellammare, Sicily.

Multiple-site growth studies in Pelorus Sound and British Columbia demonstrated a strong positive correlation between temperature and bivalve growth and condition, at sites where food availability was not low. The work of Mason *et al.* (1998) on Sydney rock oyster (*Saccostrea commercialis*) supported this. They established experimentally that changes in growth rate are predominantly controlled by initial size and water temperature, when food is abundant. Temperatures between 10 and 18°C promoted good mussel growth, while Pacific oysters appeared to grow well at a slightly higher range of 12 to 25°C, in sites where food

levels are high. In contrast, the New Zealand studies revealed that mussel condition index and shell length were negatively correlated with increasing temperature under conditions of very low food availability. This may have been due to reduction in rainfall with temperature rise from spring to summer, more stable weather conditions, lower current flows and flushing rates. The reduced inputs of nutrients and particulates from terrigenous sources, as well as lack of nutrients from oceanic upwelling and advection were seen as the causes of low food levels and consequent loss of condition and reduced growth. As well, loss in condition through reproductive activity may have occurred with temperature rises.

Prolonged periods (3 to 4 months) during spring and autumn outflows of fresh water, where salinity levels were below 20 ‰ in British Columbian sites, resulted in severely-reduced shell and flesh growth, despite the presence of associated phytoplankton blooms and satisfactory growth temperatures. Increases in shell height and meat weight may have been restricted by physiological stress in the prolonged low salinity periods, while shell thinning may have resulted from a lack of available minerals. In contrast, salinity studies in Pelorus Sound, New Zealand, and in Tasmania, showed that reduced salinity was correlated with increased growth, improved condition, higher nutrient levels, higher Chl *a* and larger quantities of particulates. These correlations reveal the input of nutrient- and organic particulate-rich fresh water into the system. Salinities ranged from 10 - 38 ‰ in the Tasmanian studies and 20-35 ‰ in the Marlborough Sounds, with no recorded adverse effects upon growth. Rapid flushing rates following inputs of fresh water in both regions restricted the severe salinity reductions to a single monthly reading of 10 ‰ in Tasmania, and one monthly reading of 20 ‰ in the upper regions of Pelorus Sound. Clearly, the period of time that bivalves were exposed to severely-reduced salinity (possibly below 20 ‰ for *C. gigas*) is the major difference between the British Columbian and the Australasian sites. Pacific oysters grown at Coffin Bay, South Australia, appeared to be severely restricted in growth in high salinity waters, above ~40‰, while oysters at sites within the bay which had salinity conditions below ~40 ‰ continued to grow. Phytoplankton levels at all sites were around 0.5 - 1.0 mg/m³, probably sufficient when combined with adequate current flow. Further laboratory studies, and more accurate methods for determining food availability, were needed to confirm the correlation between high salinity and growth restriction seen at these South Australian sites.

Subsurface inputs of nutrient-rich oceanic bottom water, arising from wind-driven upwelling, were also seen to stimulate dense concentrations of phytoplankton in close association with haloclines and thermoclines, in the outer regions Pelorus Sound and in Saldanha Bay, while the very shallow Pipeclay Lagoon in Tasmania, derived its high productivity from daily replenishment arising from a rapid tidal flushing rate.

Adequate current flow was vital to promote food availability in hanging rope culture. Correct stocking densities were established, to avoid restricting growth of bivalves through lack of available phytoplankton, especially in the centre of rafts. Oceanic bivalve culture sites needed protection from wave and wind, but also needed access to the nutrients derived from upwelling on a high energy coastline, as well as a means of adequate exchange of oceanic water. Sheltered, deep embayments which develop thermoclines from subsurface advection, and which have adequate tidal and/or wind-forced mixing to dissipate them, were shown to be ideal. Alternately, shallow oceanic embayments with a rapid tidal exchange rate also proved to be highly productive when surface waters were phytoplankton-rich. Estuarine sites either had nutrients regularly replenished by input from terrestrial sources, or a strong tidal flow replenishing food from coastal oceanic waters.

