NURSERY CULTURE

OF

SYDNEY ROCK OYSTERS,

***Saccostrea commercialis* (Iredale & Roughley, 1933)**

AND

PACIFIC OYSTERS,

***Crassostrea gigas* (Thunberg, 1793)**

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DECLARATION AND AUTHORITY OF ACCESS

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ABSTRACT

This study of settlement, nursery and growing techniques for Sydney rock oysters, *Saccostrea commercialis*, and Pacific oysters, *Crassostrea gigas*, was aimed at developing and evaluating production systems for juvenile oysters (spat). Settlement, retention (spat retained within nursery units from settlement or stocking to harvest), survival and growth of juvenile wild and hatchery produced oysters were assessed in relation to systems design and management at sites in New South Wales (NSW), Australia.

Optimum conditions for storage of Sydney rock oyster larvae were determined to allow for transport and settlement at sites remote from hatcheries. Excellent mean settlement rates were obtained for Sydney rock (76%) and Pacific oyster (68%) larvae following storage at 11°C and 6°C respectively for up to 98 h. Temperatures (11°C) were higher for Sydney rock oysters than those used commercially for the storage and remote settlement of Pacific oysters (6°C). Mean shell length and eyespot diameter for Sydney rock (292.2 μm and 20.3 μm respectively) and Pacific oysters (325.4 μm and 14.2 μm respectively) were also significantly different.

Different settlement systems and cultch (substrates on which larvae settle) were compared, for Sydney rock oysters under hatchery conditions, to optimise production of single seed (unattached spat). Larvae were set either on small chips of scallop shell, which became inconsequential as the spat grew, or on larger substrates from which the spat were subsequently detached. Similar proportions of larvae settled on small PVC discs (57%) in a 3 000 l fibreglass tank and on chips of scallop shell in four downweller units (56%). Of the nine types of commercially-used collectors tested in another hatchery experiment, slurry-coated large PVC discs consistently caught the greatest numbers of spat. However, PVC and slurry-coated PVC slats, cut from commercial grade water pipe and "aged" for two years, were also effective collectors with settlement significantly higher on PVC than on slurry-coated PVC slats. Orientation of these slats affected settlement, with significantly higher density on those positioned horizontally, compared with those positioned vertically. For horizontally positioned slats, settlement was

significantly higher on the lower surfaces. However, for the nine types of collectors above, this pattern was not generally evident.

Ten types of cultch were examined in the Port Stephens estuary for settlement, retention and post-harvest survival of oysters, to determine the most efficient collector for the production of single seed oysters from natural spatfall and for growing oysters to market size. Although tarred, timber sticks are the most commonly used collector in the NSW industry, settlement of Sydney rock and Pacific oysters was far greater on PVC collectors. Tarred sticks attracted the most barnacles at settlement. Post-harvest survival of Sydney rock oyster spat removed from collectors for culture as single seed, was high for all collector types (range 89-92%) except for bioresin slats (67%). PVC growing sticks retained significantly greater numbers of Sydney rock oysters to market size than did tarred sticks. At harvest, similar growth was obtained on the five types of growing sticks tested except for tarred sticks, where oysters had significantly greater shell lengths than those on round grooved PVC sticks. Round spiky PVC sticks with lug were the most effective type of growing stick as they retained good numbers of oysters that grew well and could be harvested without damaging the oysters or the sticks.

Single seed culture techniques were evaluated using different systems, stocking densities and sites, to determine the most effective nursery systems for Sydney rock oysters from natural spatfall or hatcheries. For newly settled hatchery spat (initial size 0.5 and 0.7 mm/spat), survival and retention was highest in onshore upwellers at the inlet to a power station in Lake Macquarie, although, growth was far greater on PVC discs deployed on an intertidal lease in Port Stephens. Density affected growth of single seed oysters in sectionalised timber trays and rotating PVC cylinders. For trays, optimum stocking densities (based on maximum biomass gain), for oysters with average initial weights of 0.1, 1.2 and 1.6 g/spat were 1.55 g spat/cm^2 (15 200 spat/m^2), 0.72 g spat/cm^2 (7 200 spat/m^2), and 0.36 g spat/cm^2 (3 600 spat/m^2) respectively. For cylinders, optimum densities for spat of 0.2 and 0.4 g/spat initial weight, were 2.0 l spat/cylinder (0.19 g spat/cm^2) and 3.0 l spat/cylinder (0.15 g spat/cm^2) respectively, based on maximum biomass gains. For similar size spat, optimum stocking density per unit area of lease space was higher for trays than cylinders. Density did not affect spat survival except for the highest density tested within cylinders (6.0 l/cylinder).

Several sites in the Port Stephens estuary were evaluated for growing single seed Sydney rock oysters, to optimise spat performance and to maximise the use of leases. Growth and survival of 4.0 g spat (initial weight) in sectionalised timber trays were monitored at a predominantly oceanic site, at a middle-estuary site and at an upper estuary site. Oyster survival over 12 months was high at all sites (average 88%), but significantly greater at the more estuarine site than at either the middle harbour or oceanic site. Spat growth was greatest at the middle harbour site and slowest at the most oceanic site. The best spat growth periods were from August-October and February-April at the two better sites, with growth depressed during the cooler months. This study indicated that vacant spat catching leases in the more oceanic areas could be used for the culture of single seed oysters. In a subsequent trial in the cooler months (April-September), Sydney rock oyster spat (initial weight 1.6 g/spat) grown on trays on an intertidal lease, exhibited better growth and survival in upwellers at the inlet site to a power station at Lake Macquarie than in intertidal trays in Port Stephens. Here, water temperatures (affected by the power station effluent), were on average 3.6°C higher than in Port Stephens. However, poor spat growth and high mortality were obtained from upwellers using heated effluent at the outlet, where water temperatures were on average 8.2°C higher than in Port Stephens.

Different types of nursery units, with larger gauge meshes to increase water circulation and to reduce siltation and fouling (Claus, 1981; Spencer, 1990), were assessed for the growth of larger Sydney rock oyster spat (initial weight 4.1 g/spat). Spat growth was significantly greater in PVC baskets than in sectionalised timber and PVC mesh trays, and significantly greater in these trays than in rotating PVC cylinders. However, mortality and the incidence of mudworm (*Polydora* spp.) in trays (9% and 3% of spat respectively) were significantly lower than in baskets (24% and 23% respectively) or cylinders (78% and 94% respectively).

While a range of environmental variables (temperature, flow rate, water circulation) are likely to influence performance in nursery systems, the density dependence of growth rates was a common factor in several experiments. Once the appropriate nursery system is chosen for spat of a particular size range, manipulation of density and biomass within that system will be a key operational consideration.

In summary, the results from this study provide the NSW oyster industry with the basis for improved management of production systems used for Sydney rock and Pacific oysters from hatcheries or the wild. Although the study focused on the NSW industry, many of the techniques and recommendations are likely to be relevant to other oyster industries.

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CHAPTER 1

INTRODUCTION, GENERAL BACKGROUND AND LITERATURE REVIEW

1.1 SCOPE OF REVIEW

This chapter is a review of the relevant literature for the Sydney rock *Saccostrea commercialis* and Pacific oyster *Crassostrea gigas*. Specifically, the systematics, biology and distribution, as well as cultivation practices used in Australia and overseas for these species are examined. The main focus is on factors that affect settlement, growth, survival and production of juvenile oysters. Where possible, comparative information for the Sydney rock and Pacific oysters is provided.

1.1.1 Systematics

A variety of approaches have been adopted by oyster taxonomists. Initially classification was based on anatomical and reproductive characteristics (Quayle, 1988), although Stenzel (1971), based his generic placement of oyster species on shell characteristics using living and fossil forms. More recently, Harry (1985, 1986; Table 1.1) emphasised geographical distribution, while Brock (1990), used cross immuno-electrophoresis to define the genera of *Ostrea*, *Crassostrea* and *Saccostrea*.

Few of the 100 (approximate) extant species of oysters found worldwide are farmed commercially and these are restricted to the molluscan family, Ostreidae. The key genera are: *Crassostrea* Sacco, 1897; *Ostrea* Linne, 1758; and *Saccostrea* Dollfus and Dautzenberg, 1920, (Matthiessen, 1991; Table 1.2). In Australia, edible oysters farmed or harvested from the wild include: the Sydney rock oyster (*Saccostrea commercialis*) which is produced mainly in New South Wales (NSW) and southern Queensland; the Pacific oyster (*Crassostrea gigas*) which is produced in Tasmania, South Australia and in specific areas in NSW and Victoria; the flat oyster (*Ostrea angasi*) which is produced in NSW, Tasmania, Victoria, Australia and in South and Western Australia; and the milky oyster (*Saccostrea amasa*) which is harvested from northern Queensland.

The species used in the present study are the Sydney rock oyster *Saccostrea commercialis* (Iredale & Roughley, 1933) and the Pacific oyster *Crassostrea gigas* (Thunberg, 1793). Thomson (1954), placed *Ostrea commercialis* Iredale & Roughley in the genus *Crassostrea*. The Sydney rock, sometimes called the commercial oyster, has been classified as a subspecies of *cucullata* (Ahmed, 1975) and as a variant of *Saccostrea mytuloides* (Arakawa, 1990a). The New Zealand rock oyster (*Saccostrea commercialis* = *Saccostrea glomerata* Gould) is considered to be a sub-species of the Sydney rock oyster (Buroker et al, 1979), which perhaps should be called *Saccostrea glomerata commercialis* as *glomerata* is the older name (S. Slack-Smith, pers. comm., 1992).

The Pacific oyster was first named and described by Thunberg in 1793. Arakawa (1990a) reported four subspecies, strains or races of the Pacific oyster, based on regional types and include Kumamoto (south of Japan), Hiroshima (central), Miyagi and Hokkaido (north). These subspecies were later reclassified (Buroker et al., 1979; Banks et al., 1991; Deupree et al., 1992). Deupree (1993) found the Tasmanian Pacific oyster populations to be similar to Miyagi oysters. Pacific oysters grown in NSW resemble those grown in Tasmania.

Scientific names are used throughout the text to describe species other than Sydney rock and Pacific oysters, for which common names are used. The synopsis for the present study was based on the classification used by Harry (1985, 1986; Table 1.1) as follows:

Phylum	Mollusca
Class	Pelecypoda
(Subclass	Lamellibranchis)
Order	Anisomyaria

Table 1.1 Systematic distribution of extant oysters in families, subfamilies and tribes (Harry, 1986).

Family	Subfamily	Tribe
Ostreidae	Crassostreinae	Crassostreini Striostreini
	Ostreinae	Undulostreini Pustulostreini Cryptostreini Ostreini
	Lophinae	Myrakeenini Lophini
Gryphaeidae	Pycnodonteinae	Neopycnodontini Hyotissini

Table 1.2. Commercial species of oysters referred to in this study.

TRIBE & GENUS	SPECIES & COMMON NAMES
OSTREINI *Ostrea* Linnaeus, 1758	*O. edulis* Linnaeus, 1758 - European/oyster.
	O. chilensis =" *O. lutaria* Hutton, 1873". " = *Tiostrea lutaria* of Buroker et al., 1983" - New Zealand Bluff oyster.
	O. lurida Carpenter, 1864 - Native/Western/Olympia oyster.
	O. angasi[1] Sowerby, 1871 - Mud/Flat/Native/Port Lincoln oyster.
CRASSOSTREINI *Crassostrea* Sacco, 1897	*C. virginica* (Gmelin, 1791) - Eastern/Atlantic/American oyster.
	C. gigas[1] (Thunberg, 1793) - Pacific/Japanese oyster.
	C. belcheri (Sowerby, 1871) - Malaysian oyster.
	C. madrasensis (Preston, 1916) - Indian backwater oyster.
STRIOSTREINI *Saccostrea* Dollfuss & Dautzenberg, 1920	*S. cucullata* (Born, 1778).
	S. echinata[1] (Quoy & Gaimard, 1835) - Black lip oyster.
	S. commercialis[1] (Iredale & Roughly, 1933) - Sydney rock/commercial oyster.
	S. glomerata Gould " = *O. glomerata* Gould, 1850 " " = *S. commercialis* of Buroker et al., 1979" - New Zealand rock oyster.
	S. amasa[1] (Iredale, 1939) " = *O. mordax*[1] Saville-Kent, 1891" - Milky oysters = "*S. mordax* (Torigoe, 1981).

1 Species harvested commercially in Australia.
\- Common names.

1.1.2 Biology

The shells of the bivalve molluscs *Crassostrea* and *Saccostrea* are connected by an elastic ligament and adductor muscle (Korringa, 1976). Sexes of the oysters are generally separate, although, hermaphrodites can occur (Roughley, 1933; Dinamani, 1974; Quayle, 1988). Oysters can change sex from year to year (Walne, 1974) and for the Pacific oyster this can be influenced by season and availability of food (Quayle, 1988). Sydney rock oysters initially develop as males (Roughley, 1933; Dinamani, 1974), similar to other cupped oysters (Galtsoff, 1964a; Arakawa, 1990b). Oysters have the ability to store energy in the form of glycogen which can be converted into gonad (eggs or sperm). The number of eggs developed by the oyster is dependent on size and species. An average market size (40-50 g) Pacific oyster from North America can produce about 50-100 x 10^6 eggs (Quayle, 1988; Matthiessen, 1991). In contrast, an adult Sydney rock oyster (35-40 g) from Port Stephens, NSW, only produces between 10-25 x 10^6 eggs per spawning (Holliday, 1992). Mature eggs are held in blind sacs called follicles. On spawning, the oyster discharges the eggs into the suprabranchial chambers and ejects them from the mantle chamber (Walne, 1974; Quayle, 1988). Spawning can be initiated by a temperature change, chemical stimulation (Quayle, 1988) or a change in salinity (Holliday, 1992). With the release of sperm from the male, external fertilisation takes place. Rapid cell division occurs within 16 h to form a swimming stage, called a "D" veliger, with diameter ranging from 50-80 μm, depending on species. The ciliated velum collects food and propels the veliger larva (Frankish et al., 1991).

Larvae begin to consume unicellular algae several days after spawning (Frankish et al., 1991). Metamorphosis begins about 18 days after spawning, when the larvae become photo-sensitive and develop an eye spot on both shells. Development into the pediveliger stage then occurs and the larvae begin to developed a ciliated, protrusible foot, complete with cement gland. Larvae are passively transported by currents and pediveligers actively seek out a suitable substratum by crawling over it with the foot. When this is located, cement is secreted from the gland in the foot, permanently attaching the shell to the substrate. Anatomical changes occur in the larvae including the loss of the foot and eye spots, and an enlargement of the gill system. Within days, the juvenile oyster (spat) produces rapid shell growth and takes on an adult appearance (Walne, 1974; Quayle, 1988; Frankish et al., 1991; Holliday, 1992).

Optimum salinities and water temperatures vary for the different stages of growth for Sydney rock and Pacific oysters (Table 1.3) and are interdependent on environmental conditions including available food levels. Generally, Pacific oysters are able to withstand wider variations of salinity and temperature (Quayle, 1988) than Sydney rock oysters. For Sydney rock oyster larvae, the optimum salinity ranges for growth and survival were found to be 23-39‰ and 27-39‰ respectively, although, larvae tolerate salinities as low as 15‰ (Nell and Holliday, 1988). Optimum growth of Pacific oyster larvae was recorded at 19-27‰ (with tolerance range 15-39‰; Nell and Holliday, 1988). Sydney rock and Pacific oyster larvae are often reared in hatcheries using temperatures in the range of 24-26°C and 26-28°C respectively (Holliday, 1992).

Optimum salinity ranges for growth of Sydney rock oyster spat, with initial weight of 1.3 mg and 0.61 g, were 25-35‰ and 20-40‰ respectively, with a tolerance range of 15-45‰ (Nell and Holliday, 1988). Nell and Livanos (1988) found that when food was not limited, growth increased with temperature for Sydney rock oyster spat (1.53 mg/spat) in the range of 12-30°C, with 30°C being the maximum tested.

Optimum growth of Pacific oyster spat, with initial weight of 1.1 mg and 0.68 g, was obtained at 15-30‰ and 15-45‰ respectively (with tolerance range 15-45‰; Nell and Holliday, 1988). Spencer (1990) recorded the best growth for Pacific oysters (initial weight range 0.02-15 g/spat) at a number of sites in the UK.

Salinity tolerance ranges for adult Sydney rock and Pacific oysters, under controlled conditions, were found to be 15-50‰ and 5-55‰ respectively (Nell and Gibbs, 1986). Under natural conditions, optimum temperature and salinity ranges for Pacific oysters were reported to be 15-20°C (20°C being the highest temperature) and 25-35‰ respectively (Quayle, 1988). Optimum temperature and salinity ranges for adult Sydney rock and Pacific oysters grown under natural conditions in NSW have not been determined yet, although, good growth and survival was observed with temperatures in the range of 18-26°C and 14-26°C respectively and salinities of 25-35‰ and 25-45‰ respectively (J. Nell, pers. comm., 1993). Nell (1991a) found under natural conditions in Port Stephens, Sydney rock oyster spat (range 0.2-25.0 g/spat) and Pacific oyster spat (range 0.2-35 g/spat) survived in the salinity range of 0-39‰ (for short periods in the lower salinities) and with temperatures in the range of 11-30°C. Hughes-Games (1977) also recorded good growth and survival for Pacific oysters (4-65 g average initial and final weights) grown in subtropical fish ponds, with salinities and temperatures as high as 41‰ and 34°C respectively.

Table 1.3

Summary of salinity and temperature ranges for Sydney rock (*Saccostrea commercialis*) and Pacific oysters (*Crassostrea gigas*).*

SPECIES	SALINITY RANGES (‰)		TEMPERATURE RANGES (°C)	
	Growing	Tolerance	Growing	Tolerance
SYDNEY ROCK				
Larvae	23-39	15-39	24-26	NA
Spat	20-40	0-41	14-28	11-30
Adult[1]	25-35	0-50	18-26	11-30
PACIFIC				
Larvae	19-27	15-39	26-28	NA
Spat	15-30	0-45	18-34	11-34
Adult	25-45	0-55	14-34	11-34

* Adapted from Nell and Gibbs (1986), Nell and Holliday (1988) and Holliday (1992).

1 Oysters will withstand salinities < 15‰ for periods of up to 2 weeks.

NA Data not available.

1.1.3 Distribution

1.1.3.1 Sydney rock oyster

Sydney rock oysters are found subtidally, growing on natural river beds (Croft, 1962a; Smith, 1982) and intertidally, on rocks and mangroves (Malcolm, 1987), and are distributed along the east coast of Australia from Maryborough in Queensland, south to Wingham inlet in Victoria (Malcolm, 1987; Moxon, 1986). A subspecies (*S. glomerata commercialis*) is also found in New Zealand (Buroker et al., 1979) and other related species, along the north coast and around the top of Australia as far south as Shark Bay in Western Australia

(Fig 1.1), as well as in some Pacific countries and in south east Asia (P. Dixon, pers, comm., 1991).

1.1.3.2 Pacific oysters

Pacific oysters in Australia originated from Japan (Thomson, 1959; Bourne, 1979; Holliday and Nell, 1987, 1990). They are now widely distributed throughout the world and in many cases this resulted from deliberate introductions to replace disease affected native stocks or to establish an industry (Mann, 1979, 1983; Quayle, 1988; Chew, 1979). They are distributed along the coast of China and Korea and form the basis of large industry in France, Spain, the UK, Ireland, the West Coast of USA and British Colombia (Chew, 1990). Total world production of Pacific oysters in 1993 was about 74.3×10^4 t (Grizel, 1993).

The Pacific oyster was first introduced into Australia after 1940 by the Commonwealth Scientific and Industrial Organisation (CSIRO), to establish an oyster industry in southern Australia (Thomson, 1952; Wolf and Medcof, 1974; Medcof and Wolf, 1975), and commercial farming began in Tasmania in the early 1970's. Tasmania and South Australia are the only locations where the imported stocks of Pacific oysters survived (Chew, 1990). Pacific oysters are now distributed along the east coast of Australia with settlement reported as far north as Moreton Bay, Queensland (Coleman, 1986; Fig 1.1). The oyster was first sighted in several NSW estuaries in 1967 (Wolf and Medcof, 1974) and is now found in 18 of the 40 oyster producing estuaries in NSW (Reid, 1990). Today, Pacific oysters are grown commercially in Victoria (Coleman, 1986), South Australia, Tasmania (Grove-Jones, 1986; O'Sullivan, 1993) and in Port Stephens, NSW (Nell, 1993). Cultivation and sale of Pacific oysters was prohibited in NSW. However, following its rapid increase in settlement in Port Stephens (Fig 1.1) and many other NSW estuaries (Holliday and Nell, 1987, 1990; Brown and Krassoi, 1990; Chew, 1990), regulations were changed to allow its cultivation and sale, but only from Port Stephens (Nell, 1993). This oyster is still classified as a noxious fish in other estuaries in NSW and farmers are required to destroy them.

1.1.4 Oyster losses and management

Oyster industries throughout the world experience major losses in production from diseases, parasites, predators and from competition (Korringa, 1976; Muthiah et al., 1987; Chew, 1988; Fisher, 1988; Ogle and Beaugez, 1988; Quayle, 1988; Bower, 1990; Hine, 1990; Lester, 1990; Hudson and Hill, 1991; Newell et al., 1991; Spencer, 1991; Lewis and Farley, 1993). These include: *Parasites and diseases* - sporozoa, haplosporea, microsporidae, cileatea, bacteria, viruses, fungi, porifera, platyhelminths, trematoda, cestoidea, nemertinea, nematoda, annelida, mollusca, crustacea; *Predators* - gastropods, crabs and starfish and; *Fouling organisms* - sponges, anemones, hydroids, bryozoa, tube worms, barnacles, mussels, tunicates and algae and bacteria (Quayle and Newkirk, 1989).

Mortalities have also been recorded from nurseries growing spat on bivalve chips, plates and from those using single seed oysters in trays (Roegner, 1989; Farley and Lewis, 1993).

1.1.4.1 Diseases and Parasites in NSW

Sydney rock oysters also suffer from a number of diseases and predators, which can severely affect production. Winter mortality (affiliation unknown) is caused by *Mikrocytos roughleyi* (Farley et al., 1988; Lester, 1990) and can cost a farm between 20 and 80% of its stock (Medcof and Malcolm, 1974; Korringa, 1976). The disease causes small blisters to develop on the palps, gills, mantle, gonad and adductor muscle, prior to the oyster gaping and dying (Roughley, 1926). It appears to affect only those oysters in the estuaries south of Port Stephens (Fig 1.1; Thomson, 1954). To avoid heavy losses, farmers either market their oysters before winter, raise the growing height of trays or move their crop upstream to the more estuarine leases (Nell and Smith, 1988).

QX disease also accounts for high mortalities of Sydney rock oysters. This disease, caused by the haplosporidian parasite *Marteilia sydneyi* (Perkins and

Wolf, 1976; Roubal et al., 1989), affects Sydney rock oysters in the northern NSW estuaries (Wolf, 1977; Potter and Hill, 1982; Nell and Smith, 1988) and in Moreton Bay, Queensland (Wolf, 1977; Smith, 1982; Moxon, 1986; Witney et al., 1988) (Fig 1.1). More recently, this disease has caused oyster mortalities in the Georges River, NSW (I. Smith, pers, comm., 1994). Haplosporidian parasite spores form in the tubular wall of the oyster. They restrict the absorption of food, eventually starving the oyster to death (Nell and Smith, 1988). Farmers in affected areas purchase half grown oysters, and finish their growth and market them before they are affected by the disease (Marshall and Espinas, 1987). As yet, there have been no reported losses of Pacific oysters from winter mortality or QX disease (Chagot et al., 1989; Queensland DPI, unpubl. data, 1991).

Production of both Sydney rock oysters (Thomson, 1954, Korringa, 1976) and Pacific oysters (Holliday and Nell, 1987) can also be severely affected by mudworm infestations; a spionid polychaete (*Polydora* spp.) enters the oyster and forms a blister of mud (Skeel, 1979). Farmers have managed to avoid mudworm by growing oysters higher in the intertidal zone (Korringa, 1976) and by regularly washing mud from their crops (Skeel, 1979; Malcolm, 1987).

1.1.4.2 Predators and competitors in NSW

In Australia, oysters exposed on sticks and trays are often preyed upon by a variety of animals including mudcrabs, starfish, oyster drills, porcupine fish, bream, toad fish and stingrays (Korringa, 1976; Thomson, 1954; Witney et al., 1988). Many NSW farmers cover their crops with wire and PVC mesh to prevent this predation. In NSW there are problems associated with competition from marine fouling organisms including ascidians, sponges, bryozoans, barnacles and mussels (Thomson, 1954; Korringa, 1976). Korringa (1976) listed the shipworm *(Banksia australis)* as a competitor of oysters in NSW as it destroyed the timber structure and sticks on which oysters were cultivated and was indirectly responsible for the death of many oysters. NSW farmers coat all timber surfaces used in the culture of oysters, with coal tar pitch and cultivate their oysters off the estuary bottom on intertidal structures to destroy marine fouling with exposure at low tide (Holliday et al., 1988).

1.1.5 Cultivation methods

1.1.5.1 History of cultivation in NSW

Historically, oysters have been cultured on a wide variety of substrates including scallop shells, old oyster shells, bamboo, roofing tiles, stones and mangrove branches (Quayle, 1988). During the 19th century, most oysters in NSW were merely collected from rocks and mangroves (Roughley, 1922, 1926; Croft, 1962a, 1962b; Thomson, 1954; Malcolm, 1987; Holliday et al., 1988). Excessive harvesting of oysters for human consumption and for lime production for mortar, resulted in the introduction of legislation restricting these harvesting practices (Roughley, 1922; Croft, 1962a, 1962b). Early attempts at farming oysters on shell and other substrates deployed on the mudflats (Roughley, 1922; Thomson, 1954; Croft, 1962a) were hampered by mudworm infestations (Skeel, 1979). To address these problems, farmers began cultivating oysters on various substrates, elevated from the mudflats, to increase intertidal exposure and allow drying of mudworm blisters. Timber stakes, often cut from mangrove trees, were partially driven into the sediment for the collection and cultivation of Sydney rock oysters (Holliday et al., 1988). These methods eventually led to the use of hardwood sticks that were coated with tar and arranged horizontally on intertidal racks (Thomson, 1954; Korringa, 1976; Curtin, 1985a; Malcolm, 1987; Holliday et al., 1988; Nell, 1993).

1.1.5.2 Current cultivation methods

For intertidal culture, hardwood sticks are nailed together in stacks consisting of five layers with about 20 sticks in each layer. The stacks are tarred and air-dried for about two months, then deployed intertidally on hardwood frames, in areas where natural oyster settlement occurs (Korringa, 1976; Malcolm, 1987; Fig 1.2A). Usually the stacks are left in catching areas for about six months and then relocated upstream for a further eight months ("depoting"), to avoid overcatch of oysters during this nursery phase. Following this, they are nailed out on timber frames in single layers for grow-out. After about three years, oysters are often knocked off the sticks and the larger ones marketed. Average yields from tarred sticks range from 30-50 oysters per stick (Holliday et al., 1988; Nell, 1993). Those oysters not large enough for market (usually about 30%) are grown to market size on wire mesh and timber trays (Fig. 1.2B; Thomson, 1954; Korringa, 1976; Holliday et al., 1988; Quayle, 1988). Compartmented timber trays, similar to those used in this study for the culture of Sydney rock oysters, have also been used with considerable success when culturing Pacific and European oysters (Spencer and Gough, 1978; Spencer et al., 1978, 1985, 1992; Spencer, 1990).

The intertidal stick and tray method of culturing oysters forms the basis of one of Australia's most valuable aquaculture industries (Holliday et al., 1988; Nell et al., 1990). Some NSW farmers also grow their oysters using subtidal culture, where oysters in trays or on sticks are suspended below floats and are constantly submerged (Holliday et al., 1988; Nell, 1993).

Farmers in NSW have been seeking alternative substrates to tarred hardwood sticks because of a decline in oyster production (Section 1.1.5.3). High oyster losses, estimated at about 95% have also been experienced from tarred sticks (Holliday and Goard, 1986). This has been attributed partly to the changes to the composition of coal tar or to the use of immature or young trees for hardwoods sticks, which farmers claim are more susceptible to infestation from marine borers. Labour costs associated with separating clumps of oysters ("culling") grown using sticks and trays account for a high proportion of total costs to NSW farmers (Marshall and Espinas, 1987; Espinas et al., 1988).

Many NSW oyster farmers now use "single seed" culture techniques for Sydney rock oysters and to a limited extent, Pacific oysters. Spat are removed from synthetic collectors deployed for natural settlement, or are obtained from hatcheries (Holliday et al., 1988). A nursery phase follows in which the unattached single oysters are grown in a number of nursery units including upwellers, sectionalised trays, PVC cylinders and PVC baskets and envelopes (Section 2.3.1). Advantages of using single seed techniques include the elimination of culling and a culture system that allows for different stocking densities and ensures oysters have a more uniform shape than those grown on substrates (Holliday et al., 1988). Unlike oysters grown on sticks, single seed oysters can be machine graded and have a larger shell cavity volume and hence an increased capacity for meat growth, than those grown on sticks (Nell and Mason, 1991).

Fig 1.1 Map of Australia and location of oyster areas.

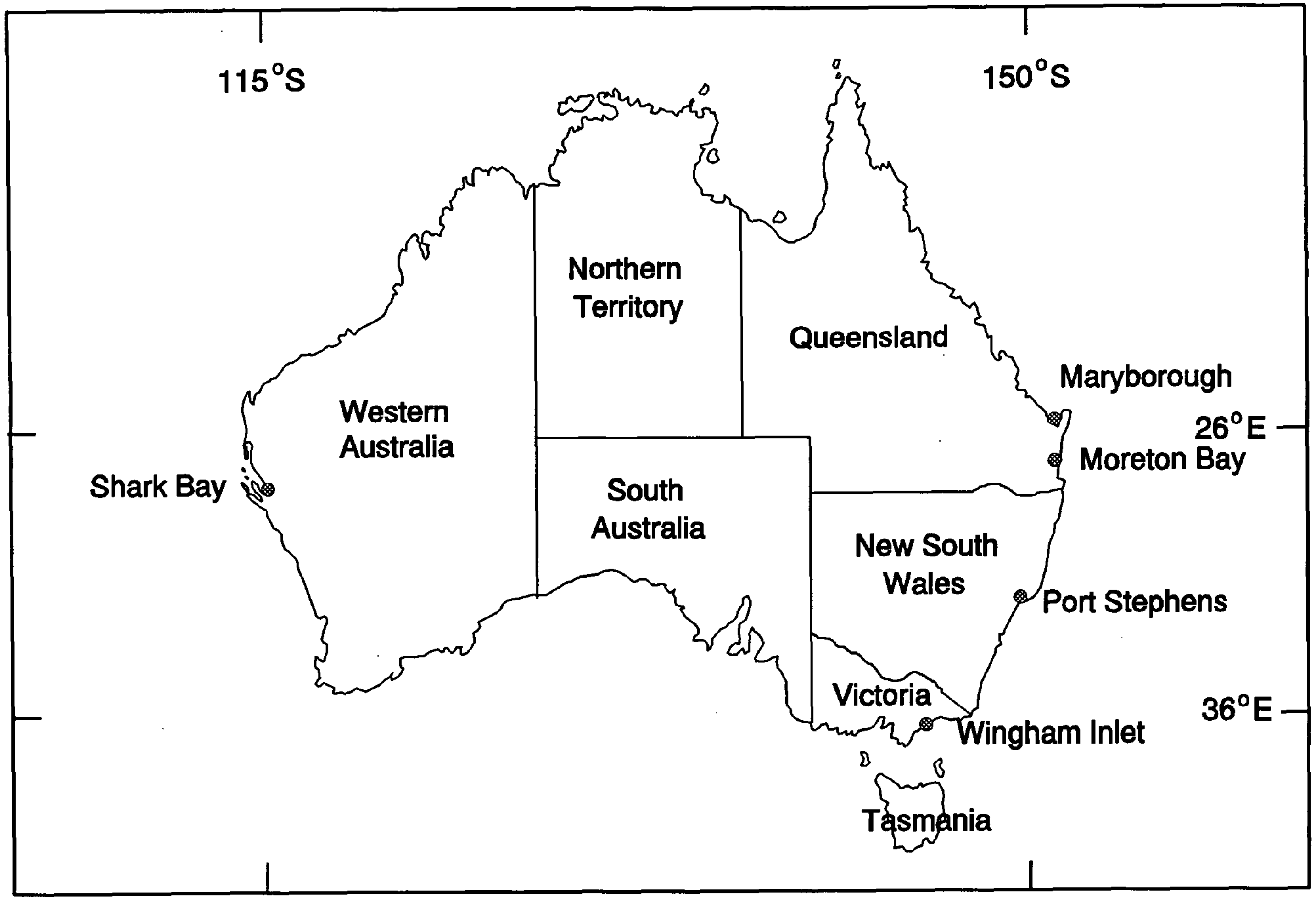

115°S
150°S
Northern Territory
Queensland
Maryborough
26°E
Moreton Bay
Western Australia
Shark Bay
South Australia
New South Wales
Port Stephens
Victoria
36°E
Wingham Inlet
Tasmania

Fig 1.2A	Tarred hardwood sticks deployed for oyster settlement on intertidal leases and supported by posts and hardwood frames in Salamander Bay, NSW.
Fig 1.2B	Traditional wire mesh and timber trays used in NSW to grow Sydney rock oysters.

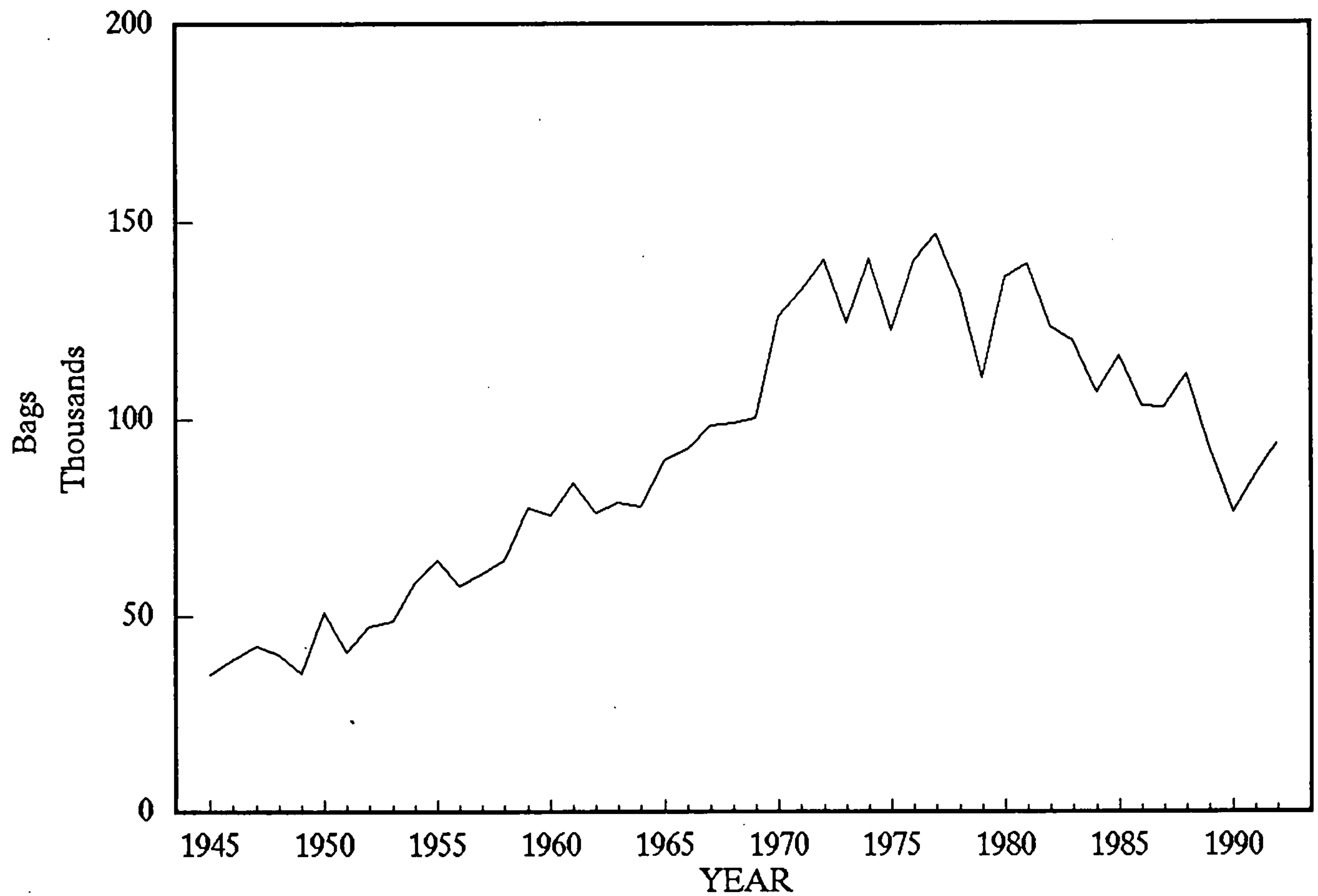
1.1.5.3 Production status - Global and NSW

Australia contributes < 1.0% of total annual world production of about 1 million tonnes (whole weight; FAO, 1991). An estimated 90.0% of world production is harvested in north temperate latitudes, 6.0% from the tropics and the remainder from the south temperate zones (Matthiessen, 1991). In Australia in 1989-90, production was comprised of about 72.0% Sydney rock and 27.0% Pacific oysters and a small production of flat oysters (Nell, 1993). NSW produces the majority of edible oysters and consumers in Australia readily accept both Sydney rock and Pacific oysters (McBride et al., 1988; Nell, 1993).

In 1983-84 there were about 787 oyster farms (about 5 400 ha in total) in NSW, although, only 276 produced in excess of 50 bags (1200 oysters/60 kg bag) of oysters per annum (Espinas et al., 1988; Maguire et al., 1988). Marshall and Espinas (1987) found in a survey of the NSW industry, that 68% of the farmers had a negative return to capital. An economic comparison of stick and single seed farming methods in Port Stephens (the largest growing area in NSW with about 30% of the total leases; Nell et al., 1994), indicated internal rate of return on invested capital ranged from -2.5 to 3.8%, with labour accounting for a high percentage (range 32-44%) of total costs (Catt, 1992). In contrast, Treadwell et al. (1991), in an economic analysis of Pacific oyster farming in Tasmania (based on single seed methods), concluded that reasonably certain returns of between 11% and 31% could be expected, depending on the duration of the production cycle and hence site.

Production of Sydney rock oysters in NSW declined from a peak of 1.15×10^6 bags in 1976/77 to 0.88×10^5 bags in 1990/91, with a total value of \$A 30.1×10^6 (Nell, 1993; Fig. 1.3). This production decline has been attributed to a number of factors including: 1) buyer resistance to oysters after an outbreak of gastroenteritis in 1978, 2) competition in the entree market from other products and from imports of Pacific oysters cultured in New Zealand and Tasmania, 3) rising production costs associated with the capital and operating costs for depuration plants, 4) the costs of implementation of government regulations to control the spread of Pacific oysters in NSW, and 5) increased incidence of disease from mudworm, winter mortality and the QX parasite (Maguire et al., 1988). Nell et al. (1990), concluded that the NSW oyster industry had entered a reconstruction period, which would result in a reduced number of farmers, relying on a variety of new growing techniques. In contrast, Pacific oyster production in Australia has increased, particularly in Tasmania, where total production in 1990/91 was worth \$A 10.7×10^6 (O'Sullivan, 1993). The Pacific oyster industry in South Australia has expanded to about 30% of the size of the Tasmanian industry (C. Sumner, pers. comm., 1995). Since the change in regulations governing its cultivation, Pacific oyster production in Port Stephens, NSW, has also increased and in 1993/94 was estimated to be worth \$A 0.6×10^6. In contrast, Sydney rock oyster production continue its decline, dropping to 0.84×10^5 bags, valued at \$A 28.1×10^6.

Fig 1.3 NSW oyster production for financial years 1945-1992, based on a bag (60 kg) containing 1 200 oysters/bag (NSW Fisheries and Oyster Returns, unpubl. data, 1992).


200
150
100
50
0
Bags
Thousands
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
YEAR

1.2 PRODUCTION OF SPAT

World production of oyster spat from hatcheries plays an important role in some oyster industries. Countries, such as the UK (Spencer, 1990; Utting and Spencer, 1992) and USA (Chew, 1990) have established or revived their oyster industries by developing hatchery techniques and in many cases, are now dependent on hatchery spat. In Australia, the Tasmanian and South Australian Pacific oyster industries are also dependent on hatcheries for seed, as natural spatfall is unreliable. Since the early 1980's, hatchery techniques were developed for the Tasmanian oyster industry and today, three commercial hatcheries produce between 50 and 80 x 10^6 Pacific oyster spat for local and interstate sales (D. O'Sullivan, pers. comm., 1994).

Following the development of hatchery techniques for breeding Sydney rock oysters in the early 1980's (Holliday, 1992), an estimated 11.3 million, 4-6 mm spat were sold to farmers in 1988/89 from commercial hatcheries operating in NSW (Frankish et al., 1991). Two commercial hatcheries are licensed in NSW to produce and sell Sydney rock and Pacific oysters, although, the majority of spat in NSW are still collected from natural spatfalls, as it is still considered by many to be far cheaper to collect than to purchase hatchery seed. Hatcheries need to recover their capital and operating costs that can be high. Quayle and Newkirk (1989) estimated that in North America and Europe, very few hatcheries were viable and that hatcheries produced less than one tenth of 1% of world oyster production.

1.2.1 Settlement substrates

Oyster larvae will settle on many different substrates in the wild but usually prefer hard clean surfaces (Quayle and Newkirk, 1989). Various alternatives substrates have been tested for both hatchery and natural settlement of oysters (Butler, 1955; Shaw, 1967; Dupuy and Rivkin, 1970, 1972; Hidu et al., 1975, 1981; Kong and Luh, 1976; O'Sullivan and Wilson, 1976; His, 1978; Gunn, 1984; Curtin, 1985c; Holliday, 1985; Indrasena et al., 1986; Haven et al., 1987; Gibbons, 1988; Quayle, 1988; Mann et al., 1990; Broadhurst et al., 1991; Ortega et al., 1991; Soniat et al., 1991).

Empty molluscs shells, including oyster shells, have been widely used around the world in laboratories and hatcheries, as a substrate for oyster settlement (Cole and Knight Jones, 1949; Hidu, 1969; Hidu and Haskin, 1971; Dupuy and Rivkin, 1972; Helm and Spencer, 1972; Hidu et al., 1978; Ogle and Flurry, 1981; Jones and Jones, 1988; Quayle, 1988; Roland and Broadley, 1990; Soniat et al., 1991). Oyster shells have also been widely used as a substrate for natural oyster settlement (Menzel, 1954; Butler, 1955; Ling, 1970; Kong and Luh, 1976; Ajana, 1979; Gunn, 1984; Quayle, 1988).

Dupuy and Rivkin (1972) found cleaning and handling of shell made its use as a substrate for oyster settlement in a hatchery laborious and expensive (to clean and handle). Quayle (1988) found, that although shell was low in costs and readily available, it was heavy, requiring considerable lifting gear and flotation (if suspended), and that it was difficult to break when separating oysters from it. Other substrates tested included glass, various plastics, mylar sheets and polished marble (Dupuy and Rivkin, 1972; Hidu et al., 1975). Dupuy and Rivkin (1970, 1972) documented a method of producing cultchless seed using various types of particles and on fibreglass and mylar surfaces. Other types of particles tested for oyster settlement include calcium carbonate, beach sand, foraminiferal sand, marble chips and other molluscs shell chips (Hidu et al., 1981). Today, hatcheries commonly use crushed bivalve shell as a substrate for pediveliger oyster larvae (Fig 1.4) within downweller systems (Section 2.1.2; O'Sullivan and Wilson, 1976; Jones and Jones, 1988; Matthiessen, 1991; Holliday 1992). Spat are often transferred to upwellers (Section 2.3.1.1) in on-shore nurseries (Bayes, 1981; Rodhouse et al., 1981; Rodhouse and Kelly, 1981; Lucas and Gerard, 1981; Claus et al., 1983; Jones and Jones, 1988; Holliday, 1992), where high mortalities have been recorded (Elston et al., 1982; Dungan and Elston, 1988; Dungan et al., 1989). Nursery operations in NSW have also experienced heavy post-set mortalities of Sydney rock spat in upwellers (Frankish et al., 1991; Nell et al., 1991).

Some hatcheries avoid the use of substrates by exposing larvae to epinephrine or norepinephrine, causing them to metamorphose without attaching to a substrate (Shpigel et al., 1989; Bonar, 1991; Section 1.2.2.1).

A variety of substrates are used globally by oyster farmers for natural spat collection. In France, these include the use of traditional limed roofing tiles, large slurry-coated PVC discs (Chinese hats; His, 1978) and hollow PVC sticks (Quayle, 1988); in British Columbia, slurry-coated wood-veneer circles, bags of shell cultch, strings of shell and self disintegrating cultch (cultchettes) (Quayle, 1988); in Japan, strings of scallop shell (ren) (Wisely et al., 1978; Shaw, 1981; Quayle, 1988; Quayle and Newkirk, 1989); in New Zealand, asbestos-cement, PVC sticks and tarred hardwood sticks (Curtin, 1985a, 1985b, 1985c, 1986; Quayle, 1988); and in Australia, tarred hardwood sticks (Korringa, 1976, Malcolm, 1987). Although timber sticks are still the main substrate used in NSW, an increasing number of farmers are now using PVC collectors (Holliday et al., 1988; Nell, 1993).

In Europe and North America there has also been a trend towards the commercial use of PVC and other synthetic collectors to increase settlement and retention and reduce operating costs (His, 1978; Jones and Jones, 1983, 1988; Gunn, 1984; Roland et al., 1988; Roland and Broadley, 1990; Nosho and Chew, 1991). The effectiveness of slurry-coated discs as an alternative substratum for the collection of natural Pacific oysters was demonstrated by His (1978). Gunn (1984) and Curtin (1986) reported commercially acceptable settlement and growth rates of Pacific oysters on hollow PVC sticks. Quayle and Newkirk (1989) recommended that the ideal cultch should be low in cost, solid, slightly rough, clean, have a high specific gravity, easy to transport, have a large surface area, allow good circulation, discourage silt build-up and be adaptable for various culture methods. As the large number of collectors types available for oyster settlement had not been evaluated, there was a need to systematically evaluate and compare each for settlement, growth, survival and retention of Sydney rock and Pacific oysters.

1.2.2 Factors affecting settlement of larvae

Previous literature reviews have listed many biotic and abiotic factors that may affect bivalve settlement (Galtsoff, 1964b; Shaw, 1967; Quayle and Newkirk, 1989; Bonar, 1991). Biotic factors include, swimming position of the larvae, gregariousness, competition, conditioning of collectors, prefouled surfaces, adult tissue extracts, shell matrix proteins, shellfish glycogen powder, mantle cavity fluids, iodinated organic molecules and neurotransmitters. Abiotic factors include, species preference for upper and under surfaces, light, spacing, orientation of collectors, siltation, current, temperature, salinity, surface tension and texture, colour of collectors, copper ions and food concentration (Galtsoff, 1964b; Shaw, 1967; Roland and Broadley, 1989; Bonar, 1991).

1.2.2.1 Biotic factors

The swimming position of the larvae at settlement may affect settlement (Hopkins, 1935; Schaefer, 1937; Cole and Knight-Jones, 1949), as pediveliger larvae often swim with their foot extended while searching for a suitable substrate on which to attach. Butler (1955) concluded that *C. virginica* probably settled on the upper surfaces of collectors in a stack, after having swam into and deflected off the collector above.

The gregarious behaviour of larvae has been shown to affect oyster settlement (Cole and Knight-Jones, 1949; Hidu, 1969; Bayne, 1969; Veitch and Hidu, 1971; Hidu and Haskin, 1971; Kenny et al., 1990). Bayne (1969) confirmed that *O. edulis* has a tendency to aggregate on previously colonised surfaces, and both he and Keck et al. (1971) found that extracts of extra-pallial fluid from settled oysters induced larval settlement.

Settlement patterns of oysters can be influenced by competition from other sedentary organisms (Knight-Jones, 1951; Butler, 1955; Shaw, 1967). Butler (1955), found a negative correlation between settlement of barnacles, which settled earlier and mainly on the under surfaces of collectors, and *C. virginica*, which settled predominantly on the upper surfaces. The poor settlement of oysters on the under surfaces was attributed to the action of the barnacle appendages while collecting food. A variety of sessile invertebrates including ascidians and bryozoans have also been found to affect settlement by covering the substrate normally colonised by oysters (Osman et al., 1989).

Cole and Knight Jones (1949) and Hadfield (1984) concluded that biofilms of marine bacteria, which grow on immersed substrates, could synthesise as chemical cues for molluscs settlement. Specific biofilms which promote oyster settlement were later isolated (Bonar et al., 1985; Weiner et al., 1985; Tritar et al., 1992). Other research found molluscs settlement could be increased on substrates through the use of L-DOPA, a chemical precursor to dopamine, and the bacterium *Shewanella colwelliana* (LST) (Cooper, 1983; Cooper and Shaw 1984; Bonar et al., 1985; Coon et al., 1985; Morse, 1985; Walch et al., 1988a, 1988b; Weiner et al., 1988, 1989a, 1989b; Fitt et al., 1989, 1990; Bonar, 1991; Tritar et al., 1992.

Oyster larvae may undergo two distinct phases of settlement; the first phase, settlement behaviour, is controlled by dopamine. Larvae which receive the necessary environmental cues (texture, light, bacterial surfaces) then enter the second phase, metamorphosis, which is controlled by the release of a neurotransmitter (such as epinephrine or norepinephrine) (Coon et al., 1985; Coon and Bonar, 1987; Coon et al., 1988; Coon et al., 1989; Weiner et al., 1989; Bonar et al., 1990; Coon et al., 1990; Bonar, 1991. Larvae exposed to epinephrine or norepinephrine (adrenalin or noradrenaline respectively), metamorphosed without attaching to a substrate and settled as true cultchless spat (Bonar et al., 1985; Coon et al., 1985, 1990; Coon and Bonar, 1986, 1987; Shpigel et al., 1989; Bonar, 1991).

Aging and conditioning of collectors (described in Section 2.1.4), can also affect oyster settlement and is important as it: 1) allows potentially toxic compounds in the collectors to leach out (Gunn, 1984; Jones and Jones, 1988; Roland and Broadley, 1990); 2) neutralises the pH on the surface of slurry-coated collectors, and 3) allows a primary fouling community (mainly bacteria) to develop (Roland and Broadley, 1990; Tritar et al., 1992).

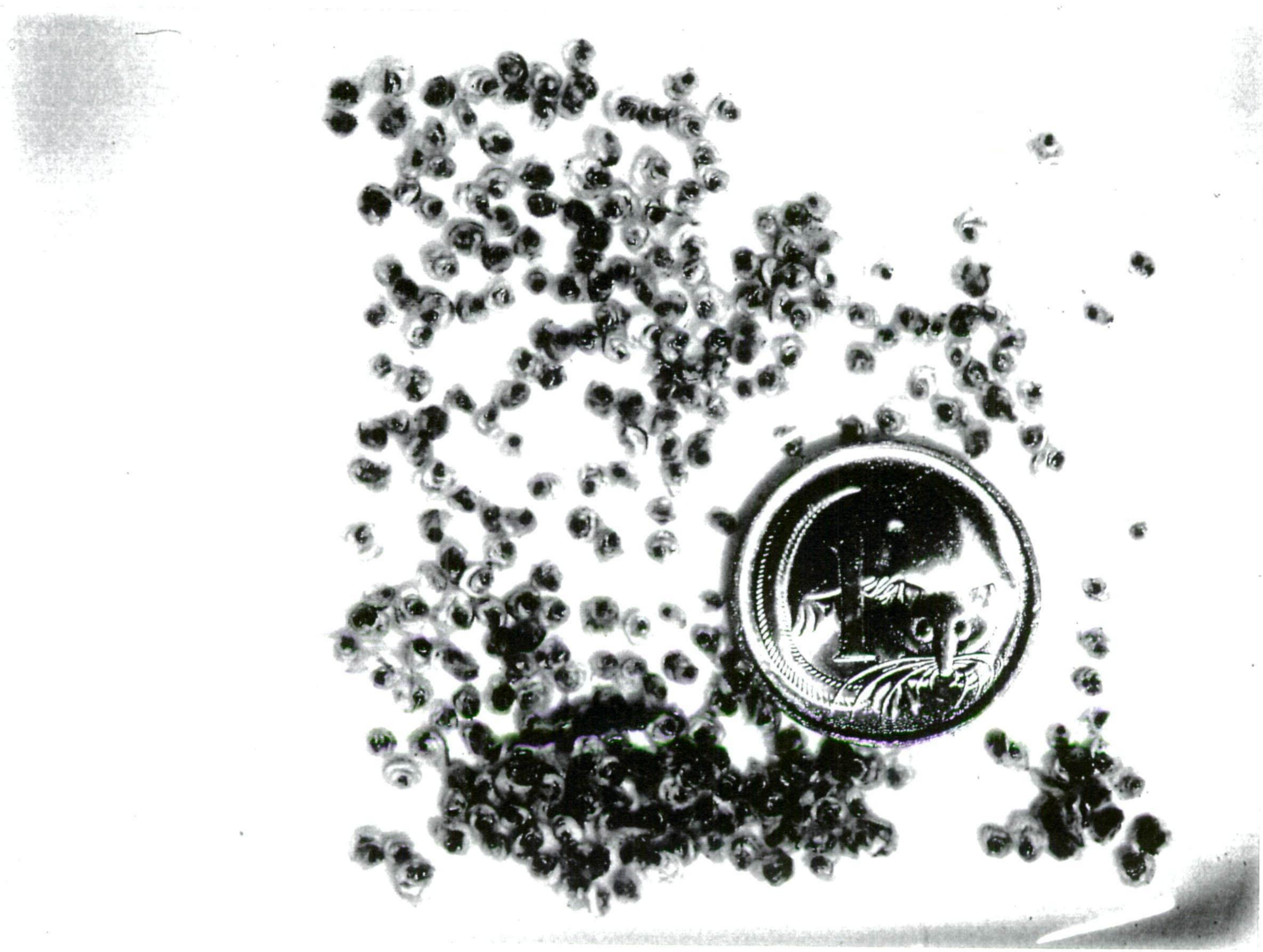
1.2.2.2 Abiotic factors

Sydney rock oysters settle mainly on the under surfaces of collectors (Thomson, 1950; Holliday and Goard, 1986), although, Dinamani and Lenz (1974) obtained similar settlement of New Zealand rock oysters *S. glomerata* on both upper and under surfaces. In that study, larvae began to settle on the upper surfaces when spat density on the under surfaces was high. Most of the commercially harvested oyster species, including *C. madrasensis*, *C. belcheri*, *O. edulis* and *O. lurida*, settle on the under surfaces of collectors (Nelson, 1927; Hopkins, 1935; Cole and Knight-Jones, 1949; Sieling, 1950; Knight-Jones, 1951; Medcof, 1955; Hidu, 1969; Richie and Menzel, 1969; Indrasena and Wanninayake, 1986). Conversely, Butler (1955) found the highest settlement of *C. virginica* on the upper surfaces. Pacific oysters have also been found to settle predominantly on the upper surfaces of collectors (Yokota, 1936; Miyazaki, 1938; Sayce and Larson, 1965; Sayce and Tufts, 1968). The study by Schaefer (1937) was an exception, and here, higher settlement of Pacific oysters were recorded on the under surfaces of collectors, possibly because of silt accumulation on the upper surfaces. For many species, the build-up of silt on collectors has also been found to adversely affect oyster settlement (Schaefer, 1937; Thomson, 1950; Butler, 1955; Shaw, 1967; Sayce and Tufts, 1968; Dinamani and Lenz, 1974). The shape of the collector may also affect settlement on larvae and silt accumulation on collector surfaces. Soong et al. (1981) found Pacific oyster larvae preferred the concave surfaces of plastic roofing boards.

The spacing between layers of collectors has also been found to affect the intensity of settlement (Bonnot, 1937; Thomson, 1950; Shaw, 1967). Thomson (1950), found settlement of Sydney rock oysters was greater when fibro-cement slats were set less than 12.5 mm apart. Thomson (1950), Ritchie and Menzel (1969), Bayne (1969) and Ajana (1979) concluded that settlement of oyster larvae increase with a reduction in light. Pomerat and Reiner (1942), also found that light affected barnacle settlement. This has been attributed to the negative phototaxis response of pediveliger larvae (Schaefer, 1937). Orientation of collectors affects settlement (Hopkins, 1935; Schaefer, 1937; Cole and Knight-Jones, 1949; Thomson, 1950; Shaw, 1967; Sayce and Tufts, 1968; Cranfield, 1970; Michener et al., 1989), with more oysters settling on surfaces positioned horizontally than those at other angles. Thomson (1950) recorded greater Sydney rock oyster settlement on horizontally deployed slats than on vertically deployed slats, although, oysters were more evenly distributed on the latter collectors. Schaefer (1937) and Thomson (1950) recorded higher settlements of both Pacific and Sydney rock oysters when collectors were positioned with the long axes parallel with the current.

Oyster settlement has also been affected by the composition and surface texture of collectors (Shaw, 1967; Cranfield, 1970). Greater settlements of *O. lutaria* and *C. madrasensis, C. belcheri* and *C. virginica* have been recorded from collector types with the roughest surfaces (Cranfield, 1970, Indrasena and Wanninayake 1986; Baker, 1992 respectively). Other factors, not discussed here, that may affect oyster settlement include temperature, salinity, feeding levels, water circulation, current (affected by distribution of cultch), method of adding larvae to tanks, aeration and sampling frequency (Gibbons, 1988; Mitchener et al., 1989; Roegner, 1989; Roland and Broadley, 1989; Baker, 1992). Conclusions drawn from the literature are often contradictory and at least confusing, as observations often differ for species and environmental conditions. Furthermore, biotic and abiotic factors may be interdependent. In this study, factors affecting settlement of Sydney rock and Pacific oysters in the hatchery and the wild are discussed.

Fig. 1.4. Single Sydney rock oysters (*S. commercialis*) settled on chips of scallop shell (courtesy I. Smith).



1.2.3 Remote settlement

Since the early 1970's, techniques for storing, transporting and setting eyed, pediveliger, oyster larvae at locations remote from the hatchery have been developed and readily accepted in North America (Chew, 1985; Chew et al., 1986; Castagna et al., 1988; Jones and Jones 1988; Roland et al., 1988; Panggabean et al., 1989; Roland and Broadley, 1989). Chew (1990) reported the extensive transfer of eyed larvae from North American hatcheries to 23 countries around the globe. This technique eliminates the high costs of transporting collectors to and from the hatchery and enables the farmer to control settlement at the farm.

Remote settling of larvae can reduce spat costs, provided survival rates are adequate. Commercial set rates for Pacific oysters range from 18-80% (Henderson, 1983; Roland et al., 1988; Lipovsky, 1991; Thomas and Burnell, 1992). Carlson (1982) suggested that storing Pacific oyster larvae at 5°C for 5 to 8 days actually increased the set rate, while Henderson (1981) showed that no reduction in set rate occurred when larvae were stored at 5°C for up to 6 days. A reduction in set rate and post set survival occurred when larvae were stored at 5°C beyond 8 days (Henderson, 1983). Roland et al. (1988), reported eyed Pacific oyster larvae fed a stored algal paste had higher settlement rates (37%) than those unfed (20-30%). At the time of this study, there were no reports of the effects of storage temperatures (above or below 5°C) on set rates of Pacific oyster larvae or of attempts at remote setting of Sydney rock oysters.

1.3 NURSERY CULTURE OF JUVENILES OYSTERS

For the purposes of this thesis, nursery culture refers to the initial production phase (production can extend over 4 years) from settlement to day 843 post-settlement. Nursery culture of bivalve molluscs is an important phase of cultivation which links the production of spat from hatcheries or natural catch with the growing phase to harvest size. It usually requires different production units and handling methods to those used for the growing phase

(Claus, 1981).

Nursery systems used globally for newly settled oyster spat from hatcheries, are often based on the production of single or unattached oysters. Early nursery systems have been developed to accommodate 0.5-4.0 mm spat using various setting systems and substrates including, timber and PVC collectors, downweller units with chips of bivalves, on-shore upwellers and large tanks with PVC collectors (O'Sullivan and Wilson, 1976; Bayes, 1981; Spencer et al., 1986; Castagna et al., 1988; Holliday et al., 1988; Jones and Jones, 1988; Roland and Broadley, 1989; Holliday 1992). Similar spat growth rates have been obtained from different nursery systems, however, evaluating the various systems which operate under different conditions is often difficult (Claus, 1981; Lucas and Gerard, 1981). With low margins of profit in commercial nurseries, slight variations in operating costs could affect the viability of the operation (Claus, 1981). However, a number of alternate techniques have been used for the nursery phases and include floating screened trays, submerged lantern nets, submerged timber and plastic trays, stacks of containers placed on the sea floor or suspended from floating longlines, floating upwellers and tide-powered upwellers (Wisely et al. 1979a, 1979c; Bayes, 1981; Hidu et al., 1981; Lucas and Gerard, 1981; Neudecker, 1981; Spencer and Hepper, 1981; Williams, 1981; Curtin, 1983; Billington, 1991). Intertidal nursery systems include, PVC baskets of folded mesh, PVC envelopes, sectionalised timber and PVC trays and PVC cylinders (His, 1978; Claus, 1981; Curtin, 1983; Gunn, 1984; Holliday et al., 1988; Spencer, 1990; Holliday, 1992; O'Sullivan, 1993 Robert et al., 1993).

As single seed oysters grow, they are moved into nursery units with larger mesh sizes to allow greater water flow and to reduce the problems from silt and fouling (Claus, 1981; Neudecker, 1981; Spencer, 1990). In Australia, farming single seed oysters on nursery trays can be a problem in estuaries with high concentrations of suspended silt (Holliday et al., 1988; Spencer, 1990), as the deposition of silt on oysters is associated with increased infestation by mudworm (*Polydora* spp.; Skeel, 1979; Wisely, et al., 1979a; Nell, 1993). In NSW, where mudworm is a major problem, the nursery phase for larger seed (>3 mm) encompasses the use of trays, PVC cylinders (Holliday et al., 1988), PVC baskets and envelopes (O'Sullivan, 1993) with larger mesh sizes. Oysters traditionally knocked off sticks after about three years are usually grown on timber trays with 20 mm mesh (Fig 1.2B; Malcolm, 1987; Holliday et al., 1988; Nell, 1993).

Despite the advantages single seed culture has compared with oysters produced using traditional methods (described in Section 1.1.5.2.; Holliday et al., 1988), initial attempts by NSW farmers to use single seed spat resulted in high mortality rates. Investigations revealed that inappropriate nursery systems were used initially and that site characteristics may also have caused problems (Holliday, 1985, 1987, 1992; Holliday et al., 1988). Nell (1991b), when growing Sydney rock oyster spat in the open and exposed waters of Port Stephens, found cylinders were unsuitable compared with sectionalised trays. Tasmanian oyster farmers are totally reliant on hatchery produced spat because of poor natural spatfalls and use on-shore and floating upwellers, baskets and envelopes and timber and PVC trays (O'Sullivan, 1993). In the present study, existing and modified nursery units were evaluated for Sydney rock oysters under a variety of environmental conditions.

1.3.1 Stocking densities

The efficiency of a nursery system is affected by the stocking densities used (Spencer et al., 1985; Jarayabhand, 1988; Spencer, 1990; Billington, 1991). Growth rates of individual oyster spat can decrease with increasing stocking density and size variation of spat (Neudecker, 1981; Newkirk, 1981; Jarayabhand, 1988; Spencer, 1990; Bacher, 1991). Combined with site, stock and production systems, stocking density is an important variable through which farmers can influence oyster performance. Trays understocked with oyster spat can increase labour and equipment costs for the farmer (Spencer et al., 1985). Settlement density on shell cultch (Roland and Albrecht, 1990) and in upwellers (Bacher and Baud, 1992) has also been shown to affect growth and survival of Pacific oysters. Prior to this study, optimum stocking densities had not been determined for Sydney rock oysters grown in the various types of nursery units.

1.4 EVALUATION OF NURSERY SITES

1.4.1 Site selection

Current velocity, wave action, availability of natural food, water temperature and salinity affect the suitability of a site for oyster culture (Walne, 1974; Wilson, 1987) and considerable variations in oyster performances have been recorded at different sites in the wild (Robinson and Horton, 1987; Brown and Hartwick, 1988; Scully et al., 1988; Hawes et al., 1990; Jones et al., 1991; Brown et al., 1993; Nell et al., 1994). Several authors have emphasised the importance of considering both environmental (sea temperature, water movement, water depth, exposure to air, siltation, turbidity, access, conflicts, salinity, oxygen, pollution and adverse conditions) and biological factors (food, predators, competitors and fouling organisms) when selecting nursery sites in the wild (Quayle and Newkirk, 1989; Roland and Broadley, 1989; Spencer, 1990). Claus et al. (1981), concluded that for the early nursery phase, there could be advantages in using nutrient enriched ponds and on-shore upwellers as many of the above factors could be controlled.

Techniques used to culture oysters in NSW vary and are often influenced by environmental conditions on the lease. Many of the NSW leases lie vacant and under-utilised for long periods and may be suitable for single seed culture. For example, spat catching leases lie vacant for about six months of the year, after settlement, when caught sticks have been moved to nursery leases upstream. Some estuarine areas in NSW are unsuitable for the culture of single juvenile oysters. They may be exposed to adverse weather so units break up with excessive wave action (Nell, 1991b) or too sheltered so units become smothered with silt (Wisely et al., 1979a). Sites within estuaries in NSW have also been found to differ in environmental conditions (Nell et al., 1994). Richardson (1991) found that food quality and quantity increased in Port Stephens towards the upper estuary and suggested it was related to higher nutrient concentrations associated with land run-off. However, Robinson and Horton (1987) obtained similar growth rates over a two year period for Pacific oysters grown at a number of estuarine sites. As single seed culture is now being adopted in NSW, nursery sites needed to be evaluated.

1.4.2 Use of heated effluent

Growth rates for Sydney rock oysters are depressed during the cooler months (Nell et al., 1994). Numerous studies have assessed the culture of marine species using heated effluent and have shown it to enhance growth rates of juvenile *C. virginica* and Pacific oysters (Huguenin and Ryther, 1974; Jones, 1976; Lutz and Porter, 1977; Margraf, 1977; Ingram, 1979; Lutz and Hess, 1979; Shaw, 1979; Malouf, 1981). Aquarium studies also indicated that, in the presence of excess food, Sydney rock oyster spat grow best at relatively high water temperatures (25-30°C; Nell and Livanos, 1988). Despite the NSW oyster industry experiencing reductions in shell growth rates during the colder winter months (average extreme temperature range for Port Stephens, 1966-1973 was 8.6-32°C; Wolf and Collins, 1979), at the time of this study there were no records of studies using heated effluent from power stations to enhance the growth of Sydney rock oysters.

1.4.3 Oyster culture in ponds

The culture of oysters using on-shore tanks or ponds, fertilised to stimulate algal blooms, has received considerable attention from researchers and oyster farmers (King, 1977; Guerrero et al., 1981; Maguire et al., 1981; Nell, 1985; Manzi et al., 1987, 1988; Holliday et al., 1988; Allan et al., 1991; Wallace and Rouse, 1992). Enriched prawn and fish ponds have been found useful for culturing oysters and reducing phytoplankton concentrations from pond effluent (Manzi et al., 1988; Shpigel and Blaylock, 1991). During winter periods, NSW farmers have trouble marketing their Sydney rock oysters, as the meats are often in poor condition (Holliday et al., 1988; Nell et al., 1994). In northern NSW, where higher winter temperatures are experienced, 160 ha of earthen ponds have been constructed for farming marine prawns. As part of this study, the bi-culture of prawns and oysters were found to have the potential to provide NSW prawn farmers with a second crop, and oyster farmers with enriched ponds to enhance spat growth in the cooler winter months and for conditioning oyster meats for market (Allan et al., 1991; Appendix 9.4).

1.4.4 Triploid oysters

Another method of enhancing oyster growth and meat condition is through the hatchery production of triploid oysters (Allen and Downing, 1986, 1990, 1991; Allen et al., 1989; Barber et al., 1992; Nell et al., 1994). Triploid Sydney rock oysters, produced by chemically treating fertilised eggs with cytochalasin B (CB) to block meiosis II, were on average 41% heavier than diploids at harvest and maintained higher dry meat weight and condition index values (Nell et al., 1994). Results from this thesis were used for the culture of triploid single seed Sydney rock oysters.

1.5 AIMS AND OBJECTIVES

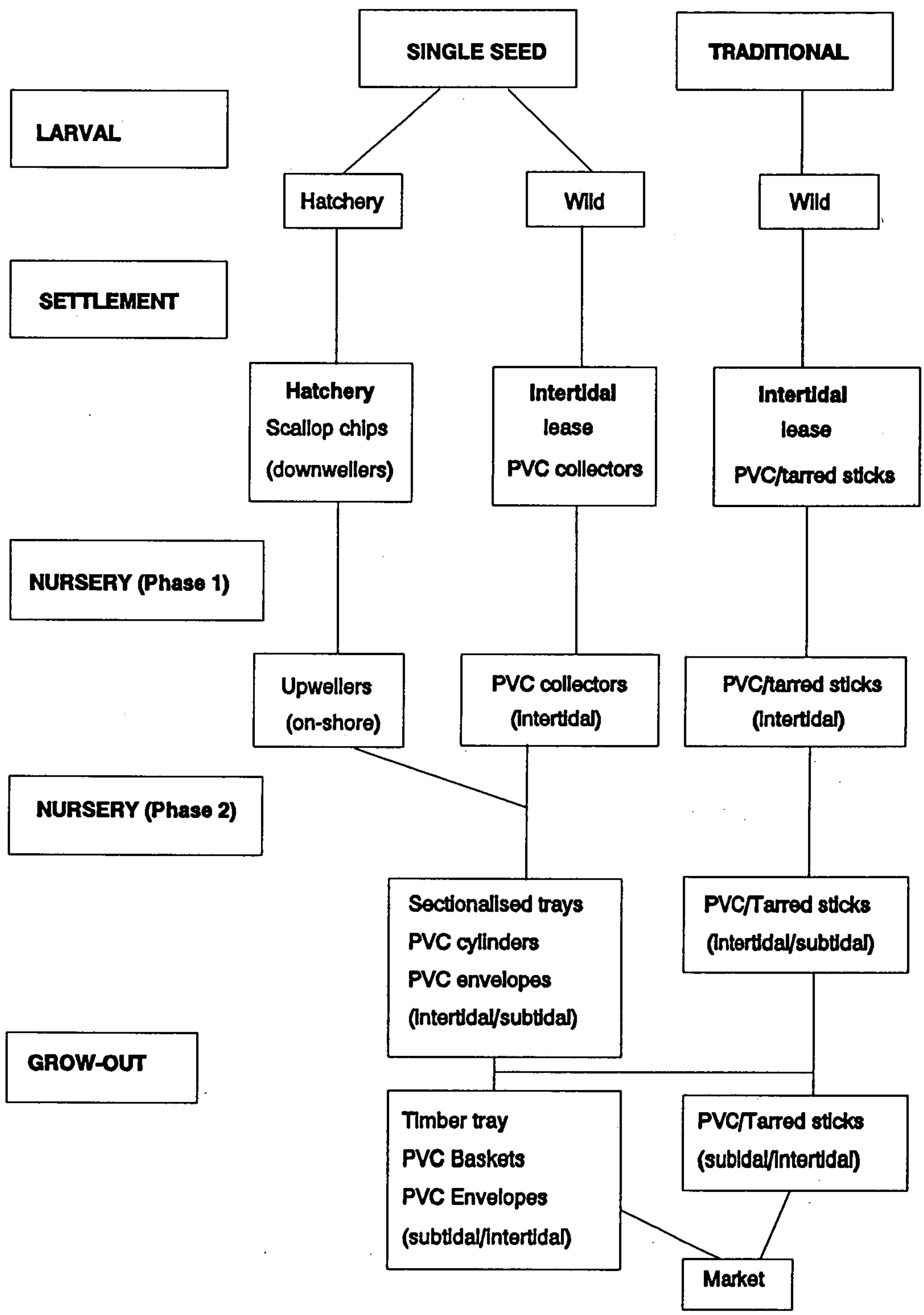
The aims of this study were to evaluate and further develop systems for nursery culture of Sydney rock and Pacific oysters, to reduce hatchery and nursery costs and enhance production for farmers. Specific objectives were to:

1. Develop the remote setting technique for Sydney rock oysters.
2. Evaluate hatchery settling techniques for Sydney rock oysters.
3. Evaluate various types of commercially-used collectors for the following:
   - settlement of Sydney rock oysters in hatcheries,
   - natural settlement of Sydney rock and Pacific oysters in the wild,
   - retention of Sydney rock oyster spat,
   - post-harvest survival of spat and
   - retention of market grade Sydney rock oysters.
4. Determine optimum stocking densities for Sydney rock oysters in sectionalised nursery trays and in PVC cylinders.

5. Evaluate sites and nursery systems for the culture of Sydney rock oysters.
6. Evaluate various types of nursery units for post-set nursery techniques and for larger Sydney rock oyster spat.
7 Develop strategies for management of nursery systems.

In this study, a practical approach was adopted to evaluate and develop techniques suitable for commercial oyster operations, particularly for NSW farmers. The thesis is comprised mainly of 17 experiments, described and/or discussed in seven chapters and appendices and arranged on the basis of comparing methods of obtaining spat (Chapter 3), optimising spat performance by varying stocking densities (Chapter 4), comparing different sites (Chapter 5), comparing different types of nursery systems for different age groups of spat (Chapter 6) and finally, by identifying common themes and providing recommendations for industry (Chapter 7). The various phases and methods of oyster culture in use in NSW at the time of this study are illustrated in Figure 1.5.

Fig 1.5. Flowchart showing the various phases of oyster production and the major systems used by the Australian industry at the time of this study.


SINGLE SEED
TRADITIONAL
LARVAL
Hatchery
Wild
Wild
SETTLEMENT
Hatchery
Scallop chips
(downwellers)
Intertidal
lease
PVC collectors
Intertidal
lease
PVC/tarred sticks
NURSERY (Phase 1)
Upwellers
(on-shore)
PVC collectors
(intertidal)
PVC/tarred sticks
(intertidal)
NURSERY (Phase 2)
Sectionalised trays
PVC cylinders
PVC envelopes
(intertidal/subtidal)
PVC/Tarred sticks
(intertidal/subtidal)
GROW-OUT
Timber tray
PVC Baskets
PVC Envelopes
(subtidal/intertidal)
PVC/Tarred sticks
(subidal/intertidal)
Market

CHAPTER 2

GENERAL MATERIALS AND METHODS

2.1 HATCHERY TECHNIQUES AND EXPERIMENTAL PROCEDURES

2.1.1 Broodstock conditioning and larval rearing

Sydney rock and Pacific oyster broodstock were obtained from Port Stephens, NSW. About 100 adult oysters were continually conditioned in the hatchery in each of four fibreglass tanks (1 700 l). Each tank was fed twice daily with about 120 l (3×10^9 cells/oyster/day) of a mixture of algal species, usually consisting of "Tahitian" *Isochrysis* aff. *galbana*, *Pavlova lutheri* and *Chaetoceros calcitrans*. Algae and water were circulated with a pump and gentle aeration. Oysters were conditioned for four to eight weeks with water temperature between 20 and 24°C, depending on gonad condition. Water in conditioning units was partially exchanged (850 l every 24 h), with a total exchange every 48 h.

Both species were stimulated to spawn by reducing salinity from 35‰ to 25‰ and by raising water temperatures by up to 10°C. Eggs were fertilised and larvae reared to pediveliger stage in 2 000 or 20 000 l fibreglass tanks, using established techniques (Loosanoff and Davis, 1963; Walne, 1974; Holliday, 1992). All sea water used was prefiltered with a 1 μm cartridge (to exclude other organisms) and stored for a minimum of 72 h prior to use. Generally, Sydney rock and Pacific oyster larvae reached the pediveliger stage 22 and 18 days respectively after fertilisation. Larval densities were estimated by counting larvae in subsamples using a Sedgewick-Rafter cell and a compound microscope.

2.1.2 Settling and post-set nursery systems

To evaluate larval settlement systems, various collector types, described in

Section 2.1.3, were deployed with larvae in the different systems. Setting systems included: 10 l and 50 l aquaria (Fig 2.1A), fibreglass tanks (2.4 x 1.6 x 0.9 m; 3 000 l; Fig 2.1B), similar to those used in commercial operations (Jones and Jones, 1988; Roland and Broadley, 1990), and downwellers (O'Sullivan and Wilson, 1976; Jones and Jones, 1988; Holliday, 1992). Downwellers consisted of ten PVC cylinders (355 mm x 80 mm high, surface area 1790 cm^2) each with 0.2 mm nylon mesh screen attached and covered with about a 1 cm layer of scallop shell chips (80-100 g/downweller) for larvae to attach. Only those scallop shell chips retained on a 200 μm screen after having passed through a 350 μm screen were used for settlement. Downweller units were partially submerged in a 1 700 l fibreglass tank with seawater and algae recirculated (at about 0.8 l/min) through the screens with a gentle overhead spray (Fig. 2.2A). Spat were transferred to upwellers, described in Section 2.3.1.1 (Fig. 2.2B), several days after settlement.

Water used for settlement and early nursery phases was partially exchanged daily, with a total exchange every 48 h. Spat were washed twice daily with a light spray of sea water to remove detritus and faeces. Settling and nursery units in the hatchery were supplied with 2.9-11.6 x 10^4 cells/ml/day, based on equal proportions of several species of algae which included some or all of the following species: *Nannochloris atomis, Dunaliella tertiolecta* "Tahitian" *Isochrysis* aff. *galbana* and *Pavlova lutheri.* Except where stated, algae and water were circulated with gentle aeration. Light was excluded from settling units (with black PVC sheets), in an attempt to reduce any phototropic responses from larvae (Shaw, 1967; Ritchie and Menzel, 1969; Jones and Jones, 1988).

2.1.3 Collector types and format

The various collectors used in this study included ten types of commercially-used oyster collectors, designed and manufactured in various countries for the collection and removal of spat and/or for on-growing spat to market size. Types of collectors included small PVC discs (D; Fig 2.3), large slurry-coated PVC discs (SCD; Fig 2.4), bioresin slats (BS), PVC slat (S), slurry-coated PVC slat (SCS) and tarred hardwood sticks (TS), (Table 2.1). Types of collectors also used for growing included flat spiky PVC sticks (FSS), round spiky PVC sticks with a lug (RSSL; Fig 2.5), round grooved PVC sticks (RGS), round spiky PVC sticks (RSS) and tarred sticks (TS), (Table 2.1). Note that tarred sticks are used commercially to collect spat for single seed culture as well as for growing oysters.

All collectors were deployed using a similar format (Table 2.1) to that used by farmers (Korringa, 1976; His, 1978; Gunn, 1984; Malcolm, 1987; Holliday et al., 1988; Jones and Jones, 1988; Roland and Broadley, 1990). For natural settlement and grow-out, collectors were positioned horizontally in several layers and fixed to parallel, intertidal, tarred hardwood battens or frames, supported by posts; these oyster racks were orientated perpendicular to the foreshore, as this was the method traditionally used by NSW farmers (Korringa, 1976; Malcolm, 1987; Holliday et al., 1988; Nell, 1993; Figs 1.2A; 2.6). Collectors were secured to the batten with galvanised wire.

2.1.4 Conditioning of collectors

Collectors were immersed in sea water to leach possible toxic substances from their surfaces and to allow the growth of a bacterial film necessary for settlement (Gunn, 1984; Jones and Jones, 1988; Weiner et al., 1989). Collectors used for settlement in the hatchery (except where stated) were immersed in fresh water for 72 h, then sea water for a further 72 h, prior to deployment. Collectors used for natural settlement were deployed on an intertidal lease a month prior to the start of settlement.

2.1.5 Assessment of settlement

Following settlement, total numbers of spat settled were either counted (where numbers were low), or estimated by counting spat settled in replicate grids (10 or 15 cm^2), randomly placed on both upper and lower surfaces of each collector. The settlement period for the present study is defined as the period when oysters and barnacles attached themselves on collectors, from deployment until settlement had largely ceased. The period of natural settlement was assessed by regular deployment and inspection (every 14 days) of slurry-coated discs and PVC slats. For the purpose of this study, oyster retention is defined as the numbers of oysters retained from initial settlement or stocking to harvest and is used in conjunction with survival to help evaluate settlement and nursery units.

Fig 2.1A. The 50 l aquaria and temperature control room used to evaluate larval settlement on various types of collectors (Section 3.3).

Fig 2.1B. Commercial-size fibreglass tanks used to evaluate oyster settlement on various types of collectors (Sections 3.2 and 3.3).

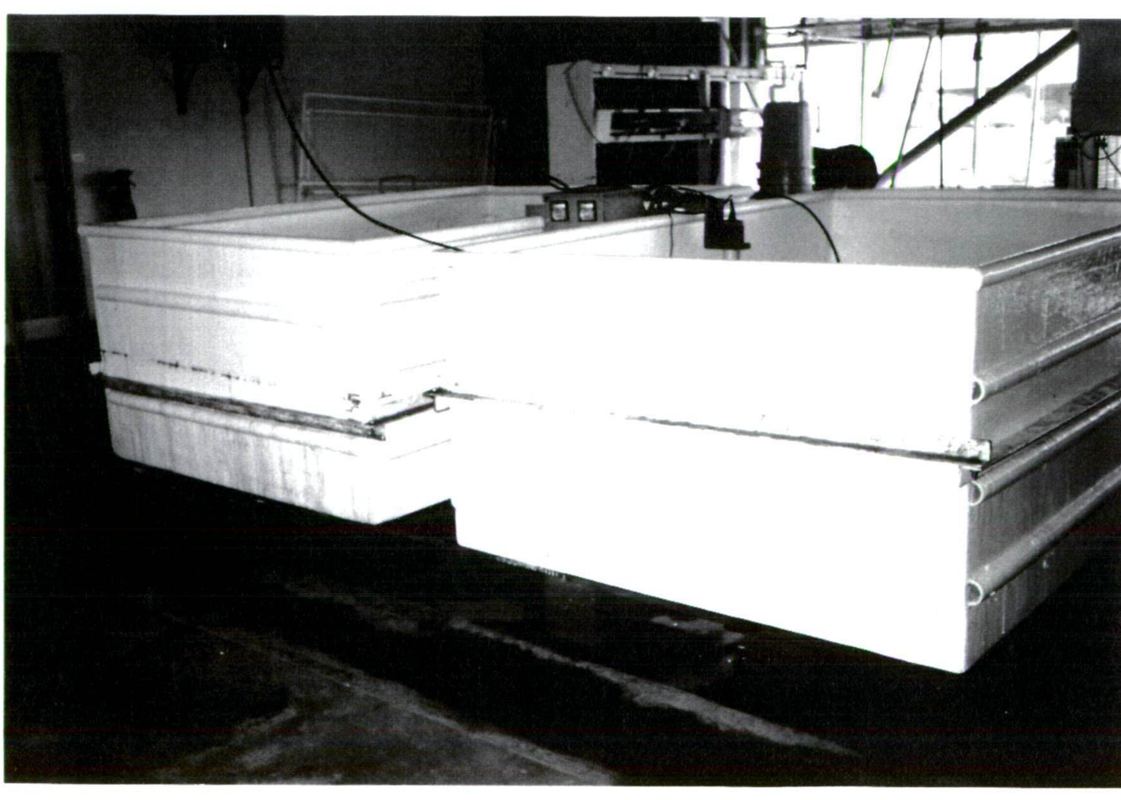


Fig 2.2A. Type of downweller unit used for hatchery settlement of Sydney rock oysters (*S. commercialis*) (Sections 3.1 and 3.2).

Fig. 2.2B. Type of upweller unit used for the nursery culture of newly settled Sydney rock oysters (*S. commercialis*) (Section 6.1).

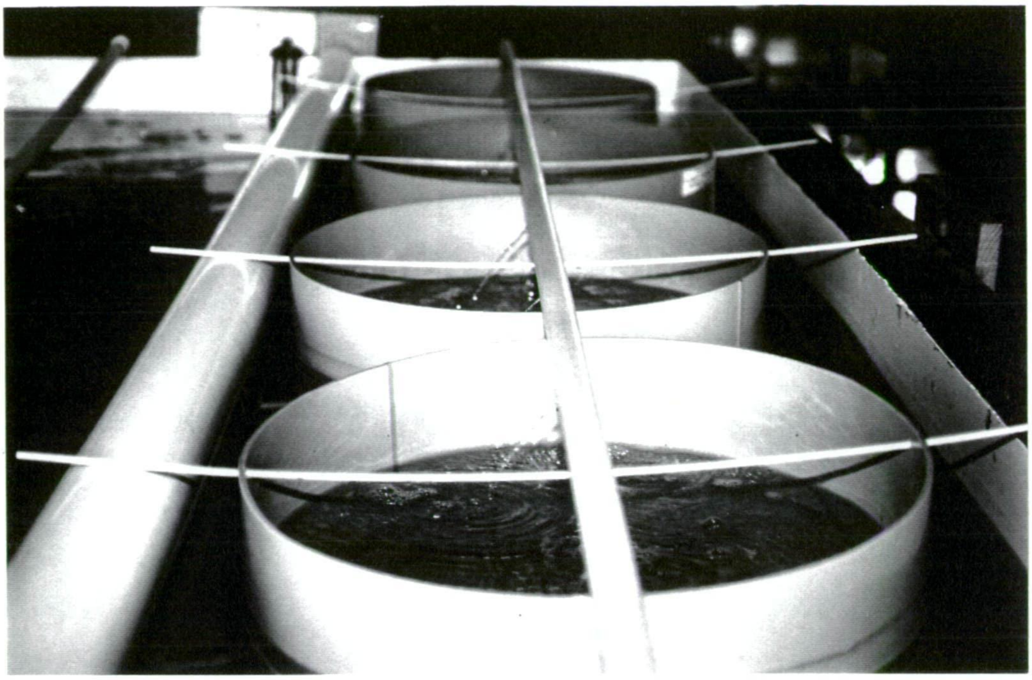


Fig 2.3. An interlocking stack of small PVC discs (D), the type used for settlement of Sydney rock (*S. commercialis*) and Pacific oysters (*C. gigas*) in the hatchery and the wild (Sections 3.2, 3.3 and 3.4).

