Summary of information from Foveaux Strait oyster (*Ostrea chilensis*, OYU 5) strategic research 2000–09: context for the 2010 strategic research plan

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New Zealand Fisheries Assessment Report 2010/20
July 2010

Published by Ministry of Fisheries
Wellington
2010

ISSN 1175-1584 (print)
ISSN 1179-5352 (online)

Michael, K.P. (2010).
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strategic research 2000–09: context for the 2010 strategic research plan.
New Zealand Fisheries Assessment Report 2010/20.

This series continues the informal
New Zealand Fisheries Assessment Research Document series
which ceased at the end of 1999.

EXECUTIVE SUMMARY

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Stakeholder strategic research plans have been established for Foveaux Strait oysters since 2000. They are living documents that focus research, and may change in response to changes in management needs, the fishery, and our knowledge of the fishery that include its interaction with fishing, its ecosystem, and the environment. The Foveaux Strait oyster strategic research plan was last revised in 2004. Since then, our understanding of the way the fishery responds to fishing, and drivers of its production have changed, as have management goals under the new Foveaux Strait oyster fisheries plan approved by the Minister of Fisheries in May 2009. The 2010 strategic research plan aims to underpin the goals of the fisheries plan, and to build on the current knowledge of the fishery. This document provides a context to develop a revised plan and summarises key results from research carried out between 2000 and 2009.

The key goal of the 2004 strategic research plan was the development of a fisheries simulation model that integrated spatially explicit stock assessment, disease, and habitat regeneration models. This goal was based on the evidence that oyster mortality from bonamia is the main driver of recruited oyster population size, and a hypothesis that complex biogenic habitat was crucial to oyster production and that habitat loss had increased disease mortality.

A length-based stock assessment model has been developed for the fishery and used for stock assessments since 2004. The model has been further developed, and has performed well. Stock assessments show that oyster mortality from bonamia is the principal driver of oyster population abundance in Foveaux Strait, and low catch limits are unlikely to have any significant effects on future stock levels. Fishery data suggests markedly different levels of oyster production in subareas of the commercial fishery. Our current knowledge of the fishery suggests spatially explicit stock assessment and spatial management strategies focused on minimising losses from bonamia may be effective in increasing the production of oysters.

An epidemiological model of bonamia was developed to predict the spread of infection and oyster mortality. The cell-by-cell comparisons of survey data frequently showed substantial lack of fit. The model was modified from a 12 cell partition of the commercial fishery area to a 48 cell partition to investigate whether a finer spatial scale analysis improved fits: it did not. The bonamia epidemics in the Foveaux Strait oyster population do not follow the conventional Susceptible-Infected-Removed (SIR) model. Development of the model emphasised the need for a better understanding of bonamia and the data required to predict the spread of infection and the mortality of oysters.

There is an inverse relationship between complex biogenic habitat and oyster production: commercial fishing for oysters is based on sand, gravel, and shell habitats with little epifauna. There was no correlation between fishing effort and bonamia infection and oyster mortality in available data suggesting that dredging disturbance was not a primary factor in bonamia dynamics. In the absence of fishing and natural disturbance, benthic taxa can colonise both fished areas and areas seeded with shell within 20 months and the growth of these animals can be relatively quick. We can not discount the role of benthic taxa in stabilising sediments, which is important to post-settlement survival of oyster spat. These data suggest an integrated habitat model would not significantly contribute to better management of the fishery at this time. Instead, spatial fishing strategies that formalise the current practice in the fishery of avoiding

vulnerable, complex habitats where oyster catch rates and oyster production are low, would be more effective.

The 2010 strategic research plan aims to underpin the oyster fisheries plan and proposes to abandon the 2004 goal of a fisheries simulation model. The main research focus will be on bonamia and strategies to minimise economic losses from disease mortality. The 2010 plan proposes to continue development of integrated spatially explicit stock assessment and disease models. These models could be used to inform the development and evaluation of spatial fishing and management strategies, research into disease processes, and the recording of data from the fishery to allow the responses of different fishery areas to fishing to be better understood.

1. BACKGROUND

Strategic research plans are drafted to underpin management goals and are of most value when management goals are specific and detailed, achievable, and clearly linked in an overall framework. Strategic research plans focus and streamline research to maximise research from investment and provide synergies over a range of research programmes. These plans usually constitute a living document where research focus changes to reflect changes in fishery goals and changes in the information required for better management of fisheries, either as a result of research outcomes or changes in the fishery itself. Since 1996 these strategic research plans have been documented through a number of processes; Ministry of Fisheries (MFish) medium term research plans (MTR), commercial stakeholder fisheries plans, and now MFish facilitated stakeholder Fisheries Plans.

MFish established research planning groups in 1996 comprising MFish staff, stakeholder representatives, other government departments, and science providers. These groups recommend research programmes generally aimed at improving stock assessment and understanding the effects of fishing. A research coordinating committee (RCC) develops strategic research plans that included 3 to 5 year medium term research plans, and recommends research projects for the following year. The shellfish MTR includes strategic research for the Foveaux Strait dredge oyster (*Ostrea chilensis*) fishery (OYU 5). This research has been mainly focused on improving information and tools for stock assessment that include surveys of the oyster population and disease status, sampling the commercial catch, developing stock assessment models and bettering understanding of the oyster disease *Bonamia exitiosa* (bonamia) (Berthe & Hine 2003) and modelling its interaction with the oyster population. Information on the effects of oyster dredging in Foveaux Strait was summarised by Michael (2007).

A 1999 amendment to the 1996 Fisheries Act provided for fisheries plans, where stakeholders (particularly quota holders) could provide independent advice to the Minister of Fisheries and, if the advice was acceptable, take over some or all of the management of their fishery under Fisheries Plans. Implementation of the Act in 2001 introduced an ecosystem approach to fisheries management (EAF) that reflected international trends, and a joint approach to management with industry and other stakeholder groups through fisheries plans. The introduction of commercial stakeholder Fisheries Plans was intended to document management goals and the frameworks of how legislative requirements of the Fisheries Act will be met. These plans were to detail how fish stocks were to be collaboratively managed with MFish. The Bluff Oyster Management Company (BOMC) developed a draft commercial stakeholder fisheries plan in 2004, but before this could be implemented, MFish introduced new, facilitated, Fisheries Plans in 2005. These plans incorporated objectives and goals from all fishery stakeholders (tangata whenua, recreational, and commercial) and aimed to meet legislative obligations and standards (e.g., MFish harvest standards and proposed effects of fishing standards) in a transparent process that incorporated stakeholder knowledge and developed strategic research plans to underpin the fishery goals. Three “Proof of Concept” Fisheries Plans were drafted, including a Foveaux Strait Dredge Oyster Fishery Plan. Development of this plan began in November 2005 and the plan was approved by the Minister of Fisheries, the Hon. Phil Heatley, in May 2009.

A bonamia epizootic in 2000 highlighted the need for a better understanding of bonamia and its interaction with the oyster fishery, and a strategic research plan (2000) was developed by NIWA and BOMC to structure this research (Andrew et al. 2000). The increasing focus on ecosystem approaches to fisheries management and interest in the possible, longer-term effects of fishing on benthic communities and habitats, oyster and blue cod (*Parapercis colias*) production, and bonamia, prompted a revision of the strategic research plan in 2004 (Michael & Dunn 2005a). The 2004 plan was developed to underpin the BOMC stakeholder fisheries plan. Key elements of this plan were managed fishing and spatial management of the fishery, increasing the data recorded by commercial fishers and its use in management, and research towards developing an oyster fishery simulation model for predicting outcomes in spatially managed areas.

2. INTRODUCTION

The Foveaux Strait (Bluff) oyster fishery (OYU 5) is a high value, iconic fishery that has been fished for about 140 years. It is an important fishery nationally with a long tradition established around the oyster season and its socio-economic importance to Southland. Oysters are highly valued by customary fishers of the Awarua Runanga as a toanga species and by recreational fishers who dredge and dive for oysters. Regional earnings from the fishery are significant, \$12–30 million annually since the 1980s. With such high values and profile, interest in research to underpin management of the fishery, to ensure the continued production of oysters, has been high since the early 1900s (Marine Department Annual Reports), and this interest has maintained a high research activity in the fishery. Early surveys have generally been in response to reduced catches, but later research, focused on providing information for management of the fishery.

Research surveys from 1906 to 1965 attempted to map the distribution of commercial densities of oysters (oyster beds), and describe their productivity and the meat quality of oysters within them (Hunter 1906, Sorenson 1968, Stead 1971c, Street & Crowther 1973). Since the 1950s, increasing research emphasis was placed on understanding the biology and ecology of oysters in Foveaux Strait (Fleming 1952, Cullen 1962, Cranfield 1968, 1970, 1971, 1975a, 1975b, 1979, Stead 1971b, Cranfield & Allen 1977, 1979, Jeffs & Creese 1996, Jeffs et al. 1997, Jeffs 1998, Cranfield & Michael 1989, Dunn et al. 1998, 2000a, Jeffs & Hickman 2000).

The status of the fishery was monitored using landings and catch rates until 1992 (see Fu & Dunn 2009). The first attempts to estimate yields from the oyster fishery lacked robustness (Stead 1971c, Allen 1979), and stock assessments based on yield estimates were implemented in 1992 and used until 2003 (Doonan & Cranfield 1992, Cranfield et al. 1993, 1996, and 1999b, Dunn et al. 2002c, 2003, Michael et al. 2001, 2004a, 2004b, Dunn & Michael 2008). Since 1996, yield was estimated for the commercial population (the portion of Foveaux Strait with high oyster densities and likely to be fished) to prevent recruitment overfishing in areas where oyster populations were rebuilding after bonamia mortality. Estimates of commercial population size between 1996 and 1999 used the portion of the population over 400 oysters per tow (roughly equivalent to a commercial catch rate of 6–8 sacks per hour considered economic by fishers in the 1970s and early 1980s) from the entire Foveaux Strait fishery area. A commercial catch rate of 6–8 sacks per hour has no biological basis, but has been used as an indicator of long-term commercial oyster densities. From 2000, estimates of commercial population size were based on estimates of the entire recruited oyster population in areas designated as ‘commercial’ by fishers (Michael et al, 2004b).

Before 2004, the Foveaux Strait oyster fishery was managed by current annual yield (CAY, Method 1 of Sullivan et al. 2005) based on survey estimates of the population in designated commercial fishery areas. Since 2004, the TACC has been based on estimates of recruit size stock abundance from the Foveaux Strait oyster stock assessment model (Dunn 2005, Fu & Dunn 2009) and projections of future recruit size stock abundance under different catch limits and levels of mortality from bonamia.