Table 17. Summary of means (M) and ranges (R) of monthly Chlorophyll a, particulate organic matter (POM), salinity, temperature and annual bivalve growth at various sites around the world.

Locality	Species	Chlorophyll a (mg/m ³)		POM (mg/l)		Salinity (‰)		Temperature (°C)		Growth (Shell)	Productivity (g C/m ² /year)	Source
		M	R	M	R	M	R	M	R			
Marlborough, New Zealand												
Pelorus-Kenepuru Sound	<i>Perna canaliculus</i>	1.42	0.8-3.1	264	55-700	32.7	29.2-34.9	14.7	11-19	50 mm/y	-	Hickman <i>et al.</i> , 1991
British Columbia, Canada												
Okover Inlet	<i>Crassostrea gigas</i>	3.76	0-9	-	-	27.7	21-28	14.3	8-22	80 mm/yr	-	Brown & Hartwick, 1988a
West Vancouver		7.94	0-50	-	-	19.3	16-23	12.2	4-19	10 mm/yr	-	Brown & Hartwick, 1988a
Galicia, Spain												
Ria de Arousa	<i>Mytilus edulis</i>	3.9	-	-	-	-	34-35	-	13-17	10 mm/month (3 summer months)	-	P-Camacho <i>et al.</i> , 1995
El Grove (Ria de Arousa)	<i>Crassostrea gigas</i>	2.13	0.5-7	-	-	34	33-35	15.2	12-19	45 - 60 mm/y	-	Ruiz <i>et al.</i> , 1992
Ria de Arousa	<i>Pecten maximus</i>	2.26	0.1-6.5	2	-	-	-	-	11-21		-	Pazos <i>et al.</i> , 1996
Ria Sada	<i>M. galloprovincialis</i>	1.4	0 - 8	-	-	-	-	12.8	11-13	3 mm/month (winter)	-	F-Rieiriz <i>et al.</i> , 1996
Ria de Arousa	Production studies										250	Varela <i>et al.</i> , 1984, Bode & Varela, 1998
Sicily, Italy												
Gulf of Castellammare	<i>C. gigas</i>	0.045	-	0.340	-	38	-	19	14-29	25 mm/y	-	Sara and Mazzola, 1997
	<i>M. galloprovincialis</i>	0.05	0.03-0.08	1.1	0.4-2.4	38	-	19	14-25	27 mm/y	-	Sara <i>et al.</i> , 1998
Japan												
Seto Inland Sea	<i>C. gigas</i>	2.92	0.3-6.8	-	-	29.8	27-32	19.6	8-30	70 mm/y	-	Kobayashi <i>et al.</i> , 1997
South Africa												
Saldanha Bay	<i>M. galloprovincialis</i>	8.62*	4-30**	-	-	-	34-35	14	10-19	120-150 mm/y (2 crops)	1241	Pitcher and Calder, 1998 Heasman <i>et al.</i> , 1998
Netherlands												
Eastern Scheldt	<i>M. edulis</i>	6.2	0.5-100	1.25	1-3	-	-	-	-	150 mg /month (whole d.w.)	200- 470	Smaal and van Stralen, 1990
Scotland												
Loch Etive	<i>M. edulis</i>	1.79	-	2.2	-	22.2	-	10.8	-	25 mm/y	-	Stirling and Okumus, 1995
Iceland												
Hvalfjordur	<i>M. edulis</i>	1.15	0-2.8	-	-	-	-	7.3	2-12	25 mm/y	-	Thorarinsdottir, 1996
Breidafjoerdur	<i>Chlamys islandica</i>	1.17	0.1-3.8	-	-	-	-	5.4	0-11.4	15 mm/y	-	Thorarinsdottir, 1994

