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Assessment of the effects of mortality due to *Bonamia* on the oyster population of Foveaux Strait in 1990 and the outlook for management in 1991

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ASSESSMENT OF THE EFFECTS OF MORTALITY DUE TO *BONAMIA* ON THE OYSTER POPULATION OF FOVEAUX STRAIT IN 1990 AND THE OUTLOOK FOR MANAGEMENT IN 1991.

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1. INTRODUCTION

1.1 Overview

Bonamia was first identified by MAF Fisheries in 1986 as the cause of the major mortality of oysters in Foveaux Strait. From 1986 the disease has continued to spread steadily throughout Foveaux Strait and has devastated the fishery. The management regime and quota have been modified over the intervening years as our knowledge of the disease increased and as the number of oysters has been reduced.

This report analyzes the impact of *Bonamia* on the fishery from the results of the multi-vessel grid pattern survey of the distribution of oysters and *Bonamia* in Foveaux Strait in June 1990, the stratified random dredge survey by the *Kaharoa* in October 1990, and the assessment of the size of the recruited oyster population by a diving survey in October 1990. The management implications of a variety of outcomes of the disease outbreak are discussed, and yields that are sustainable in the short term for these outcomes are presented.

1.2 Description of fishery

The dredge oyster *Tiostrea chilensis* supports an important fishery based in Bluff. The fishery area extends from a line between East Cape, Stewart Island and Slope Point, South Island in the east and Ruggedy Island to Centre Island lighthouse to Oraka Point in the west. The fishery is divided into 18 areas (Fig. 1) for fishing returns. Twenty three vessels (18-24 m) each operating two dredges (maximum width 3.35 m) take part in the fishery. They maintain their position on the same patch of oysters by towing in a circular path. Each vessel makes about four approximately 10 minute tows each hour. The catch is sorted on board and the undersized oysters and other material returned to the sea. The present minimum size limit for oysters is 58 mm (minimum dimension) and the present season is 1 March to 31 August.

Foveaux Strait has been commercially fished for oysters since the late 1880s. The number of vessels fishing was controlled (between seven and twelve) up to 1963, and limited again, after a rapid expansion, to 23 in 1970. Quotas have been imposed since 1963 and changed in 1968, 1969, 1970, 1971, 1975, and, in response to *Bonamia*, in 1987, 1988, 1989, and 1990 (see Fig. 2 & 3).

1.3 Effects of *Bonamia* mortality

MAF Fisheries has monitored the state of *Bonamia* infection in individual oysters and the spread of *Bonamia* through the population since 1986 (Table 1). The surveys of 1987 (Dinamani et al 1987a) and 1990 (Hine 1990b) established the prevalence of infection by *Bonamia* over the entire area of Foveaux Strait. The sampling of 1987 mapped the distribution of oyster mortality (Dinamani et al 1987b), but did not estimate the size of the surviving oyster population.

The only data available on changes in size of the population and oyster density were changes in distribution of fishing effort and catch per unit effort (CPUE) data from the fishery. Fishers return catch data from a number of subdivisions of the fishery area. Each of these subdivisions covers a number of patches of oysters. Consequently, the effect on catch rate from reduction in numbers and density of oysters only becomes apparent after *Bonamia* has killed (or the fishery removed) most of the oysters in all such patches. Fishers can target patches of oysters for reasons other than their high oyster density, so CPUE data within each area may not clearly reflect oyster abundance. Changes in distribution of fishing effort generally reflect changes in oyster abundance more reliably than changes in CPUE.

An estimate of the reduction in the oyster population from continuing mortality from *Bonamia* suggested that by 1990 the total oyster population could have been reduced to 25% of its 1986 level (Appendix 2 Michael et al 1990). It was imperative to establish the size of the surviving oyster population as well as the progress of the infection by *Bonamia* before determining management for the 1991 season.

2. IMPACT OF *BONAMIA* ON THE OYSTER POPULATION

2.1 *Bonamia* studies.

Bonamia in *Tiostrea chilensis* is serologically distinct from that occurring in the European oyster *Ostrea edulis* (Mialhe et al. 1988) and is likely therefore to be endemic. The only evidence of infection elsewhere in New Zealand is from Port Adventure (Dinamani et al. 1987a) and Port Underwood (Hine 1988a). The infections probably came in oysters transferred to these areas from Foveaux Strait.

Infective particles are released into the water by dying oysters in the autumn. Hine (1990) reports that in Europe a challenge of greater than 5000 infective particles was required before *Bonamia* and disease symptoms developed in the European oyster (*Ostrea edulis*). *Bonamia* remains largely undetectable in the tissues of infected oysters through the winter, but multiplies rapidly through the summer. The vegetative phase of *Bonamia* utilises the developing gonad tissue in the female oyster to multiply (Van Banning, 1990; Hine,1991) and effectively sterilises the animal. The proliferating *Bonamia* invades most of the oyster tissues and the oyster develops extensive lesions. The pathology of the extensive lesions of grossly infected and moribund oysters in New Zealand suggests that oysters do not survive high intensities of infection. The major mortality due to *Bonamia* is during the autumn (April-June) when the infective particles burst from the oyster (Van Banning 1990, Hine 1990).

The ligament joining valves of the oyster shell takes between two and three years to break down after death of the oyster (Street, pers comm). Such articulated valves are termed "clocks" by fishers. Mortality of adult oysters is normally very low (Cranfield & Allen 1979). In 1986 and 1987 the ratio of clocks to live oysters in uninfected populations was between 2 and 20% but much higher and closely correlated to prevalence of infection by *Bonamia* in infected populations (Fig. 4). As the major mortality occurs after the period of settlement of most fouling organisms, those oysters killed in any one year can be distinguished by their un-fouled shiny inner surfaces until the following summer. In this report they are referred to as "new clocks" and their distribution used to measure recent mortality.

2.2 Spread of *Bonamia*

From the initial infection, *Bonamia* spreads steadily through an oyster population with prevalence of infection rising to around 10% in the first year, 25% in the second, and higher levels again in the third year. Some mortality is seen in the second year but mortality rises to levels similar to the prevalence of infection in the third year (see Hine 1986a, 1986b, 1987a, 1987b, 1987c, 1987d, 1988a, 1988b, 1989a, 1990a, 1990b; Hine et al 1986; Dinamani et al 1986a, 1986b).

From 1986, when high oyster mortalities in the middle of the western beds first alerted MAF to the disease problem, *Bonamia* has spread centrifugally from the initial point of infection. The wave of new infection (prevalence of infection < 11%), reached the more peripheral northern, southern and eastern beds in 1990 (Fig. 5). The population of oysters on those beds first infected has, in the intervening four years, been reduced to around 20% of the pre-infection level. The oysters remaining on these beds continue to have a moderate (11-25%) prevalence of infection and continuing mortality.

2.3 Impact of oyster mortality on catch per unit effort (CPUE)

The landings data from 1913 show a slowly increasing trend, but with increasing fluctuation in the 1940s and 1950s (Fig. 2). From 1963, when quotas were introduced, the trend in CPUE has been similar to the trend in landings (Fig. 3). Since 1970, when the catch became limited by quota, CPUE peaked in 1978-1982 and then declined steadily (Fig. 3). The rate of this decline has increased since 1984. Different criteria were used for CPUE data in 1990; when they are corrected[1] to the same scale as the previous years, the mean catch rate was the lowest yet recorded in the fishery. The oyster population may now be smaller than it ever has been in the past.

According to Allen's model of the fishery (Allen 1979), if CPUE drops below about 65% of that for the virgin stock and fishing continues, then the stock will collapse. This behaviour is a function of the sub-stock structure in the model. Allen's simulations show that as the total equilibrium abundance is reduced, CPUE declines in an irregular fashion as individual patches of oysters are depleted serially, but suddenly drops to zero at some critical population size. While the details are dependent on the parameters used in the model, we should see the same behaviour in the Foveaux Strait fishery itself.

The catch rate in the fishery peaked at 17.1 sacks/hour in 1978. The catch rate declined irregularly till 1988, when it reached 10 sacks/hour (60% of the 1978 CPUE). CPUE fluctuated around this figure for the next two years and then in 1990 suddenly dropped to 6.4 sacks/hour. After 90 years of commercial fishing the oyster population of 1978 certainly was not at a virgin level. Nevertheless, the way the population has declined and the level to which it has dropped, are similar to that predicted by Allen. What has not happened however, is a drop in the catch rate to zero. Presumably this stems from the behaviour of fishers. As all patches are serially depleted, the minimum catch rate that is commercially acceptable is

[1] The average number of tows per hour for the whole fleet in 1990 was two (Rayns pers comm). The CPUE calculated from the new CELRs used a fishing time of 40 minutes (2 tows x 2 dredges x 10 minutes per tow = 40 minutes). CPUE calculated from the old return forms used an equivalent fishing time of one hour. The correction applied to 1990 CPUE to make it comparable to pre-1990 figures is 40/60 i.e. x 0.66.

reduced so fishing will continue until some new minimum level is reached. Therefore, the data suggest that by 1990, the total stock was below the critical threshold (probably as a result of *Bonamia* mortality) and could no longer sustain a fishery.

CPUE for individual areas of the fishery (Table 2) shows the same trend. Furthermore, the greatest declines in CPUE (and relative abundance) were in those central and western beds F9, F8, D7, E7 first infected by *Bonamia.* CPUE declined to a lesser extent in those more eastern areas D6 and E6 into which *Bonamia* spread in the following years.

2.4 Impact of oyster mortality on distribution of fishing

Oysters are distributed over a wide area of Foveaux Strait in about 50 small discrete patches which fishers target (Allen and Cranfield 1979). The general fishing strategy of each fisher, is to seek out the patch that gives the highest catch rate, and to stop fishing it only when the catch rate drops below what is considered commercially acceptable. Therefore, those areas on which fishing is focused can indicate oyster densities there are high, and conversely, those areas from which the focus shifts can indicate that oyster density there has become much reduced.

Table 3 shows the percentage of the total catch that came from each statistical area from 1975 to 1985 and 1986 to 1990. The percentage of the total catch taken in E6 has declined slightly from before 1986 to after 1986 (8.9-6.6).The catches from areas H,K,L, and F9 between 1975 and 1990 are too low to reveal any pattern (Table 3). The percentage of the catch taken in the remaining areas has changed significantly between these periods.
Three trends stand out in these changes in catch from the period before and after 1986:

1. Group 1-in five areas the mean percentage of the total catch decreased between pre– and post–1986 and continued to fall in 1990 (Table 4).

