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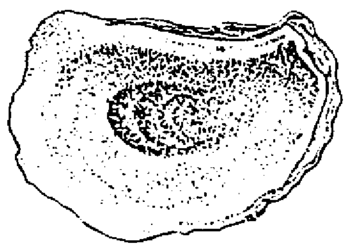
The Ecology of *Crassostrea gigas* in Australia, New Zealand, France and Washington State



Edited by
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Prepared by Maryland Sea Grant College
College Park, Maryland

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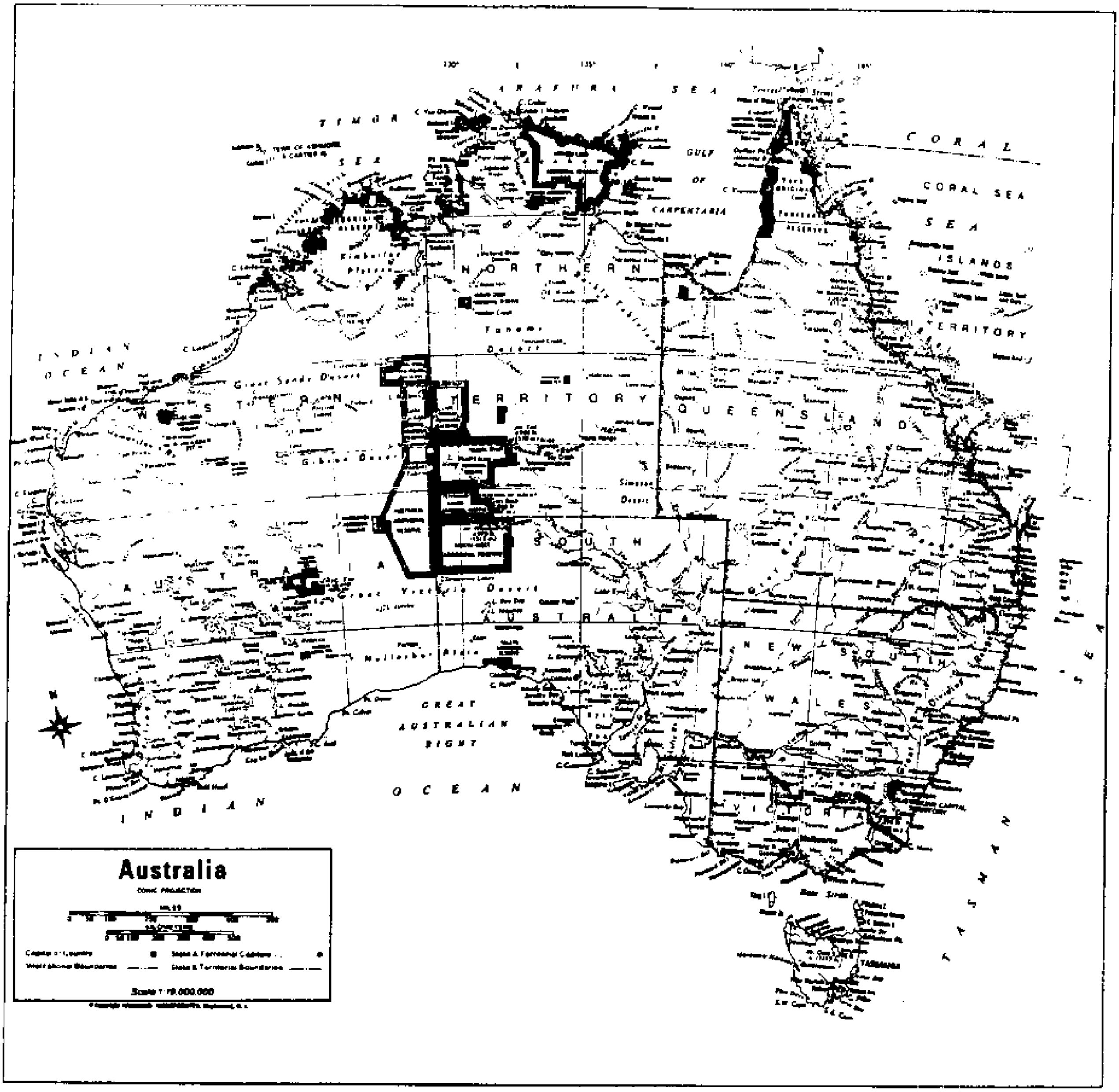
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Tanami Desert
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Kimberley Plateau
Bass Strait

Introduced Pacific Oysters in Australia

Peter Ayres

Introduction

This presentation considers the introduced Pacific oyster, *Crassostrea gigas*, in Australia and in particular in New South Wales (NSW) where it is considered by many to be undesirable and to pose potentially serious ecological, social and regulatory problems. In NSW, Pacific oysters have appeared in the midst of a century-old established oyster industry based on culture of the indigenous species, *Saccostrea commercialis* (Sydney Rock Oyster). As a result, they have been declared "Noxious Fish" by the state government and must be removed and destroyed as found. It is important to stress however that in two states, Tasmania and South Australia, the species has been introduced to create an oyster industry where none existed before.

History of Introductions

There is a certain irony in the fact that it was the Commonwealth Scientific and Industrial Research Organization (CSIRO), a federal government agency, which after several attempts, succeeded in introducing Pacific oysters from Japan. In a country where the often well intentioned but naive introduction of non-indigenous fauna and flora has led to serious ecological consequences and the extinction of some native species, reference to the Pacific oyster in NSW as a "marine rabbit" seems appropriate. Table 1 summarizes the original introductions of Pacific oysters into Australia and Table 2 its subsequent appearance in NSW.

The first recorded importation of Pacific oysters in 1940 was seized and destroyed in Sydney on the recommendation of the then superintendent of NSW State Fisheries who had earlier expressed concern about ecological consequences of its introduction. However, further consignments were imported in 1947, 1948 and 1952 and relaid in Tasmania, South Australia, and Western Australia . Only those in Northern Tasmania survived and these spawned successfully in Pittwater and Port Sorrell. It appears likely that larvae from those stocks were transported by tidal currents some 30 km eastwards to the Tamar estuary in Tasmania and became established as a self-sustaining population while all others died out. Stock transferred from Tasmania in 1955 northwards to Mallacoota Inlet in Victoria on the Australian mainland were still surviving in reduced numbers three years later. In 1967 five Pacific oysters were found 70 kms north at Pambula, NSW and again it is possible that ocean transport of larvae was responsible. On a state-by-state basis the situation may be summarized thus:

Tasmania

Pacific oyster spat observed in the Tamar River in 1958 developed into a self-sustaining population which by 1967 had multiplied to such an extent that large reefs of oysters approaching nuisance proportions had become established on foreshores. However, spatfalls were erratic in subsequent years and market size oysters were found to contain excessive levels of heavy metals, especially zinc, rendering them unfit for human consumption.

In 1977 the Tasmanian government and prospective oyster farmers established a pilot scale commercial Pacific oyster hatchery at Bicheno on the east coast. The success of this and later private hatcheries, producing close to 100 million spat annually, forms the basis of the Tasmanian Pacific oyster industry today. The original local industry based on the native mud oyster (*Ostrea angasi*) fell into decline early this century so Pacific oysters did not conflict with an existing species. The fishery is now totally reliant on hatchery produced spat and in 1989-90, 3.5 million dozen oysters worth 13.7 M$Aus were marketed. Freak warm weather conditions in 1990 resulted in some natural spawning and catch but generally Tasmanian waters are too cold and saline for reliable recruitment of Pacific oysters to occur.

South Australia

Although earlier CSIRO introductions were unsuccessful, in the early 1980's a hatchery and grow out facility was established in salt ponds in South Australia. This operation closed down and only recently have Pacific oyster spat from Tasmanian hatcheries been introduced to establish an industry. The 1989-90 production of 0.47 million dozen oysters will certainly increase. Temperatures in the area should be sufficient for larval production but near oceanic salinities suggest it is unlikely that populations will be self-sustaining.

Victoria

Stock transferred by CSIRO to Mallacoota survived until 1958 and perhaps longer but is not evident now. Attempts to emulate the South Australian experience in salt ponds eventually failed because of lack of funds. Prospective oyster farmers requested the Victorian government to permit the introduction of Pacific oyster spat from Tasmania. Assessing the potential risks and benefits, the government refused permission and decided to foster cultivation of the native mud oyster and the mussels (*Mytilus edulis* and *Mytilus planulatus*).