Locality	Species	Chlorophyll a (mg/m ³)		POM (mg/l)		Salinity (‰)		Temperature (°C)		Growth (Shell)	Productivity (g C/m ² /year)	Source
		M	R	M	R	M	R	M	R			
Tasmania, Australia												
Pittwater	<i>C. gigas</i>	2.87	0.8-9.0	-	-	34.48	31-37	12.88	7-20	50 mm/y	142 ^a	Crawford <i>et al.</i> , 1995
Pipeclay Lagoon	<i>C. gigas</i>	2.37	0.8-4.5	-	-	34.28	33-36	15.5	7-21	50 mm/y	130 ^a	Crawford <i>et al.</i> , 1995
South Australia												
Coffin Bay	<i>C. gigas</i>	-	0.5-1.3	-	-		36-45	-	13-23	0 - 50 mm/y	-	Bridger, (unpublished data)
Ceduna	<i>C. gigas</i>	-	0.3-1.7	-	-	-	-	-	-	-	-	Australian Water Quality Centre, 1996

* Mean winter/autumn value

** Highly stratified conditions; range derived from integrals of a series of depth readings.

^a based upon 10 readings throughout the year, 6 from Pittwater and 4 from Pipeclay Lagoon (Tasmania). Converted from volume productivity (Table 12) to area productivity through division by approximate mean depth (1.5 m and 2.5 m, respectively).

In common with other productive sites around the world, commercial sites in Australasia have shown generally high phytoplankton levels combined with seasonal blooms, in favourable water conditions.

Using existing sites as a guide, a potential bivalve site in temperate or warm temperate waters of coastal Western Australia will need:

- **Monthly Chl *a* levels consistently in excess of 1 mg/m³,**
- **A mean annual Chl *a* level between 2 and 3 mg/m³,**
- **Temperatures ranging between 7 and 25°C,**
- **A salinity regime where long-term reductions above or below bivalve acclimatisation limits do not occur,**
- **Adequate flow, water exchange and mixing rates,**
- **Sheltered conditions,**
- **A regular marine or terrestrial source of dissolved nutrient or particulate food.**

Under such conditions, bivalve growth would be sufficient for commercial exploitation, and a viable, sustainable bivalve industry could be developed. Areas with more limited food availability may only sustain farming systems that involve relatively lower biomasses of bivalves per unit volume of sea water.

15.0 Acknowledgments

We are particularly grateful to Iona Mitchell for supplying additional data to complement FRDC Final Report 92/54.

Flinders University is also acknowledged for supplying an unpublished honours thesis by L. Bridger.

The review was initiated by Dr. Greg Maguire who provided critical input on various drafts. Useful comments were also provided by Sandra Seidel.

16.0 References

- Australian Water Quality Centre, 1996, Phytoplankton surveys of Denial Bay and Smokey Bay, Ceduna South Australia. October 1996 - June 1996.
- Bode, A. and Varela, M. 1998, Primary production and phytoplankton in three Galician Rias Altas (NW Spain): seasonal and spatial variability. *Scientia Marina*, **62**: 319-330.
- Boyd, A.J., and Heasman, K.G. 1998, Shellfish mariculture in the Banguela system: water flow patterns within a mussel farm in Saldanha Bay, South Africa. *Journal of Shellfish Research*, **17**: 25-32.