2. Group 2-in four areas the mean percentage of the total catch increased between pre- and post-1986 and continued to increase in 1990 (Table 5).

3. Group 3-in three areas the mean percentage of the total catch has increased between pre– and post–1986, but most of this increase has been in 1989 and 1990 (Table 6).

Group 1 populations (Table 4) were heavily fished before 1986, and occupy the area where *Bonamia* prevalence and mortality has been highest between 1986 and 1990. Group 2 populations (Table 5) are in areas that have been fished heavily in the past. In 1990 they still have a low prevalence of infection by *Bonamia* and no mortality from it at present. Group 3 populations (Table 6) occupy areas on the periphery of the fishery. In 1990 they were virtually free of *Bonamia.* They have been fished only rarely up to 1989 (Table 3).

These changes in the distribution of the catch reflect changes in commercial density of oysters within each area more clearly than the CPUE data. The oyster populations seem to have been reduced to commercially unacceptable levels within the area first infected with *Bonamia* (Group 1 populations) very rapidly after 1986 (see Table 2). Populations within the eastern areas B5 and C5 and the southern areas S6 and S7 (Group 2) have borne the brunt of the fishing since. The shift of fishing to more peripheral areas (Group 3)in the last two years (particularly pronounced in 1990) seems to reflect the continuing reduction in abundance of oysters in the western and central areas due to *Bonamia.* This shift may furthermore indicate some reduction in the commercial populations in B5, C5, S6, and S7 (each of these areas in Group 2 has been fished heavily for several seasons in the pre-1986 period as well as in the post-1986 period; see Table 3).

3. RESEARCH

3.1 Distribution of oysters

As the size of the oyster population had not been estimated since 1975, the population was re-surveyed in 1990. The absolute size of the oyster population was estimated using divers directly counting oyster density. A dredge survey was carried out to investigate changes in oyster distribution. Both surveys were completed in October 1990. Before these surveys were started, the oyster industry offered MAF Fisheries five commercial oyster vessels to carry out a dredge survey of the Foveaux Strait. The multi-vessel survey was therefore used to map the present distribution of oysters and the areas most effected by *Bonamia* mortality to help stratify sampling in the other surveys.

3.1.1. Earlier Surveys

Oyster distribution has been determined during two earlier dredge surveys in 1960-62 and 1975(Table 7).

3.1.2. 1990 Multi-vessel dredge survey.

Five commercial oyster vessels carried out a dredge survey of the entire Foveaux Strait fishery area in July 1990. The main aims of the multi-vessel survey were to establish the present distribution of oysters and where the major mortalities have occurred in recent years. The survey followed a grid-pattern sampling design with tow positions at the intersections of a one nautical mile grid over the main oyster bearing areas and a two nautical mile grid on the periphery of this (Fig. 6).

All vessels followed the same dredging procedure. They used a single standard commercial dredge towed in a straight line down-tide for 370 metres (0.2 nautical mile). Tow positions were determined using radar distances off prominent features. MAF observers supervised the operation and recorded all the data to ensure that all vessels followed the same practice. The relative efficiency of the five vessels was studied by having each tow on ten common stations. As their catches on these did not differ significantly ($F[4,36] = 1.26$; 5% level $F = 2.63$), catches did not require standardising and were used directly.

3.1.2.1 Present Distribution of Oysters

The numbers of takeable oysters were used to map the present distribution of oysters (Fig. 7). The largest area of high catch (>400 oysters/tow, which equates to a commercially acceptable catch[2] using the normal towing technique, see 1.2), was found west and north of

[2] In order to tow dredges in the most consistent manner and for exactly the same distance, a straight line tow was chosen instead of the normal commercial practise of circular tows. Catch rates of these straight line tows were not calibrated against commercial circular tows during the survey. A catch of 400 oysters in one dredge towed for 5 minutes in a straight line is considered equivalent to a catch of 1000-1600

Ruapuke Island. A further series of small patches of similar density partially encircle a barren area in the centre of western Foveaux Strait.

3.1.2.2 Distribution of high mortality in the last three years

The numbers of "old clocks" were used to map the distribution of high oyster mortality over the last three years (Fig. 8). This area of high total mortality in the last three years largely coincides with the areas with low oyster density (see Fig. 7). In 1974/75 this area supported most of the commercial fishing; commercial densities of oysters do not exist there today.

3.1.2.3 Distribution of mortality of the last three months

The catches of "new clocks" were used to map the areas where the mortality reached 10% for the previous 3 month period (Fig. 9). In the centre of Foveaux Strait the areas of new clocks overlapped with those with high densities of old clocks. There, and around the periphery of the major densities of old clocks in western Foveaux Strait, the recent mortality also made inroads into the remaining patches of commercial oyster density (Fig. 9). The stations at which oysters had a high (>25%) or moderate (11-25%) prevalence of infection by *Bonamia* in June 1990 coincided with or were close to these areas of recent mortality, suggesting that *Bonamia* was the cause. All oyster populations to the east had a low (<11%) infection index (Fig. 9). The data indicate a continued spread of *Bonamia* infection centrifugally from the oyster beds with high infection rates.

3.2.2 1990 *Kaharoa* dredge survey

3.2.2.1 Relationship to 1975 dredge survey

The dredge survey of 1975 was on a one third of a nautical mile grid and covered two thirds of the oyster beds commercially fished at that time (Allen & Cranfield 1979). The data were used to estimate a map of oyster distribution. Because of the high variation in dredge efficiency, the 95% confidence intervals of the population size estimate covered an order of magnitude (Allen & Cranfield 1979). By using the same dredge and dredging techniques in 1990 as were used in 1975, the efficiency of the dredge was kept the same and precise comparisons of oyster populations occupying the same areas in both years was possible. The 1975 grid pattern survey occupied 601 stations on two cruises. To achieve a similar variance, with an realisable number of stations, the 1990 survey followed a stratified random design. The area covered in the 1975 survey was divided into four strata in the 1990 survey.

3.2.2.2 Methods

In October 1990 GRV *Kaharoa* carried out a two phase, stratified random (Francis 1984) dredge survey. The dredge was a scaled down version (1.25 m wide) of a commercial dredge. The main aim of the survey was to estimate the size of the population of oysters within the area covered in the 1975 survey. The area covered by the 1975 survey was divided into four strata based on the variance of catches of the multi-vessel survey in this area. The remainder of Foveaux Strait was divided into three strata on the same basis (Fig. 11). The chart of the

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oysters in 2 dredges towed for 10 minutes in a circle. As commercial boats normally make four such tows each hour, this equates to a catch rate of 6-8 sacks/hour (at 800 oysters/sack) which was range of the commercially acceptable catch rate in 1990.

strata was digitised and station positions randomly generated by PC software (Rand_stn, V1.4) for each stratum. Station numbers were allocated to strata proportionately to the variance of the multi-vessel survey catches. Eighty six stations were sampled in the first phase and 30 in the second (following procedures of Francis 1984). The dredge was towed in a straight line (generally up-tide) for 0.20 nautical mile (370 m). Tow positions and distance towed were plotted with GPS and Doppler Log. The numbers of takeable and undersized oysters, new clocks and old clocks were counted from each tow.

3.2.2.3 Effect of *Bonamia* mortality on size of areas of commercial density

Three of the four strata covering the 1975 survey area include much of the area covered by old clocks and low oyster density in 1990 which were the direct result of *Bonamia* mortality (see Figs.7 & 8). In 1975 they were the centre of the commercial fishery and contained much of the oyster population. In the survey of that year, Allen and Cranfield (1979) estimated that sites with commercial densities[3] gave catches greater than 148 oysters from a standard survey tow. Using this figure,they estimated that 91% of the oysters were in patches of commercial density and these patches covered 11% of the area surveyed. Following the same criteria in the four strata of the 1990 survey that covered the 1975 survey area, showed that only 15% of the oysters were now in patches of commercial density and that these patches now covered 4% of the area. The oyster population in the 1975 area had declined 97% from 1975 to 1990. For the entire 1990 survey area(containing the area covered in 1975 and all oyster-bearing areas outside this), 48% of the oysters were in patches of commercial density that covered 13% of the total area surveyed.

3.3 Abundance Estimates

3.3.1 Earlier Surveys

Oyster population size was estimated in 1960-62 and 1974-75 using a diver survey in 1960-62, a dredge survey in 1975 and a mark recapture survey in 1974 and 1975 (Table 6).

3.3.2 1990 *James Cook* dive survey

A pilot survey in June 1990 showed that diving was a practicable method of directly measuring oyster density on the sea floor. Compared to the other techniques evaluated (dredging, remote under-water television, and grab sampling), diving proved to be the most efficient method for estimating the size of the oyster population (Michael et al 1990).

In October 1990 we carried out a two phase stratified random (Francis 1984) diving survey from GRV *James Cook*. The main aim of the survey was to estimate the absolute population size (with a target CV of 10%). Nine strata were developed from the multi-vessel survey data. This number was greater than that required statistically, but it spread the dives geographically, and broke up large strata. The number of stations in each stratum was based on the variance of the multi-vessel survey data. Station positions were randomly determined (using PC

[3] Commercial densities of oysters in that year would have supported catch rates of 11.5-11.9 sacks/hour. For the sake of comparison with this present survey the same criterion is used. As today's financial climate is different from 1974 and the oyster population much reduced, 6-7 sacks/hour now seems commercially acceptable. On this basis, the extent of present commercial patches is greater than indicated here.

software, Rand_stn, V1.4 for the digitised strata) and sixty five first phase stations and 18 second phase stations (Fig.12) sampled (following the procedure of Francis 1984). At each station divers collected all oyster and shell from 4 x 1m^2 quadrats separated in a T array (Michael et al 1990). All live oysters were counted and measured, and articulated shells categorised and counted.

3.4. Estimates of Population Size

3.4.1. *Estimates of the total population*

The multi-vessel survey data of 1990 were used to delineate the oyster bearing area to which the estimates in the following section apply. The estimates include an adjustment for the population outside the areas sampled. For the 1990 dive survey this factor is 1.04.

The population estimates of 1974/75 and 1960/62 relate only to the commercially fished populations. The dredge survey in 1975 (Allen and Cranfield 1979) showed that 91% of the population was found in areas of commercial density. The estimates of the size of the oyster population in 1960/62 and 1974/75 were therefore adjusted by the same factor, 1/0.91=1.10.