New South Wales

Pacific oysters were first found here in 1967 but not reported again until 1973 when they appeared in a number of estuaries (Table 2). Conceivably larvae could have been transported to these areas by ocean currents or on the hulls of Tasmanian scallop boats, but the mechanism involved is not understood. In response to the 1973 reports the Fisheries Department issued warning notices to oyster farmers to assist in locating and destroying any Pacific oysters that might be found. Surprisingly, no reports were documented until 1985 when large numbers of Pacific oysters were found on commercial rock oyster leases in Port Stephens, 160 km north of Sydney.

Port Stephens is a large tidal inlet approximately 25 km long and 10 km wide, with a narrow entrance to the ocean and a promontory that separates the upper and lower Port areas. The Port is fed by numerous freshwater creeks but has only one major freshwater input of significance, the Karuah River to the west. Port Stephens has a mean annual salinity between 25 and 28 ppt but salinities may range from less than 10 to 35 ppt towards the ocean depending on rainfall and season. Summer (Nov-Feb) water temperatures generally exceed 25° and in winter may fall to around 13° C. Because it is a large open expanse of water, Port Stephens is generally unsuitable for tray culture of oysters. However tidal and climatic conditions are such that rock oyster spatfalls are the heaviest and most consistent of any area in NSW and so Port Stephens has traditionally supplied spat and stock for other estuaries. Overall, the rock oyster in NSW produces some 10 million dozen oysters worth 36 M$Aus annually.

How Pacific oysters got into Port Stephens in the 1980's remains a matter of conjecture but the evidence suggests they were deliberately introduced, probably as spat from Tasmania around 1982-83. The area where they were discovered in 1985 is heavily cultivated, and close to a number of oyster depot areas; it seems improbable that no one knew Pacific oysters were present before 1985. Since 1985, Pacific oysters have spread rapidly throughout Port Stephens, initially throughout the upper area and finally in 1990 became established in the outer Port also. The nature of the spread implicates a number of factors. Initially, water movements and wind kept distribution to the southern shores but as the number of mature animals increased, accidental and deliberate transfer with rock oyster stocks spread the species to other areas. Large scale survival and settlement in the outer Port followed exceptionally heavy rain and lowered salinity in 1990 and now Pacific oysters occur throughout the entire area.

Movement of Port Stephens stock to other areas north and south along the Australian east coast has led to populations becoming established in many other estuaries, at worst in nuisance proportions but generally under control. Because the 1500 km of NSW coastline has such a wide range of climate and estuarine conditions, the southern, cooler areas seem to favour Pacific oyster survival, whereas the northern areas are too warm. A local combination of temperature, salinity and estuarine type seem to be the critical factors in survival and reproduction of Pacific oysters in NSW. Port Stephens is located almost midway along the coast and so has average conditions, but I believe the important factor here is a failure to control Pacific oyster numbers in the early years after 1985. One very clear lesson is that, once introduced, Pacific oysters are impossible to eradicate. However, control of the population is effective and achievable if both government and industry are committed to the task.

The Australian Experience — Summary

1. The Pacific oyster is a rapidly growing, highly fecund, and adaptable species that accounts for some 80% of the recorded edible oyster production in the world.

2. In Australia the species has been successfully and deliberately introduced into Tasmania and South Australia but in neither case has it (a) replaced an existing commercial species because none existed before and (b) spawned in local waters on a reliable basis. All the industry needs are met by hatchery production which permits selection and manipulation (e.g., triploidy) to produce a uniform oyster generally superior to wild-caught oysters.

3. The major limiting factors in both areas appear to be low water temperature and high salinity.

4. The Pacific oyster has a limited shelf life as a live product and must be processed soon after harvest. In contrast, the NSW rock oyster will remain alive without loss or deterioration out of water for up to 3 weeks and can be safely transported long distances.

5. The NSW rock oyster industry is over a century old, utilizes a unique indigenous oyster, produces 36 M$Aus of oysters annually and is a major and important contributor to local employment and economies along the NSW coast.

6. More than 95% of NSW's commercial oyster farmers have consistently voted to retain the rock oyster as the species of choice and have spent six years controlling Pacific oysters.

7. Government regulations have not been enforced because of lack of resources and political will.

8. Oyster farmers in Port Stephens who spent six years fighting the spread of Pacific oysters have effectively been abandoned by the government and many businesses will collapse.

9. Those who have done little or nothing have been rewarded by the subsequent legalization of sale and cultivation of Pacific oysters (in Port Stephens).

10. The parallel cultivation of two oyster species is already fraught with problems and a worse-case scenario where neither can be grown and harvested economically would spell the death of the industry and the dereliction of thousands of hectares of oyster leases. This would be an environmental disaster.

11. Pacific oysters neither grow nor survive uniformly throughout NSW and it is unlikely they will ever be grown as the major species of commerce except in specific estuaries, and even then may not be economic.

12. Oceanographic experts confirm that Pacific oyster larvae could be carried up to 50 km up and down the coast from Port Stephens with possible distribution up to 200 km at certain times. Government experts say it cannot happen.

Table 1. Introductions of Pacific Oysters to Australia

1940 — Trial shipment from Japan condemned and destroyed on arrival in Sydney.

1947 — Fifty cases of Pacific oyster spat from Sendai, Japan and 5 cases from Kumamoto, Japan, placed in Oyster Harbour near King River (Tasmania). 70% mortality reported during trans-shipment.

1948 — All Pacific oysters transferred to Western Australia reported as having died.
November: A further 50 cases of Pacific oyster spat from Hiroshima relaid in Pittwater, Tasmania (estimate 7.5 million spat).

1949 — *February:* Oysters spawned in Pittwater.

1950 — *February:* Oysters spawned in Pittwater.

1951 — *January:* Oysters spawned in Pittwater.

1952 — *January toMarch:* Oysters spawned in Pittwater.
May: Some Pacific oysters transferred from Pittwater to Port Sorrell, Tasmania.
September: 75 cases of Pacific oyster spat (origin unknown) imported from Japan to Port Sorrell.

1953 — Spatfall in both Pittwater and Port Sorrell
September: Majority of oysters transferred from Pittwater to Port Sorrell.

1954 — No spatfall in Port Sorrell.

1955 — *February:* Mass spawning observed in Port Sorrell.
October: Remaining Pittwater oysters transferred to Mallacoota Inlet, Victoria.

1956 — *February:* Mass spawning in Port Sorrell.

1957 — *February:* Mass spawning in Port Sorrell.

1958 — *February:* Mass spawning in Port Sorrell.
June: Spat of Pacific oysters observed in the Mersey and Tamar Rivers, Tasmania.
October: 25% of Pacific oysters transferred to Mallacoota still alive.

1967 — *May:* Report that large areas of the Tamar River covered in Pacific oysters.