Significant and rapid declines of the oyster population in Foveaux Strait and corresponding declines in commercial catch rates are driven by disease mortality. The microcell parasite of oysters, *Bonamia exitiosa*, is thought to be endemic to *O. chilensis* in Foveaux Strait and the mortality of oysters from bonamia is a recurrent feature of the Foveaux Strait oyster population. Significant mortality events indicated by the shells of oysters that had recently died (new clocks) and oysters in poor condition, both indicative of bonamia epizootics, were recorded as long ago as 1906. Bonamia has been identified in preserved oyster tissues sampled in 1964 (Hine, NIWA, pers. comm.) at the end of an epizootic that caused a downturn in the fishery (Cranfield et al. 2005). This mortality was originally attributed to *Bucephalus longicornutus* (Hine & Jones 1994). A *B. exitiosa* epizootic was confirmed in the Foveaux Strait oyster fishery in 1986–92 (Doonan et al. 1994, Cranfield et al. 2005) and again in 2000–09 (Dunn et al. 2000c, 2002a, 2002b, 2003, Michael et al. 2002, 2004a, 2004b, 2005b, 2006, 2008a, 2008b, 2009a, 2009b, Michael 2008). Prevalence of infection between 1996 and 2000 was not determined, but is thought to be low (almost undetectable) from the low numbers of new clocks recorded in biennial oyster population surveys. Since the 1986 epizootic, research effort has focused on identifying the pathogen and its pathology (Hine et al. 1986, 1992, 1996a, 1996b, 1998, 2001, 2002, Dinamani et al. 1987a, 1987b, Hine 1990, 1991a, 1991b, 1991c, Hine & Wesney 1992a, 1992b, 1994a, 1994b, Hine & Jones 1994, Diggles & Hine 2002, Diggles et al. 2003, Diggles 2004) and later attempts to model the spread of infection and mortality of oysters (Gilbert & Michael 2006, 2008).

Research undertaken between 1986 and 1999 comprised three, independent research streams, each funded from different sources. MFish contracted research was focused on population surveys and determining the status of infection from bonamia for stock assessment; research to investigate the effects of oyster dredging in Foveaux Strait funded by the Foundation for Research Science and Technology (FRST); and an oyster enhancement programme to investigate strategies to rebuild the fishery after catastrophic mortality from bonamia (Doonan et al. 1994) undertaken by the Bluff Oyster Enhancement Company (Keogh, reports to BOMC, 1995–99) with industry funding.

The recurrence of a bonamia epizootic in 2000 forced a reassessment of information required to manage the Foveaux Strait oyster fishery. A strategic research plan (Andrew et al. 2000) was developed to focus research effort on better understanding the biology and epidemiology of bonamia, and particularly understanding disease transmission through oyster populations and its relationship with the fishery. Proposed investigations included (1) methods of detection such as in-situ hybridisation (ISH), (2) understanding the course of infection, (3) triggers for epizootics, (4) spread and interaction with oyster population, (5) the effects of stress from dredging due to altered habitat complexity on occurrence and spread of infection, (6) burial by sand, and (7) mechanical disturbance from dredge contact. The 2000 strategic research plan also proposed long-term research focusing on information for better management (determination of sustainable yields in the long term) of the fishery that included (8) a length-based stock assessment model for oysters and (9) to begin development of an epidemiological model of bonamiosis.

From the mid 1990s there was concern that complex benthic habitats and benthic communities dominated by the bryozoan *Cinctipora elegans* were critical to the production of oysters and reducing bonamia mortality, and that the effects of oyster dredging had reduced oyster productivity and increased mortality from bonamia (Cranfield et al. 1999a). The strategic research plan was updated (Michael & Dunn 2005a) to incorporate research into the effects of oyster dredging to provide information for ecosystem approaches to managing the oyster fishery. The focus of this plan was to develop an understanding of critical relationships between oyster dredging, oysters, and blue cod production, oyster mortality from bonamia, changes in benthic habitat, and their underlying processes to support ecosystem approaches to fisheries management. This plan also aimed to model these data integrating oyster population, disease, and habitat regeneration models within a fisheries simulation model to provide the predictive capacity to develop and evaluate fishing and management strategies (Figure 1). Information for this simulation model was to be provided by data routinely recorded by fishers' in-season from the fishery (fishers' logbook programme), and fishery-independent sampling out of season. To fully implement this plan, spatial management of distinctly different habitats within the fishery would require structured fishing and fleet management to assess the success of fishing strategies.

Two major bottlenecks limiting oyster abundance were identified: (a) the settlement of oyster spat and survival of juveniles for recruitment into oyster populations, and (b) the high mortality of predominantly large oysters from bonamia. Oyster settlement and spat survival is predominantly on live oysters. At a fishery scale, oyster production is likely to vary within the fishery area, and from year to year. These differences may be driven by habitat, hydrographic features within Foveaux Strait, such as weather driven gyres, environmental factors and stressors, and by oyster density. Disease transmission and oyster mortality are high in fishery areas with high oyster density. The research proposed in the 2004 plan also aimed to reduce bottlenecks by developing strategies to (10) promote the rebuilding of the Foveaux Strait oyster fishery, (11) minimise the impacts of dredging on benthic habitat, oyster, and blue cod production, (12) minimise the impacts of disease mortality, primarily from bonamia on the oyster populations, and (13) develop a predictive capacity to evaluate management strategies for the Foveaux Strait oyster fishery and its benthic habitats.

Information available in 2003 suggested that oyster dredging may reduce the productivity of oysters by affecting the composition of benthic communities and seabed characteristics critical to the settlement and survival of oysters (Cranfield et al. 1999a, 2003, 2004, Cranfield 2003), the production of other species such as blue cod (Carbines et al. 2004), and increase disease mortality in oysters (Cranfield et al. 1999a). The return of oyster shell to the seabed can facilitate the regeneration of benthic communities within 28 months (Cranfield et al. 2001), including the bryozoan *Cinctipora elegans* believed to be critical to oyster settlement and survival. Cranfield et al. (2001) proposed rotational fishing strategies that allowed for area closures after fishing to allow the regeneration of benthic communities and oyster production. Such a strategy would require fleet control and spatial management of fishery areas, similar to paddock based management.

A long-term goal of the strategic research plan (2004) was to develop a fishery simulation model with the capacity to predict the outcomes of management strategies including structured fishing of each “paddock”. This objective requires extensive development of stock assessment, disease, and habitat models. However, the research plan also recognised the need for concurrent research on oyster population dynamics, the effects of fishing on oysters, benthic habitat, and disease, and their interactions. A better understanding of these biological and ecological processes is important for both the better management of the fishery and for understanding fishery interactions which form the basis of the simulation model.

Much of the information for model development was proposed to come from a wide range of fishery scale investigations carried out by fishers, and supported by NIWA. These are experiments over the whole commercial fishery area, run concurrently with commercial fishing, with the direct involvement of fishers. This approach aimed to identify which data could be recorded by fishers in season, and what additional data needed to be recorded out of season by BOMC or fishery-independent research.

This document summarises the key results from research undertaken from 2000 to 2009 and the development of the stock assessment and disease models to fulfil the requirements of OYS200701 objective 2. This summary of the state of knowledge of the Foveaux Strait oyster fishery and how our understanding of the fisheries has changed provides a basis from which to develop the next stage of the Foveaux Strait oyster strategic research plan, to underpin goals and strategies in the Foveaux Strait oyster fisheries plan (Ministry of Fisheries 2009). The strategic research plan (2010) will be documented in a subsequent report under project OYS200801 objective 2.

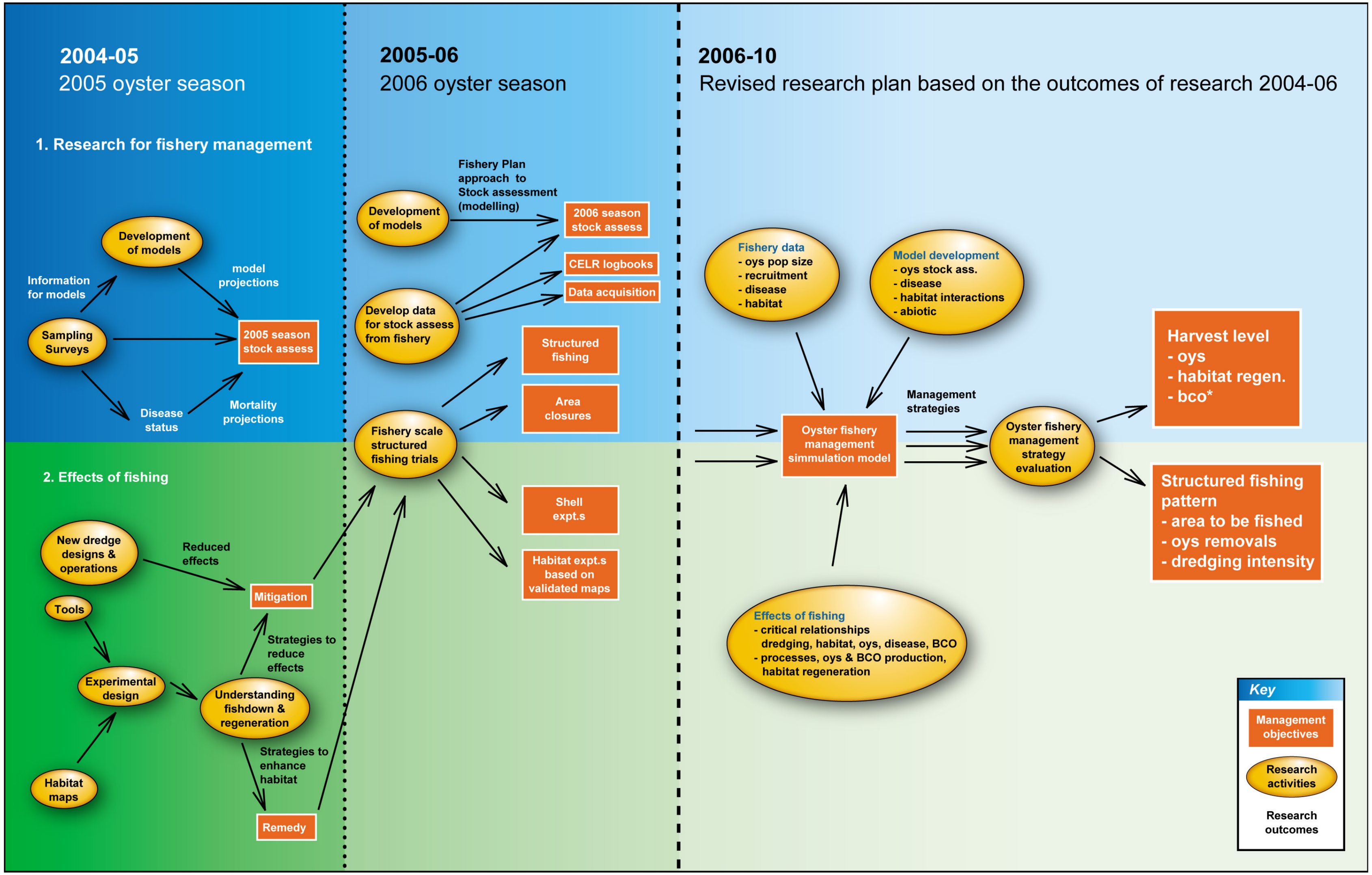

Figure 1: Overview of 2004–10 strategic research plan (Michael & Dunn 2005a).

3. KEY RESULTS FROM STRATEGIC RESEARCH

Detailed information on the Foveaux Strait oyster fishery (OYU 5), the biology and ecology of oysters, and changes its management and stock assessment are summarised in the Ministry of Fisheries working group reports (Annala et al. 2002; Michael et al. 2009b; Ministry of Fisheries 2008) and in the Foveaux Strait dredge oyster fisheries plan (Ministry of Fisheries 2009). Information from strategic research between 2000 and 2009, changes in stock assessment and an understanding of key processes that drive oyster abundance are discussed below, along with knowledge gaps and limitations constraining better assessment and management.