3.4.2. Estimates for parts of the population with different potential disease outcomes

Five possible outcomes of the *Bonamia* infection are discussed in the Management Implications section (Section, 5). A different population survived in each outcome and each outcome requires a different management regime. The first two outcomes had no harvestable populations. The size of the harvestable populations of the remaining three outcomes are discussed here.

3.4.2.1 Outcome 3. The harvestable oyster population in this outcome was defined as having no signs of heightened mortality and a low prevalence of infection by *Bonamia.* The proportion of clocks was below 15% and prevalence of *Bonamia* was below 11%. This population covers the eastern and parts of the southern and northern areas of Foveaux Strait (Fig. 13).

Population size was estimated in the following way. The area for Outcome 3 was recorded by digitising around either the 15% contour for prevalence of clocks or the 11% contour for prevalence of *Bonamia,* whichever was the inside contour. The portion of each dive stratum that lay in this area was then digitised from the plot of the Outcome 3 area overlaid on boundaries of the dive stratum. The area in each dive stratum was calculated using the program Rand_stn V 1.4. The mean oyster density in that portion of the dive stratum was calculated from the stations in it. The oyster population was estimated by multiplying the density and area and summing the estimates for each segment of the dive strata included in Outcome 3.

3.4.2.2 Outcome 4. The harvestable oyster population in this outcome includes that in Outcome 3 as well as areas that have a higher prevalence of infection (11-25%) but still show no signs of substantial mortality. Incidence of clocks was below 15% and prevalence of infection was below 25%. The added area was inside those exhibiting a low prevalence of infection and a low mortality (Fig. 13). Population size was estimated following the same procedure as in Outcome 3.

3.4.2.3 **Outcome 5.** The entire oyster population is included in this outcome. The area includes central Foveaux Strait where oyster populations have the heaviest infections of *Bonamia* and have suffered substantial mortalities, as well as the two areas with low and moderate levels of infection.

Estimates of the total legal-sized population present in 1962, 1974, 1975, and for Outcomes 3, 4, and 5 in 1990 are shown in Table 8. The estimates for 1974 and 1975 are from mark recapture experiments and cover the entire commercial fishery of that time (Cranfield & Allen 1979). The estimate for 1962 was based on a diving survey covering a sample of the oyster beds (Table 7). The reliability of this estimate is unknown as standard errors or confidence limits were not presented (Stead 1962 and 1971). With this proviso, the data indicate little change in population size between 1962 and 1975.

3.4.3. Conclusions

The total oyster population in Foveaux Strait has declined 58% between 1975 and 1990. In 1986, fishers reported large numbers of new clocks widespread in the western and central areas of Foveaux Strait. It is likely that most of the population decline has occurred since 1986. The 1990 surveys strongly suggest this mortality is due to *Bonamia* (Sections, 3.1.2.2, 3.1.2.3 and 3.2.2.3). Dinamani et al.(1987) and Hine (1990) also ascribe these high mortalities to infection by *Bonamia.*

4. YIELD ESTIMATES

4.1. Estimation of Maximum Constant Yield (MCY)

MCY was estimated using Method 2, MCY = $F_{0.1}B_{min}$ (Annala 1991). An estimate of $F_{0.1}$ was based on the exploitation rate in 1975. Cranfield and Allen (1979) estimated an exploitation rate for the commercial beds of 0.07 and 0.08 for the years 1974 and 1975, respectively. The 0.08 estimate has a lower standard error (0.009 versus 0.014) and has therefore been used in the following calculations. The exploitation rate needs to be adjusted by a factor to account for the population outside the commercial beds. The factor used, 0.91 is the same as in section 3.1.2.3. The exploitation rate for the total population in 1975 is therefore 0.08 x 0.91 = 0.073.

The exploitation rate estimate assumes that the population was in equilibrium in 1975. This requires a period of stable catch (or effort) and that this catch be sustainable. A minimum period for this stable exploitation would be the average age of the recruited population. In the period 1963-1974, the catch fluctuated around Y_{av}, 115,000 sacks (mean catch in the 12 year period, 117,142 sacks, CV 26%). The average age of the recruited population is unknown, but would be 6.9 years if we used Allen's (1979) parameter values[4]. Hence, this 12 year period is sufficient, other things being equal, for the fishery to reach equilibrium.

The exploitation rate estimated for the total population in 1975 of 0.073 was substituted for $F_{0.1}$. Because the population sustained a mean yield of 115,400 sacks for the years between

[4] With an 8% exploitation rate and 0.1 natural mortality, the average time an oyster lasts in the fishery is given by -log(0.5)/(0.1 + 0.08) = 3.9 years. Add this to the age of recruitment 3, and the average age of the recruits in the population is 6.9 years.

1963 and 1985, and a yield of 115,000 sacks in 1975 resulted in an exploitation rate of 0.073, this is probably a reasonable assumption. The population size estimate for 1990 is the lowest recorded, and has been set equal to B_{min}. MCY estimates for the three Outcomes are given in Table 9.

4.2. Estimation of Current Annual Yield (CAY)

CAY cannot be determined because it is not possible to predict the size of the oyster population in the next fishing year due to the effects of *Bonamia* mortality.

5. MANAGEMENT IMPLICATIONS OF *BONAMIA* MORTALITY

5.1 Introduction

Future management depends on what we believe the disease is ultimately going to do to the oyster population. If we believe that some of the oysters will recover from the disease and an immune population will develop, then we should close the fishery now to maximise the size of that immune population and so enhance recovery. If we believe that infected oysters do not recover, and that all the oysters in Foveaux Strait will eventually become infected and die, then we should "mine" all the oysters now before this happens. A whole continuum of management options exists between these two extremes depending on our expectations of the disease outcome.

5.2 Management to slow down the spread of *Bonamia* and reduce mortality

No chemical or biological agents are known to combat *Bonamia*. Hine (1990b) suggested the option of dredging a "firebreak" between the beds presently exhibiting low prevalence of infection and those with high levels. A practise of reducing oyster density (and hence the potential density of infective particles) is reputed to successfully control the spread of *Bonamia* in oyster farms in Ireland (see Hine 1990b). No data is available on the density changes required, and evidence from similar farming experiments in Holland seems equivocal (Van Banning 1990). The hypothesis relies on *Tiostrea chilensis* responding to *Bonamia* in the same way as the European oyster which required a challenge of >5000 infective particles to infect the oyster and cause disease.

5.3 Management of the fishery within the constraints of *Bonamia* mortality

Management will depend on how mortalities caused by *Bonamia* progress, both spatially and temporally. Up to now, *Bonamia* has spread steadily through Foveaux Strait (Fig. 5), reducing population levels and changing the spatial distribution of the oysters. We do not know when this will stop. The very high natural mortality from *Bonamia* ensures that populations with a high prevalence of infection are rapidly reduced below densities that can sustain a fishery, and may be driven below densities that will maintain recruitment.

The level of mortality in the beds infected for more than three years is much higher than that due to the heaviest of fishing and these oyster populations have been reduced to very low densities. Clearly no heavily infected oyster population can sustain itself against the attack of *Bonamia* let alone any additional mortality from fishing. The continued spread of *Bonamia* to previously uninfected beds and the increasing level of infection in moderately infected beds suggests that these beds that can still support fishing will inexorably go the same way.

The simulations of Allen (1979) show the population does not respond to fishing like other fish species. Thus he found that the fishery could be maintained only when the population was larger than 50% of the virgin population; without fishing the minimum population that could sustain itself was 10% of the virgin population. Recruitment is dependent on the availability of shells of living oysters on which spat can settle and survive. Recruitment is also affected by the reduction in fecundity through sterilization of females by *Bonamia*. All management options that allow fishing assume that the surviving oyster population will be large enough to maintain recruitment at its present level.

We looked at five possible outcomes of the infection in Foveaux Strait. A different population survived in each outcome. Each outcome requires a different management regime:

5.3.1 Outcome 1: The whole oyster population will develop a high prevalence of infection and die. The population will not recover in the future.

This is considered an unlikely outcome. Although a high percentage of oysters will die, not all are likely to. The disease is probably endemic, and in time it will probably reach a new equilibrium with the oyster population.

The management indicated by this outcome is to 'mine' the oysters as they are going to die anyway. Managing for this outcome requires no data on the size of the oyster population. The progress of *Bonamia* in the infected populations would need monitoring to substantiate oysters were not becoming resistant and surviving.

5.3.2 Outcome 2: The whole oyster population will become heavily infected and most animals die. The oysters remaining will be immune and the population will eventually recover.

The probable endemicity of the disease and the development of resistance in other oysters to similar diseases (Hine pers comm) makes us consider this the most likely outcome.

In 1987, sampling for *Bonamia* was confined within the known exploited oyster beds and samples with no *Bonamia* were common. By 1990 *Bonamia*-free samples were found only at the extreme periphery of oyster distribution, ie most of the population was at least lightly infected. The area with a moderate prevalence of *Bonamia* infection has increased considerably since 1986 (see Fig. 5), and is likely to include the whole of Foveaux Strait in time. *Bonamia* infection causes high mortalities (Fig. 4), and so we can expect most of the population to die off. The spread of *Bonamia* and its associated mortality are likely to continue, leaving only very low densities of oysters in Foveaux Strait.

In this scenario, management should maximise the size of the surviving population to hasten the recovery of the population from the recruitment of this breeding stock. This would be best done by closing the fishery now, or protecting those devastated areas where oyster populations have been driven close to irrecoverable densities. Because the fishery is closed in this outcome, the small surviving population has no short term yield.

Even if the surviving oysters are resistant, there is a risk that the population will still die off because it is below the critical size. To manage the oyster population we need an estimate of the numbers of survivors and the minimum population that will still maintain recruitment. We also need confirmation that surviving oysters have developed resistance to the disease and would need to monitor the prevalence and intensity of infection *Bonamia* in the devastated populations.

5.3.3 Outcome 3: Only populations with a low prevalence of *Bonamia* infection survive. The others die off, or are reduced to below commercial densities[5]. We assume that the populations destroyed by disease do not regenerate in the short term.

This outcome is considered less likely than Outcome 2 because *Bonamia* has continued to increase in prevalence and intensity of infection leading to high mortalities in all oyster populations it has so far reached. The surviving population in Outcome 3 should at least be sustainable in the short term (so far *Bonamia* has taken 3 years to develop from low prevalence of infection to high prevalence of infection and massive mortalities).