Table 2. Pacific Oysters in New South Wales

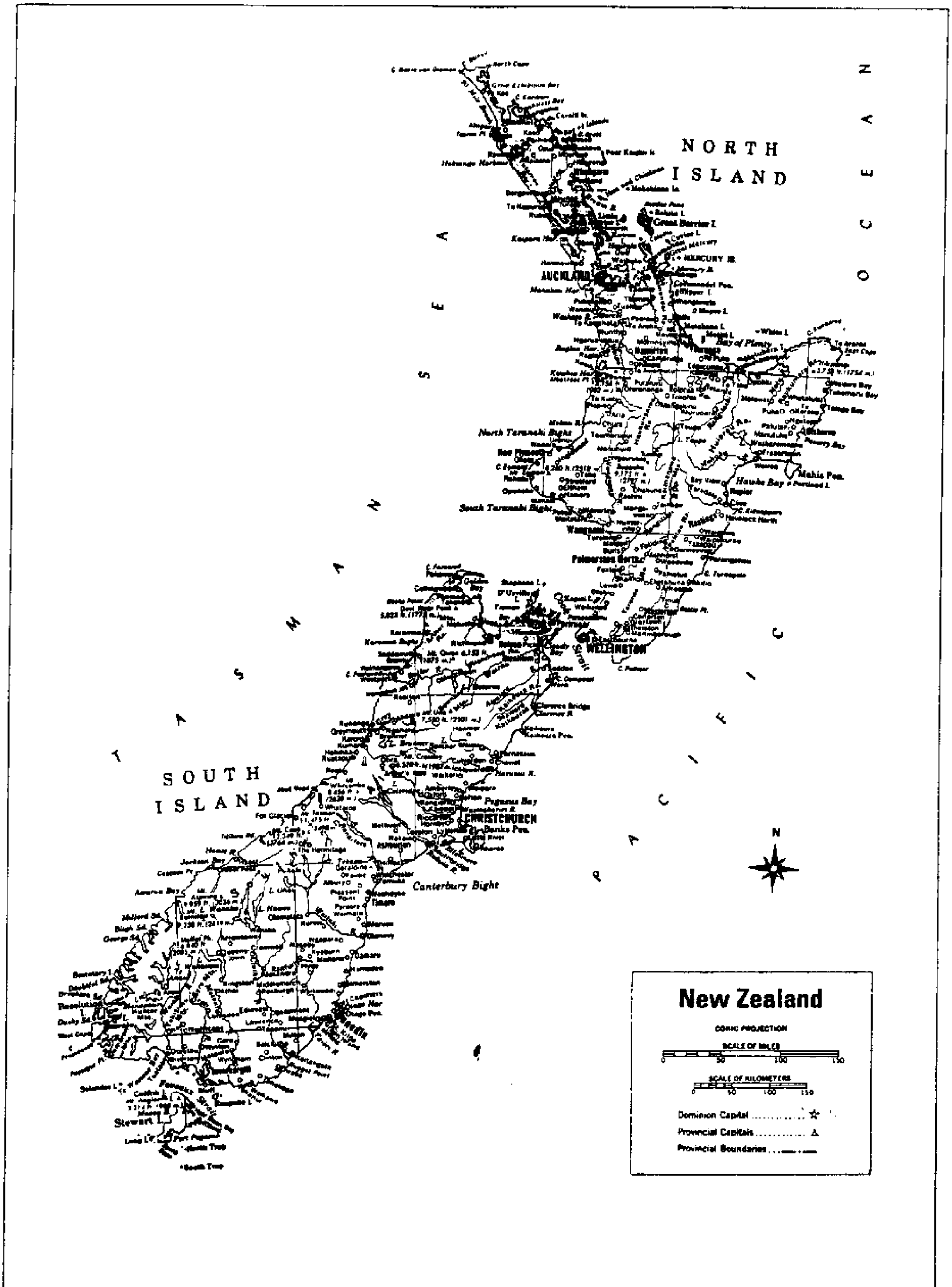
1967 — Five Pacific oysters found in the Pambula River.

1973 — *February:* 2 Pacific oysters reported from the Clyde River.
May: Pacific oysters reported from Merimbula (5), Nelson Lake, Wapengo Lake, Narooma, Bermagui and Shoalhaven River.
June: Pacific oysters reported from Karuah and Finnegans Bay (Port Stephens).
August: Pacific oysters reported from Woolooware Bay (Georges River).

1985 — Pacific oysters appear in large numbers in Port Stevens and are declared "Noxious Fish".

1986 — Small numbers of Pacific oysters occurring in most oyster cultivation areas but not becoming dominant.

1990 — Government legalizes sale (and cultivation) of Pacific oysters from Port Stephens only.


NORTH ISLAND
SOUTH ISLAND
T A S M A N   S E A
P A C I F I C   O C E A N
AUCKLAND
WELLINGTON
CHRISTCHURCH
Bay of Plenty
Hawke Bay
North Taranaki Bight
South Taranaki Bight
Canterbury Bight
Pegasus Bay
Banks Pen.
Mahia Pen.
Great Barrier I.
Stewart I.
N
New Zealand
Dominion Capital
Provincial Capitals
Provincial Boundaries

Introduced Pacific Oysters in New Zealand

Parameswar (Mani) Dinamani

Introduction

The Pacific Oyster, *Crassostrea gigas*, was introduced accidently into New Zealand and was first discovered and positively identified in 1971. Its origin, method and time of arrival are not clear but it is probable that (a) the oyster may have been in New Zealand for a number of years before it was first discovered and (b) its introduction(s) may have been facilitated through a series of events from 1950 onwards.

In brief, the New Zealand stock of Pacific oyster probably came mainly through spawnings larvae/spat of:

1. oysters on ships' hulls in Auckland Harbour, particularly a few Japanese vessels that were moored for long periods in 1966/67, close to the main spatting area of native oysters on the East Coast;

2. introduced Pacific oyster stock breeding in the 1950's in Australia, with the larvae drifting across the Tasman Sea to the West coast of northern New Zealand;

3. oysters on hulls of a large number of Korean and Japanese squid boats that fished the northwestern waters of New Zealand for long periods during the southern summer (late 1960's - early 1970's).

The New Zealand stock reveals high levels of genetic variation similar to natural populations of Japan, which is unlikely if it represented a single introduction or it came from a small founder stock.

Brief History

The spread of the oyster throughout the north of New Zealand has come about as a result of farming practices adopted for the native Rock oyster, *Saccostrea glomerata*, and initiated in 1967. Farmers relied on natural spatfall and set out cultch in one or two main spat collecting areas during the summer. They then shifted the spatted cultch to growing areas. As Pacific oysters began to settle in increasing numbers on spat collectors in the 1970's, they were effectively distributed to all other areas along with the Rock oyster spat. The Pacific oyster began to gain ascendancy over the native oyster from 1975 onwards and farmers found it impossible to grow the two species together or selectively. As a result, the Pacific oyster became the dominant farmed oyster from 1977 on.

Competition with the Native Species

Pacific oysters bred successfully in New Zealand waters over the same time period as the Rock oyster and they competed vigorously for settlement space: in 1972 the ratio of Rock oyster to Pacific oyster on a standard spat collector was 1000 to 1; by 1977 it was 1:1 and in 1978 it was 1:4 in favour of the Pacific oyster in the main spat catching area of Mahurangi. Pacific oysters grew to marketable size (~100g) in 15 to 18 months, compared with 36 months for the Rock oyster (~70g) on the same substrate. Large Pacific oysters outgrew the native on cultch surfaces and in many farms oversettlement of Pacific oyster spat smothered the smaller native oyster. As a result of its faster growth, greater size, and regular and ample spatfalls, the Pacific oyster superseded the Rock oyster within a decade of its arrival in the farms.

Environmental Requirements

In major growing areas, mean sea temperature ranges from 14 to 22°C and salinity is nearly oceanic at 33 to 35 ppt. In smaller inlets and upper reaches of bays and in large west coast harbors salinity fluctuates from 22 to 35 ppt depending upon the tidal state and incidence of freshets and rain.

Pacific oysters settle below the zone of Rock oysters in the intertidal area of rocky shores; denser settlement occurs along the lower parts of the shore in less saline waters, where dense beds form on level or gently sloping shores. As a result of oversettlement the oysters grow in clumps, die during hot spells and are easily detached in rough weather. Heavy build-up of silt occurs along the foreshore in these areas. Pacific oysters also selectively settle on upper reaches of inlets where waters are less saline (20 to 22 ppt).

Pacific oysters grow well in subtidal or suspended cultures in nearly oceanic water. Larvae and spat are optimally reared in the hatchery at 22 to 26°C and salinity of 33 to 35 ppt.

Reproduction and Spawning

Pacific oysters ripen and spawn over the same period as the native Rock oyster during the southern summer: the gonad begins to proliferate late in August when water temperature is about 14°C and some oysters spawn in September/October. The first major spawnings occur in December when water temperature rises to above 20°C; several spawnings occur throughout the summer months at temperature peaks of 22 to 24°C. Spawnings may extend to April in some years. A small percentage of oysters appears to be active throughout the breeding season.

Oysters 9 to 10 months old are fully ripe, and spawn as males; the percentage of females rises appreciably in 1+ year-old oysters, and 2 to 3-year-old oysters are predominantly female. The gonad passes through an inactive/resting phase from April through July/August in most oysters.

The larval period lasts for 21 to 24 days at mean water temperature of 20°C during December/February, but may last up to 30 days later in the season. There are normally two major spatfalls in one season.

Pacific oysters established themselves successfully throughout the 1970's with large spatfalls in the main spatting area followed by invasion of several inlets and small bays. Spatfalls began to decline from 1982 onwards, leading to near failure in 1983 and scant falls through to 1985. The causes of this decline were not clear, as successful breeding and settlement continued to occur in other areas, particularly in less saline bays and upper reaches of inlets.