3.1 The stock

The Foveaux Strait oyster fishery management area (OYU 5) extends from the western boundary in a line from Oraka Point, to Centre Island, to Black Rock Point (Codfish Island), to North Head (Stewart Island); and the eastern boundary is from Slope Point, south to East Cape (Stewart Island), and covers an area of 3300 km^2 (Figure 2). Almost all commercial dredging is carried out within the Foveaux Strait oyster stock assessment survey area (Figure 2), which covers 1074 km^2. Boundaries of statistical areas for recording catch and effort (Ministry of Fisheries catch effort landing returns, CELR) were established in 1960 and the outer boundary of the oyster fishery in 1979 (Figure 2). These are arbitrary partitions of the fishery and statistical reporting areas do not relate to the distributions of oyster densities, benthic habitats, or any fishery attributes.

The fishery is considered a single stock, and stock assessments have always used the absolute population size of recruited oysters (or a portion of the total population considered commercial) from the commercial fishery area to estimate yields and make projections of future stock size (Allen 1979, Cranfield et al. 1999b, Fu & Dunn 2009). In 1975, reportedly almost all the commercial fishery covered 374 km^2, but commercial oyster areas (of high oyster density) covered only 12 km^2 (Allen & Cranfield 1979). At that time, the oyster fishery consisted of a number of discrete small dense patches generally separated by extensive areas with low densities of oysters; 91% of the total oyster population was located in about 50 patches. However, the surveys of Stead (1971c), suggest that the distribution of oysters in high density patches may have been more extensive.

Oyster mortality from recurrent bonamia epizootics have removed areas of high (commercial) oyster density from the fishery, reducing oyster density to low background levels (Figure 3). The Foveaux Strait oyster population is likely to be highly productive and has shown an ability to quickly rebuild from low levels. The distribution of oyster density has shown similar spatial and temporal patterns over time (Figure 3). Stock assessment surveys have shown fishery areas with high oyster densities that were reduced by bonamia mortality, that have twice rebuilt in the same areas. Fishery areas that had low oyster density before the recent bonamia epizootics still have low oyster density, suggesting different levels of oyster production within the fishery.

There is increasing information on factors that may drive differences in oyster productivity between fishery areas. Environmental gradients that influence habitat composition and sediment stability, oyster larval supply, and post-settlement mortality may be key factors. Areas of high oyster density are also more at risk from bonamia mortality. Eastern fishery areas are not as productive as southern, central, and western areas, but oysters there have better meat condition.

Given the spatial and temporal differences in the distribution of oyster density within the fishery, spatially explicit harvest and management strategies could optimise harvest, market value, and the rebuilding of oyster stocks in these areas. Spatial management is generally driven by EAF, and based on either rotational or permanent closures. There are no examples of fishing strategies to spatially optimise harvest, and minimise or eliminate rotation times in New Zealand fisheries. Only the Challenger Scallop Enhancement Company has employed structured rotational fishing combined with enhancement of rotated areas (Mincher 2008), but with little success in maintaining long-term productivity in the fishery.

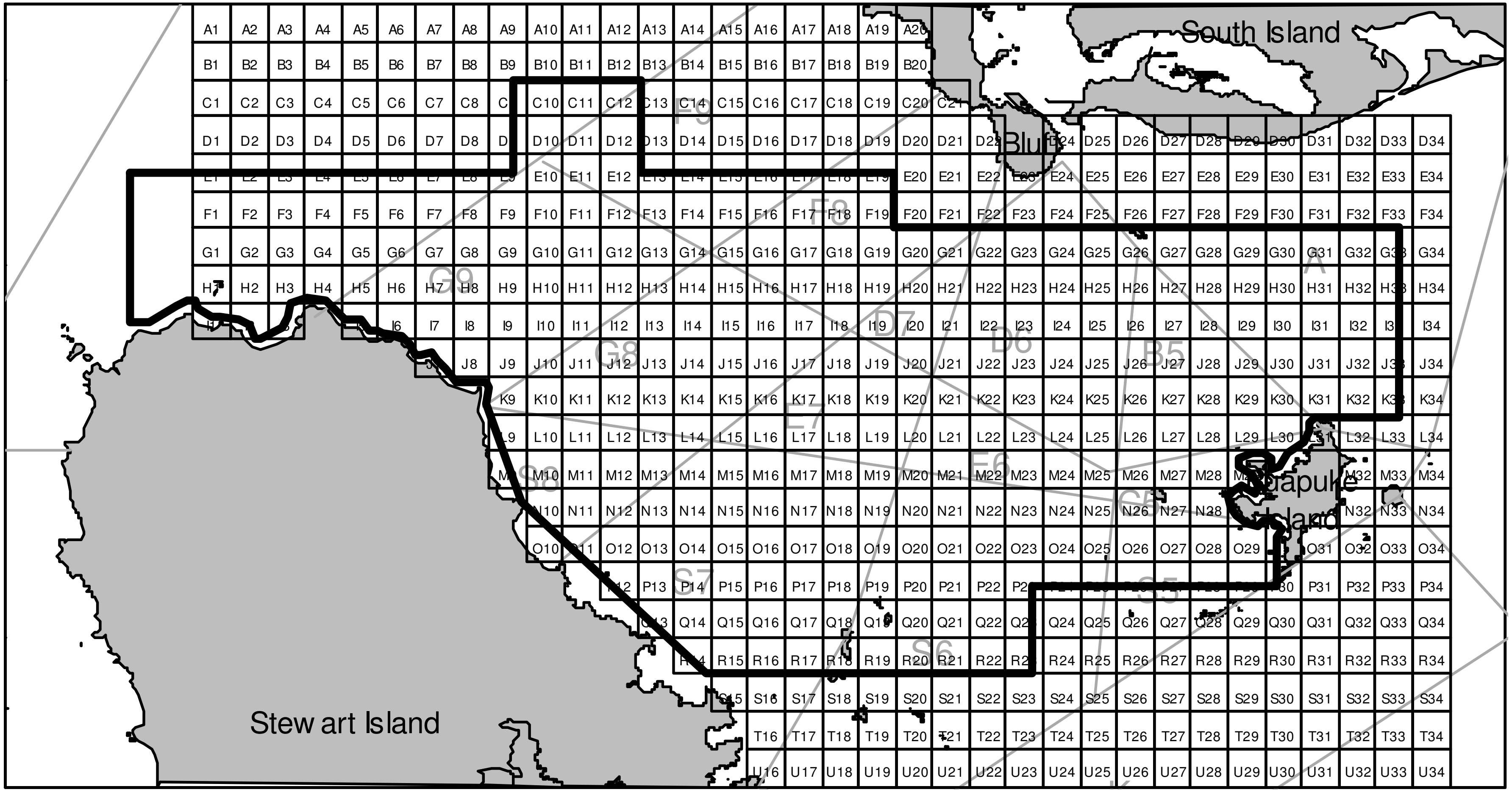

Figure 2: Foveaux Strait oyster logbook grid (1 nautical mile squares, black lines and labels) established by skippers to cover the commercial fishery area and the boundaries of the Ministry of Fisheries oyster fishery statistical reporting areas (grey lines and labels). The boundary of the stock assessment survey area is shown as a heavy black line.

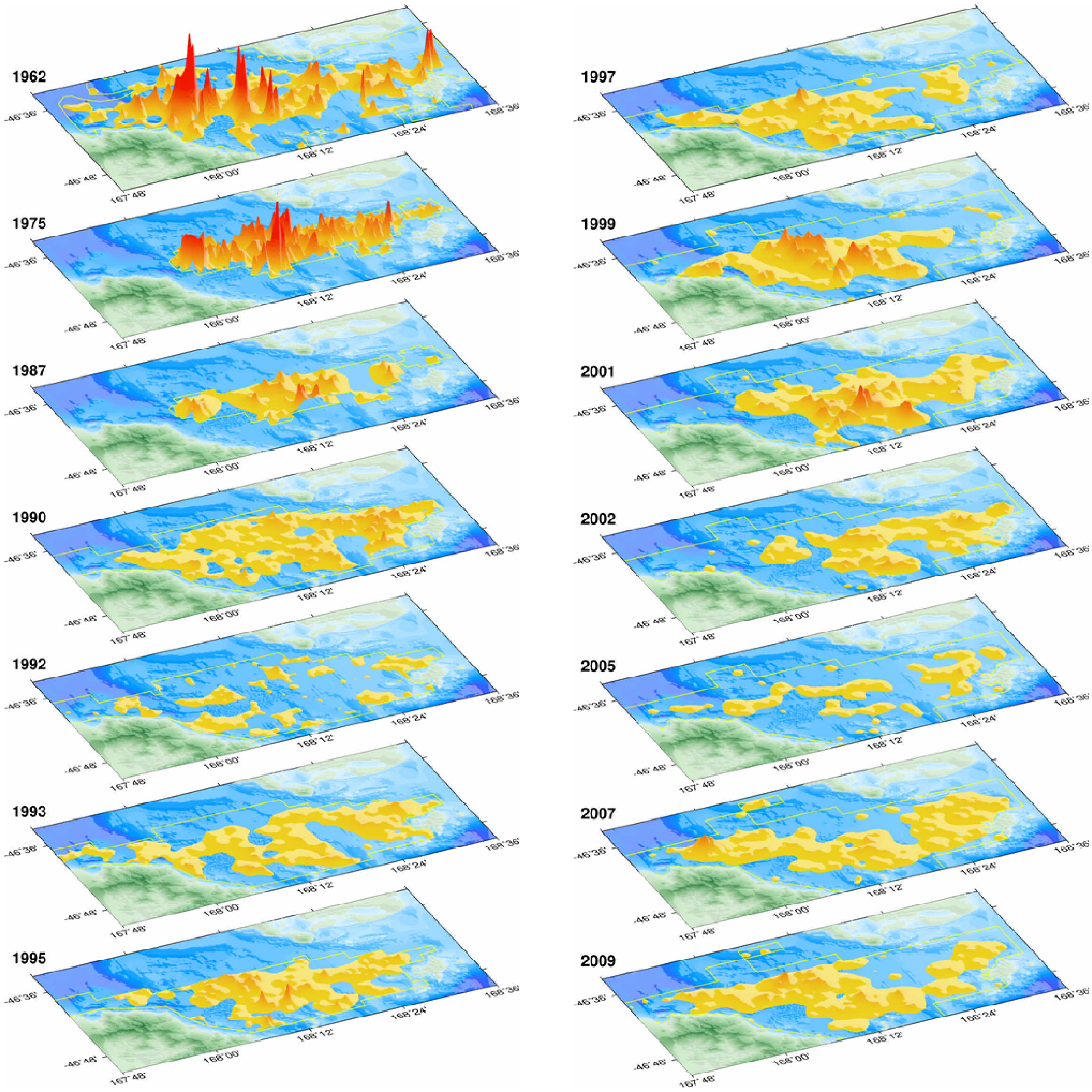

Figure 3: The distribution of recruit-size oyster density from research surveys between 1962 and 2009 showing persistent fishery areas and the effects of bonamia mortality on the stock (from the figure of Dunn (2005), updated by Fu (2009).