Management of the fishery under this outcome requires an estimate of the size of the population that has a low prevalence of infection and what proportion of it attains commercial densities. In order for a fishery to be sustained in this outcome, mortality due to *Bonamia* in surviving populations must be low. The level of infection and mortality in these populations must be monitored to confirm this outcome.

5.3.4 Outcome 4: The population with a moderate or low mortality (regardless of prevalence of infection) survives. The remaining populations with high mortalities already die off or are reduced below commercial densities.

So far there has been no sign of the spread of *Bonamia* slowing down nor of the prevalence of infection of infected populations of oysters decreasing, so this outcome is considered less likely than Outcome 3. Management of the fishery under this outcome requires an estimate of the population with a low or moderate clock ratio and what proportion of it attains commercial densities. *Bonamia* prevalence in this population would need to monitored to substantiate that it actually decreases and that little or no mortality follows.

5.3.5 Outcome 5: *Bonamia* stops killing oysters throughout the population now.

It is considered unlikely that the infection should suddenly stop now. The infection has continued to spread at the same rate through Foveaux Strait and has continued killing oysters in the same way with the same high frequency in each of the six years since the outbreak commenced. Oyster populations in Europe infected with the northern species of *Bonamia* have never recovered, and the subsequent mortality has almost destroyed infected populations.

To manage the fishery under this outcome we need to know the size of the total oyster population and what proportion of it that attains commercial densities. Disease monitoring would need to confirm this outcome (complete disappearance of infection) before management based on this outcome was embarked on.

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5 Commercial densities are defined as those populations that when fished have a commercially acceptable catch rate, ie between the mean catch rate of that season and two sacks/hour higher. The catch rate varies from season to season, and in times of low abundance the commercially acceptable catch rate appears to be lowered even within the season (*see* discussion in Section 2.2).

5.4. Summary

Outcomes 2 or 3 are considered to be the most likely disease outcomes. The yield estimate for Outcome 3 suggested by the present document (20,000 sacks) is less than 20% of what the industry caught in 1989. To remain economical with such a catch level the fishery will clearly need to restructure.

Harvesting at any of the more optimistic Outcomes 4 or 5, carries with it a higher risk of stock collapse than for Outcomes 2 and 3. To guard against any collapse permanently impairing the ability of the population to recover, more widespread and detailed monitoring of the prevalence of infection by *Bonamia* and its effect on the population will be required.

Management of this fishery is faced with a situation whose ultimate outcome is still unknown. The effectiveness of management actions will therefore be highly uncertain. Can management action stem the spread of the disease?, What level of exploitation can diseased stocks withstand? If the disease continues to spread, does immunity ultimately develop in heavily infected populations? What is the size and distribution of the surviving oyster population? The effects of management on the population must be closely monitored and its effectiveness assessed.

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Figure captions

Figure 1. The Foveaux Strait dredge oyster fishery area and areas for statistical returns.

Figure 2. Oyster(*Tiostrea chilensis*) landings in number of sacks and the number of vessels fishing, 1913-1962.

Figure 3. Oyster(*Tiostrea chilensis*) landings and yearly quotas in number of sacks, CPUE in sacks per hour, and the number of vessels fishing, 1963-1990.

Figure 4. Percent prevalence of *Bonamia* infection against percent cumulative mortality in 1986-87. The '+' are data from the cruise K02/87 and the 'o' from K10/86. The line is estimated using robust regression. Cumulative mortality is all 'clocks' divided by (all 'clocks' + oysters) with no size restrictions, ie not just recruited oysters. The *Bonamia* infection refers to recruited oysters alone. Data taken from table 4 in Dinamani et al. (1987a).

Figure 5. The spread of *Bonamia* infection between 1987 and 1990. The contours enclose areas of moderate and heavy prevalence of infection (ie. >11%). Owing to the configuration of the 1987 sample sites, only the eastern side of the 1987 contour is well determined. For the 1990 contour, all the western samples showed heavy infection and so the contour was placed around the western edge of these sites; the edge of the infection will probably lie further west. The contours were found using the package, new S (functions interp and contour). The 1987 data are from cruise K02/87 and from Table 4 in Dinamani et al. (1987a).

Figure 6. Sites sampled in multi-vessel survey of Foveaux Strait, June 1990.

Figure 7. Map of distribution of densities of surviving oysters in Foveaux Strait. Contours are 400 oysters/tow and 100 oysters/tow. Multi-vessel survey of Foveaux Strait June 1990.

Figure 8. Map of Foveaux Strait with areas of major mortality of oysters between 1987 and 1989. Contours for 50% old clocks and 20% old clocks. Multi-vessel survey June 1990.

Figure 9. Map of Foveaux Strait with areas of oyster mortality between February and June 1990. Contours 2% and 10% new clocks. Multi-vessel survey June 1990.

Figure 10. Map of commercial densities of oysters (400/tow), past high mortality (50% old clocks), new mortality (10% new clocks) and high (h, > 25%), moderate (m, 11-25%) and low (l,< 11%) prevalence of *Bonamia* in Foveaux Strait in June/July 1990.

Figure 11. Map of strata and stations used in dredge survey of oyster distribution in Foveaux Strait by GRV *Kaharoa* in October 1990. The digits show the position of the station; the value shows the stratum it belongs to.

Figure 12. Map of strata and station positions used in the dive survey of oyster distribution in Foveaux Strait using GRV *James Cook*, October 1990. The digits show the position of the station; the value shows the stratum it belongs to.

Figure 13. Boundaries of areas of importance in the 1990 assessment of the size of the surviving oyster population of Foveaux Strait. (1) The boundary of the 1990 dive survey. (2) The area of high oyster mortalities and moderate/high prevalence of *Bonamia*. (3) The area with moderate levels of new mortality (< 5% new clocks) no major mortality (2% old clocks) and light-moderate prevalence of *Bonamia* (0–25% incidence). (4) The area with light mortality (new and old clocks < 2%) and low prevalence of *Bonamia* (< 11%).

Area (1) includes the population with a sustainable yield under Outcome 5. Areas (3) and (4) includes the population with a sustainable yield under Outcome 4. Area (4) includes the population with a sustainable yield under Outcome 3.

Table 1: Investigations of *Bonamia* from 1986 to 1990 in Foveaux Strait.

Year	Month	Vessel	Stations	Sample No.	Slides	Heart Smears	Comments	Reference
1986	July	Commercial	3	12	12	–	Initial diagnosis	MAF Fisheries report to Oyster Advisory Committee 1986.
1986	Jun–Oct	Various	10	352	352	–	N.Z. – wide survey	Hine et al (1986)
1986	September	GRV *Kaharoa* K10/86	26	1110	1110	–	1st sampling to study geographic spread of *Bonamia* in Foveaux Strait	1st interim report Hine 1986a. 2nd interim report Hine 1986b.
1987	January	GRV *Kaharoa* K01/87	62	1724	1320	–	(a) 2nd study of geographic spread. (b) The first of a series of samples to study seasonal patterns.	3rd interim report, Hine 1987a. Dinamani et al (1987)a Dinamani et al (1987)b
1987	April	Commercial	2	100	100	–	2nd " " "	3rd interim report, Hine 1987a
1987	May	Commercial	3	150	150	–	3rd " " "	–
1987	June	Commercial	8	400	400	–	4th " " "	4th interim report, Hine 1987b
1987	August	Commercial	8	400	400	–	5th " " "	5th interim report, Hine 1987c
1987	November	Commercial	8	400	400	–	6th " " "	6th interim report, Hine 1987d
1988	April	Commercial	8	834	834	–	Also reported deaths in July 1989 of oysters transferred to Port Underwood from Foveaux Strait in 1984.	7th interim report, Hine 1988a
1988	December	Commercial	17	725	755	–	Recognition of importance of female oyster gonad cycle in proliferation of *Bonamia*.	8th interim report, Hine 1988b
1989	May	Commercial	8	400	400	–	First calibration of heart smear technique of diagnosing *Bonamia*.	9th interim report, Hine 1989a
1990	February	Commercial	9	552	552	97	Study of geographic spread of *Bonamia*.	10th interim report, Hine 1990a
1990	June	GRV *James Cook* JC090/08 JC090/10	64	2386	1047	2386		Report on survey, Hine 1990(b)

Table 2. CPUE (sacks/hour) for each statistical area from 1975 to 1990 in the Foveaux Strait oyster fishery.

Years before *Bonamia*

Year	A0	K0	L0	S5	S6	B5	C5	D6	E6	D7	E7	F8	G8	S7	S8	F9	G9	H0	Mean
1975	–	14.9	–	11.2	11.4	12.2	11.5	11.0	11.1	11.5	12.1	12.3	11.4	13.6	11.1	9.0	11.1	–	11.9
1976	8.3	–	–	18.8	14.4	14.2	15.3	13.9	13.2	14.3	13.1	12.1	12.9	13.5	12.1	10.7	12.0	–	13.4
1977	8.3	–	–	11.6	6.6	16.6	17.7	15.0	16.5	16.5	16.0	17.0	16.7	14.9	14.9	–	13.0	–	15.4
1978	7.7	–	–	16.9	19.7	17.3	18.1	15.8	16.8	17.9	17.1	18.2	13.9	18.3	14.3	–	14.0	–	17.1
1979	6.2	–	–	16.1	18.4	17.3	16.8	15.9	14.7	16.9	17.1	16.3	15.7	16.9	12.4	–	10.1	10.1	16.6
1980	8.1	-	-	11.9	15.5	14.9	15.5	14.1	13.4	15.3	15.4	15.5	16.0	15.3	16.9	-	14.8	15.0	15.2
1981	6.8	–	–	12.8	13.0	12.5	12.8	12.7	12.2	14.2	14.1	13.7	14.5	13.8	13.2	13.6	12.0	15.1	13.4
1982	7.3	–	6.3	5.9	11.3	12.5	10.4	12.5	13.0	13.6	14.0	12.1	14.2	13.3	14.2	15.1	11.0	13.1	13.2
1983	6.7	–	–	13.6	13.1	11.4	10.9	11.1	12.4	11.8	12.1	12.4	12.9	12.7	13.6	–	15.0	21.4	12.3
1984	6.0	–	–	11.5	14.7	12.2	14.7	12.7	15.4	12.4	13.0	12.3	14.0	14.4	15.7	11.2	9.0	–	13.8
1985	5.0	–	–	12.1	12.8	11.0	16.2	11.0	12.2	10.7	12.0	10.9	11.4	12.7	11.7	3.4	12.9	2.2	12.1

Years during *Bonamia* induced mortality

Year	A0	K0	L0	S5	S6	B5	C5	D6	E6	D7	E7	F8	G8	S7	S8	F9	G9	H0	Mean
1986	–	–	–	10.0	10.8	10.3	11.6	10.6	10.1	9.4	10.6	9.3	10.0	10.7	9.4	–	11.0	6.9	10.5
1987	–	–	–	16.4	10.5	11.1	12.2	11.6	11.5	11.5	8.9	10.1	10.4	10.2	9.0	–	–	–	10.9
1988	7.9	9.5	–	12.0	10.2	10.3	9.7	9.8	10.5	10.4	8.2	10.3	9.0	9.8	9.5	8.9	8.8	4.6	10.0
1989	8.5	12.0	–	11.8	11.6	10.2	10.2	9.1	10.7	9.7	10.8	11.7	12.8	10.5	12.1	10.0	12.2	11.0	10.7
1990[1]	3.8	7.7	–	8.1	7.1	6.3	6.9	6.3	5.0	3.1	4.1	3.9	9.7	5.0	6.1	2.0	6.1	–	6.4

1 (*see* footnote 1)

Table 3. Percentage of the total catch taken in each statistical area from 1975 to 1990, in the Foveaux Strait oyster fishery.