Genetics and Interbreeding

Odd looking oysters were detected and reported by farmers from 1974 through 1977 and were suspected to be hybrids. Experiments were carried out to test whether the Rock and Pacific oysters would hybridize. Gametic compatibility was observed in many matings, and when eggs of Rock oyster were fertilized with sperm of Pacific oyster, a higher percentage was fertilized and completed larval development. Several batches of larvae were raised; some were raised through settlement and reared as spat. However, genetic tests carried out on a small sample a year later failed to establish that they were true hybrids.

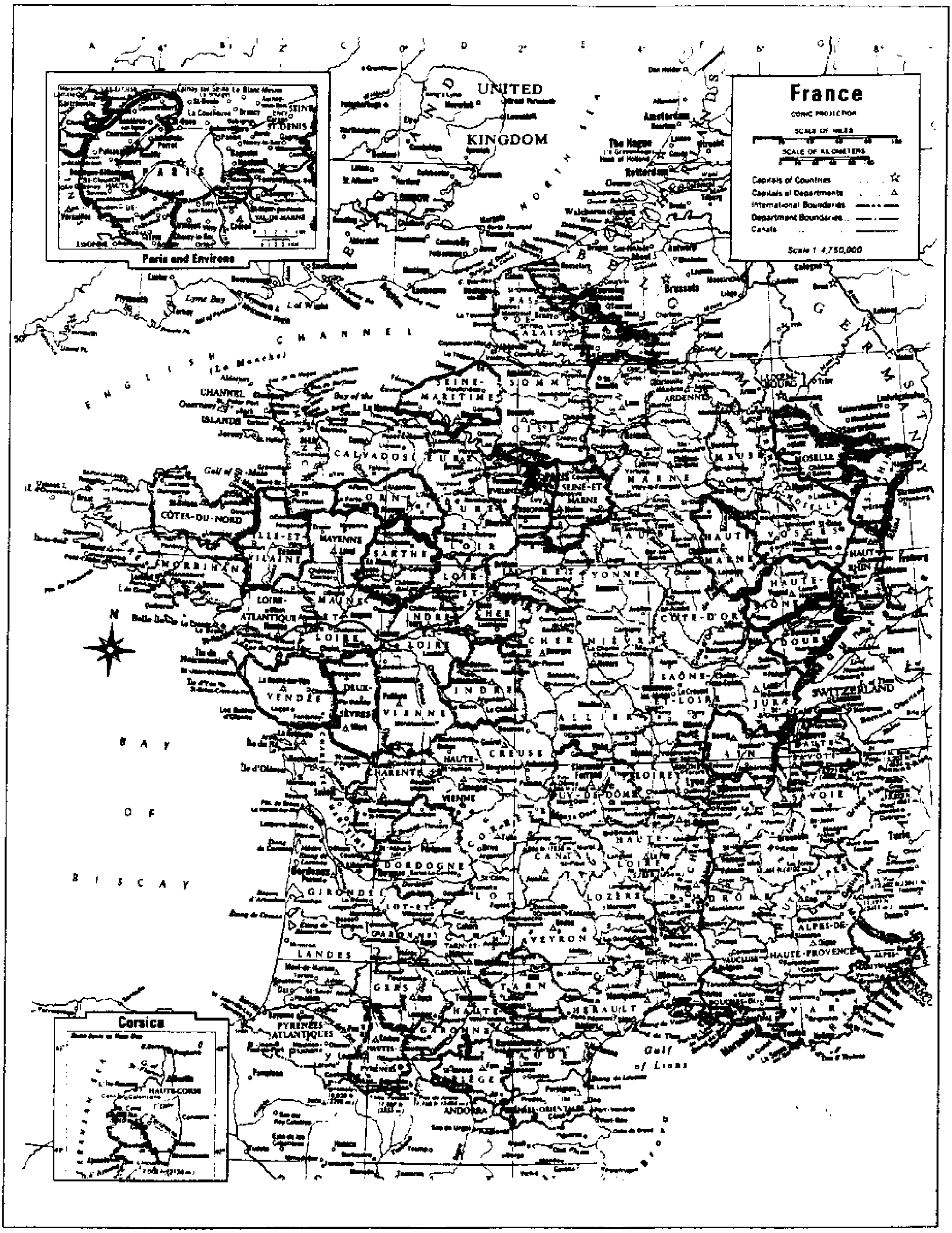
When spatfalls declined, analyses were carried out in the New Zealand population to examine whether there has been a reduction of genetic variation as a result of inbreeding or directional selection from a possibly small founder stock. The results showed that the New Zealand population has the same type and range of variation as the Pacific oyster populations in Japan. Also, genetic differences were found between oysters on the west and east coasts of New Zealand.

An important finding was the presence of two rare alleles in New Zealand Pacific oysters which have been recorded previously only in the Rock oyster. This suggests that some hybridization has occurred in nature, with the introgression of *S. glomerata* alleles into *C. gigas* during the history of the evolution of the species in New Zealand.

Diseases

No known cases of seasonal or sporadic mortality have occurred during the decade that the Pacific oyster has been actively farmed in New Zealand. Disease surveillance programs carried out since 1979 showed the presence of several associated organisms such as copepods, nematodes, ciliates and polychaetes in the mantle cavity or shell, but no pathogen or disease-causing organism was detected. Spionid polychaetes (mudworm) are particularly of concern to farmers and occur in oysters at low tidal levels and cultures close to the bottom. They render the oyster difficult to market, and in large numbers cause shell blisters and stress to the oyster but infestations can be avoided by good farm management.

In the last year or so, two incidents of disease have come to light. In one, investigations of mortalities in hatchery-reared larvae in 1991 showed the presence of iridiovirus in the velum of settling larvae similar to OVVD type recorded in *C. gigas* larvae in Washington State by Elston. In the other, extremely emaciated oysters growing on the west coast in dense clumps on the shore were discovered to be showing symptoms of nocardiosis, similar to "focal necrosis" or "multiple abscesses" described elsewhere. A disease watch is being kept up by the Fisheries Research Division with regular sampling and examination.


France
Capitals of Countries
Capitals of Departments
International Boundaries
Department Boundaries
Canals
Scale 1:4,750,000
Paris and Environs
Corsica
UNITED KINGDOM
ENGLISH CHANNEL
CHANNEL ISLANDS
BAY OF BISCAY
SWITZERLAND
Gulf of Lions
ANDORRA

Aquaculture of *Crassostrea gigas* in France

Philippe Goulletquer and Maurice Héral

Introduction

Commercial oyster landings by French oyster farmers were a record 150,000 metric tons valued at $ 210 million in 1990, close to the production of the USA of 158,000 metric tons. Two species are cultivated in France, namely the native flat oyster, *Ostrea edulis*, and the introduced cupped oyster, *Crassostrea gigas*. The latter provides 92% of the landings, enough to satisfy the French demand. Less than 3% is exported to foreign countries. Oyster culture is concentrated in bays and estuaries, where it is often the most important activity in the coastal economy. More than 35,000 people are employed in the oyster industry, which occupies 50,000 acres of state leasing grounds. Production is dependent almost entirely upon natural spatfall, which is collected on various type of spat collectors. Hatchery production is limited to marginal markets (e.g. remote setting, triploid oyster, flat oyster spat).

Historical Background

Although oyster culture represents a large business in France, it suffered from overfishing in the past. More recently, diseases and pollutants caused large upheavals and the need for new management techniques to restore and sustain production . Beginning about 1860, spat of cupped oysters, *Crassostrea angulata*, were imported by French farmers from natural beds in Portugal to compensate for the lack of flat oyster spat collected on overfished beds. However, the introduction of *C. angulata* was mostly the result of an accident in 1868: due to a storm, a boat was forced to throw its load of supposedly dead Portuguese oysters into the Gironde estuary. Environmental conditions were favorable for reproduction in the southwest of the country up to the Loire River. After 1920, production increased when spat-collectors began to be used systematically. Production reached 85,000 metric tons of *C. angulata* and 2,000 metric tons of *0. edulis* in 1960 in spite of a massive mortality of the flat oyster during the 1920's and a lack of spat settlement of *C. angulata* in the 1930's. However, an increase in the mortality rate and a decline in growth rates were both reported in the main culture areas (Bay of Marennes-Oleron, Bay of Arcachon) in the early 1960's. From 1966 to 1969, the first outbreak of "Gill disease" reduced *C. angulata* production. Drastic mortalities from a second viral disease occurred between 1970 and 1973 and caused the total disappearance of this species from the French coast. The crisis affected 5,000 oyster farmers and the economic loss was estimated to be at least $90 million a year. Therefore, an urgent solution was required to prevent unemployment.