3.2 Biological parameters

The biological parameters used for stock assessment were summarised by Fu & Dunn (2009). Better estimates of growth and mortality could improve projections from the stock assessment model (A Dunn, NIWA, pers. comm.), and area specific growth and mortality estimates will be desirable for spatially explicit stock assessments. Anecdotal evidence suggests that natural mortality varies with the fishery area, with oyster size, and over time. No new research to estimate biological parameters has been undertaken between 2000 and 2009.

A BOMC fishery scale spat monitoring programme to provide data on oyster recruitment patterns and the growth of oyster spat has been running since November 2007. The fishery is stratified by area (west, south, and east), and by oyster production (areas are designated as high or low production areas by oyster skippers). Throughout the fishery area, oyster spat settlement is similar or consistently higher at designated high production sites, compared to their paired low production sites. These data show distinct seasonal patterns of settlement for both oyster larvae and the larvae of other benthic taxa. Peak settlement of oyster spat occurs between November and February and the lowest settlement is between July and November. The latter is consistently a period of very high barnacle settlement, often occupying 90–100% coverage of settlement collector plates. The mortality of oyster spat on plates is less than 30% between November and February. Settlement strength varies between years with marked differences of up to threefold in numbers of settled oyster spat. Settler density was much higher at the western high site than southern or eastern high sites. Oyster spat that had settled in February samples were 2–4 mm in length. At the eastern high site, some spat had grown to 45 mm in length in 21 months, suggesting two-dimensional growth may vary temporally and spatially.

3.3 Oyster mortality from bonamia infection

The 2000 bonamia epizootic suggested that bonamia mortality events were a recurrent feature of the oyster fishery. The research focus of the 2000 Foveaux Strait oyster strategic research plan (Andrew et al. 2000) was to better understand bonamia and its interaction with the fishery. Andrew et al. (2000) provided a summary of information on bonamia and developed a research plan aimed at providing information and detection tools that may ultimately allow predictions of the triggers for bonamia epizootics, the spread of bonamia infection, and levels of oyster mortality. As part of this plan, Diggles & Hine (2002) undertook a number of laboratory experiments to use in situ hybridisation (ISH) to detect very light bonamia infections and to test the sensitivity of heart imprints, histology, and polymerase chain reaction (PCR) methods. They also attempted to purify bonamia from infected oysters to determine how long bonamia can live outside the host, with the aim of understanding the course of infection, fatal intensities of the infection, and the ability of bonamia parasite to survive outside the host and the likely range of spread. Investigations were also carried out to determine the effects of repeated stress on bonamia-infected oysters.

3.3.1 Methods of detecting bonamia infection

Trials to investigate the utility of a number of bonamia detection methods and their sensitivities suggest that heart smears are the most time- and cost-effective method for screening large numbers of oysters for bonamia (Diggles et al. 2003). In-situ hybridisation appears useful for screening small numbers of oysters where high sensitivity is required, but this method is also sensitive to the preservation and storage of samples, and is expensive. Histopathology should be used where detection of physiological state, other disease agents, or pathological lesions is required. Since 2000, sampling of oysters for bonamia infection included archiving tissues that can be examined for concurrent infections in the future. Polymerase chain reaction appears to have limited application for detecting bonamia infections if not used in conjunction with other diagnostic methods to standardise the analysis and minimise false positives (Diggles et al. 2003). A more reliable PCR enzyme-linked immunosorbent assay (ELISA) technique based on the selective amplification and labelling of a bonamia gene using bonamia specific primers is being developed. The labelled PCR products are detected on an ELISA multi-well plate format, which allows simultaneous detection from multiple samples. The PCR ELISA method provides high specificity, due to selective PCR amplification and target-specific capture probe technology, and high sensitivity, due to the nature of the detection substrate used in the ELISA test. The ELISA format (96 well plate) makes it suitable for screening a large number of samples. The colorimetric detection has the potential for semi-quantitative evaluation of the amount of template (bonamia DNA) present in samples, once suitable standards have being developed. Development of this method is of high priority and important to future oyster research.

3.3.2 Categories of the intensity of infection

The mean intensity of infection is the mean level of infection in infected oysters only, based on a categorical scale. Diggles et al. (2003) developed a semi-quantitative scoring technique to grade bonamia infections in heart imprints into of six stages. Stages 1 and 2 are relatively light infections and do not appear to affect oysters. Stage 3 infections are elevated and systemic, with minor tissue damage throughout the host. It appears likely they will progress to stage 4. Stage 4 infections are systemic, and all tissues are congested with infected haemocytes; death appears inevitable. Stage 5 infections differ from those of stage 4 in that tissue damage is extreme throughout the oyster, tissues have lost their integrity, and the oyster is near death. Category 0 assumes oysters are not infected, but the sensitivity of heart imprints suggests an unknown proportion of category 0 oysters may have low levels of infection. Heart imprints may underestimate low level infection by 30%. While there is some uncertainly about the true prevalence in samples, projected estimates of mortality based on the proportions of oysters in stock assessment survey tows with stage 3 and greater intensities of infection have proved to be reliable. Estimates of recruited population size from stock assessment surveys have been consistent with projections based on stock size from the previous biennial assessment survey, bonamia and fishing mortality, and expected recruitment based on the population size of pre-recruit oysters.

3.3.3 Factors that may contribute to intensification of infection

While laboratory experiments cannot account for the complex interaction of factors influencing biological and ecological processes, they can provide information on the response of oysters infected with bonamia to specific treatments in isolation of most other factors. Diggles & Hine (2002) found significant differences in the intensities of bonamia infection between those oysters that had died and those that had survived the experiments, confirming bonamia and not the treatments (except for the one hyposalinity treatment) had killed the oysters. Experiments to investigate factors increasing the prevalence of infection (number of infected oysters in the samples) found no differences between controls and treatments, but significant differences among the treatments. The three treatments with highest percentage prevalence were increasing water temperatures to 25 °C for one hour (97%), exposing oysters to infected oysters in a confined area (93%), and regular mechanical disturbance four times a day for two weeks (92%). Increasing temperature and disturbance also increased the intensity of infection, and female and spent oysters were more likely to die from high intensity infections than male and hermaphrodite oysters.

3.3.4 Predisposing factors of infection

All oysters examined in the experiments of Diggles & Hine (2002) had concurrent infections from an undescribed apicomplexan, but there were no significant differences in the intensities of apicomplexan infections between live and dead oysters, suggesting bonamia was the cause of death, but apicomplexan infections may have predisposed oysters to intensifying bonamia infections. The prevalence of bonamia in control oysters increased from 6% at the beginning of the experiment to 70–80%, and was higher for treatment oysters. Diggles & Hine (2002) suggested that holding oysters in captivity, handling, and exposure to infected oysters predisposed uninfected oysters to bonamia. Another explanation could be that most oysters sampled were infected, but many had levels of infection that could not be detected with standard techniques. Developing a cost effective, bulk, high sensitivity method for the detection of low level infections of bonamia is critical to understanding the disease dynamics and course of infection.

Bonamia research to date has focused on a single, endemic species of bonamia thought to be responsible for oyster mortalities. Hine (2002) found that 85% of oysters sampled over a five year period had undescribed apicomplexan infections. There was a statistically significant association between intensities of bonamia and apicomplexan infection. Prevalence and intensity of bonamia infection was related to the intensity of apicomplexan infection (presence of zoites), with only 3.8% of bonamia infections occurring in the absence of apicomplexan infection. The converse was not the case, as 75.3% of apicomplexan infection occurred in the absence of bonamia. Apicomplexans may increase the susceptibility of oysters to bonamia by occupying and destroying haemocytes, and by destroying connective tissue cells and utilising host glycogen reserves. These data illustrate the importance of predisposing factors in the development of bonamiosis in oysters. However, contributing factors may be varied and their interactions complex, and may include biotic and abiotic stressors such as other oyster diseases, toxic algae, and environmental stress. During the summer of 1999–2000 when the latest bonamia epizootic began, recreational divers observed a broad range of taxa dead on the seabed including fish and gastropods (Peter Moir, Southland recreational fishers' representative, pers. comm.), which suggests that some global factor may predispose oysters to bonamia.

3.3.5 Course of infection

Diggles & Hine (2002) purified bonamia from infected oysters; 2 or 3 heavily infected oysters yielded between 10^6 and 10^7 bonamia parasites. Over half of these can survive at least 4 days (and many upwards of 5 days) at normal salinities and 18 °C. Results from experiments investigating the course of bonamia infection in oysters were inconclusive. Mortality was thought to occur with 3–4 months of infection in Foveaux Strait, but inoculated oysters with high levels of bonamia died within a week in laboratory trials.

These data provide further evidence for the interaction between bonamia and the oyster fishery, and some insights into the course of infection. However, several key questions remain; *Bonamia exitiosa* was identified from oyster tissues preserved in 1964, but heightened mortality of oysters was not recorded between 1964 and 1986 (this doesn't necessarily mean there was no heightened mortality; there are reports of heightened localised mortality recorded in the Foveaux Strait fishery since 1906). Over this period of 22 years, the fishery experienced the highest fishing effort and catch rates, and consistently high catches. There is no obvious trigger (or triggers) for the 1986 bonamia epizootic, but given that bonamia was assumed to be present in the fishery, other predisposing factors are likely to be implicated. The information from Diggles & Hine (2002) shows that once the epizootic had begun, high mortality in high oyster density areas was likely to cause a cascade of infection through the fishery, with those oysters in close proximity to large numbers of dying oysters likely to be exposed to near lethal densities of bonamia parasites, and those oysters further away likely to have increasingly fewer bonamia constituting light and undetectable infections. The ability of bonamia to remain viable after four days provides the opportunity to spread infection over the entire fishery area. The diffusion of infection down a gradient could result in oysters far from to the source of infection becoming lightly infected, and a potentially long time lapse before they develop fatal infections.

3.3.6 Effects of dredging and bonamia infection

Cranfield et al. (2005) hypothesised that mechanical disturbance and the removal of epifauna by dredging may predispose oysters to bonamia. Preliminary analysis of the distribution of fishing effort accounting for 100% of the annual fishing effort from fishers' logbook data and the distribution of prevalence and intensity of bonamia infection in oysters from fishery-independent surveys between 2006 and 2009 does not support this hypothesis. No direct or immediate effects of oyster dredging on disease status can be determined from these data.