Years before *Bonamia* — **Statistical Area**

Year	A0	K0	L0	S5	S6	B5	C5	D6	E6	D7	E7	F8	G8	S7	S8	F9	G9	H0
1975	0	0.1	0	0.7	3.8	7.2	3.7	11.7	8.5	2.9	17.6	3.3	15.4	22.1	1.8	0.3	0.9	0
1976	0.9	0	0	0.4	3.3	13.1	2.6	10.5	4.9	5.1	19.5	2.7	14.2	17.7	0.5	0.4	5.2	0
1977	3.5	0	0	0.1	0	18.3	3.6	10.1	4.7	11.4	19.1	5.1	16	6.2	1.5	0	0.5	0
1978	0	0	0	0.1	1.6	29.5	5.2	13.5	3.8	13.4	15.3	2.7	4.7	9.8	0.1	0	0.1	0
1979	–	–	–	0.1	0.9	21.3	5.9	15.8	6.1	17.3	20	7.3	2.8	2.5	0.1	0	0	–
1980	0.1	–	–	0.3	2.5	18.9	1.8	7.2	4.5	16.1	23.2	2.6	15.5	4.4	2.2	0	0.1	0.7
1981	0	–	–	0.6	2.6	19.6	0.4	11.9	4.9	15.6	13	11.6	11.7	5.3	1.0	1.0	0.4	0.5
1982	0	0	0	0.1	1.6	13.7	0.4	13	6.1	15.2	20.6	8.5	15.4	3.5	1.0	0.6	0.2	0.1
1983	0	0	0	0.1	8.1	10.3	0.9	6.2	15.9	8.9	16	5.4	15.1	10.8	0.5	–	0.6	0.5
1984	0	–	–	0.1	14.6	8.6	2.2	2.6	12.8	3.4	13	5.8	17.7	16.6	2.1	0.2	0.3	–
1985	–	–	–	0.1	15.1	2.0	1.5	2.6	15.3	3.3	14.8	3.3	14.8	24.8	2.6	0	0.1	0
Mean	0.4	0	0	0.2	4.9	14.8	2.6	9.6	8.0	10.2	17.5	5.3	13	11.2	1.2	0.2	0.8	0.2

Years during *Bonamia* induced mortalities

Year	A0	K0	L0	S5	S6	B5	C5	D6	E6	D7	E7	F8	G8	S7	S8	F9	G9	H0
1986	–	–	–	0.2	31.8	3	1	2.1	9.3	1.1	12.1	0.8	11	24	0.6	–	2.9	0.8
1987	–	–	–	1	19	31	7	7	14	3	2	3	1	12	0	–	–	–
1988	0	0	0	1	20	30	9	7	4	2	5	4	0	15	2	0	0	0
1989	1	0	0	2	16	28	5	5	5	2	5	2	2	14	1	0	11	0
1990	0	0	0	6	32	25	6	2	1	0	1	0	1	12	6	0	9	–
Mean	0.2	0	0	2.1	23.8	23.4	5.6	4.6	6.7	1.6	5	2	3	15.4	1.9	0	4.6	0.2

For areas fished and where the catch was less than 0.05%, catch is shown as 0. Areas not fished are represented by -:

Table 4: Percentage of total catch in group 1 statistical areas for years 1975 to 1985, 1986 to 1990 and 1990 alone.

Statistical area	1975–1985	1986–1990	1990 alone
G8	13	3	1
E7	17	5	1
F8	5	2	0
D7	10	2	0
D6	10	5	2
Total	55%	17%	4%

Table 5: Percentage of total catch in group 2 statistical areas for years 1975 to 1985, 1986 to 1990 and 1990 alone.

Statistical area	1975–1985	1986–1990	1990 alone
B5	14	23	25
S6	5	24	32
S7	11	15	12
C5	3	6	6
Total	33%	68%	75%

Table 6: Percentage of total catch in group 3 statistical areas for years 1975 to 1985, 1986 to 1990 and for 1989 and 1990 alone.

Statistical area	1975–1985	1986–1990	1989 alone	1990 alone
G9	0.8	4.6	11	9
S8	1.2	1.9	1	6
S5	0.2	2.1	2	6
Total	2.2%	8.6%	14%	21%

Table 7: Surveys of geographical distribution of oysters and the size of the oyster population in Foveaux Strait from 1960 to 1990.

Year	Method	Vessel	Area surveyed (km^2)	No. of stn.	Sampling design	Estimate of Population size	Estimate of Density Map	Reference
1960–62	survey dredge (0.9m)	comm. oyster vessels	1,778	518	1 nautical mile grid	No	Yes	Stead 1971
1960–62	direct counts of density by divers	comm. oyster vessels	377	35	Selected dive stations over estimated commercial area	Yes	No	Stead 1971
1975	survey* dredge (1.25m)	*James Cook* J03/75 J09/75	201	593	1/3 nautical mile grid	Yes	Yes	Allen & Cranfield 1979
1974–75	mark recapt. survey	GRV *James Cook* J03/73 J02/74	(1) 243 (2) 82	–	Mark–recapture experiment over important commercial beds	Yes	No	Cranfield & Allen 1979
July 1990	comm. dredge	comm. oyster vessels	1,276	252	1 nautical mile grid over commercial beds 2 nautical mile grid over periphery	No	Yes	This report
Oct 1990	survey* dredge (1.25m)	GRV *Kaharoa* KH090/14	615	116	Two phased stratified (7) random	Direct comparison with 1974/75 dredged areas	No	This report
Oct 1990	direct counts of density by divers	GRV *James Cook* JC090/16	646	83	Two phased stratified (9) random	Yes	No	This report

* The same dredge used on both surveys

Table 8. Estimates of legal-sized (≥ 58mm minimum dimension) population of oysters for Foveaux Strait (units, millions of oysters, see Table 7 for area covered by estimate). Estimates for three populations in 1990 that are important for different disease outcomes are delineated on the basis of oyster mortality and prevalence of *Bonamia* in that year (see text and Fig. 13).

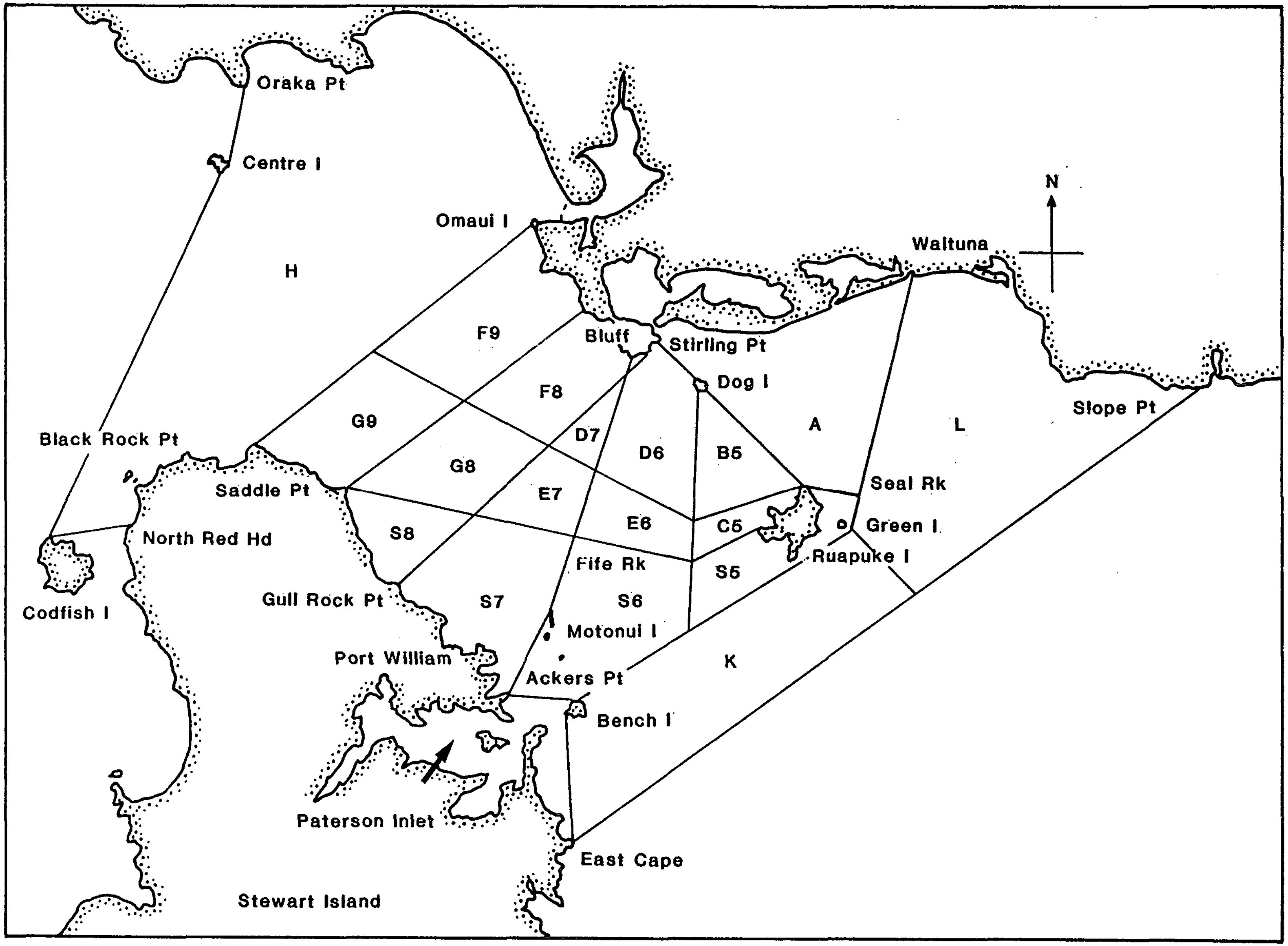
Year	Population	Population size	CV(%)	Source
1960–62	Total	1400	?	Stead 1971
1974	Total	1800	20	Cranfield & Allen 1979
1975	Total	1500	11	Cranfield & Allen 1979
1990	Outcome 5 Total population	632	13	Current work
1990	Outcome 4	384	18	Current work
1990	Outcome 3	281	22	Current work

Table 9. MCY estimates for the harvestable populations of the three outcomes in 1990 (see Table 8).