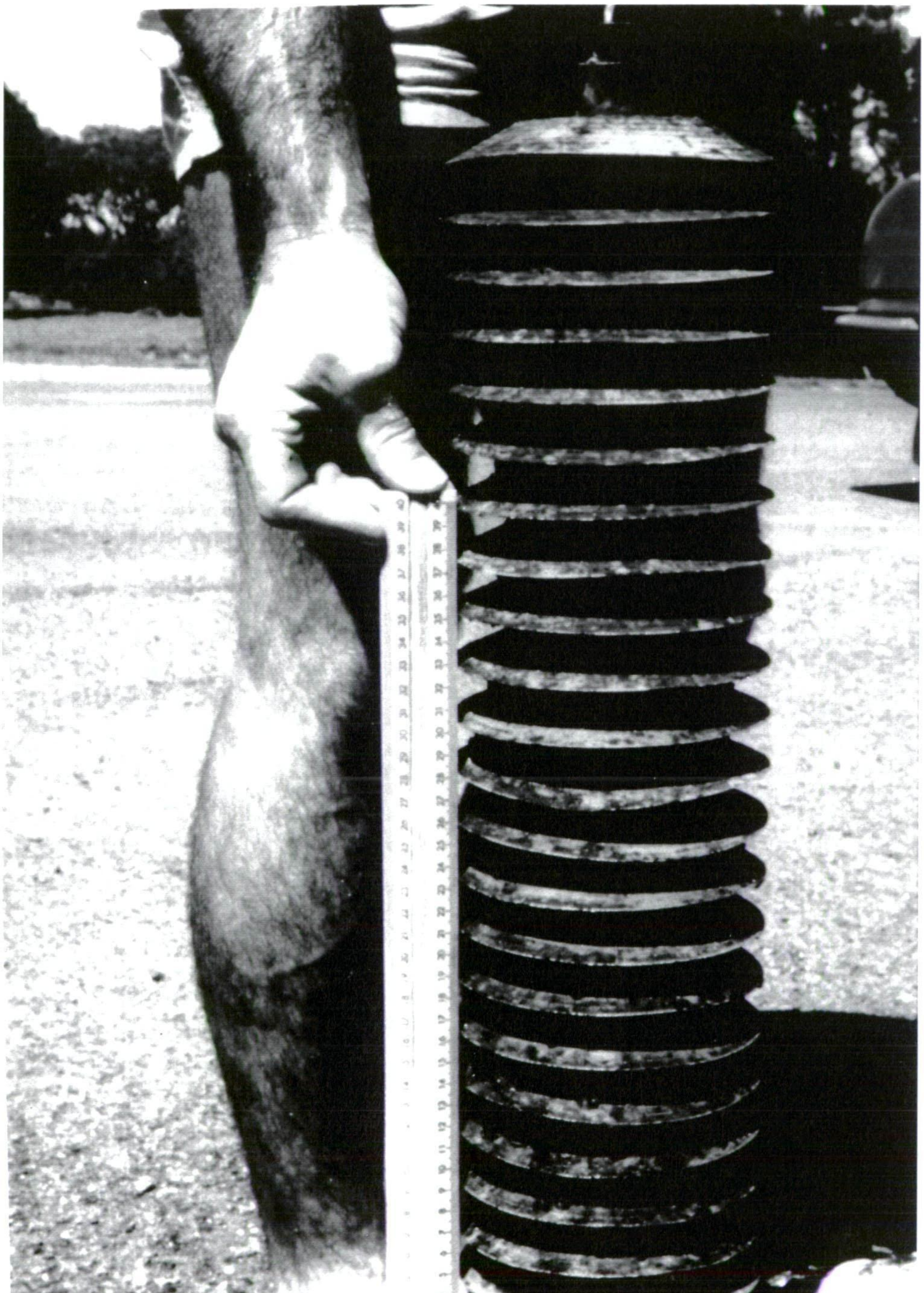


Fig 2.4. A large, slurry-coated disc (SCD) and stack, the type used for settlement of Sydney rock (*S. commercialis*) and Pacific oysters (*C. gigas*) in the hatchery and the wild (Sections 3.1, 3.3 and 3.4).

TABLE 2.1 Summary of specifications for collector types used in this study

Type & Origin	Dimensions/ collector (mm)	Surface area/ collector (cm^2)	Format of stacks No. of layers	No/layer	Total No. collectors/ treatment
PVC sticks					
Flat spiky PVC stick (FSS) (NZ)	50 width 10 cavity 1235 length 1.5 wall thickness	1359	5	4	100
Round spiky PVC stick with lug (RSSL); (NZ)	22 diam. 16 width lug 1808 length	1792	5	4	100
Round grooved (NZ) PVC stick (RGS)	22 diam. 1808 length	1250	5	4	100
Round spiky PVC stick (RSS); (NZ)	22 diam. 1808 length	1250	5	4	100
PVC discs					
PVC disc (D)[1] (Spain)	140 diam. 1.0 wall thickness	275	10	3	150
Slurry-coated[1,2] PVC disc (SCD) (France)	355 diam. 5.0 wall thickness	1790	6	1	30
Slats					
Bioresin[1,3] slat (BS); Aust)	100 width 1010 length	2020	5	3	75
PVC slat (S)[1] (Aust)	104 width 1495 length 2.0 wall thickness	3110	5	4	100
Slurry-coated[1,2] PVC slat (SCS) (Aust)	104 width 1495 length 3.0 wall thickness	3110	5	4	100
Tarred hardwood[1,4,5] stick (TS); (Aust)	20 x 20 1800 length	1440	5	12	300

1 Collectors were designed for single seed culture.
2 Disc and slats were slurry-coated with the following mix: 600 g hydrated lime, 200 g cement, 100 ml PVC bonder and 2.2 l fresh water.
3 Bioresin was impregnated on a woven fibreglass cloth.
4 Sticks coated in coal tar pitch type and air dried for 2 months prior to deployment. Spatfall was confined to upper and lower surfaces (effective area 720 cm^2).
5 Collectors were designed for spat collection and/or growing oysters to market.

Fig 2.5 Round, spiky, PVC sticks with lug (RSSL) bound in commercial format for deployment and settlement (Sections 3.3 and 3.4).

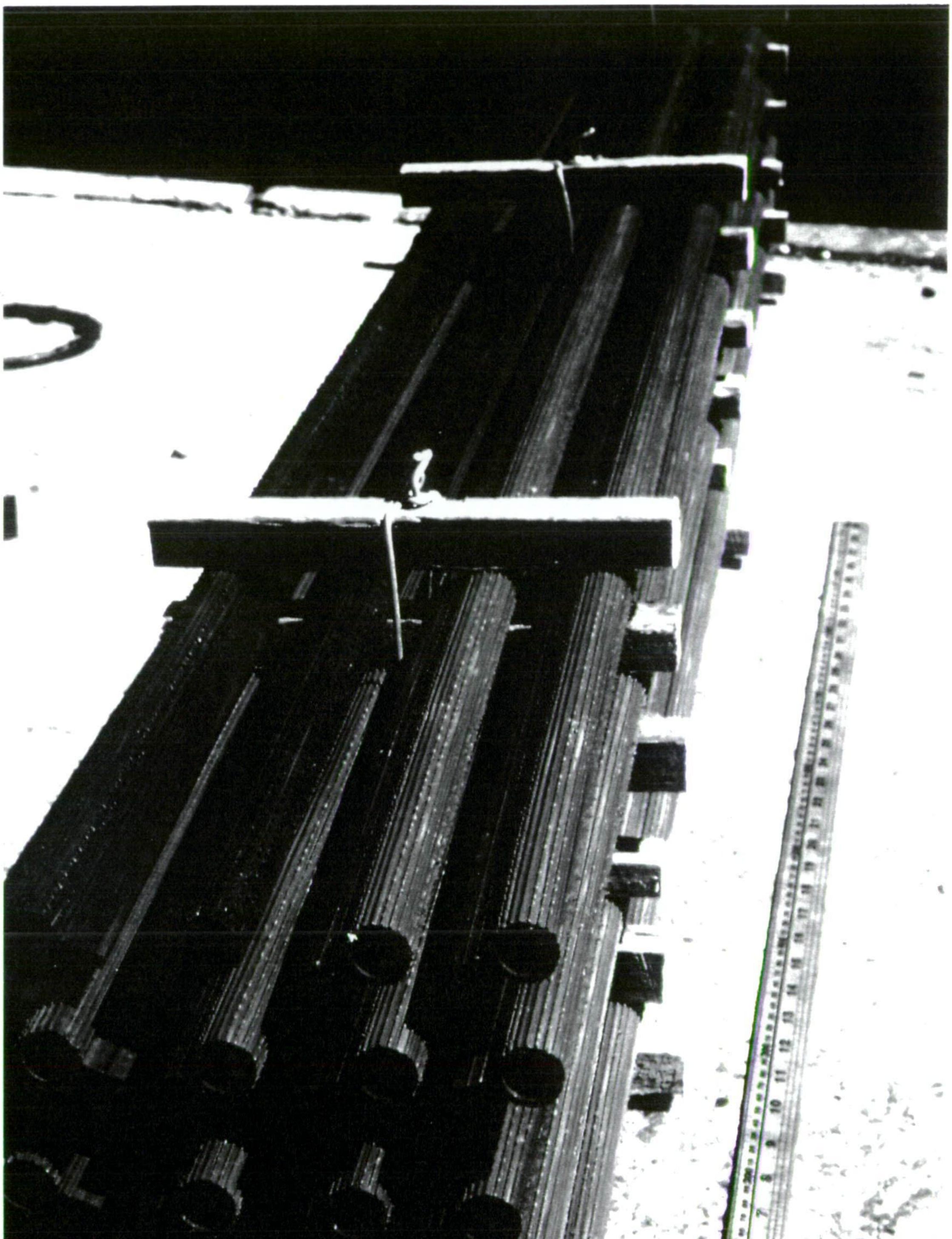


Fig 2.6 Various types of oyster collectors deployed randomly for settlement, along parallel, intertidal, tarred hardwood battens. Battens were supported by posts and set perpendicular to the foreshore in Salamander Bay, Port Stephens (Section 3.4).

2.1.6 Harvesting, grading and counting spat

Spat were detached from the various types of collectors by flexing collectors, by using a brush, or for tarred sticks, by using a paint scraper. Spat from downwellers and various nursery systems were graded with nylon and PVC nominal screen sizes of 0.5, 0.7, 0.9, 1.7, 3, 4, 8 and 12 mm (Table 2.2). The nominal screen size of 3 mm was used to grade spat, prior to stocking them in commercially-used nursery units covered with the same size mesh, ie spat were > 3 mm diameter, to avoid losses from spat becoming lodged in or falling through meshes covering nursery units. For newly settled spat, numbers were estimated by volume (by submerging spat in a finely graduated measuring cylinder) and by counting spat from a series of 1 ml subsamples using a microscope.

2.2 SITES AND DESCRIPTION

The present study was conducted using the NSW Fisheries hatchery, Port Stephens Research Centre, Taylors Beach, Salamander Bay; the NSW Agricultural temperature control rooms, Gosford; the Electricity Commission Power Station channels at Vales Point, Lake Macquarie and nine sites in six NSW estuaries (Fig 2.7). A number of sites in Port Stephens were used for the study (Fig 2.8). For natural settlement of Sydney rock oysters, collectors were deployed on a commercially-used intertidal spat catching lease in Salamander Bay (Fig 2.6). For Pacific oyster settlement, collectors were deployed on a traditional stick and tray lease at Tanilba Bay, NSW, in the inner (western) harbour of the Port (Fig 2.6). Although Tanilba Bay is a traditional growing area for the indigenous Sydney rock oyster, the Pacific oyster has recently become well established here (Holliday and Nell, 1990; Chew, 1990; Reid, 1990; Nell, 1993) and the increasing settlement over the last few years is now used for commercial production.

TABLE 2.2 Nominal screen sizes used in this study for grading Sydney rock oysters (*S. commercialis*).

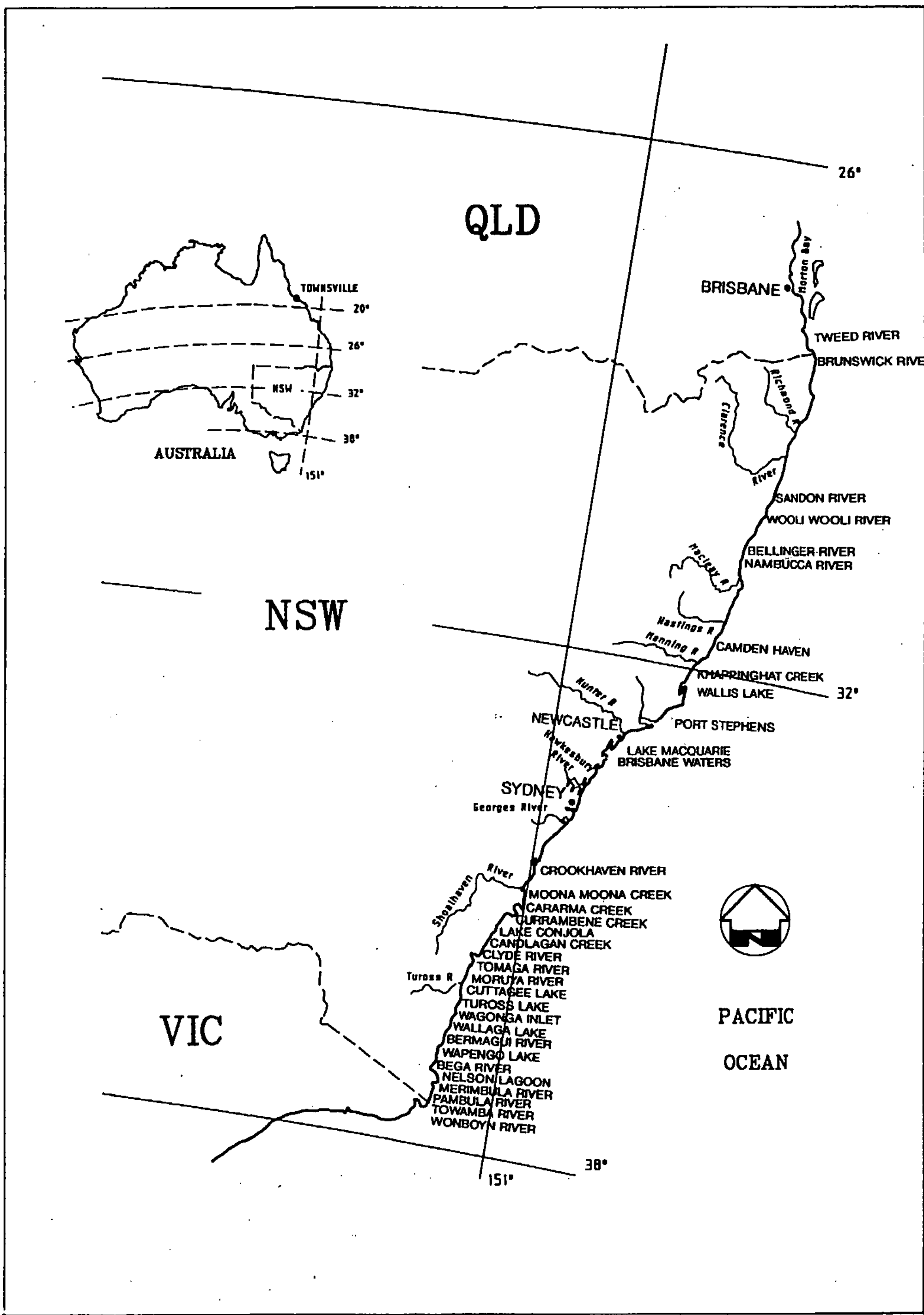
Screen Sizes[1] (mm)	Sizes of spat retained on screens (mm)			
Nominal	Measured		Shell Length[2]	
	Mean±SE	Range	Mean±SE	Range
0.5	0.6±0.01	0.5-0.7	0.9±0.01	0.7-1.2
0.7	0.9±0.01	0.9-1.0	1.2±0.02	0.8-1.5
0.9	1.2±0.01	1.1-1.2	1.4±0.02	1.0-1.8
1.25	1.7±0.01	1.7-1.8	2.2±0.03	1.6-2.7
1.7	1.4±0.1	1.2-1.6	2.3±0.1	1.8-2.9
3.0	2.9±0.9	2.3-3.4	4.1±3.1	3.0-5.5
4.0	5.0±1.0	4.2-6.1	5.2±0.1	3.9-7.7
8.0	9.4±0.3	8.9-9.9	8.5+0.2	5.8-12.4
12.0	12.6±0.1	11.6-14.5	12.6±0.2	8.8-17.2

1 Screen sizes represent a diagonal measurement.
2 Longest axis from hinge of oyster.

Growth and survival of oysters were evaluated on a number of intertidal leases in Port Stephens and included leases in the natural spat catching area of Pindimar (in the outer or eastern harbour), the traditional stick and tray areas of North Arm Cove (a middle-estuarine site) and Swan Bay (an inner-estuarine site), (Fig 2.8; Section 5.1).

Heated water from the inlet and outlet to the Vales Point Power Station, Lake Macquarie (Fig 2.9) was used when comparing sites and evaluating growth and survival of spat during winter in upwellers and nursery trays (Section 6.2). Vales Point is one of two coal powered power stations discharging heated effluent into Lake Macquarie. Growth, survival and condition of Sydney rock oysters were also assessed during winter in commercial earthen prawn farming ponds at the Clarence River (Fig 2.7) in northern NSW (Appendix 9.4). An intertidal lease at Empire Bay, Brisbane Waters (Fig 2.10) was used to evaluate retention and growth of oysters on PVC and timber sticks and was selected as it was a recognised growing site, relatively free of Sydney rock and Pacific oyster settlements (Section 3.4). An intertidal lease at Mooney Mooney Creek, Hawkesbury River (Fig 2.10), was used in an experiment to determine optimum stocking densities for spat in PVC cylinders (Section 4.2). The lease was fenced to protect stock from severe wave action which can affect shell growth of spat in cylinders (Nell, 1991b). Spat in cylinders deployed in the Hawkesbury River were also evaluated for mudworm infection, as high turbidity levels in this estuary and the build-up of silt on oysters on trays has resulted in high infestation (Wisely et al., 1979a). A protected (fenced) intertidal lease in the Hastings River (Fig 2.11) was used to compare growth and mortality of larger spat in trays, cylinders and baskets (Section 6.3). This warmer northern estuary was used to avoid Pacific oyster settlements.

Fig 2.7. Map of NSW (Australia) with locations of oyster producing estuaries.



26°
QLD
BRISBANE
Norton Bay
TOWNSVILLE
20°
26°
NSW
32°
38°
AUSTRALIA
151°
TWEED RIVER
BRUNSWICK RIVER
Richmond R
Clarence River
SANDON RIVER
WOOLI WOOLI RIVER
BELLINGER RIVER
NAMBUCCA RIVER
Macleay R
NSW
Hastings R
Manning R
CAMDEN HAVEN
KHAPPINGHAT CREEK
WALLIS LAKE
32°
Hunter R
NEWCASTLE
PORT STEPHENS
Hawkesbury River
LAKE MACQUARIE
BRISBANE WATERS
SYDNEY
Georges River
CROOKHAVEN RIVER
Shoalhaven River
MOONA MOONA CREEK
CARARMA CREEK
CURRAMBENE CREEK
LAKE CONJOLA
CANDLAGAN CREEK
CLYDE RIVER
TOMAGA RIVER
MORUYA RIVER
Tuross R
CUTTAGEE LAKE
TUROSS LAKE
WAGONGA INLET
WALLAGA LAKE
BERMAGUI RIVER
WAPENGO LAKE
BEGA RIVER
NELSON LAGOON
MERIMBULA RIVER
PAMBULA RIVER
TOWAMBA RIVER
WONBOYN RIVER
VIC
PACIFIC
OCEAN
38°
151°

Fig 2.8 Settlement and nursery sites in Port Stephens, NSW (Sections 3.4, 4.1, 5.0 and 6.1).

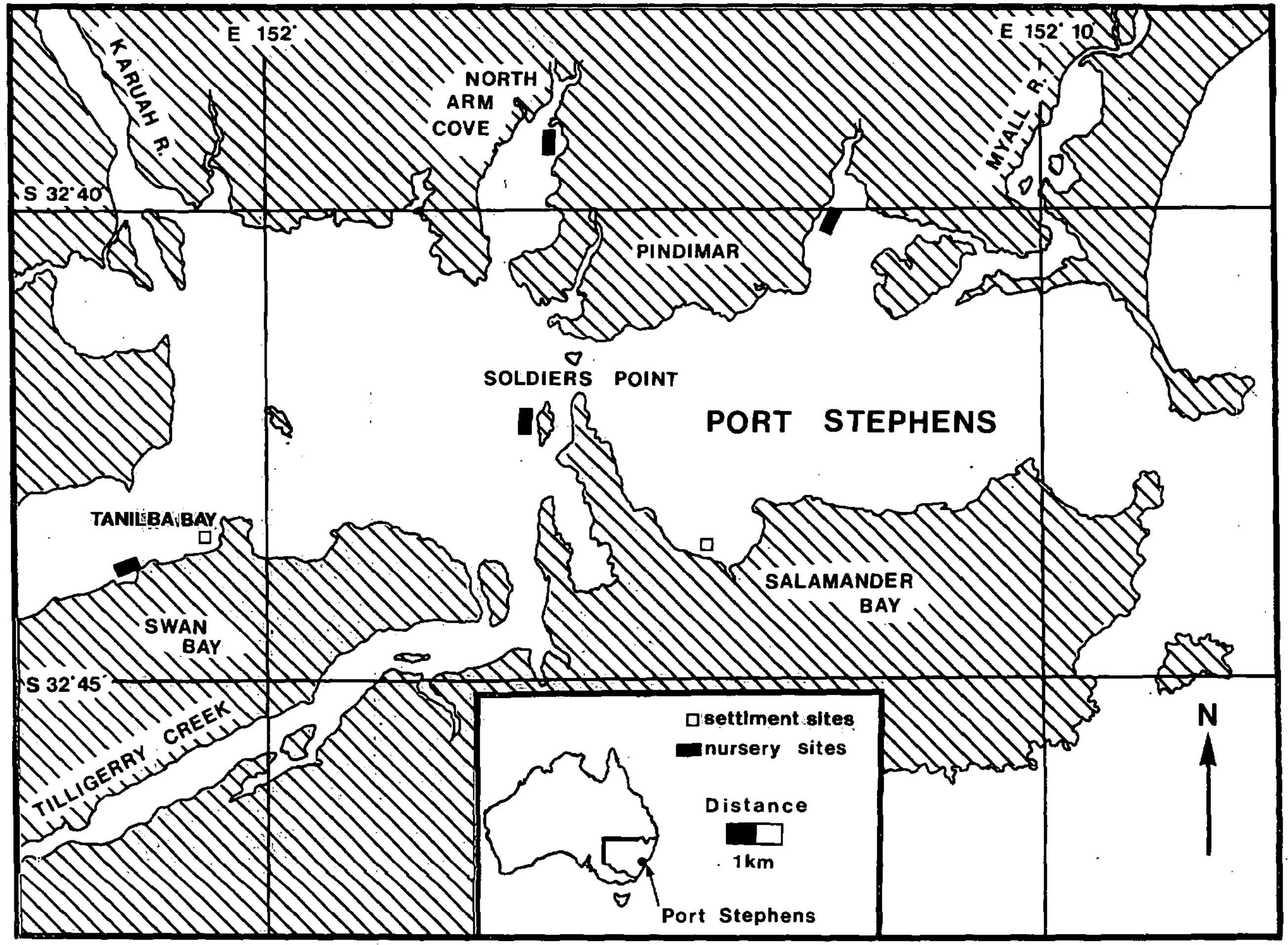

E 152'
E 152' 10'
KARUAH R.
NORTH
ARM
COVE
MYALL R.
S 32'40'
PINDIMAR
SOLDIERS POINT
PORT STEPHENS
TANILBA BAY
SALAMANDER
BAY
SWAN
BAY
S 32'45'
TILLIGERRY CREEK
settlment sites
nursery sites
Distance
1km
Port Stephens
N

Fig 2.9 Location of Vales Point Power Station, Lake Macquarie, NSW (Section 6.2).

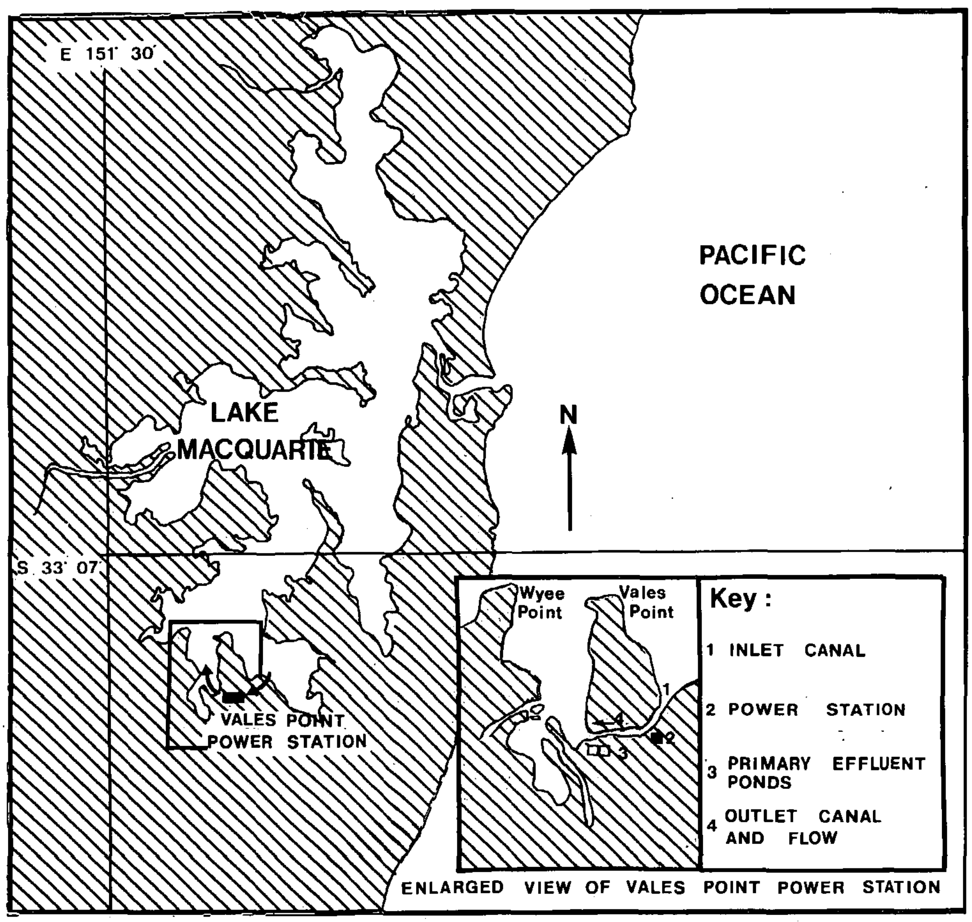

E 151° 30'
S 33° 07'
PACIFIC
OCEAN
N
LAKE
MACQUARIE
VALES POINT
POWER STATION
Wyee
Point
Vales
Point
Key :
1 INLET CANAL
2 POWER STATION
3 PRIMARY EFFLUENT PONDS
4 OUTLET CANAL AND FLOW
ENLARGED VIEW OF VALES POINT POWER STATION

Fig 2.10 Location of nursery and growing sites at Mooney Mooney Creek, Hawkesbury River and Empire Bay, Brisbane Waters, NSW (Sections 3.4, 4.2).

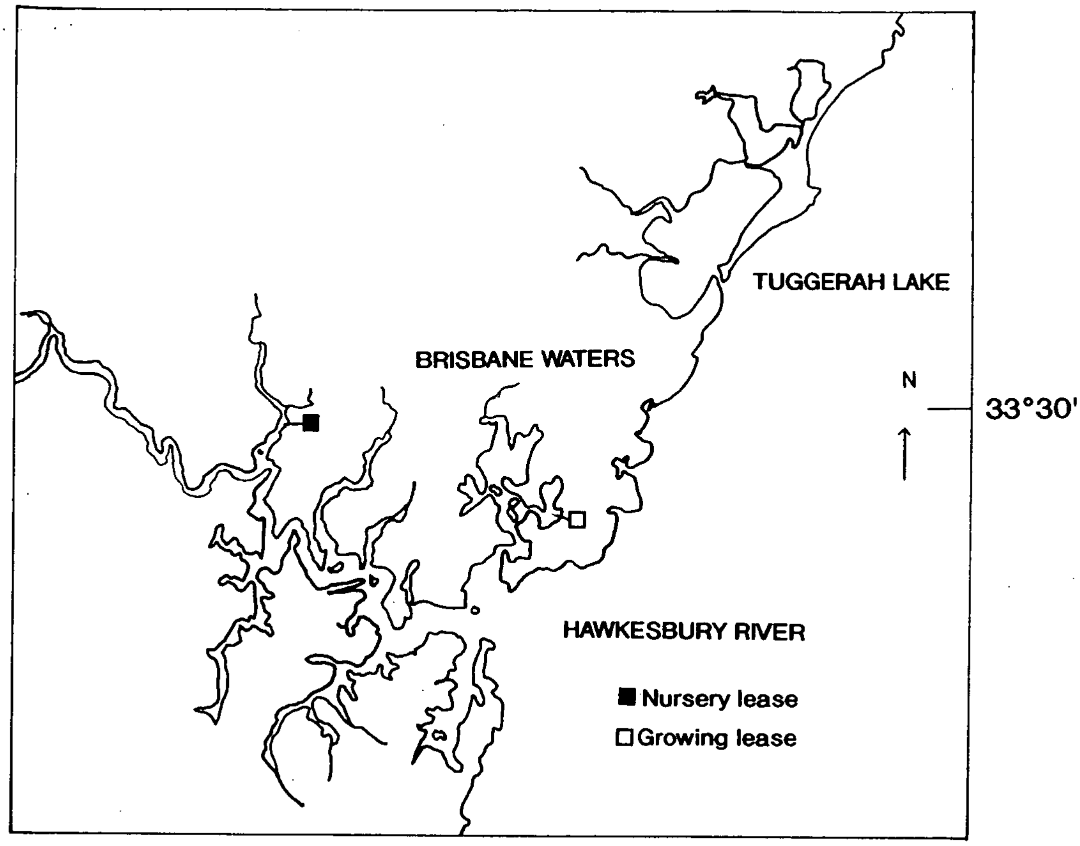
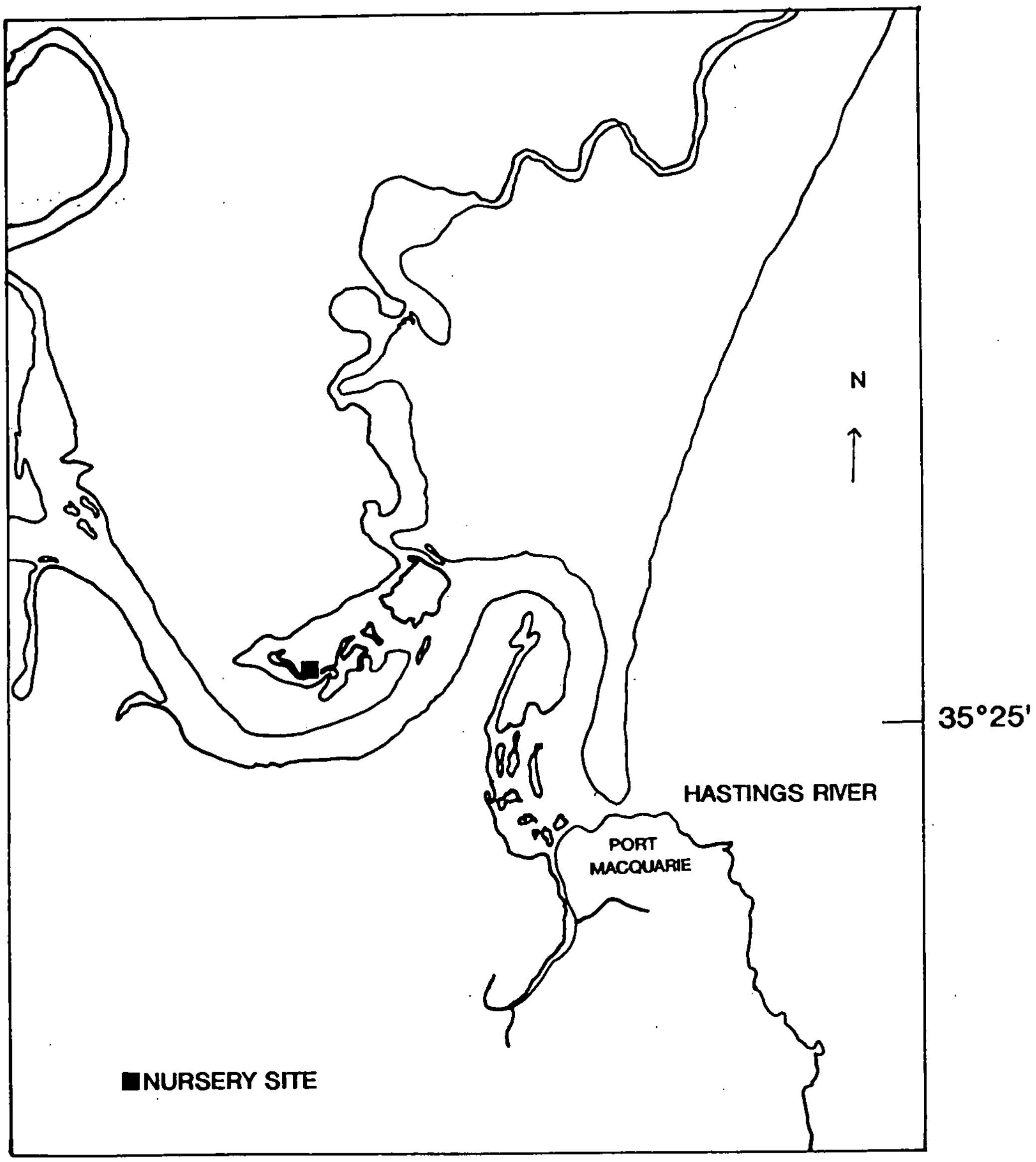

TUGGERAH LAKE
BRISBANE WATERS
N
33°30'
HAWKESBURY RIVER
Nursery lease
Growing lease

Fig 2.11 Location of the nursery site on the Hastings River, NSW (Section 6.3).


N
35°25'
HASTINGS RIVER
PORT
MACQUARIE
■NURSERY SITE

2.3 NURSERY UNITS

2.3.1 Description of units

The suitability of nursery units can be affected by site and the choice for farmers is often compounded by the variation in environmental conditions on leases, both within and between estuaries. Adverse conditions include, wave action, marine fouling and the deposition of silt on oysters (particularly in areas with inadequate water velocity), which can result in high infestation and mortalities from mudworm (Skeel, 1979; Wisely et al., 1979a). In the present study, different types of nursery units were examined under different environmental conditions, including on-shore upwellers, nursery trays, PVC cylinders and PVC baskets on intertidal leases and PVC envelopes in prawn farming ponds.

2.3.1.1 Upwellers

Passive and forced-flow upwellers (Bayes, 1981), used to grow hatchery spat attached to chips of scallop shell, consisted of PVC cylinders (450 mm diam. x 250 mm depth) with nylon mesh (diagonal measurement range 0.5-2.0 mm) attached to the base (1 590 cm^2 screen area). Up to ten cylinders were immersed in sea water in a fibreglass tank (1 000 l; Figs 2.2, 2.12). Spat were evenly distributed over screen surfaces. Water was pumped into the tanks and passed passively through screens and spat to a waste outlet. Forced-flow upweller units (Fig 1.13) were constructed from PVC pipe (1.0 m depth x 0.25 m diam.) and PVC mesh (diagonal measurement range 0.5-2.0 mm). Water was pumped directly to the oysters through the base of the vertically fixed upwellers and discharged through an outlet at the top of the pipe (Fig 2.13).

2.3.1.2 Sectionalised trays

Sectionalised nursery trays (1.94 m x 0.94 m x 0.05 m) were constructed of tarred 50 mm x 20 mm hardwood, divided crossways into six parallel sections, each 0.25 m^2 (Fig 2.14 ; Sections 4.1, 5.1, 6.2, 6.3, 6.4). Both the upper and lower tray surfaces were covered with PVC mesh (3 mm diam. mesh) to minimise oyster damage and loss of spat from wave action and to reduce predation from fish. Trays were secured by wire and timber battens on post and rail frames on intertidal leases (Fig 2.15) and in the effluent pond at Vales Point Power Station (Section 6.2).

2.3.1.3 PVC cylinders

PVC cylinders (Figs 2.16, 2.17) were 1 m x 0.32 m diam. (internal dimensions, length 0.74 m, diam. 0.27 m; total volume 42.4 l/cylinder) and constructed of 3 mm PVC mesh, with a PVC shaft and rigid buoyant PVC end caps, which caused rotation in response to changes in tidal level (Figs 2.16, 2.17). PVC cylinders have been used successfully by farmers in NSW (Anon., 1985; Holliday, 1987; Holliday et al., 1988). The manufacturer claimed that the revolving action (one revolution per tide) helped remove silt from around the oysters and reduce mudworm infestations (Anon, 1985; Holliday et al., 1988).

2.3.1.4 PVC baskets and envelopes

PVC baskets (280 mm x 470 mm; Fig 2.18) and PVC envelopes (450 mm x 900 mm; Fig 2.19) used in this study were similar to those used in France (Holliday, 1992; Robert et al., 1993). Baskets and envelopes (both made of folded plastic mesh) were supported on the intertidal post and rail by 20 x 20 mm tarred hardwood oyster sticks (Fig 2.18). In NSW, PVC baskets and envelopes are more suitable for leases exposed to wave action, as they retain oysters in position, avoiding shell abrasion and the build-up of oysters on top of one another, that can result reduced flow rates and can affect oyster growth and survival.

2.3.2 Stocking densities

For collector types, stocking densities were dependent on settlement. Unlike other nursery systems, increased density in downwellers and upwellers could be compensated by adjusting flow rates and food concentrations (algal densities) for larvae and spat. For upwellers, spat were stocked using a commercial technique of covering screen surfaces, and as spat grew, they were graded, thinned and restocked at reduced densities. Stocking densities in the present study, were often restricted by available larvae. Optimum stocking densities were determined for sectionalised timber trays using six densities, estimated on the pooled weight of a number of spat. With the exception of the smaller grade of oysters in cylinders, where five densities were used (Section 4.2), six stocking densities were used to determine optimum stocking density. For cylinders, spat were stocked on the basis of volume, as this is the method used by farmers. Stocking densities for trays and cylinders were then based on 50% coverage (or less), with useable surface area of units covered by a single closely packed layer of spat.

2.3.3 Assessment of growth and mortality

Where feasible, shell length (referred to as height by Galtsoff, 1964b), was measured along the longest axis from the hinge of the oyster (Quayle, 1988) and used as the preferred indicator of growth, followed by weight. Shell length was used because of the direct relationship between the linear dimensions of the shell and the mass for some oyster species (Quayle and Newkirk, 1989; Spencer, 1990) and as meat production was not considered an important factor for this nursery study. Oyster shell length was measured with an electronic digital caliper (NSK/MAX-CAL) and weight with electronic scales (Sartorius, Type 2254), to two decimal places. For spat settled in the hatchery on PVC discs, shell length was estimated by measuring 50 randomly selected spat, using a fine ruler and microscope, as weights could not be obtained from spat on discs.

Final average individual spat weight was estimated by weighing randomly selected live individuals from different types of units and replicates. For example, with cylinders, average individual shell length was estimated by measuring 50 spat per replicate. The total weight of all oysters in each replicate was used to calculate final biomass and biomass gain.

Mortality was determined at harvest by counting spat, with the exception of cylinders in Section 4.2, where total numbers of spat at stocking and harvest were estimated, by dividing total weight per nursery unit by the average weight and data used to estimate percentage mortality at harvest. Retention (spat retained within nursery units from stocking to harvest) was also determined by counting spat.

2.4 STATISTICAL ANALYSIS

Homogeneity of variance was confirmed using Cochran's Test (Winer, 1971). Differences between treatments were assessed using one-way ANOVA. Means were compared using Tukey's honestly significant differences method (Sokal and Rohlf, 1981). To satisfy the assumption of normality and/or homogeneity of variance, various data were transformed ($\log_{10}x$) or (arcsine $x^{0.5}$) prior to ANOVA. T-tests (Winer, 1971; Sokal and Rohlf, 1981) were used to compare differences between the following: oyster survival, average spat weight gain and biomass gain values, eye spot and shell diameters, the number of spat settled on the upper and lower surfaces of each collector type, growth, survival and retention of the various grades of spat stocked for trays and cylinders. Coefficient of variation for weight gain and shell length increase was calculated as an indicator of size variation of oysters within treatments (Sokal and Rohlf, 1981). Growth co-efficient values (G_x) were calculated to allow for differences in sampling periods and initial spat weights (Spencer and Gough, 1978).

Linear regression was used to examine the relationship between eye spot diameter and shell length for each species, and between stocking density and average weight gain. An analysis of covariance (Sokal and Rohlf, 1981) was used to determine if density affected growth. Throughout the text, data are presented as means $\pm$ standard error (means$\pm$SE), with the exception of Figures 4.1, 4.2 and 4.4, which are presented as means $\pm$ standard deviation (means$\pm$SD), as stipulated by the editors for publication of that section.

Fig 2.12 Passive upweller units at the inlet to the Vales Point power station, Lake Macquarie (Section 6.1).

Fig 2.13 PVC forced-flow upwellers at the inlet to Vales Point Power Station, Lake Macquarie (Section 6.2).

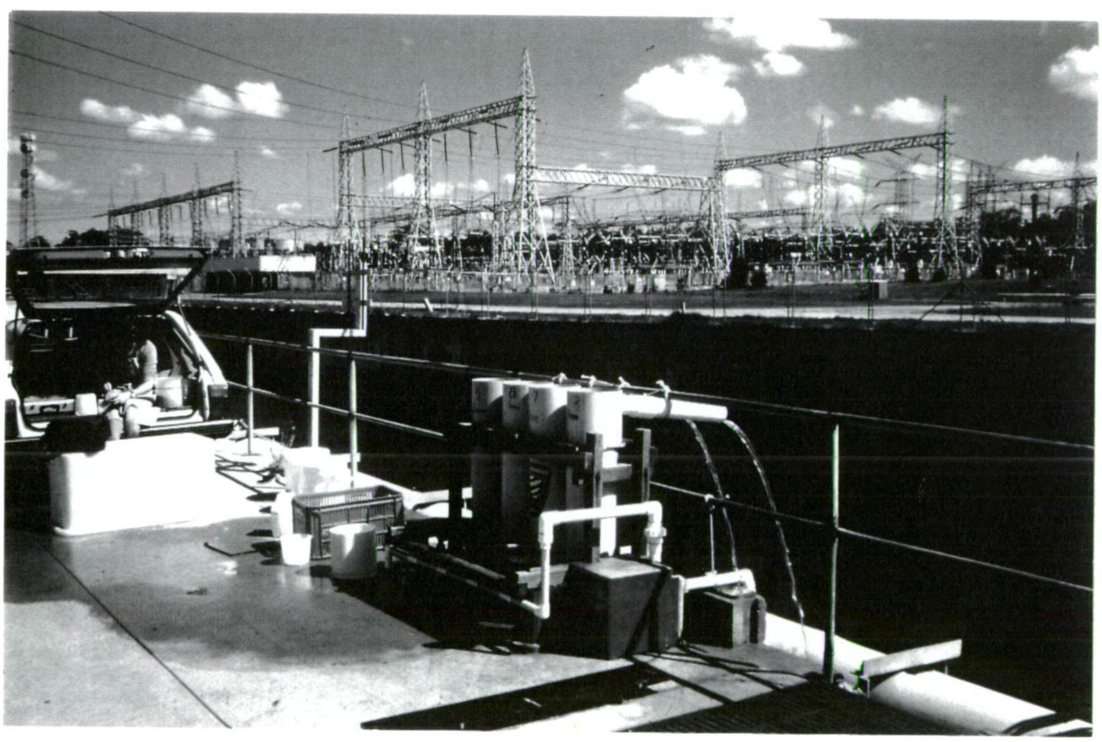


Fig 2.14 Sectionalised timber trays with six sections per tray. A range of spat densities were tested, with stocking densities based on coverage of tray floor by a single layer of closely packed spat, the method used by NSW farmers for conventional trays (Sections 4.1, 5.1, 6.2 and 6.3).

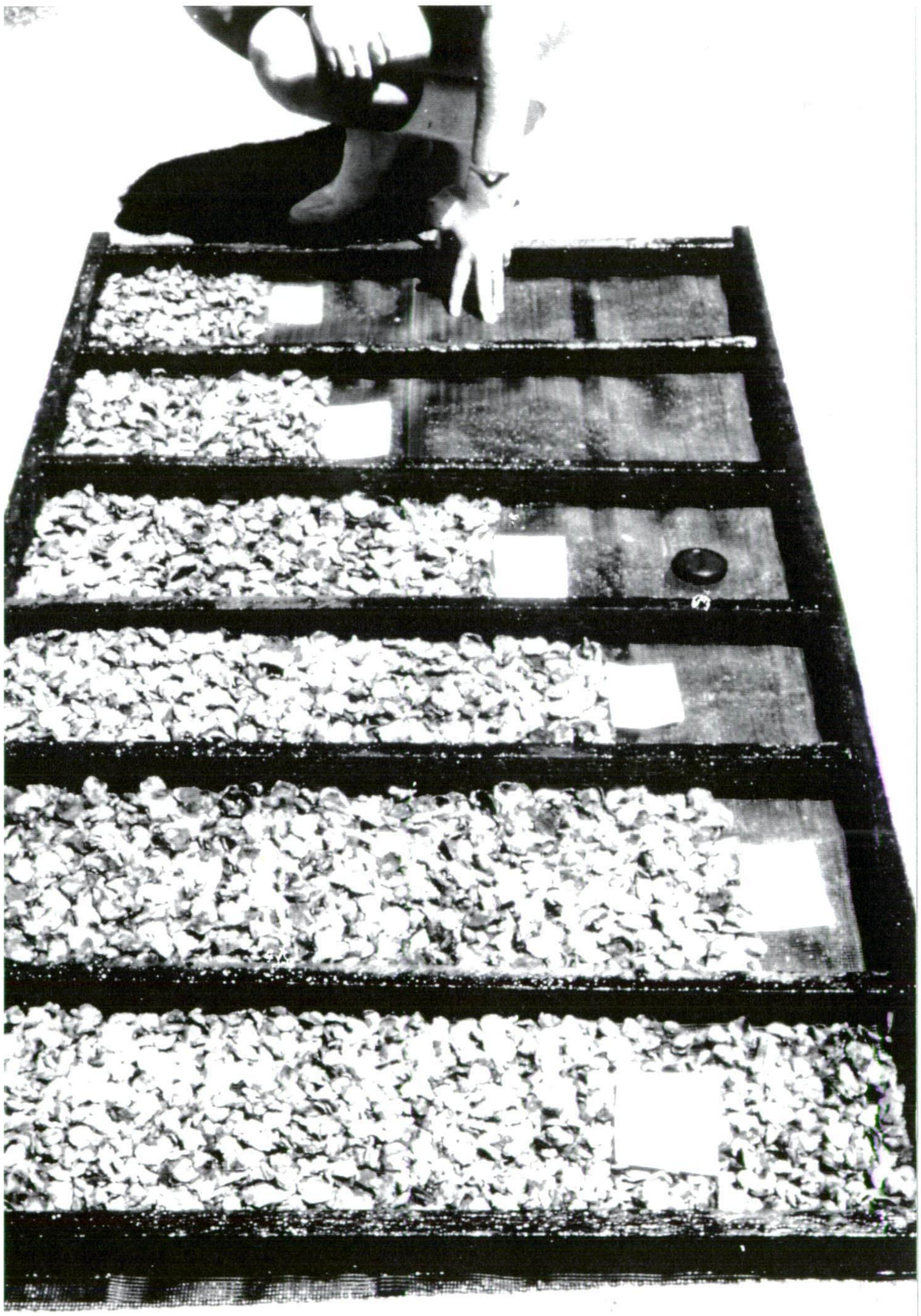


Fig 2.15 Sectionalised trays secured with batten and wire on an intertidal lease in Swan Bay, Port Stephens. Trays were positioned on elevated post and rail (Sections 4.1, 5.1 and 6.2).

Fig 2.16 PVC cylinders in the Hawkesbury River, NSW, used for growing juvenile Sydney rock oysters (*S. commercialis*). Cylinders were fixed to hardwood rails, elevated off the estuary bottom by timber posts. Oysters in the cylinders are submerged for about 90% of the time compared with about 70% for those on the traditionally used timber trays, deployed on similar frames, positioned at the same growing height (Sections 4.2 and 6.3).

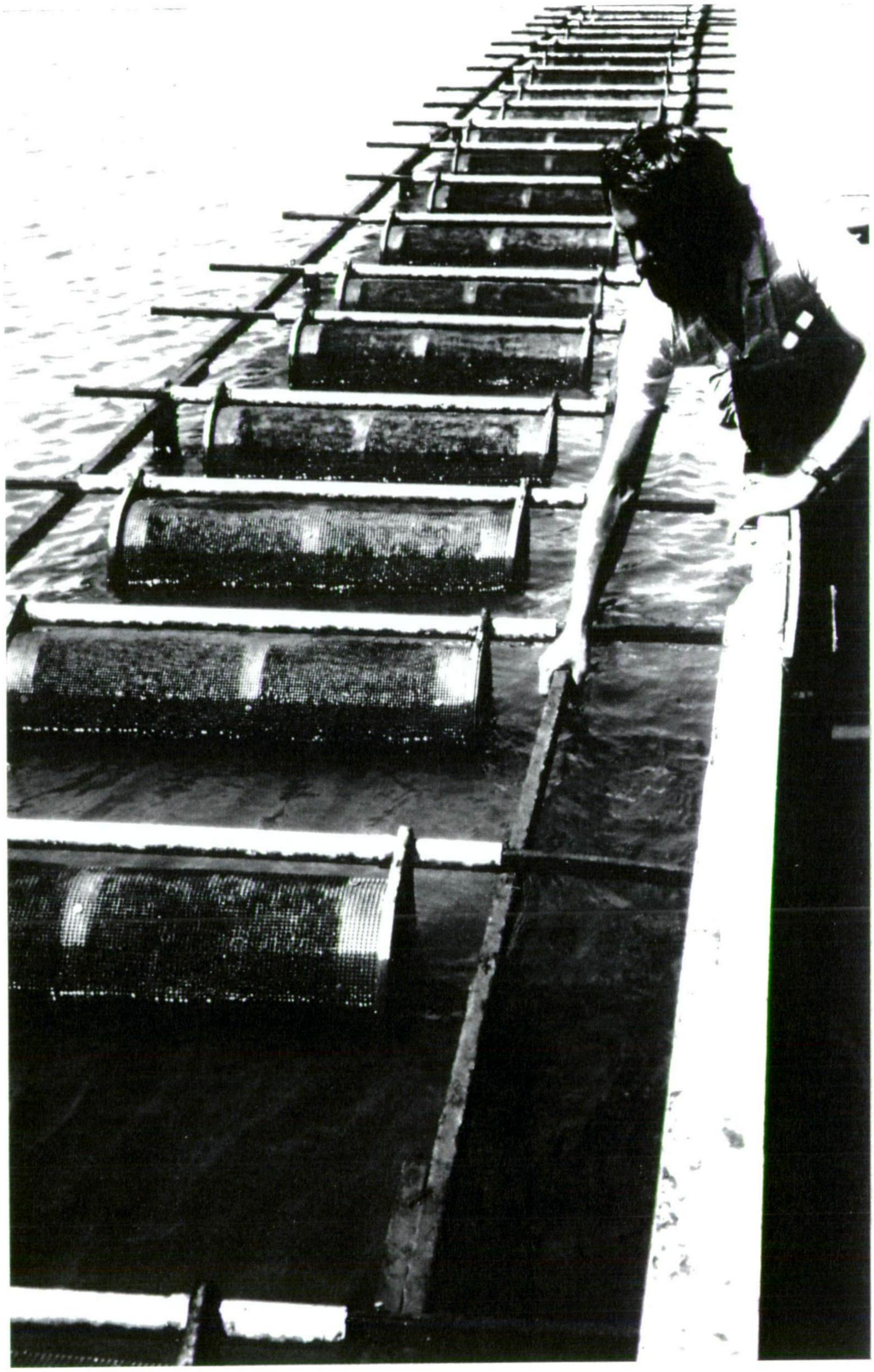
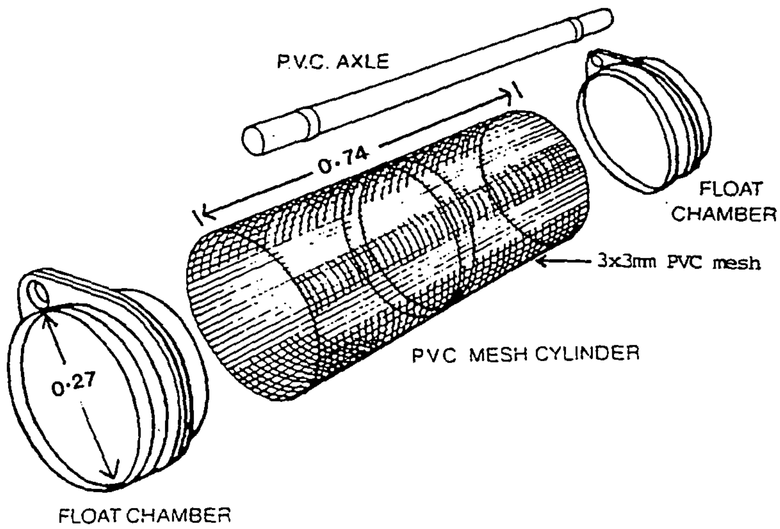


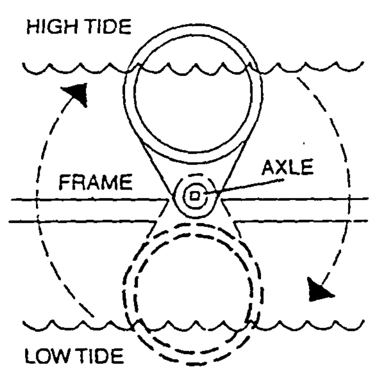
Fig. 2.17 A sketch of a PVC cylinder used for nursery culture of oysters (Sections 4.2 and 6.3):

A) showing an exploded view of the cylinder,

B) showing the rotating action of the cylinder.


P.V.C. AXLE
0·74
FLOAT
CHAMBER
3x3mm PVC mesh
0·27
PVC MESH CYLINDER
FLOAT CHAMBER

A.


HIGH TIDE
FRAME
AXLE
LOW TIDE

B.

Fig 2.18 PVC baskets used by oyster farmers for the culture of larger oyster spat. Baskets were supported by two tarred hardwood sticks inserted through the PVC mesh and secured on post and rail frames on an intertidal lease (Section 6.3).

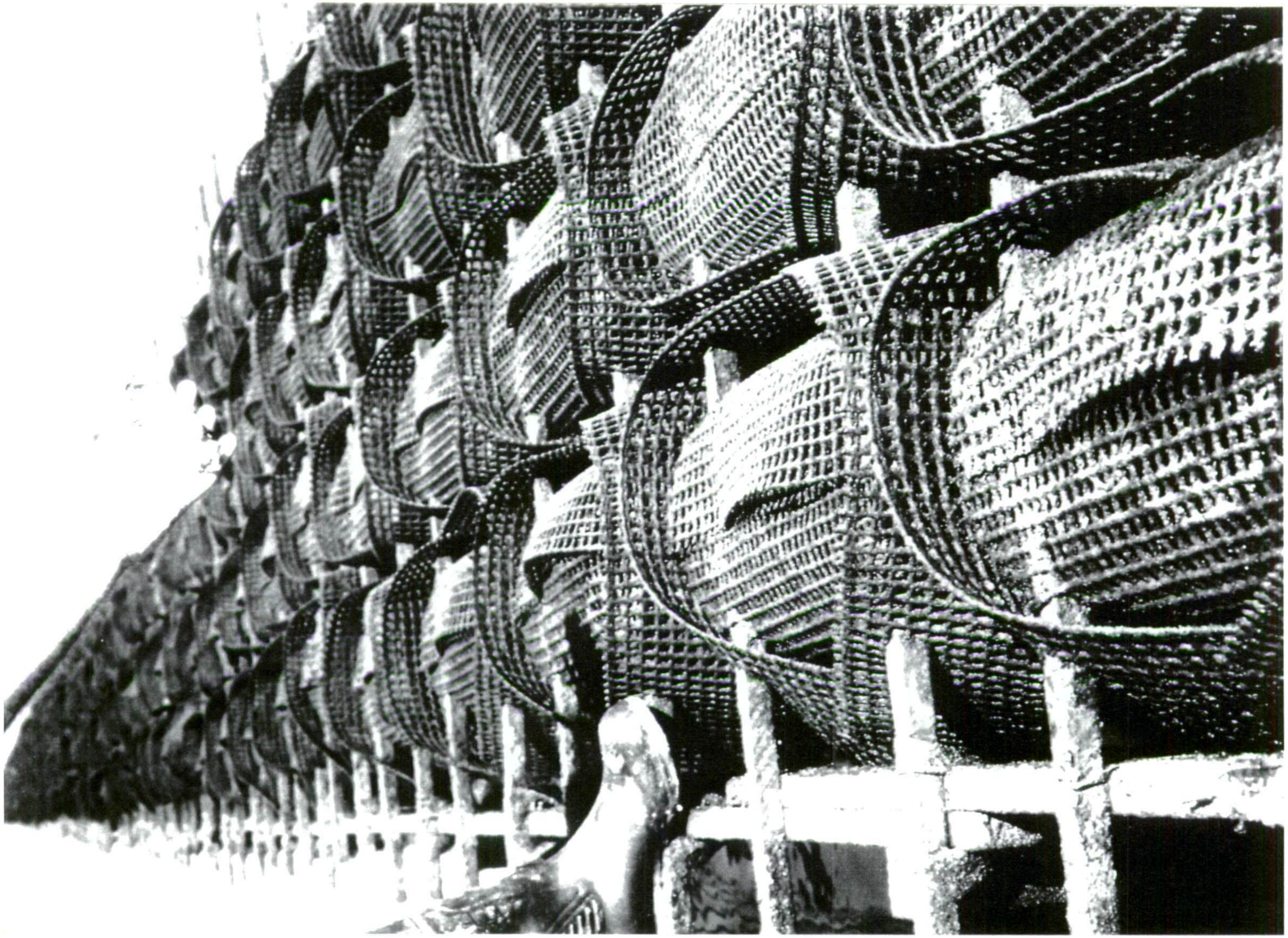
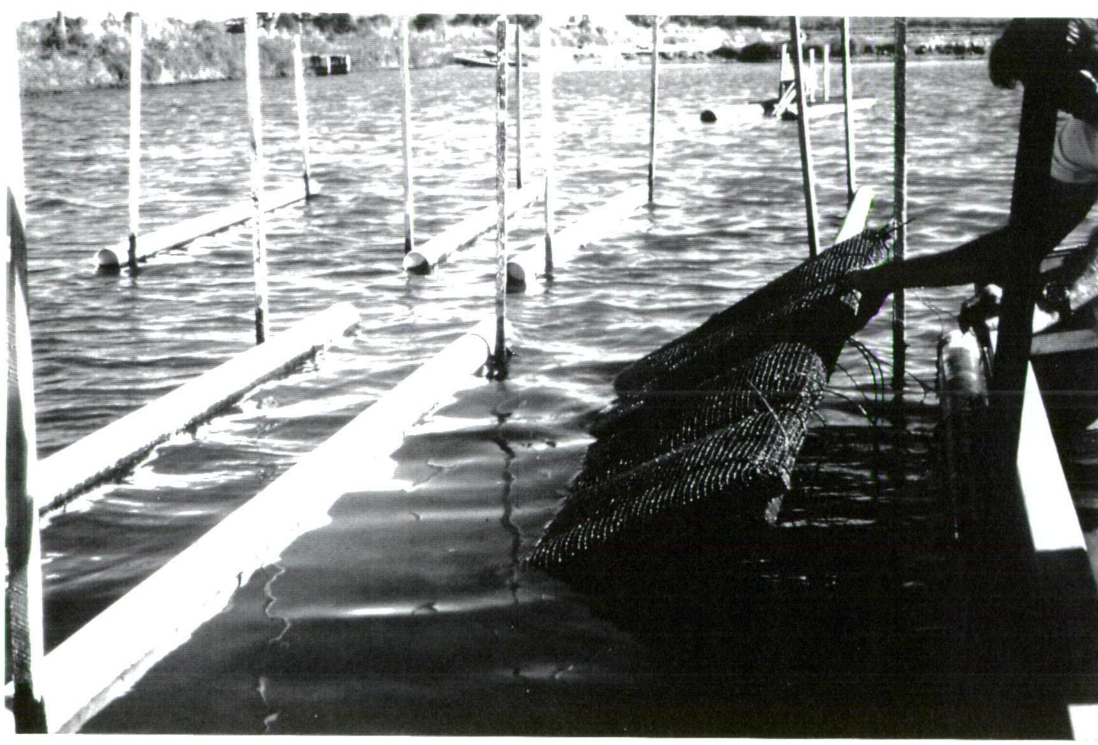


Fig 2.19 PVC envelopes are widely used by the Australian and French industries for culturing oysters. Here, PVC envelopes were deployed under pontoons in prawn ponds in northern NSW for growing spat and fattening oysters during the cooler winter months (Appendix 9.4).



CHAPTER 3

SETTLEMENT OF PEDIVELIGER LARVAE AND SPAT RETENTION

3.1 EFFECTS OF COLD STORAGE ON THE SETTING OF OYSTER LARVAE *[Published (1991), **Aquaculture** 92: 179-185]*

3.1.1 Introduction

Delayed or "remote" setting bivalve larvae described in Section 1.2.3, was developed in North America (Jones and Jones, 1983, 1988; Chew et al., 1986; Supan and Wilson, 1993). By 1986, there were 76 setting tanks in use in British Columbia using 160 million larvae in remote setting operations; this technique is now widely used for the production of Pacific oysters (Roland et al., 1988; Roland and Broadley, 1990; Chew, 1990, 1991).

In Australia, the developing oyster hatcheries produce Sydney rock and Pacific oyster seed to about 4 mm, using upwelling systems, similar to the type described by Bayes (1981). The nursery phase can be very expensive, particularly for Sydney rock oysters, which grow at approximately half the rate of Pacific oysters (Nell, 1989). Although remote setting of Pacific oyster larvae is widely used in North America, the failure rate when setting was 20-30% and only about 3.0% of larvae survived to harvest size (Roland et al., 1988; Roland and Broadley, 1990). Chew (1991), reported that 7-10 x 10^6 larvae could be stored for 5-7 days (with some reduction in set [range 20-80%] after 5 days) with storage temperatures of 2-5°C.

Remote setting has also been tested for other bivalves such as *C. virginica*, *Mytilus edulis*, *Mercenaria mercenaria*, *Venerupis japonica* and *Mya arenaria* (Chew, 1991), however, it has not previously been attempted with Sydney rock oyster larvae. The objectives of this segment were to determine whether the larvae could be stored for delayed settlement and, if so, determine the effect of storage temperature and time. Pacific oyster larvae from local broodstock (Port Stephens) were also settled following storage at 6°C for 4 days and the results used for comparison with those for Sydney rock oyster larvae.

3.1.2 Methods

3.1.2.1 Larvae

Fertilised Sydney rock and Pacific oyster eggs were reared to pediveliger stage as described in Section 2.1. To synchronise experiments, the Pacific oyster spawning was delayed by four days to allow for the anticipated difference in larval development between species. When larvae reached the pediveliger stage and small numbers were observed setting on the sides of the rearing tanks, they were harvested onto a partially submerged 200 μm screen. Larvae for each experiment were then divided volumetrically into 20 l buckets, one for each replicate. Larval concentration in each bucket was estimated by counting the larvae in each of five subsamples (1 ml) using a Sedgewick-Rafter cell and a compound microscope. Eyespot diameter and shell length were measured for 250 larvae of each species using a binocular microscope with an ocular micrometer ($\pm$0.5 μm). The larvae in each bucket were then drained through a funnel and retained using 100 μm nylon mesh (25 cm^2). The mesh was then secured as a pouch with a rubber band. Each mesh pouch contained 170$\pm$3.1 (x 10^3) and 236$\pm$10.0 (x 10^3) larvae for the experiments with Sydney rock and Pacific oyster larvae respectively. The 25 cm^2 mesh pouches of larvae used as controls (no storage) were emptied directly into the setting container.

3.1.2.2 Storage

The pouches of larvae, wrapped in damp absorbent paper, were transported for two hours to the temperature control rooms in a portable 30 l refrigerator, set at 11$\pm$0.4°C. Larvae were stored at different temperatures (1.4-11.0°C) and storage times (10-290 h). For each combination (Table 3.1), five pouches were used and held in a 5 l box (Fig 3.1), placed within one of three fan-forced, constant temperature, cool rooms. Pouches of larvae were held inside the boxes to buffer possible changes in temperature if cool room doors were opened. Damp paper towel was used to ensure that pouches did not come in contact with the floor or walls of the box or with other pouches, and that pouches remained damp. The temperature inside one of the 5 l boxes in each cool room was logged using ANRITSU type T7001 data loggers (Electron Chemical Engineering Pty Ltd, Mobbs Lane, Carlingford, NSW, 2118). The mean temperatures (°C) maintained in the cool rooms were 1.4 (range 1.1-2.1), 6.0 (range 5.3-8.8), and 11.0 (range 10.3-11.3).

3.1.2.3 Set system

After the appropriate storage interval, the 5 l boxes containing the pouches were returned to the hatchery in the portable refrigerator. Larvae were washed into 5 l beakers of seawater (25°C, 33‰) and held for 45 minutes while the motility, colour, odour and mortality of the larvae were assessed. To avoid bacterial contamination of viable larvae, those treatments with total mortality in each replicate were not placed in the set systems. For all other replicates, the larvae were confined within a downweller unit, partially submerged at a randomly allocated location inside one of five 1700 l fibreglass setting tanks (Section 2.1.2). Within each PVC screen a large, slurry-coated PVC disc (355 mm diam., 80 mm high, surface area 1790 cm^2) was provided for the larvae. Seawater (25.4±0.1°C, 29.8±0.3‰) was gently sprayed over the top of each PVC screen at the rate of 0.8 l/min. A 100% water exchange was carried out every second day, with a 50% exchange every other day, and all tanks were fed an equal mix of algal species (Section 2.1.2) at a rate of 2.9 x 10^4 cells/ml/day.

Collectors were removed after 8 days. A template with four evenly spaced wedges (each spanning the radius of the collector, giving a total surface area of 199 mm^2/wedge), was placed randomly over the top and bottom surfaces of each collector, and the oysters contained within each wedge were counted. The small numbers of spat that settled on the PVC screens were removed and enumerated by weighing.

For Sydney rock oysters, nine treatments were provided with five replicates of each. Treatments comprised one control, where larvae were drained into 25 cm^2 mesh pouches and then put to set without storage; storage for 12, 98 and 194 h at 11°C; 98, 194 and 290 h at 6°C; and 98 and 194 h at 1.4°C. For Pacific oysters, two treatments with five replicates for each were provided. These included a control (no storage) and 98 h at 6°C, close to the storage temperature and time (5°C; 144 h) used for this species by Henderson (1981).

3.1.2.4 Statistical Analyses

The experiment with Sydney rock oysters was designed to allow for two-way ANOVA of temperature (1.4, 6.0, 11.0°C) and storage time (98 h and 194 h), as well as one-way ANOVA for all combinations in Table 3.1. However, data from treatments that suffered total mortality following storage were excluded from statistical analyses. Therefore, differences in the numbers of oysters that set following different treatments were assessed using one way ANOVA. Homogeneity of variance was evaluated using the Cochran's Test (Winer, 1971) and means were compared using Tukey's honestly significant differences method (Sokal and Rohlf, 1981). Differences between set for the experiment with Pacific oysters were compared using t-tests (Sokal and Rohlf 1981). Differences between eye spot and shell diameters for the two species were compared separately using t-tests and the relationship between eye spot diameter and shell length for each species was evaluated using linear regression.

3.1.3 Results

Pacific oyster larvae reached pediveliger stage, 18 days after fertilisation and Sydney rock larvae at day 22. Set rates for Sydney rock oysters were excellent, with no significant difference ($P>0.05$) in numbers ($x\ 10^3$) which settled between controls (139 ± 9) and larvae stored at 11.0°C for 12 or 98 h (145 ± 16 and 131 ± 17 respectively) (Table 3.1). The percentage of larvae which settled was estimated to range from between 92.7 ± 10.2% and 75.6 ± 11.5% for these treatments, with some percentages over 100%. This over estimation resulted from some inaccuracies in our counting technique. Significantly fewer oysters survived ($P<0.05$) when stored for 98 h at 1.4 and 6.0°C and 194 h at 11.0°C (Table 3.1); settlement was estimated to range from 5-30% for these treatments. No larvae survived when stored for 194 h at 1.4 and 6.0°C.

There was no significant difference ($P>0.05$), in the number ($x\ 10^3$) of Pacific oysters which settled, between the controls and larvae stored for 98 h at 6.0°C (159±21 and 163±15 respectively; Table 3.1), where approximately 69.2±6.1% of larvae were estimated to have set from both treatments. Pacific oyster larvae had a significantly ($P<0.05$) larger mean shell length (325.4±1.00 μm; n=250) than Sydney rock oyster larvae (292.2±0.87 μm; n=250), although, the eyespot diameter was significantly ($P<0.05$) smaller (14.2±0.15 μm compared with 20.3±0.30 μm). Within the small size range measured for each species there was no significant relationship ($P>0.05$) between shell length and eyespot diameter.

3.1.4 Discussion

The excellent set results for Sydney rock oyster larvae stored for up to 98 h at 11°C indicate that remote setting techniques have considerable potential for this species. Relatively inexpensive, commercially available equipment can be used to maintain a temperature of 11°C and consignments of oysters could be shipped to most locations within Australia, and overseas, within 98 h. Estimates of the percentage of larvae of both species which set following optimum storage temperature and time ranged from 69% for Pacific oysters to between 76 and 93% for Sydney rock oysters. These rates are well in excess of the reported acceptable commercial rates of 20-30% for unfed Pacific oyster larvae (Supan and Wilson, 1993) and 37% for those fed on stored algal paste (Roland et al., 1988) and consistent with spat recoveries (10-80%) reported by Lipovsky (1991). In the present study, larvae were fed live algae during settlement and this may have improved set rates.

Recommended larval shell length and eyespot diameter for remote setting Pacific oysters are >300 μm and 14 μm (Jones and Jones, 1988) and 300-320 μm and 15 μm (Roland et al., 1988); the size (mean = 325 μm, range 290-373 μm) of Pacific oyster larvae in the present study was similar. Inherent differences between the local Pacific oyster strain (possibly Myagi strain; Deupree, 1993; Section 1.1.1) and those used elsewhere may account for differences in set performance. If shell length and eyespot diameter were used as criteria for when to store pediveliger larvae for delayed set, the results of this segment indicate that appropriate measurements might be 292.2 μm and 20.3 μm for Sydney rock oysters and 325.4 μm and 14.2 μm for Pacific oysters.

Typically, consignments of 2.5 x 10^6 Pacific oyster larvae are shipped in mesh pouches from North American hatcheries (Jones and Jones, 1988). The larger surface to volume ratio for smaller pouches was considered likely to result in higher larval mortality through desiccation or physical abrasion of larvae in contact with the pouch material. The mean numbers (x 10^3) of larvae used here for each pouch was 170$\pm$3.1 and 236$\pm$10.0 larvae for Sydney rock and Pacific oysters respectively and was chosen to be large enough to simulate commercial scale shipments. Larger consignments may have produced even better results. No larvae were stored beyond 194 h at 11°C, although it is possible that some may have survived. The set performance of Pacific oysters following storage at temperatures above the recorded temperatures of 2-5°C (Chew, 1991) and at 5°C (Henderson, 1983) may warrant further study if storage periods >98 h are envisaged.

TABLE 3.1

The effects of cold storage on settlement of eyed Sydney rock (*Saccostrea commercialis*) and Pacific oyster (*Crassostrea gigas*) larvae (Section 3.1; larval and spat numbers refer to numbers of oysters per replicate pouch)[1].

Time	Temp.	Sydney Rock Oysters			Pacific Oysters		
(h)	(°C)	Larvae ($\times 10^3$)	Spat ($\times 10^3$)	Set (% set)	Larvae ($\times 10^3$)	Spat ($\times 10^3$)	Set (% set)
No storage		182 ± 11^a	139 ± 9^a	77 ± 7	233 ± 10^a	159 ± 21^a	71 ± 11
12	11.0	157 ± 7^a	145 ± 16^a	93 ± 10			
98	1.4	175 ± 12^a	8 ± 2^b	4.6 ± 1			
98	6.0	186 ± 9^a	55 ± 8^b	30 ± 4	238 ± 11^a	163 ± 15^a	68 ± 7
98	11.0	177 ± 9^a	131 ± 17^a	76 ± 12			
194	1.4	147 ± 8^a	0[2]	0			
194	6.0	148 ± 7^a	0[2]	0			
194	11.0	173 ± 8^a	28 ± 5^b	16 ± 2			
290	6.0	184 ± 9^a	0[2]	0			

[1] Means±SE; n=5. Within columns, means with a common superscript do not differ significantly (P>0.05).

[2] Treatments were excluded from statistical analysis.

Fig 3.1. A 5.0 l box containing pouches of Sydney rock (*S. commercialis*) and Pacific oyster (*C. gigas*) larvae for storage (Section 3.1).

3.2 OYSTER SETTLEMENT SYSTEMS IN A HATCHERY

3.2.1 Introduction

The following section was designed to evaluate settlement techniques for cultured larvae and follows research on larvae from Section 3.1, in which promising settlement rates were obtained after larvae were stored and settled on large PVC slurry-coated discs. These represent one of a range of possible settlement systems and the next stage was to examine alternative systems.

World production of oysters is dependent on reliable techniques for the collection of spat and the development of hatcheries has fostered alternative farming methods and revived or helped establish oyster industries in the UK (Spencer, 1990; Utting and Spencer, 1992), USA (Chew, 1990) and Australia (Holliday et al., 1988; Nell, 1993). The Australian oyster industry currently obtains spat from hatcheries and natural spatfall (Holliday et al., 1988; Nell, 1993), and although NSW farmers collect spat principally from the wild, there is a growing demand for triploid Sydney rock and Pacific oyster spat from hatcheries (Nell et al., 1994). Oyster larvae are usually settled in hatcheries on collectors in tanks or on bivalve shell chips in downwellers (O'Sullivan and Wilson, 1976; Jones and Jones, 1988; Holliday, 1992; Sections 1.2, 1.3, 2.12). As the two systems had not been compared, the objective of this section was to determine the better system for Sydney rock oyster larvae by comparing settlement on small PVC discs, as might be used in a remote setting system, and on chips of scallop shell in a downweller system. Both the period required for settlement and post-set mortality of spat in each system were estimated. Distribution of spat on the 20 layers of discs and size variation of spat in the downweller unit were also determined.

3.2.2 Methods

3.2.2.1 Larvae

Sydney rock oyster larvae were reared to pediveliger stage using established techniques described in Section 2.1.1. Numbers of pediveliger larvae were estimated from 1 ml subsamples (n=4), using a Sedgwick Rafter cell (Section 2.1.1). Salinity and temperature were maintained at 30.2±0.1‰ and 25.1±0.5°C respectively. Larvae were stocked synchronously into a tank and in a downweller unit and both of which were covered with black plastic sheeting to exclude light. Different stocking densities were used for the tank and downweller unit and were based on commercial practices (Frankish et al., 1991; Jones and Jones, 1988). Rate of settlement was estimated by daily observations for numbers of pediveliger larvae in the cultures and on screens during water changes.

3.2.2.2 *Remote setting tank*

Oyster settlement was determined following settlement in a 3 000 l fibreglass tank similar to that used for remote Pacific oyster larvae (described in Section 2.1.2; Fig 2.1B; Jones and Jones, 1988; Roland and Broadley, 1990), on small PVC discs (D; Fig 2.3; Table 2.1). Pediveliger larvae were stocked at 39.6±1.2 x 10^4/tank and fed an equal mix of *P. lutheri* and T. *Isochrysis* at 177.8±7.8 x 10^3 cell/ml. Water was exchanged every 48 h. Fifteen vertical stacks of discs (20 layers/stack) were positioned on the tank floor. Each interlocking disc (diam. 140 mm, wall thickness 1 mm, surface area 275 cm^2; Table 2.1) was separated by a 25 mm gap (Fig 2.3). Discs were conditioned prior to the experiment, as described in Section 2.1. Settlement was determined at day 10 by counting total spat/disc from five randomly selected stacks (n=100). Spat were not graded or measured at harvest as they were too small and as the spat and discs were required for a growing experiment (Section 6.1). However, shell lengths of 50 randomly selected spat were measured at day 21.

3.2.2.3 *Downweller*

Spat settlement was determined from a downweller system (described in Section 2.1.2; Fig 2.2A), using chips of scallop shell in PVC and mesh screens (described in Section 2.1.2). Larvae were stocked at 19.8±0.6 x 10^4/screen and fed an equal mix of *P. lutheri* and T. *Isochrysis* at 11.6±1.0 x 10^4 cells/ml/day. Larvae were washed twice daily with a light overhead spray of sea water (at the rate of 0.8 l/min; Fig 2.2A) to remove detritus and faeces. Scallop shell chips were evenly distributed in a thin layer on the nylon mesh screens (n=4) and screens were randomly allocated a position in a downweller unit (1 700 l fibreglass tank). Water was exchanged in the downweller unit every second day, with a 50% exchange every other day. At day 15, spat were graded with 0.5, 0.7 and 0.9 mm nylon mesh screens and settlement estimated for each grade, by volume and by counting spat from 1 ml subsamples (n=4; Section 2.1.6). Spat settled on the sides of PVC downwellers were frequently brushed off, as practiced commercially (Frankish et al., 1991) and these data are included in the results. Spat mortality was estimated by counting gaping spat in each subsample (n=4).

3.2.2.4 *Statistical analysis*

For discs, the effect of layer on settlement was assessed using one-way ANOVA. Data from the downweller were transformed ($\log_{10}x$) prior to ANOVA, to assess spat mortality from the different grades. Homogeneity of variance was confirmed using Cochran's test (Winer, 1971). Means were compared using Tukey's honestly significant difference method (Sokal and Rohlf, 1981).

3.2.3 Results

3.2.3.1 *Remote setting tank*

At harvest on day 10, density on discs was 2.7 spat/cm^2 (755.5±35.9 spat/disc; range 0.4-6.8 spat/cm^2, n=100). There were no free swimming larvae observed in the tank. An estimated 57.0±12.7% of larvae had settled on the discs. Layer had no effect (P>0.05) on settlement with spat evenly distributed on all 20 layers of discs (Fig 3.2; Appendix 9.1). Although some settlement was observed on the base of the tank, data are not included in the results because of the difficulty in assessing spat numbers. No mortality was observed on discs at harvest. Shell length at day 21 was 0.95±0.01 mm/spat (range 0.7-1.2 mm/spat).

3.2.3.2 Downweller

At harvest on day 15, an estimated 109.8±2.8 x 10^3 (55.5±1.4%) of larvae had settled in the downweller system (Table 3.2) and settlement took longer than in the remote setting tank. Spat retained on the various nominal screens included: 0.8±0.1 x 10^3 (<0.5 mm); 32.7±1.7 x 10^3 (0.5 mm); 41.3±1.9 x 10^3 (0.7 mm) and; 20.2±2.2 x 10^3 (0.9 mm) (Table 3.2). Mortality of spat at harvest was low (average/unit n=4, 12.5±0.6% and 13.8±0.6 x 10^3) and confined mainly to the smallest grades (<0.5 mm and those retained on a 0.5 mm screen; Table 3.2). A number of larvae settled on individual scallop shell chips and spat grew together forming clumps (Table 3.2).

3.2.4 Discussion

Both the remote setting tank with PVC discs and the downweller containing screens with chips of scallop shell proved to be effective systems for settling Sydney rock oysters, as similar settlement was obtained (57% and 55% of larvae settled respectively). Direct comparisons of spat should be interpreted with caution as different stocking densities were used. Although larvae were allowed to complete settlement in both systems, those in the downweller unit took longer to settle (day 15) compared to discs (day 10). The rate of settlement is an important criterion for successful commercial operations and when remote settling larvae, it is often used as an indicator of their viability after storage and transport (Roland and Broadley, 1990). Although there was no attempt to manipulate settlement in this study, the slower rate of settlement in downweller units could increase handling and the overall viability of an operation as the downweller unit required a higher level of maintenance for the daily washing of larvae and screens, compared to that required for collectors in the remote setting tank.

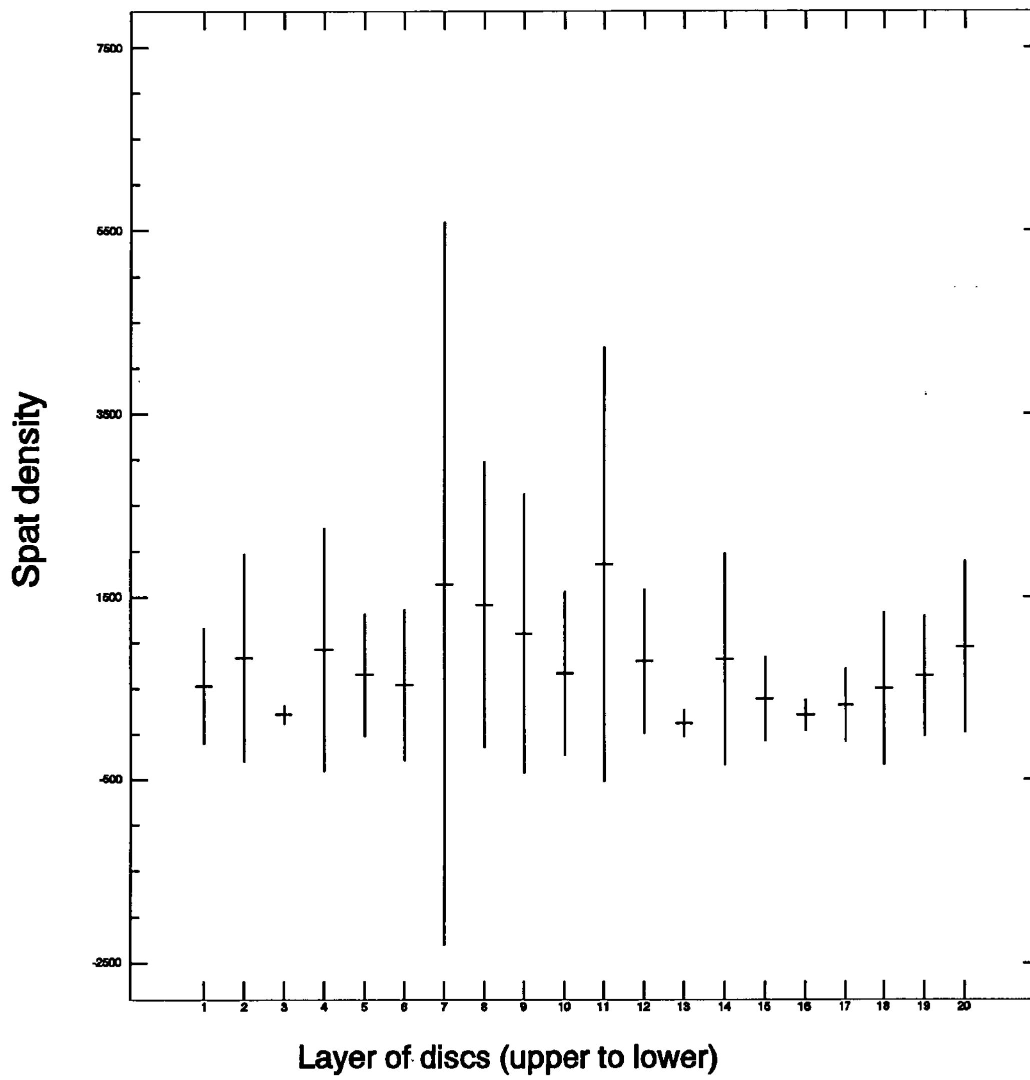
At harvest, some spat mortality was recorded from the downweller unit, although it was low (12.5%) and confined mainly to the smaller grades. Some of these spat were also damaged; mortality may have occurred shortly after settlement from brushing the newly settled spat off the sides of PVC screens. A number of larvae settled on individual scallop shell chips, forming clumps of spat. These spat are usually discarded by commercial growers, as they grow together and are difficult to separate without damaging the oysters. No mortality was observed on discs at harvest. Although mortality was low in this experiment, it should be noted that subsequent to the completion of this segment, heavy mortalities of Sydney rock oyster spat (range 0.5-2.0 mm) were recorded in downwellers and upwellers both in the hatchery and at on-shore sites in NSW (Frankish et al., 1991; Nell et al., 1991).

At harvest, spat were evenly distributed on all 20 layers of discs. An even distribution of spat on collectors is desirable for maximum retention (Section 3.4), as growth rates can decrease and size variation increase with increasing density (Neudecker, 1981; Newkirk, 1981; Jarayabhand, 1988; Bacher, 1991; Sections 3.4, 4.2). In the present study, density of spat on the various layers of the discs were viable (range 0.4-6.8 spat/cm^2) when compared with commercial operations setting Pacific oysters on PVC collectors (0.3-0.4 spat/cm^2; Jones and Jones, 1988; Roland and Broadley, 1990).

Large size variation for spat was recorded from the downweller system at day 15 and from discs at day 21 (ranges <0.5-0.9 mm/spat and 0.7-1.2 mm/spat respectively), although, it should be noted that spat were measured using a different method, as those on discs were too small to be harvested and graded on screens without damage. A large variation in spat size is undesirable in nurseries as it can increase grading and handling costs (Spencer, 1990; Sections 4.1, 4.4). In the present study, the large size variation in spat in the downweller probably resulted from the longer period of settlement.