3.3.7 Predictions of oyster mortality from infection

Doonan et al. (1994) and Cranfield et al. (2005) described the epizootic as broadly fitting a simple deterministic epizootic model and suggested that both diffusion and turbulent processes were important in the transmission of infection. A key element of the 2004–10 strategic research plan (Michael & Dunn 2005a) was to develop an epidemiological model for bonamia that could be incorporated into a fishery simulation model, and to continue annual surveys of the prevalence and intensity of infection in Foveaux Strait oysters. Development of the epidemiological model (Gilbert & Michael 2006, 2008) and data from the annual surveys of bonamia show bonamiaosis does not follow a simple epizootic model. Firstly, high prevalence and high intensity of infection can remain within localised areas for some time after the initial high mortalities had occurred even at low oyster densities. This may be due to variance in the exposure of individual oysters to infection pressure within this area and variation in the course of infection (the time taken for lowly infected oyster to develop fatal infections). Heart imprints, the main tool for detecting infection in oysters, are not reliable for detecting very low levels of infection. Low level infections may take a long time before they intensify, if at all. Secondly, bonamia surveys have shown there can be high variability of oyster density and the prevalence and intensity of infection at a small spatial scale that can not be easily incorporated into a predictive epidemiological model. Finally, information on oyster mortality in the fishery from bonamia is dependent on estimates from new clocks (the shells of oysters that had died since the last summer). The catchability of these new clocks varies spatially and their classification as new (from old clocks with fouling organisms on the inner shells) can be difficult at times. The eastern fishery is characterised by strong tidal currents and gravel substrates, and some of the shells of dead oysters are probably transported out of the area thus underestimating mortality. In western fishery areas, the sand substrate can be mobile and the shells of dead oysters may be buried in sand, initially underestimating mortality, but may eventually be scoured out of the substrate some time later and be mistaken as new clocks as their burial has preserved the articulation of the hinge and prevented the settlement of fouling organisms. The bonamia model had difficulty fitting new clock densities to the levels of mortality.

3.4 Effects of dredging

Much of the 2004 fisheries plan focused on avoiding, mitigating, and remedying the effects of oyster dredging based on the hypotheses developed from local ecological knowledge (LEK) that oyster dredging has long-lasting and cumulative effects on benthic communities of bryozoan dominated complex assemblages, and that commercial densities of oysters were found only on these biogenic reefs. Further, that these biogenic reefs are critical to oyster production (recruitment, survival, and growth), and the reduction in the biogenic reefs has been responsible for bonamia epizootics that have severely reduced the oyster population (Cranfield et al. 1999a, 2003, 2004, 2005, Cranfield & Michael 2002).

During development of the Foveaux Strait oyster fisheries plan (Ministry of Fisheries 2009), oyster skippers questioned the interpretation of the interview data they provided to the LEK study of Cranfield et al. (1999a). The fisheries plan group asked for available data to be summarised, to assess whether there was sufficient data to guide future research. As a result, two more investigations were established: interviews with the skippers interviewed by Cranfield et al (1999a) by an independent Ministry of Fisheries researcher (Hill et al. in-press), and a summary of the effects of fishing in Foveaux Strait (Michael 2007).

Hill et al. (in-press) highlighted the importance of appropriate data collection, design, and interpretation and presentation of LEK. The study examined the fishery and the effects of fishing in a wider context than that of Cranfield et al (1999a), and the range and diversity of LEK within the fishery was much more variable and broader than the LEK reported by Cranfield et al. (1999a). The Hill et al. (in-press) study called for a reassessment of the hypotheses on ecological associations and the relationship between benthic habitat and oysters. The LEK suggests that although oysters are found within biogenic reef habitats, they are not dependent on this habitat alone, and other habitats may produce higher qualities and densities of oysters. This suggests that the recovery of oyster populations may not be dependent on the recovery of biogenic reefs and forces re-evaluation of the conclusions of Cranfield et al. (1999a, 2004).

Michael (2007) summarised information on the effects of fishing, specifically oyster dredging in Foveaux Strait. There were no scientifically robust studies of specific effects of fishing at the spatial scale of Foveaux Strait, and although a number of publications have put forward hypotheses, and suggest fishery-scale effects, these are yet to be tested. A key limitation of any analysis is the paucity of historical data on the composition and distribution of benthic communities and on fishing effort at appropriate spatial scales.

The effects of fishing are gear and site specific; dredging and bottom trawling on biogenic habitats are considered the worst gear type and habitat combinations. The data available at the time (Michael 2007, Hill et al. (in-press) and data recorded in fishers' logbooks 2006–09 (Michael 2009) show fishery areas that support high densities of oysters are stable, or rebuild rapidly in the absence of disease mortality in areas fished repeatedly over many years, and these areas are characterised by sand, gravel, and shell substrates with little biogenic fauna. Although some dredge bycatch contains sessile biogenic species, sponges and mixed invertebrates (bryozoans, ascidians, and mytilids), these generally represent very low proportions of the bycatch, which is mainly shell.

Benthic communities exposed to high levels of natural disturbance generally have high resilience to change (these are considered to be mainly on sand and gravel habitats dominated by infauna). Natural disturbance is known to be considerable in Foveaux Strait, but it has not been addressed in the development of effects of fishing hypotheses. Foveaux Strait is the highest energy environment in mainland New Zealand, where oceanic swells and tidal currents shift sediments and shape habitats and their benthic communities. The shelter of Stewart Island and the depth and topography of Foveaux Strait produce gradients of natural disturbance, sediment stability, and composition. In areas where the sediments are mainly stable, dredged areas can recover from disturbance relatively quickly, within 20 months in areas enhanced with shell and within 4 years in the absence of fishing according to bycatch records in logbooks (Cranfield et al. 2001). The nature and scale of regeneration in fishery areas is not well described.

Dredging causes immediate and localised disturbance. Observations and bycatch data imply that dredges remove and damage some benthic fauna, especially erect epibenthic fauna, reducing structural complexity and habitat heterogeneity. Fishers assert that the removal of this fauna enhances both post-settlement survival and improves meat quality (Hill et al. in-press). However, the footprint of the oyster fishery is small relative to the fishery area and does not often encroach on complex sponge-dominated areas thought to be climax benthic communities in Foveaux Strait (Michael 2007).

Cranfield et al. (2005) suggested that the 1986–92 bonamia epizootic may have been caused by the increasing stress of mechanical disturbance of oysters by increasingly intense dredging and the increasing scale of modification of benthic habitat by fishing. Fishing effort (hours dredged) peaked in the late 1960s (Figure 4), well before the 1986 bonamia epizootic. The current commercial dredge (double-bit, double ring bag, bottom-opening dredge weighing about 400 kg) was introduced in 1968 (Cranfield et al. 1999a) and the introduction of heavier bit bars at the beginning of the 1984 oyster season increased the weight of these dredges to 530 kg. Cranfield et al. (1999a) inferred that the introduction of heavier dredges may have increased stress on oysters, caused the 1986 epizootic, and increased the removal of epifauna. Oyster skippers and a local engineer, Wayne Philipson of Bluff Engineering who has built these dredges since the 1970s, disagree with this generalisation. In 2009, commercial oyster dredge weights varied between 420 kg and 530 kg; the weight is primarily determined by bit bar weight and ring bag length. Although individual skippers have experimented with weights and design features since their introduction pre 1965 (David Stead, dated photograph), skippers insist that these dredges have remained relatively unchanged.

During the 2008 and 2009 disease and stock assessment surveys, oysters were sampled for the prevalence and intensity of infection by bonamia, stratified by fishing effort recorded at 1 nautical mile square grids in fishers' logbooks. The Shellfish Working Group agreed that there was no correlation between fishing effort the previous oyster season and bonamia infection in oysters the following summer (author's unpublished data). Although a lag effect of stress from dredging or some complex interaction between dredging and other factors couldn't be ruled out, dredging related stress is not the primary and immediate factor driving infection status in oysters.

A Ministry of Fisheries review of Michael (2007) concluded that "Biogenic bycatch has declined over time in the regularly-fished part of the fishery. There may have been a reduction in biogenic reefs in the strait since the 1970s, but there are few hard data, and there is no consensus that such reefs were extensive or dominated by *Cinctopora* [*elegans*]. Analysis of death assemblages shows there must have been substantial amounts of bryozoans and molluscs in the strait at some time, but other invertebrates do not leave such traces. We can say very little about changes in habitat or community composition before 1960" (Martin Cryer, Ministry of Fisheries chair, 18 September 2008, pers. comm.).

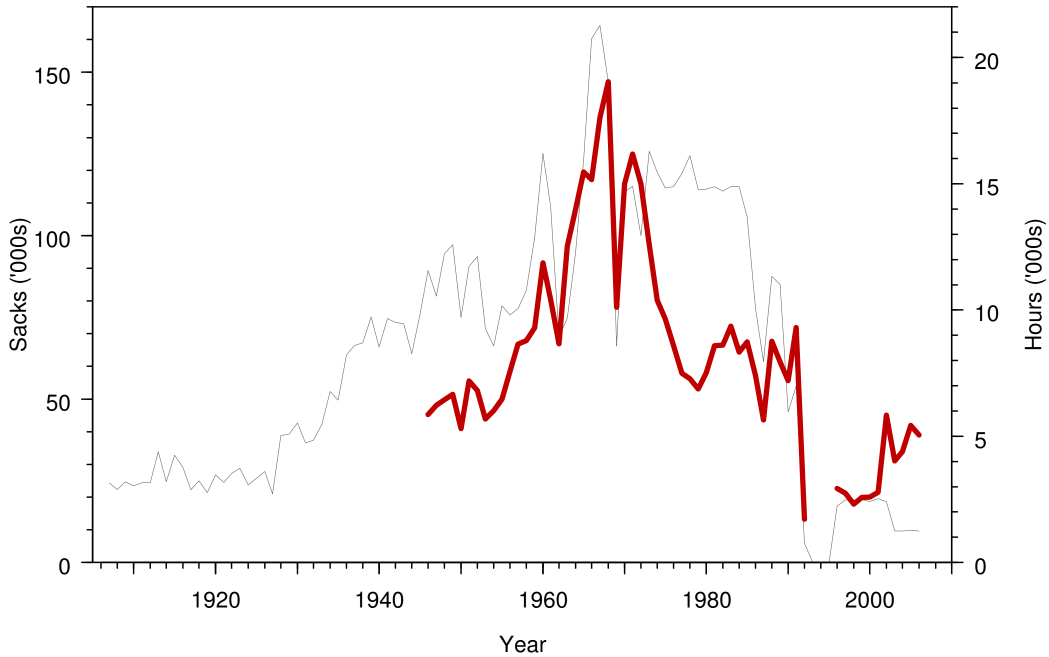

Figure 4: Number of hours dredged per season, 1948–2006 (heavy line). Where no data were available, estimates were back-calculated from revised mean annual catch rates (sacks per hour) of Dunn (2005); total number of oysters landed (sacks estimated from numbers of oysters).

3.4.1 Effects of fishing research, 2004–09

The impacts of dredging on benthic habitats, epibenthic fauna, and oysters cannot be avoided if we accept that some form of dredging is required to harvest oysters. The effects of dredging can be minimised by developing spatially managed fishing strategies to avoid these effects in unproductive, but sensitive, ecological areas, developing new fishing technologies and procedures to mitigate these effects, and by trialling oyster and habitat enhancement strategies to remedy any effects.

3.4.1.1 Spatial management and fishing strategies

Identifying key drivers of oyster production is important to both spatial management of the oyster fishery, and to the fishery simulation model for predictions to evaluate the outcomes (future stock size) of different fishing strategies. This research focus was initially developed under the assumption of the importance of complex benthic communities to oyster production.