Population	MCY (Sacks)*
Outcome 5 (Total pop)	46 000
Outcome 4	28 000
Outcome 3	20 000

* 1 sack = 1000 oysters, weighs 79 kg

Figure 1.



Oraka Pt
Centre I
Omaui I
H
Waituna
N
F9
Bluff
Stirling Pt
Dog I
F8
A
L
Slope Pt
Black Rock Pt
G9
D7
D6
B5
G8
Seal Rk
Saddle Pt
E7
E6
C5
Green I
North Red Hd
S8
Ruapuke I
Fife Rk
S5
Gull Rock Pt
S7
S6
Codfish I
Motonui I
K
Port William
Ackers Pt
Bench I
Paterson Inlet
East Cape
Stewart Island

Figure 2

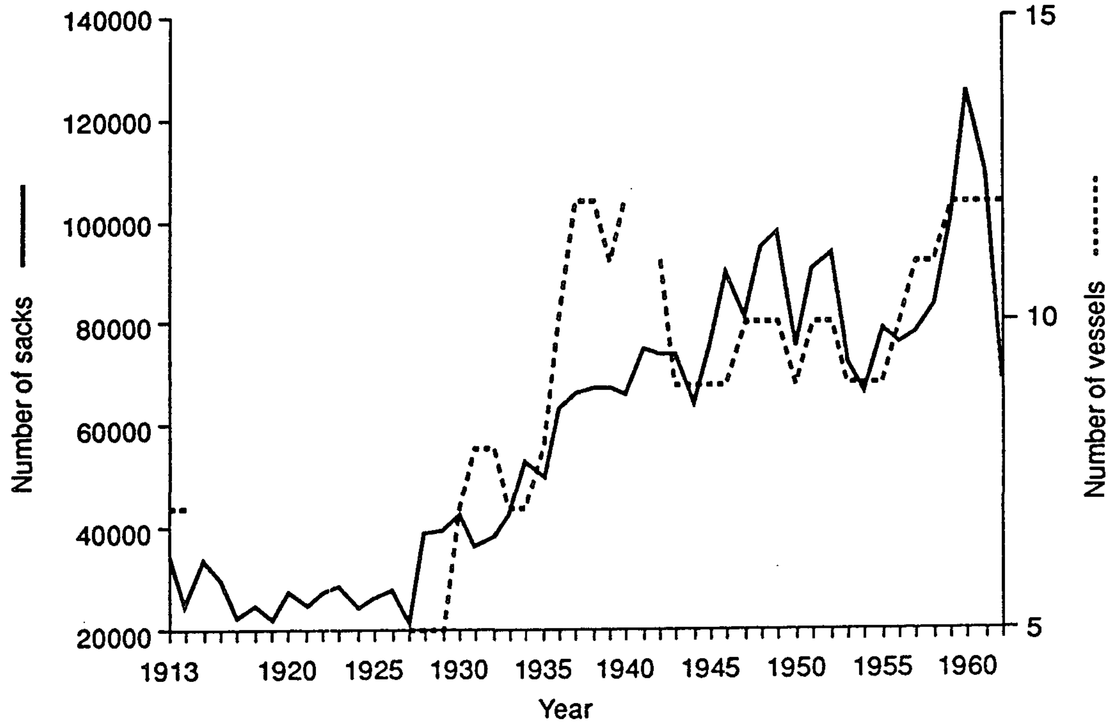


Figure 3

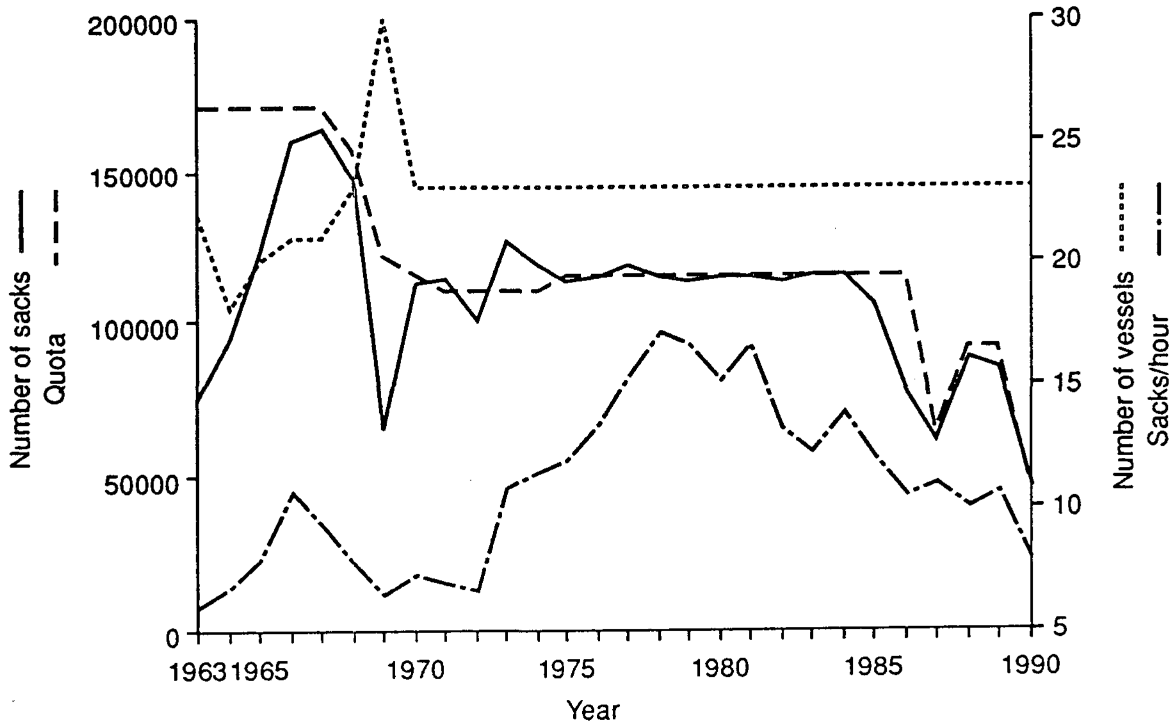


Figure 4

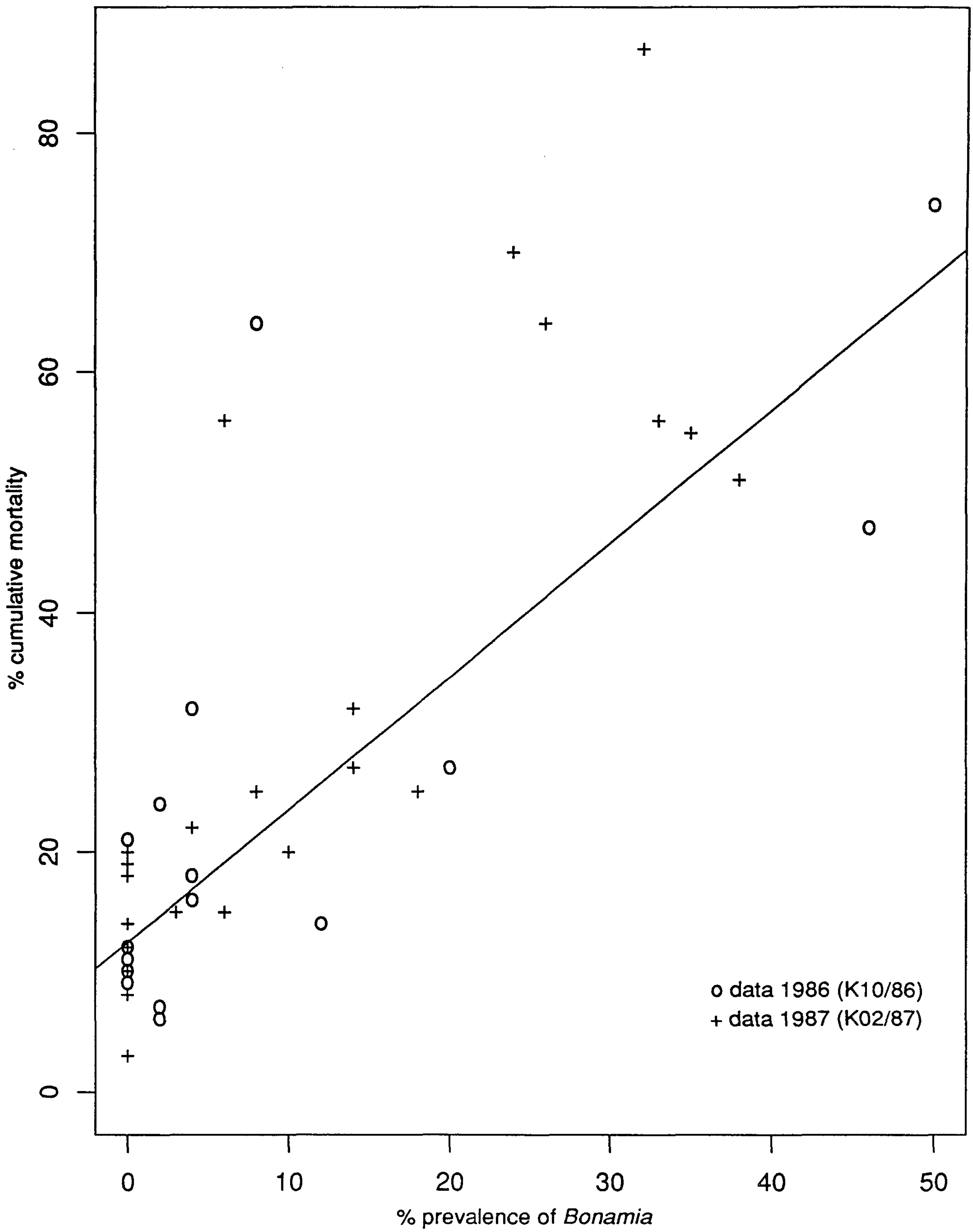

% cumulative mortality
0
20
40
60
80
0
10
20
30
40
50
% prevalence of *Bonamia*
o data 1986 (K10/86)
+ data 1987 (K02/87)