The results from this section are encouraging for hatchery operators and for farmers anticipating settling Sydney rock oysters using tanks and PVC collectors. Tanks and collectors have a number of advantages over the downweller system, as they require less labour and maintenance during settlement and as collectors can be deployed into the estuary shortly after settlement, thereby avoiding the capital and operational costs associated with spat grown in on-shore upwellers. Coutteau and Sorgeloos (1993) estimated that when culturing juvenile Pacific oysters, 53% of algal production in the hatchery was dedicated to post-set nursery phase, and Thomas and Burnell (1992) concluded that Pacific oyster larvae could be settled and grow on cultch for about half (56%) the cost of purchasing hatchery seed (4-5 mm) produced with downwellers.

Fig 3.2 Spat density and distribution of Sydney rock oysters (*S. commercialis*) on stacks (20 discs/stack) of small PVC discs, positioned vertically in a commercial fibreglass tank (means±95% confidence interval; n=5, Section 3.2). Settlement did not significantly ($P>0.05$) differ between layers.



Spat density
7500
5500
3500
1500
-500
-2500
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Layer of discs (upper to lower)

TABLE 3.2

Production data for Sydney rock oysters, *Saccostrea commercialis*, settled on scallop shell chips in downweller units (Section 3.2)[1]

Nominal Screens[2] (mm)	Live spat ($x10^3$)	Dead[3] spat ($x10^3$)	Post-set mortality (%)	Clumps[4]
<0.5	0.8±0.1	7.2±0.4[a]	6.6±0.4	0
0.5	32.7±1.7	5.0±0.2[b]	4.5±0.2	44.8±9.7
0.7	41.3±1.9	1.6±0.2[c]	1.4±0.2	413.8±69.8
0.9	20.2±2.2	0[d]	0	601.6±42.0

[1] Values are means±SE; (n=4 replicate downweller units). Within each column means with a common superscript do not differ significantly. Larvae were stocked at 19.8±0.6 $x10^4$/downweller unit.

[2] Nominal pore size of screen used to grade spat. Spat <0.5 mm passed through the 0.5 mm screen.

[3] Data were transformed ($\log_{10}x$) prior to ANOVA.

[4] Scallop shell chips with more than one spat attached.

3.3 EVALUATION OF COMMERCIALLY-USED COLLECTORS FOR OYSTER SETTLEMENT IN TANKS

*[Experiment 3 accepted, **Aquacultural Engineering**, 1995]*

3.3.1 Introduction

Results described so far in this chapter concern techniques for storing and remote setting oyster larvae. In Section 3.1, storage of Sydney rock and Pacific oyster larvae and settlement (using large slurry-coated PVC discs) were evaluated. In Section 3.2, a further comparison of settlement was made between a remote setting tank with small PVC discs and downweller unit. Discs in Section 3.2, had several advantages over downwellers, as larvae metamorphosed sooner and required less labour and maintenance during settlement. In this section, a number of commercially available collector types were evaluated in the hatchery.

Various materials have been evaluated as substrates for settlement of a number of oyster species including *C. belcheri*, *C. gasar*, the Pacific oyster, *C. virginica*, *O. edulis*, the Sydney rock oyster and *S. cucullata* (Ling, 1970; Dupuy and Rivkin, 1970 and 1972; Hidu et al., 1975; O'Sullivan and Wilson, 1976; Ajana, 1979; Gunn, 1884; Jones and Jones, 1983, 1988; Kong and Luh, 1976; Quayle, 1988; Holliday, 1992). Cultured larvae are often settled on different types of substrates depending on whether they will be detached as spat or as market size oysters, i.e. at the end of the nursery or growing phases (Holliday, 1992). Larvae are settled on valves of old oyster shells, which are deployed on the estuary floor for growout (Jones and Jones, 1988; Quayle, 1988; Holliday, 1992). However, this type of cultch is unsuitable for the production of single oysters for the half shell trade, as many larvae settle on the individual valves and eventually grow into one another forming clumps which are difficult to separate. In Europe and North America, there is an increasing use of PVC and other synthetic collectors, including the remote setting of larvae on collectors at the farm for the production of single seed oysters (His, 1978; Gunn, 1984; Chew et al., 1986; Jones and Jones, 1988; Roland et al., 1988; Chew, 1990. Unlike spat settled on bivalve shell chips, spat on collectors can be deployed directly to estuarine leases, thereby avoiding the often high capital and labour costs associated with on-shore nurseries.

The objectives of this segment were to determine the most suitable of nine types of collectors for the settlement of Sydney rock oysters in tanks. The suitability of collectors was evaluated in terms of spat density on collectors and on the period required to maximise settlement. The spat density and distribution on the upper and under surfaces of PVC slats and slats coated with a lime/cement slurry were determined and the effect of orientation of PVC slats investigated.

3.3.2 Methods

3.3.2.1 Larvae and collectors

Sydney rock oysters were reared to pediveliger stage using established techniques (Walne, 1974; Holliday, 1992). Larvae were counted in four subsamples (1 ml) using a Sedgwick Rafter, as described in Section 2.1.2. For Experiments 1 and 2, nine types of collectors were conditioned as described in Section 2.1.4. Collector types included; flat spiky PVC sticks (FSS), round spiky PVC sticks with lug (RSSL), round grooved PVC sticks (RGS), round spiky PVC sticks (RSS), small PVC discs (D), large slurry-coated PVC discs (SCD), bioresin slats (BS), PVC slats (S) and slurry-coated PVC slats (SCS). All collectors in Experiment 2 were conditioned by soaking them in sea water for 48 h before the experiment (as described in Section 2.1.4). For Experiment 3, PVC slats were cut from commercial grade PVC stormwater pipe (90 mm diam.) and aged for a period of two years on an intertidal lease in Salamander Bay, Port Stephens (Fig 2.7). Timber sticks were excluded from experiments as tar is toxic to larvae in tanks (Candidate, pers. observ., 1982). PVC slats and discs were covered with a slurry consisting of 0.1 part cement, 0.1 part fireclay, 0.5 part lime and 0.18 part PVC bonder. Fresh water was added and the slurry was mixed to a smooth paste. Settlement tanks were covered with black plastic sheeting to exclude light during settlement.

3.3.2.2 *Experiment 1-Aquaria*

Experiment 1 was conducted to compare settlement on the various collector types. Pediveliger larvae ($63.8\pm4.3 \times 10^3$/ aquarium = 1.3/ml), were stocked into 50 l polypropylene aquaria (Fig 2.1A), with four replicate aquaria provided for each collector type. Larvae were fed an equal mix of T. *Isochrysis* aff. *galbana* and *P. lutheri* at $15.7\pm0.2 \times 10^4$ cells/ml/day. Sea water was exchanged every 48 h. Temperature was maintained at 26.1±0.9°C (n=14) using an air conditioned room and salinity at 35.4±0.1‰ (n=7). Each aquaria was gently aerated with an airstone to circulate water and algae. Collector types were cut and bound into mini stacks (commercial format), modified to fit horizontally into aquaria and to provide a similar surface area (5753±145.6 cm^2/replicate; Table 3.3) for larvae to settle. The experiment was run for seven days. At harvest, all spat on collectors were counted, with the exception of the slurry-coated discs, where because of the high density, spat were estimated by counting the number in a rectangular grid (15 cm^2), randomly placed across both upper and under surfaces of each disc. Data per replicate stack were adjusted for small differences in surface area (Table 3.3).

3.3.2.3 *Experiment 2-Commercial tanks*

Experiment 2 was conducted to examine settlement of pediveligers, given a choice of settlement substrates. Two of the 3 000 l fibreglass remote setting tanks (Fig 2.1B), used in Experiments 3.2 and 3.3, were each stocked with $1.1\pm0.01 \times 10^6$ pediveliger larvae per tank (0.4/ml). Larvae were fed *P. lutheri* at $20.0\pm2.0 \times 10^3$ cells/ml. Water temperature was maintained at 26.1±1.0°C with a 2 kW silicon quartz immersion heater and thermostat. Salinity was maintained at 35.4±0.1‰ and water was exchanged every 48 h. To help distribute larvae, the tanks were vigorouly aerated during, and for two hours after, stocking of larvae, as described by Roland and Broadley (1990). Two stacks of each of the nine collector types used in Experiment 1 and described in Table 2.1 (Section 2.1.3), were randomly allocated a position in each tank, prior to stocking larvae. Collectors were deployed horizontally, in full commercial format as described in Table 2.1, and in close proximity to one another. The experiment was run for five days. Spat were counted from each surface and collector, with the exception of the slurry-coated PVC discs, where settlement was dense and estimated by counting spat in a rectangular shaped grid (10 cm^2), randomly placed across both upper and under surfaces of each disc.

3.3.2.4 Experiment 3-Slurry coating and orientation

Experiment 3 was conducted to determine the effective angle of orientation for deploying collectors, by comparing settlement on horizontal and vertical PVC slats and slurry-coated PVC slats. The distribution of settlement on the upper and under surfaces of collectors was also compared. Pediveliger larvae were stocked at $27.9 \pm 1.0 \times 10^3$ per 10 l aquarium (= 2.8 larvae/ml). Each aquarium (n=4) was randomly allocated a position in a temperature control bath. Sea water (34.0‰) in the aquaria was maintained at 25.6 ± 0.3°C (n=12). Water in aquaria was exchanged every 24 h and was not aerated; this was done to eliminate the effects of current on settlement. Larvae were fed an equal mix of T. *Isochrysis* aff. *galbana* and *P. lutheri* at $25.0 \pm 2.0 \times 10^3$ (n=12) cells/ml/day. A single layer of three slats (dimension of each slat when compressed onto a flat surface, was 250 x 60 mm and total surface area 300 cm^2) was positioned on the base of each aquaria. The three treatments were: 1) horizontally positioned PVC slats, 2) PVC slats positioned vertically at a 90° angle and separated with a thin strip of PVC cable (4 mm) and, 3) horizontally positioned PVC slats coated with a lime/cement slurry (slurry-coated PVC slats). The experiment was run for six days and at harvest, all spat were counted, with the exception of spat on the under surfaces of horizontally positioned slats. Here, spat were very densely settled and numbers were estimated by counting spat in a rectangular shaped grid (10 cm^2), randomly placed on each surface.

3.3.2.5 *Statistical analysis*

For experiments 2 and 3, differences in spat density between treatments were assessed using one-way ANOVA and homogeneity of variance was evaluated using Cochran's test (Winer, 1971). Means were compared using Tukey's honestly significant differences method (Sokal and Rohlf, 1981). T-tests (Winer, 1971) were used to compare spat density on upper and under surfaces of collectors. For Experiment 2, it should be noted that any tendency towards gregarious settlement could have transgressed the assumption of independence for ANOVA (Sokal and Rohlf, 1981).

3.3.3 Results

3.3.3.1 *Experiment 1-Aquaria*

The greatest settlement was recorded from large, slurry-coated discs, where average density for the combined upper and under surfaces was 4.9 spat/cm^2 (35.8±6.1% of larvae settled; Table 3.4). Few larvae were observed swimming in this treatment 72 h after stocking. Settlement on the other eight collector types was generally low compared to discs, with spat densities ranging from 0.001 to 0.01 spat/cm^2 (Table 3.4). Spat density on collector types ranged from 22837±7726 to 4±2 spat per stack (Table 3.4).

3.3.3.2 *Experiment 2-Commercial tanks*

As in Experiment 1, large, slurry-coated discs had the greatest spat density at harvest with 17.1±1.6 spat/cm^2 on combined upper and under surfaces. Spat density was 30.6 x 10^3/replicate stack of discs (12 discs/stack) and an estimated 16.7±5.5% of larvae stocked/tank settled on each replicate stack of discs. An estimated 33.4% of total larvae/tank settling on this collector type. The majority of larvae had also settled on discs within 72 h of stocking.

Other collector types tested had much lower spat densities at harvest that ranged from 0.01 spat/cm^2 (0.03% settled) to 0.1 spat/cm^2 (0.002% settled)

(Table 3.5). There was no significant ($P>0.05$) difference in spat density between under and upper surfaces for each collector type, with the exceptions of bioresin slats and round spiky sticks with lug, which had significantly ($P<0.05$) higher spat densities on the under and upper surfaces, respectively (Table 3.5). A settlement of spat was observed on the floor of the fibreglass tanks and data are not included in the results because of the difficulty in assessing numbers.

3.3.3.3 *Experiment 3-Slurry-coating and orientation*

Surface orientation affected settlement of Sydney rock oysters on PVC slats. Settlement was significantly ($P<0.001$) higher on horizontally deployed PVC and slurry-coated PVC slats, where spat densities were 23.8 spat/cm^2 (76.6% settled) and 18.7 spat/cm^2 (60.2% settled) respectively, than on vertically deployed slats, where density was only 0.2 spat/cm^2 (0.71% settled) (Table 3.6). For horizontally positioned slats, larval settlement was first observed at day two and day four (on slats and slurry-coated slats respectively) and was completed by day six. Conversely, the majority of larvae were still swimming in aquaria containing the vertically deployed slats on day six, and few larvae settled, despite low larval mortality. No settlement was observed on perspex aquaria. Settlement was significantly higher ($P<0.01$) on the under surfaces of the horizontally deployed slats (46.2 spat/cm^2) and slurry-coated slats (35.0 spat/cm^2) than on the upper surfaces (1.2 and 2.4 spat/cm^2 respectively). Settlement was similar ($P>0.05$) for convex and concave surfaces of vertically deployed slats (0.3 and 0.2 spat/cm^2 respectively; Table 3.6).

3.3.4 Discussion

The most effective collectors for the settlement of cultured larvae in remote setting tanks and aquaria were large slurry-coated PVC discs (SCD) and aged PVC slats and slurry-coated slats. For Experiments 1 and 2, Sydney rock oyster larvae showed a clear preference for the large slurry-coated PVC discs (4.9 and 17.1 spat/cm^2 respectively) and in Experiment 3 (where these discs were not tested), excellent spat densities were recorded from slats and slurry-coated slats (23.8 and 18.7 spat/cm^2 respectively), cut from commercially used stormwater grade pipe.

Several factors including aging period and surface texture may have affected settlement on the nine collector types tested in Experiments 1 and 2, where spat densities were low. The aging period required for large PVC discs may have differed from other collector types and accounted for the higher settlement, as they were imported from France and determining the date of manufacture was difficult. Gunn (1984), found oyster settlement increased as the leaching period for collectors in water increased from nil to 12 months. Roland and Broadley (1990), recommended a minimum period in salt or fresh water of 4-8 months for PVC collectors, with the period dependent on water temperature. The benefits of aging collectors for longer periods is supported by the results from Experiment 3, where slats cut from PVC stormwater pipe and conditioned for two years, had much higher spat densities than on the more recently manufactured type of PVC slats used in Experiments 1 and 2, although, it should be noted that slats were similar in design, but of a different grade of PVC. Although surface composition and texture of the slurry covering the large PVC discs may have also accounted for the excellent settlement compared with other collector types, it does not account for the poor settlements in Experiments 1 and 2, on PVC slats coated with the same slurry mix. Although slurry-coated and PVC slats used in Experiments 1 and 2 caught relatively low numbers of oysters, similar slats aged on an intertidal lease and exposed to larvae for a longer period were later found to be effective collectors for natural settlement of Sydney rock oysters (Section 3.4).

An even distribution of spat over all collector surfaces is important for optimal use of collectors, as growth and retention of spat in the nursery phase can also be affected by spat density on collectors (Gunn, 1984). The majority of larvae in Experiment 3, settled on the under surfaces of collectors. Hopkins (1935), Schaefer (1937) and Cole and Knight-Jones (1949) concluded that higher settlement of bivalves on the under surfaces of collectors resulted from the swimming action of pediveliger larvae, as they often swim with their foot extended while searching for a suitable substrates on which to attach. Butler

(1955), concluded that *C. virginica* probably settled on the upper surfaces of collectors in a stack, after swimming into and deflecting off the collector above. In Experiment 2, where spat densities were generally much lower, spat were evenly distributed ($P>0.05$) on upper and under surfaces of collector types, with the exceptions of bioresin slats and round spiky PVC sticks with lug, which had significantly ($P<0.05$) higher settlements on under and upper surfaces respectively. Dinamani and Lenz (1974) concluded that in nature, New Zealand rock oysters (*S. glomerata* = *S. commercialis*; Buroker et al., 1979) settled on the upper surfaces of collectors when spat density on the under surfaces was high. In Experiment 3, once oysters had started settling, gregarious behaviour of larvae (Hidu and Haskin, 1971; Keck et al., 1971; Kenny et al., 1990) may have increased the difference in numbers which finally settled on upper and under surfaces. Although not examined here, layer had no effect ($P>0.05$) on settlement on 20 layers of small PVC discs (Section 3.2), when deployed in one of the 3 000 l tanks used in this study.

Excellent spat densities were recorded on large slurry-coated discs and slats and slurry-coated slats, however, densities on some surfaces were probably far too high to be efficient. Despite the apparent low densities, on the upper surfaces of slats and slurry-coated slats in Experiment 3, these may have been more commercially useful than those on the under surfaces. In Section 3.4, much higher losses of natural Sydney rock oyster spat were recorded from larger PVC slats and slurry-coated slats and slurry-coated discs (52.9%, 42.5% and 37.3% respectively), that had much lower densities (average settlement 5.8, 3.8 and 3.4 spat/cm^2 respectively) than in this section. Gunn (1984) also found that growth of Pacific oysters declined on round grooved PVC sticks (similar to those used here) when densities exceeded 300/stick. Commercial operators settling Pacific oysters, obtain between 0.3 and 0.4 spat/cm^2 on round grooved PVC sticks (Jones and Jones, 1988; Roland and Broadley, 1990).

No attempt was made to manipulate spat densities on collector types (76.6%, 60.2% and 0.7% settlement; Table 3.6), and stocking densities in Experiment 3 were high to ensure that larval numbers did not limit settlement. However, commercial operators setting Pacific oysters on PVC collectors in tanks, remote from the hatcheries, manage settlement by altering larval stocking densities (Jones and Jones, 1988; Roland and Broadley, 1990). Stocking densities are determined by using settlement and post-set survival rates and for round PVC sticks, operators often allow for settlement of about 20% of larvae stocked, post-set survival of about 14% of these at four months and about 2.5% of larvae stocked to be eventually harvested as spat (= 72 spat/2 m PVC tube) (Roland and Broadley, 1990). Spat density and distribution on PVC collectors could also be managed by flipping the stacks of collectors over on day two of settlement and by adding more larvae (Roland and Broadley, 1990).

Rate of settlement on collectors is an important indicator of viability of larvae and settlement and for Pacific oysters, settlement is usually completed within 48 h of stocking (Roland and Broadley, 1990). In Experiment 1 and 2, substantial settlements of Sydney rock oysters were observed on large slurry-coated discs at day 3 and, in Experiment 3, on slats at day 2 and slurry-coated slats on day 4. The delay in settlement on slurry-coated slats warrants further investigation as it could make them less effective as commercial collectors.

Collectors must not only facilitate settlement and retention of spat, but also allow spat to be harvested without damage. Although not examined in this section, survival of natural Sydney rock oyster spat, harvested from collector types in Section 3.4 was high (range 89.4-93.4%) 285 days after their deployment, with the exception of bioresin slats (66.8%) (Section 3.4). Many NSW farmers slurry their collectors for natural spatfall. Farmers claim that the main advantage is an easier removal of spat with less shell damage, particularly when spat densities are low. Spat are easier to harvest and the ease of removal appears to be density dependent. Other advantages are that collectors can be easily coated after harvest, thereby avoiding the often costly process of cleaning fouling from uncoated collectors. The disadvantages with slurry are that it is often difficult to separate the unwanted chips of slurry from spat at harvest and these chips can clog the fine meshes covering nursery units, restrict water circulation and reduce growth. Finding the right slurry mix that will adhere to and remain on collectors throughout settlement, yet allow spat to be harvested, is often difficult.

Large slurry-coated PVC discs, PVC slats and slurry-coated PVC slats, were found to be the most effective collectors for the settlement of Sydney rock oysters in tanks, and could be alternative substrates for hatchery and remote setting operations. PVC slats, cut from commonly-used storm water pipe, have a number of advantages over other types of PVC collectors (eg. round PVC sticks and PVC discs) as they are readily available at most hardware suppliers in Australia, and were cheaper to purchase, currently about 25% the cost of the alternative slat and other PVC collector types (round grooved PVC sticks).

TABLE 3.3

Summary of specifications for collector types used in Experiments 1 and 2 (Section 3.3)

Collector type	Surface area/ collector (cm^2)	Surface area/ replicate (cm^2)	Origin of collectors
		EXPERIMENT 1	
PVC sticks			
Flat spiky (FSS)	340	5776	New Zealand
Round spiky with lug (RSSL)	448	5824	"
Round grooved (RGS)	313	5781	"
Round spiky (RSS)	313	5781	"
Discs			
Small PVC (D)	275	5775	Spain
Slurry-coated (SCD)	1790	5370	France
Slats			
Bioresin (B)	505	5808	Australia
PVC (S)	777	5831	"
Slurry-coated (SCS)	777	5831	"
		EXPERIMENT 2	
PVC sticks			
Flat spiky (FSS)	1359	27180	
Round spiky with lug (RSSL)	1792	35840	
Round-grooved (RGS)	1250	25000	
Round spiky (RSS)	1250	25000	
Discs			
Small PVC (D)	275	5500	
Slurry-coated (SCD)	1790	21480	
Slats			
Bioresin (B)	2020	30300	
PVC (S)	3110	46650	
Slurry-coated (SCS)	3110	46650	

TABLE 3.4

Density of Sydney rock oysters *Saccostrea commercialis* on nine commercial spat collectors in aquaria (Experiment 1; Section 3.3)[a]

	Spat density at day 7		
Collector type	Per cm^2	per replicate[b] stack	Settlement[c] (%)
Large slurry-coated PVC discs (SCD)	4.9±1.0	22837±7726	35.8±6.1
Slurry-coated PVC slats (SCS)	0.1±0.01	376±64	1.0±0.1
Flat spiky PVC sticks (FSS)	0.1±0.02	291±104	0.5±0.2
Small PVC disc (D)	0.03±0.004	122±19	0.2±0.03
PVC slats (S)	0.01±0.002	56±9	0.2±0.03
Bioresin slats (BS)	0.01±0.004	36±20	0.1±0.03
Round spiky PVC sticks + lug (RSSL)	0.004±0.002	20±8	0.03±0.01
Round spiky PVC sticks (RSS)	0.001±0.0004	5±2	0.01±0.002
Round grooved PVC sticks (RGS)	0.001±0.0004	4±2	0.01±0.003

[a] Values are means±SE; n=4. Larvae were stocked at 63.8 x 10^3/aquaria (1.3/ml).

[b] Data were adjusted for surface area and are presented as spat/replicate stack.

[c] Percentage of larvae (stocked into 50 l aquaria) which settled on replicate stacks of collector types.

TABLE 3.5

Density of Sydney rock oysters (*Saccostrea commercialis*) on nine types of spat collectors in 3 000 l tanks (Experiment 2; Section 3.3)[a]

Collector type	Spat density at day 5 (cm^2) Under	Upper	Combined Surfaces	Per replicate stack	Settlement[b] (%/replicate stack)
Large slurry-coated PVC discs (SCD)	9.2±1.1	7.9±1.0	17.1±1.6	30587±2953	16.7±5.5
Bioresin slats (BS)	0.08±0.01[c]	0.03±0.004	0.11±0.01	3307±587	0.02±0.03
Flat spiky PVC sticks (FSS)	0.04±0.004	0.03±0.004	0.07±0.01	500±90	0.02±0.004
Round spiky PVC sticks + lug (RSSL)	0.01±0.001	0.03±0.004[c]	0.04±0.004	339±91	0.02±0.004
Round grooved PVC sticks (RGS)	0.01±0.001	0.01±0.001	0.02±0.001	121±21	0.01±0.001
Slurry-coated PVC slats (SCS)	0.01±0.001	0.01±0.001	0.01±0.001	671±66	0.03±0.003
PVC slats (S)	0.01±0.0004	0.01±0.001	0.01±0.001	527±133	0.02±0.01
Small PVC disc (D)	0.004±0.001	0.003±0.001	0.01±0.001	38±17	0.002±0.001
Round spiky PVC sticks (RSS)	0.005±0.002	0.003±0.0004	0.01±0.002	36±9.0	0.002±0.0004

[a] Values are means±SE; n=4. Larvae stocking density was $1.1 \pm 0.07 \times 10^6$/tank.

[b] Percentage of larvae (stocked into 3 000 l tanks) which settled on replicate stacks of collector types.

[c] Each collector type with this superscript had significantly ($P<0.05$) higher spat density for that surface.

TABLE 3.6

Settlement of Sydney rock oysters (*Saccostrea commercialis*) on horizontally and vertically positioned PVC slats in aquaria (Section 3.3; Experiment 3).[1]

Collector Type	Numbers of spat/surface			Settlement[2]	Spat density
	Upper	Under	Combined	(%)	$(cm^2)^3$
Horizontal deployment					
PVC slats[4]	174±36	6924±238	7130±281	76.6	23.8±0.9[a]
Slurry-coated PVC slats[4]	365±35	5235±292	5601±326	60.2	18.7±1.1[b]
Vertical deployment					
	Convex	Concave	Combined		
PVC slats	43±17	24±9	67±25	0.7	0.2±0.08[c]

1 Values are means±SE; n=4.
2 Percentage of larvae (stocked into aquaria) which settled on slats. Initial larval stocking density was 2.8/ml.
3 Means with the same superscript did not differ significantly (P>0.05).
4 Values for upper and under surfaces were significantly different (P<0.001).

3.4 EVALUATION OF COMMERCIALLY-USED COLLECTORS FOR NATURAL SETTLEMENT AND RETENTION OF OYSTERS

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3.4.1 Introduction

In Section 3.3, nine types of collectors were evaluated in the hatchery for the settlement of Sydney rock oyster larvae, and large slurry-coated PVC discs, PVC slats and slurry-coated slats were found to be effective collector types. In this section, the nine collector types used in the hatchery experiments and tarred timber stick, the collector type traditionally-used by the NSW industry, were evaluated for their efficiency for the collection of spat in the wild.

In Europe, North America, Australia and New Zealand, alternative substrates have been tested to increase wild settlement and retention of oysters; these included shell cultch and PVC and other synthetic collectors (His, 1978; Gunn, 1984; Curtin, 1985a, 1985b, 1985c; Holliday et al., 1988; Quayle, 1988; Quayle and Newkirk, 1989; Nell, 1993). A decline in oyster production in NSW (Maguire et al., 1988; Nell, 1993) and inadequate returns on investment (Espinas et al., 1988; Catt, 1992) have encouraged many farmers to seek alternative farming strategies including the use of various substrates to collect and grow oysters. An increasing number of NSW farmers now remove wild spat from tarred hardwood sticks and PVC collectors for culture as single seed oysters (Holliday et al., 1988; Nell, 1993).

The objectives of this segment were; 1) to compare different commercially-available collector types in terms of their efficiency for attracting and retaining wild Sydney rock oysters and Pacific oysters 2) to compare barnacles settlement on the different collector types, 3) to determine the post-harvest survival of Sydney rock oyster spat from collector types designed for single spat production, and 4) to determine which collector types were most suitable for growing attached Sydney rock oysters to market size.

3.4.2 Methods

3.4.2.1 Collectors

The ten types of oyster collectors used for this study had been designed and manufactured for collection and subsequent removal of spat for single seed culture (single spat collectors) and/or for collecting and growing attached spat to market size. Those used for single spat collection were: small PVC discs (D), slurry-coated PVC discs (SCD), bioresin slats (BS), PVC oyster slats (S), slurry-coated PVC oyster slats (SCS) and tarred hardwood sticks (TS). It should be noted that PVC and slurry-coated PVC slats were specially manufactured as oyster collectors and were not cut from commercial grade water pipe as in Section 3.2 (Experiment 3). The types used for growing attached spat were; flat spiky PVC sticks (FSS), round spiky PVC sticks with a lug (RSSL), round grooved PVC sticks (RGS), round spiky PVC sticks (RSS) and tarred sticks (TS) (Section 2.1.3; Table 2.1). As practised commercially, all collectors were conditioned (Section 2.1.4) by deploying them on an intertidal lease a month prior to the start of settlement. Each collector type was deployed in stacks using a similar format (Table 2.1) to that used by commercial farmers (Korringa, 1976; His, 1978; Gunn, 1984; Jones and Jones, 1988; Quayle, 1988; Quayle and Newkirk, 1989; Roland and Broadley, 1990; Nell, 1993).

3.4.2.2 Experiment 1 - Sydney rock oysters

Settlement and spat retention - Ten types of collectors were deployed in the middle of a commercially-used, intertidal spat catching area in Salamander Bay (Korringa, 1976; Figs. 1.2A; 2.6, 2.8). The collectors consisted of four types of PVC sticks (FSS, RSS, RSSL, and RGS), three types of slats (BS, S, SCS), two types of PVC discs (D and SCD), and tarred sticks (TS). Replicate stacks for the ten types of collectors were deployed in January, the beginning of the commercial spat catching season (Wisely et al., 1979b; Holliday and Goard, 1986). For each treatment, five replicate stacks of collectors were secured by wire to a commercial-used timber post and rail oyster rack, oriented perpendicular to the shore. The 50 m section of rack used on the lease was about 80-130 m from the Indian Spring High Water (ISHW) beach mark. Each replicate stack was randomly allocated to a position along the timber rack and the bottom layer of each stack of collectors occupied a similar vertical intertidal position (range 0.7-0.9 m above Indian Spring Low Water [ISLW]) to that traditionally used for natural catch on tarred sticks (Thomson, 1954; Korringa, 1976).

Spat density and retention were estimated by counting the number of spat contained in a grid (10 cm^2) which was placed in a randomly allocated position on both the upper and under surfaces of each collector in each replicate stack. Data for the upper surface of the top layer and the under surface of the bottom layer of each replicate stack were excluded from analyses as the spat on these surfaces were subject to predation by fish.

Post-harvest survival of spat - Oysters collected in the above program were harvested from the six types of single spat collectors (D, SCD, S, BS, SCS and TS), 271 days after deployment. With the exception of tarred sticks (TS), a layer was randomly selected from each of the five replicate stacks of collectors per treatment and all spat were harvested as described in Section 2.1.6. For tarred sticks (TS), spat were harvested from four sticks from each of the five randomly selected layers per replicate. Spat from each replicate group (n=5) for each treatment were randomly allocated to one of six internal sections (each 0.25 m^2) of five nursery tray (1.82 x 0.94 m timber frame with 1.7 mm PVC mesh on upper and under surfaces; Section 2.3.1.2; Fig 2.14). Enough spat to cover up to 50% of the bottom surface of each internal tray section were used. Trays were randomly allocated a position along the same timber rack previously used for settlement (Section 3.4.2.2). Post-harvest survival was estimated by counting live and dead spat from each replicate section 14 days after spat were removed from collectors.

Retention and growth of market size oysters - After spat had settled, the stacks of collectors (FSS, RSS, RSSL, RGS and TS) were broken up into single layers for the grow-out phase, following normal practice by oyster farmers (Korringa, 1976; Malcolm, 1987). For each collector type, there was no significant difference ($P>0.05$) in the number of spat on sticks from different layers when deployed. The sticks were transferred from Port Stephens to an intertidal growing area in Empire Bay, Brisbane Waters (Fig 2.10).

As the seaward end of Empire Bay (about 500 m from Indian Spring High Water Mark) was subjected to wave action which may have affected retention of oysters on the collectors, the timber rack (60 m) which was perpendicular to the foreshore, was divided into two zones, inshore and offshore (split plot design). Here each replicate consisted of four sticks (a layer from the settlement phase of the experiment). Ten replicates for each type of collector were randomly allocated to a position in each zone on the lease. Top and bottom layers from each stack, which may have been affected by predation by fish during the settlement phase, were not sampled. Collectors were nailed along the post and rail lease at the growing height (about mid tidal range) used by commercial oyster farmers. PVC slats (S) were randomly allocated to positions along the rail, to observe any overcatch. To avoid losses of spat from heat stress during intertidal exposure (Potter and Hill, 1982) and from predation by fish (Korringa, 1976), all sticks were encased in shade cloth (3 mm PVC mesh) as practised by many farmers.

For the five types of collectors, spat density was estimated three times (approximately every 6 months) by counting all oysters from both surfaces of sticks from two randomly selected replicates in each zone. Retention on upper and under surfaces was not separated as oysters tended to grow around the sticks. Because the types of sticks had different surface areas, data are expressed as number of oysters/10 cm^2. To avoid future losses which may have been attributed to handling, collectors were discarded after counting. Size was determined at harvest (day 843) by randomly selecting six of each type of growing collector from each zone, removing all the oysters and measuring the shell lengths of 100 oysters/stick, chosen at random from each collector.

3.4.2.3 Experiment 2 - Pacific oysters

All of the types of collectors used in Experiment 1, with the exception of slurry-coated slats (SCS), were evaluated as substrates for settlement of Pacific oysters. For each collector type, four replicate stacks were randomly allocated a position along a timber rack set perpendicular to, and 50 m from the foreshore (ISHW mark), on a lease in the inner harbour of Port Stephens, Tanilba Bay (Fig 2.8). Collectors were deployed in November the same format used in Experiment 1 (described in Table 2.1) and occupied a similar vertical intertidal position (range 0.65-0.85 m above ISLW) to that used for growing Sydney rock oysters.

As spat density was much lower than in Experiment 1, all spat on the upper and under surfaces on all collectors were counted (at day 187), except tarred sticks (TS). For tarred sticks (TS), settlement was determined by counting all spat on four randomly selected sticks from each layer in each replicate stack. The top and bottom layers of each stack of collectors were again excluded from analyses. An assessment of post-harvest survival of spat removed from collectors and further studies on growth of Pacific oysters were not possible because of the introduction of a policy aimed at the eradication of Pacific oysters from Port Stephens and other NSW estuaries (Holliday and Nell, 1987; 1990; Nell, 1993).

3.4.2.4 Statistical Analyses

Homogeneity of variance was confirmed using Cochran's Test (Winer, 1971). For each experiment, differences among collector types were assessed using ANOVA. For Experiment 1, differences in the number of spat which settled on the upper and under surfaces of each collector type were compared separately using paired *t*-tests. Data for both surfaces were then combined and one-way ANOVA was used to assess the effect of collector type on density and retention. Means were compared using Tukey's honestly significant differences method (Sokal and Rohlf, 1981). For Experiment 1, retention data were transformed (arcsine $x^{0.5}$) prior to analyses and linear regression used to examine the relationship between spat density at day 127 and percentage loss at day 271.

The variances for post-harvest survival data were heterogeneous after transformation (arcsine $x^{0.5}$), therefore ANOVA and multiple range analyses were conducted using a lower level of significance ($P<0.01$), as recommended by Underwood (1981). A one-way ANOVA was used to determine if the number of spat per collector type was affected by layer. Two-way ANOVA was used to determine if zone, collector type or the interaction between zone and collector type were significant. As zone was not significant and there was no interaction between collector type and zone ($P>0.05$), data from zones were combined and reanalysed using one-way ANOVA. Data from growing sticks were analysed using covariance analysis to assess effects of density on growth.

3.4.3 Results

3.4.3.1 Experiment 1 - Sydney rock oysters

Settlement and spat retention - Settlement was extremely high from January to July (172 days) and spat density was very high on all collector types; PVC collectors generally caught far more oysters than the traditionally used tarred sticks (Table 3.7). Spat density was higher ($P<0.05$) on five types of PVC collectors (D, RSS, RGS, RSSL and S; 49.3±3.0 spat/10 cm^2, n=25, replicate stacks, and bioresin slats, (BS, 43.6±4.0 spat/10 cm^2, n=5 replicate stacks) than on tarred sticks (TS, 14.5±3.1 spat/10 cm^2, n=5 replicate stacks), (Table 3.7). Of the PVC collectors, flat spiky sticks (FSS) caught the lowest number of spat (21.5±3.4 spat/10 cm^2).

Spat density varied greatly between the upper and under surfaces of some of the collector types (Table 3.7; Fig 3.3). In general, spat were evenly distributed ($P>0.05$) across the upper and under surfaces of collectors which had larger concave (downward facing) surface areas. These collectors included small PVC discs (D diam. 140 mm; Fig 3.5), large slurry-coated PVC discs (SCD, diam. 355 mm; Fig 3.6), PVC slats (S; width 104 mm; Fig 3.7) and slurry-coated PVC slats (SCS; width 104 mm). Although having reasonably large surface areas, spat densities were lighter ($P<0.001$) on the flat upper surfaces of bioresin slats (BS, width 100 mm) and flat spiky PVC sticks (FSS, width 50 mm), (Table 3.7). Round spiky PVC sticks with lug (RSSL, diam. 38 mm) also had a relatively high settlement on the upper surfaces (Table 3.7). Other collector types with smaller surface areas (RGS, RSS [Fig 3.3], TS; range 20-22 mm width/diam.) also had poor spat densities ($P<0.001$) on the upper surfaces (Table 3.7). By far the highest density of barnacles ($P<0.05$) was recorded from the under surfaces of tarred sticks (TS). In contrast, no barnacles colonised slurry-coated discs (SCD), (Table 3.7).

Post-harvest survival of spat - Post-harvest survival (at day 14) was high and similar ($P>0.05$) for spat removed from tarred sticks (TS, 89.4±1.4%), slurry-coated discs (SCD, 92.0±1.2%), slurry-coated slats (SCS, 92.2±0.6%), slats (S, 93.4±1.9%) and discs (D, 91.8±1.7%). Post-harvest survival was lower ($P<0.001$) for spat removed from bioresin slats (BS, 66.8±6.2%) as spat were often damaged where they attached to the collector.

Retention of spat and growth of market size oysters - At harvest (day 843), tarred sticks (TS) had the lowest density ($P<0.05$) of Sydney rock oysters (0.8±0.03/10 cm^2, n=4 replicate layers) and the three types of round PVC sticks (RSS, RSSL, RGS) had the highest oyster density ($P<0.05$; 2.5±0.1 spat/10 cm^2, n=12 replicate layers), (Table 3.8; Fig 3.4).

Greater numbers of spat ($P>0.05$) were retained at day 271 on four types of PVC collectors (SCD, D, RSS [Table 3.7; Fig 3.4] and S; 22.1±1.4 spat/10 cm^2, n=20 replicate stacks) than on tarred sticks (TS, 8.9±1.5 spat/10 cm^2, n=5 replicate stacks). There was a direct relationship ($P<0.001$) between oyster density at day 127 and spat losses between days 127 and 271. The percentage loss of spat ranged from 31.7±10.6% from tarred sticks (TS) to 69.1±2.6% from round grooved sticks (RGS; Table 3.7). The pattern of spat loss from collector types varied over the 843 day experiment, with particularly high spat losses recorded at day 271 from those PVC collectors with high initial spat densities (RSS, RSSL and RGS) than from tarred (TS) and flat PVC (FSS) sticks (Table 3.8; Fig 3.8). Although there were differences in net spat losses from all collector types between days 271-477, 477-645 and 645-843, they were not as severe (Table 3.8; Fig 3.4).

Tarred sticks (TS) were heavily infested with marine borers and fractured when handled. PVC sticks remained intact and were easily collected from the lease without damage. With the exception of the round spiky PVC stick with lug (RSSL), all types of sticks were damaged when removing oysters at harvest. Sydney rock oysters were firmly attached to FSS, RSS RGS sticks and their shells and or the sticks fractured when attempting to separate the two.

Shell length at harvest was similar ($P>0.05$) from all types of sticks (TS, FSS, RGS, RSS, RSSL; range 47.9-53.6 mm/oyster, n=48 replicate sticks) with the exception of round grooved PVC sticks (RGS; 45.2$\pm$1.4 mm/oyster, n=12 replicate sticks), that had significantly ($P<0.05$) lower shell lengths than tarred sticks (Table 3.8). An analysis of covariance of length data showed that density had no effect on growth. Collector type affected percentage loss ($P<0.05$) between days 127 and 843, although, the differences were relatively minor (Table 3.8). There was no oyster settlement (overcatch) on the PVC slats (S) during this phase of the experiment.

3.4.3.2 *Experiment 2 - Pacific oysters*

The settlement period of Pacific oysters was from November to May (187 days). The density of Pacific oysters on collectors was much lighter than Sydney rock oysters in Experiment 1 (Table 3.9). For combined upper and under surfaces, spat density ($P<0.001$) was higher on three types of PVC collectors (SCD, RSS and D; 1.3$\pm$0.05 spat/10 cm^2, n=12 replicate stacks), than on tarred sticks (TS), PVC slats (S) and bioresin slats (BS), (0.3$\pm$0.01 spat/10 cm^2, n=12 replicate stacks; Table 3.9). Density of Pacific oysters was heaviest ($P<0.05$) on the under surfaces of tarred (TS) and round spiky sticks

(RSS) and on the upper surfaces of PVC slats (S) and discs (D) (Fig 3.3). For the rest of the collector types, there were no differences (P>0.05) in density between upper and under surfaces (Table 3.9). No barnacle settlement was detected.

3.4.4 Discussion

Exceptionally high settlement of Sydney rock oysters was recorded on all collector types during this study, when compared with previous studies in Salamander Bay (Holliday 1985; Holliday and Goard, 1986). However, the intensity of settlement of Sydney rock and Pacific oysters can differ between years (Dinamani, 1978; Holliday and Goard, 1986) and between estuaries. Those collector types on which lower numbers of spat settled in this study may not have had commercially acceptable settlement had spatfall been lighter.

With the exception of flat spiky sticks (FSS), PVC and slurry-coated PVC collectors proved to be very effective collectors for the settlement of Sydney rock and Pacific oyster and poor collectors for barnacles. Tarred sticks had the lowest spat density. Competition on tarred sticks from barnacles probably affected spat settlement and accounted for some of the spat losses, as settlement was higher than that of Sydney rock oysters and more intense on this collector (17.8/10 cm^2). Barnacles settle in a similar period to Sydney rock oysters (Holliday 1985; Holliday and Goard, 1986) and can compete for settlement space (Butler, 1955; Ling, 1970). Another possibility for the lower spat density on tarred sticks is that the release of potentially toxic hydrocarbons from coal tar pitch covering the sticks (Pope, 1987), may have affected settlement.

Gunn (1984) reported natural catches of Pacific oysters in British Columbia on round grooved PVC sticks deployed intertidally and subtidally, although his attempt at a comparative assessment of a number of test materials was unsuccessful due to a poor natural spatfall (range 0-1 spat/10 cm^2). Heavy natural catches (42 spat/10 cm^2) of Pacific oysters on PVC, two weeks after deployment in New Zealand were reported by Curtin (1985b).

Initial spat densities at day 127 had an effect (P<0.001) on the high losses of spat (range 31.7-69.1%) recorded from all collectors at day 271. As spat grew, competition for surface area was probably a contributing factor for the high losses. Sydney rock oysters were evenly distributed on the upper and under surfaces of collectors which had large concave (downward facing) surfaces. These surfaces facilitated shading of the underlying layers without creating conditions conducive to a buildup of silt on the upper surfaces. Collectors with flat surfaces, such as tarred sticks, bioresin slats and flat spiky PVC sticks, had poor settlement on their upper surfaces, possibly because of the accumulation of silt.

Previous studies have concluded that many factors affect the settlement of bivalves on the upper and under surfaces of a substratum including siltation, current, gregariousness, light, colour, type of surface and swimming position of the larvae (Galtsoff, 1964). Thompson (1954), who found that settlement of Sydney rock oysters was more intense on the under surfaces of flat fibro cement slate, concluded that light and siltation on the upper surfaces affected settlement. Dinamani and Lenz (1974), also mention the effects of siltation on flat substrates and found that New Zealand rock oysters settled mainly on the under surfaces, although larvae began to settle on the upper surface when the spat density on the under surfaces was high.

Collectors for Pacific oysters were deployed in a more estuarine site than that used for Sydney rock oysters (Fig 2.8), and the accumulation of silt on collectors was more likely to have been a problem than at the latter site. Even so, the relative differences, between upper and under surfaces, for settlement rates were much smaller than for Sydney rock oysters. For example, settlement rates for Sydney rock oysters on round spiky sticks (RSS) were more than ten times higher on the under surface compared to the upper surface, yet for Pacific oysters, the difference was only about two fold. This may indicate a difference between species in terms of relative settlement preference for upper and under surfaces. With the exception of a study by Schaefer (1937), previous studies have recorded heavier settlement of Pacific oysters on upper surfaces of collectors (Miyazaki, 1938; Sayce and Larson, 1965; Shaw, 1967; Sayce and Tufts, 1968). Except for tarred sticks, the trends were consistent across both oyster species, with similar settlement patterns on upper and under surfaces of most collector types (Fig 3.3).

The lower post-harvest survival of spat removed from bioresin slats (66.8%; Experiment 1) demonstrates the importance of the surface composition of collectors for single seed culture. Collectors must not only facilitate settlement and retention of spat, but enable harvesting of spat without damage. It is also advantageous to be able to harvest the spat without damaging the collector. The optimal time to harvest spat from collectors is when the majority have shell diameters large enough to be retained by the mesh covering the nursery growing units. In NSW, the common nominal mesh size used on sectionalised nursery trays (Section 4.1) and PVC cylinders is 3.0 mm (Section 4.2). The use of smaller mesh sizes may lead to problems caused by inadequate water flow and fouling (Lucas and Gerard, 1981).

The cost of seed is an important consideration when formulating a management strategy for the farm. In this study, seed cost (A$) was estimated at 0.08^{c}/spat (> 3.0 mm), based on settlement, retention and post-harvest survival for Sydney rock oysters on PVC slats (174×10^{6} spat/ha) and total costs to establish and operate the lease ($145 000/ha). The cost of this wild seed was estimated at one twenty fourth that of hatchery seed (based on average cost of similar size seed from the Tasmanian and NSW oyster hatcheries; 1.9^{c}/spat). Using the above, a hectare of lease from this study could produce more than the total annual oyster production for NSW (initial spat 144×10^{6}); production and lease costs were estimated based on capital and operating costs from the catching lease used in this experiment.

The most effective collector for growing Sydney rock oysters (Experiment 1) was the round spiky PVC stick with lug (RSSL), as this stick retained large numbers of oysters compared with other collector types (Figs 2.5, 3.8), and these could be harvested without damaging either oysters or sticks. As this is the first attempt to monitor oysters on sticks from settlement to market size, little quantitative information is available on losses of oysters from tarred sticks or growth rates during the traditional three-year grow-out period. However, high losses (95%) have been reported from tarred sticks (Holliday, 1985; Holliday and Goard, 1986) with average yields of only 30-50 (about 45 g) oysters/stick (Holliday et al., 1988). In this segment, the high oyster losses from collectors during grow-out has been attributed to settlement density, intraspecific competition for surface area and surface texture of the stick. However, despite the lighter settlement, tarred sticks exhibited similar loss rates to other collector types and indicated that regardless of intensity of spat settlement, final retention of oysters is affected by the capacity of the collector type to hold oysters. Factors attributed to higher retention rates on PVC sticks (RSSL, FSS, RSS and RGS) include surface texture (spiky and grooved surfaces) of sticks, higher settlements on upper surfaces and more even distribution of spat on collectors; shape and composition may have affected this settlement and distribution of spat.

Although an analysis of covariance at harvest showed density had no effect on spat growth, spat settlement on all collectors was high compared with a previous spatfall (Holliday and Goard, 1986), even better growth may have been obtained on all collector types with lower densities at settlement. Conversely, Jarayabhand and Newkirk (1989) found that with increasing stocking densities of European oysters on cultch, specific growth rates decreased, particularly for smaller oysters. Gunn (1984), also found that growth of Pacific oysters declined on round grooved PVC sticks, similar to those used in the present study, when densities climbed above 300 oysters/stick (0.24 oysters/cm^2). Hadley and Manzi (1984) concluded that food was the growth limiting factor for mussels (*Mercenaria mercenaria*) stocked at a range of densities.

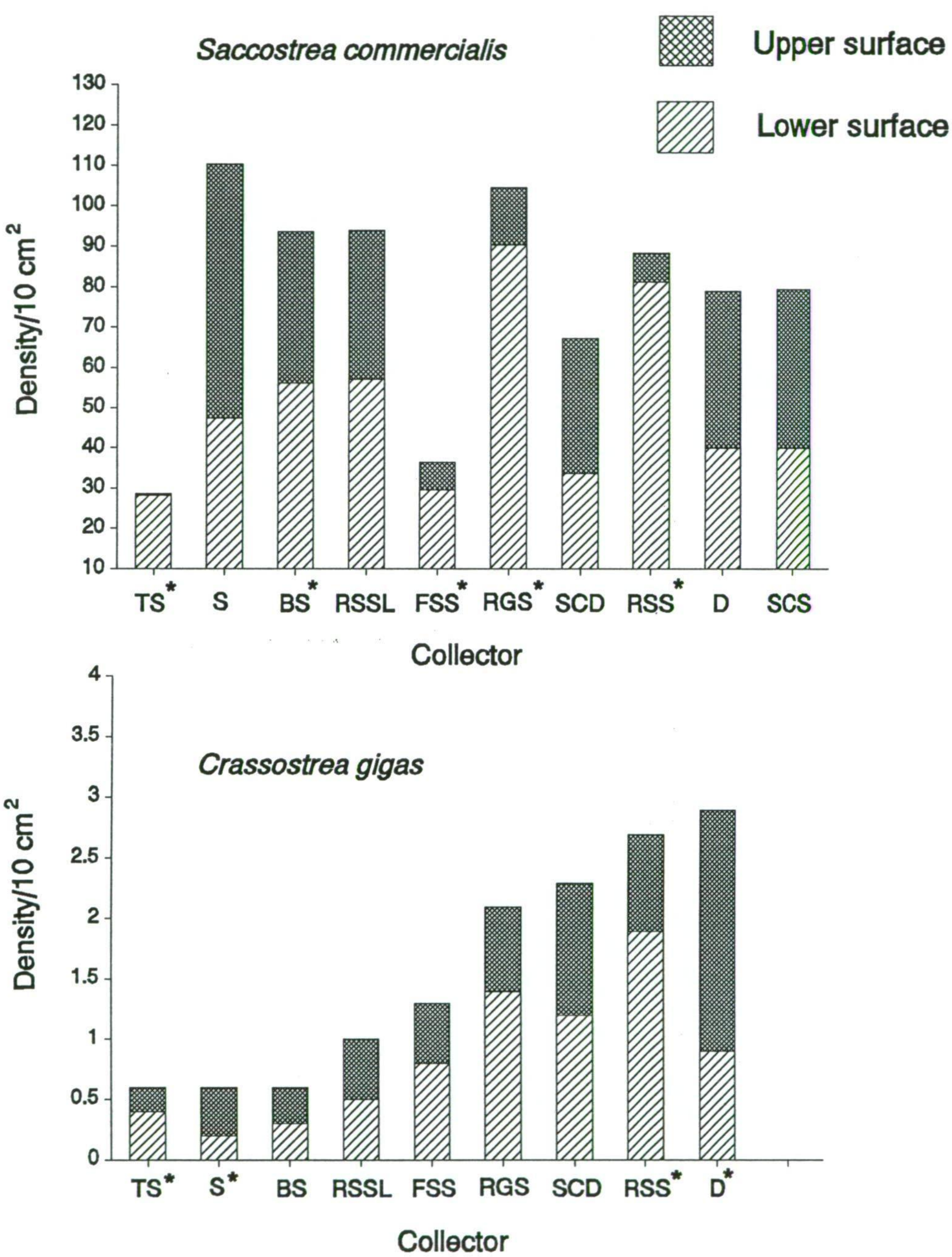
In this segment, spat densities for both Sydney rock and Pacific oysters were lower on tarred sticks than on PVC sticks. Tarred sticks were so heavily infested with marine borers that they fractured when harvested and were not reusable. Thus, the traditionally used tarred hardwood stick, which are becoming more difficult to acquire, have a lower productivity and shorter functional life than most PVC collectors tested. For PVC sticks, the higher initial costs (approximately double those of tarred sticks at the time of the study) may be compensated for by the increased life of the sticks. However, it should be noted that some types of PVC collectors were destroyed when oysters were removed at harvest. Shape, composition and surface texture of the collectors probably affected oyster and barnacle settlement and retention and subsequent growth of oysters to market size. Retention is ultimately determined by the collectors capacity to hold oysters. PVC collectors were the best for Sydney rock oyster spat production, while round spiky PVC sticks with lug proved to be the best of the PVC collectors for growing and harvesting market grade oysters. For Pacific oysters, PVC discs and sticks, with or without a slurry coating, were the best natural spat collectors. Results from this study also indicate that wild spat may be far cheaper than that from hatcheries, and farmers who used PVC collectors could require far less lease space than those who use timber sticks to collect spat.

TABLE 3.7 Density of Sydney rock oysters, *S. commercialis* and barnacles, on ten commercial spat collector types in Salamander Bay, Port Stephens, January to November (Experiment 1; Section 3.4).[1]

	Spat density at day 127 (July) (spat/10 cm^2)			Spat density at day 271 (spat/10 cm^2)	Spat losses[2] at day 271 (%)	Barnacle density at day 127 (spat/10 cm^2)
Collector type	Under	Upper	Combined[3]	Combined[3]	Combined[3]	Combined[3]
Tarred stick (TS)	28.2±5.3[a]	0.4±0.2[a]	14.5±3.1[a]	8.9±1.5[a]	31.7±10.6[a]	17.8±2.8[a]
Flat spiky stick (FSS)	29.5±3.3[ab]	7.0±2.0[ab]	21.5±3.4[ab]	13.0±1.7[ab]	36.3±7.4[ab]	0.3±0.1[de]
Slurry-coated disc (SCD)*	33.7±2.2[ab]	33.5±4.5[c]	33.6±2.9[abc]	21.3±2.9[bc]	37.3±5.1[ab]	0[e]
Slurry-coated slat (SCS)*	33.9±4.2[ab]	39.6±5.0[c]	37.5±3.7[abc]	20.0±1.9[abc]	42.5±11.0[ab]	6.1±0.5[b]
Disc (D)*	39.9±2.1[ab]	39.1±4.1[c]	39.5±3.0[bc]	26.1±3.2[c]	35.9±5.6[ab]	2.5±1.0[bcd]
Bioresin slat (BS)	56.1±5.5[abcd]	37.4±4.0[c]	43.6±4.0[bc]	21.5±2.8[bc]	51.7±4.6[ab]	0.2±0.1[de]
Round spiky stick (RSS)	81.3±12.4[cd]	7.0±3.0[ab]	44.7±5.4[bc]	16.8±2.0[abc]	60.3±6.4[ab]	3.8±1.1[bc]
Round grooved stick (RGS)	90.3±11.5[d]	14.1±5.0[b]	51.8±6.4[c]	16.3±2.9[abc]	69.1±2.6[b]	0.8±0.3[cde]
Round spiky stick with lug (RSSL)*	57.0±5.7[bcd]	36.9±8.6[c]	53.0±8.7[c]	20.0±3.1[abc]	56.9±9.1[ab]	1.4±0.6[cd]
Slat (S)*	47.4±6.5[abc]	62.9±8.9[c]	57.5±7.9[c]	26.0±2.6[c]	52.9±5.5[ab]	0.3±0.2[de]

[1] Values are means±SE, n=5. Within each column, means with a common superscript are not significantly different (P>0.05).
[2] Data were transformed (arcsine $x^{0.5}$) prior to ANOVA and multiple range analyses.
[3] Values are average spat densities from combined surfaces of collector types.
* Collector types with this superscript had similar (P>0.05) spat densities/10 cm^2 (at day 127) on under and upper surface.

Fig 3.3 Settlement of Sydney rock (*S. commercialis*) and Pacific oysters (*C. gigas*) on the upper and under surfaces of various collector types, January to July and November to June respectively (Experiments 1 and 2; Section 3.4).



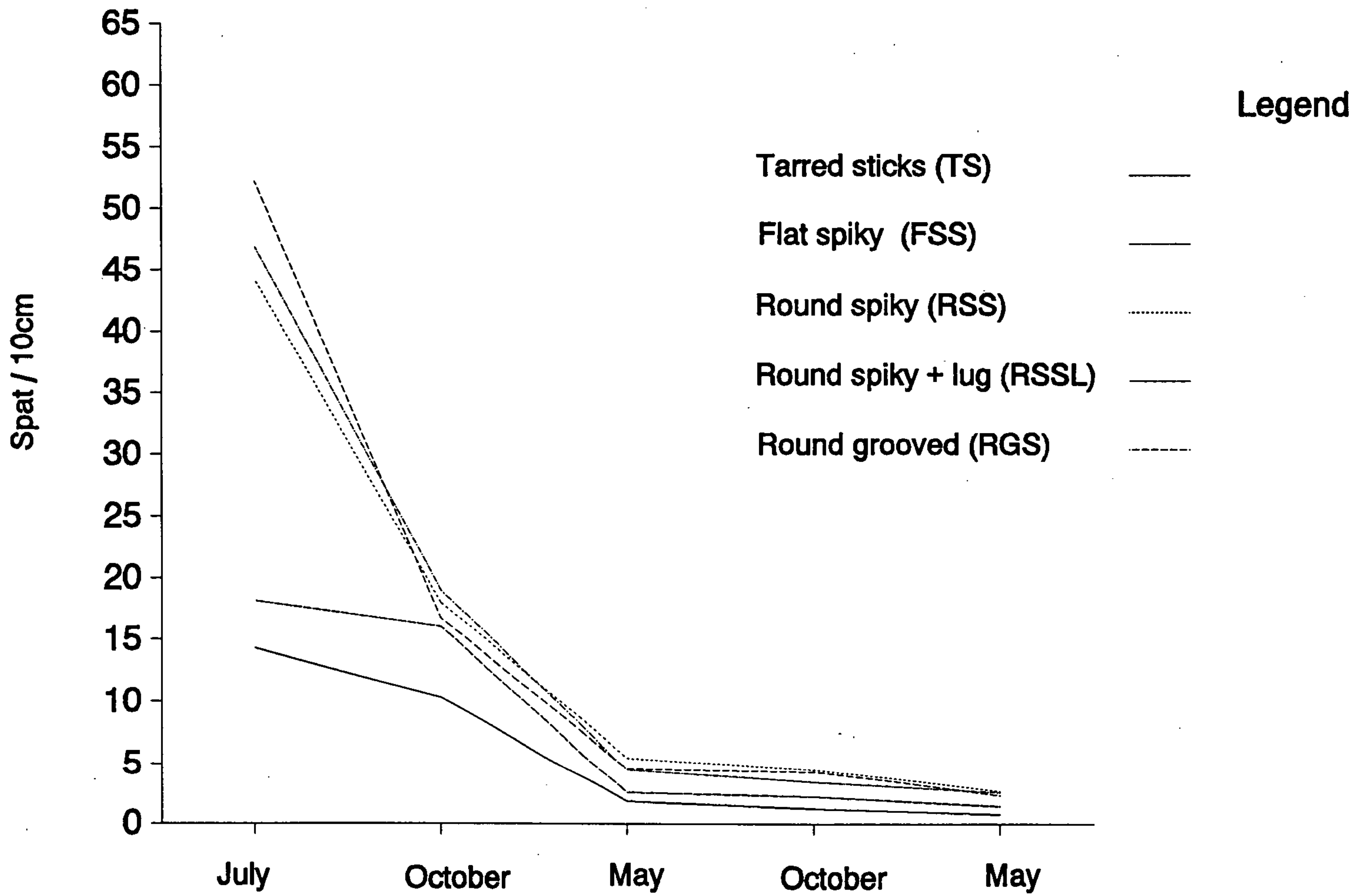
* significantly different (P<0.05) catch/surface.

TABLE 3.8 Retention, loss and growth of Sydney rock oysters (*S. commercialis*) from five types of growing sticks in Salamander Bay, Port Stephens and Empire Bay, Brisbane Waters, July to May (Experiment 1; Section 3.4)

	Spat Retention (spat/10 cm^2)						
Collector type	July[1] (day 127)	November[1] (day 271)	May[2] (day 477)	October[2] (day 645)	May[2] (day 843)	Net Loss[2,3] (%)	Shell length[2] at day 843 (mm)
Tarred stick (TS)	14.5 ± 3.1^{a}	8.9 ± 1.5^{a}	1.8 ± 0.2^{a}	1.2 ± 0.1^{a}	0.8 ± 0.03^{a}	95.0 ± 1.2^{ab}	53.6 ± 1.4^{a}
Flat spiky PVC stick (FSS)	21.5 ± 3.4^{ab}	13.0 ± 1.7^{ab}	2.5 ± 0.2^{a}	2.2 ± 0.2^{b}	1.4 ± 0.1^{b}	96.5 ± 0.8^{b}	47.9 ± 1.4^{ab}
Round spiky PVC stick (RSS)	44.7 ± 5.4^{c}	16.8 ± 2.0^{ab}	5.5 ± 0.4^{b}	4.5 ± 0.2^{d}	2.6 ± 0.2^{c}	92.6 ± 0.9^{a}	49.4 ± 0.7^{ab}
Round spiky PVC stick with lug (RSSL)	53.0 ± 8.7^{c}	20.0 ± 3.1^{ab}	4.5 ± 0.2^{b}	3.4 ± 0.1^{c}	2.5 ± 0.1^{c}	93.2 ± 0.6^{ab}	48.1 ± 1.0^{ab}
Round grooved PVC stick (RGS)	51.8 ± 6.4^{c}	16.3 ± 2.9^{ab}	4.6 ± 0.3^{b}	4.3 ± 0.1^{d}	2.3 ± 0.1^{c}	95.2 ± 0.2^{ab}	45.2 ± 1.4^{b}

1 Values are means±SE; n=5. Within each column, means with a common superscript are not significantly different (P>0.05)
2 Values are means±S; n=4. Within each column, means with a common superscript are not significantly different (P>0.05)
3 Oyster losses from day 127 to day 843. Data were transformed (arcsine $x^{0.5}$) prior to ANOVA and multiple range analyses.

Fig 3.4 Loss and retention of Sydney rock oysters (*S. commercialis*) from five types of growing sticks, when deployed in Salamander Bay and Empire Bay, NSW (Experiment 1; Section 3.4).



Legend
Tarred sticks (TS)
Flat spiky (FSS)
Round spiky (RSS)
Round spiky + lug (RSSL)
Round grooved (RGS)
Spat / 10cm
65
60
55
50
45
40
35
30
25
20
15
10
5
0
July
October
May
October
May

TABLE 3.9

Density of Pacific oysters (*Crassostrea gigas*) on nine types of commercial collectors in Tanilba Bay, Port Stephens, NSW, at day 203 (Experiment 2; Section 3.4), November to June[1].

	Spat density/10 cm^2		
Collector type	Under	Upper	Combined[2]
Tarred stick (TS)	0.4±0.1[a]	0.2±0.1[a]	0.3±0.02[a]
Slat (S)	0.2±0.1[a]	0.4±0.1[ab]	0.3±0.02[a]
Bioresin slat (BS)[*]	0.3±0.1[a]	0.3±0.1[ab]	0.3±0.01[a]
Round spiky stick with lug (RSSL)[*]	0.5±0.1[ab]	0.5±0.1[bc]	0.6±0.07[ab]
Flat spiky stick (FSS)[*]	0.8±0.3[abc]	0.5±0.2[ab]	0.6±0.23[ab]
Round grooved stick (RGS)[*]	1.4±0.3[cd]	0.7±0.1[abc]	1.0±0.21[ab]
Slurry-coated disc (SCD)[*]	1.2±0.1[bcd]	1.1±0.1[c]	1.2±0.06[b]
Round spiky stick (RSS)	1.9±0.1[d]	0.8±0.1[bc]	1.4±0.06[b]
Disc (D)	0.9±0.1[abc]	2.0±0.3[d]	1.4±0.12[b]

1 Values are means±SE, n=4. Within each column, means with a common superscript are not significantly different (P>0.05).

2 Values are average spat densities from combined surfaces (under or upper) of collector types.

* Collector types with this superscript showed no significant difference (P>0.05) in numbers of oysters/10 cm^2 settled between upper and under surface.

Fig 3.5 Sydney rock oyster (*S. commercialis*) spat caught on small, PVC discs (D) deployed in Salamander Bay, NSW (Experiment 1; Section 3.4). Note the lack of spat in the centre (under surface) of the disc, probably caused by the accumulation of air bubbles, trapped with rising tides.

Fig 3.6 Sydney rock oyster (*S. commercialis*) settlement on the under surface of a slurry-coated large, PVC disc (SCD), deployed in Salamander Bay, NSW (Experiment 1; Section 3.4). Note the two small holes to release trapped air bubbles.

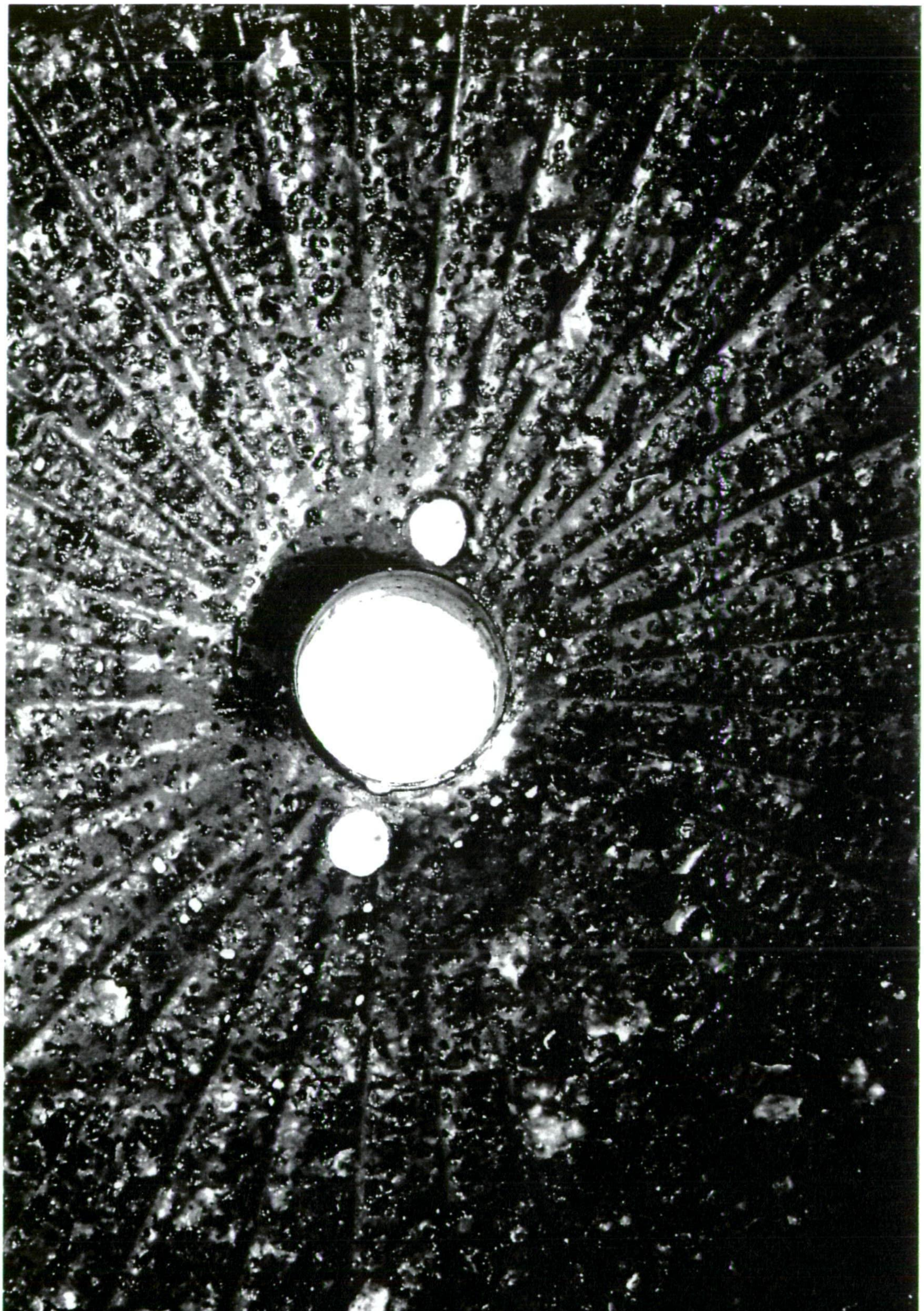


Fig 3.7 Sydney rock oyster (*S. commercialis*) spat caught on the under surface of PVC slats (S), deployed in Salamander Bay, NSW (Experiment 1; Section 3.4).

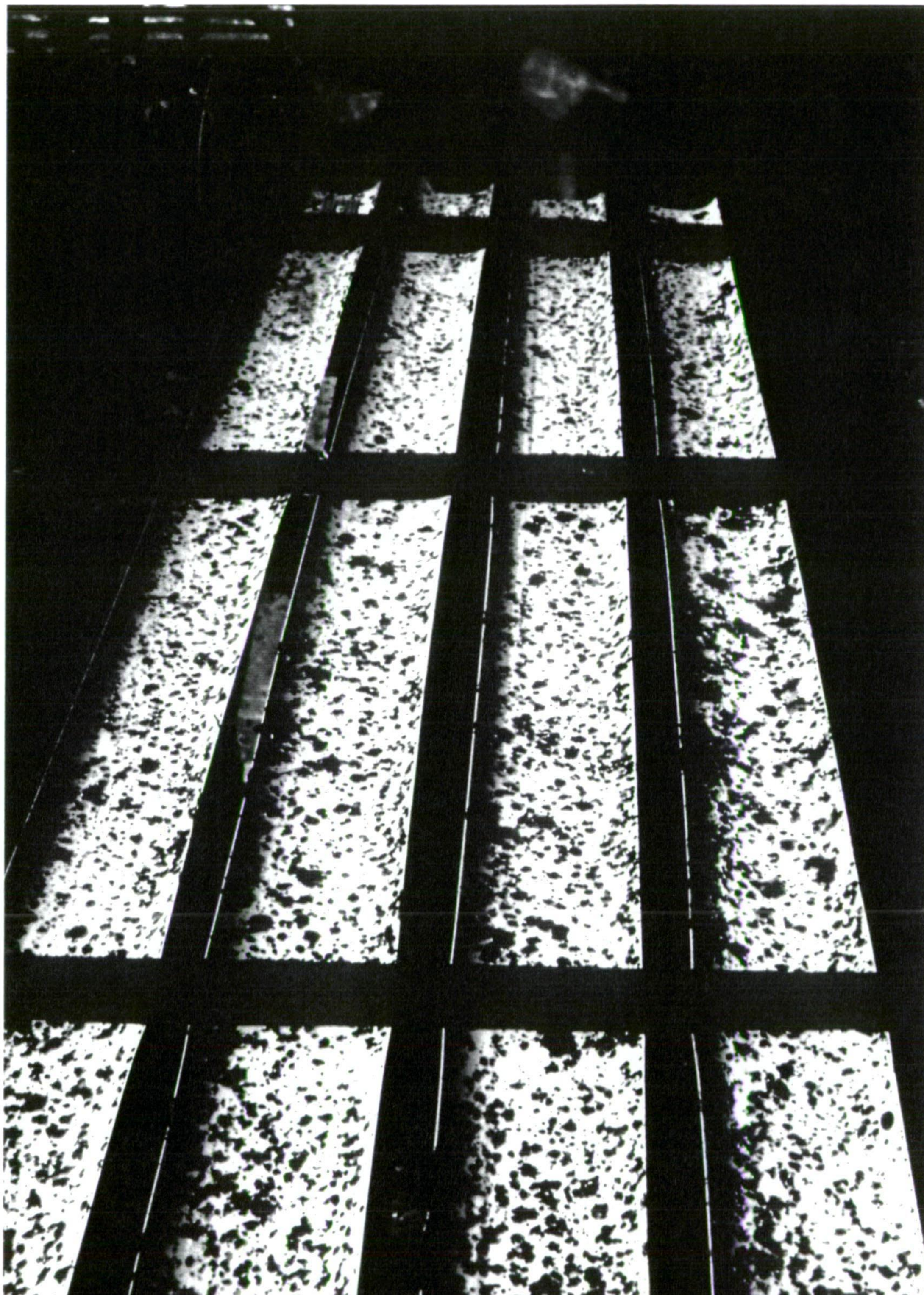


Fig 3.8 From left, a tarred, hardwood stick (TS); round, spiky, PVC stick with lug (RSSL) and flat, spiky stick (FSS) with Sydney rock oysters (*S. commercialis*) retained near harvest. Note the areas on the tarred stick devoid of oysters (Experiment 1; Section 3.4).

CHAPTER 4

STOCKING DENSITY

4.1 OPTIMUM STOCKING DENSITY FOR OYSTERS IN SECTIONALISED TRAYS *[Published (1991), **Aquaculture** 96: 7-16]*

4.1.1 Introduction

In recent years the development of hatchery techniques and modifications to collection methods that allowed natural spat to be removed and grown as single seed oysters (Chapter 3) have made the culture of unattached (single seed) Sydney rock oysters commercially possible (Holliday et al., 1988). A number of different nursery units including trays were developed for the production of single seed oysters (Neudecker, 1981; Spencer and Gough, 1978; Spencer, 1985, Spencer et al., 1978, 1992; Quayle, 1988; Section 1.3). The nursery phase in single seed culture usually requires different production units and handling methods to those used for growing oysters (Claus, 1981). Compared with oysters produced using traditional methods, single seed oysters are less likely to grow together and hence mortalities and labour costs associated with separating oysters are greatly reduced (Catt, 1992). However, high losses of spat were initially experienced by Sydney rock oyster farmers who used single seed because of inappropriate design or management of nursery systems (Holliday et al., 1988). As several nursery systems used overseas proved to be unsuitable for local conditions (Holliday, 1985), a modified sectionalised timber tray was developed for the culture of juvenile Sydney rock oysters. Stocking densities have been recommended for Pacific oysters grown in trays (Neudecker, 1981; Spencer et al., 1985; Spencer and Gough, 1978; Spencer 1990; Backer, 1991). The efficiency of a nursery system was found to be affected by the stocking densities used, with growth rates of individual oyster spat decreasing with increasing stocking density, while overall spat production (weight per unit area) increases (Neudecker, 1981; Bacher, 1991). The aim of this segment was to determine the optimum stocking densities for various size grades of Sydney rock oyster spat as part of an evaluation of sectionalised trays as intertidal nursery units.

4.1.2 Methods

Three stocking density experiments, involving the same cohort of spat, were conducted within a 12 month period using sectionalised nursery trays as described in Section 2.3.1.2 (Fig 2.14). Trays were positioned in Swan Bay, on timber post and rail at the intertidal height traditionally used by oyster farmers (Section 2.2; Figs 2.8, 2.15). Spat were detached from various types of collectors deployed in Salamander Bay (Fig. 2.8) and were then grown in forced-flow upwellers, described in Section 2.3.1.1 (Bayes, 1981; Wisely, 1983), before being stocked in nursery trays for Experiment 1.

For each experiment there were six stocking densities with four replicate tray sections per density, and treatments were randomly allotted among the sections and trays. Individual spat were not counted when stocked but were allotted on a pooled weight basis in relation to the average spat weight for an initial sample. Each month the trays were removed from the lease and average oyster weights determined as above. Dead oysters were counted, total weights recorded and live oysters returned to the trays, that were then randomly assigned on the lease to minimise any effect of lease position on growth. Each experiment was terminated when spat in the high density treatments began growing through the upper mesh layer. At the end of Experiments 1, spat were pooled and, to minimise variances in individual weight, they were graded with three PVC mesh screens with only the middle grade used to stock Experiment 2. A similar process was used to stock Experiment 3. The densities selected provided a range from very lightly stocked to densely stocked, with most of the floor area of the tray section, covered by a single layer of closely packed spat.

4.1.2.1 Experiment 1

Experiment 1 involved estimated stocking densities of 300, 1000, 1700, 2400, 3100 and 3800 spat/section (1200-15200 spat/m^2). The average initial weight was 0.09 g/spat (based on the pooled weight of 700 spat). This experiment was run for 13 weeks (January to April).

4.1.2.2 Experiment 2

Experiment 2 involved estimated densities of 200, 600, 1000, 1400, 1800, 2200 spat/section (800-8800 spat/m^2) and an average initial weight of 1.15±0.01 g/spat (n=6 for groups of 100 spat). This experiment was run for 13 weeks (April to July).

4.1.2.3 Experiment 3

Experiment 3 involved estimated densities of 300, 500, 700, 900, 1100 and 1300 spat/section (1200-5200 spat/m^2) and an average initial weight of 1.56±0.02 g/spat (n=5 for groups of 100 spat). Because growth rates in the early phase of this experiment were relatively slow, it was extended to a total period of 22 weeks (July to December). Daily salinity and temperature data (n=63) were obtained with hydrometers and thermometers at three commercial oyster depuration plants near the nursery lease in Swan Bay (Fig 2.8).

4.1.2.4 Statistical Analyses

Homogeneity of variance was confirmed using Cochran's test (Winer, 1971) and data analysed using ANOVA. Means were compared using Tukey's honestly significant differences method (Sokal and Rohlf, 1981). Linear regression was performed for all experiments to examine the relationship between stocking density and average weight gain. To satisfy the assumption of homogeneity, weight gain data for Experiment 2 was transformed ($\log_{10}x$) prior to ANOVA and regression. Survival data were transformed (arcsine $x^{0.5}$) prior to ANOVA. Data from tray sections where physical damage may have allowed losses of spat were not included in analyses.

4.1.3 Results

The estimated survival rate of the spat over the twelve month period was very high (97.5%) and was not affected by stocking density in any of the three experiments ($P>0.05$). In each of the three experiments average individual oyster weight gain decreased with increasing stocking density ($P<0.05$; Fig 4.1). However, in Experiment 1 average weight gain for the lowest stocking density (1 200 spat/m^2) was lower than that recorded at 4 000 spat/m^2 ($P<0.05$; Fig 4.1). In this experiment it was evident that a very low stocking density (1 200 spat/m^2) was unfavourable, probably because excessive oyster movement caused by wave action on the sparsely-stocked tray sections caused shell abrasion; spat were ball-shaped with thick shell walls. Spat growth was depressed during Experiments 2 and 3 (Fig 4.2) when low water temperatures were recorded in July (12.1±0.2°C) and August (13.1±0.4°C; n=20/month) (Fig 4.3). Variances for average weight were homogeneous for each sampling time except for the July samples in Experiment 2 (Fig 4.2). The standard deviation values for the July samples, in increasing order of stocking density were 0.10, 0.25, 0.08, 0.06, 0.08, and 0.08 g.

In each of the three experiments, final biomass increased with increasing stocking density over the whole range tested (Table 4.1). Biomass gain generally increased as stocking density increased until a plateau was reached (Fig 4.4). The exception was Experiment 1 for which biomass gain increased with increasing stocking density throughout the range tested. It should be noted that for Experiment 1 the optimum density was the maximum level used and a higher density may have produced even greater biomass gain values. Optimum stocking densities in terms of biomass gain for Experiments 1, 2 and 3 were 15 200, 7 200 and 3 600 spat/m^2 respectively. It should be noted that in Experiment 3, a marginally higher biomass gain was obtained at 4 400 spat/m^2 but this was not a significant improvement over stocking with 3 600 spat/m^2 ($P>0.05$). Final biomass levels at the optimum stocking density for each experiment were similar (11.3-13.0 kg/m^2; Table 4.1).

Average water temperature and salinity levels were as follows: Experiment 1 (n=63), 22.0±0.2°C, 33.6±0.3‰, ranges 16-27°C, 28-40‰; Experiment 2 (n=63), 14.3±0.3°C, 25.6±0.01‰, ranges 10-21°C, 17-36‰; and Experiment 3 (n=91), 18.8±0.3°C, 26.6±0.4‰, ranges 10-27°C, 9-39‰ (Fig 4.3).

4.1.4 Discussion

Unlike traditional cultivation methods for the Sydney rock oyster, single seed methods allow for manipulation of juvenile oyster densities. The results of the present study indicate that the choice of stocking density has a major effect on yields from sectionalised trays. In each of the three experiments, individual spat growth decreased with increasing density, probably because of competition for food. Hadley and Manzi (1984) concluded that food was the growth limiting factor for clams stocked at a range of densities.

A variety of criteria could be used to assess optimum stocking density. The higher growth rates at low densities enhance the value of individual oysters, however, the value of production per unit area may be relatively low. Neudecker (1981) concluded that for small Pacific oyster spat, maximum growth was the best criterion for optimum stocking density because faster growth rates allowed for an earlier transfer to subtidal trays with a larger mesh size. Optimum density may also be influenced by survival rate. Spencer et al. (1992) found that the cost of rearing Pacific oysters (range 0.15-90.0 g/spat) in trays was about 53% of final first sale value and that profitability was related to survival. However, in the present study, survival rates were high and unaffected by density.

The choice of stocking density should be based on economic considerations (Maguire and Leedow, 1983). However, as the data required for a comprehensive economic analysis of single seed nursery culture are not yet available, an alternative approach of using maximum biomass gain as the criterion for optimum density was used here. The estimate of biomass used in this study was total oyster weight but depending on the thickness of the shell, this is not always an accurate guide to the value of an oyster. Other factors such as meat condition, shell shape and shell size can also influence value per oyster. Specifically, farmers often sort harvested oysters into groups of differing values on the basis of shell length. For single Sydney rock oysters grown within the same type of production system, there is a close relationship between total oyster weight and shell length (C. Mason, pers. comm., 1990). For this study, optimum stocking densities for Sydney rock oysters in sectionalised trays were 1.52 g, 0.72 g and 0.36 g spat/cm^2 for spat of 0.1, 1.2 and 1.6 g/spat respectively and are consistent with those used by Spencer et al. (1992). In contrast, Neudecker (1981) recommended that small Pacific oyster spat (0.6 g) not be stocked at densities greater than 0.05 g/cm^2, although, spat were grown in less than optimal environmental conditions. Spencer and Gough (1978) concluded that oyster growth was dependent on water temperature and spat size and Spencer et al. (1985) predicted optimum stocking densities for Pacific oyster spat by using the equation: $\ln B = 2\ (7.94+0.213 \ln Wo - 0.011\ T)$, where B = initial biomass (g/tray), Wo = initial mean live weight (g/spat) and T = predicted temperature for the next month.

The management of nursery units involves more than the choice of stocking density. As the spat grow they may fill the available tray space and grow through the mesh. In Experiment 2 and 3 the tendency for the spat to grow through the mesh prior to harvest was much more evident than in Experiment 1. Towards the end of Experiments 2 and 3, there was evidence that growth rate decreased at high densities (Fig 4.2). A similar pattern was evident in the growth data for small Pacific oyster spat in subtidal nursery trays (Neudecker, 1981) and from spat grown on intertidal stackable PVC trays (Spencer et al., 1992). This emphasises the need to periodically reduce the density (number/m^2) as the spat grow. As this process is relatively labour intensive, it may be preferable to avoid high stocking densities and hence frequent handling of the trays. Neudecker (1981) recommended the adjustment of densities every 2-3 weeks, but this is likely to be too labour intensive for the oyster farming industry in NSW. Spencer et al. (1992) adjusted densities of Pacific oyster spat in trays monthly during the initial stage when growth was rapid and gradually altered this to every 6 months when they reached 0.5-0.7 g/cm^2 (densities reached 1.3 g/cm^2). However, more frequent reductions in densities than those used in the present study may be worthwhile.

Excessively small mesh sizes, particularly if exacerbated by marine fouling, could restrict flow rates and reduce the amount of food available for oysters (Claus, 1981; Neudecker, 1981; Spencer 1990). The initial tray mesh size must be small enough to retain juvenile spat but as they grow, spat can be moved to larger mesh sizes to increase water flow (Claus, 1981). In the present study, 3 mm mesh was used for the experiments over 12 months, as it prevented spat loss from wave action and provided protection against predation and heat stress during intertidal exposure (Potter and Hill, 1982). In contrast, Neudecker (1981) and Spencer et al. (1992) increased the mesh size of trays as spat grew.

Spat growth rates appeared to be depressed during the cooler months in Experiments 2 and 3 (Fig 4.2). This observation was consistent with results from a nursery experiment over 12 months at three intertidal sites within Port Stephens (Chapter 5) and those from Nell et al. (1994). Similarly, Nell and Livanos (1988) showed that in the range of 12-30°C, growth rates of Sydney rock spat, fed to excess in the laboratory, increased as temperature increased.

Sectionalised trays proved to be appropriate nursery units for Sydney rock oyster spat and were particularly successful for sustaining very high survival rates. In a twelve month period, spat in the present experiment grew from 0.09 g to 4.9-6.0 g/spat. Data for the equivalent growth phase for Sydney rock oysters grown on sticks in conventional intertidal leases are not available, but 2.5-4.0 years are usually required for them to reach market size (>40 g; Nell, 1993; Korringa, 1976).

Traditional intertidal trays, used for on-growing oysters approaching market size, are often subjected to severe wave action which washes the oysters into the tray corners resulting in overcrowding, reduced growth rates, and eventual mortality. In this study, the increased number of partitions in the sectionalised trays reduced spat movement and minimised overcrowding. The upper and under mesh layers of trays also prevent predation of spat by fish and spillage.

Claus (1981) noted that the appropriateness of nursery technology is influenced by geographic location and economic considerations and emphasised that two dimensional nursery systems require more space than more sophisticated three dimensional nursery systems; however, space is not a limitation in NSW as the Sydney rock oyster industry is based largely on two dimensional intertidal culture through to market size and the area required for nursery culture is negligible compared with that needed for the grow-out phase. However, the determination of optimum stocking densities for juvenile Sydney rock oysters in sectionalised trays will allow for more cost efficient usage of trays and lease space. Key factors include capital and operating costs associated with acquisition of trays, depreciation, replacement, lease infrastructure and labour costs for relocation of trays during grading operations (Catt, 1992). Spencer et al. (1992), estimated the cost of oyster trays and the labour to service them accounted for more than 70% of total costs.

Subsequent to the completion of this study and that in Chapter 5, sectionalised trays were widely adopted by farmers culturing single seed Sydney rock oysters. The suitability of this nursery system has helped foster the expansion of single seed oyster farming as an alternative to traditional stick culture methods.