Significant progress has been made in the development of spatial management and fishing strategies, and this objective is ongoing. A preliminary habitat map has been developed using the distribution of sediments of (Cullen 1967) and interpolation of habitat data from the video transects sampled in 2006 (Michael 2007) (Figure 5). Further development and validation of this habitat map has begun using benthic video and digital images. Seasonal patterns of commercial dredging and prospecting are recorded in fishers' logbooks (Michael 2009), and these data contain information on the distribution and proportion of sponges and mixed invertebrates in the catch. Further, a Seafood Innovations Limited programme (SILs) is investigating the drivers of oyster production to delimit high production and low production areas. The experimental approach aims to determine a time-series of data on the densities of oyster spat and benthic invertebrate settlement on cement board plates at six locations. Potential settlement surfaces for oyster spat and the composition of benthic communities will be described from sampling the bycatch of dredge catches, the use of benthic still and video cameras, and diver sampling at these sites. These data may also provide an understanding of the causes of oyster spat mortality, both biotic (predation) and abiotic (smothering or abrasion by sediment). Time series data to date show differences in the availability of oyster larvae at the spatial scale of the commercial fishery (see Section 3.2).

These characterisations may provide information on key fishery areas where productive oyster areas and vulnerable habitats occur, any overlap between these two classifications, the recruitment processes that drive oyster production, and information on limitations to survival of spat through to recruited oysters. This information will form the basis of spatial management.

Michael & Dunn (2005a) suggested that habitat may play some role in minimising the dispersal of infective bonamia particles. Habitat structures may change water flow at the seabed interface, isolating localised oyster populations from each other, and therefore reducing the ability of bonamia to transmit between populations. Further, habitat may play a direct role in minimising infection by reducing the density of infective particles. If such relationships could be established, the ability to predict the regeneration of benthic habitat will make a direct contribution to predicting the spread and impact of bonamia on localised oyster populations, as well on as on oyster production. Samples of filter feeding invertebrate species in the bycatch regularly sampled from survey tows between 2006 and 2009 had no bonamia in any species.

3.4.1.2 New dredge designs and procedures (SILs programme)

Dredging is the only method available for harvesting oysters in Foveaux Strait. Observations of oyster dredges fishing on the seabed have shown several aspects that reduce the fishing efficiency of dredges and modify benthic habitats (Stead 1966, Cranfield 1977). Commercial oyster dredges are 17% efficient: the dredge catches 17 in every 100 legal sized oysters encountered. Any improvements in fishing efficiency that reduce the total number of tows required to catch the annual harvest limit will correspondingly reduce dredging intensity (frequency of dredge tows within a localised area over a relatively short period of time) and minimise the total area dredged (the annual dredge footprint of the fishery), essentially mitigating the effects of fishing. Further, such increases in fishing efficiency may provide immediate economic gains in reduced fishing costs. Increases in efficiency could be achieved through new dredge designs or modifications to the current commercial dredge, and through improved fishing procedures based primarily on controlling towing variables such as tow length, towing speed and direction, and towing warp to depth ratios. Understanding how design features influence dredge performance is critical to developing a new oyster dredge or improving the current commercial dredge design.

The development of new dredge designs and procedures is being undertaken through a collaborative research programme between BOMC, Seafood Innovations Limited (SILs), and NIWA. Initial investigations focused on understanding how oyster dredges fish on the seabed using dredge-mounted video. Dredge trials in commercial fishery areas provided clear video of the dredge fishing on the seabed and effectively illustrated key performance issues. The most significant issue identified was dredge saturation, where the dredge became full and ceased to fish, sometimes within 2–3 minutes of the beginning of the tow. A working group of oyster skippers, fisheries scientists, and a local engineer agreed filtration was the primary issue, followed by inconsistent seabed contact. Improving dredge filtration may not prevent dredge saturation in some commercial fishery areas, but is pivotal to increasing the time it takes for a dredge to saturate, and therefore increasing the area effectively fished. Further, improved filtration by the dredge may reduce culching time by providing catches with less bycatch and a greater proportion of larger oysters. Improvements in seabed contact by the dredge can only be translated into increased efficiency if dredge saturation can be delayed or prevented.

The utility of modelling dredge, bycatch, and hydrodynamic parameters to investigate the effectiveness of different filtration variables was considered, but abandoned because it would require a level of data that was prohibitively expensive to acquire, and predictions would be very sensitive to small changes in dredging variables and design features. Greater gains in efficiency are likely to be made from structured dredge trials. Two concept dredge designs to address issues highlighted by the dredge video data were developed by skippers and the engineer: a box dredge and a triple dredge rig. Prototypes of both these designs have been built and some initial testing has been carried out. Both appear to work at least as well as the current commercial dredges. These dredges were used to investigate the effectiveness of different mesh and ring sizes on filtration efficiency and oyster selectivity.

The hypothesis that larger mesh sizes filter more bycatch and small oysters, and, by reducing bycatch, the dredge will fish more effectively on the seabed for longer before it saturates was tested in a structured trial. It was also hypothesised that larger mesh panels increase the proportions of large oysters in the catch, and therefore reduce culching effort. This trial has shown that dredge, mesh and ring bag configurations have an effect on dredge performance and that fine tuning mesh and ring bag configurations could significantly increase selectivity, and in some commercial areas minimise or delay dredge saturation. Most configurations tested were as good as, or better than the current commercial dredge. Box dredges represented extremes of catch efficiency, determined from the numbers of oysters caught and amount of bycatch, and their oyster size selectivity; the mesh on one box dredge was too large, allowing an excessive amount of catch, including legal sized oysters, to fall through the mesh. Bycatch and catch was more consistent in commercial fishery areas where the bycatch mostly comprised shell, shell hash, and sand. Areas with increased diversity and complexity of bycatch increased the variability of both volumes of bycatch and numbers of legal sized oysters, possibly resulting from some dredge tows saturating before the end of tow. The greatest gains from the next phase of these trials may come from investigating whether it is possible to prevent bycatch and small oysters from entering dredges in the first place, and therefore increasing dredge efficiency. This will be undertaken using a modified box dredge design.

Tow length, towing speed, warp–depth ratio, and current speed and direction all affect dredge efficiency (Stead 1966, 1971c, Cranfield 1977, Cranfield et al. 1991, 1997, Doonan et al. 1994). These effects vary on different habitats. The primary cause of the loss in dredge efficiency and an increase in the adverse effects on benthic habitat is saturation of the dredge. Saturation is a function of tow length and habitat type. Fine tuning tow length on different habitats could minimise the impacts of dredging on benthic habitat. Dredge contact with the seabed is determined by towing speed, warp to water depth ratio, and current speed and direction in relation to tow direction. These parameters could also be optimised for different dredges on different benthic habitats to optimise dredge efficiency.

If a more efficient dredge design can be developed, the 2010 strategic research plan will include trials to compare the efficiency between the current commercial dredge and a new dredge design. These trials will also include Before After Control Impact (BACI) experiments quantifying changes to benthic habitats and communities, and the nature and speed of colonisation by epibenthic animals.

Based on the hypotheses of Cranfield et al. (1999) that commercial densities of oysters only occurred on biogenic reefs, understanding the nature and speed of colonisation of benthic habitats was essential to determining oyster production rates and responses to dredging. These data were to be incorporated into a fisheries simulation model (see Figure 1). The data recorded between 2004 and 2009 suggest that there is no critical relationship between biogenic reefs and oyster production, resulting in a change in emphasis in the 2010 strategic research plan towards data required for spatial management of the fishery.

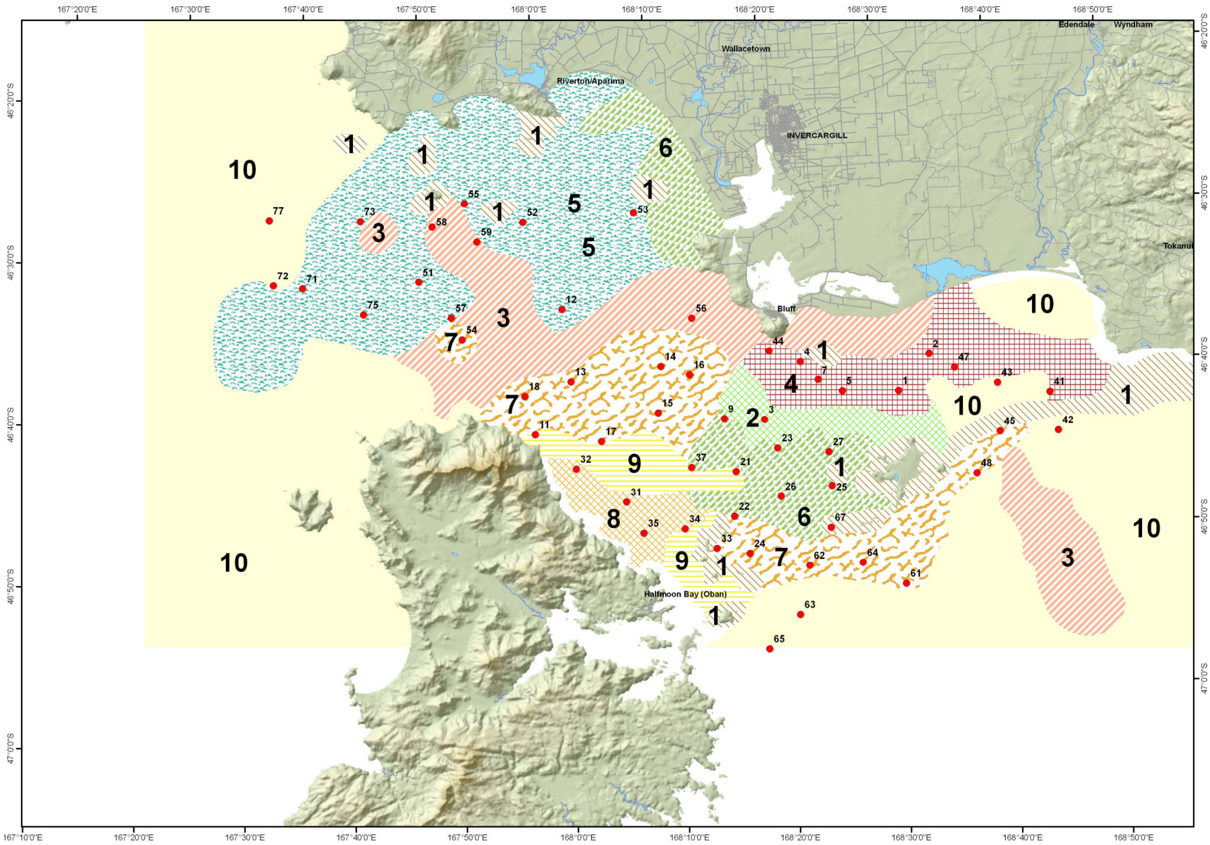

Figure 5: The distribution of subjective habitat classes based on sediment composition, structure and stability from video transects and the sediment map of Cullen & Gibb (1966). 1, rocky patch reef with epifauna, usually surrounded by sand and fine gravels; 2, flat gravels with clean shell (usually *Ostrea chilensis*, *Pseudoxyperas elongata*, and *Glycimeris modesta*); 3, flat gravels and encrusted shell (usually bound by small encrusting bryozoans (Cranfield et al. 2004 and Dennis Gordon, NIWA, pers. comm.); 4, flat gravels red algae and kaeos (*Pyura pachydermatina*); 5, gravels waves or lowly undulating gravels with clean shell in the troughs; 6, flat sand and gravel; 7, flat sand and gravel with biogenic patches; 8, biogenic areas; 9, large sand waves; and 10, sand ripple.