- Bridger, L. (unpublished data). Investigation of site-related differences in oyster growth at four locations within Coffin Bay. Honours thesis, School of Biological Sciences, Flinders University, South Australia, 1996.
- Brown, J.R. and Hartwick, E.B. 1988a, Influences of temperature, salinity and available food upon suspended culture of the Pacific oyster, *Crassostrea gigas* I. Absolute and allometric growth. *Aquaculture*, **70**: 231-251.
- Brown, J.R. and Hartwick, E.B. 1988b, Influences of temperature, salinity and available food upon suspended culture of the Pacific oyster, *Crassostrea gigas* II. Condition index and survival. *Aquaculture*, **70**: 253-267.
- Crawford, C., Mitchell, I. and Brown, A. 1996, Predictive modelling of carrying capacities of oyster (*Crassostrea gigas*) farming areas in Tasmania. Final Report to the Fisheries Research and Development Corporation. FRDC Grant 92/54 .
- Dame, R. and Libes, S. 1993, Oyster reefs and nutrient retention in tidal creeks. *Journal of Experimental Marine Biology and Ecology*, **171**: 251-258.
- Fernandez-Reiriz, M.J., Labarta, U. and Babarro, J.M.F. 1996, Comparative allometries in growth and chemical composition of mussel (*Mytilus galloprovincialis* Lmk) cultured in two zones in the Ria Sada (Galacia, NW Spain). *Journal of Shellfish Research*, **15**: 349-353.
- Gibbs, M.M., Pickmere, S.E., Woods, P.H., Payne, G.W., James, M.R., Hickman, R.W. and Illingworth, J. 1992, Nutrient and chlorophyll *a* variability at six stations associated with mussel farming in Pelorus Sound, 1984-1985. *New Zealand Journal of Marine and Freshwater Research*, **26**: 197-211
- Heasman, K.G., Pitcher, G.C., McQuaid, C.D. and Hecht, T. 1998, Shellfish mariculture in the Banguela system: raft culture of *Mytilus galloprovincialis* and the effect of rope spacing on food extraction, growth rate, production and condition of mussels. *Journal of Shellfish Research*, **17**: 33-39.
- Hickman, R.W., Waite, R.P., Illingworth, J., Meredyth-Young, J.L. and Payne, G. 1991, The relationship between farmed mussels, *Perna canaliculus*, and available food in Pelorus-Kenepuru Sound, New Zealand. *Aquaculture*, **99**: 49-68.
- Howarth, R. 1988, Nutrient limitation of net primary production in marine ecosystems. *Annual Reviews of Ecological Systems*, **19**: 89-110.
- Kobayashi, M. Hofmann, E., Powell, E., Klinck, J.M. and Kusaka, K. 1997, A population dynamics model for the Japanese oyster, *Crassostrea gigas*. *Aquaculture*, **149**: 285-321.
- Mason, C.J., Reid, D.D., and Nell, J.A. 1998, Growth characteristics of Sydney rock oysters *Saccostrea commercialis* in relation to size and temperature. *Journal of Experimental Marine Biology and Ecology*, **227**: 155-168.
- Pearce, A., Helleran, S. and Marinelli, M. 2000, Review of productivity levels of Western Australian coastal and estuarine waters for mariculture planning purposes. Fisheries Research Report No. 123. Fisheries Research Division, Fisheries WA, Western Australian Marine Research Laboratories, North Beach, 6020 Western Australia.