TABLE 4.1 Production of Sydney rock oyster (*Saccostrea commercialis*) spat at various stocking densities in sectionalised trays (Section 4.1)[1]

Stocking density (x $10^3/m^2$)	Initial biomass (kg/m^2)	Final biomass[2] (kg/m^2)	Biomass gain[2,3] (kg/m^2)
Experiment 1			
1.2	0.1	1.6±0.1	1.5±0.1[a]
4.0	0.4	5.4±0.1	5.0±0.1[b]
6.8	0.6	7.9±0.2	7.3±0.2[c]
9.6	0.8	9.8±0.4	8.9±0.4[d]
12.4	1.1	10.8±0.4	9.7±0.4[e]
15.2	1.3	12.0±0.2	10.7±0.2[f]
Experiment 2			
0.8	0.9	1.8±0.1	0.8±0.1[a]
2.4	2.8	4.8±0.1	2.0±0.1[b]
4.0	4.6	7.3±0.1	2.7±0.1[c]
5.6	6.4	9.1±0.1	2.7±0.1[c]
7.2	8.3	11.3±0.1	3.0±0.1[d]
8.8	10.1	13.0±0.1	2.9±0.1[cd]
Experiment 3			
1.2	1.9	5.2±0.2	3.3±0.2[a]
2.0	3.1	7.7±0.3	4.6±0.3[b]
2.8	4.4	10.2±0.4	5.8±0.4[c]
3.6	5.6	13.0±0.2	7.4±0.2[d]
4.4	6.9	14.3±0.2	7.5±0.2[d]
5.2	8.1	15.1±0.5	7.0±0.5[d]

[1] The average initial whole spat weight values for Experiments 1, 2 and 3 were 0.09 g, 1.15 g and 1.56 g respectively and the duration of each experiment was 13, 13 and 22 weeks (respectively).

[2] Biomass values based on whole weight of live spat.

[3] Values are means±SE; n=4. Within this column mean values from the same experiment are not significantly different if they share a common letter in the superscript (P>0.05).

Fig. 4.1

Growth of Sydney rock oyster (*Saccostrea commercialis*) spat at a range of stocking densities (n=4) in sectionalised trays (means±SD; Section 4.1).

Footnote:

[1] Means within each experiment which share a common letter in the superscript are not significantly different (P>0.01).

[2] Data for Experiment 2 were transformed ($\log_{10}x$) prior to ANOVA and regression analysis.

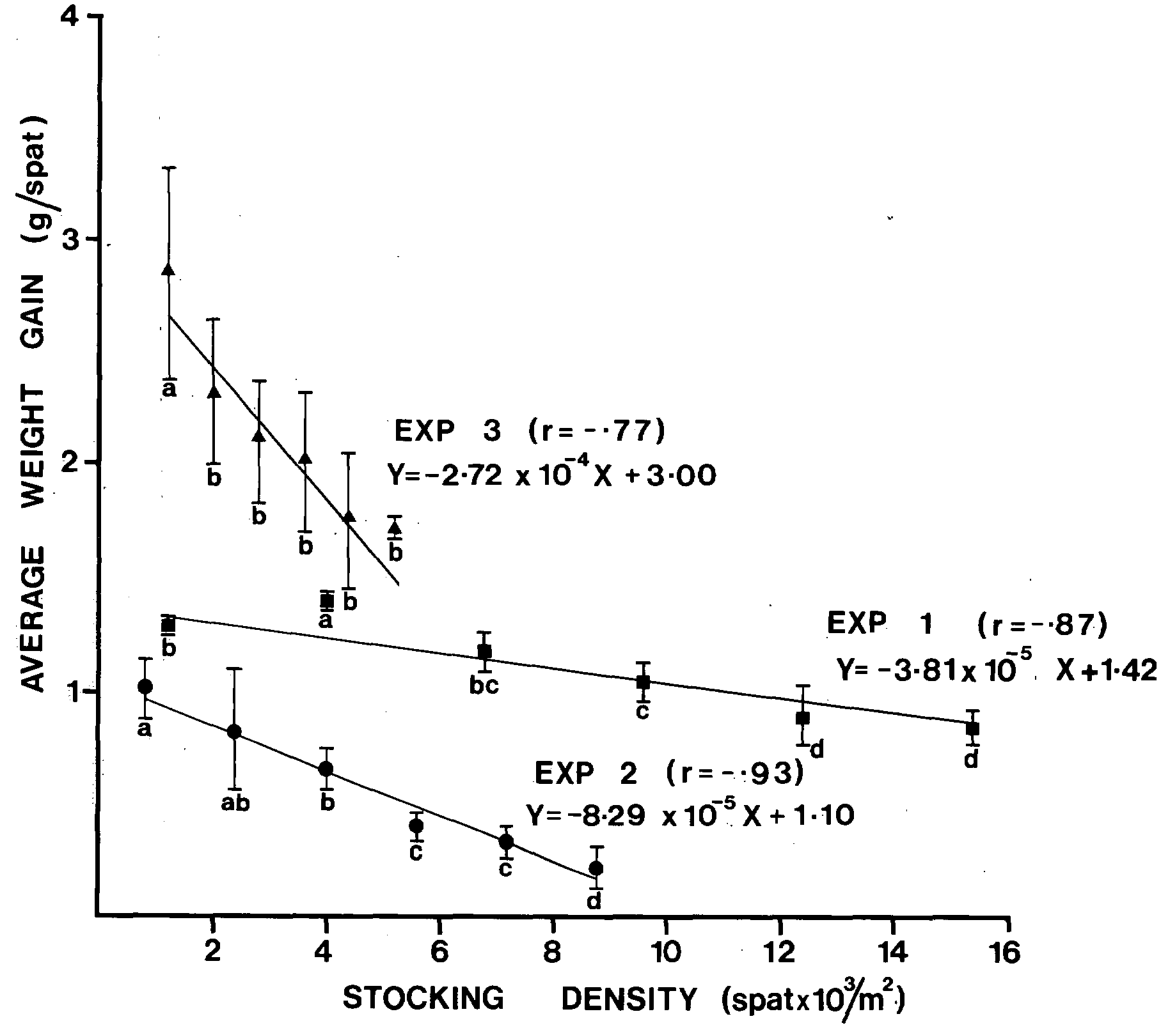

EXP 3 (r = −·77)
Y=−2·72 x 10^-4 X + 3·00
EXP 1 (r = −·87)
Y= −3·81 x 10^-5 X + 1·42
EXP 2 (r = −·93)
Y= −8·29 x 10^-5 X + 1·10
AVERAGE WEIGHT GAIN (g/spat)
STOCKING DENSITY (spat x 10^3/m^2)

Fig 4.2

Growth of Sydney rock oyster (*Saccostrea commercialis*) spat through time at a range of stocking densities (means±SD). Only the standard deviation values for the largest and smallest size groups at each sampling time have been included (Section 4.1).

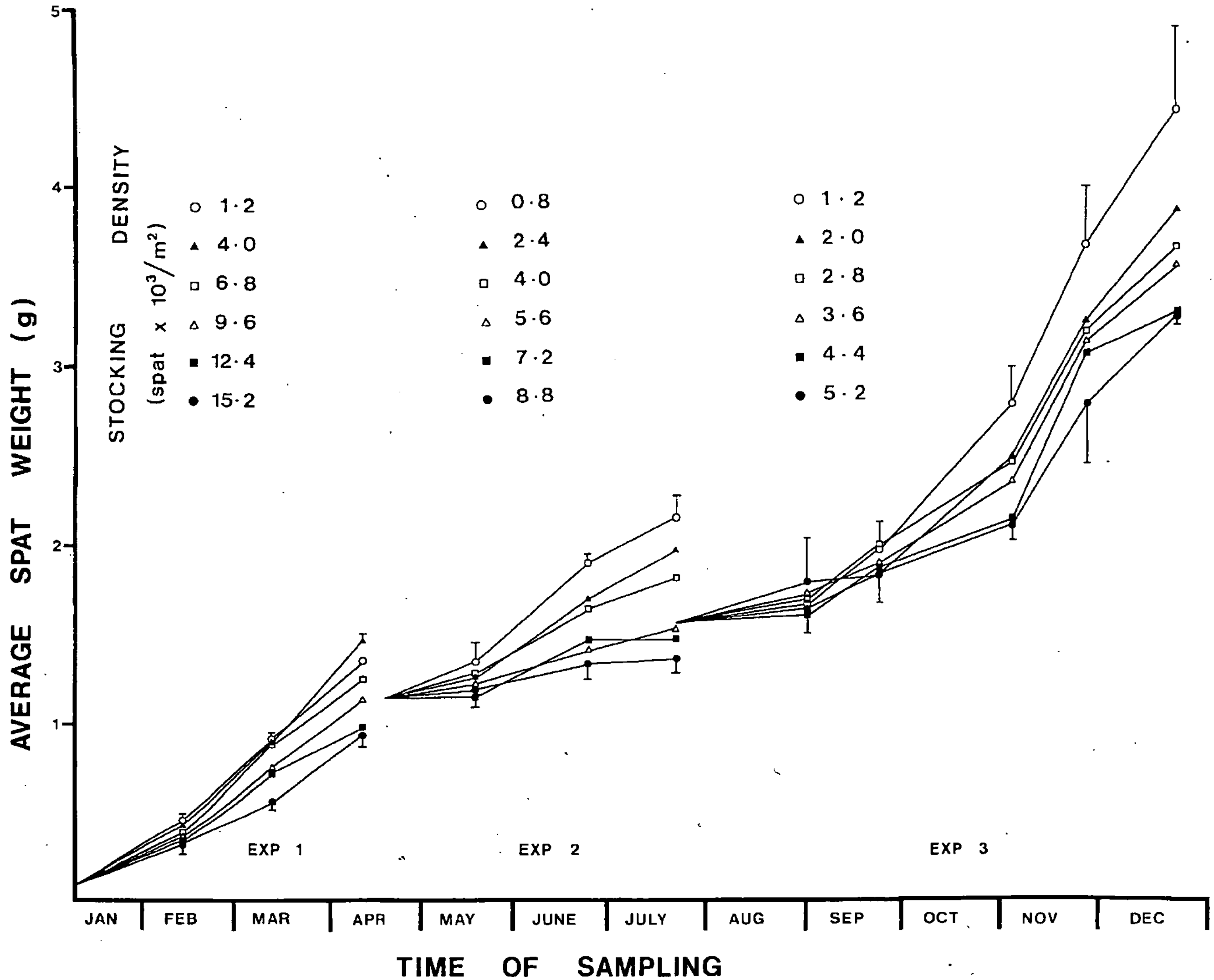
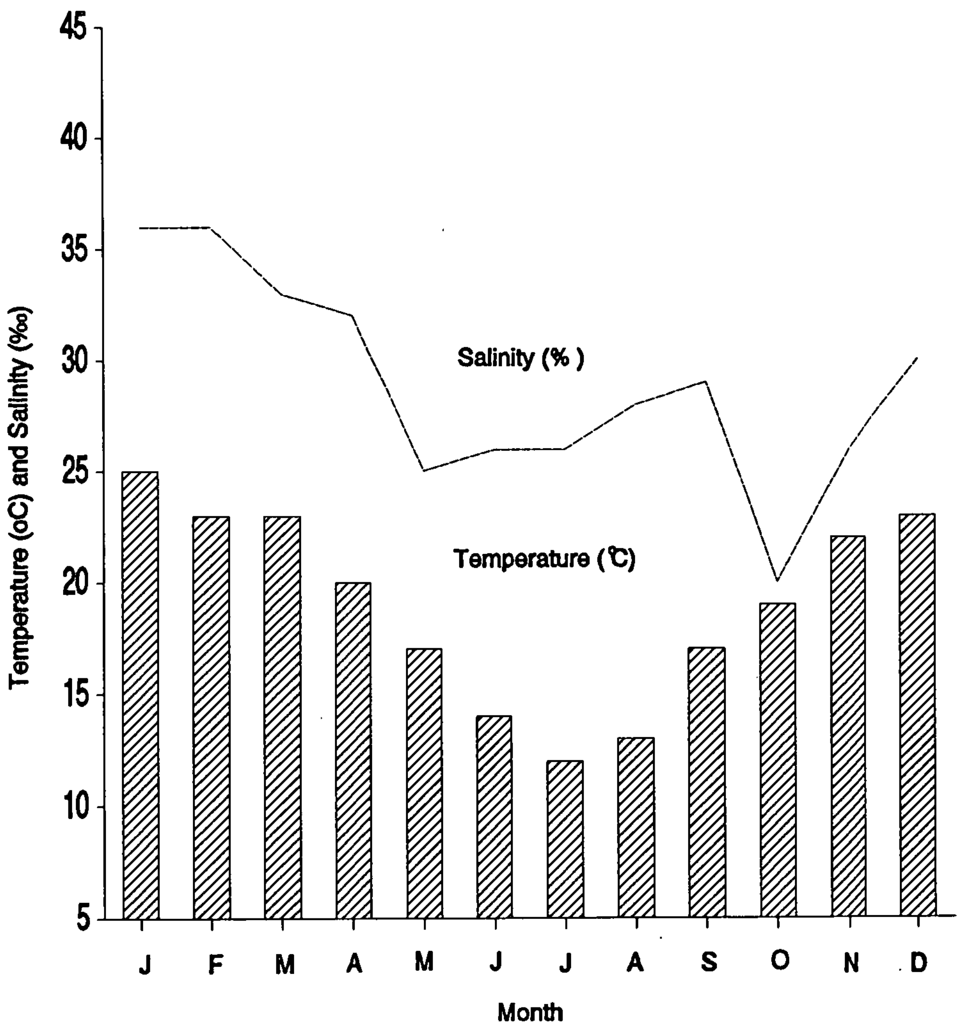

AVERAGE SPAT WEIGHT (g)
STOCKING DENSITY
(spat x 10³/m²)
1·2
4·0
6·8
9·6
12·4
15·2
0·8
2·4
4·0
5·6
7·2
8·8
1·2
2·0
2·8
3·6
4·4
5·2
EXP 1
EXP 2
EXP 3
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEP
OCT
NOV
DEC
TIME OF SAMPLING

Fig 4.3

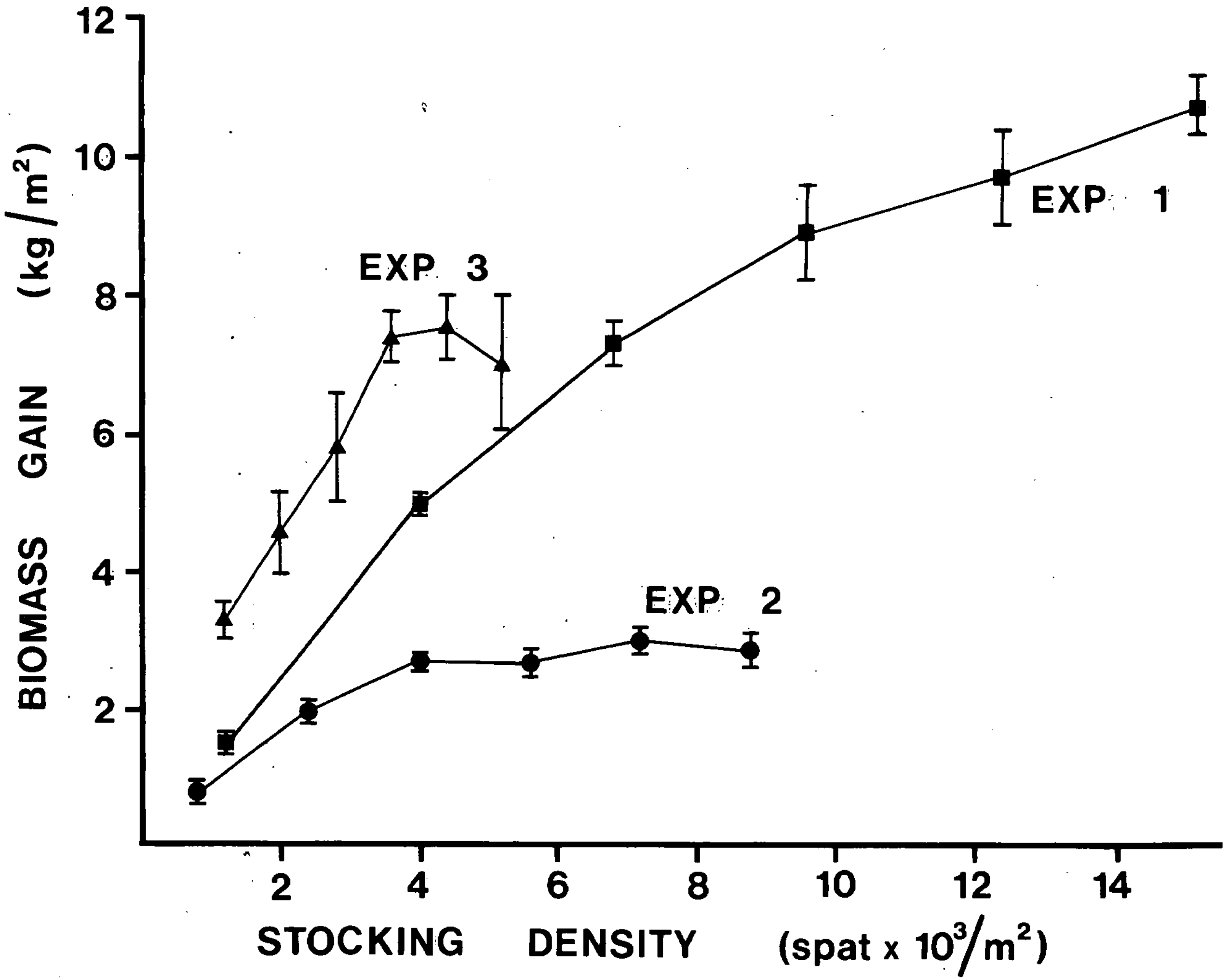
Water temperature and salinity data (n=63) for Swan Bay, January to December (Experiments 1, 2, 3; Section 4.1).



45
40
35
30
25
20
15
10
5
Temperature (oC) and Salinity (‰)
Salinity (%)
Temperature (℃)
J
F
M
A
M
J
J
A
S
O
N
D
Month

Fig 4.4

Biomass gain over the duration of the experiments for Sydney rock oyster (*S. commercialis*) spat grown at a range of stocking densities (means±SD; Experiments 1, 2, 3; n=4; Section 4.1).



BIOMASS GAIN (kg/m²)
12
10
8
6
4
2
EXP 1
EXP 2
EXP 3
2
4
6
8
10
12
14
STOCKING DENSITY (spat x 10³/m²)

4.2 OPTIMUM STOCKING DENSITY FOR OYSTERS IN PVC CYLINDERS

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4.2.1 Introduction

While trays can be very good nursery units, farming single seed oysters on nursery trays in estuaries with high levels of suspended silt can be difficult (Holliday et al., 1988), as the deposition of silt on oysters can be linked with increased infestation by mudworm commensals, which cause shell blisters and mortality (Skeel, 1979). Wisely et al. (1979a) reported heavy deposits of silt and high mudworm infestations of Sydney rock oysters grown subtidally on trays in the Hawkesbury River, NSW. A PVC cylinder which rotates with the tide, was developed by a NSW oyster farmer in response to this problem (Anon., 1985). This revolving action (one revolution per tide) helps remove silt from around the oysters. This system is being used more widely in NSW and cylinders have also been used in trials for growing Pacific oysters and other species including the European oyster and clams (Robert and Maurer, 1992), and to increase meat condition and shell quality of larger oysters for market (Robert et al., 1993).

Although the effects of stocking density have been determined for juvenile Sydney rock oysters in sectionalised trays (Section 4.1), equivalent information was required for rotating cylinders. The objectives of this segment were to determine the optimum stocking density based on survival, biomass gain, individual weight gain and shell growth for two grades of juvenile Sydney rock oysters in cylinders and to evaluate cylinders as nursery units. The effects of stocking density on size variation were also assessed as a wide range of spat sizes in a nursery system increases stock management costs (Askew, 1978; Newkirk, 1981).

4.2.2 Methods

Cylinders, described in 2.3.1.3 (Figs 2.16, 2.17) rotated in response to changes in tidal level, that ranged from 0.2 to 2.0 m above ISLW mark.

Cylinders were randomly allocated to a position on horizontal hardwood frames (20 x 50 mm, 1.3 m apart), supported 1.5 m (in the intertidal zone) from the sediment by timber posts (Fig 2.16). Each cylinder was fixed to the hardwood frames by nails driven through a tarred hardwood stick (20 x 20 mm), inserted through the PVC shaft (Fig 2.16).

Sydney rock oyster spat were obtained from the research station hatchery, Salamander Bay and were initially held in a similar upweller nursery system to that described by Bayes (1981), prior to being stocked in the experiment. Two grades of spat were used in synchronous trials. For the smaller grade the initial weight of individual spat (n=400) was 0.24±0.01 g (coefficient of variation 8.33) and the shell length (n=1000) was 13.5±0.1 mm (coefficient of variation 1.5). Five stocking densities of 0.5, 1.0, 2.0, 3.0 and 4.0 l of oysters per cylinder, with four replicate cylinders per density were used. Spat were stocked on the basis of volume as this is the method used by most oyster farmers. The total weight of oysters (n=4) for each volume were: 0.5 l (300.4±0.04 g), 1.0 l (600.4±0.1 g), 2.0 l (1200.2±0.04 g), 3.0 l (1800.3±0.03 g) and 4.0 l (2400.4±0.01 g).

For the larger grade the initial weight of individual spat (n=500) was 0.41±0.001 g and the shell length (n=200) was 18.2±0.1 mm. Six stocking densities of 0.5, 1.0, 2.0, 3.0, 4.0 and 6.0 l of oysters/cylinder with four replicate cylinders per density were used. The total weight of oysters (n=4) for each volume were: 0.5 l (245.4±0.03 g), 1.0 l (490.3±0.04 g), 2.0 l (980.3±0.1 g), 3.0 l (1470.5±0.1 g), 4.0 l (1960.4±0.1 g) and 6.0 l (2941.3± 0.1 g).

Stocking densities of 0.5 to 6.0 l of oysters/cylinder occupied between 1.2 and 14.2% of the total volume of a cylinder. To allow a comparison between oyster stocking densities on trays and cylinders, the plan view area occupied by a revolving cylinder was calculated and multiplied by two (6400 cm^2), to take account of the two alternate horizontal positions. All cylinders were deployed in the Mooney Mooney Creek, Hawkesbury River (Figs 2.7, 2.10), on a growing lease at a similar height (intertidal) to that used for growing Sydney rock oysters on sticks (Malcolm, 1987; Holliday et al., 1988). Maximum water velocity for the Hawkesbury River was measured with simple drogues and ranged from 0.5-0.7 m/s (J. Harris, pers. comm., 1992).

Environmental data were collected from Mooney Mooney Creek on five separate occasions, at two to three weekly intervals, during the experiment. All readings were taken at midday from the water surface. Temperature and dissolved oxygen were measured using a Yeokal (Yeokal Electronics, Brookvale, NSW), Dissolved Oxygen/Temperature Meter (Model 603), calibrated with a standard thermometer and Winkler titration (APHA, 1989). Nutrients were analysed using the method outlined by APHA (1989) and concentrations of plant pigment chlorophyll *a*, were measured following acetone extraction, using the spectrophotometric methods described by Major et al. (1972). Salinity was calculated from conductivity, which was recorded with a WTW (Weilheim-D. Germany) conductivity meter (Model IF 196), and pH was measured using a Orion (Orion Research Inc., Boston, MA) portable pH meter (Model 290 A), with an Orion Triod Electrode (91-57 BN), calibrated with NBS buffers (pH 4, 7 and 9), (CRC, 1971). Turbidity was measured using a Hach (Loveland, Colorado) turbidity meter and a secchi disc (300 mm diam.).

At the completion of the experiment (that was run for 120 days from February to May), the shells of dead oysters were examined for mudworm blisters and burrows. Total numbers of spat at stocking and harvest times were estimated by dividing total weight of clean spat per cylinder by the average spat weight. The data were then used to estimate percentage mortality at harvest. Final average individual spat weight was estimated by weighing 100 randomly selected live individuals per replicate and average individual shell length by measuring 50 shell lengths per replicate. The total weight of all oysters in each replicate was used to calculate final biomass and biomass gain. Initial and final volumes of oysters were measured (after immersion for about an hour to ensure cavity volume was full) using a large calibrated measuring cylinder (1.0 ± 0.005 l; n=4).

4.2.2.1 Statistical Analysis

For each grade, differences between treatments were assessed using one-way ANOVA as the number of densities within grades were different. Homogeneity of variance was confirmed using Cochran's Test (Winer, 1971) and means compared using Tukey's honestly significantly difference method (Sokal and Rohlf, 1981). To satisfy the assumption of normality and/or homogeneity of variance, volume increase data for the smaller grade were transformed ($\log_{10}x$) and mortality data for both grades were transformed (arcsine $x^{0.5}$) prior to ANOVA. Coefficient of variation (100 x SD/mean; Sokal and Rohlf, 1981) for both weight gain and shell length increase was calculated as an indicator of size variation of oysters within each treatment. Simple one parameter models were used to describe the data for both grades. For weight gain and length increase, exponential models ($y=e^{a+bx}$) gave the best fit. Two-way ANOVA indicated that for log weight data (ln x [mean initial wt/mean final wt]) and growth co-efficient values (G_{90} = 90/duration (days) x ln [mean initial spat wt/mean final spat wt]; Spencer and Gough, 1978), grade and spat density and the interaction between grade and spat density were significant ($P<0.05$; Table 4.2). Subsequently, one-way ANOVA was used for each grade to determine the effect of density.

4.2.3 Results

Mortality for the smaller grade (11.7±1.1%, range 9.7-15.2%; n=4) was unaffected by stocking density ($P>0.05$). For the larger grade, spat mortality was similar (22.5±2.3 range 19.3-25.1%; $P>0.05$; n=4) for stocking densities of 0.5-4.0 of oysters/cylinder but higher (33.3±1.7%; $P<0.05$; n=4) for 6 l/cylinder. No mudworm blisters and burrows were found in the shells of dead oysters. Maximum individual spat weight gain was recorded at densities of 0.5 and 1.0 l/cylinder for the smaller and larger grades respectively. For the smaller grade, average individual spat weight gain and average individual shell length increase declined ($P<0.001$) from 2.5±0.03 to 0.6±0.04 g/spat and 18.6±0.3 to 7.0±0.7 mm/spat respectively with increasing stocking density of 0.5 to 4.0 l of oysters/cylinder (Figs. 4.5A, 4.5B). Similarly, for the larger grade, average individual spat weight gain and average individual length increase declined ($P<0.001$) from 3.3±0.02 to 1.2±0.03 g/spat and 17.1±0.3 to 9.7±0.4 mm/spat respectively by increasing density from 0.5 to 6.0 l of oysters/cylinder (Figs 4.6A, 4.6B). Differences between the two lowest densities were not significant ($P>0.05$) for length increase and weight gain (large grade; Figs 4.6A, 4.6B).

Maximum biomass gain and volume increase were recorded for both grades at the highest densities. For the smaller grade, biomass gain and volume gain increased from 2.7±0.2 to 4.7±0.1 kg of oysters/cylinder and 5.7±0.2 to 11.1±0.5 l of oysters/cylinder respectively with increasing stocking density of 0.5 to 4.0 l of oysters/cylinder (Figs 4.5C, 4.5D). Similarly, for the larger grade, biomass gain and volume increase both increased with density from 1.6±0.02 to 4.8±0.1 kg of oysters/cylinder and 3.2±0.2 to 11.2±0.2 l of oysters/cylinder respectively with increasing stocking density of 0.5 to 6.0 l of oysters/cylinder (Figs 4.6C, 4.6D). For each size grade, there was no significant ($P<0.05$) difference in biomass gains for the smaller and larger grades at the two highest densities of 1.0-4.0 l (small size grade) and 3.0-6.0 l (large size grade) (Figs 4.5C, 4.6C).

Coefficient of variation for weight gain and shell length gain increased with stocking density for both grades ($P<0.001$). For the smaller grade, coefficient of variation for weight gain and shell length gain increased from 33.9±1.9 to 101.4±7.5 and 13.2±0.6 to 32.0±1.4 respectively as stocking density increased from 0.5 to 4.0 l of oysters/cylinder (Figs. 4.5E, 4.5F). For the larger grade, coefficient of variation for weight gain increased from 29.7±1.3 to 66.1±3.5 as stocking density increased from 0.5 to 4.0 l of oysters/cylinder and shell length gain increased from 11.1±1.2 to 20.1±1.5 as stocking density increased from 0.5 to 6.0 l of oysters/cylinder (Figs 4.6E, 4.6F). Data on frequency distribution at harvest for the smaller and larger grades of spat stocked are presented in Figures 4.7 and 4.8 respectively. Both log weights and growth coefficient values (G_{90}) decreased with increased stocking density (Table 4.2). For growth, grade stocked (0.2 and 0.4 g/spat) and spat density and the interaction between grade and spat density were significant ($P<0.05$).

Temperature (21.6±1.7, range 16.2-25.2°C), salinity (16.5±3.5, range 8.9-29.2‰) and concentrations of other environmental variables are presented in Table 4.3.

4.2.4 Discussion

The PVC cylinders were suitable for nursery culture of juvenile Sydney rock oysters ranging in average shell length from 14 to 32 mm. The rotating action of the cylinder with tidal movements appeared to reduce the build-up of silt on the oysters thereby eliminating the need to regularly wash the crop and minimising the risk of mudworm infestation (Skeel, 1979; Holliday et al., 1988). No mudworm infestations were found in this study despite the high turbidity (7.8±1.4 NTU) and low secchi disc readings (1.2±0.1 m), which indicated there was a high level of silt in the water compared with other NSW oyster producing estuaries (S. McOrrie, pers. comm., 1990). Turbidity and high concentrations of silt can affect the feeding efficiency of oysters (Quayle and Newkirk, 1989) and result in high mortalities (Quayle, 1988). High silt loads on oysters cultivation in trays in the Hawkesbury River and other NSW estuaries have resulted in high mortalities from mudworm (Wisely et al., 1979a). Mudworm infestations also cause mortality among other oyster species grown in different types of units in other countries (Korringa, 1976), although, worm infestations have been significantly lower for Pacific oysters grown in cylinders in France, compared with those grown in fixed PVC mesh bags (Robert and Maurer, 1992). For the present study, mortality (range 9.7-33.3%) was not excessive but higher than that obtained for Pacific oyster spat grown in cylinders (Robert et al., 1993) and may have resulted from prolonged periods of low salinity (minimum 8.9‰) after heavy rainfall. Nell and Holliday (1988), found that survival for 0.6 g Sydney rock oyster spat was not affected by salinities of 15-45‰.

Although mortality was unaffected ($P>0.05$) by stocking density (with the exception of 6 l of oysters/cylinder for the larger grade), spat growth declined with increasing density and biomass gain did not increase significantly at the three highest densities for each grade. Coefficient of variation for weight gain and shell length gain also increased with stocking density for both grades ($P<0.001$). This indicates that densities should be reduced periodically to optimise production. Newkirk (1981) found large variations in spat sizes in the first year for the European oyster and recommended culling a small percentage of each batch if the gains after labour costs for grading were warranted. Neudecker (1981) recommended altering densities of Pacific oysters in trays every 2-3 weeks. However, this may be excessive for Sydney rock oysters in nursery trays and altering densities every three to five months depending on growth may be adequate (Section 4.1). Spencer et al. (1985, 1992) also altered densities of Pacific oyster spat in trays and based the frequency on predicted water temperatures and growth.

When determining optimum stocking densities for juvenile Sydney rock oysters in PVC cylinders, a number of criteria need to be examined. Ultimately, optimum stocking density of oysters should be based on economic considerations (Askew, 1978; Spencer et al., 1985), as it is important to have cost-effective usage of nursery units and lease space.

If initial costs of spat are high (in NSW, this applies to hatchery spat), then the appropriate criteria for spat management should be survival followed by maximum individual spat weight gain (Spencer et al., 1992). Optimum stocking density based on maximum growth was 0.5-1.0 l oysters/cylinder for both grades of spat (equivalent to 0.01-0.09 and 0.04-0.08 g of oysters/cm^2 of lease area for the smaller and larger grades respectively). Using an economic model for European and Pacific oysters, Askew (1978) found that the time required to reach market size was crucial for the viability of an operation, as the smaller slow growing oysters (10% of the crop) required three times the growing period to reach market size. Neudecker (1981) also concluded that for juvenile Pacific oyster spat, maximum spat growth was the best criterion for optimum stocking density as rapid growth allowed for a quicker transfer from smaller to larger mesh trays and spat required a shorter growing period to reach market size. Neudecker (1981), recommended a stocking density of 0.05 g of oysters/cm^2 of tray area for maximum growth of Pacific oysters (0.6 g/oyster) on fine mesh trays, similar to that recommended in the present study, on the basis of growth rate. When making comparisons between growing units, it should be noted that trays have flat surfaces while cylinders are curved.

Maximum growth of individual oysters is not, however, always the best criterion for optimum stocking density. Spencer et al. (1985) showed that the small advantage in growth of Pacific oysters with low stocking densities, may be outweighed by the extra costs of labour and trays, even when the purchase of hatchery produced Pacific oysters accounted for 62% of production costs in the first year of growth. In NSW, the initial cost of spat harvested from collectors with natural catch is relatively low (Section 3.4), while capital and labour costs for tray culture are high (Marshall and Espinas, 1987; Catt 1992). Results from an economic analysis of single seed production of Sydney rock oysters in nursery trays indicated that labour accounted for about 38% of total costs (Catt, 1992).

An alternative criterion for optimum stocking density is maximum biomass gain. Maximum biomass gain for the present study was obtained at the highest densities for both grades of oysters, however, as increases above 2 l and 3 l oyster/cylinder for the smaller and larger grades respectively (equivalent to 0.19 and 0.15 g of oysters/cm^2 respectively) did not result in significant increases in biomass gain, these densities represent optima. At higher densities, coefficient of variation for weight gain and shell length increase was increased and oyster weight gains were reduced. Higher oyster densities can also result in undesirable change in shell shape. In Section 4.1, it was recommended that maximum biomass gain was an appropriate criteria for stocking Sydney rock oyster spat in nursery trays and that stocking densities of 1.52 g and 0.72 g of oysters/cm^2 of tray area for 0.1 g and 1.2 g spat respectively be used. Spencer et al. (1992) obtained good growth and survival for Pacific oyster spat (initial weight 0.15 g/spat) grown in trays stocked at densities of < 1 g/cm^2 and Robert et al. (1993) reported poor growth and good survival of Pacific oyster spat (initial weight 3.0 g/spat) grown in cylinders stocked at 0.23 g of oysters/cm^2 of lease area. For similar sized Sydney rock oysters stocked in trays and cylinders (0.1 and 0.2 g/spat respectively), optimum stocking density (number per unit area of lease space) was higher for trays than cylinders. However, different environmental conditions may have accounted for the difference in spat performances, as spat growth is not only dependent on spat size but water temperature (Spencer and Gough, 1978). Stocking densities could also be affected by other environmental conditions including food supply and nutrient concentrations. Chlorophyll *a* is often used as a measure of algal productivity (Brown and Hartwick, 1988). Oyster growth rates have been positively correlated with chlorophyll *a* (Mallonee and Paynter, 1989 [range 8-25 ug l^{-1}]; Brown and Hartwick, 1988 [range 9.0-49.1 ug l^{-1}]). The chlorophyll *a* concentrations for the present study (range 1.4-6.4 ug l^{-1}) were lower than those recorded by Brown and Hartwick (1988). In general, temperature, salinity (Wolf and Collins, 1979) and concentrations of chlorophyll *a* (Allan, 1980) were similar to those recorded in other estuarine environments in NSW, where Sydney rock oysters are cultivated.

Cylinders could be advantageous for growing bivalves in turbid estuaries where silt deposition on oysters impedes cultivation. For maximum growth and minimum coefficient of variation for weight gain and shell length increase, 0.2 and 0.4 g Sydney rock oyster spat should be stocked at low densities of 0.5 or 1.0 l/cylinder. To optimise biomass gain, while still maintaining rapid growth and modest size variation, stocking densities of 2.0 and 3.0 l of oysters/cylinder respectively, should be used for oysters of a similar size to the smaller and larger grades used here. Robert et al. (1993) suggested locking cylinders in position for periods as it would reduce the rumbling effects and may improve oyster growth rates. When compared with PVC baskets, oysters grown in cylinders produced higher meat and shell quality and carbohydrate content (Robert et al., 1993).

TABLE 4.2

Comparison of log weight and growth coefficient data (G_{90}) for Sydney rock oyster (*Saccostrea commercialis*) spat growth at a range of densities in rotating cylinders (February - May)[1]

	Log weight[2]	G_{90}[3]
Smaller grade (initial weight 0.2 g/spat)		
Stocking density (l/cylinder)		
0.5	2.4 ± 0.01^{a}	1.8 ± 0.01^{a}
1.0	2.2 ± 0.03^{b}	1.6 ± 0.02^{b}
2.0	1.6 ± 0.06^{c}	1.2 ± 0.05^{c}
3.0	1.4 ± 0.09^{d}	1.6 ± 0.06^{d}
4.0	1.2 ± 0.05^{e}	0.9 ± 0.04^{e}
Larger grade (initial weight 0.4 g/spat)		
0.5	2.2 ± 0.01^{a}	1.6 ± 0.01^{a}
1.0	2.2 ± 0.02^{a}	1.6 ± 0.01^{a}
2.0	1.9 ± 0.02^{b}	1.4 ± 0.01^{b}
3.0	1.7 ± 0.03^{c}	1.2 ± 0.2^{c}
4.0	1.5 ± 0.04^{d}	1.1 ± 0.04^{d}

[1] Values are mean±SE; n=4. Two-way ANOVA indicated that graded density and the interaction between grade and density were significant ($P<0.05$). Subsequently, one way ANOVA was used for each grade to determine the effect of density. For each grade means with a column with a common letter in the superscript were not significantly different ($P>0.05$)

[2] Log weight = ln (mean final weight [g/spat]/mean initial weight [g/spat]).

[3] G_{90} = 90/duration (days) x log weight.

TABLE 4.3

Environmental data from Mooney Mooney Creek, Hawkesbury River, NSW, February to May (Section 4.2).[1]

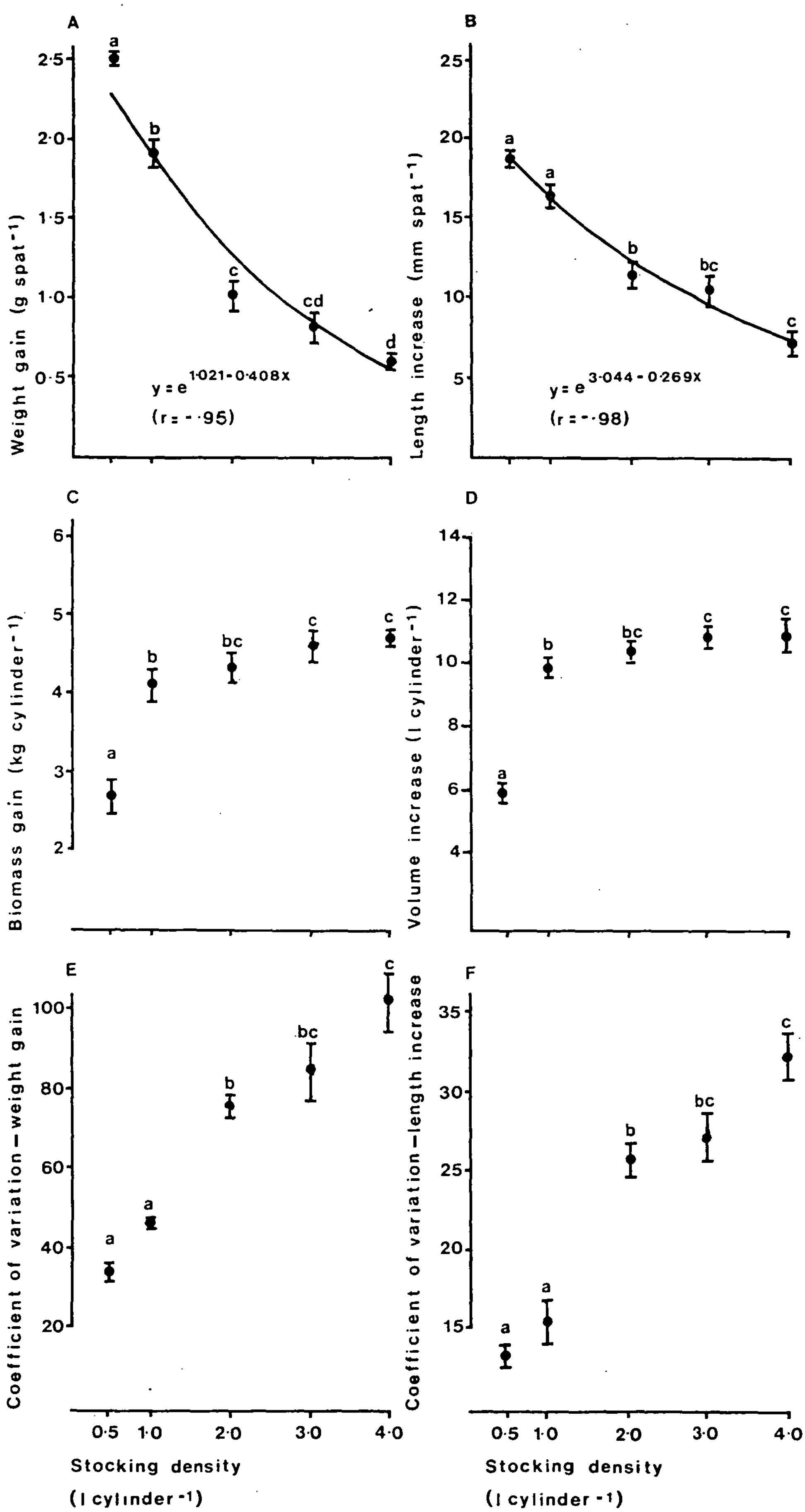
Parameter	Mean±SE	Range
Temperature (°C)	21.6 ± 1.7	16.2-25.2
Salinity (‰)	16.5 ± 3.5	8.9-29.2
pH	7.7 ± 0.1	7.5-7.9
Turbidity (NTU)	7.8 ± 1.4	5.0-12.0
Secchi depth (m)	1.2 ± 0.1	0.9-1.5
Chlorophyll *a* (ug l^{-1})	3.7 ± 0.8	1.4-6.4
Total PO_4-P (mg l^{-1})	0.03 ± 0.002	0.02-0.03
Total ammonia-N (mg l^{-1})	0.07 ± 0.02	0.02-0.12
[2] NO_x-N (mg l^{-1})	0.12 ± 0.03	0.05-0.14
Dissolved oxygen (mg l^{-1})	6.8 ± 0.5	5.6-8.4
Dissolved oxygen (% saturation)	78.4 ± 3.1	69.0-88.0

[1] Data were recorded at midday on five separate occasions and from the water surface.

[2] $NO_x = NO_2 + NO_3$.

Fig 4.5. Effects of stocking density on the performance of smaller grade (average weight 0.2 g/spat and length 13.5 mm/spat) of juvenile Sydney rock oysters (*Saccostrea commercialis*) in PVC cylinders (mean±SE; n=4; Section 4.2). Means within a graph, with a similar letter are not significantly different ($P>0.05$).

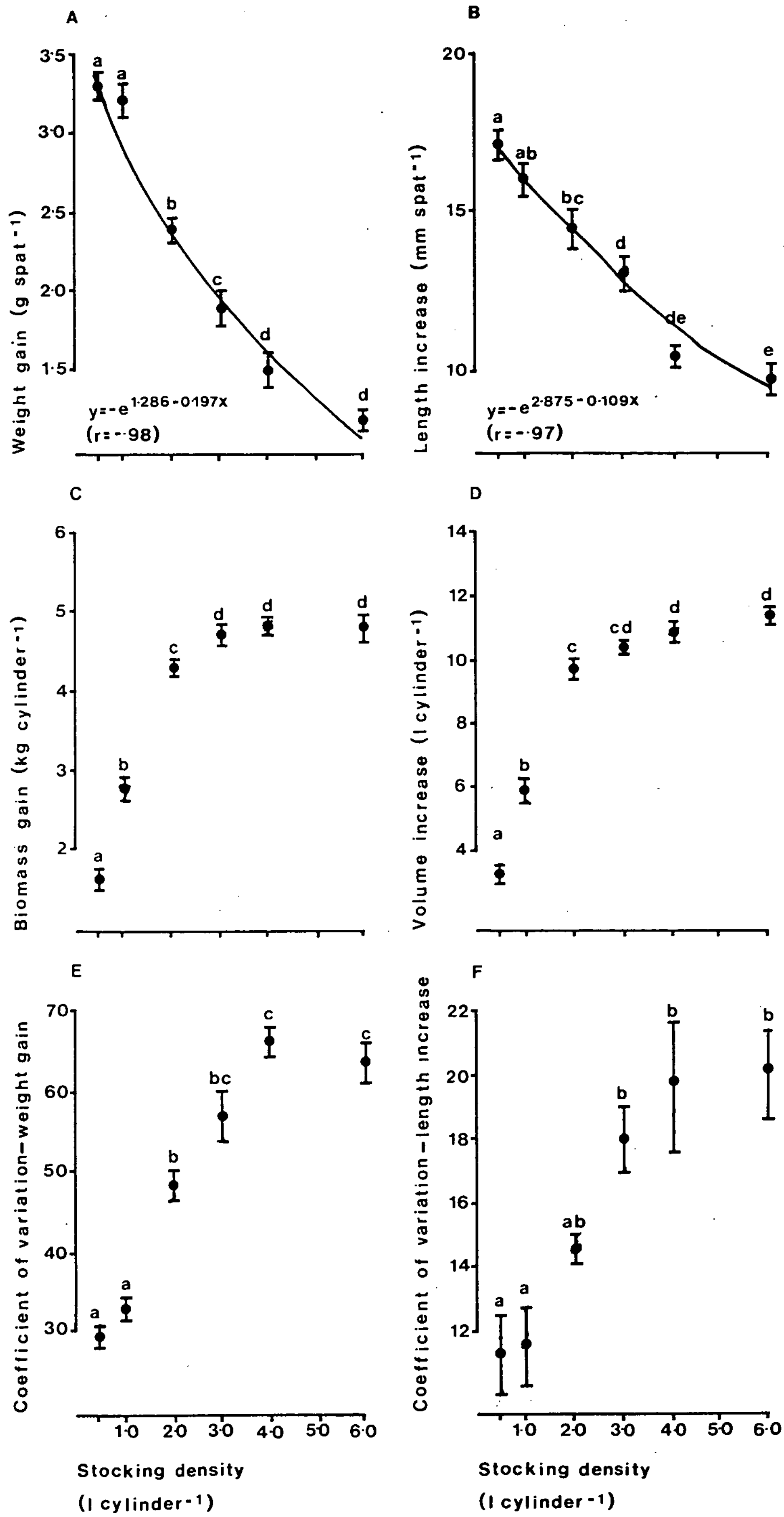
A	Weight gain
B	Length increase
C	Biomass gain
D	Volume increase
E	Coefficient of variation for weight gain
F	Coefficient of variation for length increase



A
Weight gain (g spat⁻¹)
y = e^1·021-0·408x
(r = -·95)
B
Length increase (mm spat⁻¹)
y = e^3·044-0·269x
(r = -·98)
C
Biomass gain (kg cylinder⁻¹)
D
Volume increase (l cylinder⁻¹)
E
Coefficient of variation - weight gain
F
Coefficient of variation - length increase
0·5 1·0 2·0 3·0 4·0
Stocking density
(l cylinder⁻¹)

Fig 4.6. Effects of stocking density on the performance of the larger grade (average weight 0.4 g/spat and length 18.2 mm/spat) of juvenile Sydney rock oysters (*Saccostrea commercialis*) in PVC cylinders (mean±SE; n=4; Section 4.2). Means within a graph, with a similar letter are not significantly different ($P>0.05$).

A	Weight gain
B	Length increase
C	Biomass gain
D	Volume increase
E	Coefficient of variation for weight gain
F	Coefficient of variation for length increase



A
B
C
D
E
F
Weight gain (g spat⁻¹)
Length increase (mm spat⁻¹)
Biomass gain (kg cylinder⁻¹)
Volume increase (l cylinder⁻¹)
Coefficient of variation–weight gain
Coefficient of variation–length increase
y=-e^1.286-0.197x
(r=-.98)
y=-e^2.875-0.109x
(r=-.97)
Stocking density
(l cylinder⁻¹)
Stocking density
(l cylinder⁻¹)

Fig 4.7 Frequency distribution of weights at harvest for the smaller grade of Sydney rock oyster (*Saccostrea commercialis*) spat (initial weight 0.2 g/spat) stocked at 0.5, 1.0, 2.0, 3.0, and 4.0 l/cylinder (February-May; Section 4.2).

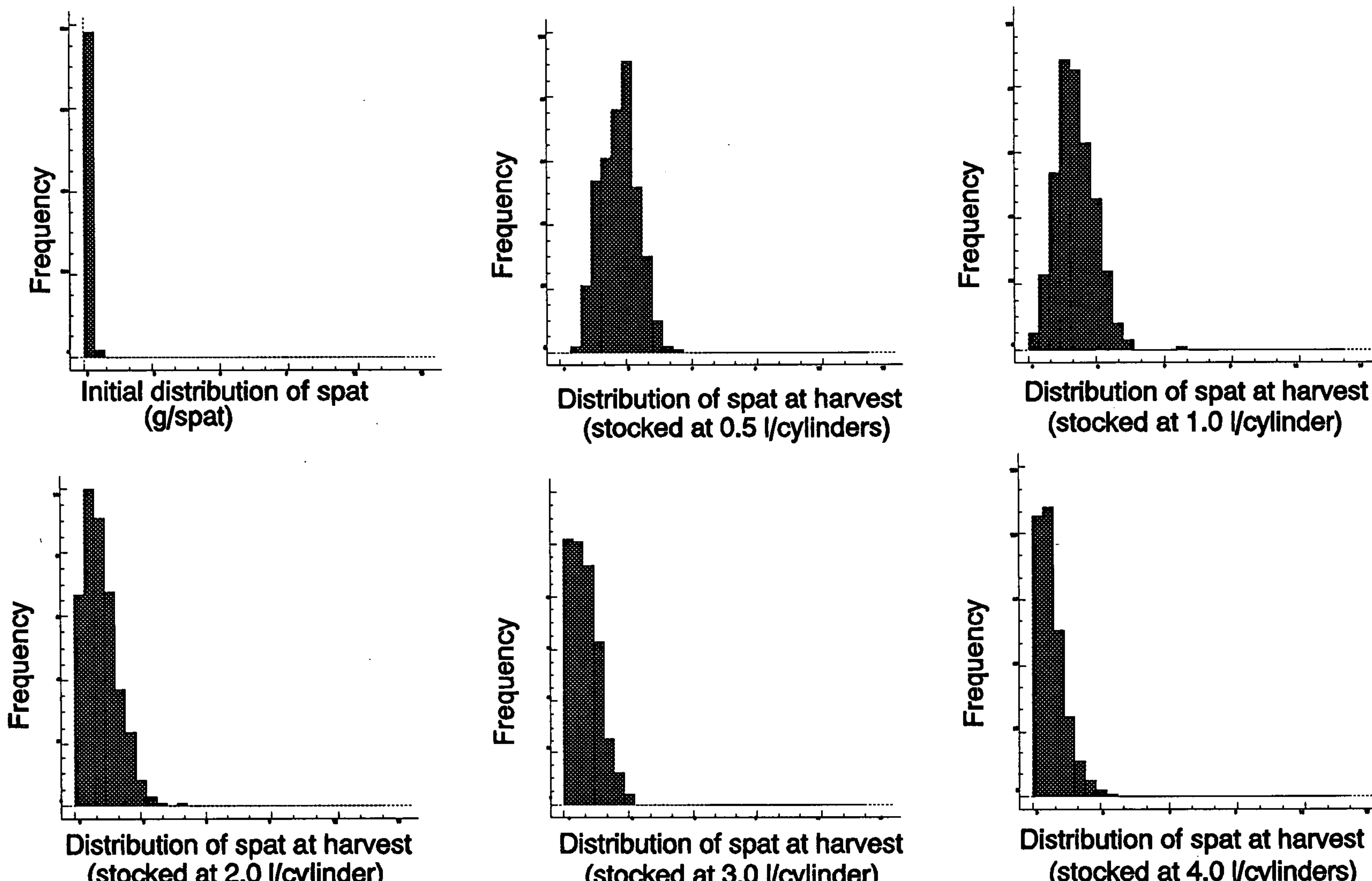
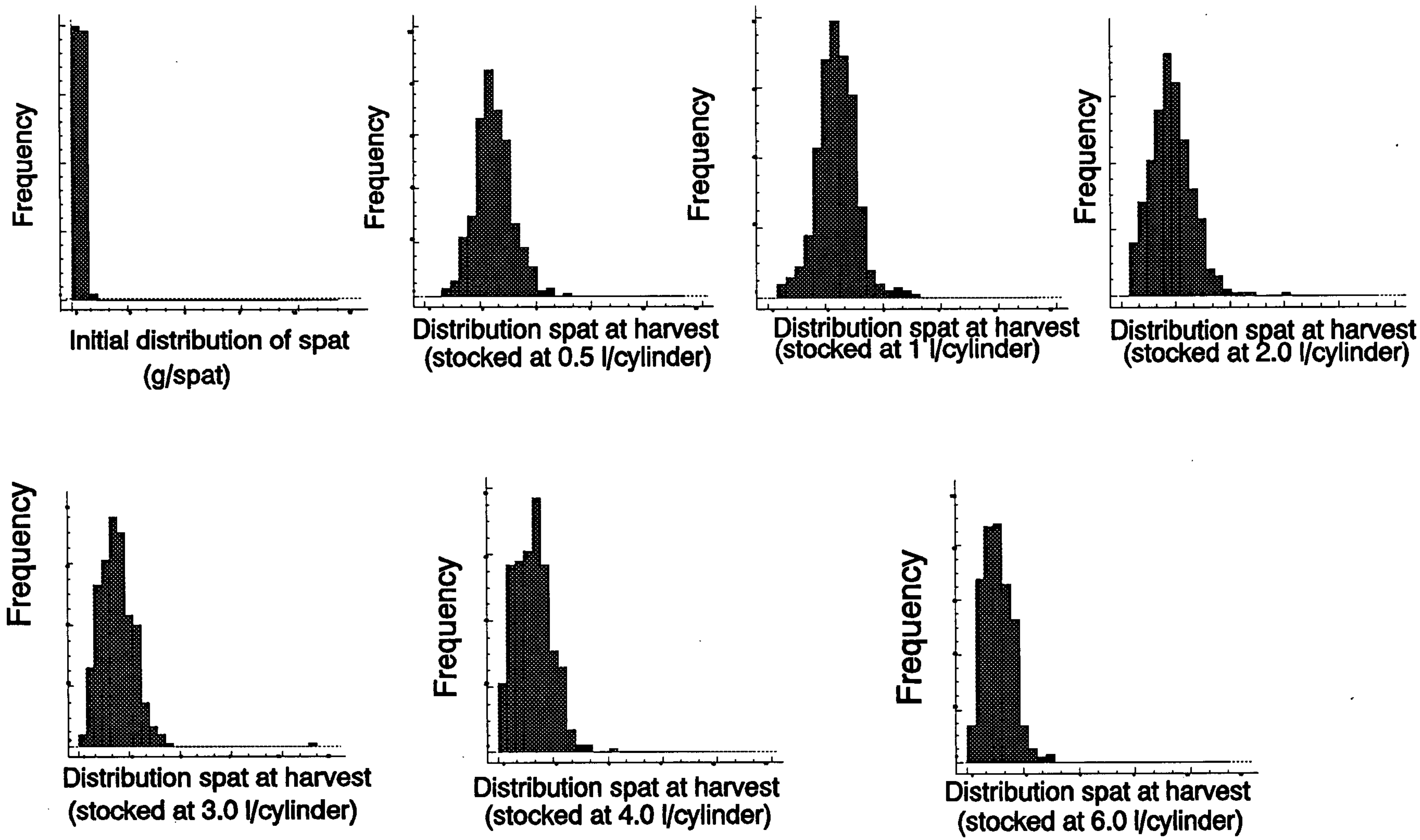

Frequency
Initial distribution of spat
(g/spat)
Frequency
Distribution of spat at harvest
(stocked at 0.5 l/cylinders)
Frequency
Distribution of spat at harvest
(stocked at 1.0 l/cylinder)
Frequency
Distribution of spat at harvest
(stocked at 2.0 l/cylinder)
Frequency
Distribution of spat at harvest
(stocked at 3.0 l/cylinder)
Frequency
Distribution of spat at harvest
(stocked at 4.0 l/cylinders)

Fig 4.8 Frequency distribution of weights at harvest for the larger grade of Sydney rock oyster (*Saccostrea commercialis*) spat (initial weight 0.4 g/spat) stocked at 0.5, 1.0, 2.0, 3.0, 4.0 and 6.0 l/cylinder (February-May; Section 4.2).


Frequency
Initial distribution of spat
(g/spat)
Frequency
Distribution spat at harvest
(stocked at 0.5 l/cylinder)
Frequency
Distribution spat at harvest
(stocked at 1 l/cylinder)
Frequency
Distribution spat at harvest
(stocked at 2.0 l/cylinder)
Frequency
Distribution spat at harvest
(stocked at 3.0 l/cylinder)
Frequency
Distribution spat at harvest
(stocked at 4.0 l/cylinder)
Frequency
Distribution spat at harvest
(stocked at 6.0 l/cylinder)

CHAPTER 5

EFFECTS OF SITE ON PERFORMANCE OF SPAT IN SECTIONALISED TRAYS

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5.1 Introduction

As indicated in Chapter 4, initial attempts by NSW oyster farmers to change from using traditional stick and tray methods to single seed, often resulted in high mortality of spat and variable growth rates. Although investigations revealed that inappropriate nursery systems were initially used, site characteristics may have also affected performances of spat in nursery units (Holliday, 1985; Holliday at al., 1988), as sites can vary greatly in their suitability due to a variety of reasons, including current velocity, natural food levels, water temperature and salinity (Wilson, 1987; Brown and Hartwick, 1988; Spencer, 1990; Hofmann et al., 1994; Section 1.4) and seasonal variation (Hofmann et al., 1992; Dekshenieks et al., 1993). Oyster farming in NSW is a complex operation with the industry established in 40 estuaries. Farms are comprised of a number of leases used for catching spat, nursery culture, growing and fattening with many leases used for several phases of the operation (Section 1.1.5.2). NSW farmers traditionally move their oyster crops to different leases within estuaries and in many cases, between estuaries, to maximise growth and survival, to avoid overcatch on the crop and to improve meat condition for market. Farmers have reported differences in growth and survival of spat and larger oysters at a range of sites within an estuary. Port Stephens has been used to produce medium sized oysters which are bought up to appropriate market size and meat condition in other estuaries eg Brisbane Waters (Fig 2.7).

The majority of spat catching leases in NSW are also vacant for about six months of the year, after the caught sticks have been moved to nursery (depot) leases upstream, to avoid any overcatch of spat. Port Stephens has traditionally been the major source of wild caught spat for the NSW industry.

The objective of this segment was to assess the differences in spat performances among sites in Port Stephens, including a spat catching lease at Pindimar, for nursery culture of single seed Sydney rock oysters. Sectionalised trays were chosen over other nursery units as they had produced good growth and survival rates at a range of densities in Port Stephens (Section 4.1).

5.2 Methods

Three sectionalised trays, described in Section 2.3.1 (Fig 2.14), were positioned at the most commonly used intertidal rack height (Malcolm, 1987) at each of four sites selected from the major farming areas within Port Stephens. Swan Bay (Fig 2.15), North Arm Cove (nursery/growing areas) and Soldiers Point (spat catching/nursery area) are located within the inner Port, and Pindimar (spat catching area) is in the outer Port (Fig 2.8). The site at Soldiers Point located in the middle of Port Stephens (Fig 2.8) was abandoned during the experiment as trays broke up because of excessive wave action.

Sydney rock oyster larvae were settled on chips of scallop shell and the spat held in forced-flow upwellers (Holliday, 1992; Section 2.3.1) prior to the experiment. Trays were stocked with approximately 300 spat/tray section (1200 spat/m^2), estimated on a weight basis for spat with an initial weight of 4.0 ± 0.04 g (n=5 for samples of 300 spat). At three monthly intervals, average spat weight was determined by weighing 100 spat from each section of trays. After six months the amount of spat in each section was reduced by half on a weight basis to prevent overcrowding. Overall mortality was estimated by dividing the total weight of spat harvested from a tray by the average final spat weight. Corrections were made for the above reduction in density. Growth coefficient values (G_{90}) were calculated to allow for differences in sampling periods and initial spat weights (Spencer and Gough, 1978; Section 4.2.2).

Temperature and salinity readings were taken monthly from the three sites at a depth of 1 m, at the time of M.L.W., using a Yeo-Kal temperature/salinity conductivity meter (Yeo-Kal Electronics, Brookvale, NSW, 2100). The experiment was run for 12 months.

5.2.1 *Statistical Analyses*

Growth and survival data were analysed using ANOVA. Survival data were transformed (arcsine $x^{0.5}$) prior to ANOVA. Homogeneity of variance was confirmed using Cochran's test (Winer, 1971). Means compared using Tukey's honestly significant differences method (Sokal and Rohlf, 1981).

5.3 Results

Survival of spat over 12 months was high at each site, but was significantly higher ($P<0.01$) at Swan Bay (96.7±1.8%) than at North Arm Cove (83.9±0.9%) and Pindimar (83.0±2.7%) (Table 5.1). Average weight gain was significantly higher at North Arm Cove than at Swan Bay which was in turn a significantly better site for growth than Pindimar ($P<0.05$; Table 5.1). At North Arm Cove spat grew from 4.0 to 16.3 g in 12 months (Fig 5.1). Overall biomass gain was similar at Swan Bay and North Arm Cove (5.8-6.0 kg/m^2) but was significantly lower ($P<0.01$) at Pindimar (2.6 kg/m^2) (Table 5.1).

Spat grew at different rates (weight gain per unit time) at different times of the year and there were similarities in the growth rate patterns for North Arm Cove and Swan Bay (Fig 5.1). Growth coefficient values (Table 5.2) indicated that spat grew best during August-October and February-April at Swan Bay (0.39±0.02; 0.46±0.05 respectively) and North Arm Cove (0.55±0.04; 0.39±0.02 respectively), while May-July was the poorest period for growth at these two sites (0.11±0.03 and 0.15±0.02 respectively). Growth rates were more uniform throughout the 12 month study at Pindimar (range 0.15-0.35) although, August-October (0.35±0.03) was also the best period for growth (Table 5.2).

For Swan Bay, North Arm Cove and Pindimar, there was little variation in temperature (n=12 [range] 19.3±1.5°C [10.4-25.6°C]; 19.7±1.5°C [12.5-25.7°C]; 19.8±1.3 [13.4-25.6°C] respectively) and salinity (32.0±1.0‰ [24.0-

35.3‰]; 33.1±0.8‰ [27.2-35.6‰]; 33.1±0.8‰ [27.2-35.8‰] respectively) (Fig 5.2; Appendix 9.3). However, there was considerable seasonal variation in temperature among the sampling periods, as indicated by pooled data for the three sites (n=9; Aug-Oct 16.7±0.9°C; Nov-Jan 24.0±0.4°C; Feb-April 23.3±0.9°C; May-July 14.3±0.7°C).

5.4 Discussion

North Arm Cove and Swan Bay proved to be the most suitable nursery sites and provided conditions for the best growth. Differences in environmental conditions at the various sites probably influenced spat performances (Table 5.1). Although there was little difference in the average salinity level among the three sites, North Arm Cove and Swan Bay, located within the inner port, are considered to be more estuarine as they are influenced by the Karuah River (Fig 2.8). Food concentration may have also affected spat growth. A more intensive monitoring of abiotic and biotic variables was conducted at a number of sites in Port Stephens by Richardson (1991), who found quantity and food quality of seston varied between sites in Port Stephens and that chlorophyll *a*, a measure of algal productivity (Brown and Hartwick, 1988), increased towards the upper estuary (probably due to higher nutrient availability). Hofmann et al. (1994) in a simulated model, found that oysters increased in size with increased food concentration and that growth was affected by turbidity, salinity and temperature, and concluded that comparisons between oyster populations could only be made with a complete environmental analysis of the sites.

Data on seasonal variation in spat growth rates using growth coefficient (G_{90}) values (Table 5.2), indicate that August-October and February-April were the better periods for growth at Swan Bay and North Arm Cove. At these two sites, the temperature data, based on pooled monthly readings, indicate that poorest growth occurred during the coolest period (May-July; 14.3±0.7°C). The observation that growth was depressed during the cooler months is consistent with results from other studies (Wisely et al., 1979c; Spencer et al., 1978; Nell and Livanos, 1988; Nell et al., 1994). Similarly, growth coefficient values calculated from growth data in Chapter 4, indicate that, at equivalent initial biomass levels, the slowest growth rates in that 12 month study occurred during the coolest months. While the use of growth coefficient values largely overcomes the problem of differences in initial weights, it should be noted that these values tend to decrease as spat weight increases (Spencer and Gough, 1978). Wilson (1987), concluded that growth of European oysters cultured at a number of sites in Ireland was affected by differences in temperature, organic content and current velocity. Although current velocity was not recorded for this study, it is possible that differences between the three sites may have also affected oyster growth.

The results from this segment have been encouraging and have shown that farmers can maximise growth and survival of juvenile single seed oysters by relocating their crops to different leases within an estuary. Unlike the stick method, single seed oysters can be easily relocated to alternate areas, as large numbers of spat can be contained in relatively few portable nursery units. It is also possible for farmers to capitalise on the better seasonal spat growth at the different sites. Despite the better spat growth rates in the upper-estuary, leases at the more-oceanic site at Pindimar could still be useful, when vacant for six months of the year, for the nursery culture of Sydney rock oysters. Many of the catching leases are now permanently vacant as farmers are using far less lease space for the collection of single seed oysters (on PVC collectors) than that required for tarred hardwood growing sticks.

TABLE 5.1 Performance of Sydney rock oyster (*Saccostrea commercialis*) spat at three sites in Port Stephens, NSW, over 12 months (Section 5.1).

Sites	Average weight[1,2] gain (g/spat)	Survival[1,3] (%)	Biomass[1,4] gain (kg/m^2)
Swan Bay	10.4±0.6[a]	96.7±1.8[a]	6.0±0.5[a]
North Arm Cove	12.3±0.3[b]	83.9±0.9[b]	5.8±0.1[a]
Pindimar	6.0±0.3[c]	83.0±2.7[b]	2.6±0.3[b]

[1] Values are means±SE; (n=3). Within each column means with a common superscript are not significantly different ($P<0.05$).
[2] Average initial weight of spat was 4.0±0.04 g.
[3] Data transformed (arcsine $x^{0.5}$) prior to analysis.
[4] Sectionalised trays were stocked at 1 200 spat/m^2 but midway through the twelve month study, spat densities were reduced by half to prevent overcrowding. Biomass gain values are based on an initial density of 600 spat/m^2.

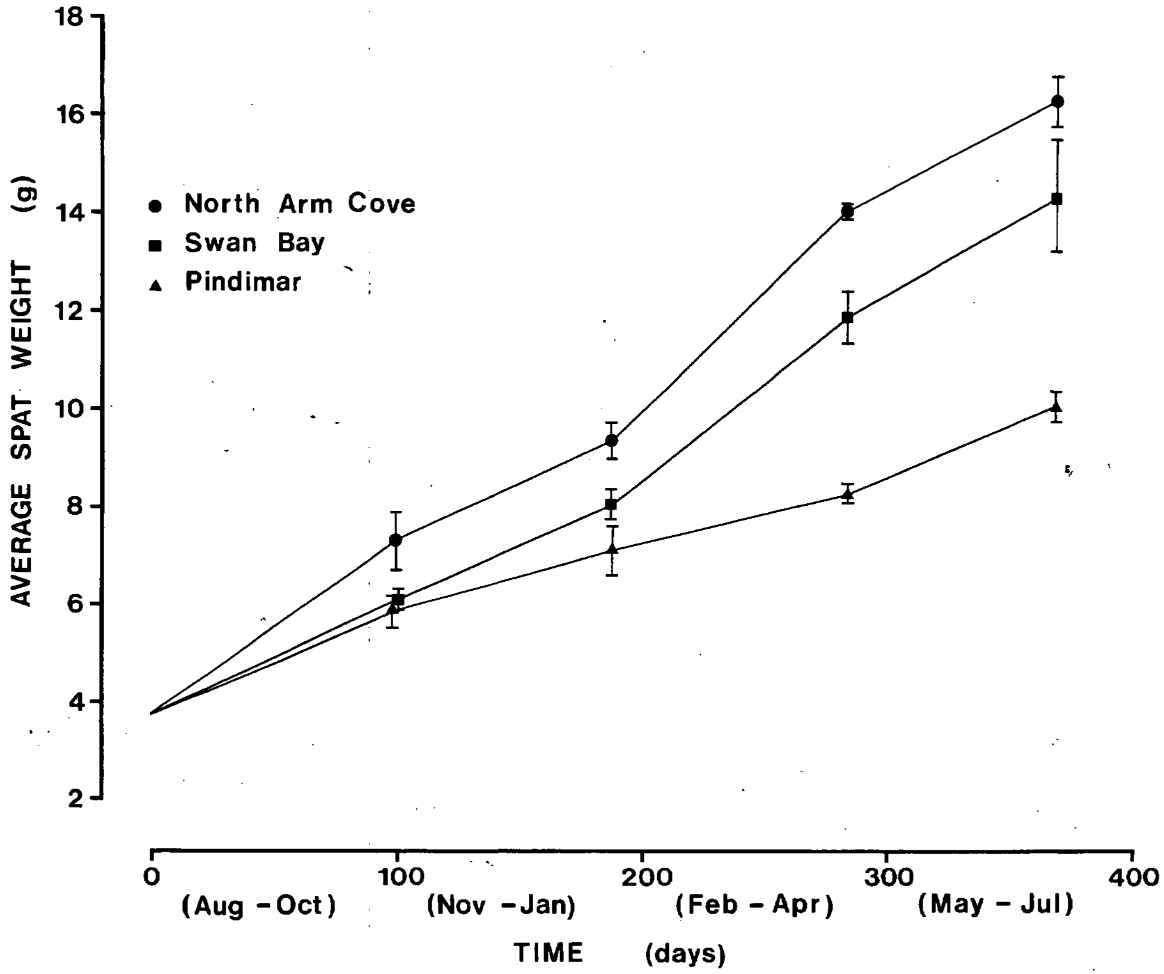
TABLE 5.2 Growth coefficient values for Sydney rock oyster (*Saccostrea commercialis*) spat grown at three sites in Port Stephens, NSW, for 12 months (Section 5.1).[1]

Site	Growth Coefficient (G_{90})[2]			
	Aug-Oct	Nov-Jan	Feb-April	May-July
Swan Bay	0.39±0.02	0.27±0.01	0.46±0.05	0.11±0.03
North Arm Cove	0.55±0.04	0.24±0.06	0.39±0.02	0.15±0.02
Pindimar	0.35±0.03	0.19±0.02	0.15±0.02	0.20±0.02

[1] Values are means±SE; (n=3). Average initial weight of the spat was 4.0±0.04 g. The initial weight for the period between sampling dates was the same as the final weight for the preceding period.

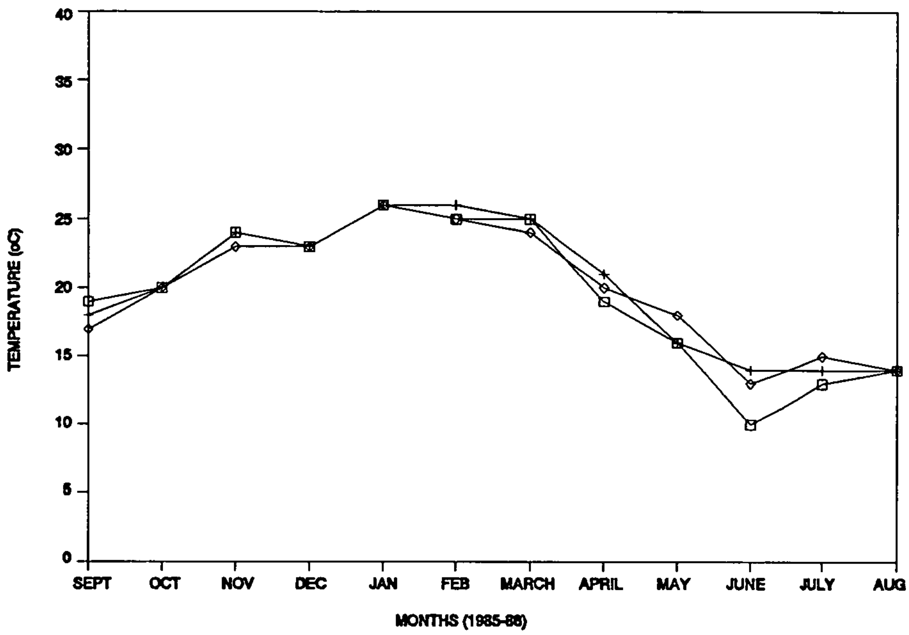
[2] G_{90} = 90/duration (days) x ln (Wt/Wo); Wo and Wt are the average initial and final weights of spat (g/spat) for a period respectively.

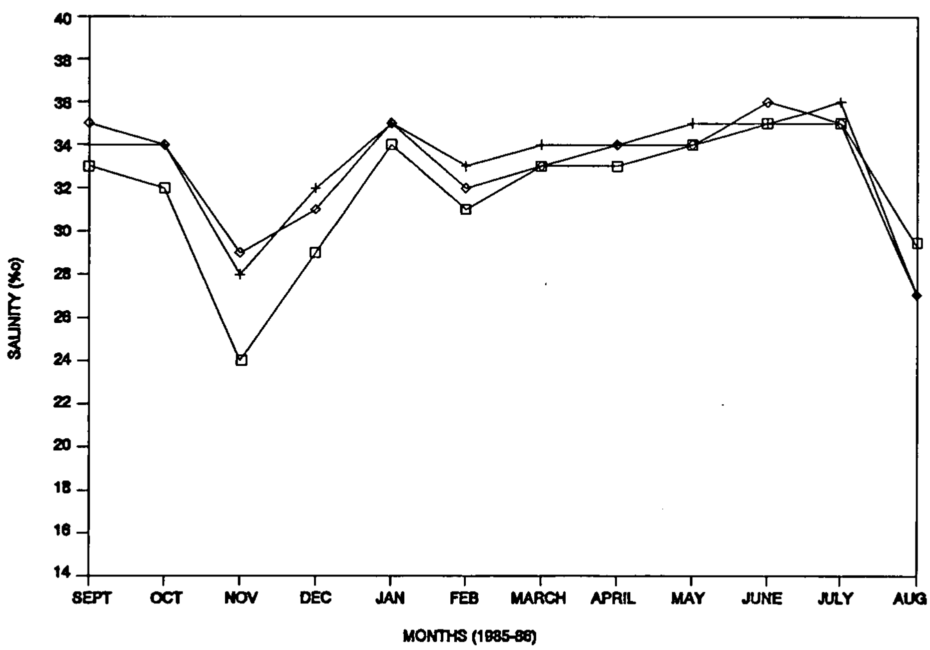
Fig 5.1 Growth of Sydney rock oyster (*S. commercialis*) spat in sectionalised trays over 12 months at three sites in Port Stephens, NSW. Values are means±SD; n=3 (Section 5.1).



AVERAGE SPAT WEIGHT (g)
18
16
14
12
10
8
6
4
2
North Arm Cove
Swan Bay
Pindimar
0
100
200
300
400
(Aug - Oct)
(Nov - Jan)
(Feb - Apr)
(May - Jul)
TIME (days)

Fig 5.2 Monthly temperature and salinity data for Swan Bay, North Arm Cove and Pindimar, Port Stephens, NSW (Section 5.1; Appendix 9.3).





□ SWAN BAY + NORTH ARM COVE ◇ PINDIMAR

CHAPTER 6

COMPARISON OF NURSERY SYSTEMS

6.1 POST-SET NURSERY SYSTEMS

6.1.1 Introduction

In Chapter 3, techniques used to settle cultured oyster larvae on chips of bivalves for transfer to on-shore upwellers and on collectors for the nursery phase on estuarine leases were compared. In this chapter, the performances of spat from these two settlement systems are assessed in subsequent nursery phases.

Spat settled on chips of bivalve shell are usually transferred to on-shore upwellers for the nursery phase (Bayes, 1981; Lucas and Gerard, 1981; Claus et al., 1983; Holliday, 1992). Thomas and Burnell (1992) concluded that Pacific oyster larvae could be settled and grown on solid cultch for about half (56%) the cost of purchasing hatchery seed (4-5 mm) on shell chips. The alternative method of settling larvae on PVC collectors has produced encouraging results for hatchery and nursery operators (Gunn, 1984; Jones and Jones, 1988; Roland and Broadley, 1990; Chapter 3), and unlike spat from downwellers, collectors can be deployed on estuarine leases shortly after settlement, thereby avoiding many of the capital and labour costs associated with on-shore nurseries. However, high losses of wild caught spat were observed from collector types in Section 3.4.

The objective of this segment was to evaluate the performance of juvenile Sydney rock oyster spat on small PVC discs deployed on an intertidal lease, and on chips of scallop shell in on-shore upwellers, using the following criteria: 1) spat growth and survival; 2) spat retention and; 3) variation in spat sizes at harvest and the suitability of spat for stocking into trays and cylinders for growing.

6.1.2 Methods

6.1.2.1 Spat

Sydney rock oyster spat were obtained for the present study from a synchronous settlement described in Section 3.2 (Table 6.1). The spat on small PVC discs (D) were grown in a large fibreglass tank (Fig 2.1B) in a hatchery for 21 days until those settled on chips of scallop shell in downwellers had grown to a suitable size (>0.5 mm) for stocking in on-shore upwellers. Spat were grown in synchronous trials as follows.

6.1.2.2 Nursery sites

Small PVC discs were deployed on the same intertidal lease at North Arm Cove (Fig 2.8) used in Section 5.1; the results in that section confirmed earlier observations that this was a good nursery site, albeit for spat in trays. This lease was protected from wave action by timber, perimeter fences and at the time the area was relatively free from wild settlements of Sydney rock and Pacific oysters. Spat on scallop shell chips were stocked in upweller units at the inlet to Vales Point Power Station, Lake Macquarie (Figs 2.9, 2.12), where salinity levels were consistently high and silt concentrations low (Anon., 1983) and where power and continuous surveilance was readily available. Different sites were chosen to evaluate the different systems as it was not feasible to establish the treatments at both sites, because there was no electricity to operate the pump for the upwellers at North Arm Cove. Initial trials have indicated that the power station inlet was a good site for spat grown in upwellers.

6.1.2.3 Experiment 1-Discs (D)

Initial density of spat (755.0 ± 1.0/disc) on small PVC discs (D; described in Tables 2.1, 3.3; Fig 2.3) was determined at settlement on day 10 (Section 3.2) by counting spat per discs (n=100). Initial size was estimated at day 21 (0.95 ± 0.01 mm/spat) by measuring shell lengths for 50 randomly selected spat using a ruler and microscope, as spat could not be harvested and graded with screens. Five replicate groups, each comprised of three stacks of 20 discs, were enclosed in PVC mesh bags (12 mm) to reduce predation from fish and crabs. Discs were randomly allocated a position on a post and rail frame, with the middle of each stack occupying the traditional growing level on the intertidal lease (Malcolm, 1987). To ensure that overcatch of oysters did not confound results, natural settlement was assessed by regular deployment and inspection of additional stacks of discs. Once deployed, discs were left untouched until harvest; this is consistent with commercial practices involving tarred sticks (Holliday et al., 1988; Nell, 1993) (Table 6.1).

The experiment was run for 41 days from January to February and was terminated when spat were observed growing onto one another. Spat retention and survival were estimated by counting spat from a randomly selected stack (20 discs) from each replicate group (n=5). Spat were later flexed off the discs and graded using 1.7, 3.0, 4.0 and 8.0 mm screens (Section 2.1.6) and post-harvest mortality assessed. Oysters from each replicate stack were then stocked (3266.6±452.4) into PVC cylinders (n=5; described in Section 2.3.1.3) and grown for 35 days (February to March; Table 6.1). Cylinders were covered with a fine mesh (1.5 mm) to retain spat and were positioned on the same intertidal lease used for settlement (Fig 1.2A; Section 3.4). Spat were harvested from cylinders (at day 97), graded, using screen sizes of 4.0, 8.0 and 12.0 mm and live and dead spat counted from each grade.

6.1.2.4 Experiment 2 - Upwellers

Spat stocked in upwellers (described in Section 2.3.1.1; Figs 2,2B, 2.12) were graded with 0.5 and 0.7 mm screens (described in Section 2.1.7; Table 2.2) and numbers were estimated from volume and by counting spat in 1 ml subsamples (n=4). The two grades consisted of $104.5 \pm 1.1 \times 10^4$, 0.5 mm spat and $12.2 \pm 0.1 \times 10^4$, 0.7 mm spat. Both grades were initially stocked into two upweller screens (with 0.5 mm mesh screens; Fig 2.2B), using a commercial technique of covering screen surfaces with a thin layer of spat (Frankish et al., 1991). As spat grew, they were washed daily to remove silt and faeces and graded (at 2 week intervals), thinned and restocked at uniform sizes and at reduced densities (Bayes, 1981; Frankish et al., 1991; Holliday, 1992). Eventually, spat filled 15 upweller screens (mostly with larger meshes), in two upweller tanks (Fig 2.12). Flow-rates for upwellers ranged from 6-12 l/min depending on spat size and density and were based on the commercial technique of maximising flow without washing spat out the overflow (Frankish et al., 1991). At harvest, spat were graded using 0.5, 1.7, 3.0, 4.0 and 8.0 mm screens, and numbers for each grade estimated by weight and by counting live and dead spat from 1 ml subsamples (n=5). This experiment was run for 102 days from January to April (Table 6.1).

6.1.2.5 Statistical analysis

For Experiment 1, differences between layers of discs were assessed using one-way ANOVA. Numbers of spat retained on discs were transformed ($\log_{10}x$) prior to ANOVA. Homogeneity of variance was confirmed using Cochran's test (Winer, 1971) and means compared using Tukey's honestly significant difference method (Sokal and Rohlf, 1981).

TABLE 6.1

Steps used to settle Sydney rock oysters, *Saccostrea commercialis*, in a hatchery and grow spat in synchronous experiments on small PVC discs (D) and in upwellers (Sections 3.2, 6.1).

DAY	ACTIVITY	
	Section 3.2 - Settlement	
1	Larvae stocked in 3 000 l tank with on PVC discs (D; 15 stacks, 20 D/stack).	Larvae stocked in 4 downwellers with chips of scallop shell.
10	Settlement completed.	
15		Settlement completed.
	Section 6.1 - Nursery *Experiment 1*	*Experiment 2*
21-Jan	Spat on discs (15 stacks in 5 PVC bags with 3 stacks/bag) deployed at North Arm Cove.	Upwellers (2) stocked with 0.5 and 0.7 mm spat at inlet to power station, Lake Macquarie.
62-Feb (41 of exp)	Spat harvested from discs and deployed at Salamander Bay in 5 cylinders, to assess post-harvest survival.	
118-Mar (97 of exp)	Spat harvested from cylinders.	
133-Apr (102 of exp)		Spat harvested from upwellers. Spat now contained in 15 upwellers.

6.1.3 Results

6.1.3.1 Experiment 1-Discs

Spat were harvested from discs at day 41 because spat were observed forcing one another off the discs as competition increased for the limited space. Spat growth was excellent (5.7 ± 0.5 mm shell length increase; n=5; Table 6.2), however, only an estimated 5.9 ± 0.7% of spat that settled on discs in the hatchery were retained (Table 6.2), and survival was low (4.6 ± 0.7% spat/disc; n=5; Table 6.2). For replicate stacks, density at harvest was 1.2 spat/cm^2 (range 0.3-2.8 spat/cm^2; n=5), with an average of 317 ± 37 spat retained/disc. Retention of spat was similar ($P>0.05$) on the 20 layers of discs (Fig 6.1; Appendix 9.2).

There was a wide variation in spat sizes on discs at harvest (range 3.1-19.9 mm/shell length) and percentages for the various grades retained at harvest are presented in Table 6.3. An estimated 85.2% of spat harvested from discs were of a suitable size for stocking into commercially-used 3 mm PVC mesh covering sectionalised trays or PVC cylinders. Post-harvest survival of spat at day 97 from PVC cylinders, was high (97.5 ± 0.5%; n=5) and relative amounts of spat retained on the 4, 8 and 12 mm screens are presented in Table 6.4. Negligible (< 1 spat/disc) settlements of oysters or barnacles were recorded on control discs during this experiment.

6.1.3.2 Experiment 2 - Upwellers

Spat growth (shell length increase) in upwellers at harvest was poor (1.6 ± 0.01 mm/spat; n=5), however, survival and retention were high (69.3 ± 0.7% and 97.7% respectively; n=5) compared with discs. There was a wide variation in spat sizes at harvest with percentages for the various grades presented in Table 6.3. Only 24.3% of the total spat harvested from upwellers were suitable for stocking in nursery units covered with commercially-used 3 mm PVC mesh (Table 6.3).

6.1.4 Discussion

Although a comparison is drawn in this section, between performances of spat on small PVC discs grown on an intertidal lease and single seed oysters grown in on-shore upwellers, caution must be used when interpreting the results, as the different nursery systems were established at different sites and as the experiments were terminated at different times (Table 6.1).

Spat grew much faster on discs with spat harvested 61 days earlier than from upwellers, however, survival and retention (4.6% and 5.9% respectively) were lower compared to upwellers (69.3% and 97.7% respectively). Both retention and survival were examined in this study to help with the evaluation of the nursery systems by differentiating between mortality and physical loss of spat from discs. Eckmayer (1983) also found growth was greater for hatchery reared *C. virginica* spat set on mylar sheeting than those set on crushed oyster shell and also recorded high mortality with hatchery spat grown in the wild. In the present study, the majority of mortality from discs was from the physical loss of spat and hence the poor retention. This loss probably resulted from overcrowding; as spat grew, so did competition for the limited space, and the loss may have been avoided if they were harvested earlier. High mortality of spat was observed in the centre of the underside of the discs and probably resulted from the build-up of air, observed being trapped under the discs with rising tides. Despite the apparent low retention of spat on discs (1.2/cm^2; 317$\pm$37 spat/disc), harvest density was much better than that obtained by commercial operators in British Columbia, who expect to harvest (at 4 months) an average of 72, 10 mm spat (0.1 spat/cm^2) Pacific oyster spat from round grooved PVC sticks (Roland and Broadley, 1990). NSW farmers using this type of disc now position the stacks on a slight angle to release any air bubbles trapped beneath them. Alternatively, large PVC discs with holes to release trapped air, can be used (Fig 3.6).