3.4.1.3 Oyster fishery enhancement through shell return

Further to the hypotheses that oyster dredging severely reduces oyster production (Cranfield et al. 1999, 2001, 2003), Cranfield (2004) hypothesised that oyster production was dependent on an optimum stage of regeneration, showed that benthic habitat has regenerated relatively quickly in the absence of dredging, and the speed of regeneration can be increased by shell return (Cranfield et al. 2001). No data were available on the critical relationships between oyster production (including disease mortality), benthic habitat, and changes caused by dredging. The 2004 strategic research plan aimed to develop and test habitat enhancement strategies to assess and remedy the effects of dredging.

The return of oyster shell to increase oyster productivity has been practised for hundreds of years and is still important in many commercial oyster fisheries, especially in the United States. Oyster shell return strategies in Foveaux Strait were expected to have a number of benefits beyond providing settlement surfaces for oyster larvae and enhancing the survival of settlers. Small oysters (spat and wings) on the shells of oysters landed as part of the commercial catch, and normally lost to the fishery, could be returned with oyster shell after processing. Returned oyster shell could also provide settlement surfaces, structure, and stability for the settlement of other benthic taxa, and habitat for mobile species. These shell structures may also provide refugia for blue cod for larval settlement, enhance the survival of juveniles, and encourage the immigration of larger blue cod.

Street et al. (1973) investigated oyster shell return in an area off the north coast of Bird Island (eastern Foveaux Strait), in 24 m depth, between June 1970 and February 1972. Survival and growth of spat returned within 48 hours was initially good, as was the natural settlement of spat on returned shell. The shell reef was up to 220 mm high off the seabed, and was eventually buried by moving sediment. The authors concluded that the survival and growth of returned spat and settlement on shells was sufficiently encouraging to warrant large-scale experiments.

Another trial of enhancing benthic habitat with freshly shucked oyster shells in 1996 had shown promise in remedying the effects of dredging and enhancing habitat regeneration. A plot of returned shell provided three-dimensional structure and complexity on the seafloor, benthic epifauna on the oyster shells promoted regeneration of biogenic reef species, and oyster spat enhanced natural settlement of oysters. The diversity of benthic organisms had increased significantly in 30 months (Cranfield et al. 2001) from freshly returned shell to a diverse biogenic reef of ascidians, sponges, molluscs (including oysters), and echinoderms, surround by fish, mainly blue cod and tarakihi (*Nemadactylus macropterus*).

A pilot shell return trial was undertaken initially as a BOMC project and then as a SILs research programme. The pilot trial tested two treatments against a control. One treatment used oyster shell opened and returned during the winter oyster season, over a period when oyster settlement is at its lowest. The settlement of other taxa between winter and the peak oyster settlement period in summer (December–February) may reduce settlement space available to oysters. The second treatment used weathered shell returned in spring (November), just before the peak period for oyster settlement. Shell from oyster processing was stockpiled and available for this purpose. Settlement densities and subsequent survival in these two treatments was compared with control areas that had not been stocked with shell.

The pilot trial investigated methodologies for shell return, and structured the investigations to enable observations from two previous shell return trials to be quantified. Reliable systems were established for returning fresh and weathered shell. Weathered shell is the most cost effective option, and limited data suggest that settlement and survival may be better on weathered shell. Monitoring shell plots with camera systems proved useful, but had limitations in quantitatively estimating shell densities and distribution. Still camera systems were good for describing and quantifying colonisation processes. Future investigations, particularly with benthic video camera systems, need to limit sampling to ideal sea conditions, and undertake less frequent, but more intense, sampling to provide wider coverage. Wider beam side scan systems should also be considered to obtain large scale qualitative descriptions. Increasing the ability to estimate shell density will improve our estimates of shell retention, oyster spat settlement density, and survival.

Oyster shell may act as sedimentary particles that can be moved, accumulated, and buried by the high energy oceanic swells and strong tidal currents of Foveaux Strait (Stead 1971a, Cranfield et al. 2003). Previous shell return trials were unsuccessful because the shell was either transported out of the area by tides and swell, or buried. Weathered shell remained in piles and within the plots for longer than fresh shell returned over the six month oyster season. This may have been due to the volume of shell, and that it was deployed after the winter storms, or because it was deployed at the time of year when most colonisation by benthic fauna occurs. The increased colonisation may have provided a more stable three-dimensional reef structure, possibly bound by small benthic organisms. The main problem with these structures was that they filled with fine sediment, smothering any oyster spat within them. Anecdotal evidence suggests that spreading oyster shell within plots just before the main settlement period is likely to be more effective in increasing oyster production, and piles of shell more effective in the regeneration of benthic communities than commercial oyster areas. Weathered shell is about 30% less expensive to deploy for equivalent shell volume because of the fewer days required in deploying it.

The survival of spat over 10 mm in length returned on fresh shell was expected to be high based on data from harbour trials. Data from the shell return trial suggests better than 4% survival after three years, but this is not as high as expected. Significant proportions of shell returned to sea remained in the experimental plots for at least 20 months, but after this most shell was either transported out of the experimental area or buried during large storms. The selection of sites where sediment transport and the effects of storms can be minimised is a critical component of shell return success.

Pilot study results suggest some promise for shell return as an enhancement strategy. Shells provide preferred settlement surfaces for oyster spat, and settlement densities on oyster shell can be high. The limiting factor appears to be the high post-settlement mortality of spat and the high mortality of spat returned on oyster shell. These findings are consistent with an earlier study of shell return, Street et al (1973). Site selection and the method of stocking may improve survival. Even with relatively low spat survival, shell return may be economic. The utility of shell return for establishing natal satellite populations in the commercial fishery will be reliant on available, stable habitat and a supply of oyster larvae for settlement.

Video and still camera data showed complex benthic communities of sponges, ascidians, and bryozoans become established within 20 months. Mobile animals such as starfish, urchins, and large gastropods moved onto these shell patches, which also attracted large numbers of blue cod. Three large winter storms in 2007 (and possibly some bottom trawling) broke up and dispersed these developing shell reefs and buried remaining patches in fine sediment. Divers confirmed these observations in December 2007. Although most of these plots were obliterated, traces of shell reefs remained to allow qualitative descriptions of benthic communities, and scattered shells remain within some plots that provide some information on settlement and survival of oyster spat. One of the most important observations was the speed of colonisation on the shells. *Crella incrustans* and some colonial ascidians are known to be effective early colonisers, but other sponge species such as *Chondropsis* spp. and the bryozoan *Cinctipora elegans* have previously been considered fragile and slow to colonise. Both these latter groups have been amongst the early, prolific colonisers, and have grown relatively quickly. These observations are also consistent with results from other shell return areas.

Data from stock assessment surveys and benthic video suggest that clean shells for settlement surfaces are not a limiting factor in oyster settlement in most fishery areas. The sampling of shell by dredging showed relatively high densities of oyster settlers on both returned shell and other shells, especially tuatua shell (*Oxyperas elongata*). High mortality of oyster spat from predation has been recorded in previous spat settlement trials (Cranfield 1975a). The high post-settlement mortality indicated by the ongoing sampling suggests that stability of settled surfaces and sediments are also important. Shells with settled oyster spat may be tumbled by the strong currents and the spat may be abraded off the shell; shells may also be buried by moving sediment (author's observations).

3.5 Stock assessment

Key objectives of both the 2000 and 2004 strategic research plans were the development of models to better inform management of the oyster fishery. The 2000 plan proposed long-term research to determine sustainable yields in the long term that included a length-based stock assessment model for oysters, and development of an epidemiological model of bonamiosis. The length-based model for stock assessment was well advanced by 2004 (Dunn 2005). The goal was to develop a fisheries simulation model that included spatially explicit stock assessment based on oyster population dynamics, habitat regeneration (linked to oyster production), and the spread of infection and mortality from bonamia. The fisheries simulation model development was considered difficult, but achievable. The simulation model aimed to integrate stock assessment, habitat regeneration, and disease models to provide information for ecosystem approaches to managing the oyster fishery.

The 2004 plan proposed to move from reactive management based on single species stock assessment to adaptive fisheries management. These adaptive strategies were to provide proactive ecosystem-based management with the capacity to evaluate different management options. Development of these strategies required an understanding of critical relationships between oyster dredging, oyster production, oyster mortality from bonamia, and changes in benthic habitat, and their underlying processes. Because of the high data requirements for this simulation model, data from the fishery would need to be routinely recorded by fishers in-season, and from fishery-independent sampling out of season.

Since 2004, projections from the stock assessment model have been used for OYU 5 assessments, to determine the risk of different harvest levels to future stock size. The initial model was further refined. An epidemiological model of bonamia has been developed. This disease model has highlighted the limitations of knowledge of the pathology of bonamia and of the available data. Further development of the model has only marginally improved fits to these data. Information on the patterns and speed of colonisation by benthic fauna has been recorded from spat monitoring and shell return investigations, and, in time, can be further derived from fishers' logbook data. Fishers have recorded a suite of data on catch and effort, bycatch, recruitment, and disease mortality in their logbooks. These data cover all commercial oyster fishing events each season. Logbook data quality continues to improve and comparability between vessels is currently being assessed.

3.5.1 Stock assessment model

Assessment and monitoring of the Foveaux Strait oyster fishery (OYU 5) was historically managed using catch rates and by estimating current annual yield (CAY); an overview is given in the Introduction (Section 2). Since 2004, the TACC has been based on estimates of recruit size stock abundance from the Foveaux Strait oyster stock assessment model and projections of future recruit size stock abundance under different catch limits and heightened mortality from bonamia (see Fu & Dunn 2009 for details).

Dunn (2005) presented a Bayesian, length-based, single-sex, stock assessment model for Foveaux Strait dredge oysters that he updated in 2007. The stock assessment was implemented using Bayesian estimation with the general-purpose stock assessment program CASAL v2.20 (Bull et al. 2008). The basic model and the revised model are updated biennially with new data that include the revised catch history and unstandardised CPUE, commercial catch sampling for size structure of the catch, and abundance indices from the January or February surveys since 2004. Previously, stock assessment surveys have been undertaken in October after the oyster season to allow sufficient time for the assessment and MFish processes before the following season began in March. Disease surveys were undertaken between January and March when bonamia infection is most readily detected.

The model estimates of the state of the Foveaux Strait oyster stock suggest that exploitation rates have been low, and the stock continues to recover following a dramatic reduction in the vulnerable abundance since the 2000 outbreak of the recent bonamia epizootic. Current estimates suggest that spawning stock population in 2009 was about 25% (23–28%) B_0, and recruit-sized stock abundance (rB2009) was about 20% (17–23%) of initial state (rB1907) (Fu & Dunn 2009).

It is unlikely that the estimates of historical stock size are reliable, given assumptions about annual recruitment and the use of the historical catch-effort indices of abundance. In particular, the selectivity and epidemiology of bonamia is not well understood. However, model estimates of recent and current status agree closely with recent CPUE trends and survey abundance indices (Fu & Dunn 2009).