Introduction of the Japanese Oyster *Crassostrea gigas*

Spat of C. *gigas* were first imported from Japan in 1966 by an oysterman looking for growth rate improvements at a time when the C. *angulata* production was reduced by overstocking. The nonofficial aspect of these imports and the concomitant increased mortality of C. *angulata* prompted the research institute IFREMER to call for their ban. Investigations were conducted to evaluate the quality of the oyster beds in Japan with regards to pathology, fouling organisms, and oyster quality. Experts concluded that C. *gigas* appeared healthy and no relationship was established between the pathology observed in France, the mortality of C. *angulata*, and the status of oysters in Japan. The introduction of C. *gigas* was approved since the whole industry was on the verge of collapse. The introduction was performed through large imports in two stages aimed at (l) building sanctuaries and (2) supplying the oystermen with spat.

Sanctuaries — "Resur" Operation

After an evaluation of the sanitary quality of C. *gigas* beds in British Columbia (Canada), adult oysters were imported to constitute broodstocks. Histological control was used for each transfer to ensure the oyster quality. This operation lasted from 1971 to 1973. An additional batch was introduced in 1975 to the Bay of Marennes-Oleron. Populations were successfully established in three areas, all located south of La Rochelle.

Spat Supply

From 1971 to 1977, spat was imported from Japan to sustain the aquaculture activity. Each imported batch of spat was inspected and certified for origin, sanitation, and presence of predators. For disease, histological analyses were performed and an index of meat quality was established. Each batch was immersed in freshwater to reduce the risk of importing species such as the flatworm *Pseudostylochus*.

Reasons for the Success of the Introduction

The extensive introduction of C. *gigas* was so successful that production exceeded the record for C. *angulata* in less than ten years and is still increasing. There are several possible reasons for this rapid success:

Biological

C. *gigas* is resistant to any disease affecting C. *angulata* (viral diseases), *0. edulis* (*Marteilia* and *Bonamia*), and clams (*Perkinsus*).

Environmental conditions in the southwest of France favored C. *gigas* to such an extent that the spat supply is sufficient for the entire industry. However, C. *gigas* dominates only a few intertidal zones outside the breeding areas (e.g., Gironde estuary), which reduces the ecological cost of this introduction. The sanctuaries and the growth of the cultivated broodstock provided a spat supply as early as 1975. In the Bay of Marennes-Oleron, spat recruitment has been successful since the introduction, except that abnormally low temperatures were responsible in 1972, 1981 and 1986 for a low spatfall. Recently, the yearly production has been estimated to be

15 trillion spat in Marennes-Oleron and Arcachon bays.

No competition occurred between the Portuguese oyster *C. angulata* and *C. gigas* nor with other species. Extensive mortalities caused the disappearance of the *C. angulata*. With a low population (e.g. 15,000 tons of *C. angulata* and 8,000 tons of *C. gigas* in 1972), the hybridization observed experimentally between the two species was not a constraint to the growth of the *C. gigas* population.

The carrying capacity of the estuarine areas was large, allowing for optimal growth and reproduction of *C. gigas*. At that time, a total weight of 70g was reached in 18 months and the yield by aquaculture was maximal. In addition, oyster habitat was fully available for settlement because an almost monoculture of *C. angulata* had been practiced in these bays. Accordingly, the extension of the *C. gigas* population was facilitated.

In spite of the relatively small number of introduced individual oysters that participated effectively in the building of the population, no inbreeding problem has been observed. Genetic variation is still high according to electrophoretic analyses.

Several exotic species that have accompanied *C. gigas* have survived in limited areas in spite of the practice of immersing spat collectors in freshwater. These are the cnidarian *Aiptasia pulchella*, the mollusc *Anomia chinensis*, and the cirripeds *Balanus amphitrite* and *Balanus albicostatus*. Two seaweeds are also associated with this introduction on the Mediterranean coast, namely *Laminaria japonica* and *Undaria pinnatifida*. Their limited biomass and distribution do not represent an ecological problem. Culture of *Undaria pinnatifida* is currently being assessed.

Human Component

The introduction schedule was well prepared and preliminary scientific investigations in Japan maximized benefits while limiting the associated risks. Many sanitary precautions were taken to control the introduction.

Because the *C. angulata* and *C. gigas* share many similarities (reproduction, recruitment, etc.) the aquaculture practices in France were directly applicable to *C. gigas* without drastic changes. Thus, the skills of oyster farmers were sufficient to handle the modification. Additional advice by IFREMER scientists to optimize recruitment (e.g. timing for spat-collector deployment) maximized the success of the operations.

Eventually, the new oyster benefitted from an overall acceptance by consumers. They found a high quality product, with a specific taste per breeding area, similar to that for *C. angulata*. Oyster consumption has increased along with production.

Aquaculture of *C. gigas*

Currently, the aquaculture of the Japanese oyster is widely distributed along the French coastline, in estuarine areas, bays, and lagoons. This distribution, mainly extended by aquaculture activities, is well beyond what would have been a "natural" population.

Reproduction

Gametogenesis is initiated when temperature reaches 10° C, and ripening accelerates above 15° C. In southwest France increasing temperatures are accompanied by a concomitant salinity increase (25-35 ppt). Temperature is critical for the distribution of C. *gigas* on the Atlantic coast and the English Channel. In Brittany, no spawning occurs even though ripening is observed. In contrast, in the Mediterranean open sea and lagoons, high salinity (37 ppt) associated with high temperatures (22-30° C) impedes successful reproduction. Reproduction of C. *gigas* occurs only on the Atlantic coast in summer (July-August) when seawater temperature is above 18°C. Thus, spat production relies totally on breeding areas located South of La Rochelle; Bay of Marennes-Oleron, Gironde estuary and Bay of Arcachon.

Production of gonads and gametes has been estimated to comprise 7% of the body weight for yearling oysters, 60% for two year-olds and 80% for three-year olds. A single spawning occurs per summer and optimum spat settlement is observed at 21- 22° C after a 2-week pelagic larval stage.

Growth and Biology

In contrast to the conditions required for spat survival, C. *gigas* will grow in various environmental conditions. Oyster growth is observed in upper estuaries until salinity declines to 15 ppt (range of yearly variability 2-25 ppt). This euryhaline species is also deployed in hypersaline ponds (45-50 ppt); mortality occurs above 50 ppt. C. *gigas* displays high filtration activity, even at 5° C (4 liters per g dry meat weight from October to May and 5 liters from June to September). This is particularly important with regard to overstocking and ecosystem carrying capacity. Growth rate declines and higher mortality rates have been observed with increased stocking biomass (e.g., the market size that was reached in 18 months in 1972 now requires more than 4 years in the Marennes-Oleron Bay), resulting in new management techniques being required. Summer mortalities (20%) have been observed in intertidal areas when temperature peaks and are related to a physiological disorder during reproduction (i.e., glycogen deficit).