Environmental conditions may have also affected the performances of the newly settled spat on discs. Greater survival and retention were recorded from the same type of disc deployed in the spat catching area in Salamander Bay (Fig 2.8) during a similar period (Section 3.4). Salamander Bay is closer to the entrance and considered to be a more oceanic site (with a lower silt load) than at North Arm Cove (a middle harbour site; Section 5.1). In the present study conducted during summer, spat growth in upwellers was slower compared to discs, however, good growth was obtained in a later study conducted at the same site, in winter (Section 6.2). Bayes (1981) concluded that turbidity may affect growth and survival of juvenile Pacific oyster spat and that nursery sites with the lowest silt load sustain the highest survival rates. Quayle and Newkirk (1989) suggested that high silt levels could interfere with the oysters filtration activities and affect their feeding efficiency. High salinities (33.6 ± 1.4‰; Section 6.2) and low silt loads (3.6 ± 0.7 mg/l total suspended solids) were also recorded at the Vales Point Power Station during the present study (Nell, 1987) and are consistent with those for Salamander Bay (Richardson, 1991).

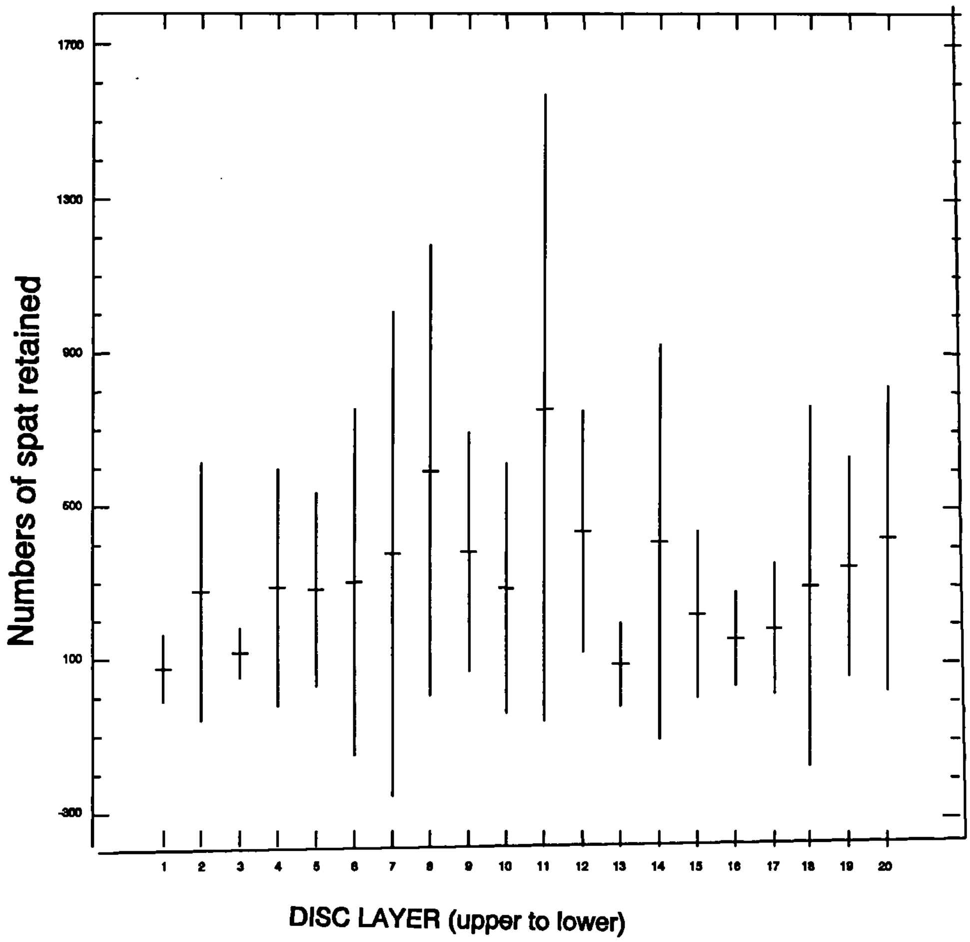
Both nursery systems had a wide range of spat sizes at harvest (Table 6.3). A large variation in spat sizes is undesirable, as it increases the necessity for grading spat (Newkirk, 1981; Askew, 1987; Section 4.1). However in this section, 85.2% of spat harvested from discs were suitable for stocking and growing in nursery units covered with the larger 3 mm commercially-used PVC mesh used by farmers.

Costs of establishing and operating a nursery will ultimately influence the farmers choice of nursery systems. Foreshore sites in NSW in areas considered suitable for on-shore nurseries are often relatively expensive compared to intertidal nursery leases. The management technique for discs (and other collectors) deployed on leases is also simpler and cheaper compared to upwellers which require daily washing and weekly grading of spat. The method of collecting and growing spat on collectors is described by NSW farmers as "the set and forget method", as collectors receive little or no attention from deployment to harvest. Moreover, in the present study, spat production may have increased if discs had been harvested earlier. Using spat costs, survival and retention as the criteria, upwellers proved to be the most suitable nursery unit for growing juvenile hatchery spat (initial size range 0.5-0.7 mm), as survival and retention (69.3% and 97.7% respectively) were greater than for discs 4.6% and 5.9% respectively). Spencer et al. (1992)

concluded that when initial costs of spat are high, survival may be the appropriate criteria for spat management (labour), which can account for up to 62% of production costs in the first year (Spencer et al., 1985).

Despite the poor retention and survival of spat on discs, growth rate was encouraging. It may be possible to improve survival and retention of spat on discs by harvesting them earlier, by positioning discs on an angle (to release trapped air) and by using nursery sites with lower silt concentrations than those used in this study. Based on survival and retention, upwellers were the best system for newly settled Sydney rock oyster spat from the hatchery (initial size range 0.5-0.7 mm). However it should be noted that, although spat survival was high in upwellers in this section, subsequent survival of spat in upwellers in NSW has been consistently low (Frankish et al., 1991; Nell et al., 1991) and the cause of this mortality is the subject of current investigation.

Fig 6.1 Retention of Sydney rock oyster (*S. commercialis*) spat on vertical stacks (20 discs/stack) of small, PVC discs at North Arm Cove, Port Stephens, NSW (means±95% confidence interval; n=5; Experiment 1, Section 6.1).



Numbers of spat retained
1700
1300
900
500
100
-300
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
DISC LAYER (upper to lower)

TABLE 6.2

Average growth, survival and retention of juvenile Sydney rock oysters (*Saccostrea commercialis*) for combined grades from small PVC discs and upwellers (Experiments 1 and 2; Section 6.1).

Nursery System	Shell Growth[1] (length increase) (mm)	Survival[1] (%)	Retention[1,2] (%)
Experiment 1[3]			
Discs	5.7 ± 0.5	4.6 ± 0.7	5.9 ± 0.7
Experiment 2			
Upwellers	1.6 ± 0.01	69.3 ± 0.7	97.7 ± 1.0

1 Values are means±SE; n=5.
2 Total spat retained by the nursery system at harvest.
3 This experiment was terminated 61 days earlier than Experiment 2.

TABLE 6.3

Size distribution of Sydney rock oysters (*Saccostrea commercialis*) harvested from small PVC discs (D) and upweller units (Experiments 1 and 2; Section 6.1).

Size Ranges Stocked (mm)	Size Grades of Spat at Harvest (mm)				
	0.5	1.7	3.0	4.0	8.0
	Size distribution of spat (%)[1,2]				
Experiment 1[3]					
Discs					
0.95	-	15.4±2.4	35.0±2.0	40.1±2.6	9.5±1.3
Experiment 2					
Upwellers					
0.6	3.4±0.1	72.2±0.6	21.0±0.3	2.6±0.1	0.7±0.1

[1] Values are means±SE; n=5.
[2] Spat from various nursery units graded on nominal screens.
[3] This experiment was terminated 61 days earlier than Experiment 2.

TABLE 6.4

Survival of Sydney rock oyster (*Saccostrea commercialis*) spat (at day 97), grown in PVC cylinders for 35 days after being harvested at day 62 from small PVC discs (Experiment 1; Section 6.1).

Screen sizes (mm)	Spat per grade[1] (%)	Survival[1,2] (%)
4.0	11.5 ± 1.6	99.5 ± 0.1
8.0	35.2 ± 1.8	97.7 ± 0.8
12.0	53.4 ± 3.3	95.4 ± 0.7

[1] Values are means±SE; n=5. Spat were stocked at 3267±452/cylinder.
[2] Live spat at harvest.

6.2 NURSERY SYSTEMS FOR SMALLER SPAT (1.6 g) - USING THERMAL EFFLUENT [*Published (1991), **Fisheries Bulletin** 5: 1-7*]

6.2.1 Introduction

In Section 4.1, small single Sydney rock oysters (1.6 g/spat) were successfully grown in sectionalised trays on intertidal leases in Port Stephens. However, growth for that experiment and a subsequent experiment (Section 5.1) using larger spat (4.0 g/spat), was depressed during the cooler months. The observation that growth rates of spat were depressed during cooler months was consistent with the findings of (Wisely et al., 1979c; Spencer et al., 1978; Nell et al., 1994). An option to enhance the culture of juvenile oysters is through the use of thermal effluent (Jones, 1976; Margraf, 1977; Malouf, 1981). Aquarium studies also indicated that, in the presence of excess food, Sydney rock oyster spat grew best at high water temperatures (30°C; Nell and Livanos, 1988). The objective of this segment was to assess the performance of small Sydney rock oysters in sectionalised trays and in forced-flow upwellers using thermal effluent during the cooler months.

6.2.2 Methods

This experiment was established at three sites: the Swan Bay lease used in Sections 4.1 and 5.1 (Fig. 2.8), the inlet channel of Vales Point Power Station used in Section 6.1 and the outlet (primary effluent pond) of Vales Point Power Station. Vales Point is at Lake Macquarie (Fig. 2.9), about 100 km south of Port Stephens (Fig 2.7). Upwellers were used at the inlet and outlet sites at the power station while sectionalised trays were used at the outlet site and on the intertidal lease in Swan Bay. As the water level in ponds at the outlet site was constant, trays at this site had to be subtidal. Upwellers could not be installed on the lease at Swan Bay, as there was no electricity to operate the pump. It was also not feasible to install trays or cylinders in or adjacent to the inlet channel at the power station because of the strong current.

Four forced-flow upweller units described in Section 2.3.1.1, were positioned vertically at the inlet channel and the primary effluent pond (Fig 2.13). Water was pumped from the effluent pond rather than the outlet channel because turbulence in the channel produces gas bubbles which may have deleterious effects on oysters (Malouf et al., 1972). Surface water from the outlet channel is diverted into the primary effluent pond. Hatchery produced spat were grown in forced upwellers prior to stocking at 1 000 spat/unit. Each week the units were cleaned and seawater flow rates through each unit maintained at 32 l/min (20 ml/min/g). Although Spencer (1990) recommended flow rates of 20-50 ml/min/g for Pacific oysters in upwellers, higher flow rates were not possible for this study as spat would have washed out with the overflow. Four sectionalised nursery trays were stocked with oysters with three sections of each tray (comprised of six sections), stocked with 400 spat/section (1600 spat/m^2). The sectionalised trays were positioned subtidally on a fixed timber frame at a depth of 0.5 m in the primary effluent pond. All dead oysters in the upwellers and trays were counted to estimate survival rates and weight gain values were based on initial and final samples of 100-400 spat/replicate. The average initial weight of the spat was 1.63±0.03 g (n=16 groups of spat).

Weekly temperature and salinity readings were obtained (using a thermometer and hydrometer) at Swan Bay from data recorded at a commercial oyster purification plant adjacent to the nursery lease and from the inlet and outlet sites at the power station. The experiment was run for 18 weeks from April to September.

6.2.2.1 Statistical Analysis

T-tests (Winer, 1971) were used to compare oyster survival, average spat weight gain and biomass gain values for sites where similar nursery systems were used. Survival data were transformed (arcsine $x^{0.5}$) prior to analysis and homogeneity of variance was confirmed using Cochran's test (Winer, 1971).

6.2.3 Results

The best growth (4.1±0.2 g/spat for whole oyster weight gain), survival

(99.1±0.3%) and biomass gain (4.0±0.2 kg/1 000 spat stocked) results were obtained in the upwellers at the inlet channel site (Table 6.5). The poorest results for growth, survival and biomass gain were recorded at the primary effluent pond site in upwellers (0.3±0.1 g/spat, 84.6±0.7% and -0.1±0.4 kg/1000 spat stocked, respectively) and trays (1.7±0.2 g, 30.8±0.1% and -0.03±0.2 kg/1 000 spat stocked, respectively). The intertidal sectionalised trays in Swan Bay produced good growth (2.6±0.2 g), survival (85.0±2.8%) and biomass gain (1.9±0.2 kg/1 000 spat stocked) results (Table 6.5).

There was little difference in salinity among the three sites. Average values [n=24 (range)] were as follows: 33.6±0.3‰ (31-36‰) at the inlet, 33.5±0.3‰ (31-36‰) in the primary effluent pond and 31.6±0.6‰ (26-36‰) at the intertidal site in Swan Bay. There was considerable variation in average water temperature. Average values [n=24 (range)] were: 18.5±0.7°C (14-28°C) at the inlet, 23.1±0.8°C (19-35°C) in the primary effluent pond, and 14.9±0.7°C (11-21°C) for the Swan Bay site. Thus, water temperatures at the inlet and outlet sites were, on average, 3.6 and 8.2°C higher than in Port Stephens, respectively (Fig 6.2).

6.2.4 Discussion

As it was not possible to install both trays and upwellers at all three sites, direct comparisons among sites must be interpreted with caution. However, by far the best growth, survival and biomass gain results were recorded from upwellers at the inlet site. Spat in trays at Port Stephens also grew well with a high survival rate (Table 6.5). Spat in upwellers and trays at the outlet site either grew poorly or suffered higher mortality than those in upwellers at the inlet channel. In contrast, Margraf (1977) obtained faster growth of the *C. virginica* in the outlet channel of a power station than in the inlet channel or at an estuarine control site. The difference between growth of spat in trays at the outlet site and Port Stephens was even more notable as trays were subtidal at the outlet site and intertidal in Port Stephens. Previous studies on leases showed that subtidally grown Sydney rock oysters (30-39 g) had a growth rate twice that of intertidally grown oysters (Wisely et al., 1979c; Nell, 1989).

Growth rates of juvenile spat could be enhanced during cooler months by using thermal effluent from a power station. Previous studies in Lake Macquarie (Anon., 1983) showed that water at the inlet to the Vales Point power station had consistently higher winter minimum and summer maximum water temperatures than other areas in Lake Macquarie distant from the power station. During the present study, the inlet site was on average 4.6°C colder than the primary effluent pond although it was 3.6°C warmer (from mixing with the heated outlet water) than the control site in Swan Bay, Port Stephens. Nell and Livanos (1988) found that in the range 12-30°C, growth rates of Sydney rock oyster spat, fed to excess, increased as temperature increased. In the present study, temperatures in the effluent pond were well in excess of 30°C (maximum 35°C).

Malouf (1981) concluded that there are many factors which can adversely affect bivalves grown in thermal effluent, including temperature fluctuations, contamination of effluent with chlorine, increased disease risks and inadequate food levels to sustain the metabolic requirements of poikilothermic animals at elevated temperatures. Hodgson (1979) suggested that thermal effluent from Vales Point Power Station may have a growth limiting effect on entrained phytoplankton, perhaps due to mechanical damage, chlorination and turbidity in the thermal plume; however, he found no significant difference in chlorophyll *a* levels between the inlet and outlet sites. In addition, the primary effluent pond was designed to receive floating hydrocarbon contaminants that were skimmed off from the outlet channel, although, in this segment there was no evidence of hydrocarbon contamination. It is not clear which, if any, of these factors actually depressed growth and survival rates in the primary effluent pond.

Even greater growth rates may have been possible if higher flow rates in upwellers could have been maintained. It is worth noting that for upwellers, stocking density and an increase in biomass can be compensated by increasing flow rates, with effective flow rates ultimately dependent on design of units (Spencer, 1990). For maximum growth of Pacific oyster spat, Spencer (1990) recommended increasing flow rates in upwellers from 20 to 50 ml/min/g live spat, when food content of the water was low and to maintain the optimum filtration rate of oysters at 20% (Spencer, 1988). Despite using lower flow rates than recommended by Spencer (1988), the greatest growth and survival in the present study was from spat in upwellers.

The results from this segment have been encouraging and shown that growth and survival of small Sydney rock oyster spat can enhanced during the cooler months using forced-flow upwellers and intake water indirectly heated by a power station. Following the completion of this study, a commercial nursery facility for Sydney rock oysters was established at the inlet to Vales Point Power Station.

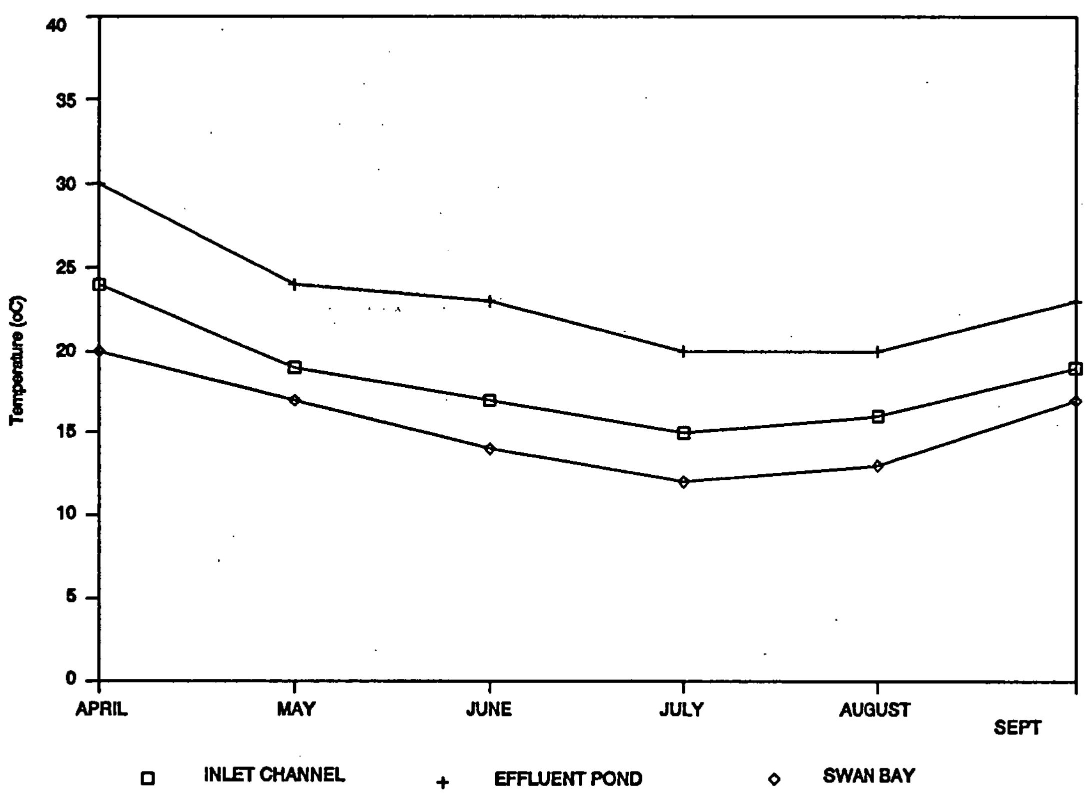
TABLE 6.5 Growth and survival data of Sydney rock oyster (*Saccostrea commercialis*) spat grown at the inlet and outlet to Vales Point Power Station and on an intertidal lease in Swan Bay, Port Stephens, NSW (Section 6.2)[1].

Sites	Average Weight[2] gain (g/ spat)		Survival (%)		Biomass Gain (kg/1000 spat stocked)	
	Upweller	Tray[3]	Upweller	Tray	Upweller	Tray
Power Station Inlet Channel	4.1 ± 0.2^a	----	99.1 ± 0.3^a	----	4.0 ± 0.2^a	----
Power Station Effluent Pond	0.3 ± 0.1^b	1.7 ± 0.2^a	84.6 ± 1.2^b	30.8 ± 0.1^a	-0.1 ± 0.4^b	-0.03 ± 0.2^a
Swan Bay	-----	2.6 ± 0.2^b	-----	85.0 ± 2.8^b	-----	1.9 ± 0.2^b

[1] Values are means±SE; n=4. Within each column means with a common superscript are not significantly different ($P<0.05$).
[2] Average initial weight was 1.63 g/spat. Spat were stocked in trays at $1200/m^2$ and 1000 spat/upweller.
[3] Trays were subtidal at the effluent pond and intertidal at Swan Bay.

Fig. 6.2

Temperature data for the inlet and effluent pond at Vales Point Power Station, Lake Macquarie and the intertidal site at Swan Bay, Port Stephens, NSW (n=4; Section 6.2).



40
35
30
25
20
15
10
5
0
Temperature (oC)
APRIL
MAY
JUNE
JULY
AUGUST
SEPT
INLET CHANNEL
EFFLUENT POND
SWAN BAY

6.3 NURSERY UNITS FOR LARGER SPAT (4.1 g)

6.3.1 Introduction

In Sections 4.1 and 4.2, good growth and survival were observed in sectionalised trays and PVC cylinders for a range of Sydney rock oyster spat sizes. In this section, a number of different types of nursery units were evaluated for the final nursery phase for larger Sydney rock spat.

Nursery systems used globally for oyster production are often based on single seed techniques (Section 1.3) including lantern nets, submerged trays, floating upwellers, tide-powered upwellers, PVC baskets made of folded mesh, PVC envelopes, intertidal sectionalised timber trays and PVC cylinders and PVC and wooden stackable trays (Bayes, 1981; Lucas and Gerard, 1981; Spencer and Hepper, 1981; Holliday et al., 1988; Spencer, 1990; Spencer, 1990; O'Sullivan, 1993; Robert et al., 1993). However, when comparing the performance of smaller spat (initial size range 9-20 mm/spat) then those used in this section, Nell (1991b) found that growth rates in cylinders were lower than for trays, and concluded that cylinders were unsuitable for leases exposed to wave action. Robert et al. (1993), using similar sized Pacific oyster spat to those used in the present study, also found that spat growth rates in cylinders were lower than for spat grown in PVC mesh bags. An increasing number of NSW oyster farmers are also now growing single seed oysters in PVC baskets made of folded mesh (Section 1.1.5.2; Fig 6.3; Nell, 1993).

As there had been no comparison of the different types of nursery units for larger single spat, the objective of this segment was to compare sectionalised trays, PVC cylinders and PVC baskets for the culture of Sydney rock oyster spat using the following criteria: 1) growth and survival of spat; 2) the level of mudworm infestation in spat and; 3) susceptibility of the nursery systems to marine fouling, particularly mussel settlement. Upwellers were not used in this study as they could not be installed on the intertidal lease and as there was no electricity to operate the pump.

6.3.2 Methods

6.3.2.1 Nursery units

Sectionalised trays, baskets and cylinders (n=4; Figs 2.14, 2.18, 2.16) as described in Section 2.3, were each divided into two compartments/replicate and covered with 9 mm PVC mesh. For each tray, only two of the six compartments (0.25 m^2 area/compartment) were stocked with spat. Cylinders were equally divided into two compartments/replicate (0.16 m^2 available surface area/compartment) by a 9 mm PVC mesh partition and both compartments were stocked with spat. For each replicate, two baskets (0.13 m^2 area/basket) were joined with two oyster sticks and both baskets were stocked with spat (Fig 6.3).

6.3.2.2 Stocking

Spat were obtained from sectionalised nursery trays from Port Stephens. Average initial whole weight and length of the spat were 4.1±0.5 g and 35.7±1.9 mm respectively (n=360). Trays, cylinders and baskets were stocked with 90 (0.15 g spat/cm^2), 50 (0.13 g spat/cm^2) and 30 (0.38 g spat/cm^2) Sydney rock oyster spat/unit respectively, at densities that covered 25% of the useable surface area (based on a visual assessment of spat coverage). This density was well below that recommended in Sections 4.1 and 4.2, for maximum biomass gain of Sydney rock oysters in sectionalised trays and cylinders and below that recommended by Spencer (1990) for Pacific oyster spat (0.5-1.0 g/cm^2) in trays with meshes of 5 mm or larger, but considered suitable for maximising individual oyster weight gains (Section 4.1). The lower stocking density was also used to reduce the effects of density on growth and to avoid the need to thin spat numbers during the experiment. For cylinders, maximum individual oyster weight gain for 0.2-0.4 g/spat was obtained with slightly lower stocking densities of 0.09 and 0.08 g/cm^2 respectively (Section 4.2). However it should be noted, that useable surface area of cylinder is based on an estimate.

6.3.2.3 Site

Trays, baskets and cylinders were deployed on timber post and rail frames at the traditional growing height, on a sheltered intertidal growing lease (enclosed by a fence to exclude waves) in the Hastings River (Figs 2.11, 6.3). Cylinders were positioned at the same growing height used by NSW farmers, although, they were immersed for longer periods during ebb tides and rotated and hung 300 mm below the other types of growing units (Fig 2.16). The lease was divided into two zones to assess differences in environmental conditions over the length of the lease. For each treatment, replicate units (n=2) were randomly allocated to a position in each zone. At harvest, whole weights and lengths (30 oysters/compartment) were recorded and oysters opened (10/compartment) and examined for mudworm infestation. Data from replicate compartments were combined for analysis. The experiment was run for 220 days from December to July.

6.3.2.4 Statistical analysis

Two-way ANOVA was used to determine if zone, nursery system and or interaction between zone and nursery system were significant. Data from zones were combined, as zone had no effect ($P>0.05$) on growth or survival and analysed using a one-way ANOVA. Homogeneity of variance was confirmed using Cochran's test (Winer 1971). Mortality data was transformed (arcsine $x^{0.5}$) prior to ANOVA. Means were compared using Tukey's honestly significant difference method (Sokal and Rohlf, 1981). An analysis of covariance of data from replicates was used to assess the effect of decreasing density (mortality) on spat growth.

6.3.3 Results

Growth of spat (whole weight gain) was significantly ($P<0.05$) greater in PVC baskets (14.2 g/spat) than in trays (11.6 g/spat), and significantly greater in trays than in cylinders (9.8 g/spat; Table 6.6). Oyster shell length was similar ($P>0.05$) in trays (53.1 mm/spat) and baskets (52.6 mm/spat), but smaller ($P<0.05$) in cylinders (39.9 mm/spat; Table 6.6). Spat growth for each type of growing unit was independent of density and hence did not increase with mortality and/or with the reduced spat density ($P>0.05$). Mortality and the incidence of mudworm in trays (9.2 and 2.5% respectively) were significantly lower than in baskets (23.8% and 22.5% respectively) or in cylinders (77.8% and 94.1% respectively) (Table 6.6). Oysters in the baskets and cylinders were heavily covered in hairy mussels (*Trichomya hirsuta*) and in many instances, oysters and mussels were joined together in clumps. No mussels were found on oysters in trays.

6.3.4 Discussion

The higher growth rate of oysters in baskets compared to those in sectionalised trays and cylinders may have resulted from restricted water flow, as tray compartments were divided with timber partitions and cylinders constructed with solid PVC end caps. When comparing oyster growth rates in two nursery systems, Lucas and Gerard (1981) recorded the best growth from systems that allowed maximum water flow. Spat growth for each type of nursery unit, was not density dependent and did not increase with mortality and with reduced spat density. There was also no pattern between growth and density for the various types of nursery units, as spat in cylinders had the highest mortality (78%) and the lowest growth and density. The use of low stocking densities (25% coverage of effective surface area) could explain the lack of density effects on growth.

Cylinders had the lowest spat growth of the three types of nursery units tested (Table 6.6). The difference is even more noticeable as spat in cylinders were submerged for longer periods than those in trays and baskets. Wisely et al. (1979a) and Nell (1989) found a correlation between increased immersion time and higher growth rates of Sydney rock oysters. Nell (1991b) and Robert et al. (1993) attributed the slower growth of sydney rock and Pacific oyster spat respectively to wave action and the subsequent tumbling of spat in cylinders and Robert et al. (1993) suggested locking them in position during the growing season to improve shell growth. The regular movement of the revolving cylinders may have removed new growing edge (frill) from spat, however, in the present study, the lease was in a sheltered area and well protected from severe wave action by a timber, perimeter fence.

Oyster growth in the cylinders was probably affected by the high incidence of mudworm infestation (94.1%), as mudworm can accumulate silt within the shell cavity and affect the oysters ability to filter and feed (Skeel, 1979). The higher infestation rate of oysters in cylinders compared to those in trays (2.5%) or baskets (22.5%) may have resulted from the lower growing level and longer immersion time (Skeel, 1979). Wisely et al. (1979a) also attributed high mortality (55%) of Sydney rock oysters grown subtidally in the Hawkesbury River (Fig 2.10) in trays, to mudworm infestations. The lack of wave action on the sheltered lease may have also assisted the worm by allowing the build-up of silt on spat. The presence of hairy mussels on spat in baskets and cylinders may also have assisted the spread of mudworm, as mussels clumped oysters together, reducing circulation and aiding the build-up of silt and the retention of moisture during exposure at low tide. Intertidal culture was adopted in NSW to avoid worm infection and to dry and kill the worm by exposing the crop at low tide (Holliday et al., 1988; Skeel, 1979). It is not clear why large numbers of mussels settled and grew in baskets and cylinders and not in the trays and this warrants further investigation.

Although oyster growth rates in cylinders were lower than other types of units in this study, cylinders are widely used by the NSW industry (Holliday et al., 1988; Nell, 1993). Caution must also be exercised when applying the results from this study to other estuaries, as variables that affect growth and survival, including disease, parasites, floods and fouling organisms, can change between estuaries (Wisely et al., 1979b). In contrast to this study, good growth and survival were recorded for Sydney rock oyster spat grown at a range of densities in cylinders in the Hawkesbury River (Section 4.2), and they have been found to be advantageous for improving meat and shell quality and carbohydrate content in larger (20 g/oyster) Pacific oysters (Robert et al., 1993). The choice of nursery unit will ultimately depend on site and environmental conditions, and NSW farmers should avoid using cylinders in areas affected by hairy mussels and mudworm.

TABLE 6.6

Comparison of Sydney rock oyster (*Saccostrea commercialis*) spat grown intertidally in sectionalised trays, PVC baskets and PVC cylinders in the Hastings River, NSW, December to July (Section 6.3).[1]

Growing units	Performance indicators of oysters at harvest[2]			
	Whole weight (g)	Length (mm)	Mortality[4] (%)	Mudworm[3,4] (%)
Baskets	14.2 ± 0.6^{c}	52.6 ± 0.8^{b}	23.8 ± 5.3^{b}	22.5 ± 7.5^{b}
Sectionalised trays	11.6 ± 0.2^{b}	53.1 ± 0.9^{b}	9.2 ± 1.7^{a}	2.5 ± 2.3^{a}
Cylinders	9.8 ± 0.7^{a}	39.9 ± 1.3^{a}	77.8 ± 4.9^{c}	94.1 ± 6.1^{c}

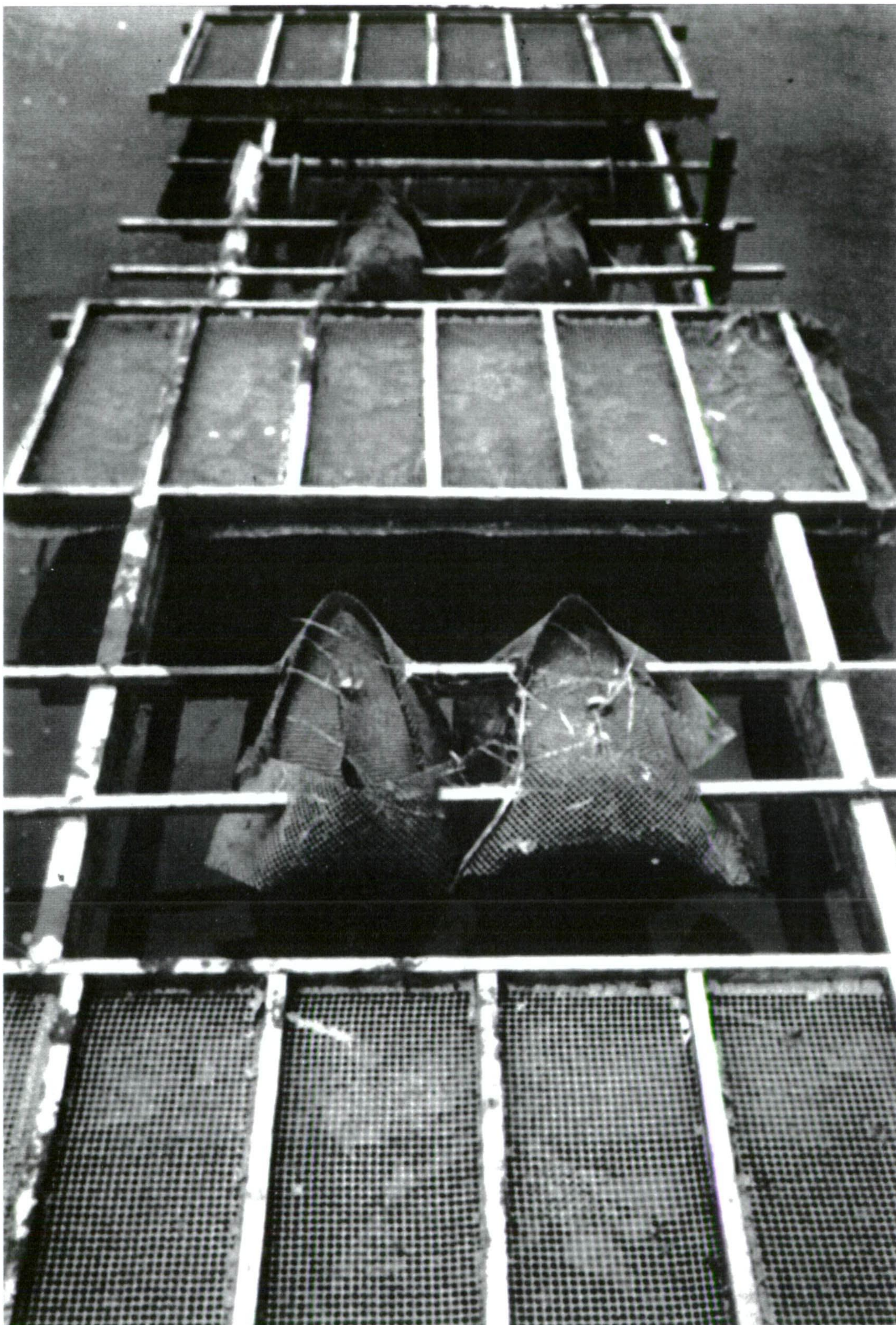
1 Values are means±SE; n=4. Within each column, means with a common superscript do not differ significantly (P>0.05).

2 Initial whole weight and length of spat were (n=360), 4.1±0.9 g and 35.7±3.8 mm respectively.

3 Percentage of live oysters infected with mudworm (*Polydora* spp.).

4 Data transformed arcsine $x^{0.5}$ prior to ANOVA.

Fig 6.3 Sectionalised trays, PVC baskets and PVC cylinders stocked with 4.1 g Sydney rock oyster (*S. commercialis*) spat and positioned on an intertidal lease in the Hastings River, NSW (Section 6.3).



CHAPTER 7

GENERAL DISCUSSION

7.1 INTRODUCTION

Production for the NSW oyster industry (the major producer in Australia) has continued to decline since the mid 1970's, principally due to high production costs. The overall objective of this thesis was to develop suitable culture methods and management strategies to reverse the declining production trend and improve the competitiveness of Australian oyster industry, particularly for NSW farmers. During this study, settlement, retention, survival and growth of juvenile Sydney rock and Pacific oysters were investigated using different types of nursery systems, different types of cultch were examined for settlement and retention, different nursery and growing systems were assessed (including single seed culture and the traditional stick and tray method) and a variety of estuarine and on-shore locations were compared. Finally, the retention and growth to market size of Sydney rock oyster spat attached to different types of commercially-available collectors were compared. Most of the results of this research have been published (Appendix 9.5). The aim of this chapter is to review the conclusions from individual experiments, identify common themes or constraints, discuss the results and provide a series of recommendations to assist in the management of oyster operations.

7.2 SETTLEMENT

The technique of storing oyster larvae and settling them at sites away from hatcheries (remote setting) is widely used in the United States for the commercial settlement of Pacific oyster larvae (Chew et al., 1986). The main advantage is that it eliminates the costs of transporting large volumes of cultch between the hatchery and the farms. Optimum storage temperatures were determined for Sydney rock oyster larvae and the remote setting technique evaluated for this species and for Pacific oysters. Optimal storage temperatures for Sydney rock oysters exceeded those used commercially in the United States for Pacific oysters (5°C; Henderson, 1981, 1983) (Section 3.1). Excellent settlement rates after storage were recorded for both species, with settlement of Pacific oysters higher (68%) than for other studies (range 20-30%; Henderson, 1983; Roland et al., 1988); the higher density may have resulted from feeding larvae live algae during settlement. Even higher temperatures than those in this study (11°C for Sydney rock and 5°C for Pacific oyster larvae) could have also been suitable for larval storage and may make storage and transport for the remote setting technique cheaper. The development of remote setting techniques for Sydney rock oyster industry provides farmers with a more effective means of transporting larvae from hatcheries for settlement at the farm.

Throughout this study, a number of differences between Sydney rock and Pacific oysters were observed and these could be useful in formulating strategies to improve farm management, particularly when catching spat and controlling overcatch on crops. Larval growth rates of Pacific oysters exceeded those of Sydney rock oysters and optimum temperatures for storage, shell lengths and eyespot diameters (which could be useful criteria to determine if larvae are ready for storage) were also different (Section 3.1). Other differences between species included the settlement period and area of settlement in the wild (Section 3.3). Both species settled over an extended period (>6 months), with Pacific oysters settling predominantly in the more estuarine areas of Port Stephens (Fig 2.8), from November to June, and Sydney rock oysters in the more oceanic areas, from January to July. Factors affecting settlement and settlement preference for upper and under surfaces of the different collector types also varied between species (Sections 3.3 and 3.4) and are discussed later. For Pacific oysters, the extended settlement period in the upper-estuarine, the traditional areas used for cultivation of Sydney rock oysters in Port Stephens, has compounded problems of overcatch for farmers that are discussed later. Experiments with Pacific oysters were terminated early, just after spat settled, because of the introduction of a Government policy aimed at their eradication from NSW waterways (Chew, 1990; Holliday and Nell, 1990). However, between 1985 and 1990, Pacific oysters had spread to 18 of the 40 oyster producing estuaries in NSW (Nell, 1993) and the high numbers of Pacific oysters, which had settled on rocky foreshores and on oyster cultivation in Port Stephens, led the Government to licence farmers to catch, grow and market wild Pacific oysters in this estuary. Many of these farmers now use the information generated from this study to catch and cultivate single seed Pacific oysters.

Many factors have been found to affect oyster settlement. An understanding of factors affecting settlement and larval preference for particular substrates could improve productivity for hatcheries and farms. Conclusions drawn from the literature citing factors affecting settlement are often contradictory, if not confusing, as observations have differed in relation to species and environmental conditions; and in some studies where factors are interdependent (Galtsoff, 1964b; Shaw, 1967; Quayle and Newkirk, 1989; Bonar, 1991). In the present study, settlement was affected by a number of abiotic factors including collector type, shape and orientation of collectors and composition and surface texture of collectors. Collector type affected settlement and retention of Sydney rock oysters and settlement of Pacific oysters. Of the ten types of commercially-available collectors evaluated for natural settlements, PVC and slurry-coated PVC collectors caught far more Sydney rock and Pacific oysters and fewer barnacles than traditionally-used tarred hardwood sticks.

Orientation affected settlement in the hatchery, with more larvae settling on collectors positioned horizontally than on those positioned vertically (Section 3.3). Excellent settlement was recorded in the wild from collector types positioned horizontally (Section 3.4). Thomson (1950) and Gunn (1984) also recorded greater natural settlement of Sydney rock and Pacific oysters respectively on horizontally positioned collectors. In the present study, more oysters caught on under surfaces, and once larvae had started settling, their gregarious behaviour (Hidu and Haskin, 1971; Keck et al., 1971; Kenny et al., 1990) may have increased the difference in numbers which settled on upper and under surfaces.

The shape of different collector types may have also influenced natural settlement of Sydney rock oysters. In the present study, there was similar settlement on both surfaces of collectors that had large concave (downward facing) surfaces. These collector types were prone to the build-up of silt on the upper surfaces and hence developed conditions that were not conducive to larval settlement (Section 3.4). Dinamani and Lenz (1974) also reported the effects of silt on flat collector surfaces and concluded that natural settlement for a subspecies of Sydney rock oysters occurred on the upper surfaces only when spat density on the under surfaces was high. In contrast, density of Pacific oysters in the present study was greater on the upper surfaces of some collector types with flat surfaces, despite the potential for them to accumulate silt on these surfaces. In the hatchery, where light and silt were excluded from treatments (Sections 3.3), the highest settlements per unit area were generally on collector types with the largest surface area (discs, slats and wider sticks, range 38-140 mm diam.; Tables 3.3, 3.4; Fig 3.8) and lowest on collector types with the smallest surface areas (round spiky and round smooth sticks; 22 mm diam.). Hopkins (1935), Schaefer (1937) and Cole and Knight-Jones (1949) concluded that higher settlements of bivalves on under surfaces of collectors resulted from the swimming action of pediveliger larvae, as they often swim with their foot extended while searching for a suitable substrate on which to attach. Butler (1955), concluded that *C. virginica* probably settled on the upper surfaces of collectors in a stack, after swimming into and deflecting off the collector above.

Composition and surface texture of collectors may have also affected settlement. Several types of PVC collectors that attracted good settlements, were impregnated during the extrusion process with lime and calcium, or were covered in a lime/cement slurry, prior to settlement. Large PVC discs coated in a slurry had consistently high spat densities in both the hatchery and the wild. There was no significant difference between wild settlement of Sydney rock oysters on stacks of slats and slurry-coated slats, although, settlement was recorded after an extended period (6 months; Section 3.4). Slurry recipes used in this study were based on those used by the French industry on roofing tiles and large PVC discs (His, 1978). Hardwood caught the least number of spat in the wild when coated with coal tar pitch (used commercially to prevent damage to sticks from marine borers). The coating on tarred sticks probably affected settlement and subsequent retention of market grade oysters. Tarred sticks were not used in the hatchery as tar is toxic to larvae in a static environment (candidate, pers., observ., 1982). The smooth, surface texture of tar (which became soft with exposure to sunlight at low tide) may have also affected retention, as oysters and barnacles competed for the limited growing space.

In NSW, many farmers coat their slats with slurry for natural spatfall, claiming easier removal of single seed spat at harvest (particularly when spat densities are low on collectors). Farmers also claim that collectors are easier to re-coat after harvesting spat as they can avoid the timely and costly process of cleaning collectors. The main disadvantages with slurry are that it is difficult to separate from spat at harvest, it tends to clog the fine meshes covering nursery units and that it can restrict water movement and hence result in depressed growth rates and siltation problems.

Settlement may have been affected by biotic factors such as "aging" period for collectors, competition from sedentary organisms, and the gregarious behaviour of larvae. Collectors should be aged and conditioned (Section 2.1.4), as this allows any potentially toxic compounds to leach out (also neutralising the pH of the slurry-coated collectors) and allows a primary fouling film (mainly bacteria) to develop on collectors (Section 1.2.2). Compared with wild catch, few larvae settled in the hatchery on collector types that were new (not aged), and with the exception of large slurry-coated discs, density on many collector types was low. Spat density was consistently high on large slurry-coated PVC discs (Sections 3.1, 3.3, 3.4), that were imported from France and possibly aged more than other collector types. Spat density on PVC slats and slurry-coated PVC slats (aged for two years), were higher than similar and newer PVC slats and slurry-coated PVC slats (Section 3.3). Roland and Broadley (1990), recommended that collectors for use in tanks be aged in salt or fresh water for a minimum period of 4-8 months, with this period dependent on water temperatures. In contrast, excellent natural settlements of Sydney rock oysters were obtained on the same batch of new collectors when they were conditioned on an oyster lease for a month prior to the start of settlement (Section 3.4). In this experiment, settlement was observed on some collector types as early as a month after deployment and up until day 127, and the higher densities probably resulted from longer exposure to leaching and settlement. Settlement probably increased over time, possibly because gregarious larvae aggregated on colonised surfaces (Keck et al., 1971; Kenny et al., 1990). Gunn (1984), found that leaching PVC pipe intertidally at 3 m for seven days to 12 months, increased spat settlement in tanks (from nil to 5-10% and from nil to 25% respectively), but recommended that new tubes for natural settlement need only be conditioned for one week. Competition from barnacles may have also affected settlement and retention of oysters on tarred sticks, as barnacles settled more densely on these sticks than do oysters (Section 3.4). Few barnacles settled on PVC collector types with rough, spiky, grooved, or on rough slurry-coated surfaces.

The rate of settlement is important for hatcheries and remote setting operations and is often used as an indicator of the viability of larvae. In the present study, substantial settlement of Sydney rock oysters was observed on PVC slats, two days after stocking, on large slurry-coated PVC discs at day 3 and on slurry-coated PVC slats at day 4 (Section 3.3). Differences between the species may account for the slower settlement rate for the slurry-coated collector types. When remote setting Pacific oysters, operators anticipate completing settlement within 48 h of stocking (Roland and Broadley, 1990).

An evenly distributed and light spat settlement over the total surface of collectors is important for optimal use of collectors and space. For settlement in the hatchery and the wild, spat densities often differed between upper and under surfaces of the various collector types. For settlement in the hatchery, layer within a stack, had no effect ($P>0.05$) on oyster settlement (using 20 layers of small PVC discs; Section 3.2). However, densities for wild Sydney rock oysters (range 1.5-5.8 spat/cm^2) were generally too high to be efficient, and high losses of spat (range 32-69%) were recorded from all collector types at day 271 and from growing sticks at day 843 (range 93-96%; Section 3.4). Despite the apparent low spat densities obtained on some collector types in the hatchery, these densities may have been more viable than the very dense settlements on slurry-coated discs and slats (Tables 3.4, 3.5, 3.6). Commercial operators settling Pacific oysters, obtain between 0.3 and 0.4 spat/cm^2 on round grooved PVC sticks (Jones and Jones, 1988; Roland and

Broadley, 1990). Hatchery operators can manipulate spat densities by altering larval stocking densities, determined by using anticipated settlement and post-set survival rates (Jones and Jones, 1988; Roland and Broadley, 1990). Spat density and distribution on PVC collectors is also managed by flipping stacks of collectors over on day two of settlement and by adding more larvae (Roland and Broadley, 1990).

7.3 POST-HARVEST SURVIVAL AND RETENTION

Collectors must not only facilitate settlement, growth and retention of spat, but enable harvest without damaging the spat or the collectors. Post-harvest survival of Sydney rock oyster spat for culture as single oysters was high for most collector types (range 89-93%), 285 days after their deployment, with the exception of bioresin slats (67%; Section 3.4). Bioresin slats were found to be unsuitable because the lower valve of spat remained attached to collectors during harvest, effectively destroying oysters (Section 3.4).

Nursery units must be capable of retaining spat while offering protection from predation. Retention was used in this study to help evaluate the various systems by differentiating between dead spat and those lost from collectors and nursery units. Retention of spat on collectors at days 127 and 843 was affected by density (Section 3.4). Of the collector types tested, tarred sticks had the lowest oyster settlement and retention. Despite lighter settlement, tarred sticks exhibited similar oyster loss rates to PVC sticks, with low numbers of market grade oysters retained at harvest (0.1 oysters/cm^2 or 115 oysters/stick), compared to the three types of round PVC sticks (average 0.3 oysters/cm^2 or 353 oysters/stick) (Section 3.4). Few spat were lost from single seed nursery units compared to collectors, as spat were totally enclosed by mesh.

7.4 DENSITY AND SPAT PERFORMANCE

Density is an important factor when developing management strategies for the nursery and growing operations, as it can affect growth and survival of oysters. In the present study, density affected the growth and size variation of juvenile Sydney rock oysters (Sections 3.4, 4.1, 4.2). Spat growth rates in sectionalised trays and cylinders declined with increasing stocking densities, and for cylinders, coefficient of variation for weight gain and shell length gain, increased with density (Sections 4.1, 4.2). Survival of spat grown at a range of densities and sizes was unaffected by density, with the exception of the largest grade and highest stocking density used for cylinders (Section 4.2). The findings from the present study are consistent with other studies on the effects of density on oyster growth (Neudecker, 1981; Bacher, 1991) and size variation (Newkirk, 1981; Jarayabhand, 1988; Spencer, 1990). Spat growth decreases with increasing density, probably because of competition for food. Hadley and Manzi (1984) concluded that food was the growth limiting factor for clams grown at a range of densities. Spat densities should also be periodically reduced as part of farm management, to avoid declines in yields and oyster size variations, as a wide variation of spat sizes is undesirable and increases the necessity for grading (Newkirk, 1981; Askew, 1987) and the associated handling costs. Unlike the stick method, single seed culture allows easier manipulation of stocking densities and was found in the present study to be an important means by which a farmer can improve management and enhance oyster growth and survival.

In one part of this study with wild spat on sticks, density had no effect on growth (Section 3.4) and here, the lack of covariance may have been an anomaly and undetectable because of factors other than density. Despite significant ($P<0.05$) differences in spat density at harvest on day 843 (range 0.8-2.6 spat/cm^2), between timber and PVC sticks (range 0.8-2.6 spat/cm^2; Table 3.8), growth was similar on collector types, with the exception of round grooved PVC sticks, that had lower ($P<0.05$) shell lengths than timber sticks (Section 3.4). Conversely, Gunn (1984) and Newkirk and Jarayabhand (1989) found that spat growth rates on cultch decreased with increasing stocking densities, and Gunn (1984) found Pacific oyster growth declined on round grooved PVC sticks (similar to those used in this study), when densities were > 0.24 oysters/cm^2.

Settlement was particularly heavy on collector types compared to other studies in Salamander Bay (Holliday, 1985; Holliday and Goard, 1986), and although density had no effect on growth, there was a direct relationship ($P<0.001$) between density on collectors at day 127 and spat losses between days 127 and 271 (range 32-69% loss). This pattern of loss varied between collector types until harvest (day 843), with particularly high losses from those collector types with high initial densities. Competition between spat, for the limited growing area on collectors, was probably a contributing factor for this high loss and a lighter settlement on PVC collectors may have resulted in better individual spat growth and retention. It may also be possible to manage density and distribution of wild spat by regularly inspecting and relocating collectors (when density was sufficient) to leases unaffected by spatfall and by flipping collectors over during settlement (Roland and Broadley, 1990), as described earlier.

Spat densities need to be adjusted more frequently during the peak growth seasons, as growth rates vary with environmental conditions and seasons. Generally, maximum growth was recorded in the present study from sectionalised trays on an intertidal lease during the autumn and spring periods and growth was depressed during the winter months (Sections 4.1, 5.1, 6.2). The findings are consistent with those of Nell et al. (1994), who recorded seasonal differences in growth of triploid Sydney rock oysters in Port Stephens. Spencer (1990) recommended stocking Pacific oyster spat at higher densities (up to 2.0 g/cm^2) during the cooler months and Spencer et al. (1985, 1992) used predicted water temperature and spat size to estimate optimum stocking densities. Management of the density/growth relationship and growing seasons effectively allows farmers to maximise the use of the nursery units and lease space without sacrificing growth or survival.

The choice of stocking density can also be affected by food supply (algal) and nutrient concentrations, as oyster growth rates have been positively correlated with Chlorophyll *a* (used as a measure of algal productivity; Brown and Hartwick, 1988). Although the Chlorophyll *a* concentrations for the present study (Section 4.2) were below those recorded by Brown and Hartwick (1988), they were within the range recorded for three NSW estuaries, Georges River, Jervis Bay and Port Stephens, over a 12 month period (Allan, 1980). A more comprehensive study of algal and nutrient concentrations was conducted in

Port Stephens by Richardson (1991), who found the food quantity and quality of seston varied between sites and increased in the upper estuarine areas, possibly because of the higher concentrations of nutrients. Hofmann et al. (1994), recommended that, when comparing performances of oysters at different sites, a complete analysis of food supply and associated physical parameters and an energy model should be conducted.

A variety of criteria can be used by farmers when formulating strategies for nursery culture, to determine optimum stocking density and when to alter density during grow-out. Although the higher growth rates at low densities enhanced the value of individual oysters, the value of production per unit area may have been relatively low. Therefore, biomass gain should generally be used as the basis for optimum stocking density of oysters, as this criteria take into account costs associated with seed, growing units and lease space. The findings of this study are consistent with those of Spencer et al. (1985) who concluded that small advantages in spat growth at low densities were outweighed by extra costs of trays and labour. A more comprehensive analysis of spat sizes versus price data (for both hatchery and wild spat) is required for the NSW oyster industry.

7.5 NURSERY UNITS

The choice of nursery units will be influenced by spat performances, environmental conditions and effects from disease, parasites and fouling. In the present study, tarred hardwood sticks, PVC collectors, sectionalised trays, PVC cylinders, PVC baskets and on-shore upwellers all proved to be effective units for the nursery culture of Sydney rock oysters in some situations (Sections 3.4, 4.1, 4.2, 5.1, 6.2, 6.3). These units may be suitable for the various phases of production and hence farmers can choose from the different culture systems (Fig 7.1). Catt (1992) found the simplest and most cost effective production system for NSW farmers was for them to catch and grow wild spat to market using tarred sticks, however, he concluded that the return on capital investment was low. In the present study, PVC collectors proved to be far more effective nursery units than the traditionally-used timber sticks, as they were effective both in the hatchery and the wild, retained significantly more oysters at harvest, were unaffected by marine borers and in some cases were reusable. Although PVC growing sticks were more expensive to purchase than timber sticks (about twice the cost at time of purchase), the higher yields from PVC collectors from settlement, retention and reuse may compensate for their higher initial costs. When comparing different growing methods for Pacific oysters, Spencer et al. (1992), concluded that profitability was related to oyster survival. However in this study, survival rates for Sydney rock oysters grown at a range of densities and sizes were generally high, and except for the highest density tested in cylinders (Section 4.2), unaffected by density.

Based on seed costs (from Tasmanian and NSW hatcheries @ about A$2.00/100 for 6 mm spat; candidate unpubl., data, 1994) and retention, on-shore upwellers were the most effective unit for newly settled hatchery spat (stocked in the range of 0.5-1.25 mm/spat). Compared to small PVC discs, upwellers sustained the highest survival (69.3%) of newly settled Sydney rock oyster spat and retained (97.7%) the greatest number of these spat. They also had the highest growth of larger spat (4.0 g/spat) during the cooler months (Section 5.1). Small PVC discs had greater growth of newly settled spat during the warmer months compared to upwellers. For discs, greater growth, survival and retention were recorded from an intertidal lease in Port Stephens for wild caught spat compared to newly settled hatchery spat (Section 6.1). The poor survival and retention on discs in North Arm Cove (Section 6.1) were probably caused by air entrapped under discs with the rising tides and NSW farmers using this type of collector now deploy them on an angle to release air.

Performance of larger Sydney rock oyster spat ($\geq$ 4.0 mm) grown on an intertidal lease was affected by type of nursery units (Section 6.3). Sectionalised trays, PVC baskets and PVC cylinders covered with larger mesh (9.0 mm) also proved to be very effective nursery units and their use is illustrated in Figure 7.1. Although better growth rates were obtained in baskets than in trays and cylinders, trays were generally found to be more effective as they had good growth and survival rates at high densities (Sections 4.1, 4.2) and spat were unaffected by mussel settlement and mudworm (Section 6.3). Nursery trays are now more widely used in NSW and Tasmania because spat generally perform well under a variety of environmental conditions. Despite the poor performances of larger spat in cylinders in the Hastings River, good spat growth and survival were obtained in the Hawkesbury River (Section 4.2). Robert et al. (1993) found cylinders fitted with larger meshes useful for improving meat condition and shell quality of mature Pacific oysters, prior to being marketed. Despite the conflicting results from the present study, cylinders are also widely used by NSW farmers. The most economic approach to farm management is for farmers to select the most appropriate nursery units, to minimise the types of units and to select the most useful mesh sizes.

7.6 SITE AND ENVIRONMENTAL CONDITIONS

Findings from this study, conducted at nine sites and in six estuaries, illustrate the importance of site selection for a successful nursery operation. Spat performance is greatly affected by environmental conditions. The suitability of a site for nursery culture is influenced by a number of factors including turbidity, salinity, natural food levels, water temperature, wave action and current velocity (Wilson, 1987; Spencer, 1990). In the present study, survival of newly settled Sydney rock oyster spat on PVC discs was higher at Swan Bay, the upper-estuarine site in Port Stephens (Fig 2.8; Section 3.4) than at North Arm Cove, the middle-estuarine site or at Pindimar, the predominantly oceanic site (Section 5.1). Pindimar is historically a major natural spat collection area in Port Stephens and generally has higher salinities (Richardson, 1991) and lower turbidity concentrations (S. M^{c}Orrie, unpubl. data, 1991) than other estuarine sites. Survival of spat was also high in upwellers at the inlet to a power station, where consistently high salinity (33.6±0.3‰; Sections 6.1, 6.2) and low turbidity have been recorded (Hodgson, 1979; Anon., 1883; Nell, 1987). Generally, salinities at the various sites used for nursery culture of Sydney rock oysters were within the range found by Nell and Holliday (1988) to be optimal for their growth and survival (Section 1.1.2). Hatchery and nursery operators generally prefer sites with high salinity and low turbidity for the larval and post-set nursery phases, although, for Pacific oysters salinities can be reduced to 25‰ for these phases

(Nell and Holliday, 1988; Holliday, 1992). Turbidity and specifically high concentrations of silt can affect growth and survival of juvenile oysters (Bayes, 1981; Quayle and Newkirk, 1989). Spencer (1990) also recommended nursery sites with low silt loads for Pacific oysters, to avoid the costly process of continually removing silt from oysters. Conversely, greater growth and survival of larger Sydney rock oyster spat (initial weight 4.0 g/spat) was obtained from the more estuarine sites in Port Stephens (the traditional nursery and growing leases), than those closer to the entrance. Urban and Kirchman (1992) found that for *C. virginica*, larger oyster spat (8.7 g/spat) could filter effectively in turbid waters and could even benefit from the silt load.

Food concentrations may have also affected spat performances at the different sites. Greatest growth and survival of Sydney rock oyster spat were obtained at Swan Bay and North Arm Cove, sites in Port Stephens (Section 5.1). Although an intensive monitoring of abiotic and biotic variables was not conducted during this study, Richardson (1991) found that oyster food concentrations were higher at the more estuarine sites in Port Stephens and concluded that these resulted from the higher nutrient levels associated with run-off from rural enterprises. Hofmann et al. (1994) in a simulated model, also found that oysters increased in size with increased food concentration and concluded that growth was affected by turbidity, salinity and temperature. Berg and Newell (1986), who found food quantity was lowest during the winter period and highest during the summer, concluded that there was a correlation between availability of food and oyster growth. Spencer (1988) found the growth of Pacific oyster spat in upwellers, was affected by food concentration and flow rate and concluded that maximum growth was obtained when spat filtered 20% of suspended material from the water. Despite sustaining the lowest growth and survival rates, the more oceanic site at Pindimar is still considered to be suitable for the nursery culture of Sydney rock oysters, particularly during the winter months when spatfall has ceased and leases are mostly vacant.

Growth of Sydney rock oyster spat in the present study was enhanced with water temperatures in the range of 16-28°C (Sections 4.1, 5.1, 6.2) and spat performances were adversely affected outside of this range. However, other variables may also have been influential in these spatial or temporal comparisons. Although only minor overall differences in temperature were observed between intertidal sites, the considerable seasonal differences probably depressed spat growth during the cooler months (Sections 4.1, 5.1). Thermal effluent (range 14-28°C) at the inlet to the power station also enhanced growth and survival of spat in upwellers during the cooler months, compared to spat on trays on an intertidal lease in Port Stephens (range 10-26°C) and those in upwellers and trays in heated effluent (range 19-35°C) at the power station outlet (Section 6.2). Water temperatures at the outlet were considered to be above optimal, as survival (30.8%) and growth of spat were poor (Section 6.2). Spencer (1990) recorded the best growth for Pacific oyster spat with temperatures in the range of 18-22°C, (although, 22°C was the highest temperature tested). Shafee and Sabatie (1986), experienced high mortalities (77%) during the warmer months, when growing juvenile Pacific oysters subtidally. Malouf (1981), recommended avoiding elevated temperatures when growing bivalves in power station effluent, as food concentrations may be inadequate to sustain metabolic requirements. Nell and Livanos (1988) found that in the range 12-30°C, growth rates of Sydney rock oyster spat, fed to excess in aquaria, increased as temperature increased. Thermal effluent has considerable potential for use in nursery culture for Sydney rock oysters, although, it is important that such sites have high food concentrations.

Mudworm (*Polydora* spp.) affected the performance of spat in nursery units. Mudworm causes major losses to the NSW industry as infested oysters are rendered unmarketable or suffer high mortalities (Skeel, 1979; Nell, 1993). In the present study, spat in sectionalised trays were unaffected by mudworm, however, those in cylinders and baskets in the Hastings River, were affected, with infection higher in cylinders than in baskets (Section 6.3). Although cylinders were positioned on an intertidal rack at a traditionally used height used by NSW farmers for other nursery systems, with outgoing tides, cylinders rotated and hung below the growing height used for trays and baskets. In contrast, mudworm was not detected from spat in cylinders deployed in the Hawkesbury River. Oysters on traditionally-used timber trays (Fig 1.2B) have suffered from the accumulation of silt and infestation from mudworm in the

Hawkesbury River (Wisely et al., 1979b; Holliday et al., 1988, Nell, 1994). Despite the poor result for cylinders in the Hastings River, they are valued as nursery units and are widely used by NSW farmers in other estuaries, who claim the revolving action reduces the build-up of silt on the oysters and eliminates mudworm. Robert and Maurer (1992), also found that cylinders significantly reduce mudworm infestation of Pacific oyster spat.

Environmental conditions associated with the location and costs of nursery sites can affect the performance of spat in nursery units and the suitability of a site. Sectionalised trays were found to be unsuitable for the exposed lease at Soldiers Point (Fig 2.8) as trays were destroyed by severe wave action. Here, sticks and baskets later proved to be more suitable nursery and growing units (candidate, pers. observ., 1992). PVC baskets and cylinders were found to be unsuitable in the Hastings River because spat were affected by mudworm infestation and mussel settlement. Nell (1991b), concluded that cylinders were also unsuitable for culturing oysters on leases exposed to wave action, as their revolving action was too severe and affected spat growth. On-shore upwellers, although the most suitable system for newly settled spat, need to be located near a power supply to operate pumps, and adjacent to unpolluted waterways with high nutrient and food concentrations, and low silt loads. In NSW, suitable on-shore sites for upwellers are often difficult to acquire because of the already pressure for development of coastal resources and from existing urban development. Spencer and Gough (1978) also concluded that on the basis of cost, oyster cultivation systems that relied on the use of pumped water may not be viable in the future. In the present study, sectionalised timber trays were generally the best nursery system for Sydney rock oyster spat as they had good growth and survival rates at high densities and were effective at different sites.

As single seed culture of oysters is relatively new to NSW, further evaluation of sites is needed. In addition to the use of heated effluent from power stations, commercial earthen prawn ponds in far northern NSW offered considerable potential for the winter nursery culture of Sydney rock oysters. Here, average weight gain of spat (average initial weight 2.2 g) grown in PVC envelopes in the inlet channel (closed to the estuary) to a 20 ha prawn farm was 2.2 g/spat after 12 weeks (Allan et al., 1991; Appendix 9.4) and compared well with those grown at similar densities on trays in Port Stephens (Section 4.1).

7.7 COMPARISON OF SINGLE SEED AND STICK CULTURE

The production of oysters by single seed techniques has a number of advantages over the traditional stick method. In NSW, wild caught spat harvested from collectors for culture as single seed were estimated to be far cheaper to purchase than hatchery produced seed (Section 3.4). The production of seed in hatchery can be expensive (Holliday, 1992) and Quayle and Newkirk (1989) estimated that in North America and Europe, very few hatcheries were viable, producing less than 1% of world production in total. Culling costs for stick culture, estimated by Catt (1992) at 33% of total labour costs, could also be reduced with single seed culture. Overcatch of Pacific oysters, that settles predominantly in the traditionally-used nursery and growing areas for Sydney rock oysters, is easier to manage with single seed culture, as nursery units can be relocated to unaffected leases or air dried to expose and kill unwanted newly settled spat. Conversely, major losses have been experienced by NSW farmers when handling tarred sticks laden with oysters, to dry and kill the overcatch (C. Mason, pers. comm., 1987). Processors and outlets in Australia are now demanding the better quality oyster produced by the single seed technique, as these oysters are more uniform in shaped (unattached) and can be machine graded, counted and packaged more efficiently.

Single seed culture has a number of disadvantages. Catt (1992) found timber sticks to be more cost-efficient than the single seed system for the production of Sydney rock oysters in Port Stephens. As many NSW farmers are still in the transition stage between the two techniques, labour cost to handle and grade single seed are relatively high and estimated at 32% of total labour costs (Catt, 1992). Sticks are also more effective on the exposed leases as trays can be destroyed and spat in cylinders affected by wave action (Sections 5.1, 6.3). Smith et al. (1995) also found Sydney rock oysters glued onto PVC slats at a low density grew along the substrate and were heavier, with higher and longer shells at harvest than those grown loose in trays as single seed oysters. By using PVC rather than timber growing sticks, farmers could further enhance their production with higher retention of oysters. Despite the disadvantages, many NSW farmers are changing to the single seed technique to avoid culling losses, to manage overcatch, and to meet market demands. There is also a growing demand in NSW for hatchery produced triploid Sydney rock and Pacific oysters for enhanced growth and meat condition (Nell et al., 1994) and to reduce estuarine broodstock populations and hence overcatch.

7.8 CONCLUSIONS AND RECOMMENDATIONS

A number of the findings from this study are being used by the Australian oyster industry. Farmers can choose from a number of strategies, for the production of wild and hatchery produced seed, using various culture systems for the different phases of production, as illustrated in Figure 7.1. Although this study concentrates on developing strategies for management of Sydney rock and Pacific oysters for the Australian industry, findings are also applicable to other oyster industries. Specific conclusions, recommendations and strategies for management follow:

1. Eyed Sydney rock and Pacific oyster larvae can be successfully stored for 98 h (at 11°C and 5°C respectively), transported and settled on PVC collectors in tanks or on chips of scallop shell in downwellers, at farms remote from hatcheries.

2. A number of differences between Sydney rock and Pacific oysters were observed and these can assist farmers in controlling overcatch on their crops and for improved management of seed collection. Differences between species include larval growth rates, temperatures for larval storage, larval shell lengths and eyespot diameters (useful criteria to determine if larvae are ready for storage), area of natural settlement and settlement period, settlement preference for upper and under surfaces of the different collector types and growth rates of juvenile oysters.

3 PVC spat collectors should be conditioned prior to settlement in the hatchery, by immersing them in sea water for a minimum of 48 h. Newly manufactured PVC collectors should be aged (preferably on an intertidal lease) for a period of 6 months to 2 years prior to use. For natural settlement, new PVC collectors can be aged and conditioned by deploying them in an intertidal position on a lease, at least a month prior to the start of settlement.

4 PVC collectors can be deployed from settlement tanks directly to estuarine leases, avoiding the capital and labour costs associated with upwellers and on-shore nurseries.

5 For settlement in a hatchery, large slurry-coated PVC discs and horizontally positioned PVC slats and slurry-coated PVC slats were the most suitable collectors for Sydney rock oysters.

6 PVC slats are recommended as the most cost-effective collector for wild Sydney rock oysters and could be a suitable alternative to other types of PVC collectors used for remote setting hatchery larvae. PVC slats and slurry-coated PVC slats, cut from commonly-used stormwater pipe, have a number of advantages over other types of PVC collectors, as they are readily available at most hardware suppliers in Australia and are cheaper to purchase (currently about 25% the cost of the alternative PVC slat and other PVC collector types, eg. round grooved PVC sticks).

7 For settlement, collectors should be deployed in a horizontal position, or for PVC discs, on a slight angle to ensure air bubbles are not trapped under collectors.

8 Reusable PVC collectors are an effective alternative to the traditionally-used tarred hardwood stick and increased productivity from greater settlement and retention of oysters may compensate for the higher initial costs of PVC.

9 Tarred timber sticks should be phased out as they caught and retained the lowest number of oysters, were affected by marine borers and were difficult to handle at harvest.

10 Round spiky PVC sticks (with lug, RSSL) were the most effective growing stick, as they retained good numbers of market grade Sydney rock oysters and could be harvested with damage to the crop or the sticks.

11 Wild caught Sydney rock oyster spat was estimated to be far cheaper than hatchery produced seed. However in the future, the oyster industry may become dependent on hatcheries for the production of triploid oysters.

12 Based on seed costs and retention, on-shore upwellers are the best nursery units for newly settled hatchery spat grown in the range of 0.5-4.0 mm.

13 Both natural and hatchery produced spat ($\geq$ 4 mm) can be successfully harvested from collectors and grown in sectionalised trays and cylinders, with the choice of nursery unit largely dependent on environmental conditions.

14 Sectionalised trays were generally the most effective nursery units for single seed Sydney rock oysters ($\geq$ 4 mm). However on exposed leases, sticks and PVC baskets appear to be more appropriate units. The use of cylinders should be avoided in areas affected by hairy mussel settlement.

15 A strong relationship exists between spat growth and density. The determination of optimum stocking densities for trays and cylinders and the comparative assessment of various types of nursery units allows farmers to formulate strategies to increase productivity through improved crop management. For hatchery spat, stocking density should be largely based on spat costs, survival and retention. For wild

spat harvested from collectors, biomass gain should be used as the main criterion for stocking density, until more comprehensive economic analyses are undertaken.

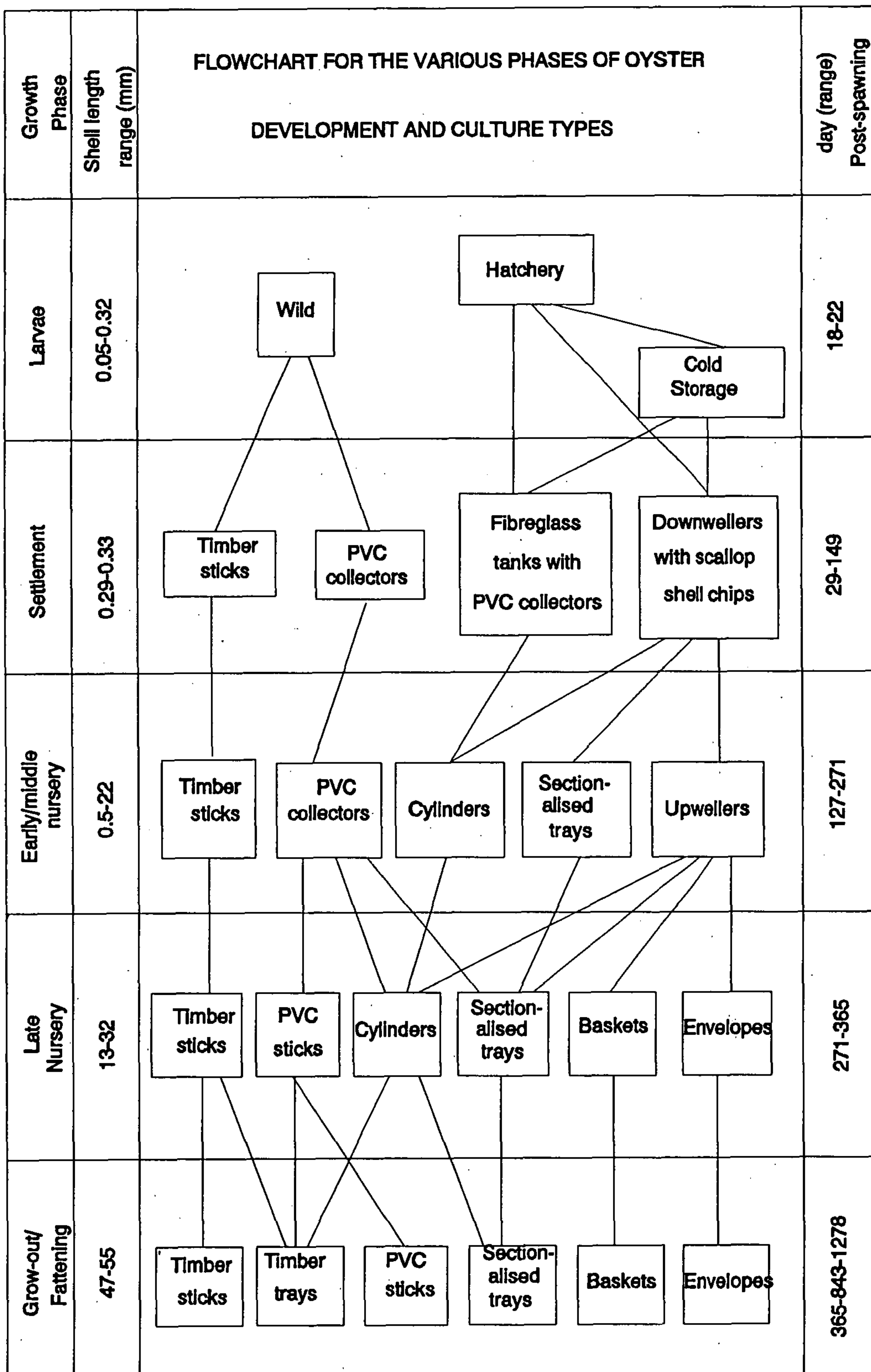
16 Densities should be periodically reduced during grow-out to avoid size variations and to optimise growth and production. Spat size, water temperature and growth rates should also be considered when determining intervals for restocking nursery units.

17 Growth and survival of spat can be enhanced through the farmers choice of site and season. Oceanic sites (higher salinity and lower turbidity) are recommended for newly settled Sydney rock oyster spat and estuarine sites with higher nutrient concentrations for the late nursery and growing phases. Farmers can capitalise on seasonal growth of single seed oysters on sectionalised trays by relocating crops to different sites within an estuary.

18 Maximum growth and survival of Sydney rock oyster spat was obtained with water temperatures in the range of 14-28°C. Growth rates are also probably dependent on primary productivity of the water.

19 On-shore sites, including heated effluent from power stations and the use of prawn farming ponds in northern NSW, showed considerable potential for the nursery culture of spat during the cooler months and warrant further investigation.

Fig. 7.1 Flowchart showing the various phases and culture types available for the production of Sydney rock oysters.


FLOWCHART FOR THE VARIOUS PHASES OF OYSTER DEVELOPMENT AND CULTURE TYPES
Growth Phase
Shell length range (mm)
day (range) Post-spawning
Larvae
0.05-0.32
18-22
Wild
Hatchery
Cold Storage
Settlement
0.29-0.33
29-149
Timber sticks
PVC collectors
Fibreglass tanks with PVC collectors
Downwellers with scallop shell chips
Early/middle nursery
0.5-22
127-271
Timber sticks
PVC collectors
Cylinders
Section-alised trays
Upwellers
Late Nursery
13-32
271-365
Timber sticks
PVC sticks
Cylinders
Section-alised trays
Baskets
Envelopes
Grow-out/ Fattening
47-55
365-843-1278
Timber sticks
Timber trays
PVC sticks
Section-alised trays
Baskets
Envelopes

8 REFERENCES

Ahmed, M., 1975. Speciation in living oysters. In: F. Russell and M. Yonge (Editors), Advancee in Marine Biolgy, Academic Press London, 13: 357-397.

Ajana, A. M., 1979. Preliminary investigation into some factors affecting the settlement of the larvae of the mangrove oyster *Crassostrea gasar* (Adanson) in the Lagos Lagoon. Malacologia, 18: 271-275.

Allan, G. L., 1980. The development of marine fouling communities in NSW. (Unpubl., thesis), Univ. NSW, 114 pp.

Allan, G. L., Holliday, J. E. and Frances, J., 1991. Growing and winter conditioning Sydney rock oysters (*Saccostrea commercialis*) in prawn farming ponds in northern NSW. In: Nursery culture of Sydney rock oysters, *Saccostrea commercialis* and Pacific oysters, *Crassostrea gigas*. Final report to Fishing Industry Research and Development Council, NSW Fisheries, Salamander Bay, NSW, pp 142-148.

Allen, Jr., S. K. and Downing, S. L., 1986. Performances of triploid Pacific oysters, *Crassostrea gigas* (Thunberg). I. Survival, growth, glycogen content and sexual maturation in yearlings. J. Exp. Mar. Biol. Ecol., 102: 197-208.

Allen, Jr., S. K. and Downing, S. L., 1990. Performances of triploid Pacific oysters, *Crassostrea gigas*: gametogenesis. Canadian J. Fish. and Aqua. Sci., (47): 1213-1222.

Allen, Jr., S. K. and Downing, S. L., 1991. Consumers and experts alike perfer the taste of sterile triploid over gravid Pacific oysters (*Crassostrea gigas*, Thunberg, 1793). J. Shellfish Res., 10: 19-22.

Allen, Jr., S. K., Downing, S. L. and Chew, K. K., 1989. Hatchery manual for producing triploid oysters. Univ. Washington Press, WA, 27 pp.

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* *References and units are as required by the journal 'Aquaculture,' where the majority of this thesis was published.*

Anonymous, 1983. Environmental Audit of Lake Macquarie. State Pollution Control Comm., Sydney, NSW, 159 pp.

Anonymous, 1985. Mesh cylinders: Do they herald a revolution? Aust. Oyster, 4 (3): 8-9.

Anonymous, 1988. Quarterly Review of the Rural Economy, 10 (4): 378.

APHA (Ameri. Public Health Assoc.), 1989. Inorganic and non-metallic constituents. In: L. Clesceri, A. Greenberg, R. Trussell and M. Franson (Editors), Standard Methods for the Examination of Water and Wastewater, 17th Edition, Part 4000. APHA, Washington, DC., 210 pp.

Arakawa, K. Y., 1990a. Commercially important species of oysters in the world. Mar. Behav. Physiol., 17: 1-13.

Arakawa, K. Y., 1990b. Natural spat collecting in the Pacific oyster *Crassostrea gigas* (Thunberg). Mar. Behav. Physiol., 17: 95-128.

Askew, C. G., 1978. A generalized growth and mortality model for assessing the economics of bivalve culture. Aquaculture, 14: 91-104.

Bacher, C., 1991. Effects of oyster stocking level and competing mollusks on the growth performance of *Crassostrea gigas*, with the aid of a coupled growth model. In: S. Lockwood (Editor), The Ecology and Management Aspects of Extensive Mariculture - A Symposium held in Nantes. IFREMER, 192, pp 41-47.

Bacher, C. and Baud, J. P., 1992. Intensive rearing of juvenile oysters *Crassostrea gigas* in an upwelling system. Aquat. Living Resour., Vivantes Aquat., IFREMER, 5 (2): 2.

Baker, P., 1992. Roles of phyiscal cues in oyster larval settlement choice. J. Shellfish Res., 11: 189.

Banks, M. A., Goldrick, D. J. and Hedgecock, D., 1991. Discriminating Kumamoto and Pacific oysters using molecular markers. J. Shellfish Res., 10: 511-512.

Barber, B. J., Mann, R. and Allen., 1992. Optimization of triploid induction for the oyster *Crassostrea virginica* (Gemlin). Aquaculture, 106: 21-26.

Bayes, J. C., 1981. Forced upwelling nurseries for oysters and clams using impounded water systems. In: C. Claus, N. de Pauw and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. European Maricul. Soc. Spec. Publ., 7, Bredene, Belgium, pp. 73-83.

Bayne, B. L., 1969. The gregarious behaviour of the larvae of *Ostrea edulis* L. at settlement. J. Mar. Biol. Assoc. UK., 49: 327-355.

Berg, J. A. and Newell, R. I., 1986. Temporal and Spatial variations in the composition of seston available to the suspension feeder *Crassostrea virginica*. Estuar. Coast and Shelf Sci., 23: 375-386.

Billington, M., 1991. Cultchless oyster seed: Equipment, systems and servicing, Feb, 1991. In: T. Nosho and K. Chew (Editors), Remote Setting and Nursery Culture for Shellfish Growers: Workshop Record. Olympia, WA, pp 43-44.

Bonar, D. B., 1991. Cultchless oyster production and enhanced setting with epinephrine and L-dopa. In: T. Nosho and K. Chew (Editors), Remote Setting and Nursery Culture for Shellfish Growers. Washington Univ., Seattle, WA: Sea Grant Program, pp. 14-21.

Bonar, D. B., Coon, S. L., Walch, M, Weiner, R. M. and Fitt, W., 1990. Control of oyster settlement and metamorphosis by endogenous and exogenous chemical cues. Bull. Mar Sci., 46: 484-498.

Bonar, D. B., Coon, S. L., Weiner, R. M. and Colwell, R. R., 1985. Induction of oyster metamorphosis by bacterial products and biogenic amines. Bull. Mar. Sci., 37: 763.

Bonnot, P., 1937. Setting and survival of spat of the Olympia oyster, *Ostrea lurida*, on upper and lower horizontal surfaces. California Div. Fish and Game, 23: 224-228.

Born, I. V., 1778. Index rerum naturalium Musei Caesarei Vindobonensis, Pars I, Testacea. Verzeichniss der naturlichen Setenheiten des K. K. naturalien Kabinet Zu Wien, Erster Theil, Schalthiere. Officina Krausiana, Vienna, 458 pp.

Bourne, N., 1979. Pacific oysters, *Crassostrea gigas* (Thunberg) in British Columbia and the South Pacific Islands. In: R. Mann (Editor), Exotic Species in Mariculture, Cambridge, MA, London MIT Press, pp. 1-53.

Bower, S. M., 1990. Shellfish diseases on the West coast of Canada. Bull. Aqua. Assoc., Dept. Fish. Oceans, Nanaimo, B. C., Canada, pp 19-22.

Broadhurst, R. C. and Soniat, T. M. Haywood, E. L., 1991. J. Shellfish Res., 10: 275.

Brock, V., 1990. Intergeneric distances between *Ostrea, Crassostrea* and *Saccostrea*, studied by means of crossed immuno-electrophoresis. Mar. Ecol., Prog. Univ. Odense, Denmark, 68: 58-63.

Brown, B. L. Butt, A. J. and Paynter, K. T., 1993. Growth of the Eastern oyster, *Crassostrea virginica*, in floating rafts in North Carolina. J. Shellfish Res., 12: 139.

Brown, J. R. and Hartwick, E. B., 1988. Influences of temperature, salinity and available food upon suspended culture of the Pacific oyster, *Crassostrea gigas*. I. Absolute and algometric growth. Aquaculture, 70: 231-251.

Brown, K. R. and Krassoi, F. R., 1990. Impact of Pacific oysters on Port Stephens Environment. Univ. Technol., Sydney, (unpubl.), 40 pp.

Buroker, N. E., Chanley, P., Cranfield, H. J. and Dinamani, P., 1983. Systematic status of two oyster populations of the genus *Tiostrea* from New Zealand and Chile. Mar. Biol., 77 (2): 191-200.

Buroker, N. E., Hersberger, W. K. and Chew, K. K., 1979. Population genetics of family Ostreidae. I. Intraspecific studies of *Crassostrea gigas* and *Saccostrea commercialis*. Mar. Biol., 54: 157-169.

Butler, P. A., 1955. Selective setting of oyster larvae on artificial cultch. Proc. Natl. Shellfish Assoc., 45: 95-105.

Carlson, B. K., 1982. Settlement and subsequent survival of commercially-reared eyed-pediveliger larvae of the Pacific oyster *Crassostrea gigas* (Thunberg). 1981 NSA West Coast Section Meeting. J. Shellfish Res., 2: p 116.

Carpenter, P. P., 1864. Supplementary report on the present state of our knowledge with regard to mollusca of the West Coast of North America. Rept. British Assoc. Adv. Sci., pp. 139-183.

Castagna, M., Gibbons, M. C. and Kurkowski, k. 1988. Remote setting and post-set strategies for growing *Crassostrea virginica* in Virginia. J. Shellfish Res., 7: 571-572.

Catt, C., 1992. Comparing oyster production methods: An economic modelling project on stick and single seed tray culture of Sydney rock oysters in Port Stephens, New South Wales (unpubl.). NSW Dept. Agric., Maitland, NSW, 39 pp.

Chagot, D., Hervio, D., Mourton, C., Boulo, V., Mialhe, E. and Grizel, H., 1989. Interactions between *Bonamia Ostrea* (Asceptospora) and Haemocytes of the flat oyster (*Ostrea edulis*) and of the cup shaped oyster (*Crassostrea gigas*): In Vitro analysis of entry mechanisms. Dev. & Comp. Immunol., 13, 409 pp.

Chew, K. K., 1979. The Pacific oyster (*Crassostrea gigas*) on the West Coast of the United States. In: R. Mann (Editor), Exotic Species in Mariculture. MIT Press, Cambridge MA, London, pp. 54-82.

Chew, K., 1985. A review of West coast oyster fisheries and the present impact of remote setting of oyster seed. J. Shellfish Res., 5: 33.

Chew, K. K., 1988. Oyster aquaculture in the Pacific Northwest. In: S. Keller (Editor), Proc., Fourth Alaska Aquac. Conf., 1987. Sitka, Alaska, No. 88-4, pp 67-75.

Chew, K., 1990. Global bivalve shellfish introductions. World Aquaculture, 21 (3): 9-22.

Chew, K. K., 1991. Hatchery development and remote setting of the Pacific oyster larvae. Aquaculture Mag., July/Aug, pp. 72-75.