Figure 5

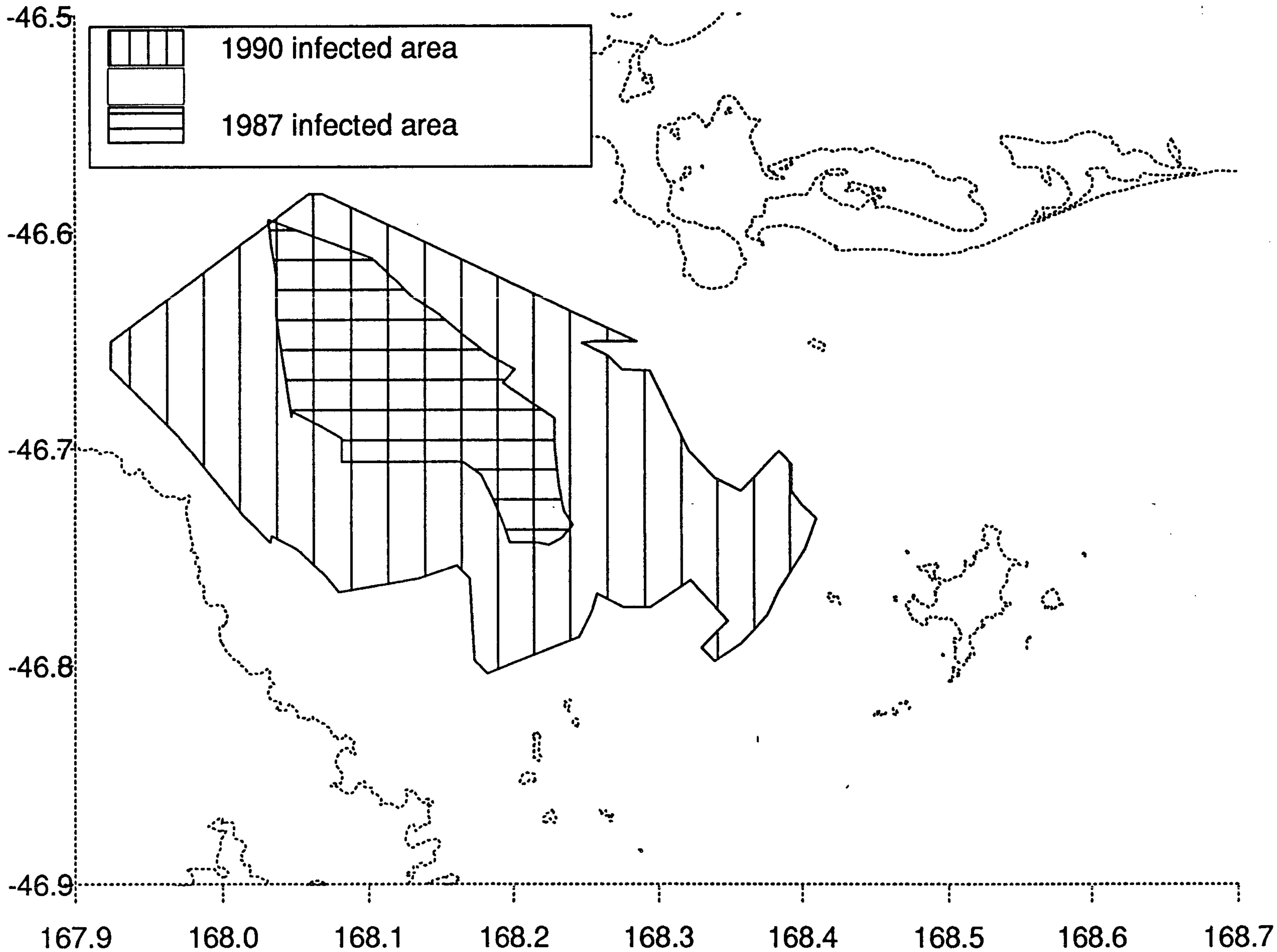
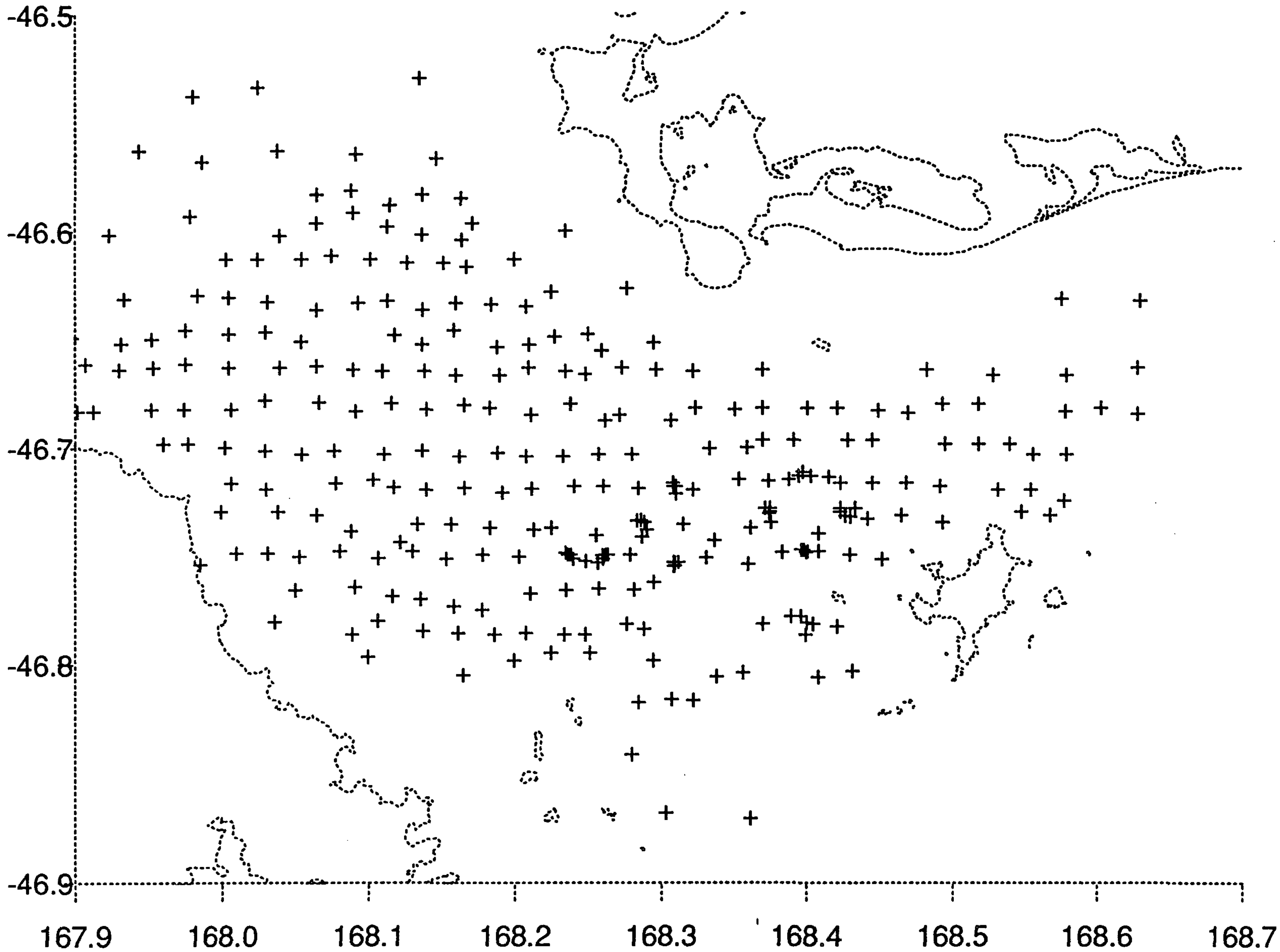
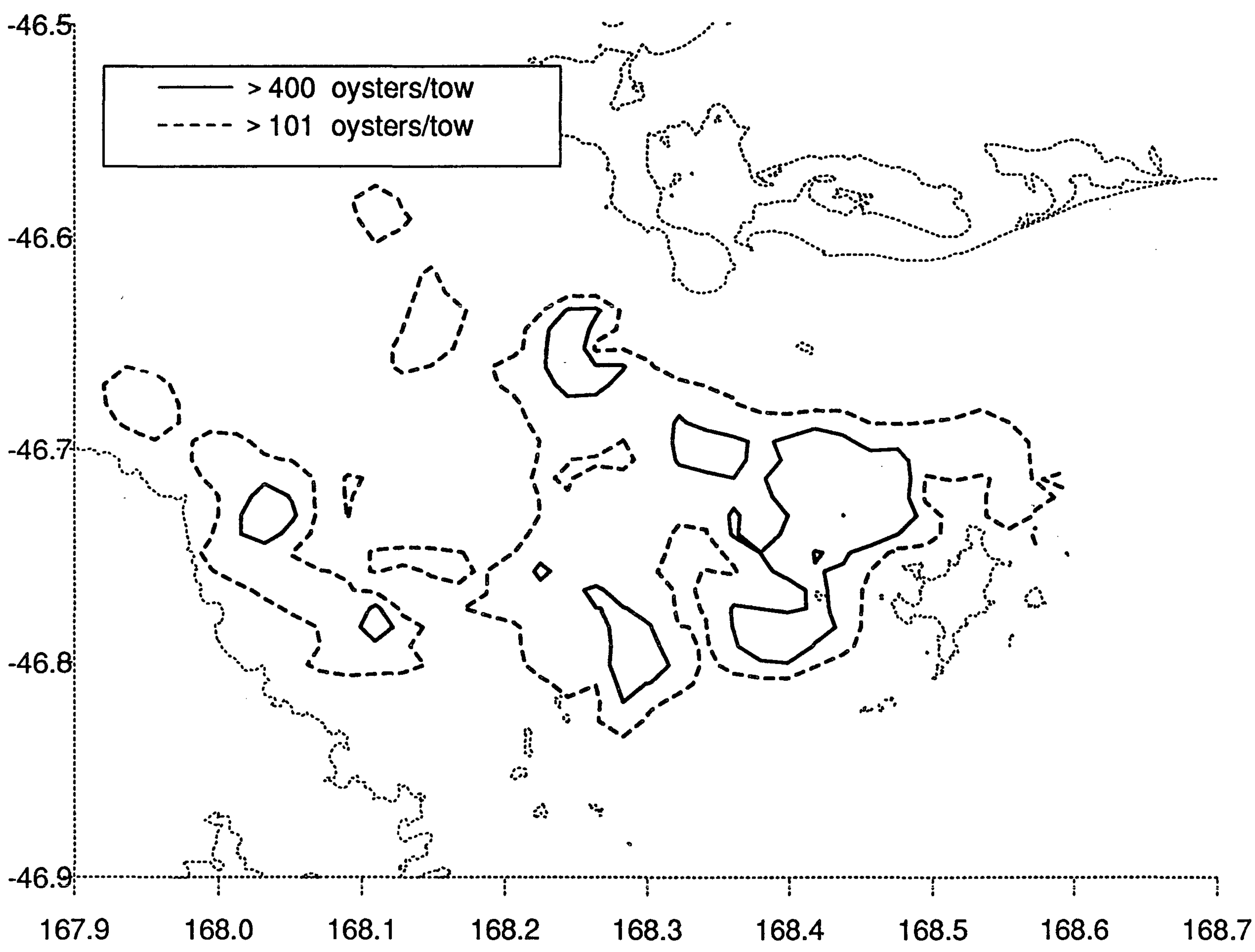