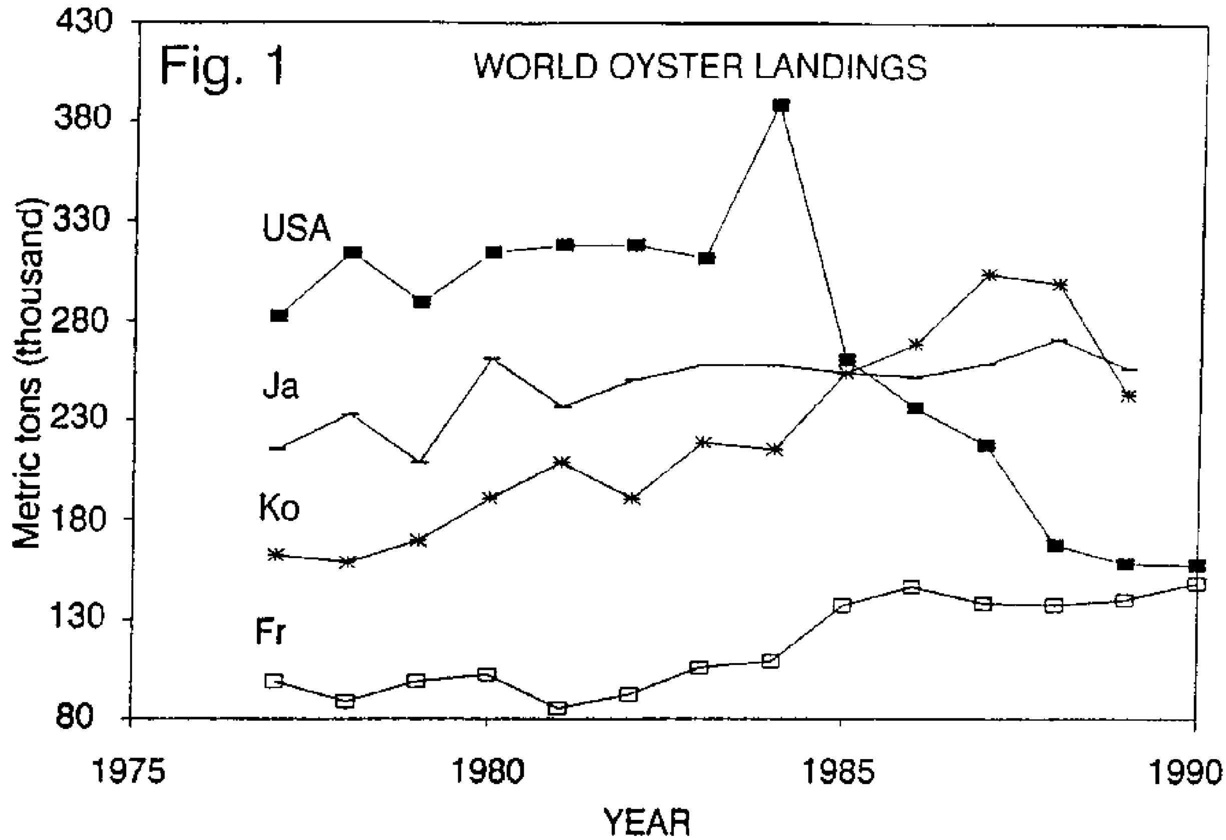
Special Problems

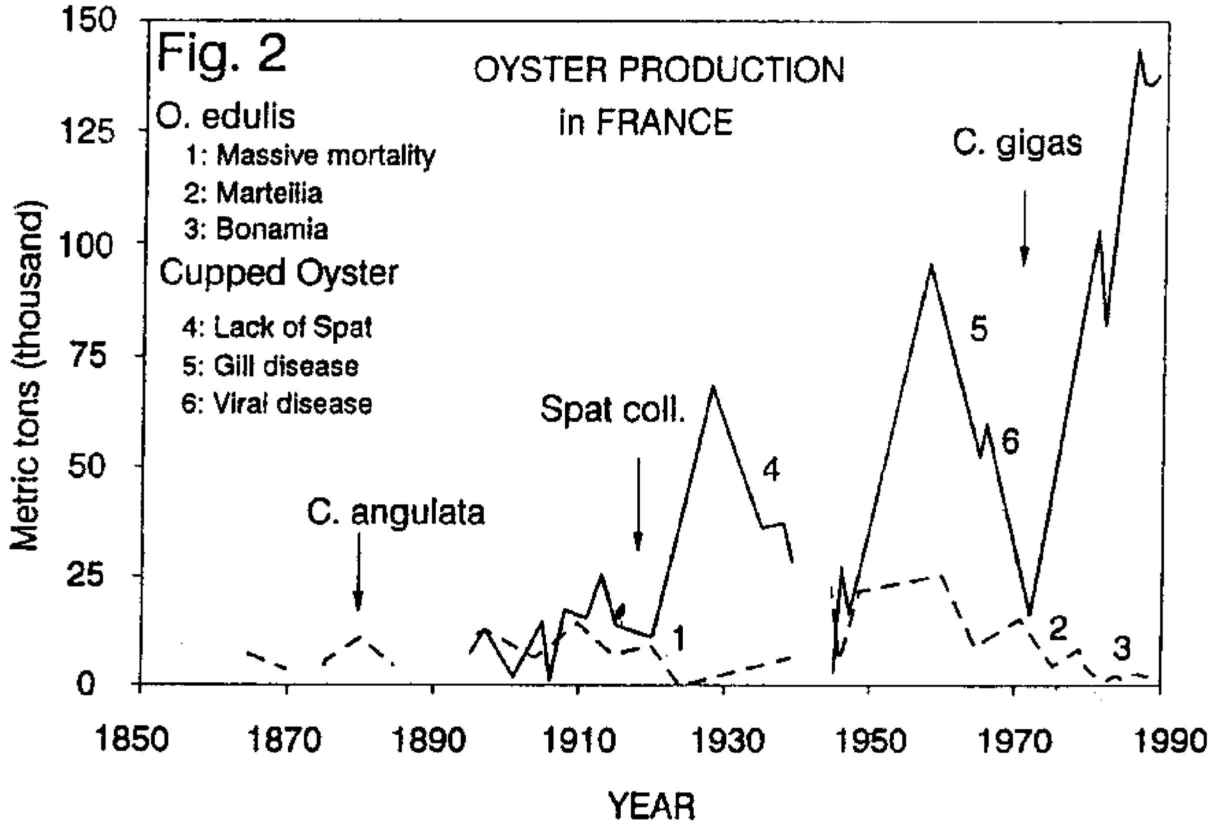
Contaminants. No spatfall occurred in Arcachon Bay between 1977 and 1981. At that time, experiments demonstrated the high toxicity of TBT acetate used in antifouling paints on veligers and phytoplankton (a $0.1\mu.L^{-1}$ concentration affects larval development). Shell abnormalities were also observed on adults at $0.01\mu.L^{-1}$. The 1982 regulation restricting TBT use lead to a prompt spatfall recovery.

Anoxic Waters. In 1975 and 1986, severe dystrophic crises in the Thau Lagoon on the Mediterranean coast resulted in anaerobiosis and high oyster mortality.

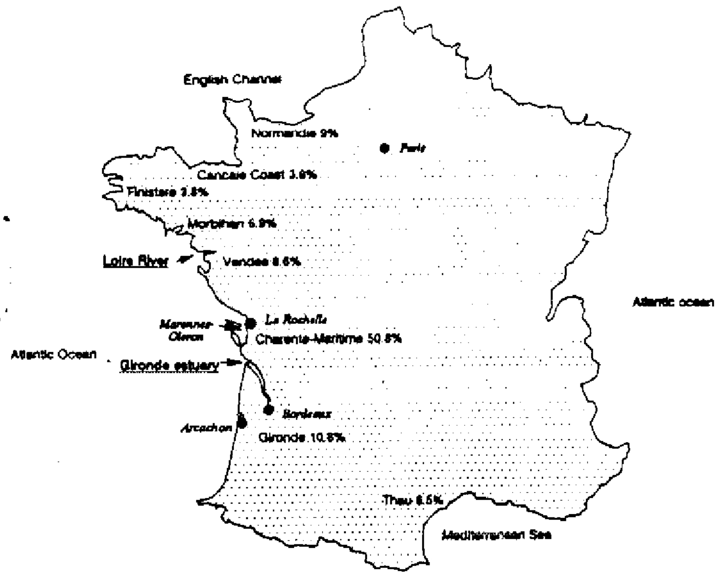
Trophic Competition. Recently, increased populations of the gastropod *Crepidula fornicata* in specific areas have been responsible for disturbance of water circulation patterns (e.g., sedimentation) and trophic competition with the oyster. Annual management, based on population dynamics studies, limits the effect of this gastropod.

Deterioration of Shellfish Grounds. Oyster overstocking has induced sedimentation of large quantities of biodeposits. Other farming structures (e.g., iron tables to hold shellbags) have also affected water circulation and sedimentation patterns. So far, management practices and regulations (e.g., timing for structure deployment) have limited the effect on the ecosystem.





Figures 1 and 2.



Oyster Sales in 1986
(% per culture area)

Reproductive areas (o)
& Spat transplanting
Operations

Figure 3.