Chew, K. K., Beattie, J. H. and Donaldson, J. D., 1986. Bivalve molluscs hatchery techniques, maturation and triggering of spawning. In: Aquaculture, Shellfish Culture Development and Management. Proc. Intern. Seminar, La Rochelle, France, IFREMER, pp. 229-248.

Claus, C., 1981. Trends in nursery rearing of bivalve molluscs. In: C. Claus, N. de Pauw and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. European Maricul. Soc. Spec. Publ., 7, Bredene, Belgium, pp. 1-33.

Claus, C., Maeckelberghe, H. and De Pauw, W., 1983. Onshore nursery rearing of bivalve molluscs in Belgium. Aquacultural Eng., 2: 13-26.

Coleman, N., 1986. A review of introductions of the Pacific oyster (*Crassostrea gigas*) around the world and a discussion of the possible ecological consequences of introducing the species into Victoria, Australia. Mar. Sci. Lab. Tech. Report, No 56. Victorian Dept. Cons. Forest and Lands, Queenscliff, Vic., (unpubl.), 39 pp.

Cole, H. A. and Knight-Jones, E. W., 1949. The setting behaviour of larvae of the European flat oyster *Ostrea edulis* L., and its influence on methods of cultivation and spat collection. Fish. Invest. London, Series II, 17: 1-39.

Cooper, K., 1983. Potential for application of the chemical dopa to commercial bivalve setting systems. J. Shellfish Res., 3: 110-111.

Cooper, K. L. and Shaw, W. N., 1984. The effects of environmental factors on the ability of chemical cues to trigger settlement and metamorphosis of the Pacific oyster, *Crassostrea gigas* (Thunberg). J. ShellFish Res., 4: 85-86.

Coon, S. L. and Bonar, D. B., 1986. Chemical production of cultchless oyster spat using epinephrine and norepinephrine. Aquaculture 58: 255-262.

Coon, S. L. and Bonar, B., 1987. Pharmacological evidence that alpha$_1$-adrenoceptors mediate metamorphosis of the Pacific oyster, *Crassostrea gigas*. Neuroscience, 23: 1169-1174.

Coon, S. L., Bonar, D. B. and Fitt, W., 1988. An integrated model of oyster settlement and metamorphosis. J. Shellfish Res., 7: 548-549.

Coon, S. L., Bonar, D. B. and Weiner, R. M., 1985. Induction of settlement and metamorphosis of the Pacific oyster, *Crassostrea gigas* (Thunberg), by L-Dopa and catecholamines. J. Exp. Mar. Biol. Ecol., 94: 211-221.

Coon, S. L., Bonar, D. B. and Weiner, R. M., 1989. Endogenous control of oyster settlement and metamorphosis. J. Shellfish Res., 8: 455-456.

Coon, S. L., Fitt, W. K. and Bonar, D. B., 1990. Competence and delay of metamorphosis in the Pacific oyster *Crassostrea gigas*. Mar. Biol., 106, pp. 379-387.

Coutteau, P. and Sorgeloos, P., 1993. Substitute diets for live algae in the intensive rearing of bivalve molluscs - a state of the art report. World Aquaculture, 24: 45-52.

CRC (Chemical Rubber Company), 1971. Handbook of Chemistry and Physics, 52nd Edition. CRC, Cleveland, Ohio, p. D-105.

Cranfield, H. J., 1970. Some effects of experimental procedure on settlement of *Ostrea lutaria* Hutton. NZ. J. Mar. Freshwater Res., 4: 63-69.

Croft, H. C., 1962a. The wonder of the oyster (Part 1). The Fisherman, Sydney, 1 (2): 10-14.

Croft, H. C., 1962b. The wonder of the oyster (Part 2). Farming on sticks, rocks, shellbeds and trays. The Fisherman, Sydney, 1 (3): 13-15 and 21-26.

Curtin, L., 1983. Ongrowing undersize oysters. Catch '83, 10 (2): 13-14.

Curtin, L., 1985a. Pacific oyster farming methods. Ministry Agriculture and Fisheries Report, Fish. Man. Div., Auckland, NZ, pp. 1-7.

Curtin, L., 1985b. Natural spatfall experiments in Kaipara. Shellfish. Newsletter, NZ, 26, p. 5.

Curtin, L., 1985c. Single oysters from natural spatfall. Shellfish. Newsletter, NZ, 27, p. 6.

Curtin, L., 1986. Oyster spatfall and developments. Shellfish. Newsletter, NZ, 29, p. 3.

Dekshenieks, M. M., Hofmann, E. E. and Powell, E. N., 1993. Environmental effects on the growth and development of Eastern oyster, *Crassostrea virginica* (Gmelin, 1791), larvae: A modeling study. J. Shellfish Res., 12: 241-254.

Deupree, R. H., 1993. Genetic characterization of deep-cupped Pacific oysters (*Crassostrea gigas*) from Tasmania, Australia. Unpubl., Thesis, Univ, Washington, WA, 91 pp.

Deupree, R. H., Downing, S. L., Hershberger, W. K., Chew, K. K., 1992. Characterization of Kumamoto-like Pacific oysters from Tasmania, Australia with starch-gel electrophoresis. Aquaculture '92, In: Growing Towards The 21st Century. Orlando, FL, p. 78.

Dinamani, P., 1974. Reproductive cycle and gonadial changes in the New Zealand rock oyster, *Crassostrea glomerata*. NZ. J. Mar. Freshwater Res., 8: 39-65.

Dinamani, P., 1978. Wary researchers watching alien's rapid rise. Catch, 5 (10): 24-25.

Dinamani, P. and Lenz P. A., 1974. Some aspects of spatfall of the New Zealand rock oyster during 1974. Veliger, 20: 17-26.

Dollfus, G. F. and Dautzenberg, P., 1920. Conchyliologie du Miocenenioycn dubaisin de la Loise, pt. I: Pelecypodes (Suite et fin): Soc, Geol., France, Mein, 27, Paleoinologie 22 (2-4), 471 pp.

Dungan, C. F. and Elston, R. A., 1988. Histopathological and ultrastructural characteristics of bacterial destruction of the hinge ligaments of cultured juvenile Pacific oysters, *Crassostrea gigas*. Aquaculture, 72: 1-14.

Dungan, C. F., Elston, R. A. and Schieve, M. H., 1989. Evidence for colonisation and destruction of hinge ligaments in cultured juvenile Pacific oysters (*Crassostrea gigas*) by cytophaga-like bacteria. Appl. Envir. Microbiol., 55: 1128-1135.

Dupuy, J. L. and Rivkin, S., 1970. Cultch-free spat present and future. In: J. Avault (Editor), Boudreaux and E. Jaspers (Assoc. Editors), Proc. First Annual Workshop World Maricul. Soc., Louisiana State Univ., Baton Rouge, LA, pp. 157-158.

Dupuy, J. L. and Rivkin, S., 1972. The development of laboratory techniques for the production of cultch-free spat of the oyster, *Crassostrea virginica*. Chesapeake Sci., 13, pp. 45-52.

Eckmayer, W. J., 1983. Growth and survival of hatchery-reared American oysters set on three types of cultch and in Bon Secour Bay, Alabama. Nth. Ameri. J. Fish. Man., 3: 171-175.

Elston, R., Elliot, E. L. and Colewell, R. R., 1982. Shell fragility, growth depression, and mortality of juvenile American and European oysters (*Crassostrea virginica* and *Ostrea edulis*) and of hard clams (*Mercenaria mercenaria*) associated with surface coating Vibrio spp. bacteria. J. Shellfish Res., 2: 94.

Espinas, V. Marshall, G and Rish, B., 1988. Economic survey of the New South Wales oyster farming industry: 1981-82 to 1983-84: Part 2 - Physical aspects. Div. Marketing and Econ. Serv. Misc. Bull., No. 54., Dept. Agric., NSW, Sydney, 48 pp.

FAO, 1991. Fishery Statistics. Rome: FAO of UN., 68, 278 pp.

Farley, C. A. and Lewis, E. J., 1993. Juvenile oyster mortality studies. J. Shellfish Res., 12: 366.

Farley, C. A. Wolf, P. H. and Elston, R. A. 1988. A long-term study of "Microcell" disease in oysters with a description of New Genus, *Mikrocytos* (G.N.), and *Mikrocytos roughleyi* (SP.N.). Fishery Bull., 86 (3): 581-593.

Fisher, W. S., 1988. Disease process in marine bivalve molluscs. American Fish. Soc. Spec. Publ., 18, 315 pp.

Fitt, W. K., Coon, S. L., Walch, M., Weiner, R. M., Colwell, R. R. and Bonar, D. B., 1990. Settlement behaviour and metamorphosis of oyster larvae (*Crassostrea gigas*) in response to bacterial supernatants. Mar. Biol., 106: 389-394.

Fitt, W. K., Haymans, D. E. and Coon, S. L., 1989. Production and role of ammonia, an inducer of settlement of veliger larvae of oysters. J. Shellfish Res., 8: 456.

Frankish, K. R., Goard, L. J. and O'Connor, W. A., 1991. The development of hatchery rearing techniques of the Sydney rock oysters (*Saccostrea commercialis*). Brackish Water Fish Culture Res. Stn., Salamander Bay, NSW, (unpubl.), 25 pp.

Galtsoff, P. S., 1964a. Season of attachment and growth of sedentary marine organisms at Lamoine, Maine. Ecol., 27: 150-158.

Galtsoff, P. S., 1964b. The Americian oyster *Crassostrea virginica* Gmelin. Fish. Bull., 64, 440 pp.

Gibbons, M. C., 1988. Development of nursery techniques for remote-set larvae of *Crassostrea virginica* in Virginia. J. Shellfish Res., 7: 160.

Gmelin, J. F., 1791. Caroli a Linné Systema naturae per regna tria naturae. Ed. 13, 1: 3321-3901.

Gould, A. A., 1850. Molluscs from the South Pacific. Proc. Boston. Soc. Natl. Hist., 3: 340-346.

Grizel, H., 1993. World bivalve culture. World Aquaculture, 24: 19-23.

Grove-Jones, R., 1986. Experimental cultivation of native (*Ostrea angasi*) and Pacific (*Crassostrea gigas*) oysters in South Australia. South Aust. Dept. Fish. Report, Adelaide, SA (unpubl., report), 64 pp.

Gunn, C. R., 1984. A report on the development and use of an artificial cultch suitable for off bottom oyster culture in British Columbia. Fish. Development Report No 33, Mar. Resour., Branch, BC, 25 pp.

Guerrero Valero. S., Farina, T. T. and Silva Abuin. A., 1981. Large-scale outdoor algal production for rearing seed oysters and clams to juvenile stage. In: C. Claus, N. de Pauw and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. European Maricul. Soc. Spec. Publ., 7, Bredene, Belgium, pp. 117-139.

Hadfield, M. G., 1984. Settlement requirements of molluscan larvae: New data on chemical and genetic roles. Aquaculture, 39: 283-298.

Hadley, N. H. and Manzi, J. J., 1984. Growth of seed clams, *Mercenaria mercenaria*, at various densities in a commercial scale nursery system. Aquaculture, 36 (4): 369-379.

Harry, H. W., 1985. Synopsis of the supraspecific classification of living oysters (Bivalvia: *Gryphaeidae* and *Ostreidae*). Veliger, 28: 121-158.

Harry, H. W., 1986. The relevancy of the genetic concept to the geographic distribution of living oysters (*Gryphaeidae and Ostreidae*). Amer. Malacol. Bull., 4: 157-162.

Haven, D. S. Zeigler, J. M. Dealteris, J. T. and Whitcomb, J. P., 1987. Comparative attachment, growth and mortalities of oyster (*Crassostrea virginica*) spat on slate and oyster shell in the James River, Virginia. J. Shellfish Res., 6: 45-48.

Hawes, R. O. Scully, K. and Hidu, H., 1990. Growth rate of two diverse populations of Americian oysters, *Crassostrea virginica*, and their reciprocal crosses. In: T. Gjedrem (Editor), Genetics in Aquaculture III, 85: 327.

Helm, M. M and Spencer, B. E., 1972. The importance of rate of aeration in hatchery cultures of the larvae of *Ostrea edulis* L. J. Cons. Int. Explor. Mer., 34: 244-255.

Henderson, B. A., 1981. Practical methods of handling and settling eyed-pediveliger larvae of the Pacific oyster *Crassostrea gigas* (Thunberg). J. Shellfish Res., 2: 119-120.

Henderson, B. A., 1983. Handling and remote setting techniques for Pacific oyster larvae *Crassostrea gigas* (unpubl. thesis). Oregon State Univ. Oregon, 37 pp.

Hidu, H., 1969. Gregarious setting in the American oyster *Crassostrea virginica* Gmelin. Chesapeake Sci., 10 (2): 85-92.

Hidu, H., Chapman, S. and Soule, P.W., 1975. Cultchless setting of European oysters, *Ostrea edulis*, using polished marble. Proc. Natl. Shellfish Assoc. 65: 13-14.

Hidu, H., Chapman, S. and Dean, D., 1981. Oyster mariculture in subboreal (Marine, USA) waters: cultchless setting and nursery culture of

European and American oysters. J. Shellfish Res., 1: 57-67.

Hidu, H. and Haskin, H., 1971. Setting of the American oyster related to environmental factors and larval behaviour. Proc. Natl. Shellfish Assoc., 61: 35-50.

Hidu, H. Valleau, W. G. and Vertich, F. P., 1978. Gregarious setting in European and Americian oysters - Response to surface chemistry vs waterbourne pheromones. Proc. Natl. Shellfish Assoc., 68: 11-16.

Hine, P. M., 1990. Parasites and diseases of commercially important molluscs in New Zealand. In: J. Barret (Editor), Advances in Tropical Aquaculture-Workshop held in Tahiti, 1989, Actes Colloq. IFREMER, 9, pp. 199-206.

His, E., 1978. Une expérience de production de "naissain naturel un a un" sa croissance dans le bassin D'Arcachon. Science et Pêche, Bull. l'Inst. Pêche Marit., 280, 12 pp.

Hodgson, B. R., 1979. The hydrology and zooplankton ecology of Lake Macquarie and the recreational and commercial fishery in the Tuggerah Lakes, NSW. (unpubl. thesis), Univ. NSW, Kensington, 585 pp.

Hofmann, E. E., Klinck, J. M., Powell, J. N., Boyles, S. and Ellis, M., 1994. Modeling oyster populations II. Adult size and reproductive effort. J. Shellfish Res., 13: 165-182.

Hofmann, E. E., Powell, J. N. and Wilson, E. A., 1992. Modeling oyster populations III. Critical feeding periods, growth and reproduction. J. Shellfish Res., 11: 399-416.

Holliday, J. E., 1985. Current oyster spat research in NSW. Aust. Fish., 44 (3): 24-26.

Holliday, J. E., 1987. Nursery culture of juvenile Sydney rock oysters (*Saccostrea commercialis*). In: Collected Open Day Booklets (1973 to 1988)-Brackish Water Fish Cult. Res. Stn., Salamander Bay, NSW, Report (unpubl.,), pp. 440-446.

Holliday, J. E., 1992. International Developments in Oyster Hatchery Technology. Fish. Div. Misc. Bull., No 1., Dept. of Agric., NSW, Sydney (Revised edition), 101 pp.

Holliday, J. E. and Goard, L. J., 1986. Survey of Sydney rock oyster larvae settlement at Port Stephens, NSW. Aust. Fish., 45 (3): 27-28.

Holliday, J. E. and Nell, J. A., 1987. The Pacific oyster in New South Wales. Agfact F2.1.3 Dept. Agric., NSW, 4 pp.

Holliday, J. E. and Nell, J. A., 1990. Pacific oysters in New South Wales. Agfact, F2.1.3, 2nd Ed., NSW Agric. & Fish., Sydney, NSW, 4 pp.

Holliday, J. E., Maguire, G. B. and Nell, J. A., 1988. Alternative cultivation methods for the Sydney rock oyster (*Saccostrea commercialis*). In: L. Evans and D. O'Sullivan (Editors), Proc. First Aust. Shellfish Aqua. Conf., Curtin Univ. Technol., Perth, WA, pp. 234-265.

Hopkins, A. E., 1935. Attachment of larvae of the Olympia oyster *Ostrea lurida* to plane surfaces. Ecology, 16 (1): 82-87.

Hudson, E. B. and Hill, B. J., 1991. Impact and spread of bonamiasis in the UK. Aquaculture, 93 (3): 279-285.

Hughes-Games, W. L., 1977. Growing the Japanese oyster, *Crassostrea gigas*, in sub-tropical seawater fish ponds. I. Growth rate, Survival and quality index. Aquaculture, 11: 217-229.

Huguenin, J. E. and Ryther, J. A., 1974. The use of power plant waste in marine aquaculture. Proc. 10th Annu. Conf. Mar. Tech. Soc., Woods Hole Oceanic Inst., Woods Hole, MA, pp. 431-445.

Hutton, F. W., 1873. Catalogue of the tertiary mollusca and echinodermata of New Zealand, in the collection of the Colonial Mus. and Geol. Surv. Dept., Wellington, NZ, 16, 48 pp.

Indrasena, W. M. and Wanninayake, T. B., 1986. Settlement and growth of oyster spat in Trincomalee Bay, Sri Lanka. In: J. Maclean, L. Dizon and L. Hosillos (Editors), Proc. First Asian Fish. Forum, Manila, pp. 59-62.

Ingram, M. V., 1979. Waste heat aquaculture in the United Kingdom-A general review and particulars of Marine Farms Ltd., Hinkley Point, Bridgewater, Sommerset, England. In: B. Godfriaux, A. Eble, A. Farmanfarmaian, C. Guerra and C. Stephens (Editors), Power Plant Waste Heat Utilization in Aquaculture, Allalheld, Osmun and Co., Montclair, NJ, pp. 231-234.

Iredale, T., 1939. Mollusca. Part 1 Sci. Rep. Great Barrier Reed Expedition 5 (6): 209-245.

Iredale, T. and Roughley, T. C., 1933. The scientific name of the commercial oyster of New South Wales. Proc. Linn. Soc. NSW., 58: 278.

Jarayabhand, P., 1988. The effects of age, size and stocking density on survival and growth of *Ostrea edulis.* J. Shellfish Res., 7: 164-165.

Jarayabhand, P. and Newkirk, G. F., 1989. Effects of intraspecific competition on growth of the European oyster, *Ostrea edulis* Linnaeus, 1750. J. Shellfish Res., 2: 359-365.

Jones, G., 1976. Cooling water farm set to go commercial. Fish Farming Int., 3 (4): 14-15.

Jones, D. R. and Allen, S. K., 1991. Oyster grow-out techniques for the mid-Atlantic: A Delaware Bay model. J. Shellfish Res., 10: 296-297.

Jones, G. and Jones, B., 1983. Methods for setting hatchery produced oyster larvae. Mar. Res. Branch, Min. Envir. Prov. British Columbia, BC., 4, 94 pp.

Jones, G. and Jones, B. L., 1988. Advances in remote setting of oyster larvae. Aqua. Assoc. British Columbia, Nanaimo, BC., 88 pp.

Keck, R., Maurer, D., Kauer, C. and Sheppard, W. A., 1971. Chemical stimulants affecting larval settlement in the American oyster. Proc. National Shellfish Assoc., 61, pp. 24-28.

Kenny, P. D., Michener, W. K. and Allen, D. M., 1990. Spatial and temporal patterns of oyster settlement in a high salinity estuary. J. Shellfish Res., 9: 329-339.

King, M. G., 1977. Cultivation of the Pacific oyster (*Crassostrea gigas*) in a non-tidal hypersaline pond. Aquaculture, 11: 123-136.

Knight-Jones, E. W., 1951. Aspects of the setting behaviour of larvae of *Ostrea edulis* on Essex oyster beds. Cons. Perm. Internatl. Explor. Mar. Proc-verb. Reun., 128 (2): 30-34.

Kong, C. P. and Luh, L. A., 1976. Notes on the efficiency of various materials tested as oyster spat collectors in Cowie Bay, Sabah. Malaysian Agric. J., 50 (94): 462-479.

Korringa, P., 1976. Farming the Cupped Oysters of the Genus *Crassostrea* - Developments in Aqua. and Fish. Sci. Elsevier, Amsterdam, 2, 224 pp.

Lawrence, D. R. and Scott, G. I., 1982. The determination and use of condition index of oysters. Estuaries, 5: 23-27.

Lester, R. J. G., 1990. Diseases of cultured molluscs in Australia. In: J. Barret (Editor), Advances in Tropical Aquaculture, Tahiti (French Polynesia). Actes Colloq. IFREMER, 9: 207-216.

Lewis, E. J. and Farley, C. A., 1993. 1992-1993 East coast oyster disease survey. J. Shellfish Res., 12: 367.

Ling, Y. S., 1970. Preliminary studies on the collection of oyster spat in Johore straits. J. Singapore Natl. Acad. Aci., 2: 14-18.

Linnaeus, C., 1758. Systema naturae per tria regna naturae. Ed. 10, Stockholm, (1), 823 pp.

Lipovsky, V. 1991. Remote setting of Pacific oyster larvae. In: T. Nosho and K. Chew (Editors), Remote Setting and Nursery Culture for Shellfish Growers - Workshop Record. Washington Univ., WA: Sea Grant Program, 10-11 pp.

Loosanoff, V. L. and Davis, H. C., 1963. Rearing of bivalve mollusks. In: F. Russell (Editor), Advances in Mar. Biol., Academic Press, London, 1, pp. 1-136.

Lucas, A. and Gerard, A., 1981. Space requirement and energy cost in some types of bivalve nurseries. In: C. Claus, N. De Pauw, and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. European Maricul. Soc. Spec. Publ., 7, Bredene, Belgium, pp. 151-170.

Lutz, R. A. and Hess, C. T., 1979. Biological and radiological analysis of the potential of nuclear power plant effluent waters for shellfish culture. In: B. Godfriaux, A. Eble, A. Farmanfarmaian, C. Guerra and C. Stephens (Editors), Power Plant Waste Heat Utilization in Aquaculture, Allalheld, Osmun and Co., Montclair, NJ, pp. 109-138.

Lutz, R. A. and Porter, B., 1977. Experimental culture of blue mussels *Mytilus edulis* in heated effluent waters of a nuclear power plant. Proc. World Maricul. Soc., 8, pp. 427-445.

Maguire, G. B. and Leedow, M. I., 1983. A study of the optimum stocking density and feed rate for school prawns *Metapenaeus macleayi* (Haswell) in some Australian brackish water farming ponds. Aquaculture, 30: 285-297.

Maguire, G. B., Nell, J. A. and Allan G. L., 1988. Production trends in oyster farming and other mariculture industries in New South Wales. In: J.

Paynter and N. Preston (Editors), Proc. Aust. Maricul. Assoc., Third Annual Conf., Lismore, NSW, pp. 28-35.

Maguire, G. B., Wisely, B. and Skeel, M. E., 1981. Cultivation of the Sydney rock oyster *Crassostrea commercialis* (Iredale & Roughley) in prawn farming ponds. Aquaculture, 24: 63-75.

Major, G. A., Dal Pont, G., Kyle, J. and Newell, B., 1972. Laboratory techniques in marine chemistry. Commonwealth Science and Industrial Research Organisation, Div. Fish. Oceanogr. Rep., No. 51, Sydney, NSW, 55 pp.

Malcolm, W. B., 1987. The Sydney rock oyster. Agfact F 3.1.1, Dept. Agric., NSW, Sydney, NSW, 12 pp.

Mallonee, M. E. and Paynter, K. T., 1989. Water qualities associated with rapid oyster growth. J. Shellfish Res., 8: 486.

Malouf, R. E., 1981. Use of heated effluents for the nursery culture of bivalve molluscs: its problems and potential. In: C. Claus, N. de Pauw, and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. European Maricul. Soc. Spec. Publ., 7, Bredene, Belgium, pp. 171-188.

Malouf, R. E., Keck, R., Maurer, D. and Epifanio, C., 1972. Occurrence of gas-bubble disease in three species of bivalve molluscs. J. Fish. Res. Board. Can., 29: 588-589.

Mann, R., 1979. Exotic species in aquaculture: An overview of when, why and how. In: R. Mann (Editor), Exotic Species in Mariculture. MIT Press, Cambridge, MA, London, pp. 331-357.

Mann, R., 1983. The role of the introduced bivalve mollusc species in mariculture. J. World Maricul. Soc., 14: 546-559.

Mann, R., Barber, B. J., Whitcomb, J. P. and Walker, K. S., 1990. Settlement of oysters, *Crassostrea virginica* (Gmelin, 1791), on oyster shell, expanded shale and tire chips in the James River, Virginia. J. Shellfish Res., 9: 173-175.

Manzi, J. J., Hadley, N. H., Battey, C. R. and Holloway, J., 1987. Culture of bivalve mollusks in shrimp ponds. J. World Aquaculture Soc., 18: 23.

Manzi, J. J., O'Rourke, C. B., Bobo, M. Y., Steele, G. H. and Smiley, R. A., 1988. Results of an oyster-shrimp pond bioculture study. J. Shellfish Res., 7: 205-206.

Margraf, F. J., 1977. The growth rate of oysters held in the intake and discharge canals of an electric generating station and in natural waters. Proc. World Maricul. Soc., 8: 915-926.

Marshall, G. and Espinas, V., 1987. Economic survey of the New South Wales oyster farming industry 1981-82 to 1983-84 - 1. Financial aspects. Misc. Bull., No. 48., Dept. Agric., NSW, Sydney, 59 p.

Matthiessen, G. C., 1991. Oyster culture. In: C. Nash (Editor), Production of Aquatic Animals. World Animal Science. Elsevier, Amsterdam, pp. 89-119.

McBride, R. L., Nell, J. A. and Easton, K. M., 1988. Acceptability of the Sydney rock and Pacific oyster. Food Technol. Aust., 40: 287-290.

Medcof, J. C., 1955. Day and night characteristics of spatfall and of behaviour of oyster larvae. J. Fish. Res. Bd. Can., 12: 270-286.

Medcof, J. C. and Malcolm, W. B., 1974. Making the best of a natural resource: Oyster culture in New South Wales. The Fisherman, Sydney, 4 (10): 1-2 and 22-23.

Medcof, J. C. and Wolf, P. H., 1975. Spread of Pacific oyster worries NSW culturists. Aust. Fish., 34: 1-7.

Menzel, R. W., 1954. The prodissoconchs and the setting behaviour of three species of oysters. Proc. Natl. Shellfish Assoc., 44: 104-112.

Michener, W. K., Barnard, A. H., Jefferson, W. H., Kenny, P. D. and Brunt, J. W., 1989. Spatial settlement patterns of oysters in South Carolina. J. Shellfish Res., 8: 458.

Miyazaki, I., 1938. On fouling organisms in the oyster farm. Bull. Jap. Soc. Sci. Fish., 6: 223-232.

Morse, D. E., 1985. Neurotransmitter-mimetic inducers of larval settlement and metamorphosis. Bull. Maricul. Sci., 37: 297-706.

Moxon, A. J., 1986. Economic survey of the oyster industry in southern Queensland. Queensland Dept. Primary Industries Report, Brisbane, Qld, 19 pp.

Muthiah, P., Sundararjan, D., Srinivasan, G. and Vaithinathan, N., 1987. Pest and predators of oysters. In: K. Nayar and S. Mahadevan (Editors), Oyster Culture Status and Prospects, 38, pp. 71-74.

Nell, J. A., 1985. Pond fattening of oysters. Dept. Agric., NSW, Agfact F2.1.2., Agdex 486, 12, 2 pp.

Nell, J. A., 1987. The 1987 update on Pacific oyster research. In: Collected Open Day Booklets, Brackish Water Fish Culture Res. Stn. 1973-1988, NSW Agric. & Fish., Salamander Bay, (unpubl.), pp. 456-461.

Nell, J. A., 1988. Pacific oyster research. In: Collected Open Day Booklets, Brackish Water Fish Culture Research Station 1973-1988, NSW Agric. & Fish., Salamander Bay, NSW, (unpubl.), pp. 516-519.

Nell, J. A., 1989. Pacific Oyster Research - Proceedings Brackish Water Fish Culture Res. Stn., Open Day, Salamander Bay, NSW (unpubl.), 17-19 pp.

Nell, J. A., 1991a. Comparative growth study of Sydney rock oysters (*Saccostrea commercialis*) and Pacific oysters (*Crassostrea gigas*) in Port Stephens, NSW. In: Pacific Oysters in New South Wales - Final Report to FRDC 1991. NSW Dept. Agric. & Fish., Salamander Bay, NSW (unpubl.), pp. 8-11.

Nell, J. A., 1991b. Comparison of growth and mortality of Sydney rock oysters (*Saccostrea commercialis*) grown in trays, cylinders and sticks in Port Stephens, NSW. In: Pacific Oyster Report, NSW Fish., Salamander Bay, NSW (unpubl.), pp. 192-202.

Nell, J. A., 1993. Farming the Sydney rock oyster (*Saccostrea commercialis*) in Australia. Review in Aquatic Sciences, 1 (2): 97-120.

Nell, J. A., Cox, E., Smith, I. R. and Maguire, G. B., 1994. Studies on triploid oysters in Australia. I. The farming potential of triploid Sydney rock oysters *Saccostrea commercialis* (Iredale and Roughley). Aquaculture, 126: 243-255.

Nell, J. A. and Gibbs, P. J., 1986. Salinity tolerance and absorption of L-methionine by some Australian bivalve molluscs. Aust. J. Mar. Freshwater Res., 37: 721-727.

Nell, J. A. and Holliday, J. E., 1988. Effects of salinity on the growth and survival of Sydney rock oyster (*Saccostrea commercialis*) and Pacific oyster (*Crassostrea gigas*) larvae and spat. Aquaculture, 68: 39-44.

Nell, J. A. and Livanos, G., 1988. Effects of fluoride concentration in seawater on growth and fluoride accumulation by Sydney rock oyster

(*Saccostrea commercialis*) and flat oyster (*Ostrea angasi*) spat. Water. Res., 22: 749-753.

Nell, J. A. and Mason, C. J., 1991. Comparison of shell density, percentage cavity volume and shell weight of Sydney rock oysters (*Saccostrea commercialis*) and Pacific oysters (*Crassostrea gigas*). In: Pacific oysters in New South Wales. Final Report-Fishing Industry Research and Development Council, NSW Fisheries, Brackish Water Fish Culture Res. Stn., Salamander Bay, NSW, (unpubl.), pp. 52-60.

Nell, J. A. and Smith, I. R., 1988. Management, production and disease interactions in oyster culture. In: D. Bryden (Editor), Fish Diseases - Refresher Course for Veterinarians, Proc. 106. Univ. Sydney, NSW, pp. 127-133.

Nell, J. A., Smith, I. R. and Holliday, J. E., 1990. An overview of the Sydney rock oyster (*Saccostrea commercialis*) industry in New South Wales. Agric. Sci., 3 (2): 29-30.

Nell, J. A., O'Connor, W. A., Goard, L. J. and Callinan, R. B., 1991. An evaluation of hatchery hygiene protocol and bacterial concentrations for hatchery reared Sydney rock oyster *Saccostrea commercialis* (Iredale & Roughley) spat. Preliminary Report to Marine Culture Developments Pty Ltd, NSW Fisheries, Brackish Water Fish Culture Res. Stn., Salamander Bay, NSW. (unpubl.), report, 20 pp.

Nelson, T. C., 1927. Report of Department of Biology for the year ending June 30, 1926. N. J. Agric. Exp. Stn., pp. 103-113.

Neudecker, T., 1981. Experimental offshore nursery-growing of *Crassostrea gigas* Thunberg in Germany. In: C. Claus, N. de Pauw and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. European Maricul. Soc. Spec. Publ., 7, Bredene, Belgium, pp. 197-210.

Newell, R. I. Barber, B. J. and Fegley, S. R., 1991. Variability in the relationship between larval settlement and recruitment in populations of the oyster *Crassostrea virginica*. J. Shellfish Res., 10: 310-311.

Newkirk, G. F., 1981. On the unpredictability of bivalve growth rates: Is a slow growing juvenile oyster a runt for life? In: C. Claus, N. de Pauw and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. European Maricul. Soc. Spec. Publ., 7, Bredene, Belgium, pp. 211-218.

Nosho, T. Y. and Chew, K. K., 1991. Remote setting and nursery culture for shellfish growers - Workshop Record. Washington Sea Grant Program, Washington, WA, 68 pp.

Ogle, J. T. and Beaugez, K., 1988. Oyster hatcheries on the Gulf Coast: History, current techonology and future trends. J. Shellfish Res., 7: 505-509.

Ogle, J. and Flurry, K., 1981. Studies on various substrates in relation to setting of oyster larvae with comments on commercial applications. J. Shellfish Res., 1: 120.

Ortega, S. Fegley, S. Newell, R. and Barber, B., 1991. Measuring oyster spatfall: A comparison of methods. J. Shellfish Res., 10: 311.

O'Sullivan, D. D., 1993. Oyster farming in Australia. World Aquaculture, 24: 33-42.

O' Sullivan, B. W. and Wilson, J. H., 1976. Development of an experimental oyster hatchery. Fish Farm. Inter., NY, 3: 12-15.

Osman, R. W., Whitlatch, R. B. and Zajac, R. W., 1989. Effects of resident species on recruitment into a community: larval settlement versus post-settlement mortality in the oyster *Crassostrea virginica*. Maricul. Ecol., 54: 61-73.

Panggabean, L., Waterstrat, P. R., Downing, S. L. and Beattie, J. L. 1989. Storage and transportation of straight-hinge oyster larvae. J. Shellfish Res., 8: 323-324.

Perkins, F. A. and Wolf, 1976. Fine structure of *Marteilia sydneyi* sp. haplosporidian pathogen of Australian oysters. J. Parasitol., 62: 528-538.

Pomerat, C. M. and Reiner, E. R., 1942. The influence of surface angle and of light on the attachment of barnacles and other sedentary organisms. Biol. Bull., 82: 14-25.

Pope, G. X., 1987. Koppers' oyster tar. In: Collected Open Day Booklets, Brackish Water Fish Culture Research Station 1973-1988, NSW Agric. & Fish., Salamander Bay, NSW, (unpubl.), pp. 480-486.

Potter, M. A. and Hill, B. J., 1982. Heat mortality in the Sydney rock oyster, *Saccostrea* (*Crassostrea*) *commercialis* and the effectiveness of some control methods. Aquaculture, 29: 101-108.

Preston, H. B., 1916. Records of the Indian Museum - Report on a collection of Mollusca from the Cochin and Ennur backwaters, 12, Part 1 (4): 27-59.

Quayle, D. B., 1988. Pacific oyster culture in British Columbia. Canadian Bull. Fish. Aqua. Sci., 218, 241 pp.

Quayle, D. B. and Newkirk, G. F., 1989. Farming bivalve molluscs: Methods for study and development. Advances in world aquaculture Vol. 1. Louisiana State Univ., Baton Rouge, LA. 294 pp.

Quoy, J. R. and Gaimard, P., 1835. 'Voyage de 1' Astrolabe'. Zoologie, 3 p.

Reid, D. D., 1990. Pacific oyster survey. Internal Report 49, NSW Fisheries Research Inst., Cronulla, Sydney, (unpubl.), 23 pp.

Richardson, D. L., 1991. Some aspects of food and feeding in the Sydney rock oyster *Saccostrea commercialis* (Iredale & Roughley) in Port Stephens, NSW. Univ. New England, Northern Rivers, Lismore, NSW (unpubl. thesis), 117 pp.

Ritchie, T. P. and Menzel, R. W., 1969. Influence of light on larval settlement of American oysters. Proc. Natl. Shellfish Assoc., 59: 116-120.

Robert, R. and Maurer, D., 1992. Croissance de l'huitre japonaise *Crassostrea gigas* en cylindre rotatif Stanway. Premiers re-sultats en France. IFREMER, Actes Colloq., 14: 41-60.

Robert, R., Trut, G., Borel, M. and Maurer, D., 1993. Growth, fatness and gross biochemical composition of the Japanese oyster, *Crassostrea gigas*, in Stanway cylinders in the Bay of Arcachon, France. Aquaculture, 110: 249-261.

Robinson, A and Horton, H., 1987. Environmental effects on the growth of sibling Pacific oysters *Crassostrea gigas* (Thunberg) and overwintering spat. J. Shellfish Res., 6: 49-53.

Rodhouse, P. G., Ottway, B. and Burnell, G. M., 1981. Bivalve production and food chain efficiency in an experimental nursery system. J. Maricul. Biol. Assoc., UK., 61: 243-256.

Rodhouse, P. G. and O'Kelly, M., 1981. Flow requirements of oysters *Ostrea edulis* L. and *Crassostrea gigas* Thunberg in an upweller column system of culture. Aquaculture, 22: 1-10.

Roegner, G. C., 1989. Monitoring the initial recruitment pattens of *Crassostrea virginica* (Gmelin) spat along a tidal gradient. J. Shellfish Res., 8: 458.

Roegner, G. C. and Mann, R., 1990. Settlement patterns of *Crassostrea virginica* (Gmelin, 1971) larvae in relation to tidal zonation. J. Shellfish Res., 9: 341-6.

Roland, W. G. and Albrecht, K. J., 1990. Production of Pacific oysters *Crassostrea gigas* Thunberg from wild caught and hatchery produced seed grown at several densities on oyster shells. Aquaculture and Fish. Man., 21: 31-38.

Roland, W. G. and Broadley, T. A., 1989. Investigations into remote setting Pacific oyster larvae. J. Shellfish Res., 8: 415-416.

Roland, W. G. and Broadley, T. A., 1990. A manual for producing oyster seed by remote settling. Min. Agric. and Fish., Aquaculture and Comm. Fish. Branch, 58 pp.

Roland, B., Broadley, T. and Sutherland, I., 1988. Update on remote setting Pacific oyster larvae in British Columbia. B.C. Aquaculture Information Bull., 15, 10 pp.

Roubal, F. R., Masel, J. and Lester, R. J. G., 1989. Studies on *Marteilia sydneyi*, agent of QX disease in the Sydney rock oyster, *Saccostrea commercialis*, with implications for its life cycle. Aust. J. Mar. Freshwater Res., 40: 155-167.

Roughley, T. C., 1922. Oyster culture on the Georges River, New South Wales. Museum Applied Arts & Sci. Sydney Tech. Education Series, 25, 69 pp.

Roughley, T. C., 1926. An investigation of the causes of an oyster mortality on the Georges River, New South wales 1924-1925. Proc. Linn. Soc. NSW. 51: 446-491.

Roughley, T. C., 1933. The life history of the Australian oyster (*Ostrea commercialis*). Proc. Linn. Soc. NSW., 58: 279-333.

Sacco, F., 1897. I molluschi dei terreni Terziarii del Piemonte e della Liguria. Part 23 (*Ostreidae*, *Anomiidae e Dimyidae*). Bollettino dei musei di Zoologia e di anatamia comparata della R. Univ., Torino, 12 (298): 99-100.

Saville-Kent, W., 1891. Oysters and oyster fisheries of Queensland. Govt. Printer Brisbane, Qld, 35 pp.

Sayce, C. S. and Larson, C. C., 1965. Willapa oyster studies annual progress report. Dept. Fish. Res. Div. Washington, WA, 94 pp.

Sayce, C. S. and Tufts, D. F., 1968. Willapa oyster studies, Part 2, Dept. Fish. Res. Div. Washington, WA, 101 pp.

Schaefer, M. B., 1937. Attachment of larvae of *O. gigas*, the Japanese oyster, to plane surfaces. Ecol., 18: 523-527.

Scully, K. C. Hawes, R. O. and Hidu, H., 1988. First year growth of two diverse populations of Americian oysters, *Crassostrea virginica* (Gmelin) and their reciprocal crosses. J. Shellfish Res., 7: 174-175.

Shafee, M. S. and Sabatie, M. R., 1986. Growth and mortality of Pacific oysters in Oualidia Lagoon (Morocco). Aquaculture, 53: 201-214.

Shaw, W. N., 1967. Seasonal fouling and oyster setting on asbestos plates in Broad Creek, Talbot County, Maryland, 1963-65. Chesapeake Sci., 8 (4): 228-236.

Shaw, W. N., 1979. Overview of ongoing sea Grant projects in the United States utilizing heated water effluents and its future potential. In: B. Godfriaux, A. Eble, A. Farmanfarmaian, C. Guerra and C. Stephens (Editors), Power Plant Waste Heat Utilization in Aquaculture, Allalheld, Osmun and Co., Montclair, NJ, pp. 243-246.

Shaw, W. N., 1981. The role nurseries play in the culture of molluscs in Japan. In: C. Claus, N. de Pauw and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. European Maricul. Soc. Spec. Publ., 7, Bredene, Belgium, pp. 269-281.

Shpigel, M. and Blaylock, R. A., 1991. The Pacific oyster, *Crassostrea gigas*, as a biological filter for a marine aquaculture pond. Aquaculture 92: 187-197.

Shpigel, M., Coon, S. L. and Kleinot, P., 1989. Growth and survival of cultchless spat of *ostrea edulis* Linnaeus, 1750 produced using Epinephrine and shell chips. J. Shell., Res., 8 (2): 355-357.

Sieling, F. W., 1950. Influence of seasoning and position of oyster shells on oyster setting. Dept. Res. and Ed. Solomons, MD, pp. 57-61.

Skeel, M., 1979. Shell-boring worms (Spionidae: *Polychaeta*) infecting cultivated bivalve molluscs in Australia. J. World Maricul. Soc., 10: 529-533.

Smith, G. S., 1982. What happened to the Queensland Oyster Industry? A lesson from history. Aust. Fish., 41 (3): 42-45.

Smith, I. R., Sheridan, A. K. and Nell, J. A., 1995. Evaluation of growing methods for use in a Sydney rock *Saccostrea commercialis* (Iredale and Roughley) selective breeding program. Aquaculture, 131: 189-195.

Sokal, R. R. and Rohlf, F. J., 1981. Biometry. Freeman, NY, 859 pp.

Soniat, T. M., Broadhurst, R. C. and Haywood, E. L. 1991. Alternatives to clamshell as cultch for oysters, and the use of gypsum for the production of cultchless oysters. J. Shellfish Res., 10: 405-410.

Soong, K. Y., Chen, C. P. and Tan, T. H., 1981. Setting of oysters (*Crassostreagigas* Thunberg) and barnacles (*Balanus amphitrite albicostatus* Pilsbry) in Shhun-Sun. Rep. Inst. Fish. Biol., Taipei, 3 (4): 103-113.

Sowerby, G. B., 1870-1871. Monograph of the genus *Ostraea*. In: L. Reeve (Editor), Illustrations of The Shells of Molluscous Animals. Reeve & Co., London, 33 (18): 2.

Spencer, B. E., 1988. Growth and filtration of juvenile oysters in experimental outdoor pumped upwelling systems. Aquaculture, 75: 139-158.

Spencer, B., 1990. Cultivation of Pacific oysters. Lab. Health MAFF Direct. Fish. Res. Lowestoff, UK, 63, 47 pp.

Spencer, B. E., 1991. Predators and methods of control in shellfish cultivation. In: N. de Pauw and J. Joyce (Editors), Aquaculture and the Environment -Aquaculture Europe '91, Dublin, Spec. Publ., European Aqua. Soc., 14, p. 14.

Spencer, B. E. and Gough, C. J., 1978. The growth and survival of experimental batches of hatchery-reared spat of *Ostrea edulis* L. and *Crassostrea gigas* Thunberg, using different methods of tray cultivation. Aquaculture, 13: 293-312.

Spencer, B. E., and Hepper, B. T., 1981. Tide-powered upwelling systems for growing nursery-size bivalves in the sea. In: C. Claus, N. de Pauw and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. Spec.

Publ. Maricul. Soc., Bredene, Belgium, 7: 283-309.

Spencer, B. E., Akester, M. J and Mayer, I., 1986. Growth and survival of seed oysters in outdoor pumped upweller systems supplied with fertilised sea water. Aquaculture, 55: 173-189.

Spencer, B. E., Edwards, D. B. and Millican, P. F., 1992. Growing hatchery-reared Pacific oysters (*Crassostrea gigas* Thunberg) to market size in trays - observations on costed small-scale culture methods and rough-handling trials. Aquaculture, 106 : 261-274.

Spencer, B. E., Gough, C. J. and Thomas, M. J., 1985. A strategy for growing hatchery-reared Pacific oysters (*Crassostrea gigas* Thunberg) to market size-experiments and observations on costed small-scale trials. Aquaculture, 50: 175-192.

Spencer, B. E., Key, D., Millican, P. F. and Thomas, M. J., 1978. The effects of intertidal exposure on the growth and survival of hatchery-reared Pacific oysters (*Crassostrea gigas* Thunberg) kept in trays during their first ongrowing season. Aquaculture 13: 191-203.

Stenzel, H. B., 1971. Oysters. In: R. Moore (Editor), Treatise on Invertebrate Palenontology. Geol. Soc. Ameri. Inc., Boulder, Co., Part N, Mollusca 6, Bivalvia, Geol. Soc., Ameri., N953-N1224, 3 (6), 271 pp.

Supan, J. and Wilson, C., 1993. Oyster seed alternatives for Louisiana. World Aquaculture 24 (4): 79-82.

Thomas, J. and Burnell, G. 1992. Commercial trials to assess the growth and survival of remote set Pacific oyster (*Crassostrea gigas*) larvae in shallow nursery ponds. Aquaculture '92, - Growing Towards The 21st Century, World Aqua. Soc., pp. 215-216.

Thomson, J. M., 1950. The effect of the orientation of cultch material on the setting of the Sydney rock oyster. Aust. J. Mar. Freshwater Res., 1: 140-154.

Thomson, J. M., 1952. The acclamation and growth of the Pacific oyster (*Gryphaea gigas*) in Australia. Aust. J. Mar. Freshwater Res., 3: 64-73.

Thomson, J. M., 1954. Handbook for oyster-farmers. Division of Fisheries Circular, CSIRO, Sydney, NSW, 3: 21 p.

Thomson, J. M., 1959. The naturalisation of the Pacific oyster in Australia. Aust. J. Mar. Freshwater Res., 10: 144-149.

Thomas, J. and Burnell, G., 1992. Commercial trials to assess the growth and survival of remote set Pacific oyster (*Crassostrea gigas*) larvae in shallow nursery ponds. Aquaculture '92. Orlando, FL, pp. 215-216.

Thunberg, C. P., 1793. Teckning och beskrifning pa en stor Ostronsort Ifran, Japan. K. Svenska Vetensk. Akad., Handlingar, 14: 140-142.

Torigoe, K., 1981. Oysters in Japan. J. Sci., Hiroshima Univ. Ser. B. Div. 1, 29 (2): 291-498.

Treadwell, R., McKelvie, L. and Maguire, G. B., 1991. Profitability of selected aquacultural species. Discussion Paper 91.11. ABARE, Canberra, 85 pp.

Tritar, S., Prieur, D. and Weiner, R. 1992. Effects of bacterial films on the settlement of the oysters, *Crassostrea gigas* (Thunberg, 1793) and *Ostrea edulis*, Linnaeus, 1750 and the scallop *Pecten maximus* (Linnaeus, 1758). J. Shellfish Res., 11: 325-330.

Underwood, A. J., 1981. Techniques of analysis of variance in experimental marine biology and ecology. Oceanogr. Mar. Biol. Ann. Rev., 19: 513-605.

Urban, E. R. and Kirchman, D. L., 1992. The effect of kaolinite clay on the feeding activity of the Eastern oyster *Crassostrea virginica* (Gmelin). J. Exp. Mar. Biol. Ecol., 160: 47-60.

Utting, S. D. and Spencer, B. E., 1992. Introductions of marine bivalve molluscs into the United Kingdom for commercial culture - case histories. ICES Mar. Sci. Symp., 194: 84-91.

Veitch, F. P. and Hidu, H., 1971. Gregarious setting in the American oyster *Crassostrea virginica* Gmelin: 1. Properties of a partially purified 'Setting factor'. Chesapeake Sci., 12: 173-178.

Walch, M., Dagasan, L., Coon, S. L., Weiner, R. M., Bonar, D. B., Colwell, R. R. 1988a. Identification of soluble microbial products that induce settlement behaviour in oyster larvae (*Crassostrea* spp.). J. Shellfish Res., 7: 551.

Walch, M., Labare, M. P., Weiner, R. M., Colwell, R. R., Fitt, W. and Bonar, D. B., 1988b. Use of specific bacterial biofilms and their products to enhance spat set of the oyster *Crassostrea virginica* and *C. gigas*. J. Shellfish Res., 7: 179-180.

Wallace, R. K. and Rouse, D. b., 1992. Growth and survival of Eastern oysters in an earthern pond. J. Shellfish Res., 11: 208-209.

Walne, P.R., 1974. Culture of Bivalve Molluscs. Fishing News (Books), West Byfleet, England, 173 pp.

Weiner, R. M. Coyne, V. Raiken, S. F. and Brayton, P., 1988. *Alteromonas colwelliana*, a new species from oyster water. Int. J. Syst. Bacteriol. 38: 240-244.

Weiner, R. M. Segall, A. M. and Colwell, R. R., 1985. Characterization of a marine bacterium associated with *Crassostrea virginica* (the Eastern Oyster). Appl. Envir. Microbiol., 49: 83-90.

Weiner, R. M., Walch, M., Fuqua, C., Sledjeski, D., Dagasan, L. and Coon, S. 1989a. Molecular cues of *Crassostrea* set that are synthesized by bacteria. J. Shellfish Res., 8: 459-460.

Weiner, R. M., Walch, M., Labare, M. P., Bonar, D. B. and Colwell, R. R., 1989b. Effects of biofilms of the marine bacterium *Alteromonas colwelliana* (LST) on set of the oysters *Crassostrea gigas* (Thunberg, 1793) and *C. virginica* (Gmelin, 1791). J. Shellfish Res., 8: 117-123.

Williams, P., 1981. Offshore nursery-culture using the upwelling principle. In: C. Claus, N. de Pauw and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. European Maricul. Soc. Spec. Publ., 7, Bredene, Belgium, pp. 311-315.

Wilson, J. H., 1987. Environmental parameters controlling growth of *Ostrea edulis* L. and *Pecten maximus* L. in suspended culture. Aquaculture, 64: 119-131.

Winer, B. J., 1971. Statistical Principles in Experimental Design. 2nd Ed. McGraw-Hill Kogakusha Ltd, Tokyo, 907 pp.

Wisely, B., 1983. Hatchery spat production holds promise. Aust. Fish., 42 (10): 14-16.

Wisely, H. B., Holliday, J. E. and Reid, B. L., 1979a. Experimental deepwater culture of the Sydney rock oyster (*Crassostrea commercialis*). IV. Pilot production of raft oysters. Aquaculture, 17: 77-83.

Wisely, H. B., Holliday, J. E. and Reid, B. L., 1979b. Experimental deepwater culture of the Sydney rock oyster (*Crassostrea commercialis=Saccostrea cucullata*). 1. Growth of vertical clumps of oysters ('Ren'). Aquaculture, 16: 127-140.

Wisely, H. B., Holliday, J. E. and Reid, B. L. 1979c. Experimental deepwater culture of the Sydney rock oyster (*Crassostrea commercialis=Saccostrea commercialis*) 2. Pontoon tray culture. Aquaculture, 16: 141-146.

Wisely, H. B., Okamoto, R. and Reid, B. L. 1978. Pacific oyster (*Crassostrea gigas*) spatfall prediction at Hiroshima, Japan, 1977. Aquaculture, 15:227-241.

Witney, E., Beumer, J. and Smith, G., 1988. Oyster culture in Queensland. Information Series Q188017. Dept. Primary Industry, Brisbane, Queensland, 27 pp.

Wolf, P. H., 1977. Life cycle and ecology of *Marteilia sydneyi* in the Australian oyster, *Crassostrea commercialis.* Mar. Fish. Rev., 41: 70-71.

Wolf, P. H. and Collins, A. J. 1979. Summary of daily temperature and salinity records for major oyster-producing estuaries of New South Wales - 1966-1973. NSW Fisheries, Sydney, (unpubl.), 107 pp.

Wolf, P. H. and Medcof, J. C., 1974. Be on your guard against the Pacific oysters. The Fisherman, Sydney 4 (10): 3-5 and 24-25.

Yokota, T., 1936. Attachment of larvae of the Japanese oyster, *Ostrea gigas.* Fish. Exp. Stn. Miyagi Prefecture, Yosyoka Kwai Si. Rep, 6, 11 pp.

Yoshihisa, F., 1979. Enzyme polymorphism and population structure of the Pacific oyster, *Crassostrea gigas.* Tokyo J. Agric. Res. 30 (1): 32-42.

9 APPENDICES

APPENDIX 9.1

Average settlement of Sydney rock oyster (*Saccostrea commercialis*) larvae on various layers of small PVC discs in a hatchery (Section 3.2)[1]

Layer and position of disc in tank[2]	Average spat settlement on discs
1	527.2 ± 228.5
2	836.0 ± 409.5
3	214.0 ± 37.6
4	926.0 ± 480.6
5	648.2 ± 241.5
6	540.2 ± 297.5
7	1643.8 ± 1420.9
8	1415.2 ± 563.5
9	1101.0 ± 551.8
10	667.8 ± 323.4
11	1856.8 ± 855.0
12	796.8 ± 284.1
13	118.6 ± 52.2
14	822.8 ± 417.3
15	385.0 ± 166.6
16	207.6 ± 61.6
17	314.0 ± 144.2
18	496.6 ± 300.9
19	638.0 ± 238.2
20	953.2 ± 339.4

1 Values are means±SE; n=5. Settlement was not significantly different between layer (P>0.05). Data were transformed ($\log_{10}x$) prior to ANOVA.

2 Stacks of discs were positioned vertically in the tank 1 (top disc) to 20.

APPENDIX 9.2

Average retention of Sydney rock oyster (*Saccostrea commercialis*) spat on various layers of small PVC disc deployed at North Arm Cove (Experiment 1, Section 6.1)

Layer and position[2] on disc in the stack	Average retention on disc
1	78.0±31.0
2	280.0±122.0
3	118.2±23.2
4	291.0±112.0
5	286.0±91.1
6	305.2±163.0
7	379.2±227.1
8	595.2±211.3
9	384.2±113.0
10	290.0±118.1
11	757.0±293.0
12	438.0±114.0
13	91.2±39.3
14	411.0±185.0
15	223.0±78.1
16	159.2±45.0
17	186.0±62.1
18	298.0±169.0
19	349.0±103.1
20	422.0±143.1

[1] Values are means±SE; n=5. Retention was not significantly different between layers (P>0.05). Data transformed ($\log_{10}x$) prior to ANOVA

[2] Stacks of discs position 1 (top) to 20 on an intertidal lease

APPENDIX 9.3

Monthly temperature and salinity data for nursery sites in Port Stephens, NSW (Section 5.1)[1]

	Swan Bay		North Arm Cove		Pindimar	
Month	Temp	Salinity	Temp	Salinity	Temp	Salinity
Aug	14.5	29.2	12.5	27.2	14.5	27.2
Sep	16.2	33.0	16.5	34.0	17.0	35.0
Oct	19.5	32.0	20.0	34.0	19.5	34.0
Nov	23.5	24.0	24.0	27.5	23.0	29.0
Dec	23.0	29.0	23.0	32.0	22.5	31.0
Jan	25.6	34.4	25.9	35.4	25.6	35.1
Feb	25.4	30.5	25.7	32.6	25.1	32.3
Mar	24.8	32.8	24.7	33.7	24.4	32.6
Apr	19.0	33.1	20.6	34.3	20.4	34.1
May	16.0	35.3	16.0	35.3	17.5	35.8
June	10.4	34.9	14.0	35.6	13.4	35.4
July	13.2	35.2	13.7	35.5	14.8	35.4
Mean±SE	19.3±1.5	32.0±1.0	19.7±1.5	33.1±0.8	19.8±1.3	33.1±0.8
Range	10-26	24-35	13-26	27-36	13-26	27-36

1 Data based on individual monthly readings.

APPENDIX 9.4

Growing and winter conditioning Sydney rock oysters (*Saccostrea commercialis*) in prawn farming ponds in northern NSW

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ABSTRACT

Allan, G. L., Holliday, J. E. and Frances, J. Growing and winter conditioning Sydney rock oysters (*Saccostrea commercialis*) in prawn farming ponds in northern NSW.

Small Sydney rock oyster spat (*Saccostrea commercialis*) (average initial weight 2.2±0.1 g; mean±SE; n=8) and larger spat (average initial weight 17.2±0.3 g; n=8) were grown in continuously submerged PVC mesh bags in a 2 ha fertilised brackish water pond (20 ML), stocked with leader prawns (*Penaeus monodon*), and in the water inlet channel (1.5 km x 15 m; 22.5 ML) of a prawn farm adjacent to the Clarence River, NSW. Despite reduced salinity levels (<15 ‰) survival rates of spat and larger spat were high in both the pond and channel (83.5% and 88.5% respectively). Survival, weight gain and total biomass gain for spat and condition index of larger oysters were all significantly (P<0.001) better in the inlet channel than in the pond. After 12 weeks average weight gain and biomass gain values for spat in the inlet channel were 2.2 g and 467.8 g respectively compared with 0.7 g and 55.4 g respectively for spat in the pond. For condition index, site and time effects were significant (P<0.001) and there was a significant interaction (P<0.001). Oyster condition in the ponds declined steadily over time from 11.4% at the start of the experiment to 5.7% after 12 weeks, however, in the channel, oyster condition decreased initially, but then improved to similar levels

obtained at stocking. No mudworm infestation was observed in oysters.

INTRODUCTION

The culture of oysters using on shore tanks or ponds which are fertilised to stimulate algal blooms has received considerable attention from research workers (King, 1977; Maguire et al., 1981; Nell, 1985; Manzi et al., 1987) and oyster farmers (Holliday et al., 1988). NSW oyster farmers have trouble marketing their oysters during winter as the meats are often in poor condition (Holliday, et al., 1988). Enriched ponds may be useful for fattening oysters during these periods.

In NSW 160 ha of earthen ponds have been constructed for farming marine prawns. The bi-culture of prawns and oysters together may provide prawn farmers with a second crop and oysters farmers with enriched ponds for winter growth and conditioning of oysters. Effluent quality may also be enhanced. The objectives of this study were to assess the potential for using the water inlet channel and a fertilised 2 ha pond at a prawn farm, for growing spat and fattening or maintaining market condition of larger oysters.

METHODS

A prawn farm adjacent to the Clarence River, NSW and with 20 ha of ponds, was chosen for this study. Two sites were used; a 2 ha fertilised pond (20 ML) used for growing leader prawns *Penaeus monodon* and the water inlet channel (1.5 km long, 15 m wide; 22.5 ML) for the farm. The inlet channel was supplied by pump and hence was closed to the estuary. In the pond oysters were located approximately 9 m downstream from a paddle wheel (Air-O_2) aerator and in the channel approximately 16 m downstream from twin 400 mm diameter pump outlet pipes. Both aerators and pumps generated a strong current when in operation.

Four replicate units, each with eight individual sections were placed at each site. Growing units consisted of four mesh bags (450 x 900 mm; 6 mm mesh) supported by a tarred hardwood frame (1800 x 900 mm). A hardwood stake separated the frame into two halves and, as the top and bottom surfaces of each bag were stapled to this stake, each bag was separated into two sections (450 x 450 mm). The growing units were suspended beneath floating PVC pontoons at a depth of approximately 300 mm. The experiment was run for 12 weeks from March to June.

Small spat

An equivalent volume of oyster spat (average weight 2.2±0.1 g; means±SE) was stocked in each section. The average number and weight of oysters in each section was 262±2.5 and 523.6±2.0 g respectively. At harvest, the number and weight of live and dead oysters was determined and the survival, average individual weight gain and the total biomass gain calculated for each section of each unit. Total recovery of oysters (live plus dead) for all sections was similar and greater than 90% and survival was based on the number of oysters present at the end of the experiment.

Large spat

Four replicate growing units, each with four sections, were placed at each site. Forty large spat (average initial weight 17.2±0.3 g in good condition) were placed in each section. Eight oysters, (two from each section) were sampled every two weeks, and total weight, shell weight and oyster dry mean condition index determined for each oyster. An average for each replicate was then calculated.

Condition index (%) = dry meat weight (g) x 100/cavity volume (Lawrence and Scott, 1982).

Statistical analysis

The effects of site, and replicate growing units within sites, on performance indices for small spat were assessed using single-factor nested ANOVAs.

Survival data were transformed (arcsine $x^{0.5}$) prior to analysis to satisfy assumptions of homogeneity and normality. For larger spat, an average for whole weight and condition index (based on eight individual oysters) for each replicate unit was calculated for each site and each sampling period. ANOVA comparisons between means were made using Tukey's honestly significantly difference method (Sokal and Rohlf, 1981) and homogeneity of variance assessed using Cochran's test (Winer, 1971). The effects of site and time (fixed factor) were analysed using two-factor ANOVA.

RESULTS

Performance indices for spat are given in Table 1. Survival was high (>82%) for all treatments, however, it was significantly ($P<0.001$) higher in the channel (average for all units 88.5%) than in the pond (average for all units 83.5%). Both growth and biomass gain in the pond (0.7 g/oyster and 55.4 g respectively) were significantly ($P<0.001$) lower than in the channel (2.2 g/oyster and 467.8 g respectively) (Table 2).

Poor growth was recorded for the large oysters and the effects of time and site were not significant ($P>0.05$). For condition index, however, site and time effects were significant ($P<0.001$) and there was a significant interaction ($P<0.001$). Oyster condition in the ponds declined steadily over time from 11.4% at the start of the experiment to 5.7% after 12 weeks. In the channel, however, oyster condition decreased initially but then improved to similar levels obtained at stocking (Table 2). No mudworm (spionid polychaete) infestation was observed in oysters.

Salinity levels were depressed throughout the study following prolonged rainfall. Mean salinity in the pond based on nine readings taken by prawn farm staff was 10.4‰ (range 7-14‰) and in the channel 11.9‰ (range 9-15‰). The mean temperature was 20.7°C (range 17.5-24.0°C) and was similar at both sites.

DISCUSSION

The low salinity recorded during this experiment prevented an accurate assessment of the potential for growing and fattening oysters at prawn farms. However, it was encouraging that survival rates of both spat (2.2 g/spat) and larger spat (17.2 g/spat) were very high, despite salinity levels remaining below the lower level of this range for the duration of this experiment.

Nell and Holliday (1988) found that the optimum salinity for growth of small Sydney rock oyster spat was 25-35‰ and that growth increased over the range 15-25‰. Growth of spat in the pond during the present study was slow, with an average increase of only 0.7 g/oyster. Despite low salinities, however, growth of spat in the channel was encouraging, with an average weight gain of 2.2 g/oyster over 12 weeks. This compared well with growth rates of approximately 1.8 g/oyster over 22 weeks for oysters at similar densities on trays in Port Stephens, NSW where average salinity and temperature values were 26.6 ‰ and 18.8°C respectively (Holliday et al., 1991). However, it should be noted that faster growth rates have been recorded for oysters at lower densities (Holliday et al., 1991) and/or using different culture systems (Holliday et al., 1988).

Maguire et al. (1981) found that condition of oysters in prawn farming ponds improved rapidly over time, although oysters did not grow rapidly and mortality and mudworm infection rates were high. In addition, there was a thick accumulation of decaying organic material on the upper shell of pond oysters. In the present study no problems were observed with mudworm and, although there was some algal growth and accumulating of silt on the upper surface of oysters in the pond. The condition index of larger oysters at the start of the experiment (11.4 or 11.8%; Table 1) indicated that they were in good condition (J. Nell, pers. comm., 1991). In the fertilised pond oysters lost condition and juveniles grew very slowly, although, oysters maintained better condition and juveniles grew well in the adjacent water inlet channel, which had similar temperature and salinity regimes. The ability to hold oysters in good condition can be of value to oyster farmers who wish to maintain continuity of supply for marketing.

Results from this study indicate that water inlet channels at prawn farms, which are similar to the one described here, may offer considerable potential for oyster cultivation. Although disappointing results were recorded in the fertilised prawn farming ponds, better growth and condition of oysters in ponds may have been achieved under more favourable salinity conditions.

REFERENCES

Holliday, J. E., Maguire, G. B. and Nell, J. A., 1988. Alternative cultivation methods for the Sydney rock oyster (*Saccostrea commercialis*). In: L. H. Evans and D. O'Sullivan (Editors), Proc. First Aust. Shellfish Aquaculture Conf., 23-27 October, Perth, W. A., pp. 234-265.

Holliday, J. E., Maguire, G. B. and Nell, J. E., 1991. Optimum stocking density for nursery culture of Sydney rock oysters (*Saccostrea commercialis*). Aquaculture, 96: 7-16.

King, M. G., 1977. Cultivation of the Pacific oyster (*Crassostrea gigas*) in a non-tidal hypersaline pond. Aquaculture, 11: 123-136.

Lawrence, D. R. and Scott, G. I., 1982. The determination and use of condition index of oysters. Estuaries, 5 (1): 23-27.

Maguire, G. B., Wisely, B. and Skeel, M. E., 1981. Cultivation of the Sydney rock oyster *Crassostrea commercialis* (Iredale and Roughley) in prawn farming ponds. Aquaculture, 24: 63-75.

Manzi, J. J., Hadley, N. H., Battey, C. R. and Holloway, J., 1987. Culture of bivalve molluscs in shrimp ponds. J. World Aquaculture Soc., (Aquaculture Communiques), 18 (1): 23.

Nell, J. A., 1985. Pond fattening of oysters. NSW Dept. Agric., Agfact F2.1.2., Agdex 486/12, 2 pp.

Nell, J. A. and Holliday, J. E., 1988. Effects of salinity on the growth and survival of Sydney rock oyster (*Saccostrea commercialis*) and Pacific oyster (*Crassostrea gigas*) larvae and spat. Aquaculture, 18: 39-44.

Winer, B. J., 1971. Statistical Principles in Experimental Design. 2nd Ed. McGraw-Hill, NY, 957 pp.

TABLE 1

Performance indices for Sydney rock oyster (*S. commercialis*) spat (2.2 g/spat average initial weight) grown in a fertilised 2 ha pond and the water inlet channel of a prawn farm adjacent to the Clarence River, NSW[1]

Site/Growing unit		Survival[2] (%)	Average weight gain (g/oyster)	Total biomass gain (g)
Pond	1	79.2±1.5	0.9±0.1	46.4±12.3
	2	86.6±0.6	0.6±0.1	59.3±5.0
	3	82.3±2.0	0.7±0.0	48.2±13.0
	4	85.7±0.9	0.7±0.0	67.6±7.3
Channel	1	88.6±0.8	2.1±0.1	465.4±15.1
	2	89.7±1.0	2.3±0.1	503.1±25.6
	3	86.6±1.1	2.3±0.1	459.9±16.1
	4	89.1±1.0	2.2±0.0	442.6±19.1

1 Values are means±SE (n= 8 replicate sections). Nested ANOVA results indicated that all performance indicators were significantly ($P < 0.001$) higher in the channel than in the pond. The variation due to differences between replicates was also significant ($P < 0.05$), however, the variation accounted for only 17.4%, 0.9% and 0.4% of the total variation for survival, average weight gain and total biomass gain in that order.

2 Data transformed (arcsine $x^{0.5}$) prior to analysis.

TABLE 2

Condition index and whole weight of Sydney rock oysters (*S. commercialis*) grown in a 2 ha pond and the water inlet channel of a prawn farm adjacent to the Clarence River, NSW[1]

Week	Condition Index (%)[2]		Whole weight (g/oyster)[3]	
	Pond	Channel	Pond	Channel
0	11.4±0.4[abc]	11.8±0.4[ab]	17.1±0.3	17.4±0.5
2	9.1±0.2[d]	8.6±0.8[dc]	16.9±0.3	17.8±0.5
4	6.6±0.1[ef]	9.5±0.4[cd]	18.1±0.5	18.5±0.5
6	6.0±0.3[3]	9.3±0.4[cd]	17.5±0.4	18.5±0.5
8	6.0±0.4[f]	10.6±0.6[bcd]	17.2±0.1	17.4±0.4
10	5.6±0.2[f]	12.0±0.6[ab]	18.0±0.2	18.5±0.6
12	5.7±0.3[f]	12.8±0.4[a]	18.2±0.5	18.5±0.4

1 Values are x±SE; n=4 replicate trays.

2 Results of two-factor ANOVA indicated that both site and dates significantly ($P<0.001$) affected condition index. As there was a significant interaction ($P<0.001$) between site and date a comparison of means for all combinations of time and site was made. For condition index, means (at any site or date) sharing a common letter in the superscript were not significantly different ($P>0.05$).

3 Effects of site and date on whole oyster weight were not significant ($P>0.05$).

APPENDIX 9.5

Refereed publications arising from this thesis

1 Holliday, J. E., 1995. Effects of surface orientation and slurry-coating on settlement of Sydney rock oysters, *Saccostrea commercialis*, on PVC slats in a hatchery. Accepted 1995, Aquacultural Engineering.

2 Holliday, J. E., Allan, G. L. and Frances, J., 1991. Cold storage effects on setting of larvae of the Sydney rock oyster, *Saccostrea commercialis*, and the Pacific oyster, *Crassostrea gigas*. Aquaculture, 92: 179-185.

3 Holliday, J. E., Allan, G. L. and Nell, J., 1993. Effects of stocking density on juvenile Sydney rock oysters, *Saccostrea commercialis*, (Iredale & Roughley) in cylinders. Aquaculture, 109: 13-26.

4 Holliday, J. E., Allan, G. L., Frances, J. and Diver, L. P., 1993. Evaluation of commercially-used collectors for Sydney rock oysters, *Saccostrea commercialis* and Pacific oysters, *Crassostrea gigas*. Aquacultural Engineering, 12: 63-79.

5 Holliday, J.E., Maguire, G.B. and Nell, J.A. 1991. Optimum stocking density for nursery culture of Sydney rock oysters (*Saccostrea commercialis*). Aquaculture, 96: 7-16.

6 Holliday, J. E., Maguire, G. B. and Nell, J. A., 1991. Evaluation of sites for nursery culture of single Sydney rock oysters (*Saccostrea commercialis*). Department of Agriculture, NSW, Fish. Bull., 5, 7 pp.

Please refer to the pocket in the back cover of this thesis for copies of the above.

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Evaluation of Commercially-used Collectors for Sydney Rock Oysters, *Saccostrea commercialis* and Pacific Oysters, *Crassostrea gigas*

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ABSTRACT

*Ten types of commercially-used collectors were evaluated for natural settlement and retention of juvenile Sydney rock oysters (*Saccostrea commercialis*) and barnacles (*Balanus *spp.), over 271 days in Port Stephens, NSW, Australia. Juvenile Sydney rock oysters (spat) from six collector types were then removed and on-grown in timber and PVC mesh trays for 14 days, to assess whether collector type affected post-harvest survival. Retention and growth of Sydney rock oysters to market size were also assessed 843 days after deployment, on five types of collectors used for on-growing. Nine of the collector types were also evaluated as substrates for settlement of Pacific oysters (*Crassostrea gigas*) in Port Stephens. Density at settlement and retention of juvenile and adult oysters was higher on PVC collectors than on traditionally-used tarred sticks.*

Density of Sydney rock oyster spat, was higher ($P < 0{\cdot}05$) on five types of PVC collectors, and the bioresin slats than on tarred sticks. Retention of spat on four types of PVC collectors was also higher ($P < 0{\cdot}05$) than on tarred sticks between 172 and 271 days. There was a significant relationship ($P < 0{\cdot}001$) between oyster density at day 172 and spat losses at day 271. More barnicles settled on tarred sticks than on other substances ($P < 0{\cdot}05$). Post-harvest survival of single Sydney rock oyster spat 14 days after removal from collectors was high (89–94%) and similar ($P > 0{\cdot}05$) for four types of PVC collectors and tarred sticks ($P < 0{\cdot}05$). However, survival of spat removed from bioresin slats was lower (66·8%).

At harvest (day 843), the highest ($P < 0{\cdot}05$) number of market size Sydney rock oysters were retained on four types of PVC sticks and the lowest number on tarred sticks. With the exception of flat spiky PVC sticks, which had a higher percentage loss than round spiky PVC sticks ($P < 0{\cdot}01$), oyster losses between day 172 and harvest for all five types of *on-growing collectors were uniformly high (range 92·6–96·5%; $P > 0{\cdot}05$), despite the differences in initial spat density. Spat density of Pacific oysters was higher ($P < 0{\cdot}001$) on three types of PVC collectors than on tarred sticks, PVC slats and bioresin slats.*

INTRODUCTION

Oyster industries may obtain juvenile oysters (spat) from hatcheries, or through natural spatfall where a wide variety of substrates may be used (Quayle, 1988). The majority of Sydney rock oyster (*Saccostrea commercialis*) marketed in Australia are produced in New South Wales (NSW). Farmers have traditionally relied on hardwood sticks, coated with tar to deter marine borers, as the major substrate for spat collection and grow-out of attached oysters to market size (Korringa, 1976; Malcolm, 1987). Of the 16 NSW estuaries used for the commercial collection of Sydney rock oysters, the majority of juvenile oysters are collected from Port Stephens (Espinas *et al.*, 1988). Since 1984, the Pacific oyster (*Crassostrea gigas*) has become well established in Port Stephens (Chew, 1990; Holliday & Nell, 1990) and it is now also commercially grown in this estuary (Bird *et al.*, 1991).

Many NSW farmers remove spat from tarred hardwood sticks and PVC collectors and on-grow these oysters using single seed culture techniques (Holliday *et al.*, 1988, 1991*a*). A decline in production from 140 000 bags in 1975 to 100 000 bags (approximately 1200 oysters/bag) in 1987 (Malcolm, 1987; Maguire *et al.*, 1988) and inadequate returns on investment (Espinas *et al.*, 1988) have encouraged many farmers to seek alternative substrates for the collection and grow-out of oysters.

Various materials have been evaluated in estuaries or hatcheries as surface for settlement of a number of species of oysters including *C. belcheri*; *C. gasar*; *C. gigas*; *C. virginica*; *Ostrea edulis*; *S. commercialis* and *S. cucullata* (Dupuy & Rivkin, 1970, 1972; Ling, 1970; Hidu *et al.*, 1975; Kong & Luh, 1976; O'Sullivan & Wilson, 1976; Ajana, 1979; Curtin, 1985*a*; Holliday, 1985*a*; Jones & Jones, 1988). In Europe and North America there has been a move away from traditional methods to the commercial use of PVC and other synthetic collectors to increase settlement and retention of Pacific oysters (Jones & Jones, 1988; Roland *et al.*, 1988) and to reduce operating costs (His, 1978; Gunn, 1984).

The objectives of this study were: (1) to assess the intensity of settlement and retention of Sydney rock oysters, Pacific oysters and barnacles on different, commercially-available collector types; (2) to determine the post-harvest survival of Sydney rock oyster spat from collector types designed for single spat production and (3) to determine which collector types were most suitable for on-growing Sydney rock oysters to market size.

METHODS

Collectors

The ten types of oyster collectors used for this study had been designed and manufactured for collection and removal of spat for single seed culture (single spat collectors) and/or for collecting and on-growing spat to market size. Those used for single spat collection were: PVC discs (D), slurry-coated PVC discs (SCD), bioresin slats (BS), PVC slats (S), slurry-coated PVC slats (SCS) and tarred hardwood sticks (TS) (Table 1). The types of on-growing collectors used were; flat spiky PVC sticks (FSS), round spiky PVC sticks with a lug (RSSL), round grooved PVC sticks (RGS), round spiky PVC sticks (RSS) and tarred sticks (TS), (Table 1). Tarred sticks (TS) are used to collect spat for single seed culture, or for on-growing on the sticks.

As practiced commercially, all collectors were conditioned by deploying them at least one month prior to the start of settlement (Gunn, 1984; Jones & Jones, 1988; Roland & Broadley, 1990). Conditioning of collectors by immersing them in sea water for a period before settlement is important as it; (1) allows potentially toxic compounds in the collectors to leach out; (2) neutralises the pH on the surface of slurry coated collectors, and; (3) allows a primary fouling community (mainly bacteria) to develop (Morse, 1985; Roland *et al.*, 1988; Roland & Broadley, 1990). Each collector type was deployed in stacks using a similar format (described in Table 1) to that used by commercial farmers (Korringa, 1976; His, 1978; Gunn, 1984; Jones & Jones, 1988; Roland & Broadley, 1990).

Experiment 1 — Sydney rock oysters

Settlement and spat retention

Ten types of collectors were deployed in the middle of a commercially-used, intertidal spat catching area in Salamander Bay, NSW (32° 43′ S; 152° 5′ E; Korringa, 1976). The collectors consisted of four types of PVC sticks (FSS, RSS, RSSL, and RGS), three types of slats (BS, S, SCS), two types of PVC discs (D and SCD), and tarred sticks (TS). Replicate

TABLE 1
Summary of Specifications for Collector Types used in Experiments 1 and 2

Type	*Dimensions/collector (mm)*	*Surface area/ collector (cm^2)*	*Format of stacks*		*Total no. collectors/ treatment*
			No. of layers	*No/layer*	
PVC Sticks					
Flat spiky PVC stick (FSS)	50 width 10 cavity 1 235 length 1·5 wall thickness	1 359	5	4	100
Round spiky PVC stick with lug (RSSL)	22 diameter 16 width lug 1 808 length	1 792	5	4	100
Round grooved PVC stick (RGS)	22 diameter 1 808 length	1 250	5	4	100
Round spiky PVC stick (RSS)	22 diameter 1 808 length	1 250	5	4	100
PVC discs					
PVC disc (D)[a]	140 diameter 1·0 wall thickness	275	10	3	150
Slurry-coated[a,b] PVC disc (SCD)	355 diameter 5·0 wall thickness	1 790	6	1	30
Slats					
Bioresin[a,c] slat (BS)	100 width 1 010 length	2 020	5	3	75
PVC slat (S)[a,d]	104 width 1 495 length 2·0 wall thickness	3 110	5	4	100
Slurry-coated[a,b] PVC slat (SCS)	104 width 1 495 length 3·0 wall thickness	3 110	5	4	100
Tarred hardwood[a,e,f] *stick* (TS).	20 × 20 1 800 length	1 440	5	12	300

[a]Collectors were designed for single seed culture.
[b]Disc and slats were slurry-coated with the following mix: 600 g hydrated lime, 200 g cement, 100 ml PVC bonder and 2·2 litres fresh water.
[c]Bioresin was impregnated on a woven fibreglass cloth.
[d]Slats were 2 years old.
[e]Sticks coated in coal tar pitch type and air dried for 2 months prior to deployment. Spatfall was confined to upper and lower surfaces (effective area 720 cm^2).
[f]Collectors were designed for spat collection and/or on-growing oysters to market.

stacks for the ten types of collectors were deployed in January, the beginning of the commercial spat catching season (Wisely *et al.*, 1979; Holliday & Goard, 1986). For each treatment, five replicate stacks of collectors were secured by wire to a timber post and rail rack which was set perpendicular to the shore. The 50 m section of rack used on the lease was about 80–130 m from the Indian Spring High Water (ISHW) mark. Each replicate stack was randomly allocated to a position along the timber rack and the bottom layer of each stack of collectors occupied a similar vertical intertidal position (range 0·7–0·9 m above Indian Spring Low Water [ISLW]) to that traditionally used for natural catch on tarred sticks (Thomson, 1954; Korringa, 1976).

Spat density and retention were estimated by counting the number of spat contained in a grid (10 cm^2) which was placed in a randomly allocated position on both the upper and lower surfaces of each collector in each replicate stack. Data for the upper surface of the top layer and the lower surface of the bottom layer of each replicate stack were excluded from analysis as the spat on these surfaces were subject to predation by fish.

Post-harvest survival of spat

Oysters collected in the above program were harvested from the six types of single spat collectors (D, SCD, S, BS, SCS and TS), 271 days after deployment. With the exception of tarred sticks (TS), a layer was randomly selected from each of the five replicate stacks of collectors per treatment and all spat were harvested by either flexing and brushing. For tarred sticks (TS), spat from four sticks from each of the five randomly selected layers per replicate were harvested, using a paint scraper. The spat from each replicate group ($n = 5$) for each treatment were randomly allocated to one of six internal sections (each 0·25 m^2) of a nursery tray (1·82 × 0·94 m timber frame with 1·7 mm PVC mesh on upper and lower surfaces). Enough spat to cover 50% of the bottom surface of each internal tray section were used, as recommended by Holliday *et al.* (1991*a*). The five trays were randomly allocated a position along the same timber rack used previously. Post-harvest survival was estimated by counting live and dead spat from each replicate section 14 days after spat were removed from collectors.

Retension and growth of market size oysters

The stacks of collectors for on-growing (FSS, RSS, RSSL, RGS and TS), on which spat had settled, were broken up into single layers for the grow-out phase, following normal practice by oyster farmers (Korringa, 1976; Malcolm, 1987). For each collector type, there was no difference

($P > 0{\cdot}05$) in the number of spat on sticks from different layers when deployed. The sticks were transferred from Port Stephens to an intertidal growing area in Empire Bay, Brisbane Waters, NSW (33° 30′ S; 151° 20′ E). This estuary is not subject to the common problem of settlement of spat on existing Sydney rock and Pacific oysters (overcatch), as is common in Port Stephens.

As the front of the Empire Bay area (about 500 m from ISHW mark) was subjected to wave action which may have affected retention of oysters on the collectors, the timber rack (60 m) which was perpendicular to the foreshore, was divided into two zones (inshore and offshore). Here each replicate consisted of 4 sticks (a layer from the settlement phase of the experiment). Ten replicates for each type of on-growing collector were randomly allocated to a position in each zone on the lease. Top and bottom layers from each stack, which may have been affected by predation by fish during the settlement phase, were not sampled. Collectors were nailed along the post and rail lease at the growing height (about mid tidal range) used by commercial oyster farmers. PVC slats (S) were randomly allocated to positions along the rail, to observe any overcatch. To avoid losses of spat from heat stress during intertidal exposure (Potter & Hill, 1982) and from predation by fish (Korringa, 1976; Holliday *et al.*, 1991*a*), all sticks were encased in shade cloth (3 mm PVC mesh) as practised by many farmers.

For the five types of collectors, spat density was estimated three times (approximately every six months) by counting all oysters from both surfaces of sticks from two randomly selected replicates in each zone. Retention on upper and lower surfaces were not separated as oysters tended to grow around the sticks. Since the types of sticks had different surface areas, data are expressed as number of oysters per 10 cm^2. To avoid future losses which may have been attributed to handling, collectors were discarded after counting. Size was determined at harvest by randomly selecting six of each type of on-growing collector from each zone, removing all the oysters and measuring the shell lengths of 100 oysters/stick, chosen at random from each collector.

Experiment 2 — Pacific oysters

All of the types of collectors used in Experiment 1, with the exception of slurry-coated slats (SCS), were evaluated as substrates for settlement of Pacific oysters. For each collector type, four replicate stacks were randomly allocated a position along a timber rack set perpendicular to, and 50 m from the foreshore (ISHW mark), on a lease in the inner harbour of Port Stephens, Tanilba Bay, NSW (32° 43′ S; 152° 00′ E).

Although this is a traditional growing area for the Sydney rock oyster, consistent settlement of Pacific oysters has been recently recorded in this area (Holliday & Nell, 1990). Collectors were deployed in the same format used in Experiment 1 (described in Table 1) and occupied a similar vertical intertidal position (range 0·65–0·85 m above ISLW) to that used for growing Sydney rock oysters.

As spat density was much lower than in Experiment 1, all spat on the upper and lower surfaces on all collectors were counted, except tarred sticks (TS). For tarred sticks (TS), settlement was determined by counting all spat on four randomly selected sticks from each layer in each replicate stack. The top and bottom layers of each stack of collectors were again excluded from analyses. An assessment of post-harvest survival of spat removed from collectors and further studies on grow-out of Pacific oysters were not possible because of the introduction of a policy aimed at the eradication of Pacific oysters from Port Stephens and other NSW estuaries (Holliday & Nell, 1990).

Statistical analyses

For each experiment, differences among collector types were assessed using ANOVA. For Experiment 1, differences in the number of spat which settled on the upper and lower surfaces of each collector type were compared separately using t-tests. Data for both surfaces were then combined and one-way ANOVA was used to assess the effect of collector type on density and retention. Homogeneity of variance was tested using Cochran's Test (Winer, 1971) and means were compared using Tukey's w method (Sokal & Rohlf, 1981). For Experiment 1, retention data were transformed (arcsine $x^{0 \cdot 5}$) prior to analyses, and linear regression used to examine the relationship between spat density at day 127 and percentage loss at day 271.

The variances for post-harvest survival data were heterogeneous after transformation (arcsine $x^{0 \cdot 5}$), therefore ANOVA and multiple range analyses were conducted using a lower level of significance ($P < 0 \cdot 01$), as recommended by Underwood (1981).

A one-way ANOVA was used to determine if the number of spat per collector type was affected by layer. Two-way ANOVA was used to determine if zone, collector type or the interaction between zone and collector type were significant. As zone was not significant and there was no interaction between collector type and zone ($P > 0 \cdot 05$), data from zones were combined and reanalysed using one-way ANOVA. Throughout this paper data are presented as untransformed means ± standard error ($\bar{x} \pm$ SE).

RESULTS

Experiment 1 — Sydney rock oysters

Settlement and spat retention

Settlement was extremely high from January to July (172 days) and spat density was very high on all collector types (range 1122–19 562 spat/collector). PVC collectors generally caught far more oysters than the traditionally used tarred sticks (Table 2). Spat density was higher ($P < 0{\cdot}05$) on five types of PVC collectors (D, RSS, RGS, RSSL and S; $49{\cdot}3 \pm 3{\cdot}0$ spat/10 cm^2, $n = 25$, replicate stacks, and bioresin slats, (BS, $43{\cdot}6 \pm 4{\cdot}0$ spat/10 m^2, $n = 5$ replicate stacks) than on tarred sticks (TS, $14{\cdot}5 \pm 3{\cdot}1$ spat/10 cm^2, $n = 5$ replicate stacks) (Table 2).