While uncertainty exists in levels of future recruitment and continued bonamia related mortality, projections indicate that current catch levels between 7.5 and 15 million oysters are unlikely to have any significant effects on future stock levels. Instead, disease mortality and recruitment will determine future stock status.

3.5.2 Epidemiological model

The development of an epidemiological model of bonamia was intended to provide a better understanding of bonamiosis in the oyster population so that when an outbreak occurred, the model could be used to predict the spatial spread of bonamia in the fishery, oyster mortality from infection, and the decline of infection and oyster mortality that would allow fishery areas to rebuild. By integrating the disease model into a larger, spatially explicit stock assessment model, management and fishing strategies could be evaluated with simulations of alternative management strategies so that an optimum strategy could be applied. The mortality due to bonamia during an epizootic is so high that even a small reduction resulting from optimally timing and locating the right level of fishing effort would be of economic value (Gilbert & Michael unpublished results).

The bonamia model was developed using the standard Susceptible-Infected-Removed (SIR) epidemiological model framework. This cannot explain how an epidemic originates, but after it starts, susceptible oysters pick up infection from infected oysters and the disease progresses until they are removed. The population was modelled in a grid of cells. Oysters that die from bonamia infect other oysters in the same cell, but infection is spread to adjacent and distant cells. The infection progresses from light to heavy infection and to death. New pre-recruits enter the cells and oysters die from bonamia, fishing, and natural causes. The hinged shells of dead oysters (clocks) gradually deteriorate from a new to an old state.

The basic framework of the model represents our understanding of the interactions between bonamia and oysters, and the survey data used in the model are assumed to fairly represent what happens in the fishery. The model fits were examined by comparing predictions with survey data. This was done cell-by-cell or using overall means, and comparing the numbers of pre-recruits, recruits, new clocks and old clocks based on the proportions of lightly and heavily infected pre-recruits and recruits. There was a modest alignment between the fitted and the surveyed overall means, but the cell-by-cell comparisons frequently showed substantial lack of fit. Many alternative ways in which the processes operated were tried but none satisfactorily fitted all the data. The model was modified from a 12 cell partition of the commercial fishery area to a 48 cell partition to investigate whether a finer spatial scale analysis improved fits; it did not (Gilbert & Michael unpublished results).

A number of issues contributed to the lack of fit. The lack of spatial consistency within surveys, sharp temporal fluctuations in prevalence that could not be fitted, and sharp fluctuations from year to year were estimated in entering pre-recruit numbers (i.e., new susceptible oysters), but this did not explain the fluctuations in prevalence. Clock numbers did not correspond to bonamia prevalence and old clock numbers did not correspond to new clock numbers in previous time steps. Estimated spikes in entry numbers of pre-recruits always occurred in non-surveyed years, and so did new clocks of pre-recruits and of recruits. It is implausible that surveys always missed these big events. Further, the lack of age data on oysters and clocks means that it is more difficult to estimate rate parameters well.

The bonamia epidemics in the Foveaux Strait oyster population do not follow the conventional Susceptible-Infected-Removed (SIR) model. Such a model predicts smooth changes in disease prevalence both temporally and spatially and the survey data show fluctuations that are too sharp. One possible explanation for the model failure is that bonamia requires certain conditions to intensify and infection either dies out of infected areas or remains dormant under alternative conditions (Gilbert & Michael unpublished results).

3.5.3 Habitat model

Under the hypotheses of Cranfield et al (1999a, 2005) epibenthic communities, especially bryozoan dominated communities, were critical to oyster production, and therefore any predictions of future stock status were tied to predictions of the regeneration of benthic communities. A model of habitat regeneration was assumed to be a pivotal part of the fisheries simulation model. The review of LEK and fishery data on the relationships between oysters and benthic communities, and subsequent information on the habitats, where commercial oyster fishery areas were rebuilding showed a less critical relationship. Anecdotal evidence and research to date has not established a clear relationship between oyster production and other benthic taxa (except oysters) for the settlement of oyster larvae and the post-settlement survival of spat. The current hypotheses suggest oyster production is greatest on stable substrates with lots of shell, but little other macrobenthic fauna. Sediment stability and shell for settlement surfaces facilitate the settlement of oyster larvae and increase post-settlement survival of oyster spat. Further, the absence of extensive and complex epibenthic assemblages reduce predation, competition for settlement space and food, and the over colonisation and smothering of oyster spat by other animals. We have not yet established the role of benthic fauna in stabilising sediments and reducing abiotic mortality of spat from erosion or the burial of settlement surfaces.

While research into the effects of dredging on oysters, sediment structure, and benthic communities will continue to provide detailed and conclusive information for better management of the fishery, research in other areas, especially bonamia mortality, is a much higher priority and likely to provide grater gains to both the fishery and its economics.

3.5.4 Data from the fishery (logbooks)

A key objective of the 2004 strategic research plan was to manage the fishery using data routinely recorded by fishers during the oyster fishing season. Data for the fisheries simulation model were mostly to be provided by oyster skippers from a fisher's logbook programme. Such a programme has the ability to routinely collect fine spatial-scale catch and effort data, indicate levels of disease mortality, stages of benthic habitat regeneration, and provide information on rebuilding of oyster populations at low cost, but with high spatial and temporal coverage. Time series of these data sets provide the power to investigate spatial and temporal patterns of oyster production in the fishery, providing these data are of adequate accuracy and of a consistent standard across the whole fleet. Further, the format of logbooks is not difficult to change (unlike changes to the data recorded by MFish catch effort landing reports (CELRs) allowing the data recorded to change and meet the needs of changing management of the fishery. Fundamental to management of the oyster fishery is the ability to establish indices between catch and effort and the relative abundance of oysters. Catch and effort recorded from the fishery is a good indicator of oyster density (Alistair Dunn, NIWA, pers. comm.), and unstandardised catch and effort data are used by the stock assessment model.

A voluntary logbook scheme was introduced between 1996 and 1998 (Cranfield et al. 2001). BOMC continued the voluntary logbook scheme from 1999 to 2003 (Dunn et al. 1999, 2002c, Dunn & Michael 2001) and between 36% and 45% of the total annual commercial catch was recorded in logbooks over that period. Spatial and temporal patterns of fishing vary with individual vessels in the oyster fleet, and for the logbook data to be representative of the fishery, 100% coverage is required. These early logbooks provided a basis for a new logbook format.

BOMC established a paid industry logbook programme for the 2006 oyster season. Since then, fishers have recorded data on catch and effort, disease mortality, bycatch, and recruitment from 100% of fishing, in addition to furnishing MFish CELRs. These logbook data are recorded at a spatial-scale of 1 nautical mile square grid (see Figure 2). Logbook refreshers were held at the beginning of each season and data monitored by BOMC staff. Whilst catch and effort data have been more consistent than other data in 2006, other data categories have improved markedly in 2007–09. In 2010, assessments of the data variability within the fleet will be investigated as part of an in-season supplementary survey, to provide a quantitative assessment of data quality for management.

A software package (oysterTools) has been developed to run in R (free software environment for statistical computing and graphics) that compiles and runs on a wide variety of platforms, including Windows. OysterTools could be used to summarise logbook data in real-time and graphical outputs posted to websites that allow fisher access. BOMC staff have been trained to enter and range check fishers' data, and produce summaries on demand for the 2009 oyster season. More importantly, this will allow real-time feedback of data quality, enabling problems to be remedied early on, minimise data loss, and maximise data accuracy and consistency. Ongoing development of data formats, improvements in data accuracy and consistency, and the development of data acquisition, storage, summary and display technology is a high priority for future research.

3.5.5 Future directions

The 2004 strategic research plan key goal was to develop a fisheries simulation model. Since 2004, a length-based oyster stock assessment model has provided projections of future recruit size stock abundance under different catch limits and levels of oyster mortality from bonamia. Data from the fishery (catch and effort data, and size structure of the commercial catch) and biennial oyster population surveys are used to update the model for biennial stock assessments. Annual surveys to determine the status of bonamia infection and to make projections of oyster mortality before the oyster season are also undertaken. Stock assessments can be further refined with better estimates of mortality, recruitment, growth, and variance for these parameters.

While the size of the recruited stock is important in tracking long-term trends in the oyster population for assessments, it tells us little about the distribution of oyster density important to the commercial fishery and oyster production. Fishers are more concerned about the number, size, and distribution of areas of relatively high oyster density (oyster beds) that determine catch rates and profitability. Further, the size and meat condition of oysters is becoming increasingly important in fishing strategies. Model projections from spatially discrete subareas of the fishery partitioned by habitats and oyster productivity could provide information to better manage the fishery, rather than managing it as a single homogeneous area.

The integration of a habitat model is considered a low priority given the lack of relationship between epibenthic communities and oyster production. Integration of a disease model is critical to better predictions and evaluations of management strategies. The development of the epidemiological model for bonamia has highlighted the lack of data on fine spatial and temporal scales, and specific differences in the way bonamia interacts in the oyster fishery compared to standard epidemiological theory of susceptibility and infection. There is persistent infection at low oyster densities even after long periods of mortality, high fine-scale spatial and temporal variability of infection, and a poor relationship between infection and new clock catchability. These problems suggest the urgent need for research to understand bonamia and its course of infection and mortality in oysters beyond the data on the distribution of prevalence and intensity of infection currently recorded from annual disease surveys.

The stock assessment model has performed well to date, mortality from infection by bonamia is the principal driver of oyster population abundance in Foveaux Strait, and low catch limits are unlikely to have any significant effects on future stock levels. Stakeholders have requested that a more adaptive approach to managing the fishery be investigated. Under conservative catch limits, the fishery may be monitored from fishery data and annual surveys of disease status, with formal stock assessments at longer intervals (5 yearly instead of the current biennial assessments). In the case of new epizootics, or if higher catch limits are sought, different management strategies such as more regular stock assessments and other strategies may be employed. Should a new epizootic reduce the oyster population below 10% B_0, some consideration needs to be given to the MFish harvest strategy standards and their applicability to the unique conditions experienced in the fishery from disease mortality. Conditional to any strategy will be the validation of data recorded in fishers' logbooks and consideration of whether they are accurate enough to provide robust analyses.

4. SUMMARY

Minimising losses from bonamia is the most important management issue for the Foveaux Strait oyster fishery. Research to provide better, more cost effective detection of low level infections, a better understanding of bonamia and its interaction with the oyster fishery, and the development of spatial fishing and management strategies is critical to minimise these losses. Initial efforts will be focused on a better understanding of bonamia, especially the course of infection. Developing appropriate detection tools are essential for this research. Recording appropriate data for spatial management is also a high priority, as this will allow the effectiveness of spatial management for Foveaux Strait oysters to be assessed. Integral to this assessment is the development of spatially explicit stock assessment models that integrate components for bonamia infection and mortality, and provide the ability to evaluate spatial management and fishing strategies.

5. ACKNOWLEDGMENTS

I thank Graeme Wright, Victoria Pearsey, Brian and Stephen Hawke, and William Calder, the oyster vessel skippers, BOMC, and BOMC staff. Thanks also to Allen Frazer and Rose Grindley at the Ministry of Fisheries, Alistair Dunn, Dan Fu, Peter Smith, Jeff Forman, and Brian Sanders at NIWA. Thanks also to Reyn Naylor for his helpful comments on this report.

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