- Pérez Camacho, A., Labarta, U. and Beiras, R. 1995, Growth of mussels (*Mytilus edulis galloprovincialis*) on cultivation rafts: influence of seed source, cultivation site and phytoplankton availability. *Aquaculture*, **138**: 349-362.
- Pazos, A.J., Roman, G., Acosta, C.P., Abad, M. and Sanchez, J.L. 1996, Stereological studies on the gametogenic cycle of the scallop, *Pecten maximus*, in suspended culture in Ria de Arousa (Galicia, NW Spain). *Aquaculture*, **142**: 119-135.
- Pitcher, G.C. and Calder, D. 1998, Shellfish mariculture in the Banguela system: phytoplankton and the availability of food for commercial mussel farms in Saldanha Bay, South Africa. *Journal of Shellfish Research*, **17**: 15-24.
- Ruiz, C., Abad, M., Sedano, F., Garcia-Martin, L.O. and Sánchez López, J.L. 1992, Influence of seasonal environmental changes on the gamete production and biochemical composition of *Crassostrea gigas* (Thunberg) in suspended culture in El Grove, Galicia, Spain. *Journal of Experimental Marine Biology and Ecology*, **155**: 249-262.
- Sara, G. and Mazzola, A. 1997, Effects of trophic and environmental conditions on the growth of *Crassostrea gigas* in culture. *Aquaculture*, **153**: 81-91.
- Sara, G., Manganaro, A., Cortese, G., Pusceddu, A. and Mazzola, A. 1998, The relationship between food availability and growth in *Mytilus galloprovincialis* in the open sea (southern Mediterranean). *Aquaculture*, **167**: 1-15.
- Smaal, A.C. and van Stralen, M.R. 1990, Average annual growth and condition of mussels as a function of food source. *Hydrobiologia*, **195**: 179-188.
- Stirling, H.P. and Okumus, I. 1995, Growth and production of mussels (*Mytilus edulis* L.) suspended at salmon cages and shellfish farms in two Scottish sea lochs. *Aquaculture*, **134**: 193-210.
- Thorarinsdottir, G.G. 1994, The Iceland scallop, *Chlamys islandica* (O. F. Mueller), in Breidafjoerdur, west Iceland. 3. Growth in suspended culture. *Aquaculture*: **120**: 295-303.
- Thorarinsdottir, G.G. 1996, Gonad development, larval settlement and growth of *Mytilus edulis* L. in a suspended population in Hvalfjordur, south west Iceland. *Aquaculture Research*, **27**: 57-65.
- Treadwell, R., McKelvie, L. and Maguire, G.B. 1991, Profitability of selected aquacultural species. Australian Bureau of Agricultural and Research Economics.
- Varela, M., Fuentes, J.M., Penas, E. and Cabanas, J.M. 1984, Producción primaria de las Rías Baixas de Galicia. Cuadernos da Area de Ciencias Mariñas. Seminario de Estudos Galegos, **1**: 173-182.

List of Fisheries Research Reports

Not all have been listed here, a complete list is available online at <http://www.wa.gov.au/westfish>