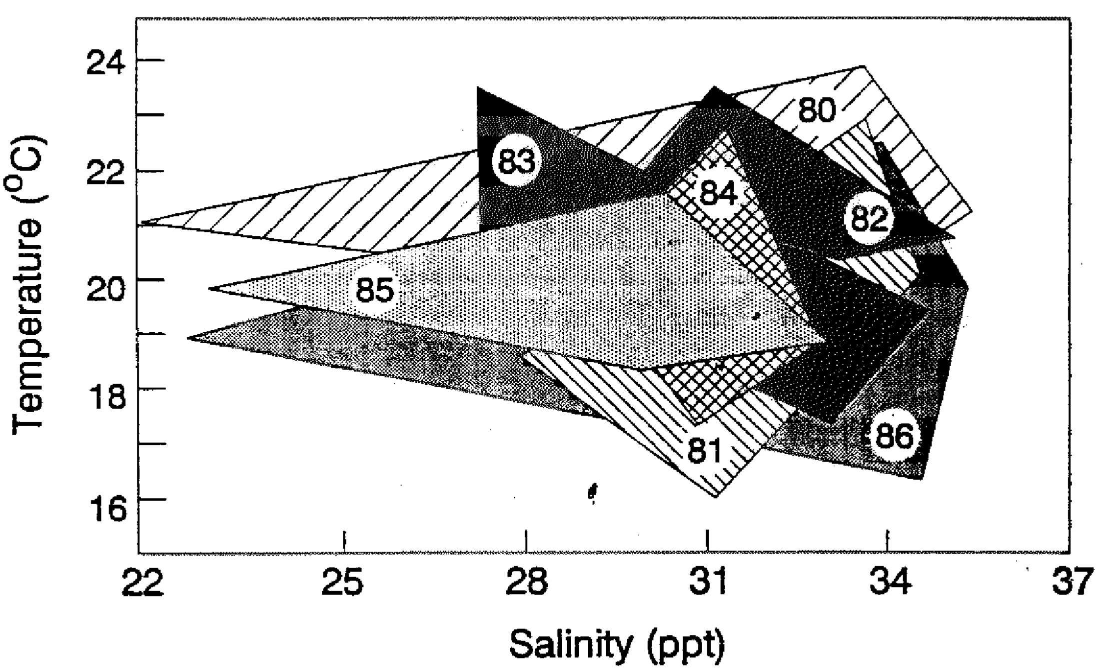


Figure 4. Environmental conditions in the Bay of Marennes-Oleron (1980-1986) during the pelagic stage of oyster larvae. Note, the spatfall in 1981 and 1986 was reduced by low summer temperatures (after Héral, 1990).

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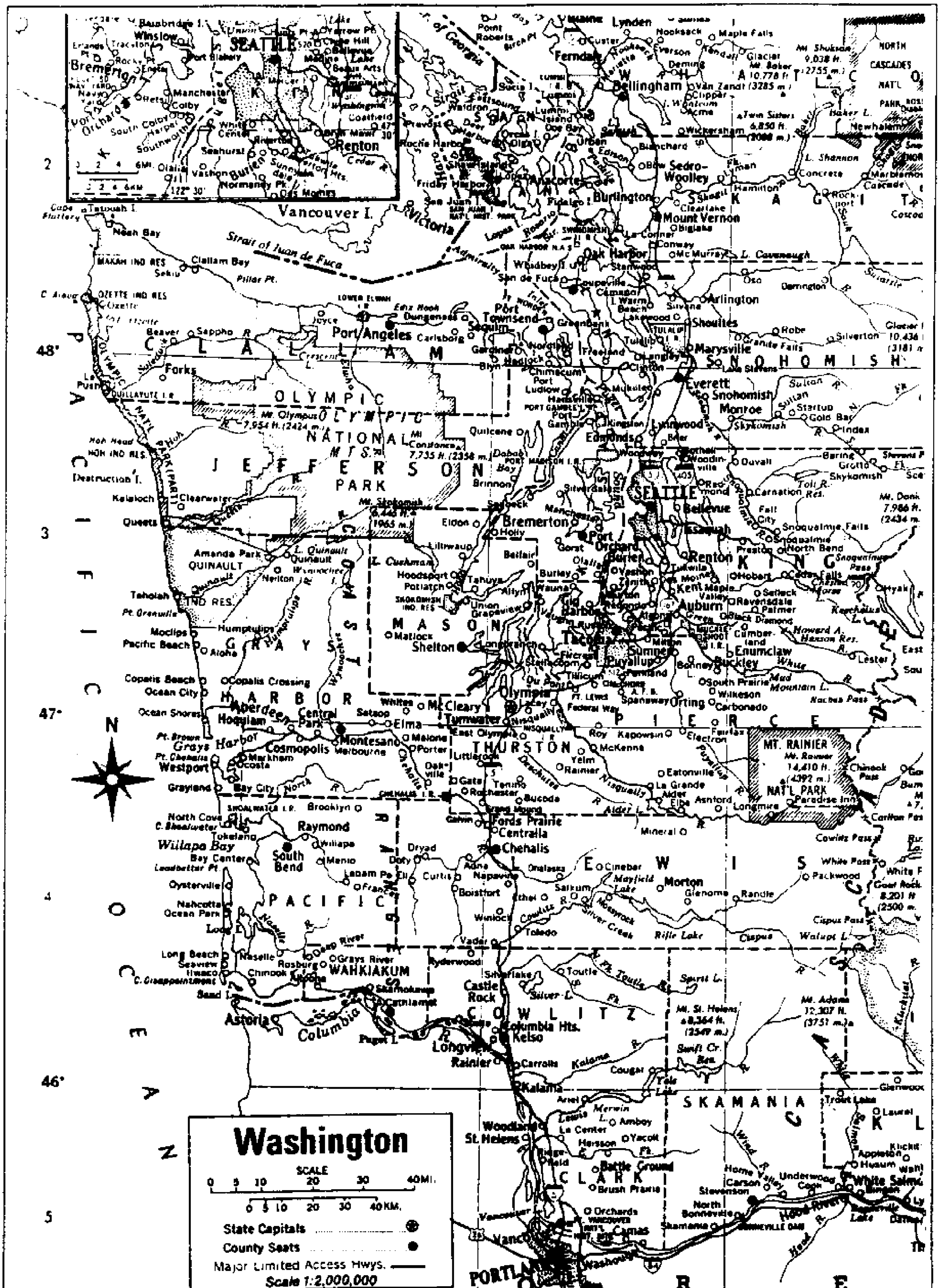
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WHATCOM
ISLAND
SAN JUAN
MT. RAINIER NAT'L PARK
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Strait of Juan de Fuca
Victoria
SEATTLE
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Everett
Bellingham
Port Angeles
Bremerton
Aberdeen
Hoquiam
Shelton
Chehalis
Centralia
Longview
Kelso
Astoria
PORTLAND
Vancouver
Columbia R.
Willapa Bay
Grays Harbor
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Ecological and Biological Considerations for the Introduced Pacific Oyster to the West Coast of the United States

Kenneth K. Chew

Introduction

Recent statistics from the U.S. Department of Commerce indicate that the 1990 oyster industry on the west coast (5 million kg. of meat) now ranks as the largest in comparison to those in other coastal regions of the United States. This is due primarily to the production of the Pacific oyster *(Crassostrea gigas)* which was originally introduced from Japan.

At the turn of the century the main oyster fishing on the west coast was for the Olympia or native oyster *(Ostrea lurida)*. With the decline of the native oyster industry, the east coast or American oyster *(Crassostrea virginica)* was introduced for cultivation primarily in the State of Washington and parts of British Columbia. Survival was not good for this species and ultimately the Pacific oyster was introduced and became the mainstay of the present west coast oyster industry. There are several published accounts of this introduction (Schaefer 1938; Quayle 1988; Chew 1984, 1990). Although experimental introductions were positive in terms of adaptation to the oyster growing areas of Washington State, it was not until the 1920's that large quantities of Pacific oyster seed were introduced from Japan to the Pacific coast. This oyster has adapted well to a wide range of environmental conditions and is probably the most globally widespread and ubiquitous oyster species in the world (Chew 1990).

Reproduction and Spawning

It is apparent that the Pacific oyster is not only the most adaptable oyster to a wide range of hydrographic and environmental conditions, but it is a very fecund species of bivalve. During the breeding season the reproductive organs may form at least 50% of the body volume (Quayle 1988). The sexes of this species are separate and can only be determined by examination of reproductive tissues. Although there are indications that protangery does exist, environmental conditions apparently have considerable influence on determination of sex in the oyster. There appears to be a tendency for females to change to males where and when the food supply is poor, and for males to become females where and when supply of food is good. Thus, in areas with good food supply the sex ratio in older oysters shows a predominance of females, whereas the reverse is true in areas of low food supply.

Conditioning for spawning of Pacific oysters has been well established in hatcheries along the Pacific coast. Generally oysters can be brought into the hatchery during late winter or early spring and conditioned for varying lengths of time with gradual increases in temperatures and adequate food. Spawning can be generally initiated at an average of 21-22° C, although in some cases spawning can be initiated below this temperature. Quayle (1988) has observed natural spawning at temperatures as low as 15° C, but this may have been a result of chemical stimulation. Initiation of spawning may be accomplished not only by increased temperature, but also by chemical stimulation, or a combination of both. The presence of sex products is enough to stimulate spawning, making it possible to force large numbers of oysters to spawn simultaneously.