Spat density varied greatly between the upper and lower surfaces of some of the collector types (Table 2). In general, spat were evenly distributed ($P > 0{\cdot}05$) across the upper and lower surfaces of collectors which had larger concave (downward facing) surface areas (Table 2). These collectors included PVC discs (D, diam 140 mm), slurry-coated PVC discs (SCD, diam 355 mm), PVC slats (S, width 104 mm) and slurry-coated PVC slats (SCS, width 104 mm). Round spiky PVC sticks with lug (RSSL, diam 38 mm) also had a high settlement (Table 2). Although having reasonably large surface areas, spat densities were lighter ($P < 0{\cdot}001$) on the flat upper surfaces of bioresin slats (BS, width 100 mm) and flat spiky PVC sticks (FSS, width 50 mm) (Table 2). Other collector types with smaller surface areas (range 20–22 mm width/diam) also had poor spat densities ($P < 0{\cdot}001$) on the upper surfaces (Table 2). By far, the highest density of barnacles ($P < 0{\cdot}05$) was recorded from the lower surfaces of tarred sticks (TS), with no settlement on slurry-coated discs (SCD) (Table 2).

Higher numbers of spat ($P > 0{\cdot}05$) were retained at day 271 on four types of PVC collectors (SCD, D, RSS and S; $22{\cdot}1 \pm 1{\cdot}4$ spat/10 cm^2, $n = 20$ replicate stacks) than on tarred sticks (TS, $8{\cdot}9 \pm 1{\cdot}5$ spat/10 cm^2, $n = 5$ replicate stacks). There was a significant relationship ($P < 0{\cdot}001$) between oyster density at day 172 and spat losses at day 271. The percentage loss of spat ranged from $31{\cdot}7 \pm 10{\cdot}6$% from tarred sticks (TS) to $69{\cdot}1 \pm 2{\cdot}6$% from round grooved sticks (RGS; Table 2).

Post-harvest survival of spat

Post-harvest survival (at day 14) was high and similar ($P > 0{\cdot}01$) for spat removed from tarred sticks (TS, $89{\cdot}4 \pm 1{\cdot}4$%), slurry-coated discs (SCD, $92{\cdot}0 \pm 1{\cdot}2$%), slurry-coated slats (SCS, $92{\cdot}2 \pm 0{\cdot}6$%), slats (S, $93{\cdot}4 \pm 1{\cdot}9$%) and discs (D, $91{\cdot}8 \pm 1{\cdot}7$%). Post-harvest survival was lower

TABLE 2

Density of Sydney Rock Oysters *Saccostrea commercialis*, on 10 Commercial Spat Collector Types in Salamander Bay, Port Stephens, NSW, January to October 1988 (Experiment 1)[a]

Collector type	*Spat density at day 127 (July) (spat/10 cm²)*			*Spat density at day 217 (October) (spat/10 cm²) Combined*	*Spat losses July–Oct 1988 (%) Combined*	*Barnacle density at day 127 (spat/10 cm²) Combined*
	Lower	*Upper*	*Combined*			
Tarred stick (TS)	28·2 ± 5·3	0·4 ± 0·2	14·5 ± 3·1a	8·9 ± 1·5a	31·7 ± 10·6a	17·8 ± 2·8a
Flat spiky stick (FSS)	29·5 ± 3·3	7·0 ± 2·0	21·5 ± 3·4ab	13·0 ± 1·7ab	36·3 ± 7·4ab	0·3 ± 0·1de
Slurry-coated disc (SCD)[b]	33·7 ± 2·5	33·5 ± 4·5	33·6 ± 2·9abc	21·3 ± 2·9bc	37·3 ± 5·1ab	0e
Slurry-coated slat (SCS)[b]	33·9 ± 4·2	39·6 ± 5·0	37·5 ± 3·7abc	20·0 ± 1·9abc	42·5 ± 11·0ab	6·1 ± 0·5b
Disc (D)[b]	39·9 ± 2·1	39·1 ± 4·1	40·8 ± 3·2bc	26·1 ± 3·2c	35·9 ± 5·6ab	2·5 ± 1·0bcd
Bioresin slat (BS)	56·1 ± 5·5	37·4 ± 4·0	43·6 ± 4·0bc	21·5 ± 2·8abc	51·7 ± 4·6ab	0·2 ± 0·1de
Round spiky stick (RSS)	81·3 ± 12·4	7·0 ± 3·0	44·7 ± 5·4bc	16·8 ± 2·0bc	60·3 ± 6·4ab	3·8 ± 1·1bc
Round grooved stick (RGS)	90·3 ± 11·5	14·1 ± 5·0	51·8 ± 6·4c	16·3 ± 2·9abc	69·1 ± 2·6b	0·8 ± 0·3cde
Round spiky stick with lug (RSSL)[b]	57·0 ± 5·7	36·9 ± 8·6	53·0 ± 8·7c	20·0 ± 3·1abc	56·9 ± 9·1ab	1·4 ± 0·6cd
Slat (S)[b]	47·4 ± 6·5	62·9 ± 8·9	57·5 ± 7·9c	26·0 ± 2·6c	52·9 ± 5·5ab	0·3 ± 0·2de

[a]Values are $\bar{x} \pm$ SE, $n = 5$. Within each column, means with a common letter are not significantly different ($P > 0{\cdot}05$).
[b]Each collector type with this superscript showed no significant difference ($P > 0{\cdot}05$) in spat density/10 m² on lower or upper surface.

($P < 0{\cdot}001$) for spat removed from bioresin slats (BS, $66{\cdot}8 \pm 6{\cdot}2\%$) as spat were often damaged where they attached to the collector.

Retention and growth of market size oysters

The pattern of retention was similar at each six monthly interval, thus only the initial spat density at day 127 and final retention data are presented (Table 3). At harvest (day 843), tarred sticks (TS) had the lowest density ($P < 0{\cdot}05$) of Sydney rock oysters ($0{\cdot}8 \pm 0{\cdot}03/10$ cm^2, $n = 4$ replicate layers) and the three types of round PVC sticks (RSS, RSSL, RGS) had the highest oyster density ($P < 0{\cdot}05$; $2{\cdot}5 \pm 0{\cdot}1$ spat/10 cm^2, $n = 12$ replicate layers) (Table 3). Tarred sticks (TS) were heavily infested with marine borers and fractured when handled. Shell length at harvest was similar ($P > 0{\cdot}05$) from all types of PVC sticks (FSS, RSS, RSSL, RGS; range 46·9–48·5 mm/oyster, $n = 60$ replicate sticks) and smaller ($P < 0{\cdot}05$) than that recorded from tarred sticks (TS, $55{\cdot}1 \pm 0{\cdot}6$ mm/oyster, $n = 12$ replicate sticks; Table 3). Collector type affected percentage loss ($P < 0{\cdot}05$) between days 127 and 843, although, the differences were relatively minor (Table 3). There was no oyster settlement (overcatch) on the PVC slats (S) during this phase of the experi-

TABLE 3

Density of Sydney Rock Oysters *Saccostrea commercialis*, on Five Collector Types in Salamander Bay, Port Stephens and Empire Bay, Brisbane Waters, NSW, July 1988 to May 1990) (Experiment 1)[a]

Collector type	*Spat density at day 127 (spat/10 cm²)*	*Oyster density at day 843 (oysters/10 cm²)*	*Shell length at day 843 (mm)*	*Net loss [b]between days 127 and 843 (%)*
Tarred Hardwood stick				
Tarred stick (TS)	$14{\cdot}5 \pm 3{\cdot}1$a	$0{\cdot}8 \pm 0{\cdot}03$a	$55{\cdot}1 \pm 0{\cdot}6$a	$95{\cdot}0 \pm 1{\cdot}2$ab
PVC sticks				
Flat spiky stick (FSS)	$21{\cdot}5 \pm 3{\cdot}4$ab	$1{\cdot}4 \pm 0{\cdot}1$b	$48{\cdot}2 \pm 1{\cdot}2$b	$96{\cdot}5 \pm 0{\cdot}8$b
Round spiky stick (RSS)	$44{\cdot}7 \pm 5{\cdot}4$c	$2{\cdot}6 \pm 0{\cdot}2$c	$48{\cdot}5 \pm 0{\cdot}8$b	$92{\cdot}6 \pm 0{\cdot}9$a
Round spiky stick with lug (RSSL)	$53{\cdot}0 \pm 8{\cdot}7$c	$2{\cdot}5 \pm 0{\cdot}1$c	$48{\cdot}2 \pm 0{\cdot}9$b	$93{\cdot}2 \pm 0{\cdot}6$ab
Round grooved stick (RGS)	$51{\cdot}8 \pm 6{\cdot}4$c	$2{\cdot}3 \pm 0{\cdot}1$c	$46{\cdot}9 \pm 1{\cdot}4$b	$95{\cdot}2 \pm 0{\cdot}2$ab

[a]Values are $\bar{x} \pm$ SE, $n = 4$. Within each column, means with a common letter are not significantly different ($P > 0{\cdot}05$).
[b]Data were transformed (arcsine$^{0{\cdot}5}$) prior to ANOVA.

ment. With the exception of the round spiky PVC stick with lug (RSSL) all types of sticks were damaged during harvesting when removing oysters.

Experiment 2 — Pacific oysters

The settlement period of Pacific oysters was from November to May (187 days). The density of Pacific oysters on collectors was much lighter than Sydney rock oysters in Experiment 1 (Table 4). For combined upper and lower surfaces, spat density ($P < 0{\cdot}001$) was higher on three types of PVC collectors (SCD, RSS and D; $2{\cdot}6 \pm 0{\cdot}3$ spat/10 cm^2, $n = 12$ replicate stacks), than on tarred sticks (TS), PVC slats (S) and bioresin slats (BS), ($0{\cdot}5 \pm 0{\cdot}1$ spat/10 cm^2, $n = 12$ replicate stacks; Table 4). Density of Pacific oysters was heaviest ($P < 0{\cdot}05$) on the lower surfaces of tarred (TS) and round spiky sticks (RSS) and on the upper surfaces of PVC slats (S) and discs (D). For the rest of the collector types, there were no differences ($P > 0{\cdot}05$) in density between upper and lower surfaces (Table 4). No barnacle settlement was detected.

TABLE 4

Density of Pacific Oysters *Crassostrea gigas*, on Nine Types of Commercial Collectors in Tanilba Bay, Port Stephens, NSW, November 1988 to June 1989 (Experiment 2)[a]

Collector type	*Spat density/10 cm^2*		
	Lower	*Upper*	*Combined*[b]
Tarred stick (TS)	$0{\cdot}4 \pm 0{\cdot}1$	$0{\cdot}2 \pm 0{\cdot}1$	$0{\cdot}5 \pm 0{\cdot}1$a
Slat (S)	$0{\cdot}2 \pm 0{\cdot}1$	$0{\cdot}4 \pm 0{\cdot}1$	$0{\cdot}5 \pm 0{\cdot}1$a
Bioresin slat (BS)[b]	$0{\cdot}3 \pm 0{\cdot}1$	$0{\cdot}3 \pm 0{\cdot}1$	$0{\cdot}6 \pm 0{\cdot}1$a
Round spiky stick with lug (RSSL)[b]	$0{\cdot}5 \pm 0{\cdot}1$	$0{\cdot}5 \pm 0{\cdot}1$	$1{\cdot}1 \pm 0{\cdot}1$ab
Flat spiky stick (FSS)[b]	$0{\cdot}8 \pm 0{\cdot}3$	$0{\cdot}5 \pm 0{\cdot}2$	$1{\cdot}3 \pm 0{\cdot}4$ab
Round grooved stick (RGS)[b]	$1{\cdot}4 \pm 0{\cdot}3$	$0{\cdot}7 \pm 0{\cdot}1$	$2{\cdot}0 \pm 0{\cdot}5$ab
Slurry-coated disc (SCD)[b]	$1{\cdot}2 \pm 0{\cdot}1$	$1{\cdot}1 \pm 0{\cdot}1$	$2{\cdot}4 \pm 0{\cdot}1$b
Round spiky stick (RSS)	$1{\cdot}9 \pm 0{\cdot}1$	$0{\cdot}8 \pm 0{\cdot}1$	$2{\cdot}7 \pm 0{\cdot}1$b
Disc (D)	$0{\cdot}9 \pm 0{\cdot}1$	$2{\cdot}0 \pm 0{\cdot}3$	$2{\cdot}8 \pm 0{\cdot}7$b

[a]Values are $\bar{x} \pm$ SE, $n = 4$. Within each column, means with a common letter are not significantly different ($P > 0{\cdot}05$).

[b]Each collector type with this superscript showed no significant difference ($P > 0{\cdot}05$) in numbers of oysters/10 cm^2 settled between upper and lower surface.

DISCUSSION

Settlement during this study was high and commercially acceptable on all collector types when compared with previous studies in Salamander Bay (Holliday 1985*b*; Holliday & Goard, 1986). However, Holliday and Goard (1986) also reported a poor spatfall on tarred sticks in Salamander Bay. An intensity of settlement of Sydney rock and Pacific oysters can fluctuate between years (Dinamani, 1978) and in different estuaries, those collector types on which lower numbers of spat settled in this study may not have had commercially acceptable settlement had spatfall been lighter.

PVC and slurry-coated PVC collectors proved to be very effective collectors for the settlement of Sydney rock and Pacific oyster and poor collectors for barnacles. Tarred sticks had the lowest spat density after both 127 and 271 days. This may have been due to the coal tar covering the sticks. Coal tar pitch, with its antifouling properties designed to prevent infestation from marine borers, becomes soft and volatile and releases flammable vapours when heated (Pope, 1987). This is particularly important when sticks are exposed to sunlight at low tide. Competition on tarred sticks from barnacles probably also affected spat settlement and accounted for some of the spat losses, as settlement was higher than that of Sydney rock oysters and more intense on this collector (17·8/10 cm^2). Barnacles settle in a similar period to Sydney rock oysters (Holliday 1985*b*; Holliday & Goard, 1986) and can complete for settlement space (Butler, 1955; Ling, 1970).

Gunn (1984) reported natural catches of Pacific oysters in British Columbia on round grooved PVC sticks deployed intertidally, although, his attempt at a comparative assessment of a number of test materials was unsuccessful due to a poor natural spatfall (range 0–1 spat/10 cm^2). Heavy natural catches (42 spat/10 cm^2) of Pacific oysters on PVC, two weeks after deployment in New Zealand were later reported by Curtin (1985*b*).

Initial spat densities at day 127 had an effect ($P < 0{\cdot}001$) on the high losses of spat (range 31·7–69·1%) recorded from all collectors at day 271. As spat grew, competition for surface area was probably a contributing factor for the high losses.

Sydney rock oysters were evenly distributed on the upper and lower surfaces of collectors which had large concave (downward facing) surfaces which facilitated shading of the underlying layers without creating conditions conducive to a build up of silt on the upper surfaces. Collectors with flat surfaces, such as tarred sticks, bioresin slats and flat spiky PVC sticks, had poor settlement on their upper surfaces, possibly as a result of the accumulation of silt.

Previous studies have concluded that many factors affect the settlement of bivalves on the upper and lower surfaces of a substratum including siltation, current, gregariousness, light, colour, type of surface and swimming position of the larvae (Galtsoff, 1964). Thomson (1954), who found that settlement of Sydney rock oysters was more intense on the lower surfaces of flat fibro-cement slate, concluded that light and siltation on the upper surfaces affected settlement. Dinamani and Lenz (1974), also mention the effects of siltation on flat substrates and found that New Zealand rock oysters (*S. glomerata*), a subspecies of the Sydney rock oyster (Buroker *et al.*, 1979), settled mainly on the lower surfaces, although larvae began to settle on the upper surface when the spat density on the lower surfaces was high.

The collectors for Pacific oysters were deployed in a more estuarine site than that used for Sydney rock oysters (Holliday *et al.*, 1991*b*), and the accumulation of silt on collectors was more likely to have been a problem than at the latter site. Even so, settlement of Pacific oysters was heavier on the upper surfaces of some flat collectors. This may indicate a difference between species in terms of relative settlement preference for upper and lower surfaces. With the exception of a study by Schaefer (1937), previous studies have recorded heavier settlement of Pacific oysters on upper surfaces of collectors (Miyazaki, 1938; Sayce & Larson, 1965; Shaw, 1967; Sayce & Tufts, 1968).

The lower post-harvest survival of spat removed from bioresin slats (66·8%; Experiment 1) demonstrates the importance of the surface composition of collectors for single seed culture. Collectors must not only facilitate settlement and retention of spat, but enable harvesting of spat without damage. It is also advantageous to be able to harvest the spat without damaging the collector. The optimal time to harvest spat from collectors is when the majority have shell diameters large enough to be retained by the mesh covering the nursery growing units. In NSW, the common nominal mesh size used on sectionalised nursery trays (Holliday *et al.*, 1991*a*) and PVC cylinders is 3·0 mm (J. E. Holliday, unpublished data, 1991). The use of smaller mesh sizes may lead to problems caused by inadequate water flow and fouling (Lucas & Gerard, 1981).

The most effective collector for on-growing Sydney rock oysters (Experiment 1) was the round spiky PVC stick with lug, as this stick retained large numbers of oysters, and these could be harvested without damaging either oysters or sticks. Little quantitative information is available on losses of oysters from tarred sticks or growth rates during the traditional three-year grow-out period, although high losses (95%) have been reported from tarred sticks (Holliday, 1985*b*; Holliday & Goard, 1986) with average yields of only 30–50 (about 45 g) oysters/stick (Holliday *et al.*, 1988). In this study, the high oyster losses from collectors during grow-out has been attributed to settlement density, intraspecific competition for surface area and surface texture of the stick. However, despite the lighter settlement, tarred sticks exhibited similar loss rates to other collector types.

The highest shell growth was on tarred sticks, which also had the lowest density of settlement. The higher numbers of spat which settled on PVC sticks may have reduced oyster growth, as competition for food probably increased with density. However, flat spiky sticks had a lower oyster density at harvest than other PVC sticks but a similar average shell length (Table 3). Jarayabhand and Newkirk (1989) found that with increasing stocking densities of European oysters (*O. edulis*) on cultch, specific growth rates decreased, particularly for smaller oysters. Food was found to be a growth limiting factor for mussels (*Mercenaria mercenaria*) stocked at a range of densities (Hadley & Manzi, 1984). Holliday *et al.* (1991*b*) also suggested that food may have affected growth rates of juvenile Sydney rock spat grown at a range of densities.

In this study, spat densities for both Sydney rock and Pacific oysters were lower on tarred sticks than on PVC sticks. Tarred sticks were so heavily infested with marine borers that they fractured when harvested and were not reusable. Thus, the traditionally used tarred hardwood stick, which are becoming more difficult to acquire, have a lower productivity and functional life than most PVC collectors tested. For PVC sticks, the higher initial costs (approximately double those of tarred sticks at the time of the study) are effectively reduced by the increased life of the sticks. Shape, composition and surface texture of the collectors affected oyster and barnacle settlement, retention and growth. PVC collectors were the best for Sydney rock oyster spat production, while round spiky PVC sticks with lug proved to be the best of the PVC collectors for on-growing and harvesting market grade oysters. For Pacific oysters, PVC discs and sticks, with or without a slurry coating, were the best spat collectors.

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REFERENCES

Ajana, A. M. (1979). Preliminary investigation into some factors affecting the settlement of the larvae of the mangrove oyster *Crassostrea gasar* (Adanson) in the Lagos Lagoon. *Malacologia*, **18**, 271–5.

Bird, P., Arnold, G. & Holliday, J. (1991). Storage life of purified live Pacific and Sydney rock oysters. Department of Health Report, North Ryde, NSW, Aust., pp. 1–8.

Buroker, N. E., Hersberger, W. K. & Chew, K. K. (1979). Population genetics of family Ostreidae. I. Intraspecific studies of *Crassostrea gigas* and *Saccostrea commercialis*. *Mar. Biol.*, **54**, 157–69.

Butler, P. A. (1955). Selective setting of oyster larvae on artificial clutch. *Proc. Natl. Shellfish Assoc.*, **45**, 95–105.

Chew, K. (1990). Global bivalve shellfish introductions. *World Aquaculture*, **21** (3), 9–22.

Curtin, L. (1985*a*). Pacific oyster farming methods, Ministry Agriculture and Fisheries Report, Fisheries Management Division, Auckland, New Zealand, pp. 1–7.

Curtin, L. (1985*b*). Natural spatfall experiments in Kaipara. *Shellfisheries Newsletter, (New Zealand)*, **26**, 5.

Dinamani, P. (1978). Wary researchers watching alien's rapid rise. *Catch*, **5** (10) 24–5.

Dinamani, P. & Lenz, P. A. (1974). Some aspects of spatfall of the New Zealand rock oyster during 1974. *Veliger*, **20**, 17–26.

Dupuy, J. L. & Rivkin, S. (1970). Cultch-free spat present and future. In *Proc. First Annual Workshop World Maricul. Soc.*, pp. 157–8.

Dupuy, J. L. & Rivkin, S. (1972). The development of laboratory techniques for the production of cultch-free spat of the oyster. *Crassostrea virginica. Ches. Sci.*, **13**, 45–52.

Espinas, V., Marshall, G. & Rish, B. (1988). Economic survey of the New South Wales oyster farming industry: 1981–82 to 1983–84. Part 2 — Physical Aspects. Div. Marketing and Economic Services, Misc. Bull., 54. NSW Agri. & Fish., Sydney, 48 pp.

Galtsoff, P. S. (1964). Season of attachment and growth of sedentary marine organisms at Lamoine, Maine. *Ecol.*, **27**, 150–8.

Gunn, C. R. (1984). A report on the development and use of an artificial cultch suitable for off bottom oyster culture in British Columbia, Fisheries Development Report No 33, Marine Resources Branch, BC, 25 pp.

Hadley, N. H. & Manzi, J. J. (1984). Growth of seed clams, *Mercenaria mercenaria*, at various densities in a commercial scale nursery system. *Aquaculture*, **36**, 369–79.

Hidu, H., Chapman, S. & Soule, P. W. (1975). Cultchless setting of European oysters. *Ostrea edulis*, using polished marble. *Proc. Natl. Shellfish Assoc.*, **65**, 13–14.

His, E. (1978). Une expérience de production de 'haissain naturel un a un' sa croissance dans le bassin d'Arcachon. *Science et Pêche, Bull. Inst. Pêches Marit.*, **280**, 12 pp.

Holliday, J. E. (1985*a*). International Developments in Oyster Hatchery Technology. *Fish. Div. Misc. Bull.*, No. 1, Dept. of Agriculture, NSW, Sydney, 101 pp.

Holliday, J. E. (1985*b*). Current oyster spat research in NSW. *Aust. Fish.*, **44** (3), 24–6.

Holliday, J. E. & Goard, L. J. (1986). Survey of Sydney rock oyster larvae settlement at Port Stephens, NSW. *Aust. Fish.*, **45** (3), 27–8.

Holliday, J. E. & Nell, J. A. (1990). Pacific oysters in New South Wales. Agfact, F2.1.3, 2nd edn, NSW Agriculture & Fisheries, Sydney, 4 pp.

Holliday, J. E., Maguire, G. B. & Nell, J. A. (1988). Alternative cultivation methods for the Sydney rock oyster (*Saccostrea commercialis*). In *Proc. First Aust. Shell. Aqua. Conf.*, Perth, October 1988, ed. L. H. Evans & D. O'Sullivan. Curtin University of Technology, Perth, WA, pp. 234–65.

Holliday, J. E., Maguire, G. B. & Nell, J. A. (1991*a*). Optimum stocking density for nursery culture of Sydney rock oysters (*Saccostrea commercialis*). *Aquaculture*, **96**, 7–16.

Holliday, J. E., Maguire, G. B. & Nell, J. A. (1991*b*). Evaluation of sites for the nursery culture of single Sydney rock oysters (*Saccostrea commercialis*). *Fish. Bull.*, **5**, NSW Agri. & Fish., Sydney, 7 pp.

Jarayabhand, P. & Newkirk, G. F. (1989). Effects of intraspecific competition on growth of the European oyster *Ostrea edulis* Linnaeus, 1750. *J. Shellfish Res.*, **2** (8), 359–65.

Jones, G. & Jones, B. L. (1988). Advances in Remote Setting of Oyster Larvae. Aqua. Assoc. of BC, Nanaimo, BC, 88 pp.

Kong, C. P. & Luh, L. A. (1976). Notes on the efficiency of various materials tested as oyster spat collectors in Cowie Bay, Sabah. *Malaysian Agric., J.*, **50** (94), 462–79.

Korringa, P. (1976). *Farming the Cupped Oysters of the Genus* Crassostrea. Elsevier, Amsterdam, 224 pp.

Ling, Y. S. (1970). Preliminary studies on the collection of oyster spat in Johore straits. *J. Singapore Natl. Acad. Aci.*, **2** (1), 14–18.

Lucas, A. & Gerard, A. (1981). Space requirement and some energy costs in some typesof bivalve nurseries. In *Nursery Culture of Bivalve Molluscs*, ed. C. Claus, N. De Pauw & E. Jaspers. European Mariculture Soc. Special Pub. No 7, Bredene, Belgium, pp. 151–70.

Maguire, G. B., Nell, J. & Allan, G. (1988). Production trends in oyster farming and other mariculture industries in New South Wales. In *Proceedings of the Australian Mariculture Association Third Annual Conference*, ed. J. Paynter & N. Preston, Lismore, NSW, pp. 28–35.

Malcolm, W. B. (1987). The Sydney rock oyster. Agfact F3.1.1, Dept. of Agri., NSW, Sydney, 12 pp.

Miyazaki, I. (1938). On fouling organisms in the oyster farm. *Bull. Jpn. Soc. Sci. Fish.*, **6** (5), 223–32.

Morse, D. E. (1985). Neurotransmitter-mimetic inducers of larval settlement and metamorphosis. *Bull. Mar. Sci.*, **37** (2), 697–706.

O'Sullivan, B. W. & Wilson, J. H. (1976). Development of an experimental oyster hatchery. *Fish Farm. Internat.*, **3** (3), 12–15.

Pope, G. X. (1987). Koppers' oyster tar. In *Collected Open Day Booklets*, Brackish Water Fish Culture Research Station 1973–1988. NSW Agriculture & Fisheries, Salamander Bay, NSW, unpublished report, pp. 480–6.

Potter, M. A. & Hill, B. J. (1982). Heat mortality in the Sydney rock oyster, *Saccostrea (Crassostrea) commercialis* and the effectiveness of some control methods. *Aquaculture*, **29**, 101–8.

Quayle, D. B. (1988). Pacific oyster culture in British Columbia. *Canadian Bull. Fish. Aqua. Sci.*, **218**, 218–41.

Roland, W. G. & Broadley, T. A. (1990). A manual for producing oyster seed by remote settling, Min. Agric. and Fish., Aquaculture and Comm. Fish. Branch, 58 pp.

Roland, B., Sutherland, I. & Broadley, T. (1988). Update on remote setting Pacific oyster larvae in British Columbia. BC Aquaculture Information Bull., Vol. 15, 10 pp.

Sayce, C. S. & Larson, C. C. (1965). Willapa oyster studies annual progress report, Dept. Fish. Res. Div. Washington, 94 pp.

Sayce, C. S. & Tufts, D. F. (1968). Willapa oyster studies. Part 2, Dept. Fish. Res. Div. Washington, 101 pp.

Schaefer, M. B. (1937). Attachment of larvae of *O. gigas*, the Japanese oyster, to plane surfaces. *Ecol.*, **18**, 523–7.

Shaw, W. N. (1967). Seasonal fouling and oyster setting on asbestos plates in Broad Creek, Talbot Country, Maryland, 1963–65. *Ches. Sci.*, **8**, 228–36.

Sokal, R. R. & Rohlf, F. J. (1981). *Biometry*, Freeman, New York, 859 pp.

Thomson, J. M. (1954). Handbook for oyster-farmers, Division of Fisheries Circular, CSIRO Sydney, NSW, Vol. 3, 21 pp.

Underwood, A. J. (1981). Techniques of analysis of variance in experimental marine biology and ecology. *Oceanogr. Mar. Biol. Ann. Rev.*, **19**, 513–605.

Winer, B. J. (1971). *Statistical Principles in Experimental Design*, 2nd edn, McGraw-Hill Kogakusha Ltd, Tokyo, 907 pp.

Wisley, H. B., Holliday, J. E. & Reid, B. L. (1979). Experimental deepwater culture of the Sydney rock oyster (*Crassostrea commercialis* = *Saccostrea cucullata*). 1. Growth of vertical clumps of oysters ('Ren'). *Aquaculture*, **16**, 127–40.

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Effects of stocking density on juvenile Sydney rock oysters, *Saccostrea commercialis* (Iredale & Roughley), in cylinders

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ABSTRACT

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Two size grades (13.5 and 18.2 mm average shell length spat^{-1}) of juvenile Sydney rock oysters, (*Saccostrea commercialis* Iredale & Roughley) were grown at a range of stocking densities (0.5 to 6.0 l of oysters cylinder^{-1}) in PVC cylinders for 3 months. Cylinders were deployed on horizontal hardwood frames on an intertidal lease, where they rotated in response to changes in tidal level. For each grade, spat mortality was similar ($P>0.05$) for stocking densities of 0.5 to 4.0 l cylinder^{-1} (mean $\pm$ s.e. 11.7 ± 1.1% and 22.5 ± 2.3%, respectively) but higher for the larger grade (33.3 ± 1.7%; $P<0.05$) at the highest stocking density. For both grades, weight gain and length increase declined as stocking density increased ($P<0.001$), although differences for initial densities above 3.0 and 4.0 l of oysters cylinder^{-1}, for the smaller and larger grades respectively, were not significant ($P>0.05$). Biomass gain and volume of oysters both increased with increasing stocking density ($P<0.05$), although increases above initial densities of 2.0 and 3.0 l of oysters cylinder^{-1}, for the smaller and larger grades, respectively, were not significant ($P>0.05$). For both grades, coefficient of variation for weight gain and shell length increase data increased ($P<0.001$) with density. For maximum growth and minimum coefficient of variation for weight gain and shell length increase, 0.2 and 0.4 g spat should be stocked at low densities of 0.5 or 1.0 l cylinder^{-1}. To optimise biomass gain, while minimising growth reductions and size variation, 0.2 and 0.4 g spat should be stocked at densities of 2.0 and 3.0 l of oysters cylinder^{-1}, respectively.

INTRODUCTION

The oyster industry in New South Wales (N.S.W.), Australia has progressed from using rocks and mangrove sticks, as substrates for both the collection and growth of oysters, to the use of tarred hardwood sticks (Korringa, 1976; Malcolm, 1987; Holliday et al., 1988; Quayle, 1988). Sydney rock oys-

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ters (*Saccostrea commercialis* Iredale & Roughley) are generally caught and either grown to market size on the sticks or knocked off the sticks and grown on tarred wooden trays (Malcolm, 1987); however, many oyster farmers now use "single-seed" culture techniques (Holliday et al., 1988), taking advantage of either natural spat (removed from synthetic collectors) or hatchery-produced spat. A nursery phase follows where the unattached single oysters are grown in sectionalised trays or PVC cylinders (Holliday et al., 1988). Single-seed culture eliminates laborious culling (separation of oysters), allows machine grading and ensures oysters are of more uniform shape (Holliday et al., 1988) with a larger shell cavity volume than oysters grown on sticks (Nell and Mason, 1991).

As single-seed oysters are grown, they are moved into nursery units with larger mesh sizes to allow greater water flow and to reduce the problem of fouling (Holliday et al., 1991). Farming single-seed oysters on nursery trays in estuaries with high levels of suspended silt can be difficult (Holliday et al., 1988). In these areas the deposition of silt on oysters is associated with increased infestation by mudworm (*Polydora* spp.) commensals which burrow into the oysters through the shell and cause shell blisters and mortality (Skeel, 1979). Wisely et al. (1979) reported heavy deposits of silt and high mudworm infestations of Sydney rock oysters grown subtidally on trays in the Hawkesbury River, N.S.W. A PVC cylinder (Stanway Oyster Cylinder Pty Ltd., Brooklyn, N.S.W.) which rotates with the tide, was developed by a N.S.W. oyster farmer in response to this problem. This revolving action (one revolution per tide) helps remove silt from around the oysters.

Combined with site, stock and production systems, stocking density is an important option by which a farmer can influence oyster performance. Although the effects of stocking density have been determined for juvenile Sydney rock oysters in sectionalised trays (Holliday et al., 1991), they are yet to be determined for cylinders, which are rapidly growing in popularity in N.S.W. Cylinders have also been used in trials for growing other oyster species as well as clams, and to increase meat condition of oysters for market (Robert et al., 1991). The objective of this study was to determine the optimum stocking density based on survival, biomass gain, individual weight gain and shell increase for two grades of juvenile Sydney rock oysters in cylinders. The effects of stocking density on size variation were also assessed, as a wide range of spat sizes in a nursery system increases stock management costs (Askew, 1978; Newkirk, 1981).

MATERIALS AND METHODS

Cylinders (length 1.0, diam. 0.32 m; internal dimensions, length 0.74 m, diam 0.27 m; total volume 42.4 l $cylinder^{-1}$) were constructed of 3-mm PVC mesh, a PVC shaft and rigid buoyant PVC end caps which caused rotation

(Figs. 1, 2) in response to changes in tidal level, that ranged from 0.2 to 2.0 m. Cylinders were randomly allocated to a position on horizontal hardwood frames (20 × 50 mm, 1.3 m apart), supported 1.5 m (in the intertidal zone) from the sediment by timber posts (Fig. 1). Each cylinder was fixed to the hardwood frames by nails driven through a tarred hardwood stick (20 × 20 mm), inserted through the PVC shaft (Fig. 1).

Sydney rock oyster spat were obtained from a hatchery and initially held in a similar upweller nursery system to that described by Bayes (1981), prior to being stocked in the experiment. Two grades of spat from the same spawning were used. For the smaller grade the initial weight of individual spat ($\bar{x} \pm$ s.e., $n=400$) was 0.24 ± 0.01 g and the shell length ($n=1000$) was 13.5 ± 0.1 mm. Five stocking densities of 0.5, 1.0, 2.0, 3.0 and 4.0 l of oysters per cylinder, with four replicate cylinders per density were used. Spat were stocked on the basis of volume as this is the method used by most oyster farmers. The total weights of oysters ($n=4$) for each volume were: 0.5 l (300.4 ± 0.04 g), 1.0 l (600.4 ± 0.1 g), 2.0 l (1200.2 ± 0.04 g), 3.0 l (1800.3 ± 0.03 g) and 4.0 l (2400.4 ± 0.01 g).

For the larger grade the initial weight of individual spat ($\bar{x} \pm$ s.e., $n=500$)

Fig. 1. PVC cylinders in the Hawkesbury River, N.S.W., used for growing juvenile Sydney rock oysters. The cylinders are fixed to hardwood frames elevated off the estuary bottom by timber posts. Oysters in the cylinders are submerged for about 90% of the time compared with about 70% for those on the traditionally used timber trays deployed on similar frames at the same growing height.

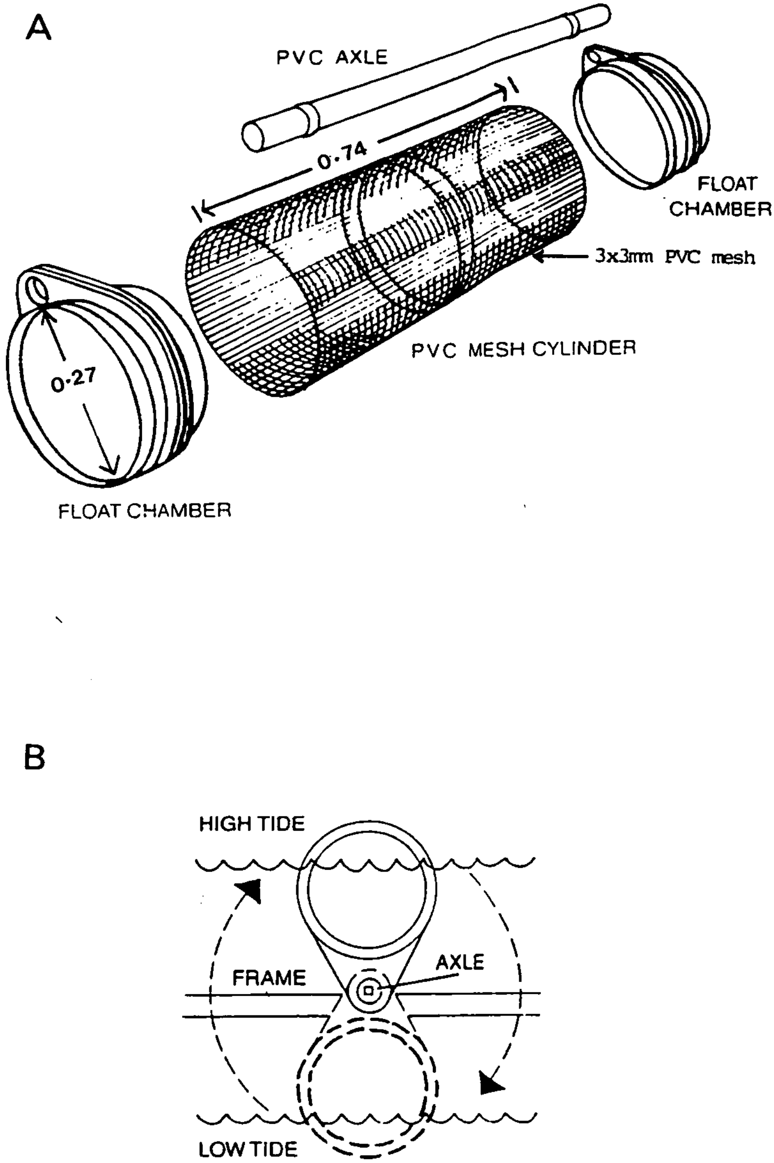

Fig. 2. PVC cylinder for oyster nursery culture. (A) An exploded view of the cylinder. (B) The rotating action of the cylinder.

was 0.41 ± 0.001 g and the shell length ($n=200$) was 18.2 ± 0.1 mm. Six stocking densities of 0.5, 1.0, 2.0, 3.0, 4.0 and 6.0 l of oysters cylinder^{-1} with four replicate cylinders per density were used. The total weights of oysters ($n=4$) for each volume were: 0.5 l (245.4 ± 0.03 g), 1.0 l (490.3 ± 0.04 g), 2.0 l (980.3±0.1 g), 3.0 l (1470.5±0.1 g), 4.0 l (1960.4±0.1 g) and 6.0 l (2941.3±0.1 g).

For the smaller grade of oysters (0.2 g oyster^{-1}), 1 l of oysters cylinder^{-1} is equivalent to 14.2 g of oysters l^{-1}. For the larger grade (0.4 g oyster^{-1}), 1 l of oysters cylinder^{-1} is equivalent to 12.0 g of oysters l^{-1}. Stocking densities of 0.5 to 6.0 l of oysters cylinder^{-1} occupied between 1.2 and 14.2% of the total volume of a cylinder. To allow a comparison between oyster stocking densities on trays and cylinders, the area occupied by a revolving cylinder was calculated (6400 cm^2). All cylinders were deployed in the Mooney Mooney Creek, Hawkesbury River, N.S.W. (33° 30'S; 151° 15'E), on a growing lease at a similar height (intertidal) to that used for growing Sydney rock oysters on sticks (Malcolm, 1987; Holliday et al., 1988). Maximum water velocity for the Hawkesbury River was measured with simple drogues and ranged from 0.5 to 0.7 m/s (J. Harris, personal communication, 1992).

Environmental data were collected from the Mooney Mooney Creek on five separate occasions, at 2- to 3-weekly intervals, during the experiment. All readings were taken at midday from the water surface. Temperature and dissolved oxygen were measured using a Yeokal (Yeokal Electronics, Brookvale, N.S.W.), Dissolved Oxygen/Temperature Meter (Model 603), calibrated with a standard thermometer and Winklers titration (APHA, 1989). Nutrients were analysed using the method outlined by APHA (1989) and concentrations of plant pigment, chlorophyll *a*, were measured following acetone extraction, using the spectrophotometric methods described by Major et al. (1972). Salinity was calculated from conductivity, which was recorded with a WTW (Weilheim-D, Germany) conductivity meter (Model IF 196), and pH was measured using an Orion (Orion Research Inc., Boston, MA) portable pH meter (Model 290 A), with an Orion Triod Electrode (91–57 BN), calibrated with NBS buffers (pH 4, 7 and 9), (CRC, 1971). Turbidity was measured using a Hach (Loveland, CO) turbidity meter and a Secchi disc (diam. 300 mm).

At the completion of the experiment, the shells of dead oysters were examined for mudworm blisters and burrows. Total numbers of spat at stocking and harvest times were estimated by dividing total weight per cylinder by the average weight. The data were then used to estimate percentage mortality at harvest. Final average individual spat weight was estimated by weighing 100 randomly selected live individuals per replicate and average individual shell length by measuring 50 shell lengths per replicate. The total weight of all oysters in each replicate was used to calculate final biomass and biomass gain. Initial and final volumes of oysters were measured (after immersion to fill cavity volume) using a large calibrated measuring cylinder (1.0±0.005 l). The experiment ran for 120 days (February to May 1990), as this was the recommended period between grading and thinning for oysters on sectionalised trays (Holliday et al., 1991).

Statistical procedures

For each grade, differences between treatments were assessed using one-way ANOVA as the numbers of densities within grades were different. Homogeneity of variance was evaluated using Cochran's Test (Winer, 1971) and means were compared using Tukey's honestly significantly difference procedure (Sokal and Rohlf, 1981). To satisfy the assumption of normality and/or homogeneity of variance, volume increase data for the smaller grade were transformed (log x) and mortality data for both grades were transformed (arcsine $x^{0.5}$) prior to ANOVA. Coefficient of variation ($100 \times$ s.d./$\bar{x}$; Sokal and Rohlf, 1981) for both weight gain and shell length increase was calculated as an indicator of size variation of oysters within each treatment. Simple one-parameter models were used to describe the data for both grades. For weight gain and length increase, exponential models ($y=e^{a+bx}$) gave the best fit.

RESULTS

Mortality for the smaller grade (11.7 ± 1.1%, range 9.7–15.2%) was unaffected by stocking density ($P > 0.05$). For the larger grade, spat mortality was similar (22.5 ± 2.3%, range 19.3–25.1%; $P > 0.05$) for stocking densities of 0.5–4.0 l of oysters cylinder^{-1} but higher (33.3 ± 1.7%; $P < 0.05$) for 6 l cylinder^{-1}. No mudworm infestations (blisters) were found in this study despite the high turbidity (7.8 ± 1.4 NTU) and low Secchi disc readings (1.2 ± 0.1 m), which indicated there was a high level of silt in the water compared with other N.S.W. oyster-producing estuaries (S. McOrrie, personal communication, 1990). Maximum individual spat weight gain was recorded at densities of 0.5 and 1.0 l cylinder^{-1} for the smaller and larger grades, respectively. For the smaller grade, average individual spat weight gain and average individual shell length increase declined ($P < 0.001$) from 2.5 ± 0.03 to 0.6 ± 0.04 g spat^{-1} and 18.6 ± 0.3 to 7.0 ± 0.7 mm spat^{-1}, respectively, with increasing stocking density of 0.5 to 4.0 l of oysters cylinder^{-1} (Figs. 3A, 3B). Similarly, for the larger grade, average individual spat weight gain and average individual length increase declined ($P < 0.001$) from 3.3 ± 0.02 to 1.2 ± 0.03 g spat^{-1} and 17.1 ± 0.3 to 9.7 ± 0.4 mm spat^{-1}, respectively, by increasing density from 0.5 to 6.0 l of oysters cylinder^{-1} (Figs. 4A, 4B). There was a significant decrease in the exponential relationship between density and growth (weight gain and length increase) for both grades (Figs. 3A, 3B, 4A, 4B).

Maximum total biomass gain and volume increase were recorded for both grades at the highest densities. For the smaller grade, biomass gain and vol-

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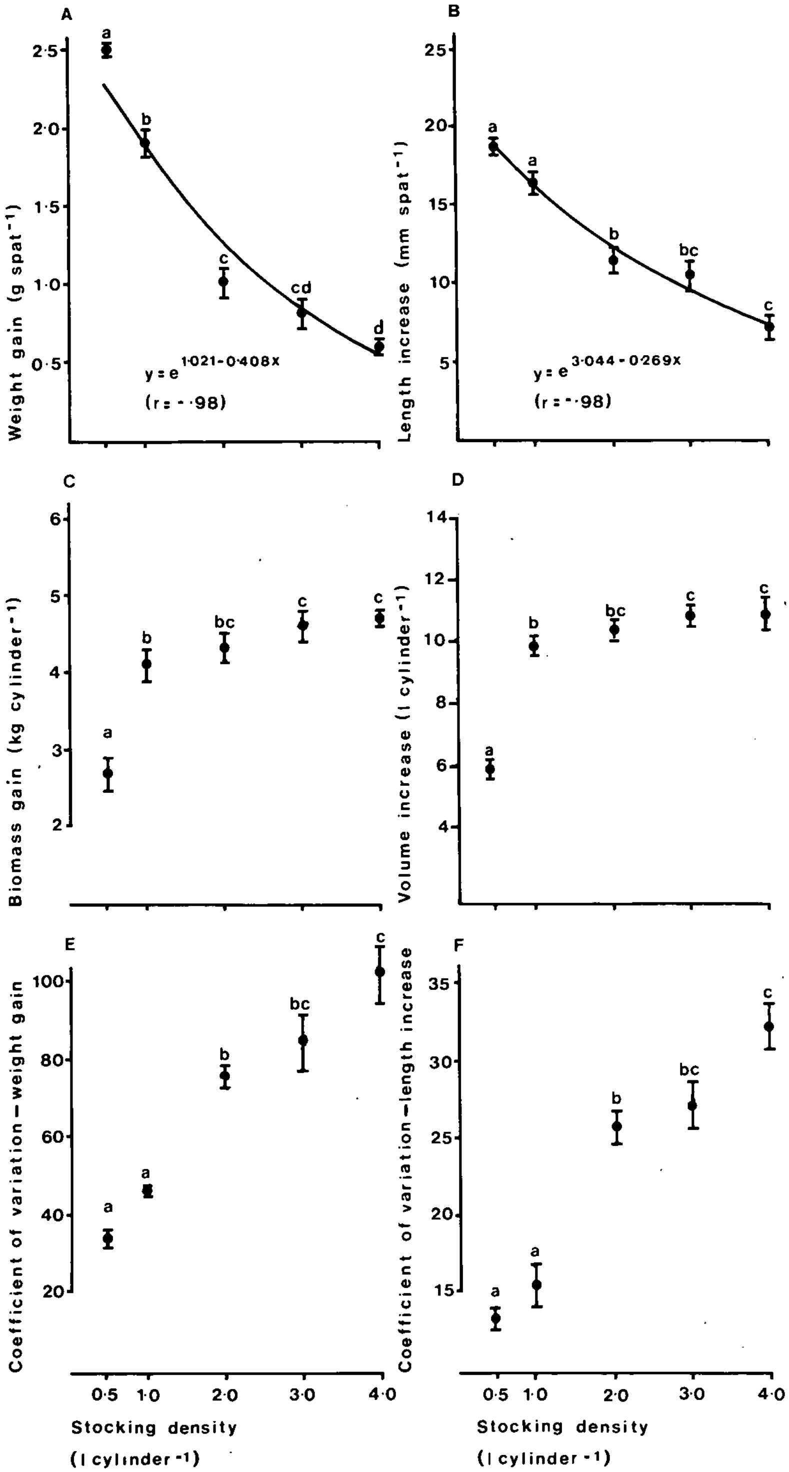
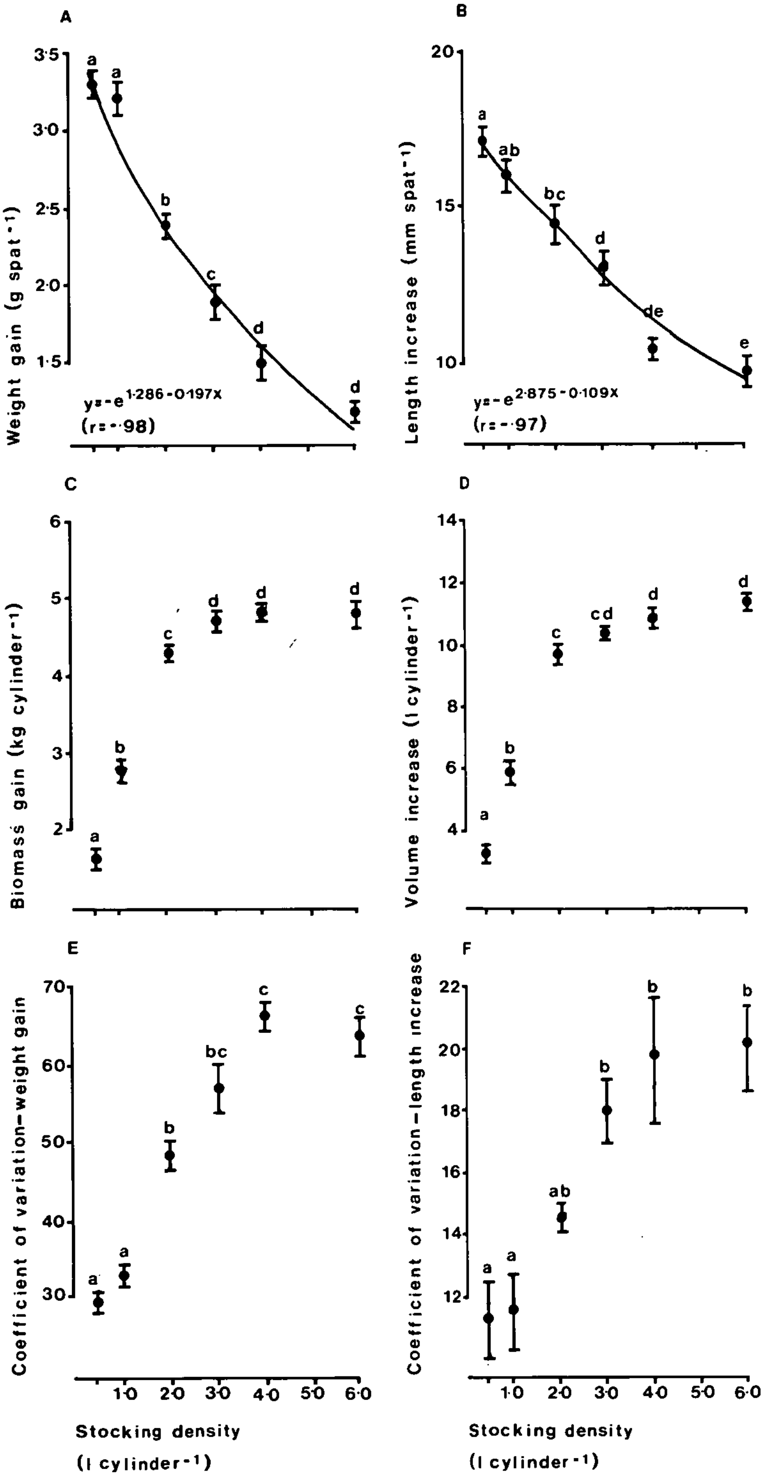
Fig. 3. Effects of stocking density on the smaller grade (average weight 0.2 g spat^{-1} and length 13.5 mm spat^{-1}) of juvenile Sydney rock oysters (*Saccostrea commercialis*) in PVC cylinders: (A) weight gain, (B) shell length increase, (C) biomass gain, (D) volume increase, (E) coefficient of variation for weight gain data, and (F) coefficient of variation for shell length increase data. Symbols represent means and vertical bars standard errors of the means ($n=4$). Means with a similar letter are not significantly different ($P > 0.05$).


A
Weight gain (g spat⁻¹)
$y = e^{1.021-0.408x}$
(r = -·98)
B
Length increase (mm spat⁻¹)
$y = e^{3.044-0.269x}$
(r = -·98)
C
Biomass gain (kg cylinder⁻¹)
D
Volume increase (l cylinder⁻¹)
E
Coefficient of variation – weight gain
F
Coefficient of variation – length increase
Stocking density
(l cylinder⁻¹)


A
Weight gain (g spat⁻¹)
y=-e^1·286-0·197x
(r=-·98)
B
Length increase (mm spat⁻¹)
y=-e^2·875-0·109x
(r=-·97)
C
Biomass gain (kg cylinder⁻¹)
D
Volume increase (l cylinder⁻¹)
E
Coefficient of variation–weight gain
F
Coefficient of variation–length increase
Stocking density
(l cylinder⁻¹)
Stocking density
(l cylinder⁻¹)

ume gain increased from 2.7±0.2 to 4.7±0.1 kg of oysters cylinder^{-1} and 5.7±0.2 to 11.1±0.5 l of oysters cylinder^{-1}, respectively, with increasing stocking density of 0.5 to 4.0 l of oysters cylinder^{-1} (Figs. 3C, 3D). Similarly, for the larger grade, total biomass gain and volume increase both increased with density from 1.6±0.02 to 4.8±0.1 kg of oysters cylinder^{-1} and 3.2±0.2 to 11.2±0.2 l of oysters cylinder^{-1}, respectively, with increasing stocking density of 0.5 to 6.0 l of oysters cylinder^{-1}. Differences between the two lowest densities were not significant ($P>0.05$) for length increase (smaller and larger grades) and weight gain (large grade; Figs. 4C, 4D).

Coefficient of variation for weight gain and shell length gain increased with stocking density for both grades ($P<0.001$). For the smaller grade, coefficient of variation for weight gain and shell length gain increased from 33.9±1.9 to 101.4±7.5 and 13.2±0.6 to 32.0±1.4, respectively, as stocking density increased from 0.5 to 4.0 l of oysters cylinder^{-1} (Figs. 3E, 3F). For the larger grade, coefficient of variation for weight gain increased from 29.7±1.3 to 66.1±3.5 by increasing stocking density from 0.5 to 4.0 l of oysters cylinder^{-1} and shell length gain increased from 11.1±1.2 to 20.1±1.5 by increasing stocking density from 0.5 to 6.0 l of oysters cylinder^{-1} (Figs. 4E, 4F).

TABLE 1

Environmental data from Mooney Mooney Creek, Hawkesbury River, N.S.W., February to May 1990[1]

Parameter	Mean±s.e.	Range
Temperature (°C)	21.6 ±1.7	16.2 –25.2
Salinity (‰)	16.5 ±3.5	8.9 –29.2
pH	7.7 ±0.1	7.5 –7.9
Turbidity (NTU)	7.8 ±1.4	5.0 –12.0
Secchi depth (m)	1.2 ±0.1	0.9 –1.5
Chlorophyll *a* (μg l^{-1})	3.7 ±0.8	1.4 –6.4
Total PO_4-P (mg l^{-1})	0.03±0.002	0.02–0.03
NH_3-N (mg l^{-1})	0.07±0.02	0.02–0.12
NO_x-N (mg l^{-1})[2]	0.12±0.03	0.05–0.14
Dissolved oxygen (mg l^{-1})	6.8 ±0.5	5.6 –8.4
Dissolved oxygen (% saturation)	78.4 ±3.1	69.0 –88.0

[1]Data were recorded at midday on five separate occasions and from the water surface.
[2]$NO_x = NO_2 + NO_3$.

Fig. 4. Effects of stocking density on the larger grade (average weight 0.4 g spat^{-1} and length 18.2 mm spat^{-1}) of juvenile Sydney rock oyster (*Saccostrea commercialis*) in PVC cylinders: (A) weight gain, (B) shell length increase, (C) biomass gain, (D) volume increase, (E) coefficient of variation for weight gain data, and (F) coefficient of variation for shell length increase data. Symbols represent means and vertical bars standard errors of the means ($n=4$). Means with a similar letter are not significantly different ($P>0.05$).

Temperature (21.6 ± 1.7°C, range 16.2–25.2°C), salinity (16.5 ± 3.5‰, range 8.9–29.2‰) and concentrations of other environmental variables are presented in Table 1. In general, temperature, salinity (Wolf and Collins, 1979) and concentrations of chlorophyll *a* (G. Allan, personal communication, 1992) were similar to those recorded in other estuarine environments in N.S.W., where Sydney rock oysters are cultivated.

DISCUSSION

The PVC cylinders previously described (Fig. 2) were suitable for nursery culture of juvenile Sydney rock oysters ranging in average shell length from 14 to 32 mm. The rotating action of the cylinder with tidal movements appeared to reduce the build-up of silt on the oysters, thereby eliminating the need to regularly wash the crop and minimising the risk of mudworm infestation (Skeel, 1979; Holliday et al., 1988). Turbidity has a direct influence on oyster culture as it can result in high concentrations of silt, which can affect the feeding efficiency of oysters (Quayle and Newkirk, 1989) and result in high mortalities (Quayle, 1988). High silt loads on oysters cultivated in trays in the Hawkesbury River and other N.S.W. estuaries have resulted in high mortalities from mudworm (Wisely et al., 1979). Mortality from mudworm infestations also affects other oyster species grown in different types on units in other countries (Korringa, 1976), although worm infestations have been significantly lower for Pacific oysters grown in cylinders in France, compared with those grown in fixed PVC mesh bags (Robert et al., 1991). For the present study, mortality (range 9.7–33.3%) was not excessive and may have resulted from the low salinity (minimum 8.9‰) after heavy rainfall. Nell and Holliday (1988) found that survival for 0.6-g Sydney rock oyster spat was not affected by salinities of 15–45‰; however, the effect of lower salinities (<15‰) on this species has not been reported.

Although mortality was unaffected ($P > 0.05$) by stocking density (with the exception of 6 l of oysters cylinder^{-1} for the larger grade), spat growth declined with increasing density, and biomass gain did not increase significantly at the three highest densities for each grade. The increase in coefficient of variation with density indicates that densities should be reduced periodically to optimise production. Newkirk (1981) found large variations in spat sizes in the first year for the European oyster (*Ostrea edulis* L.) and recommended culling a small percentage of each batch if the gains after labour costs for grading were warranted. Neudecker (1981) recommended altering densities of Pacific oysters (*Crassostrea gigas* Thunberg) every 2–3 weeks; however, Holliday et al. (1991) considered this excessive for Sydney rock oysters in nursery trays and altered densities every 3–5 months during a 12-month experiment.

When determining optimum stocking densities for juvenile Sydney rock oysters in PVC cylinders, a number of criteria need to be examined. Ultimately, optimum stocking density of oysters should be based on economic considerations (Askew, 1978; Spencer et al., 1985), as it is important to have cost-effective usage of nursery units and lease space. Unfortunately, data for a comprehensive economic analysis of single-seed culture based on Sydney rock oysters were not available.

If initial costs of spat are high, then the appropriate criteria for optimum stocking density should be survival, followed by maximum individual spat weight gain. Optimum stocking density based on maximum growth was 0.5–1.0 l oysters cylinder^{1} for both grades of spat (equivalent to 0.01–0.09 and 0.04–0.08 g of oysters cm^{-2} of area for the smaller and larger grades, respectively). Using an economic model for European and Pacific oysters, Askew (1978) found that the time required to reach market size was crucial for the viability of an operation, as the smaller slow-growing oysters (10% of the crop) required three times the growing period to reach market size. Neudecker (1981) also concluded that for juvenile Pacific oyster spat, maximum spat growth was the best criterion for optimum stocking density as rapid growth allowed for a quicker transfer from smaller to larger mesh trays and spat required a shorter growing period to reach market size. Neudecker (1981) recommended a stocking density of 0.05 g of oysters cm^{-2} of tray area for maximum growth of Pacific oysters (0.6 g oyster^{-1}) on fine mesh trays, which was similar to that recommended in the present study. When making comparisons between growing units, it should be noted that trays have flat surfaces while cylinders are curved.

Maximum growth of individual oysters is not, however, always the best criterion for optimum stocking density. Spencer et al. (1985) showed that the small advantage in growth of Pacific oysters with low stocking densities may be outweighed by the extra costs of labour and trays, even when the purchase of hatchery-produced Pacific oysters accounted for 62% of production costs in the first year of growth. In N.S.W., the initial cost of spat harvested from collectors with natural catch is relatively low (Holliday et al., 1988), while capital and labour costs for tray culture are high (Marshall and Espinas, 1987). Results from an economic analysis of single-seed production of Sydney rock oysters in nursery trays indicated that labour accounted for about 38% of total costs (C. Catt, personal communication, 1992).

An alternative criterion for optimum stocking density is maximum biomass gain. Maximum biomass gain for the present study was obtained at the highest densities for both grades of oysters; however, as increases above 2 l and 3 l oyster cylinder^{-1} for the smaller and larger grades, respectively (equivalent to 0.19 and 0.15 g of oysters cm^{-2} of area, respectively) did not result in significant increases in biomass gain, these densities represent optimums. At higher densities, coefficient of variation for weight gain and length increase was increased and oyster weight gains were reduced. Holliday et al.

(1991) used maximum biomass gain as a criterion for stocking Sydney rock oyster spat in nursery trays and recommended stocking densities of 0.15 and 0.86 g of oysters cm^{-2} of tray area for 0.1 and 1.2 g spat, respectively. Robert et al. (1991) reported good growth and survival of Pacific oysters (initial weight of 3.0 g) in cylinders stocked at a higher density (0.23 g of oysters cm^{-2} of area) to those used in the present study. For similar sized Sydney rock oysters, optimum stocking densities for cylinders, based on spat performance, are likely to be lower than for trays. Thus oyster culture using cylinders may require more space, although, in N.S.W., lease space in not considered to be limited (Holliday et al., 1991), and in areas with high silt loads, the use of cylinders should be considered as an alternative to trays.

Stocking densities could also be affected by environmental conditions such as food supply and nutrient concentrations. Chlorophyll *a* is often used as a measure of food abundance (Brown and Hartwick, 1988). Oyster growth rates have been positively correlated with chlorophyll *a* (Mallonee and Paynter, 1989 [range 8–25 $\mu g\ l^{-1}$]; Brown and Hartwick, 1988 [range 9.0–49.1 $\mu g\ l^{-1}$]). The chlorophyll *a* concentrations for the present study (range 1.4–6.4 $\mu g\ l^{-1}$) were lower than those recorded by Brown and Hartwick (1988), but within the range for N.S.W. oyster-producing estuaries (G. Allan, personal communication, 1992) and for the oyster-producing area of Arcachon, France (Robert et al., 1991).

Cylinders could be advantageous for growing bivalves in turbid estuaries where silt deposits on oysters impedes cultivation. For maximum growth and minimum coefficient of variation for weight gain and shell length increase, 0.2 and 0.4 g Sydney rock oyster spat should be stocked at low densities of 0.5 or 1.0 l $cylinder^{-1}$. To optimise biomass gain, while minimising growth reductions and size variation, stocking densities of 2.0 and 3.0 l of oysters $cylinder^{-1}$, respectively, should be used for oysters of a similar size to the smaller and larger grades used here.

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REFERENCES

APHA (American Public Health Association), 1989. Determination of inorganic non-metallic constituents. In: L. Clesceri, A. Greenberg, R. Trussell and M. Franson (Editors), Standard Methods for the Examination of Water and Wastewater, 17th Edition, Part 4000. APHA, Washington, DC, pp. 4.1–4.210.

Askew, C.G., 1978. A generalized growth and mortality model for assessing the economics of bivalve culture. Aquaculture, 14: 91–104.

Bayes, J.C., 1981. Forced upwelling nurseries for oysters and clams using impounded water systems. In: C. Claus, N. de Pauw, and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. European Mariculture Society Special Publication 7, Bredene, Belgium, pp. 73–83.

Brown, J.R. and Hartwick, E.B., 1988. 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.

CRC (Chemical Rubber Company), 1971. Handbook of Chemistry and Physics, 52nd edn. CRC, Cleveland, OH, pp. D-105.

Holliday, J.E., Maguire, G.B. and Nell, J.A., 1988. Alternative cultivation methods for the Sydney rock oyster (*Saccostrea commercialis*). In: L.H. Evans and D. O'Sullivan (Editors), Proceedings First Australian Shellfish Aquaculture Conference, Perth, October 1988. Curtin University of Technology, Perth, W.A., pp. 234–265.

Holliday, J.E., Maguire, G.B. and Nell, J.A., 1991. Optimum stocking density for nursery culture of Sydney rock oysters (*Saccostrea commercialis*). Aquaculture, 96: 7–16.

Korringa, P., 1976. Farming the Cupped Oysters of the Genus *Crassostrea*. Elsevier, Amsterdam, 224 pp.

Major, G.A., Dal Pont, G., Kyle, J. and Newell, B., 1972. Laboratory Techniques in Marine Chemistry. Commonwealth Science and Industrial Research Organisation, Div. Fish. Oceanogr. Rep., No. 51, Sydney, N.S.W., 55 pp.

Malcolm, W.B., 1987. The Sydney rock oyster. Agfact F 3.1.1, Dept. Agriculture N.S.W., 12 pp.

Mallonee, M.E. and Paynter, K.T., 1989. Water qualities associated with rapid oyster growth. J. Shellfish Res., 8(2): p. 486 (abstr.).

Marshall, G. and Espinas, V., 1987. Economic survey of the New South Wales oyster farming industry. I. Financial aspects. Div. Marketing and Economic Services. Misc. Bull., No. 48., Dept. Agriculture N.S.W., Sydney, 59 pp.

Nell, J.A. and Holliday, J.E., 1988. Effects of salinity on the growth and survival of Sydney rock oyster (*Saccostrea commercialis*) and Pacific oyster (*Crassostrea gigas*) larvae and spat. Aquaculture, 68: 39–44.

Nell, J.A. and Mason, C.J., 1991. Comparison of shell density, percentage cavity volume and shell weight of Sydney rock oysters (*Saccostrea commercialis*) and Pacific oysters (*Crassostrea gigas*). In: Pacific Oysters in New South Wales. Final Report, Fishing Industry Research and Development Council, N.S.W. Fisheries, Brackish Water Fish Culture Research Station, unpublished report, Salamander Bay, pp. 52–60.

Neudecker, T., 1981. Experimental offshore nursery-growing of *Crassostrea gigas* Thunberg in Germany. In: C. Claus, N. de Pauw and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. European Mariculture Society Special Publication 7, Bredene, Belgium, pp. 197–210.

Newkirk, G.F., 1981. On the unpredictability of bivalve growth rates: is a slow growing juvenile oyster a runt for life? In: C. Claus, N. de Pauw and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. European Mariculture Society Special Publication 7, Bredene, Belgium, pp. 211–218.

Quayle, D.B., 1988. Pacific Oyster Culture in British Columbia. Can. Bull. Fish. Aquat. Sci. 218, 241 pp.

Quayle, D.B. and Newkirk, G.F., 1989. Farming Bivalve Molluscs: Methods for Study and Development. Advances in World Aquaculture Vol. 1. Louisiana State University, Baton Rouge, LA, 294 pp.

Robert, R., Trut, G., Borel, M. and Maurer, D., 1991. Growth, fatness and gross biochemical composition of the Japanese oyster *Crassostrea gigas* in Stanway cylinders in the Bay of Arcachon, France. IFREMER Report, Station D'Arcachon, Quai Du Cdt Silhouette, Arcachon, 23 pp.

Skeel, M.E., 1979. Shell-boring worms (Spionidae: Polychaeta) infecting cultivated bivalve molluscs in Australia. J. World Maricult. Soc., 10: 529–533.

Sokal, R.R. and Rohlf, F.J., 1981. Biometry. Freeman, New York, NY, 859 pp.

Spencer, B.E., Gough, C.J. and Thomas, M.J., 1985. A strategy for growing hatchery-reared Pacific oysters (*Crassostrea gigas* Thunberg) to market size: experiments and observations on costed small-scale trials. Aquaculture, 50: 175–192.

Winer, B.J., 1971. Statistical Principles in Experimental Design, 2nd edn. McGraw-Hill Kogakusha Ltd, Tokyo, 907 pp.

Wisely, H.B., Holliday, J.E. and Reid, B.L., 1979. Experimental deepwater culture of the Sydney rock oyster (*Crassostrea commercialis* = *Saccostrea commercialis*). 2. Pontoon tray culture. Aquaculture, 16: 141–146.

Wolf, P.H. and Collins, A.J., 1979. Summary of daily temperature and salinity records for major oyster-producing estuaries of New South Wales 1966–1973. N.S.W. State Fisheries, Sydney, 107 pp.

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Cold storage effects on setting of larvae of the Sydney rock oyster, *Saccostrea commercialis*, and the Pacific oyster, *Crassostrea gigas*

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ABSTRACT

Holliday, J.E., Allan, G.L. and Frances, J., 1991. Cold storage effects on setting of larvae of the Sydney rock oyster, *Saccostrea commercialis*, and the Pacific oyster, *Crassostrea gigas*. *Aquaculture*, 92: 179–185.

Cold storage and transport of pediveliger stage larvae to commercial growers for delayed on-site setting reduces the cost of using hatchery produced seed. The percentage of Sydney rock oyster (*Saccostrea commercialis*) larvae which set following cold storage at 11 °C for up to 98 h was excellent (77–85%). Percentage of Pacific oyster (*Crassostrea gigas*) larvae set (68%) was unaffected by a storage temperature of 6 °C for 98 h. Shell length and eyespot diameters may be useful criteria for assessing when pediveliger stage larvae are ready for storage. Critical values for shell length and eyespot diameter for Sydney rock oyster larvae were 292.2 μm and 20.3 μm and for Pacific oyster larvae were 325.4 μm and 14.2 μm, respectively.

INTRODUCTION

Delayed or "remote" setting involves the storage and transport of pediveliger (competent to metamorphose) larvae from the hatchery to a site where the oysters are to be on-grown. The technique of remote setting of larvae was first attempted in North America during the early 1970s, using Pacific oysters (*Crassostrea gigas*) (Jones and Jones, 1988). Remote setting techniques with Pacific oyster larvae have gained wide acceptance in North America with commercial set rates of approximately 20–30% (Henderson, 1983; Roland et al., 1988).

Carlson (1981) suggested that storing Pacific oyster larvae at 5 °C for 5–8 days actually increased the set rate, while Henderson (1981) showed that no reduction in set rate occurred when larvae were stored at 5 °C for up to 6 days. A reduction in set rate and post-set survival occurred when larvae were stored at 5 °C beyond 8 days (Henderson, 1983). No reports of the effects of storage

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temperatures above or below 5°C on set rates of Pacific oyster larvae were found.

Australia's developing Pacific oyster industry in Tasmania, with an estimated half shell production of 1.6 million dozen for 1988/1989 (Anonymous, 1988), is totally dependent upon hatchery production. In New South Wales, production of Sydney rock oysters (*Saccostrea commercialis*) was estimated at 10.5 million dozen for 1988/1989 (Anonymous, 1988). This industry is based on the collection of juvenile oysters (spat) in the wild (Holliday et al., 1988). However, following the development of hatchery techniques for breeding Sydney rock oysters (Holliday, 1985), an estimated 12 million 4–6-mm spat were sold to farmers from the two commercial hatcheries in New South Wales in 1988/1989 (J. Nell, personal communication, 1990).

In Australia, hatchery produced Sydney rock and Pacific oyster seed is grown to about 4 mm shell length, usually in an upwelling nursery system, similar to the type described by Bayes (1981). The nursery phase can be very expensive, particularly for Sydney rock oysters, which grow at approximately half the rate of Pacific oysters (Nell, 1989).

Remote setting has not previously been attempted using the Sydney rock oyster. The objectives of this study were to determine whether the larvae could be stored for delayed settlement and, if so, to determine the effect of storage temperature and time. Local strains of Pacific oyster larvae were also settled following storage at 6°C for 4 days for comparison with Sydney rock oyster larvae.

METHODS

Larvae

Sydney rock and Pacific oyster broodstock were obtained from Port Stephens, N.S.W. Both species were stimulated to spawn on the same day by reducing salinity from 35 to 25‰. The fertilized eggs and larvae were then reared to pediveliger stage at 25 ± 1°C and 30 ± 1‰ using established techniques (Walne, 1974; Holliday, 1985). Pacific oyster larvae reached the pediveliger stage 18 days after fertilization; Sydney rock oyster larvae after 22 days.

When larvae reached the pediveliger stage, and there were small numbers observed setting on the sides of the rearing tanks, they were harvested onto a partially submerged 200-μm screen. Larvae for each experiment were then divided volumetrically into 20-l buckets, one for each replicate. The larval concentrations in each bucket were estimated by counting the larvae in each of five subsamples using a Sedgewick–Rafter cell and a compound microscope. Eyespot diameter and shell length were measured for 250 larvae of each species using a binocular microscope with an ocular micrometer (± 0.5 μm).

The larvae in each bucket were then drained through a funnel and retained using 100-μm nylon mesh (25 cm^2). The mesh was then secured with a rubber band. Each mesh pouch contained (means ± s.e., $\times 10^3$) 170 ± 3.1 and 2.36 ± 10.0 larvae for the experiments with Sydney rock and Pacific oyster larvae, respectively. The 25-cm^2 mesh pouches of larvae used as controls (no storage) were emptied directly into the setting container.

Storage

The pouches of larvae, wrapped in damp absorbant paper, were transported for 2 h to the temperature control rooms in a portable 30-l refrigerator, set at 11 ± 0.4 °C. They were then rearranged into 5-l boxes, one for each treatment, and placed inside one of three fan-forced constant temperature cool rooms. The temperature inside one of the 5-l boxes in each cool room was logged using ANRITSU type T7001 data loggers (Electron Chemical Engineering Pty Ltd., Mobbs Lane, Carlingford, N.S.W. 2118). The mean temperatures (°C) maintained in the cool rooms were 1.4 (range 1.1–2.1), 6.0 (range 5.3–8.8), and 11.0 (range 10.3–11.3).

Set system

After the appropriate storage interval, the 5-l boxes containing the concentrated larvae in pouches were returned to the hatchery in the portable refrigerator. Larvae were washed into 5-l beakers of seawater (25 °C, 33‰) and held for 45 min while the motility, colour, odour and mortality of the larvae were assessed. To avoid bacterial contamination of viable larvae, those treatments with total mortality in each replicate were not placed in the set systems. For each other replicate, the larvae were confined within a PVC screen (450 mm diameter, 150 mm deep, 200 μm mesh size), partially submerged at a randomly allocated location inside one of five 1700-l fibreglass setting tanks. Within each PVC screen a conical shaped, lime and cement-coated PVC collector (355 mm diameter, 80 mm high, surface area 1790 cm^2) was provided for the larvae to attach. Maximum numbers of Sydney rock oysters had attached to this type of collector during hatchery trials using a variety of commercially available collectors (J.E. Holliday et al., unpublished data, 1989). Seawater (25.4 ± 0.1 °C, 29.8 ± 0.3‰) was gently sprayed over the top of each PVC screen at the rate of 0.8 l/min. A 100% water exchange was carried out every second day, with a 50% exchange every other day, and tanks were fed an equal mix of algal species ("Tahitian" *Isochrysis* aff. *galbana, Pavlova lutheri* and *Dunaliella tertiolecta*) at a rate of 2.9×10^4 cells ml^{-1} day^{-1}.

The collectors were removed after 8 days. A template with four evenly spaced wedges (each spanning the radius of the collector, giving a total surface area of 199 mm^2) was randomly placed over the top and bottom surfaces of each collector, and the oysters contained within each wedge were counted. Oysters that settled on the PVC screens were removed and enumerated by weighing.

For Sydney rock oysters, nine treatments were provided with five replicates of each. Treatments comprised a control, where larvae were drained into 25-cm^2 mesh pouches and then put to set without storage; storage for 12, 98 and 194 h at 11°C; 98, 194 and 290 h at 6°C; and 98 and 194 h at 1.4°C.

For Pacific oysters, two treatments with five replicates for each were provided. These included a control (no storage) and 98 h at 6°C, close to the reported recommended storage temperature and time (5°C; 144 h) for this species (Henderson, 1981).

Statistical analyses

For the experiment with Sydney rock oysters, differences in the numbers of oysters that set following different treatments were assessed using one-way ANOVA. Homogeneity of variance was evaluated using Cochran's Test (Winer, 1971) and means were compared using Tukey's honesty significant differences method (Sokal and Rohlf, 1981). Data from treatments that suffered total mortality following storage were excluded from statistical analyses. Differences between set for the experiment with Pacific oysters were compared using a *t*-test (Sokal and Rohlf, 1981). The differences between eyespot and shell diameters for the two species were compared separately using *t*-tests and the relationship between eyespot diameter and shell length for each species was evaluated using linear regression.

RESULTS

Set rates for Sydney rock oysters were excellent, with no significant difference ($P>0.05$) in numbers ($\times 10^3$) which settled between controls (139 ± 9 (means $\pm$ s.e.)) and larvae stored at 11°C for 12 or 98 h (145 ± 16 and 131 ± 17, respectively) (Table 1). The percentage of larvae which settled was estimated to range from between 77 and 85% for these treatments. Significantly fewer oysters survived ($P<0.05$) when stored for 98 h at 1.4 and 6°C and 194 h at 11°C (Table 1). The percentage of larvae which set was estimated to range from 5 to 33% for these treatments. No larvae survived when stored for 194 h at 1.4 and 6°C.

There was no significant difference ($P>0.05$) in the number ($\times 10^3$) of Pacific oysters which settled between the controls and larvae stored for 98 h at 6°C (159 ± 21 and 163 ± 15, respectively) (Table 1). Approximately 68% of larvae were estimated to have set from both treatments.

The faster growing Pacific oyster larvae had a significantly ($P<0.05$) larger mean shell length (325.4 ± 1.00 μm; $n=250$) than Sydney rock oyster larvae (292.2 ± 0.87 μm; $n=250$), although the eyespot diameter was significantly ($P<0.05$) smaller (14.2 ± 0.15 μm compared with 20.3 ± 0.30 μm). Within the small size range measured for each species there was no significant relationship ($P>0.05$) between shell length and eyespot diameter.

TABLE 1

The effects of cold storage on settlement of eyed Sydney rock (*Saccostrea commercialis*) and Pacific (*Crassostrea gigas*) oyster larvae[1]

Time (h)	Temp. (°C)	Sydney rock		Pacific	
		Larvae ($\times 10^3$)	Spat set ($\times 10^3$)	Larvae ($\times 10^3$)	Spat set ($\times 10^3$)
No storage		182 ± 11^a	139 ± 9^a	233 ± 10^a	159 ± 21^a
12	11.0	157 ± 7^a	145 ± 16^a		
98	1.4	175 ± 12^a	8 ± 2^b		
98	6.0	186 ± 9^a	55 ± 8^b	238 ± 11^a	163 ± 15^a
98	11.0	177 ± 9^a	131 ± 17^a		
194	1.4	147 ± 8^a	0[2]		
194	6.0	148 ± 7^a	0[2]		
194	11.0	173 ± 8^a	28 ± 5^b		
290	6.0	184 ± 9^a	0[2]		

[1]Mean ± s.e. Within columns, means with a common superscript do not differ significantly ($P > 0.05$), $n = 5$.
[2]Treatments excluded from statistical analysis.

DISCUSSION

The excellent set results for Sydney rock oyster larvae stored for up to 98 h at 11 °C indicate that remote setting techniques have considerable potential for this species. Relatively inexpensive, commercially available equipment can be used to maintain a temperature of 11 °C and consignments of oysters could be shipped to most locations within Australia, and overseas, within 98 h.

Estimates of the percentage of larvae of both species which set following optimum storage temperature and time ranged from 68% for Pacific oysters to between 77 and 85% for Sydney rock oysters. These rates are well in excess of the reported acceptable commercial rates of 20–30% for unfed Pacific oyster larvae and 37% for those fed on stored algal paste (Roland et al., 1988). In the present study larvae were fed live algae during settlement and this may have improved set rates.

Recommended larval shell lengths and eyespot diameters for remote setting Pacific oysters are > 300 μm and 14 μm (Jones and Jones, 1988) and 300–320 μm and 15 μm (Roland et al., 1988). The size (325 μm, range 290–373 μm) of Pacific oyster larvae in the present study was similar. Inherent differences between the local Pacific oyster strain and those used elsewhere may account for differences in set performance. If shell length and eyespot diameter were used as criteria for when to store pediveliger larvae for delayed set, the results of the present study indicate that appropriate measurements would be 292.2 μm and 20.3 μm for Sydney rock oysters and 325.4 μm and 14.2 μm for Pacific oysters.

Typically, consignments of 2.5×10^6 Pacific oyster larvae are shipped in mesh pouches from the North American hatcheries (Jones and Jones, 1988). The larger surface-to-volume ratio for smaller pouches was considered likely to result in higher larval mortality through desiccation or physical abrasion of larvae in contact with the pouch material. The mean number ($\times 10^3$) of larvae used here for each pouch was 170 ± 3.1 and 236 ± 10.0 larvae for Sydney rock and Pacific oysters, respectively, and was chosen to be large enough to simulate commercial scale shipments. Larger consignments may have produced even better results. No larvae were stored beyond 194 h at 11°C, although it is possible that some may have survived. The set performance of Pacific oysters following storage at temperatures above the recommended temperature of 5°C (Henderson, 1983) is also well worth examining.

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REFERENCES

Anonymous, 1988. Fisheries products. Q. Rev. Rural Econ., 10(4): 378.

Bayes, J.C., 1981. Forced upwelling in nurseries for oysters and clams using impounded water systems. In: C. Claus, N. de Pauw and E. Jaspers (Editors), European Mariculture Society Special Publication No. 7. Institute for Marine Scientific Research, Bredene, Belgium, pp. 73–83.

Carlson, B.K., 1981. Settlement and subsequent survival of commercially-reared eyed-pediveliger larvae of the Pacific oyster *Crassostrea gigas* (Thurnberg). Abstract, 1981 NSA West Coast Section Meeting. J. Shellfish Res., 2(1): 116.

Henderson, B.A., 1981. Practical methods of handling and settling eyed-pediveliger larvae of the Pacific oyster *Crassostrea gigas* (Thurnberg). J. Shellfish Res., 2(1): 119–120.

Henderson, B.A., 1983. Handling and Remote Setting Techniques for Pacific Oyster Larvae *Crassostrea gigas*. Unpublished M.Sc. Thesis, Oregon State University OR, 37 pp.

Holliday, J.E., 1985. International Developments in Oyster Hatchery Technology. Department of Agriculture N.S.W., Sydney, Fish. Misc. Bull. 1: 101 pp.

Holliday, J.E., Maguire, G.B. and Nell, J.A., 1988. Alternative cultivation methods for the Sydney rock oyster (*Saccostrea commercialis*). In: L.H. Evans and D. O'Sullivan (Editors), Proceedings First National Shellfish Aquaculture Conference, Curtin University of Technology, Perth, W.A., pp. 234–265.

Jones, G.G. and Jones, B.L., 1988. Advances in Remote Setting of Oyster Larvae. Aquaculture Assoc. of BC, Nanaimo, BC, 88 pp.

Nell, J.A., 1989. Pacific oyster research. Proceedings Brackish Water Fish Culture Research Station Open Day, 1989, pp. 17–19.

Roland, W.G., Sutherland, I.R. and Broadley, T.A., 1988. Update on remote setting Pacific oyster larvae in British Columbia. British Columbia Aquaculture Information Bull. No. 15: 10 pp.

Sokal, R.R. and Rohlf, F.J., 1981. Biometry. W.H. Freeman and Co., New York, NY, 859 pp.

Walne, P.R., 1974. Culture of Bivalve Molluscs. Fishing News (Books), West Byfleet, Great Britain, 173 pp.

Winer, B.J., 1971. Statistical Principles in Experimental Design. McGraw-Hill Kogakuska, Tokyo, pp. 205–210.

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Optimum stocking density for nursery culture of Sydney rock oysters (*Saccostrea commercialis*)

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ABSTRACT

Holliday, J.E., Maguire, G.B. and Nell, J.A., 1991. Optimum stocking density for nursery culture of Sydney rock oysters *(Saccostrea commercialis). Aquaculture,* 96: 7–16.

Growth rates of juvenile Sydney rock oysters *(Saccostrea commercialis)* declined with increasing stocking density ($P<0.01$) in intertidal sectionalised trays in three 3–5-month experiments. Optimum stocking densities based on maximum biomass gain results (kg/m^2) for oysters with average initial whole weights of 0.09, 1.15 and 1.56 g/oyster were obtained at densities of 15 200, 7200 and 3600 oysters/m^2, in that order. The estimated survival rate of oysters during the 12-month study was high (97.5%).

INTRODUCTION

Nursery culture of bivalve molluscs is an important phase of cultivation which links the production of small juveniles (spat) from hatcheries or natural spatfall with the grow-out phase to harvest size (Claus, 1981). Traditional methods for farming Sydney rock oysters *(Saccostrea commercialis)* to market size involve collecting spat on tarred hardwood sticks and on-growing them on sticks for 3–4 years. After being removed from the sticks, oysters which are below market size may be finished in intertidal trays (Korringa, 1976). This approach has formed the basis of one of Australia's most valuable aquacultural industries (Holliday et al., 1988; Nell et al., 1990).

In recent years the development of hatchery techniques and collection methods for natural spatfall has made the culture of unattached (single-seed) Sydney rock oysters commercially possible (Holliday, 1985a). Compared with oysters produced using traditional methods, single-seed oysters are less likely to grow together and hence mortalities and labour costs associated with sep-

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arating oysters are greatly reduced (Holliday et al., 1988). However, high losses of spat were initially experienced by Sydney rock oyster farmers who used single seed because of inappropriate design or management of nursery systems. The nursery phase in single-seed culture usually requires different production units and handling methods from those used for the grow-out phase (Claus, 1981). As several nursery systems used overseas proved to be unsuitable for local conditions, a system had to be developed to suit the Sydney rock oyster (Holliday, 1985b). The efficiency of a nursery system is affected by the stocking densities used, as growth rates of individual oyster spat decrease with increasing stocking density, while overall spat production (weight per unit area) increases (Neudecker, 1981).

The aim of the present study was to determine the optimum stocking densities for various size grades of Sydney rock oyster spat as part of an evaluation of sectionalised trays as intertidal nursery units for this species.

MATERIALS AND METHODS

Sectionalised nursery trays (1.94×0.94×0.05 m) constructed of tarred 50×20 mm hardwood were divided crossways into six parallel sections of 0.25 m^2 each. Both the upper and lower tray surfaces were covered with PVC mesh (diagonal mesh size 3 mm). Three stocking density experiments were conducted within a 12-month period using these trays positioned on timber post and rail at the intertidal rack height used by commercial oyster farmers in Swan Bay, Port Stephens, N.S.W., Australia (32° 44′S; 152°E; Fig. 1).

Spat were detached from various types of collectors used on a catching lease in Salamander Bay, Port Stephens (Fig. 1) and were then on-grown in forced-flow upwellers (Bayes, 1981; Wisely, 1983), before being stocked in nursery trays for the first experiment.