- 83 The Western Rock Lobster fishery 1985/86. Brown, R.S.; Barker, E.H. (1990.)
 - 84 The Marine open shelf environment: review of human influences. Hancock, D.A. (1990.)
 - 85 A Description of the British United Trawlers / Southern Ocean Trawlers operation in the Great Australian Bight during the period 19.11.77 to 28.5.79. Walker, M.H.; Blight, S.J.; Clarke, D.P. (1989.)
 - 86 The Demersal trawl resources of the Great Australian Bight as indicated by the fishing operations of the stern trawlers Othello, Orsino and Cassio in the period 19.11.77 to 28.5.79. Walker, M.H.; Clarke, D.P. (1990.)
 - 87 The recreational marron fishery in Western Australia summarised research statistics, 1971 - 1987. Morrissy, N.M.; Fellows, C.J. (1990.)
 - 88 A synopsis of the biology and the exploitation of the Australasian pilchard, *Sardinops neopilchardus* (Steindachner). Part 1: Biology. Fletcher, W.J. (1990.)
 - 89 Relationships among partial and whole lengths and weights for Western Australian pink snapper *Chrysophrys auratus* (Sparidae). Moran, M.J.; Burton, C. (1990.)
 - 90 A Summary of projects financed by the Fisheries Research and Development Fund 1965-1983. (1991.)
 - 91 A synopsis of the biology and the exploitation of the Australasian pilchard, *Sardinops neopilchardus* (Steindachner) Part II : History of stock assessment and exploitation. Fletcher, W.J. (1991.)
 - 92 Spread of the introduced yabbie *Cherax albidus* Clark, 1936 in Western Australia. Morrissy, N.M.; Cassells, G. (1992.)
 - 93 Biological synopsis of the black bream, *Acanthopagrus butcheri* (Munro) (Teleostei: Sparidae). Norriss, J. V.; Tregonning, J. E.; Lenanton, R. C. J.; Sarre, G. A. (2002.)
 - 94 to 98 No reports were published under these numbers.
 - 99 An Investigation of weight loss of marron (*Cherax tenuimanus*) during live transport to market. Morrissy, N.; Walker, P.; Fellows, C.; Moore, W. (1993.)
 - 100 The Impact of trawling for saucer scallops and western king prawns on the benthic communities in coastal waters off south-western Australia. (FRDC final report 90/019) Laurenson, L.B.J.; Unsworth, P.; Penn, J.W.; Lenanton, R.C.J.; Fisheries Research and Development Corporation (1993.)
 - 101 The Big Bank region of the limited entry fishery for the western rock lobster *Panulirus cygnus*. Chubb, C.F.; Barker, E.H.; Dibden, C.J. (1994.)
 - 102 A Review of international aquaculture development and selected species in environments relevant to Western Australia. Lawrence, C. S. (1995.)
 - 103 Identifying the developmental stages for eggs of the Australian pilchard, *Sardinops sagax*. White, K.V.; Fletcher, W. J. (1998.)
 - 104 Assessment of the effects of a trial period of unattended recreational netting in selected estuaries of temperate Western Australia. Lenanton, R.C.; Allison, R.; Ayvazian, S.G.; Western Australia. Fisheries Dept. (1996.)
 - 105 The western rock lobster fishery 1986/7 to 1990/91. Chubb, C.F.; Barker, E.H.; Brown, R.S.; Western Australia. Fisheries Dept. (1996.)
 - 106 Environmental and biological aspects of the mass mortality of pilchards (Autumn 1995) in Western Australia. Fletcher, W.J.; Jones, B; Pearce, A.F.; Hosja, W.; Western Australia. Fisheries Dept. (1997.)
 - 107 Chemical composition of yabbies, *Cherax albidus* Clark 1936 from Western Australian farm dams. Francesconi, Kevin A.; Morrissy, Noel M. (1996.)
 - 108 Aspects of the biology and stock assessment of the whitebait, *Hyperlophus vittatus*, in south western Australia. Gaughan, D.J.; Fletcher, W.J; Tregonning, R.J.; Goh, J. (1996.)
 - 109 The western rock lobster fishery 1991/92 to 1992/93. Chubb, C.F.; Barker, E.H.; Fisheries Western Australia (1998.)
 - 110 A Research vessel survey of bottom types in the area of the Abrolhos Islands and mid-west trawl fishery. Dibden, C.J.; Joll, L.M. (1998.)
 - 111 Sea temperature variability off Western Australia 1990 to 1994. Pearce, Alan; Roszbach, Mark; Tait, Marion; Brown, Rhys (1999.)
 - 112 Final report, FRDC project 94/075: enhancement of yabbie production from Western Australian farm dams. Lawrence, Craig; Morrissy, Noel; Bellanger, Justin; Cheng, Yuk Wing; Fisheries Research and Development Corporation (1998.)
 - 113 Catch, effort and the conversion from gill nets to traps in the Peel-Harvey and Cockburn Sound blue swimmer crab (*Portunus pelagicus*) fisheries. Melville-Smith, R.; Cliff, M.; Anderton, S.M. (1999.)
 - 114 The Western Australian scallop industry. Harris, D.C.; Joll, L.M.; Watson, R.A. (1999.)
 - 115 Statistical analysis of Gascoyne region recreational fishing study July 1996. Sumner, N.R.; Steckis, R.A. (1999.)
 - 116 The western rock lobster fishery 1993/94 to 1994/95. Chubb, C.F.; Barker, E.H.; Fisheries Western Australia (2000.)
 - 117 A 12-month survey of coastal recreational boat fishing between Augusta and Kalbarri on the west coast of Western Australia during 1996-97. Sumner, N.R.; Williamson, P.C. (1999.)
 - 118 A study into Western Australia's open access and wetline fisheries. Crowe, F.; Lehre, W.; Lenanton, R. J. C. (1999.)
 - 119 Final report : FRDC project 95/037 : The biology and stock assessment of the tropical sardine, *Sardinella lemuru*, off the mid-west coast of Western Australia. Gaughan, D.J.; Mitchell, R.W.D.; Fisheries Research and Development Corporation (Australia); Western Australian Marine Research Laboratories. (2000.)
 - 120 A 12 month survey of recreational fishing in the Leschenault Estuary of Western Australia during 1998. Malseed, B. E.; Sumner, N.R.; Williamson, P.C. (2000.)
 - 121 Synopsis of the biology and exploitation of the blue swimmer crab, *Portunus pelagicus* Linnaeus, in Western Australia. Kangas, M.I. (2000.)
 - 122 Western rock lobster mail surveys of licensed recreational fishers 1986/87 to 1998/99 Melville-Smith, R.; Anderton, S.M. (2000.)
-