Although the average optimal salinity range for spawning seems to be between 25 and 3 ppt, Japan has reported that the salinity range for development (breeding) is between 11 and 32 ppt, with the optimum between 20 and 25 ppt. Various attempts have been made to cross *Crassostrea gigas* of the Miyagi variety from northern Japan (the normal oyster cultured along the Pacific coast of the United States) with other species of *Crassostrea*, including *C. virginica, C. rivularis, and C. gigas* of the Kumamoto variety. Crosses on the west coast between *C. virginica* and *C. gigas* have only been moderately successful, and much is still not understood concerning the genetic makeup between these two species. However, crosses between the Pacific oyster and *C. rivularis* show promise and more experiments are being conducted at the University of Washington School of Fisheries, Experimental Shellfish Hatchery by Sandra Downing. It appears from her work that a cross of a *C. gigas* (female) by *C. rivularis* (male) is the most successful. Crosses between the two varieties of *C. gigas* (Miyagi and Kumamoto) seem to attain moderate to good success.

Commercial hatcheries are breeding Kumamoto varieties because they are highly desired for of their deep cup morphology. Although the Miyagi variety is the main hatchery oyster used by west coast oyster growers, experimental plantings from hatchery stocks of *C. rivularis* and *C. gigas* of the Kumamoto variety are being made on a limited scale. Both of these latter species have positive attributes for market. It should be noted that for unknown reasons (although pollution is suspect), Kumamoto stocks from the southern island of Kyushu in Japan have essentially disappeared and many Japanese oyster growers have switched to nori seaweed culture.

Competition with the Native Oyster *(Ostrea lurida)*

As indicated above, the Pacific oyster was introduced in the early part of the century to augment the declining native oyster industry, especially in the State of Washington. Since its introduction, the Pacific oysters has essentially taken over most intertidal areas that have potential for growing oysters. There are a few native oyster beds available in southern Puget Sound, but their production is very limited.

Relative to the question of competition with the native oyster, the Pacific oyster has essentially dominated. It has been postulated that there is a lack of adequate food to sustain native oysters,or that there may be some physiological effect, namely, metabolic competition maybe taking place. This has been proven, although in Willapa Bay there has been in most years a good natural set of native oysters on Pacific oyster shells. However, once they grow to about 1 cm, the native oysters died. At that time it was thought that *C. gigas'* metabolites, or feces and pseudofeces, were affecting survivorship of the native oysters, or that there were problems related to available nutrients from phytoplankton that had been greatly reduced by the more intensive feeding and filtering of the Pacific oyster. This has never been proven. There are some small reefs of native oysters still available in isolated locations in southern Puget Sound as well as Willapa Bay in the state of Washington.

Disease

Generally the Pacific oyster is hardy. Up until the late 1960's, the Pacific oyster had very low mortalities compared to C. *virginica* stocks in the Gulf or mid-Atlantic coasts. I ran tests documenting yearling single oysters from a common stock of oysters distributed in trays at California's Humboldt Bay and Oregon's Yaquina Bay from the State of Washington in the 1960's. Less than 10% of these yearling Pacific oysters placed in various experimental situations succumbed during two years of monitoring. Mortalities occurred in British Columbia (Quayle 1988) in 1960 when an disease outbreak lead to loss of 30% of the Pacific oysters. This was referred to as the Denman Island disease, in which pustules on the oyster meat were characteristic. The disease developed in early spring during April when temperatures were just beginning to rise to 9° C from the winter low of about 7° C. The disease apparently disappeared by mid-July when water temperatures had reached 18° C. This cyclical disease existed for only a couple of years in British Columbia, before subsiding with no major mortalities noted since. The causative organism was never identified.

There was a major mortality of Pacific oysters in the State of Washington beginning in the mid 1960's through the early 1970's during the late summer months. As much as 60-80% of some groups of oysters growing into their second summer were dying on specific shellfish beds. This mortality was usually associated with a bed that had warmer temperatures than normal, as well as poor circulation. After extensive sampling and histological studies, no disease organism was ever related to this major mortality which occurred in parts of various bays in Washington as well as Humboldt Bay in California. Later research by the University of Washington tended to indicate that perhaps these mortalities related to physiological stress. Experiments by Perdue et al. (1981) indicated that when the mortalities occurred, the oysters were usually fully ripe. Sampling of the tissues of those families that had the highest mortalities revealed virtually no glycogen as an energy reserve. There was speculation that this lack of glycogen was a consequence of the high fecundity of C. *gigas*, accomplished at the expense of stored energy necessary to keep the individual oysters alive. The mortality of Pacific oysters along the west coast declined greatly by the mid to late 1970's.

Predation and Parasitism

Unfortunately, two major predators were introduced with Japanese oyster seed over the years. These are the Japanese oyster drill *(Ocenebra japonica)* and the turbellarian flatworm *(Pseudostylochus ostreophagus)*. These two species have become well adapted in various oyster growing bays in the State of Washington as well as Humboldt Bay in California Further, the flatworm, which attacks primarily young spat, is a major problem now in southern Puget Sound.

Relative to predation by indigenous organisms, these might be as follows: (1) Red rock crab *(Cancer productus)*. This crab is quite common in the states of Washington and California where it consumes large numbers of oysters. (2) *Cancer oregonensis*. This small crab has been identified as a serious predator on juvenile oysters under 45 cm. (3) Starfish. Several species of starfish attack oysters, but usually on those grown low in the intertidal zone. (4) California bat stingray *(Holorhynus californicus).* This stingray has been linked to consuming oysters growing in the intertidal zone. (5) Birds. It is generally understood that ducks, particularly the lesser scaup, or bluebill *(Aythya affinis)* and the surf and white winged scoters *(Mellanita)* frequent oyster beds in large numbers in winter. At times a considerable portion of the birds' diet may be made up of clams, mussels, and in some cases young Pacific oysters up to 2 cm in diameter.

Success in Aquaculture

It is no secret that oyster culture for the west coast of the United States is very important. Of all the oyster meat produced from the Pacific coast, it would be safe to estimate that over 98% of its production is for C. *gigas.* Because of innovations on remote setting of eyed larvae, dependence on natural catches of seed is now minimal. Almost all of the oysters that are being cultivated on the west coast come from hatcheries and unquestionably this has helped to fuel the success of West Coast oyster culture. This process of remote setting is continually being updated and refined and it is generally understood that many countries and the east coast of the United States are looking for this avenue of producing hatchery eyed larvae to supplement the supply of seed.

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Biographical Notes

PETER AYRES was a senior scientist with the UK government Fisheries Department until 1982. In 1978 and 1980, he was seconded to provide advice on shellfish sanitation to Australian authorities and in 1982 took up a permanent appointment with the then NSW State Fisheries Department. Fisheries was integrated with the Department of Agriculture and Dr. Ayres became Chief of the Division of Fisheries until his resignation in 1987. He is now a self-employed consultant specializing in fisheries, environmental, and aquaculture matters. The Oyster Farmers Association of Australia made Dr. Ayres an honorary life member in recognition of his contribution to the industry.

KEN CHEW is Professor in the School of Fisheries, University of Washington, Seattle, Washington. He is also Director of the Administrative Center for The Western Regional Aquaculture Consortium, one of five USDA regional aquaculture centers in the U.S. His training and expertise is in shellfish biology and culture, but his familiarity with global aquaculture has led to his serving as a science advisor to many countries concerned with encouraging aquaculture and managing their fisheries. He and his graduate students have spent many years studying C. *gigas* in the Pacific Northwest.

PARAMESWAR DINAMANI is a retired malacologist who worked for the New Zealand government from 1969 to 1987. He was the Senior Scientist in the Aquaculture Section of the Ministry of Agriculture and Fisheries' Fisheries Research Division, and was responsible for the division's research related to oyster farming. He reported on the occurrence of C. *gigas* in northern New Zealand and followed the course of the spread of the invader as it overwhelmed the native oyster resource.

PHILIPPE GOULLETQUER became an Assistant Research Scientist at the Chesapeake Biological Laboratory of the University of Maryland System after receiving his Ph.D. from the University of Western Brittany, France, in 1989. His dissertation research was in the field of aquaculture and fisheries, and he worked at France's National Laboratory for Mariculture Ecosystems from 1983 to 1989. He is familiar with the culture of C. *gigas* in France.