For each experiment there were six stocking densities (Table 1) with four replicate tray sections per density and treatments were randomly allotted among the sections and trays. Individual spat were not counted when stocked but were allotted on a pooled-weight basis in relation to the average spat weight for an initial sample. Each month the trays were removed from the lease and average oyster weights were determined as above. Dead oysters were counted, total weights recorded and live oysters returned to the trays which were then randomly assigned on the lease to minimise any effect of lease position on growth. Each experiment was terminated when spat in the high-density treatments began growing through the upper mesh layer. At the end of Experiments 1 and 2, spat were pooled and, to minimise variances in individual weight, the pooled spat were graded with three PVC mesh screens with only the middle grade used to stock the next experiment. The densities used were selected to provide a range from very lightly stocked to densely stocked with most of the floor area of the tray section being covered by a single layer of closely packed spat.

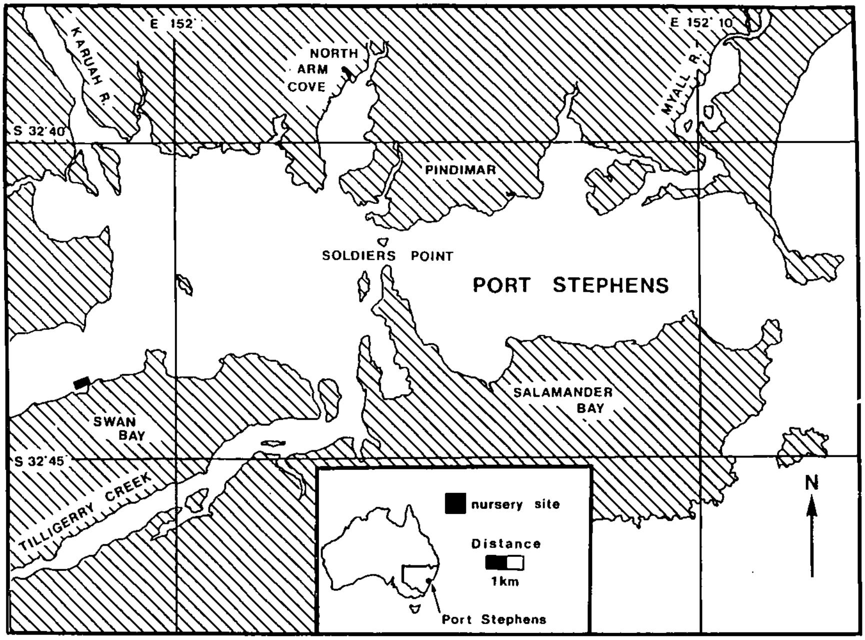

Fig. 1. Map of Port Stephens, N.S.W., Australia, with the nursery lease in Swan Bay used for Experiments 1, 2 and 3.

Experiment 1 involved estimated stocking densities of 300, 1000, 1700, 2400, 3100 and 3800 spat/section (1200–15 200 spat/m^2). The average initial weight was 0.09 g/spat (based on the pooled weight of 700 spat). This experiment ran for 13 weeks (January to April).

Experiment 2 involved estimated densities of 200, 600, 1000, 1400, 1800 and 2200 spat/section (800–8800 spat/m^2) and an average initial weight of 1.15 ± 0.02 g/spat ($\bar{x} \pm$ s.d.; $n=6$ for groups of 100 spat). This experiment ran for 13 weeks (April to July).

Experiment 3 involved estimated densities of 300, 500, 700, 900, 1100 and 1300 spat/section (1200–5200 spat/m^2) and an average initial weight of 1.56 ± 0.07 g/spat ($\bar{x} \pm$ s.d.; $n=5$ for groups of 100 spat). Because growth rates in the early phase of this experiment were relatively slow, it was extended to a total period of 22 weeks (July to December).

Daily salinity and temperature data were obtained with hydrometers and thermometers at three commercial oyster depuration plants near the nursery lease in Swan Bay (Fig. 1).

Statistical analyses

Homogeneity of variance was confirmed using Cochran's test (Winer, 1971) and data were analysed using ANOVA. Mean values were compared using the

TABLE 1

Production of Sydney rock oyster spat *(Saccostrea commercialis)* at various stocking densities in sectionalised trays ($\bar{x} \pm$ s.d.)[1]

Stocking density (spat $\times 10^3/m^2$)	Final biomass[2] (kg/m^2)	Biomass gain[2,3] (kg/m^2)
Experiment 1		
1.2	1.6±0.1	1.5±0.1[a]
4.0	5.4±0.1	5.0±0.1[b]
6.8	7.9±0.3	7.3±0.3[c]
9.6	9.8±0.7	8.9±0.7[d]
12.4	10.8±0.7	9.7±0.7[e]
15.2	12.0±0.4	10.7±0.4[f]
Experiment 2		
0.8	1.8±0.1	0.8±0.1[a]
2.4	4.8±0.1	2.0±0.1[b]
4.0	7.3±0.1	2.7±0.1[c]
5.6	9.1±0.2	2.7±0.2[c]
7.2	11.3±0.2	3.0±0.2[d]
8.8	13.0±0.2	2.9±0.2[cd]
Experiment 3		
1.2	5.2±0.3	3.3±0.3[a]
2.0	7.7±0.6	4.6±0.6[b]
2.8	10.2±0.8	5.8±0.8[c]
3.6	13.0±0.3	7.4±0.3[d]
4.4	14.3±0.4	7.5±0.4[d]
5.2	15.1±1.0	7.0±1.0[d]

[1]The average initial whole-spat weight values for Experiments 1, 2 and 3 were 0.09 g, 1.15 g and 1.56 g, in that order and the duration of the experiments was 13, 13 and 22 weeks, respectively.
[2]Biomass values based on whole weight of live spat.
[3]Within this column mean values from the same experiment are not significantly different if they share a superscript ($P > 0.05$).

"least-significant differences" technique (Sokal and Rohlf, 1981). Linear regression was performed for all experiments to examine the relationship between stocking density and average weight gain. To satisfy the assumption of homogeneity, weight gain data for Experiment 2 were transformed (log x) prior to ANOVA and regression. Survival data were transformed (arcsine $x^{0.5}$) prior to ANOVA. Results from tray sections where physical damage to the section may have allowed losses of spat were not included in analyses. Throughout this paper data are presented as mean ± standard deviation ($\bar{x} \pm$ s.d.).

RESULTS

The estimated survival rate of the spat over the 12-month period was very high (97.5%) and was not affected by stocking density in any of the three experiments ($P > 0.05$).

In each of the three experiments average individual oyster weight gain decreased with increasing stocking density ($P<0.05$; Fig. 2). However, in Experiment 1 average weight gain for the lowest stocking density (1200 spat/m^2) was lower than that recorded at 4000 spat/m^2 ($P<0.05$; Fig. 2). In this experiment it was evident that a very low stocking density (1200 spat/m^2) was unfavourable, probably because excessive oyster movement caused by wave action on the sparsely stocked tray sections caused shell abrasion; spat were ball-shaped with thick shell walls. At equivalent densities (no./m^2) the effect of stocking density on growth was much more pronounced (Fig. 2). Spat growth was depressed during Experiments 2 and 3 (Fig. 3) when low water temperatures were recorded in July (12.1 ± 1.1 °C) and August (13.1 ± 1.8 °C; n=20/month). Variances were homogeneous for each sampling time except for the July samples in Experiment 2 (Fig. 3). The standard deviation values for the July samples, in increasing order of stocking density, were 0.10, 0.25, 0.08, 0.06, 0.08, and 0.08 g.

In each of the three experiments, final biomass increased with increasing stocking density over the whole range tested (Table 1). Biomass gain generally increased as stocking density increased until a plateau was reached (Fig. 4). The exception was Experiment 1 for which biomass gain increased with

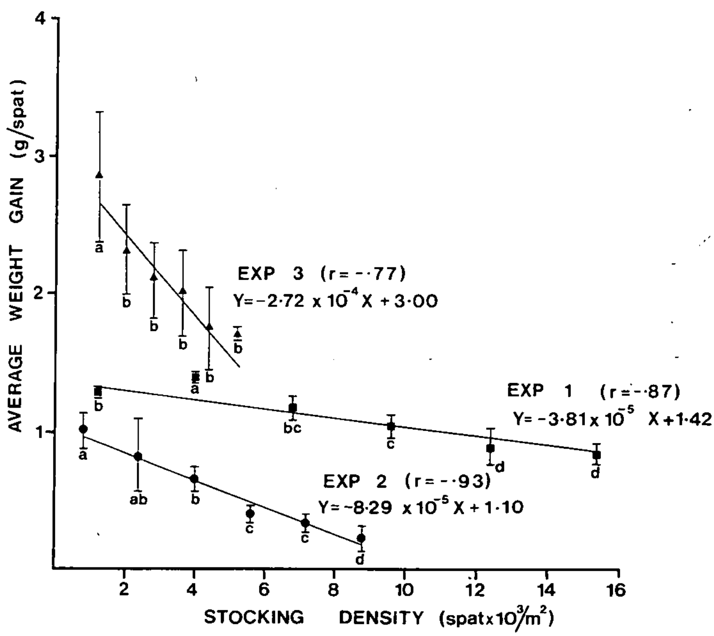

Fig. 2. Growth of Sydney rock oyster spat *(Saccostrea commercialis)* at a range of stocking densities in sectionalised trays. Means, within each experiment, which share a superscript are not significantly different ($P>0.01$). Data for Experiment 2 were transformed (log X) prior to ANOVA and regression analysis.

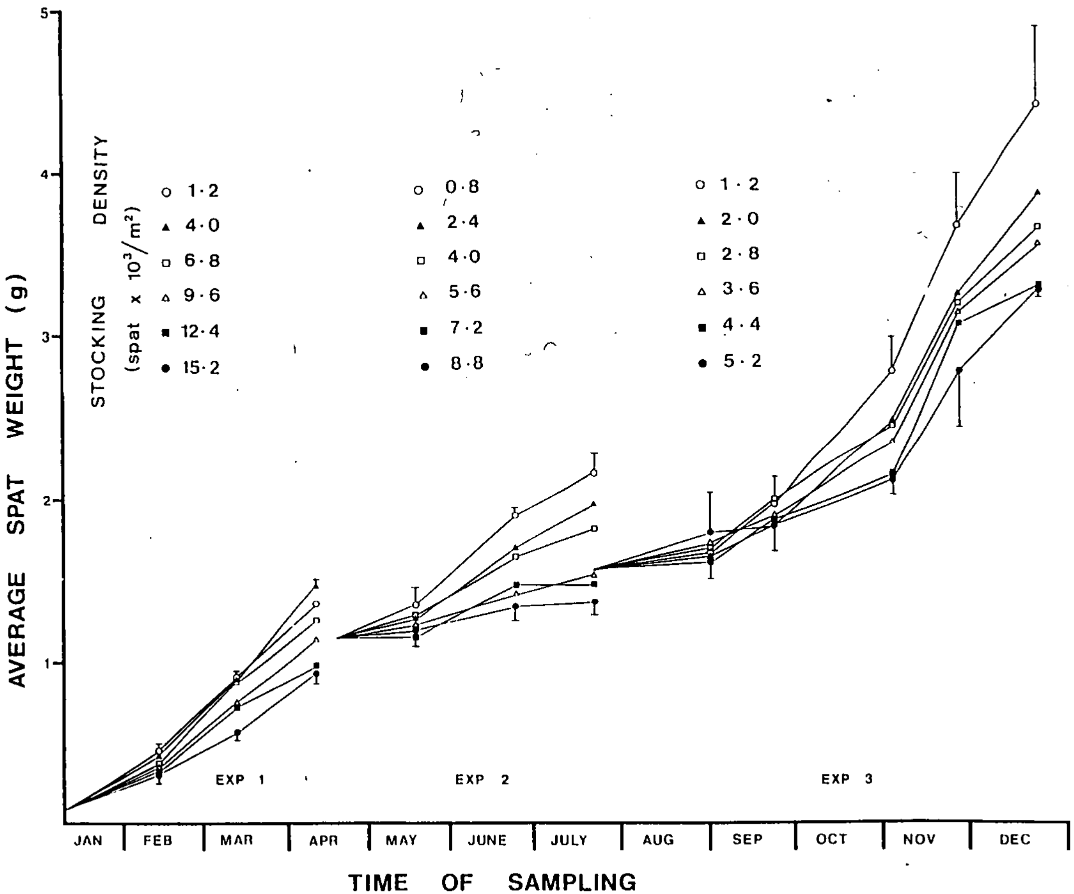

Fig. 3. Weight of Sydney rock oyster *(Saccostrea commercialis)* spat through time at a range of stocking densities ($\bar{x} \pm$s.d.). Only the standard deviation values for the largest and smallest size groups at each sampling time have been included.

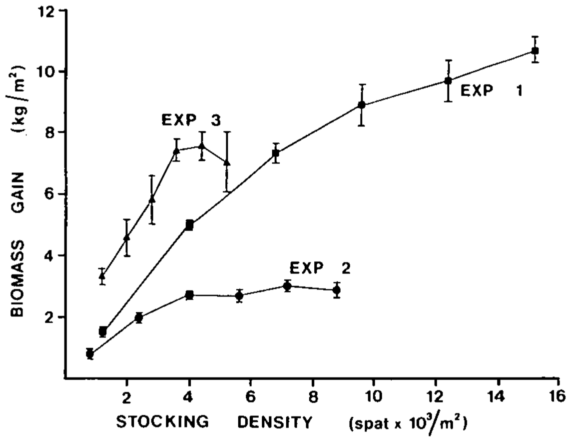

Fig. 4. Biomass gain over the duration of the experiments for Sydney rock oyster *(Saccostrea commercialis)* spat grown at a range of stocking densities.

increasing stocking density throughout the range tested. It should be noted that for Experiment 1 the optimum density was the maximum level used and a higher density might have produced even better biomass gain values. The optimum stocking densities in terms of biomass gain for Experiments 1, 2 and 3 were 15 200, 7200 and 3600 spat/m^2 in that order. It should be noted that in Experiment 3 a marginally higher biomass gain was obtained at 4400 spat/m^2 but this was not a significant improvement over stocking with 3600 spat/m^2 ($P > 0.05$). Final biomass levels at the optimum stocking density for each experiment were similar (11.3–13.0 kg/m^2, Table 1).

Average water temperature and salinity levels were as follows: Experiment 1 ($n=63$), 22.0 ± 1.7°C, 33.6 ± 2.1‰, ranges 16–27°C, 28–40‰; Experiment 2 ($n=63$), 14.3 ± 2.5°C, 25.6 ± 0.6‰, ranges 10–21°C, 17–36‰; and Experiment 3 ($n=91$), 18.8 ± 3.3°C, 26.6 ± 4.0‰, ranges 10–27°C, 9–39‰.

DISCUSSION

Unlike traditional cultivation methods for the Sydney rock oyster, single-seed methods allow for manipulation of juvenile oyster densities. The results of the present study indicate that the choice of stocking density has a major effect on yields from sectionalised trays. In each of the three experiments, individual spat growth decreased with increasing density, probably because of competition for food. Hadley and Manzi (1984) concluded that food was the growth-limiting factor for clams *(Mercenaria mercenaria)* stocked at a range of densities in a raceway nursery system.

A variety of criteria could be used to assess optimum stocking density. The higher growth rates at low densities enhance the value of individual oysters;

however, the value of production per unit area may be relatively low. Neudecker (1981) concluded that for small Pacific oyster spat *(Crassostrea gigas),* maximum growth was the best criterion for optimum stocking density because faster growth rates allowed for an earlier transfer to subtidal trays with a larger mesh size. Optimum density may also be influenced by survival rate, although in all of the present experiments estimated survival rates were very high and unaffected by density. The choice of stocking density should be based on economic considerations (Maguire and Leedow, 1983). As the data required for a comprehensive economic analysis of single-seed nursery culture are not yet available, an alternative approach of using maximum biomass gain as the criterion for optimum density was used here. The estimate of biomass used in this study was total oyster weight but, depending on the thickness of the shell, this is not always an accurate guide to the value of an oyster. Other factors such as meat condition, shell shape and shell size can also influence value per oyster. Specifically, farmers often sort harvested oysters into groups of differing values on the basis of shell length. However, for single Sydney rock oysters, there is a close relationship between total oyster weight and shell length (C.J. Mason, pers. commun., 1990).

The management of nursery units involves more than the choice of stocking density. As the spat grow they may fill the available tray space and grow through the mesh. In Experiments 2 and 3 the tendency for the spat to grow through the mesh prior to harvest was much more evident than in Experiment 1. Towards the end of Experiments 2 and 3, there was evidence that growth rate decreased at high densities (Fig. 3). A similar pattern was evident in the growth data for small Pacific oyster spat in subtidal nursery trays (Neudecker, 1981). This emphasises the need to periodically reduce the density (no./m^2) as the spat grow. As this process is relatively labour-intensive, it may be preferable to avoid high stocking densities and hence frequent handling of the trays. Neudecker (1981) recommended the adjustment of densities every 2–3 weeks, but this is likely to be too labour-intensive for the oyster-farming industry in New South Wales. However, more frequent reductions in densities than those used in the present study may be worthwhile.

Excessively small mesh sizes, particularly if exacerbated by marine fouling, could restrict flow rates and reduce the amount of food available for oysters. The initial tray mesh size must be small enough to retain juvenile spat but as they grow, spat can be moved to larger mesh sizes to increase water flow. In the present study 3-mm mesh was used for the 12-month duration of the experiments as it prevented spat loss due to wave action and provided protection against predation and heat stress during intertidal exposure (Potter and Hill, 1982). In contrast, Neudecker (1981) increased the mesh size as the spat grew.

Spat growth rates appeared to be depressed during the cooler months in Experiments 2 and 3 (Fig. 3). This observation was consistent with results from a nursery experiment over 12 months at three intertidal sites within Port Stephens (Holliday et al., in press). Similarly, Nell and Livanos (1988) showed that in the range of 12–30°C, growth rates of Sydney rock spat, fed to excess in the laboratory, increased as temperature increased.

Sectionalised trays proved to be appropriate nursery units for Sydney rock oyster spat and were particularly successful for sustaining very high survival rates. In a 12-month period spat in the present experiment grew from 0.09 g to 4.9–6.0 g/spat. Data for the equivalent growth phase for Sydney rock oysters grown on sticks in conventional intertidal leases are not available, but 3–4 years are usually required for them to reach market size (> 40 g; Korringa, 1976).

Traditional intertidal trays used for on-growing oysters approaching market size are often subjected to severe wave action which washes the oysters into the tray corners resulting in overcrowding, reduced growth rates, and eventual mortality. In this study, the increased number of partitions in the sectionalised trays reduced spat movement and minimised overcrowding. The upper and lower mesh layers also prevent predation of spat by fish and spillage from trays.

Claus (1981) noted that the appropriateness of nursery technology is influenced by geographic location and economic considerations and emphasised that two-dimensional nursery systems require more space than more sophisticated three-dimensional nursery systems. However, space is not a limitation in New South Wales as the Sydney rock oyster industry is based largely on two-dimensional intertidal culture through to market size and the area required for nursery culture is negligible compared with that needed for the grow-out phase. The determination of optimum stocking densities for juvenile Sydney rock oysters in sectionalised trays will allow for more cost-efficient usage of trays and lease space. Key factors include capital and operating costs associated with acquisition of trays, depreciation, replacement, lease infrastructure and labour costs for relocation of trays during grading operations.

Subsequent to the completion of this study and that by Holliday et al. (in press), sectionalised trays were widely adopted by farmers culturing single-seed Sydney rock oysters (Holliday et al., 1988). The suitability of this nursery system has helped foster the expansion of single-seed oyster farming as an alternative to traditional stick culture methods which no longer provide adequate return on capital in some estuaries in New South Wales (Marshall and Espinas, 1987; Espinas et al., 1988).

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REFERENCES

Bayes, J.C., 1981. Forced upwelling nurseries for oysters and clams using impounded water systems. In: C. Claus, N. de Pauw and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. Eur. Maricult. Soc. Spec. Publ. 7, Bredene, Belgium, pp. 73–83.

Claus, C., 1981. Trends in nursery rearing of bivalve molluscs. In: C. Claus, N. de Pauw and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. Eur. Maricult. Soc. Spec. Publ. 7, Bredene, Belgium, pp. 1–33.

Espinas, V., Marshall, G. and Rish, B., 1988. Economic Survey of the New South Wales Oyster Farming Industry: 1981–82 to 1983–84. Part 2 – Physical aspects. Div. Market. Econ. Serv. Misc. Bull., 54. Dept. Agriculture, N.S.W., Sydney, 48 pp.

Hadley, N.H. and Manzi, J.J., 1984. Growth of seed clams, *Mercenaria mercenaria*, at various densities in a commercial scale nursery system. Aquaculture, 36(4): 369–379.

Holliday, J.E., 1985a. International Developments in Oyster Hatchery Technology. Fish. Div. Misc. Bull., 1. Dept. of Agriculture, N.S.W., Sydney, 101 pp.

Holliday, J.E., 1985b. Current oyster spat research in N.S.W. Aust. Fish., 44(3): 24–26.

Holliday, J.E., Maguire, G.B. and Nell, J.A., 1988. Alternative cultivation methods for the Sydney rock oyster *(Saccostrea commercialis)*. In: L.H. Evans and D. O'Sullivan (Editors), Proceedings First Australian Shellfish Aquaculture Conference, Perth, October 1988. Curtin University of Technology, Perth, W.A., pp. 234–265.

Holliday, J.E., Maguire, G.B. and Nell, J.A. (in press). Evaluation of sites for nursery culture of single seed Sydney rock oysters *(Saccostrea commercialis)*. Fish. Div. Bull., N.S.W. Agriculture and Fisheries, Sydney.

Korringa, P., 1976. Farming the Cupped Oysters of the Genus *Crassostrea*. Elsevier, Amsterdam, 224 pp.

Maguire, G.B. and Leedow, M.I., 1983. A study of the optimum stocking density and feed rate for school prawns *Metapenaeus macleayi* (Haswell) in some Australian brackish water farming ponds. Aquaculture, 30: 285–297.

Marshall, G. and Espinas, V., 1987. Economic Survey of the New South Wales Oyster Farming Industry – Financial Aspects. Div. Market. Econ. Serv. Misc. Bull., 48. Dept. of Agriculture, N.S.W., Sydney, 59 pp.

Nell, J.A. and Livanos, G., 1988. Effects of fluoride concentration in seawater on growth and fluoride accumulation by Sydney rock oyster *(Saccostrea commercialis)* and flat oyster *(Ostrea angasi)* spat. Water Res., 22: 749–753.

Nell, J.A., Smith, I.R. and Holliday, J.E., 1990. An overview of the Sydney rock oyster *(Saccostrea commercialis)* industry in New South Wales. Agric. Sci., 8(2): 29–30.

Neudecker, T., 1981. Experimental offshore nursery-growing of *Crassostrea gigas* Thunberg in Germany. In: C. Claus, N. de Pauw and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. Eur. Maricult. Soc. Spec. Publ. 7, Bredene, Belgium, pp. 197–210.

Potter, M.A. and Hill, B.J., 1982. Heat mortality in the Sydney rock oyster, *Saccostrea (Crassostrea) commercialis* and the effectiveness of some control methods. Aquaculture, 29: 101–108.

Sokal, R.R. and Rohlf, F.J., 1981. Biometry. Freeman, New York, NY, 859 pp.

Winer, B.J., 1971. Statistical Principles in Experimental Design, 2nd edn. McGraw-Hill Kogakusha Ltd, Tokyo, 907 pp.

Wisely, B., 1983. Hatchery spat production holds promise. Aust. Fish., 42(10): 14–16.

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Summary. Growth and survival of oyster spat were measured at three sites and under various conditions in Port Stephens, NSW. Survival of Sydney rock oyster spat over 12 months was high at three nursery sites (87.9 ± 7.7%). It was significantly higher at Swan Bay than at North Arm Cove and Pindimar. The average weight gain (g/spat) was higher at North Arm Cove than at Swan Bay which was a much better site for growth than Pindimar. Biomass gain (2.6 ± 0.5 kg/m^2) was significantly lower at Pindimar than at other sites (5.8-6.0 kg/m^2). The best three-month periods for spat growth at North Arm Cove and Swan Bay were August-October and February-April while the poorest period was May-July. Both these sites showed considerable potential as nursery sites.

Enhancement of growth rate of spat was investigated during cooler months using heated effluent from the Vales Point Power Station, Lake Macquarie, NSW. Spat were grown for 18 weeks in sectionalised trays and/or in forced-flow upwellers at the inlet and outlet (effluent pond) of the power station and at a control site (Swan Bay). The largest biomass gain was obtained in upwellers at the inlet site (4.0 ± 0.3 kg/1000 spat stocked) while spat in upwellers or trays at the outlet (effluent pond) lost 0.03-0.1 kg/1000 spat. Water temperatures at the inlet and outlet sites were, on the average, 3.6 and 8.2°C higher, respectively, than at Swan Bay. The inlet channel was a promising site for nursery culture during cooler months.

INTRODUCTION

One of Australia's most valuable aquaculture industries is based on the Sydney rock oyster, *Saccostrea commercialis* (Holliday *et al.*, 1988; Nell *et al.*, 1990). Conventional intertidal methods of growing this oyster involve catching spat in summer on crates of tarred hardwood sticks (Malcolm, 1987) which are deployed for six months on more oceanic leases, separating the crates into single layers of sticks and transporting them to estuarine leases where they are on-grown to market size in three to four years (Korringa, 1976; Malcolm, 1987; Maguire *et al.*, 1988). Oysters still below market size when removed from sticks are placed in trays and on-grown to market size. The nursery phase in this traditional system begins at settlement and usually lasts twelve months when oysters remain within the crates of sticks protected from predation by fish. After the initial phase on catching leases, the crates are moved to special nursery (depot) leases in the upper reaches of estuaries. Single seed culture, an alternative approach to farming this species, is now being used by many farmers in New South Wales. Unattached spat from hatcheries or natural spatfall, are grown in trays or other enclosed units (Holliday *et al.*, 1988). The nursery phase in single seed culture usually requires different production units and handling methods to those used for the grow-out phase (Claus, 1981). Compared with oysters produced using traditional methods, single seed oysters are less likely to grow together and hence mortalities and labour costs associated with separating oysters ('culling') are greatly reduced (Holliday *et al.*, 1988).

Initial attempts by NSW farmers to use single seed spat resulted in high mortality rates. Investigations revealed that inappropriate nursery systems were used and site characteristics might also have caused problems (Holliday, 1985a). Nursery or grow-out sites can vary greatly in their suitability due to a variety of reasons including current velocity, wave action, natural food levels, water temperature and salinity (Wilson, 1987; Brown and Hartwick, 1988). In the majority of estuaries in New South Wales, spat catching leases are vacant for about six months of the year after the caught sticks have been moved to depot leases upstream. These vacant leases may be good nursery areas for the culture of single Sydney rock oysters.

Another option to enhance the culture of juvenile oysters is through the use of thermal effluent (Jones, 1976; Margraf, 1977; Malouf, 1981). Aquarium studies indicate that, in the presence of excess food, Sydney rock oyster spat grow best at high water temperatures (30°C; Nell and Livanos, 1988).

This study assesses the differences among sites in Port Stephens and determines the suitability of thermal effluent for nursery culture of single seed Sydney rock oysters. This is part of a larger study which included the determination of optimum stocking densities for spat of different sizes (Holliday *et al.*, 1991).

MATERIALS AND METHODS

Experiment 1—Evaluation of nursery sites in Port Stephens

Three sectionalised trays (Figure 1) were positioned at the intertidal rack height (Malcolm, 1987) at each of four sites selected from the major farming areas

Figure 1. Sectionalised trays secured with wire on an intertidal, commercial oyster lease in Swan Bay, Port Stephens, NSW.

in Port Stephens. Swan Bay, North Arm Cove and Soldiers Point are located in the inner port and Pindimar (a major spat collection area) is in the outer port (Figure 2). This experiment was carried out from August 1985 to August 1986. The site at Soldiers Point was abandoned during this period as the trays broke up due to excessive wave action.

Sydney rock oyster larvae were settled on scallop shell chips in the hatchery at the Research Station, Salamander Bay and the spat were held in forced-flow upwellers (Holliday, 1985b) before the experiment. Sectionalised nursery trays (1.94 x 0.94 m) constructed of tarred 50 x 20 mm hardwood were divided into six parallel sections (0.25 m^2; Figure 3) to minimise oyster damage by wave action and to maintain a more even surface coverage of spat. Both upper and lower tray surfaces were covered with a PVC mesh (3 mm) to eliminate the loss of spat by wave action and predation by fish. The trays were stocked with approximately 300 spat/tray section (1200 spat/m^2), estimated on a weight basis for spat with an initial weight of 4.0 ± 0.1 g ($\bar{x}$ ± SD; n = 5 for samples of 300 spat). At three-monthly intervals, the average spat weight was determined by weighing 100 spat from each section of the tray. After six months, the amount of spat in each section was reduced by half on a weight basis to prevent overcrowding. Overall mortality was estimated by dividing the total weight of spat harvested from a tray by the average final spat weight. Corrections were made for the reduction in density. Growth coefficient values (G_{90}) were calculated to allow for

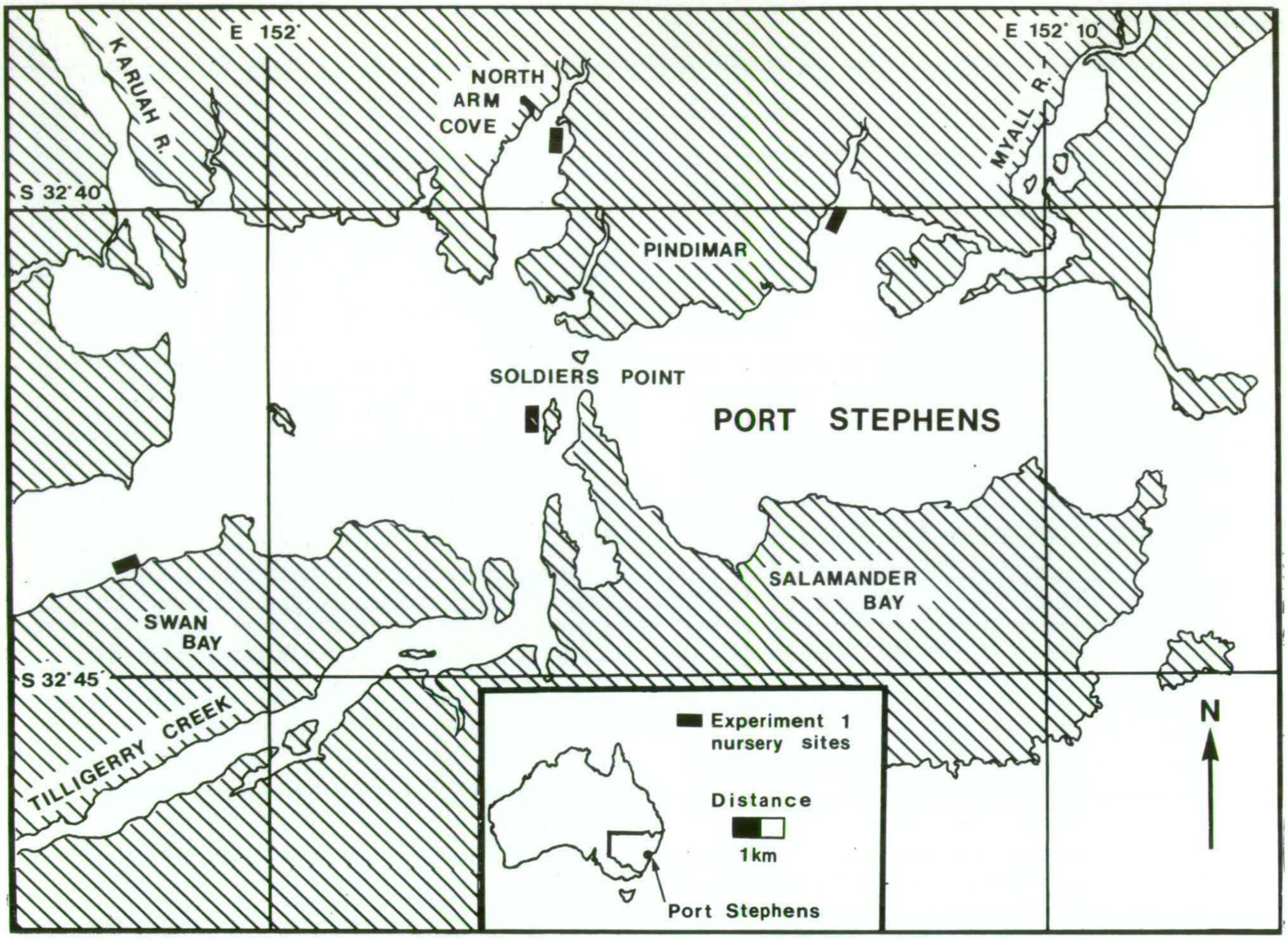

Figure 2. Location of nursery sites in Port Stephens, NSW, for Experiment 1.

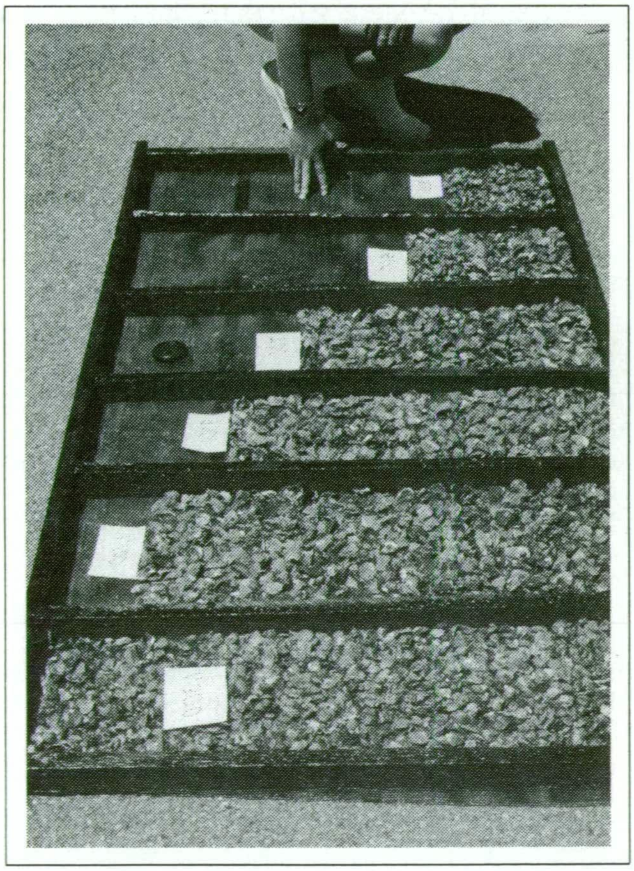

Figure 3. Sectionalised oyster tray stocked with Sydney rock oyster spat at a range of densities for a complementary study (Holliday *et al.*, 1991)

differences in sampling periods and initial spat weights (Spencer and Gough, 1978) as shown below:

$$G_{90} = \frac{90}{\text{Duration (days)}} \times \ln \frac{\text{Final weight (g /spat)}}{\text{Initial weight (g /spat)}}$$

Temperature and salinity readings were taken monthly from the three sites at a depth of 1 m, during M.L.W. (mean low water), using a Yeo-Kal temperature/salinity conductivity meter (Yeo-Kal Electronics, Brookvale, NSW 2100).

Experiment 2—Nursery culture using thermal effluent

This experiment was established at three sites: the Swan Bay lease used in Experiment 1, the inlet and outlet (primary effluent pond) channels of Vales Point Power Station. Vales Point is at Lake Macquarie, NSW (Figure 4), about 100 km south of Port Stephens. Upwellers were used at the inlet and outlet sites at the power station while sectionalised trays were used at the outlet site and on the intertidal lease in Swan Bay. As water level at the outlet site was constant, the trays at this site had to be subtidal. Upwellers could not be installed on the lease at Swan Bay because there was no electricity to operate the pump. It was also not feasible to install trays in or adjacent to the inlet channel at the power station because of the water depth and strong current. The experiment was conducted from April to September 1986 (18 weeks).

Four forced-flow upweller units (constructed from PVC pipe, 1 m x 250 mm diameter; Figure 5), were positioned vertically at the inlet channel and the

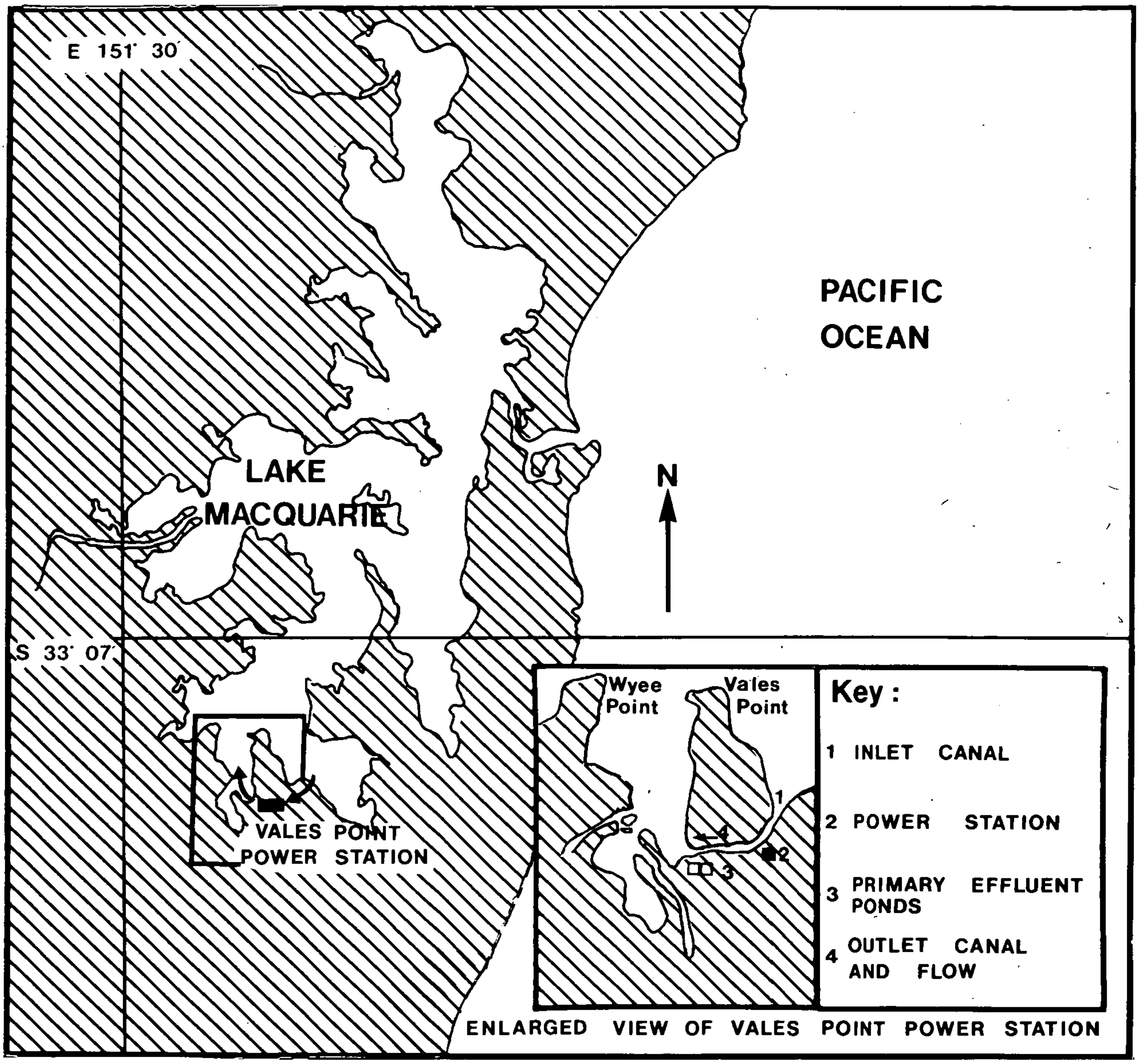

Figure 4. Location of Vales Point Power Station, Lake Macquarie, NSW (33° 05' S, 151° 48' E), for Experiment 2.

primary effluent pond. Water was pumped from the effluent pond rather than the outlet channel because turbulence in the channel produces gas bubbles which may have deleterious effects on oysters (Malouf *et al.*, 1972). Surface water from the outlet channel is diverted into the primary effluent pond. The upweller units were stocked with 1000 spat/unit. Each week, the units were cleaned and the flow rate of seawater through each unit adjusted to 32 L/min. Four groups of three sections within sectionalised trays were stocked with 400 spat/section (1600 spat/m^2). The sectionalised trays were positioned subtidally on a fixed timber frame at a depth of 0.5 m in the primary effluent pond and intertidally at Swan Bay. All dead oysters in the upwellers and trays were counted to estimate survival rates and weight gain values were based on initial and final samples of 100-400 spat/replicate. The average initial weight of the spat was 1.63 ± 0.13g ($\bar{x}$ ± SD; n = 16 groups of spat).

Weekly temperature and salinity data were obtained at Swan Bay from data recorded from readings made at a commercial oyster purification plant adjacent to the nursery lease, using a thermometer and hydrometer. Weekly readings at the inlet and outlet sites at the power station were obtained using the method for Experiment 1.

Statistical analyses

Homogeneity of variance was confirmed using Cochran's test (Winer, 1971) and for Experiment 1, growth and survival data were analysed using ANOVA and mean values were compared using the 'least-significant differences' technique (Sokal and Rohlf, 1981). For Experiment 2, 't-tests' (Winer, 1971) were used to compare oyster survival, average spat weight gain and biomass gain values for sites where similar nursery systems were used. Survival data were transformed (arcsine $x^{0.5}$) before ANOVA. Throughout this paper, data are presented as mean ± standard deviation ($\bar{x}$ ± SD).

RESULTS

Experiment 1

Survival of spat over 12 months was high at each site (87.9 ± 7.7%, n = 3 sites) but was significantly higher ($P < 0.01$) at Swan Bay than at North Arm Cove and Pindimar (Table 1). The average weight gain was

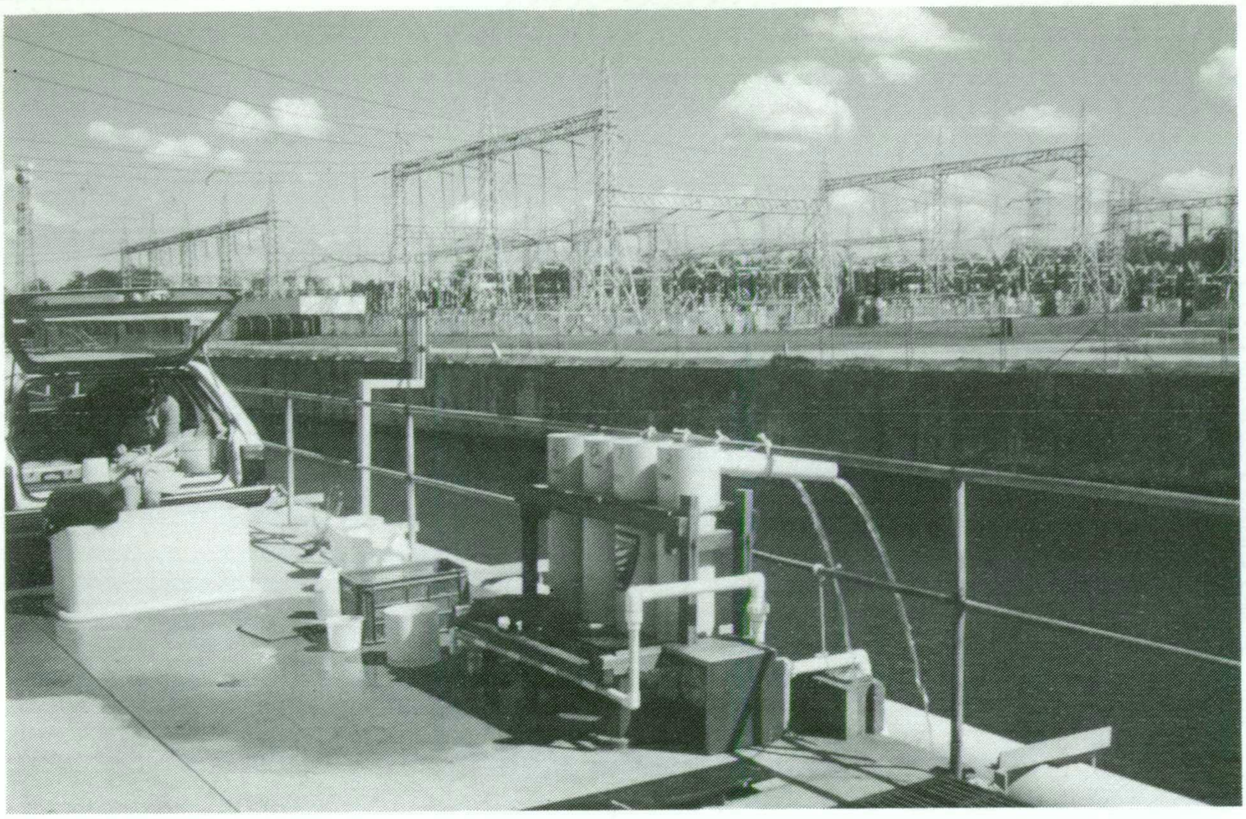

Figure 5. Forced-flow upwellers at the inlet channel for Vales Point Power Station, Lake Macquarie, NSW.

significantly higher at North Arm Cove than at Swan Bay which was a significantly better site for growth than Pindimar ($P < 0.05$; Table 1). At North Arm Cove, spat grew from 4.0 to 16.3 g (Figure 6). The overall biomass gain was similar at Swan Bay and North Arm Cove (5.8-6.0 kg/m^2) but was significantly lower ($P < 0.01$) at Pindimar (2.6 kg/m^2; Table 1).

Spat grew at different rates (weight gain per unit time) at different times of the year and there were similarities in the growth rate patterns of spat for North Arm Cove and Swan Bay (Figure 6). Growth coefficient values (Table 2) indicated that spat grew best during August-October and February-April at Swan Bay (0.39 ± 0.03; 0.46 ± 0.08 respectively) and North Arm Cove (0.55 ± 0.07; 0.39 ± 0.03 respectively), while May-July was the poorest period for growth at these two sites (0.11 ± 0.05 and 0.15 ± 0.03 respectively). Growth rates were more uniform throughout the study at Pindimar (range 0.15-0.35) although August-October (0.35 ± 0.05) was also the best period for growth (Table 2).

There was little variation in temperature (Figure 7) and salinity (Figure 8) among sites although there was considerable seasonal variation.

Experiment 2

The best growth (4.1 ± 0.4 g/spat), survival (99.1 ± 0.6%) and biomass gain (4.0 ± 0.3 kg/1000 spat stocked) results were obtained in the upwellers at the site of the inlet channel (Table 3). The poorest results for growth, survival and biomass gain were recorded in upwellers (0.3 ± 0.2 g/spat, 84.6 ± 1.4% and -0.1 ± 0.8 kg/1000 spat stocked, respectively) and trays (1.7 ± 0.3 g, 30.8 ± 0.2% and -0.03 ± 0.3 kg/1000 spat stocked, respectively) at the site of the primary effluent pond. The intertidal sectionalised trays in

Table 1. Performance of Sydney rock oyster (*Saccostrea commercialis*) spat at three nursery sites in Port Stephens, NSW over 12 months ($\bar{x}$ ± SD, n = 3; Experiment 1).

Site	Average weight[a,b] gain (g/spat)	Survival[a,c] (%)	Biomass[a,d] gain (kg/m^2)
Swan Bay	10.4±1.1[A]	96.7±3.1[A]	6.0±0.9[A]
North Arm Cove	12.3±0.5[B]	83.9±1.6[B]	5.8±0.2[A]
Pindimar	6.0±0.5[C]	83.0±4.7[B]	2.6±0.5[B]

[a] Within each column, means with different superscripts are significantly different ($P < 0.05$).

[b] Average initial weight of spat was 4.0 ± 0.1g.

[c] Data was transformed (arcsine $x^{0.5}$) before analysis.

[d] Sectionalised trays were stocked at 1200 spat/m^2 but midway through the 12-month study, spat densities were reduced by half to prevent overcrowding. Biomass gain values are based on an initial density of 600 spat/m^2.

Table 2. Growth coefficient values for Sydney rock oyster (*Saccostrea commercialis*) spat grown at three sites in Port Stephens, NSW for 12 months ($\bar{x} \pm$ SD, n = 3; Experiment 1)[a].

Site	Growth coefficient (G_{90})[b]			
	Aug-Oct	Nov-Jan	Feb-April	May-July
Swan Bay	0.39±0.03	0.27±0.02	0.46±0.08	0.11±0.05
North Arm Cove	0.55±0.07	0.24±0.10	0.39±0.03	0.15±0.03
Pindimar	0.35±0.05	0.19±0.03	0.15±0.03	0.20±0.02

[a] The experiment was carried out from 29.7.85 to 5.8.86 and the average initial weight of the spat was 4.0 ± 0.1g. The initial weight for the period between sampling dates was the same as the final weight for the preceding period.

[b] $$G_{90} = \frac{90}{\text{Duration (days)}} \times \ln \frac{(W_t)}{(W_o)}$$

W_o and W_t are the average initial and final weights of spat (g/spat) for a period respectively.

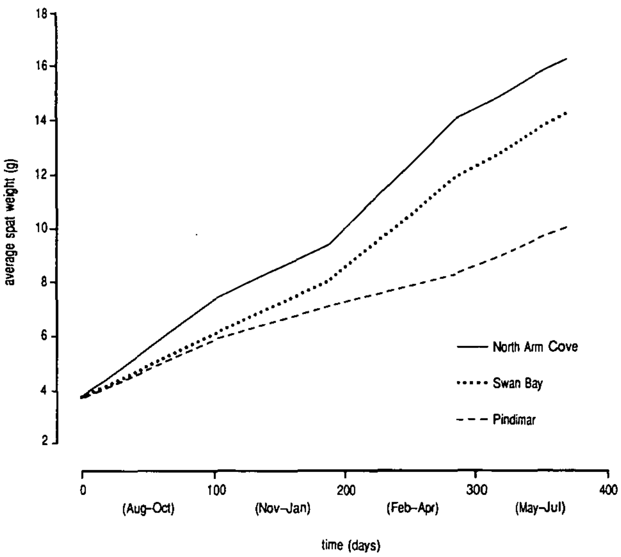

Figure 6. Growth of Sydney rock oyster (*Saccostrea commercialis*) spat in sectionalised trays over 12 months at nursery sites in Port Stephens, NSW (Experiment 1).

Swan Bay produced good growth (2.6 ± 0.3 g), survival (85.0 ± 5.6%) and biomass gain (1.9 ± 0.4 kg/1000 spat stocked) results (Table 3).

There was little difference in salinity among the three sites. Average values [$\bar{x} \pm$ SD, n = 24 (range)] were as follows: 33.6 ± 1.4‰ (31-36‰) at the inlet, 33.5 ± 1.5‰ (31-36‰) in the primary effluent pond and 31.6 ± 3.0‰ (26-36‰) at the intertidal site in Swan Bay. There was considerable variation in average water temperature. Average values [$\bar{x} \pm$ SD, n = 24 (range)] were: 18.5 ± 3.4°C (14 - 28°C) at the inlet, 23.1 ± 4.1°C (19-35°C) in the primary effluent pond, and 14.9 ± 3.4°C (11-21°C) for the Swan Bay site. Thus, water temperatures at the inlet and outlet sites were, on the average, 3.6 and 8.2°C higher than in Port Stephens, respectively (Figure 9).

DISCUSSION

North Arm Cove and Swan Bay proved to be the most suitable nursery sites for the culture of single Sydney rock oysters in Experiment 1 (Table 1). Although there was little difference in the average

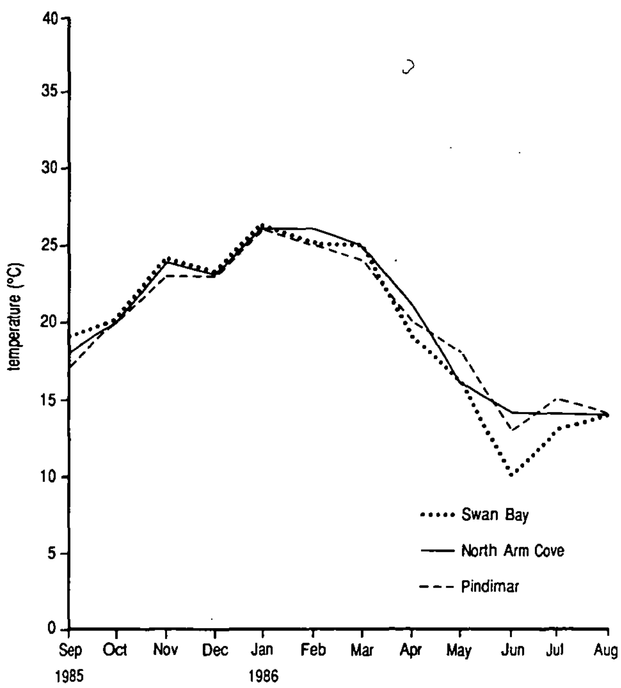

Figure 7. Temperature data for the three nursery sites in Port Stephens, NSW, from September 1985 to August 1986 (Experiment 1).

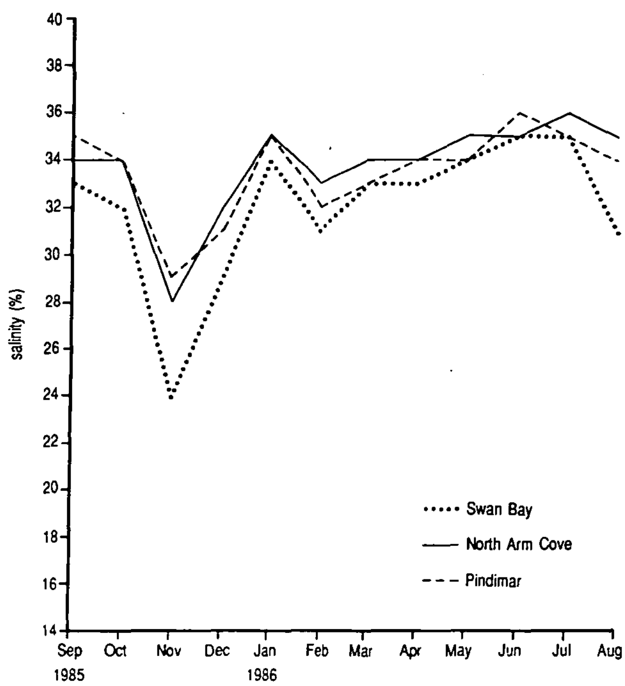

Figure 8. Salinity data for three nursery sites in Port Stephens, NSW, from September 1985 to August 1986 (Experiment 1).

Table 3. Growth and survival data of Sydney rock oyster (*Saccostrea commercialis*) spat grown at the inlet and outlet to Vales Point Power Station and on an intertidal lease in Swan Bay, Port Stephens, NSW ($\bar{x}$ ± SD; n = 4, Experiment 2)[a].

Site	Average weight[b] gain (g/ spat)		Survival (%)		Biomass gain (kg/1000 spat stocked)	
	Upweller	Tray[c]	Upweller	Tray	Upweller	Tray
Power Station inlet channel	4.1 ± 0.4^{A}	-	99.1 ± 0.6^{A}	-	4.0 ± 0.3^{A}	-
Power Station effluent pond	0.3 ± 0.2^{B}	1.7 ± 0.3^{A}	84.6 ± 1.4^{B}	30.8 ± 0.2^{A}	-0.1 ± 0.8^{B}	-0.03 ± 0.3^{A}
Swan Bay	-	2.6 ± 0.3^{B}	-	85.0 ± 5.6^{B}	-	1.9 ± 0.4^{B}

[a] Within each column, means with different superscripts are significantly different (P < 0.05).
[b] Average initial weight of the spat was 1.63g. Spat were stocked in trays at 1200/m^2 and 1000 spat/upweller.
[c] Trays were subtidal at the effluent pond and intertidal at Swan Bay.

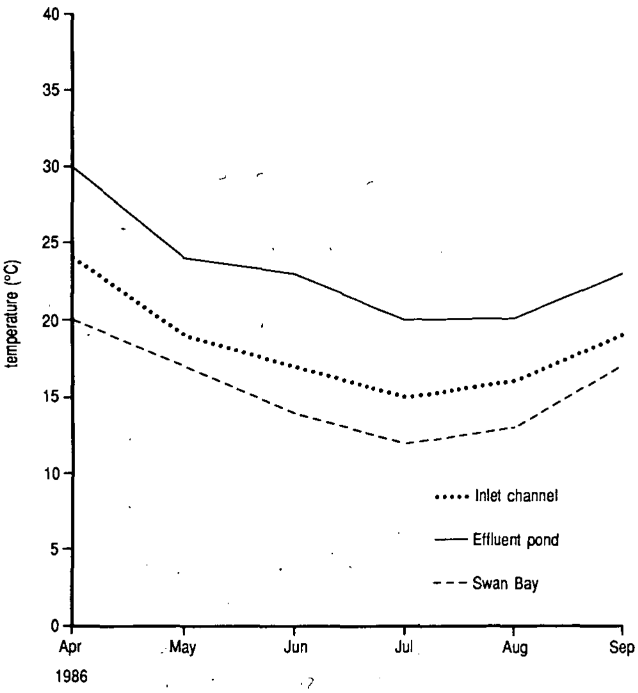

Figure 9. Temperature data for the inlet channel and outlet (effluent pond) at Vales Point Power Station and the intertidal site at Swan Bay, Port Stephens, NSW, 1986 (Experiment 2).

salinity level among the three sites, North Arm Cove and Swan Bay, located in the inner port, are considered to be more estuarine as they are influenced by the Karuah River (Figure 2). However, more intensive monitoring of abiotic and biotic variables, for example potential food supply, than was undertaken in this study would be needed to explain differences in growth results among the three sites (Brown and Hartwick, 1988).

Data on seasonal variation in spat growth rates using growth coefficient (G_{90}) values (Table 2), indicate that August-October and February-April were the better periods for growth at Swan Bay and North Arm Cove. At these two sites, the temperature data, although based on monthly readings, indicate that the poorest growth occurred during the coolest period (May-July). Similarly, growth coefficient values calculated from growth data presented by Holliday *et al.* (1991) indicate that, at equivalent initial biomass levels, the slowest growth rates in that 12-month study occurred during the coolest months. While the use of growth coefficient values largely overcomes the problem of differences in initial weights, it should be noted that these values tend to decrease as spat weight increases (Spencer and Gough, 1978).

The observation that growth rates of spat were depressed during cooler months was consistent with the findings of Nell and Livanos (1988) who showed that in the range 12-30°C, growth rates of Sydney rock oyster spat, fed to excess, increased as temperature increased. Experiment 2 was conducted to see if growth rates of juvenile spat could be enhanced during cooler months by using thermal effluent from a power station. Previous studies in Lake Macquarie (Anon, 1983) showed that water at the inlet to the Vales Point Power Station had consistently higher minimum winter and maximum summer water temperatures than other areas in Lake Macquarie distant from the power station. In this study, the inlet site was on the average 4.6°C colder than the primary effluent pond although it was 3.6°C warmer (from mixing with the heated outlet water) than the control site in Swan Bay, Port Stephens.

As it was not possible to install both trays and upwellers at all three sites in Experiment 2, direct comparisons among sites must be interpreted with caution. However, by far the best growth, survival and biomass gain results were recorded from upwellers at the inlet site. Spat in trays at Port Stephens also grew well with a high survival rate (Table 3). Spat in upwellers and trays at the outlet site either grew poorly or suffered higher mortality than those in upwellers at the inlet channel. In contrast, Margraf (1977) obtained faster growth of the American oyster (*Crassostrea virginica*) in the outlet channel of a power station than in the inlet channel or at an estuarine control site. The difference between spat growth in trays at the outlet site and Port Stephens was even more notable as trays were subtidal at the outlet site and intertidal in Port Stephens. Previous studies on leases showed that subtidally grown Sydney rock oysters (30-39g) had a growth rate twice that of intertidally grown oysters (Wisely *et al.*, 1979; Nell, 1989).

Malouf (1981) concluded that there are many factors which can adversely affect bivalves grown in thermal effluent, including temperature fluctuations, contamination of effluent with chlorine, increased disease risks and inadequate food levels to sustain the metabolic requirements of poikilothermic animals at elevated temperatures. Hodgson (1979) suggested that thermal effluent from Vales Point Power Station may have a growth limiting effect on entrained phytoplankton, perhaps due to mechanical damage, chlorination and turbidity in the thermal plume. However, he found no significant difference in chlorophyll-a levels between the inlet and outlet sites. In addition, the primary effluent pond was designed to receive floating hydrocarbon contaminants that were skimmed off from the outlet channel, although in this study there was no evidence of hydrocarbon contamination. It is not clear which, if any, of these factors actually depressed growth and survival rates in the primary effluent pond.

The results for the inlet channel were very encouraging and, following the completion of this study, a commercial nursery facility for Sydney rock oysters was established at this site. The study has also shown that the spat catching leases at Pindimar, which are vacant for six months of the year, could be used for the nursery culture of Sydney rock oysters, even though spat growth was better at the more estuarine leases in Swan Bay and North Arm Cove.

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REFERENCES

Anonymous (1983) *Environmental audit of Lake Macquarie*, State Pollution Control Commission, Sydney, NSW.

Brown, J.R. and Hartwick, E.B. (1988) 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.

Claus, C. (1981) Trends in nursery rearing of bivalve molluscs, *Nursery culturing of bivalve molluscs (Claus, C., de Pauw, N. and Jaspers, E. ed.)*, pp. 1-33. European Mariculture Society Special Publication 7, Bredene, Belgium.

Hodgson, B.R. (1979) The hydrology and zooplankton ecology of Lake Macquarie and the recreational and commercial fishery in the Tuggerah Lakes, NSW. Unpublished Ph.D. thesis, University of NSW, Kensington, Sydney.

Holliday, J.E. (1985a) Current oyster spat research in N.S.W. *Aust. Fish.*, **44(3)**, 24-26.

Holliday, J.E. (1985b) International developments in oyster hatchery technology. *Fish. Div. Misc. Bull. No 1.*, Dept. of Agriculture, NSW, Sydney.

Holliday, J.E., Maguire, G.B. and Nell, J.A. (1988) Alternative cultivation methods for the Sydney rock oyster (*Saccostrea commercialis*), *Proceedings First Australian Shellfish Aquaculture Conference, Perth, October 1988, Curtin University of Technology, Perth, WA (Evans, L. H. and O'Sullivan, D. ed.)*, pp. 234-265.

Holliday, J.E., Maguire, G.B. and Nell, J.A. (1991) Optimum stocking density for nursery culture of Sydney rock oysters (*Saccostrea commercialis*). *Aquaculture*, **96**, 7/16.

Jones, G. (1976) Cooling water farm set to go commercial. *Fish Farming Int.*, **3(4)**, 14-15.

Korringa, P. (1976) *Farming the cupped oysters of the genus Crassostrea*. Elsevier, Amsterdam.

Maguire, G.B., Nell, J.A. and Allan, G.L. (1988) Production trends in oyster farming and other mariculture industries in New South Wales. *Proceedings of the Australian Mariculture Association Third Annual Conference, Lismore, NSW, June 1988 (Paynter, J. and Preston, N. ed.)*, pp. 28-35.

Malcolm, W.B. (1987) *The Sydney rock oyster*. Agfact F 3.1.1, Department of Agriculture, NSW.

Malouf, R.E. (1981) Use of heated effluents for the nursery culture of bivalve molluscs: its problems and potential, *Nursery culturing of bivalve molluscs (Claus, C., de Pauw, N. and Jaspers, E. ed.)*, pp. 171-188. European Mariculture Society Special Publication 7, Bredene, Belgium.

Malouf, R.E., Keck, R., Maurer, D. and Epifanio, C. (1972) Occurrence of gas-bubble disease in three species of bivalve molluscs. *J. Fish. Res. Board. Can.*, **29**, 588-589.

Margraf, F.J. (1977) The growth rate of oysters held in the intake and discharge canals of an electric generating station and in natural waters. *Proc. World Maricul. Soc.*, **8**, 915-926.

Nell, J.A. (1989) *The 1987 update on Pacific oyster research*. Collected Open Day booklets, pp. 456-465, Brackish Water Fish Culture Research Station 1973-1988, NSW Agriculture & Fisheries, Salamander Bay.

Nell, J.A. and Livanos, G. (1988) Effects of fluoride concentration in seawater on growth and fluoride accumulation by Sydney rock oyster (*Saccostrea commercialis*) and flat oyster (*Ostrea angasi*) spat. *Wat. Res.*, **22**, 749-753.

Nell, J.A., Smith, I.R. and Holliday, J.E. (1990) An overview of the Sydney rock oyster (*Saccostrea commercialis*) industry in New South Wales. *Agric. Sci.*, **3(2)**, 29-30.

Sokal, R. R. and Rohlf, F.J. (1981) *Biometry*. Freeman, New York, NY.

Spencer, B.E. and Gough, C.J. (1978) The growth and survival of experimental batches of hatchery-reared spat of *Ostrea edulis* L. and *Crassostrea gigas* Thunberg, using different methods of tray cultivation. *Aquaculture*, **13**, 293-312.

Wilson, J.H. (1987) Environmental parameters controlling growth of *Ostrea edulis* L. and *Pecten maximus* L. in suspended culture. *Aquaculture*, **64**, 119-131.

Winer, B.J. (1971) *Statistical principles in experimental design*. 2nd ed. McGraw-Hill Kogakusha Ltd, Tokyo.

Wisely, H.B., Holliday, J.E. and Reid, B.L. (1979) Experimental deepwater culture of the Sydney rock oyster (*Crassostrea commercialis* = *Saccostrea cucullata*). 2. Pontoon tray cultivation. *Aquaculture*, **16**, 141-146.

Effects of surface orientation and slurry-coating on settlement of Sydney rock oysters, *Saccostrea commercialis*, on PVC slats in a hatchery

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ABSTRACT

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Settlement of hatchery reared Sydney rock (Saccostrea commercialis) oysters on PVC slats positioned horizontally and vertically, and from similar slats coated with a lime and cement slurry, was compared. Settlement on the horizontally positioned PVC slats (76.6% of larvae stocked settled; 23.8 spat/cm^2), was significantly ($P<0.05$) higher than on vertically positioned PVC slats (only 0.71% of larvae stocked settled; 0.2 spat/cm^2). Settlement of larvae was significantly higher ($P<0.05$) on the PVC slats than on similar slats coated with a cement slurry (60.2% of larvae stocked settled; 18.7 spat/cm^2).

Significantly ($P<0.05$) higher settlements were recorded from the under surfaces of horizontally positioned slats and slurry-coated slats (6924±238 and 5235±292 spat/slat respectively) than from their upper surfaces (174±36 and 365±35 spat/slat respectively). However for vertically positioned slats, settlement was similar ($P>0.05$) for the convex and concave surfaces (43±17 and 24±9 spat/slat respectively). These results indicate that PVC slats and slurry-coated PVC slats positioned horizontally, are suitable for settlement of Sydney rock oyster larvae in a hatchery.

INTRODUCTION

World production of oysters is dependent on reliable techniques for the collection of spat. The development of hatchery techniques has revived or help establish oyster industries in the UK (Spencer, 1990; Utting & Spencer, 1992), USA (Chew, 1990) and Australia (Holliday *et al.*, 1988). Delayed or "remote" setting pediveliger larvae on collectors at sites remote from hatcheries (Chew *et al.*, 1986; Jones & Jones 1988; Roland *et al.*, 1988) is also widely used in North America (Chew, 1990). The Australian oyster industry obtains its seed from both hatcheries and natural spatfall (Holliday *et al.*, 1988; Nell, 1993).

Many hatcheries settle oyster larvae on chips of scallop shell, using downweller systems (O'Sullivan & Wilson, 1976; Holliday 1992) and transferred them to upwellers, in on-shore nurseries (Bayes, 1981; Jones & Jones, 1988). High spat mortalities have been recorded in these on-shore nurseries (Dungan & Elston, 1988; Dungan *et al.*, 1989), that can experience variable operating costs and a low margins of profit (Claus, 1981).

Various materials have been examined to find suitable substrates for both hatchery and natural settlement of oysters (Dupuy & Rivkin, 1972; Hidu *et al.*, 1975; Kong & Luh, 1976; O'Sullivan & Wilson, 1976; Curtin, 1985). In Europe and North America there has been a trend towards the commercial use of PVC and other synthetic collectors (Jones & Jones, 1988; Roland *et al.*, 1988) to increase settlement and retention and reduce operating costs (His, 1978; Gunn, 1984). Unlike scallop shell chips, collectors can be deployed from settlement tanks, directly to estuarine leases, thereby avoiding the often high capital and labour costs associated with on-shore nurseries. Holliday *et al.* (1993) systematically evaluated a number of commercially available collectors for natural settlement, growth, survival and retention of Sydney rock and Pacific oysters and found that the density of spat was higher on plastic collector types including slats, than on traditionally used tarred hardwood sticks.

Many biological and environmental factors affect settlement of bivalves including swimming position of the larvae, gregariousness and competition among larvae or other organisms, siltation, light, turbidity, conditioning of collectors and colour and texture, spacing and orientation of collectors (Galtsoff, 1964; Shaw, 1967).

The objectives of this study were to evaluate PVC slats for use as collectors for hatchery reared larvae and to compare settlement on horizontal and vertical surfaces and on horizontal surfaces of slats coated with a lime/cement slurry.

METHODS

Sydney rock oyster were reared to pediveliger stage using established hatchery techniques (Walne, 1974; Holliday, 1992). The number of pediveliger larvae was estimated by subsample (n=4) and counted using a Sedgwick rafter. The three treatments were: 1) horizontally positioned PVC slats, 2) PVC slats positioned vertically at a 90° angle and separated with a thin strip of PVC cable (4 mm) and 3) horizontally positioned PVC slats coated with a lime/cement slurry (slurry-coated PVC slats). The slurry for Treatment 3, consisted of 0.1 part cement, 0.1 part fireclay, 0.5 part lime, 0.18 part PVC bonder and fresh water, added and mixed to a smooth paste.

To ensure that leaching of potentially toxic materials from new PVC collectors did not affect results, all slats (cut from 90 mm diameter commercial stormwater grade PVC pipe) were 'aged' by securing them on an intertidal lease in Salamander Bay, Port Stephens, NSW, for about two years. This aging process to allow for leaching of any toxic substances from slats has been found to enhanced settlement (Gunn, 1984; Roland & Broadley, 1990). Slats were then lightly scrubbed and conditioned by soaking them in sea water for 48 hours before the experiment, to allow a primary fouling community (mainly bacteria) to develop (Morse, 1985; Roland & Broadley, 1990); some biofilms of marine bacterium have been found to synthesise chemical cues for oyster settlement (Shpigel *et al.*, 1989; Weiner *et al.*, 1989; Coon *et al.*, 1990; Fitt *et al.*, 1990).

A single layer of three slats (dimension of each slat was 250 x 60 mm and total surface area 300 cm^2) was deployed on the base of four, 10 l perspex aquaria for each treatment. Each aquarium was randomly allocated a position in a temperature control bath, covered with black plastic sheeting and positioned in a darkened room. Sea water (34.0 g/l) in the aquaria was maintained at 25.6 ± 0.3°C. Water was not aerated, but exchanged every 24 h. Aquaria were stocked with pediveliger larvae at $27.9\pm1.0 \times 10^3$ (2.8 larvae/ml) and fed an equal mix of Tahitian *Isochrysis* aff. *galbana* and *Pavlova lutheri* at $25.0\pm2.0 \times 10^3$ cells/ml/day.

All spat which settled on slats were counted, with the exception of spat on the under surfaces of horizontally positioned slats. Here, spat were very densely settled and numbers were estimated by counting spat which occurred in a randomly placed, rectangular shaped grid (10 cm^2). The experiment ran for six days.

Statistical analysis

Differences between treatments were assessed using one-way ANOVA, homogeneity of variance evaluated using Cochran's Test (Winer, 1971) and means compared using Students Newman-Keuls (Winer, 1971). T-test (Winer, 1971) were used to compare settlement between upper and under surfaces of slats.

RESULTS AND DISCUSSION

Surface orientation of collectors affected settlement of Sydney rock oysters. Settlement was significantly higher on horizontally deployed PVC and slurry-coated PVC slats, where 76.6% (7130±281 spat/slat; 23.8 spat/cm^2) and 60.2% (5601±326 spat/slat; 18.7 spat/cm^2) respectively of larvae stocked settled, than on vertically deployed slats, where only 0.71% of larvae stocked settled (67±25 spat/slat and 0.2 spat/cm^2) (Table 1). For horizontally positioned slats, larval settlement was first observed at day two and day four (on non-coated and slurry-coated slats respectively) and was completed by day six. Conversely, the majority of larvae were still swimming in aquaria containing the vertically deployed slats on day six, and few larvae settled despite low larval mortality.

Settlement was significantly higher ($P<0.05$) on the under surfaces of the horizontally deployed slats (6924±238 spat/slat; 46.2 spat/cm^2) and slurry-coated slats (5235±292 spat/slat; 35.0 spat/cm^2) than on the upper surfaces (174±36 spat/slat; 1.2 spat/cm^2 and 365±35 spat/slat; 2.4 spat/cm^2 respectively). Settlement was similar ($P>0.05$) for convex and concave surfaces of vertically deployed slats (43±17 spat/slat; 0.3 spat/cm^2 and 24±9 spat/slat; 0.2 spat/cm^2 respectively).

An even distribution of spat on all collector surfaces is important to optimise collectors (Holliday *et al.*, 1993). For PVC and slurry-coated PVC collectors, the majority of larvae settled on the under surfaces of collectors. Hopkins (1935), Schaefer (1937) and Cole & Knight-Jones (1949) concluded that higher settlements of bivalves on the under surfaces of collectors resulted from the swimming action of pediveliger larvae, as they often swim with their foot extended while searching for a suitable substrata on which to attach. Butler

(1955), concluded that *C. virginica* probably settled on the upper surfaces of collectors in a stack, after having swam into and deflected off the collector above. However in the present study, collectors were in a single layer and not stacked. Regardless, once oysters had started settling, gregarious behaviour of larvae (Hidu & Haskin, 1971; Keck *et al.*, 1971; Kenny *et al.*, 1990) may have increased the difference in numbers which settled on upper and under surfaces.

Growth, survival and retention of spat in the nursery phase is affected by spat density on collectors (Holliday *et al.*, 1993). Although excellent settlement was recorded in the present study, density on the under surfaces of slats and slurry-coated slats was probably far too high to be viable. Holliday *et al.*, 1993 recorded high losses (52.9% and 42.5% for slats and slurry-coated slats respectively) in five months of natural Sydney rock oyster spat from larger slats, that had much lower densities (average settlement 4.7 and 6.3 spat/cm^2 on under surfaces of slats and slurry-coated slats respectively) than in the present study. Settlement on the upper surfaces of slats and slurry-coated slats, although lower than that recorded by Holliday *et al.* (1993; 3.4 and 4.0 spat/cm^2 for slats and slurry-coated slats respectively), may have been more commercially viable than for the under surfaces. For remote settlement of Pacific oysters, commercial operators in British Columbia obtain between 0.3 and 0.4 spat/cm^2 on round grooved PVC sticks (Jones & Jones, 1988; Roland & Broadley, 1990).

Commercial operators in British Columbia manage spat settlement on collectors by altering larval stocking densities, determine by using settlement and post-set survival rates (Jones & Jones, 1988; Roland & Broadley, 1990). Average settlement of Pacific oysters obtained on PVC tubes is about 20% of larvae stocked; at four months post-set survival of 14% and about 2.5% of larvae stocked are eventually harvested as spat (Roland & Broadley, 1990). Spat density and distribution on PVC collectors is also be managed by flipping collectors over on day two of settlement and by adding more larvae (Roland & Broadley, 1990).

Substantial settlement of Sydney rock oysters was observed on slats on day 2 and slurry-coated slats on day 4. The delayed settlement on the slurry-coated slats could affect their viability as a commercial collector, as settlement rate of Pacific oysters is used as an indicator of viability of settlement for commercial operations and is usually completed within 48 hours of stocking (Roland & Broadley, 1990).

High post-harvest survival of natural Sydney rock oyster spat, harvested from slats and slurry-coated slats (93.4% and 92.2% respectively), was recorded by Holliday *et al.* (1993), 285 days after the deployment of collectors.

Horizontally positioned, PVC slats and slurry-coated PVC slats were found to be suitable collectors for settlement of hatchery reared Sydney rock oysters. PVC slats could become an alternative substrate to operators who use and other types of PVC collectors. PVC slats, cut from commonly-used storm water pipe, have a number of advantages over other types of PVC collectors (eg. round PVC sticks and PVC discs) as they are readily available at most hardware suppliers and in Australia, are cheaper to purchase. PVC slats (104 x 1495; 3110 cm^2) used commercially by farmers for natural settlement of Sydney rock and Pacific oysters (Holliday *et al.*, 1993) are currently about 25% the cost of the cheapest alternative PVC collector type. PVC collectors can also be deployed from settlement tanks directly to estuarine leases, avoiding the capital and labour costs associated with upwellers and on-shore nurseries.

TABLE 1

Settlement of Sydney rock oysters (*Saccostrea commercialis*) on horizontally and vertically positioned PVC slats in aquaria[1].

Collector Type	Numbers of spat/surface			Settlement[2]	Spat density
	Upper	Under	Combined[3]	(%)	(cm^2)
Horizontal deployment					
PVC slats[4]	174±36	6924±238	7130±281	76.6	23.8±0.9[a]
Slurry-coated PVC slats[4]	365±35	5235±292	5601±326	60.2	18.7±1.1[b]
Vertical deployment					
	Convex	Concave	Combined		
PVC slats	43±17	24±9	67±25	0.7	0.2±0.08[c]

1 Values are means±SE; n=4.
2 Percentage of larvae (stocked into aquaria) which settled on slats. Initial larval stocking density was 2.8/ml.
3 Means with the same superscript did not differ significantly (P>0.05).
4 Values for upper and under surfaces were significantly different (P<0.001).

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REFERENCES

Bayes, J. C. (1981). Forced upwelling nurseries for oysters and clams using impounded water systems. In: C. Claus, N. de Pauw, and E. Jaspers, (Editors), Nursery Culturing of Bivalve Molluscs. *European Mar. Soc.*, Spec. Publ., Bredene, Belgium, **7**: 73-83.

Buroker, N. E., Hersberger, W. K. & Chew, K. K. (1979). Population genetics of family Ostreidae. I. Intraspecific studies of *Crassostrea gigas* and *Saccostrea commercialis*. *Mar. Biol.*, **54**: 157-169.

Butler, P. A. (1955). Selective setting of oyster larvae on artificial cultch. *Proc. Natl. Shellfish Assoc.*, **45**: 95-105.

Chew, K. K., Beattie, J. H. & Donaldson, J. D. (1986). Bivalve molluscs hatchery techniques, maturation and triggering of spawning. In: Aquaculture, Shellfish Culture Development and Management. Proc. Intern. Seminar, La Rochelle, France, IFREMER, pp 229-248.

Chew, K. (1990). Global bivalve shellfish introductions. *World Aquaculture*, **21** (3): 9-22.

Claus, C. (1981). Trends in nursery rearing of bivalve molluscs. In: C. Claus, N. de Pauw and E. Jaspers (Editors), Nursery Culturing of Bivalve Molluscs. *European Mar. Soc. Spec. Publ.*, **7**, Bredene, Belgium, pp. 1-33.

Claus, C., Maeckelberghe, H. & De Pauw, W. (1983). Onshore nursery rearing of bivalve molluscs in Belgium. *Aquacultural Eng.*, **2**: 13-26.

Cole, H. A. & Knight-Jones, E. W. (1949). The setting behaviour of larvae of the European flat oyster *Ostrea edulis* L., and its influence on methods of cultivation and spat collection. *Fish. Invest.* London Series II, **17** (3): 39 p.

Coon, S. L., Fitt, W. K. & Bonar, D. B. (1990). Competence and delay of metamorphosis in the Pacific oyster *Crassostrea gigas*. *Mar. Biol.*, **106**, pp 379-387.

Curtin, L. (1985). Single oysters from natural spatfall. Shellfisheries Newsletter, New Zealand, (**27**): 6.

Dupuy, J. L. & Rivkin, S. (1972). The development of laboratory techniques for the production of cultch-free spat of the oyster, *Crassostrea virginica. Chesapeake Sci.*, **13**: 45-52.

Dungan, C. F. & Elston, R. A. (1988). Histopathological and ultrastructural characteristics of bacterial destruction of the hinge ligaments of cultured juvenile Pacific oysters, *Crassostrea gigas. Aquaculture*, **72** (1-2): 1-14.

Dungan, C. F., Elston, R. A. & Schieve, M. H. (1989). Evidence for colonisation and destruction of hinge ligaments in cultured juvenile Pacific oysters (*Crassostrea gigas*) by cytophaga-like bacteria. *Appl. Environ. Microbiol.*, **55** (5): 1128-1135.

Fitt, W. K., Coon, S. L., Walch, M., Weiner, R. M., Colwell, R. R. 7 Bonar, D. B. (1990). Settlement behaviour and metamorphosis of oyster larvae (*Crassostrea gigas*) in response to bacterial supernatants. *Mar. Biol.*, **106**, pp 389-394.

Galtsoff, P. S. (1964). Season of attachment and growth of sedentary marine organisms at Lamoine, *Maine. Ecol.*, **27**: 150-158.

Gunn, C. R. (1984). A report on the development and use of an artificial cultch suitable for off bottom oyster culture in British Columbia. Fisheries Development Report No 33, Marine Resources Branch, British Columbia, 25 pp.

Hidu, H. & Hasken, H. (1971). Setting of the American oyster related to environmental factors and larval behaviour. *Proc. Natl. Shellfish Assoc.*, **61**: 35-50.

Hidu, H., Chapman, S. & Soule, P.W. (1975). Cultchless setting of European oysters, *Ostrea edulis*, using polished marble. *Proc. Natl. Shellfish Assoc.* **65**: 13-14.

His, E. (1978). Une experience de production de "naissain naturel un a un" sa croissance dans le bassin D'Arcachon. *Sci. et Peche, Bull. I Instit.* Peche Maritimes, **280**, 12 pp.

Holliday, J. E. (1992). International Developments in Oyster Hatchery Technology. Fish. Div. *Misc. Bull.*, (Revised edition) Dept. of Agric., NSW, Sydney, **1**: 101 p.

Holliday, J. E., Allan, G. L., Frances, J. & Diver, L. P. (1993). Evaluation of commercially-used collectors for Sydney rock oysters, *Saccostrea commercialis* and Pacific oysters, *Crassostrea gigas. Aquacultural Eng.*, **12**: 63-79.

Holliday, J. E., Maguire, G. B. & Nell, J. A. (1988). Alternative cultivation methods for the Sydney rock oyster (*Saccostrea commercialis*). In: L. H. Evans and D.

O'Sullivan (Editors), Proc. First Aust. Shellfish Aqua. Conf., Curtin Uni. Technol., Perth, WA, pp. 234-265.

Hopkins, A. E. (1935). Attachment of larvae of the Olympia oyster *Ostrea lurida* to plane surfaces. *Ecology*, **16** (1): 82-87.

Jones, G. & Jones, B. L. (1988). Advances in remote setting of oyster larvae. Aqua. Assoc. of BC, Nanaimo, BC. 88 p.

Keck, R., Maurer, D., Kauer, C. & Sheppard, W. A. (1971). Chemical stimulants affecting larval settlement in the American oyster. *Proc. Natl. Shellfish Assoc.*, **61**, pp 24-28.

Kenny, P. D., Michener, W. K. & Allen, D. M. (1990). Spatial and temporal patterns of oyster settlement in a high salinity estuary. *J. Shellfish Res.*, (9) **2**: 329-339.

Kong, C. P. & Luh, L. A. (1976). Notes on the efficiency of various materials tested as oyster spat collectors in Cowie Bay, Sabah. *J. Malaysian Agric.*, (50) **94**: 462-479.

Morse, D. E. (1985). Neurotransmitter-mimetic inducers of larval settlement and metamorphosis. *Bull. Mar. Sci.*, (37) **2**: 297-706.

Nell, J. A. (1993). Farming the Sydney rock oyster (*Saccostrea commercialis*) in Australia. *Review in Aquatic Sci.*, (1) **2**: 97-120.

O' Sullivan, B. W. & Wilson, J. H. (1976). Development of an experimental oyster hatchery. *Fish Farm. Inter.*, NY, **3** (3): 12-15.

Roland, B., Broadley, T. & Sutherland, I. (1988). Update on remote setting Pacific oyster larvae in British Columbia. B.C. *Aqua. Information Bull.*, **15**: 10 p.

Roland, W. G. & Broadley, T. A. (1990). A manual for producing oyster seed by remote settling. Min. Agric. and Fish., Aquaculture and Comm. Fish. Branch, 58 p.

Schaefer, M. B. (1937). Attachment of larvae of *O. gigas*, the Japanese oyster, to plane surfaces. *Ecol.*, **18**: 523-527.

Shaw, W. N. (1967). Seasonal fouling and oyster setting on asbestos plates in Broad Creek, Talbot County, Maryland, 1963-65. *Chesapeake Sci.*, **8** (4): 228-236.

Shpigel, M., Coon, S. L. & Kleinot, P. (1989). Growth and survival of cultchless spat of *Ostrea edulis* Linnaeus, 1750 produced using Epinephrine and shell chips. *J. Shell., Res.*, **8** (2) : 355-357.

Spencer, B. (1990). Cultivation of Pacific oysters. Lab. Health MAFF Direct. *Fish. Res.* Lowestoff, **63**, 47 pp.

Utting, S. D. & Spencer, B. E. (1992). Introductions of marine bivalve molluscs into the United Kingdom for commercial culture - case histories. *ICES Mar. Sci. Symp.*, **194**: 84-91.

Walne, P.R. (1974). Culture of bivalve molluscs. Fishing News (Books), West Byfleet, England, 173 pp.

Weiner, R. M., Walch, M., Labare, M. P., Bonar, D. B. & Colwell, R. R. (1989). Effects of biofilms of the marine bacterium *Alteromonas colwelliana* (LST) on set of the oysters *Crassostrea gigas* (Thunberg, 1793) and *C. virginica* (Gmelin, 1791). *J. Shellfish Res.*, **8** (1): 117-123.

Winer, B. J. (1971). Statistical Principles in Experimental Design. 2nd Ed. McGraw-Hill Kogakusha Ltd, Tokyo, 907 pp.