Fisheries Research Reports *cont'd.*

- 123 Review of productivity levels of Western Australian coastal and estuarine waters for mariculture planning purposes. CDRom in back pocket has title "Chlorophyll-*a* concentration in Western Australian coastal waters - a source document by S. Hellenen and A. Pearce" (document in PDF format) Pearce, A.; Hellenen, S.; Marinelli, M. (2000.)
 - 124 The Evaluation of a recreational fishing stock enhancement trial of black bream (*Acanthopagrus butcheri*) in the Swan River, Western Australia Dibden, C.J.; Jenkins, G.; Sarre, G.A.; Lenanton, R.C.J.; Ayvazian, S.G. (2000.)
 - 125 A history of foreign fishing activities and fishery-independent surveys of the demersal finfish resources in the Kimberley region of Western Australia. [Part funded by Fisheries Research and Development Corporation Project 94/026] Nowara, G.B.; Newman, S.J. (2001.)
 - 126 A 12 month survey of recreational fishing in the Swan-Canning Estuary Basin of Western Australia during 1998-99. Malseed, B. E.; Sumner, N.R. (2001.)
 - 127 A 12 month survey of recreational fishing in the Peel-Harvey Estuary of Western Australia during 1998-99. Malseed, B. E.; Sumner, N.R. (2001.)
 - 128 Aquaculture and related biological attributes of abalone species in Australia - a review Freeman, K.A. (2001.)
 - 129 Morphology and incidence of yabby (*Cherax albidus*) burrows in Western Australia. Lawrence, C.S.; Brown, J.I.; Bellanger, J.E. (2001.)
 - 130 Environmental requirements and tolerances of rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) with special reference to Western Australia : a review. Molony, B. (2001.)
 - 131 Pilchard (*Sardinops sagax*) nursery areas and recruitment process assessment between different regions in southern Western Australia. Gaughan, D.J.; Baudains, G.A.; Mitchell, R.W.D.; Leary, T.I. (2002.)
 - 133 Preliminary assessment and seasonal fluctuations in the fish biota inhabiting the concentrator ponds of Dampier Salt, Port Hedland, with options for the potential application of results. Molony, B.; Parry, G. (2002.)
 - 134 Towards an assessment of the natural and human use impacts on the marine environment of the Abrolhos Islands. Volume 1, Summary of existing information and current levels of human use. CDRom in back pocket has title "Abrolhos Habitat Survey". Webster, F.J; Dibden, C.J.; Weir, K.E.; Chubb, C.F. (2002.) Volume 2, Strategic research and development plan. Chubb, C.F.; Webster, F.J; Dibden, C.J.; Weir, K.E. (2002.)
 - 135 The western rock lobster fishery 1995/96 to 1996/97. Chubb, C.F.; Barker, E.H. (2002.)
 - 136 Assessment of gonad staging systems and other methods used in the study of the reproductive biology of narrow-barred Spanish mackerel, *Scomberomorus commerson*, in Western Australia. Mackie, Michael; Lewis, Paul (2001.)
 - 137 Annual report on the monitoring of the recreational marron fishery in 2000, with an analysis of long-term data and changes within this fishery. Molony, B.; Bird, C. (2002.)
 - 138 Historical diving profiles for pearl oyster divers in Western Australia. Lulofs, H.M.A. and Sumner, N.R. (2002)
 - 139 A 12-month survey of recreational fishing in the Gascoyne bioregion of Western Australia during 1998-99. Sumner, N.R.; Willimson, P.C.; Malseed, B.E. (2002.)
-