1990 infected area
1987 infected area
-46.5
-46.6
-46.7
-46.8
-46.9
167.9
168.0
168.1
168.2
168.3
168.4
168.5
168.6
168.7

Figure 6



-46.5
-46.6
-46.7
-46.8
-46.9
167.9
168.0
168.1
168.2
168.3
168.4
168.5
168.6
168.7

Figure 7



> 400 oysters/tow
> 101 oysters/tow
-46.5
-46.6
-46.7
-46.8
-46.9
167.9
168.0
168.1
168.2
168.3
168.4
168.5
168.6
168.7

Figure 8

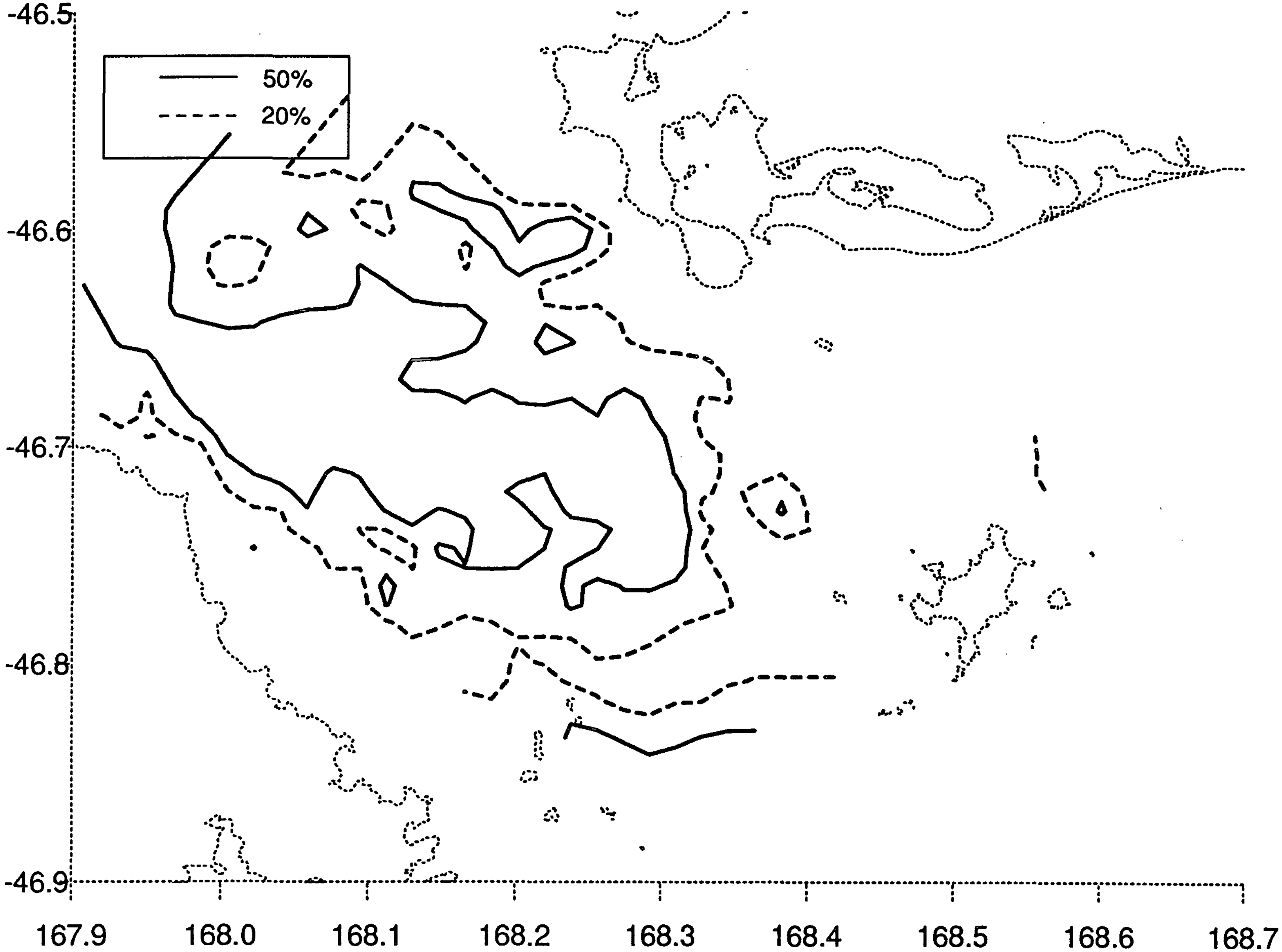

50%
20%
-46.5
-46.6
-46.7
-46.8
-46.9
167.9
168.0
168.1
168.2
168.3
168.4
168.5
168.6
168.7

Figure 9

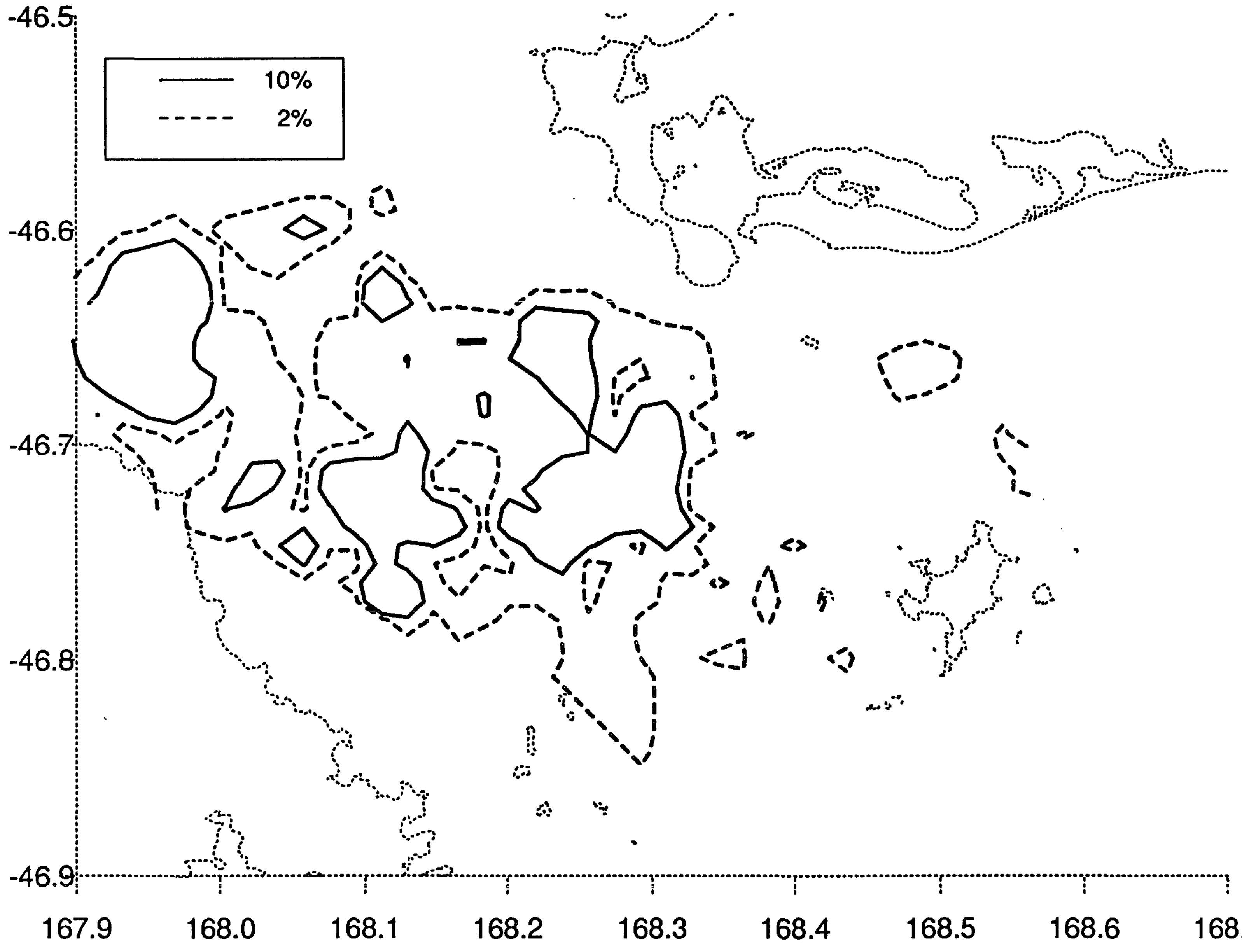
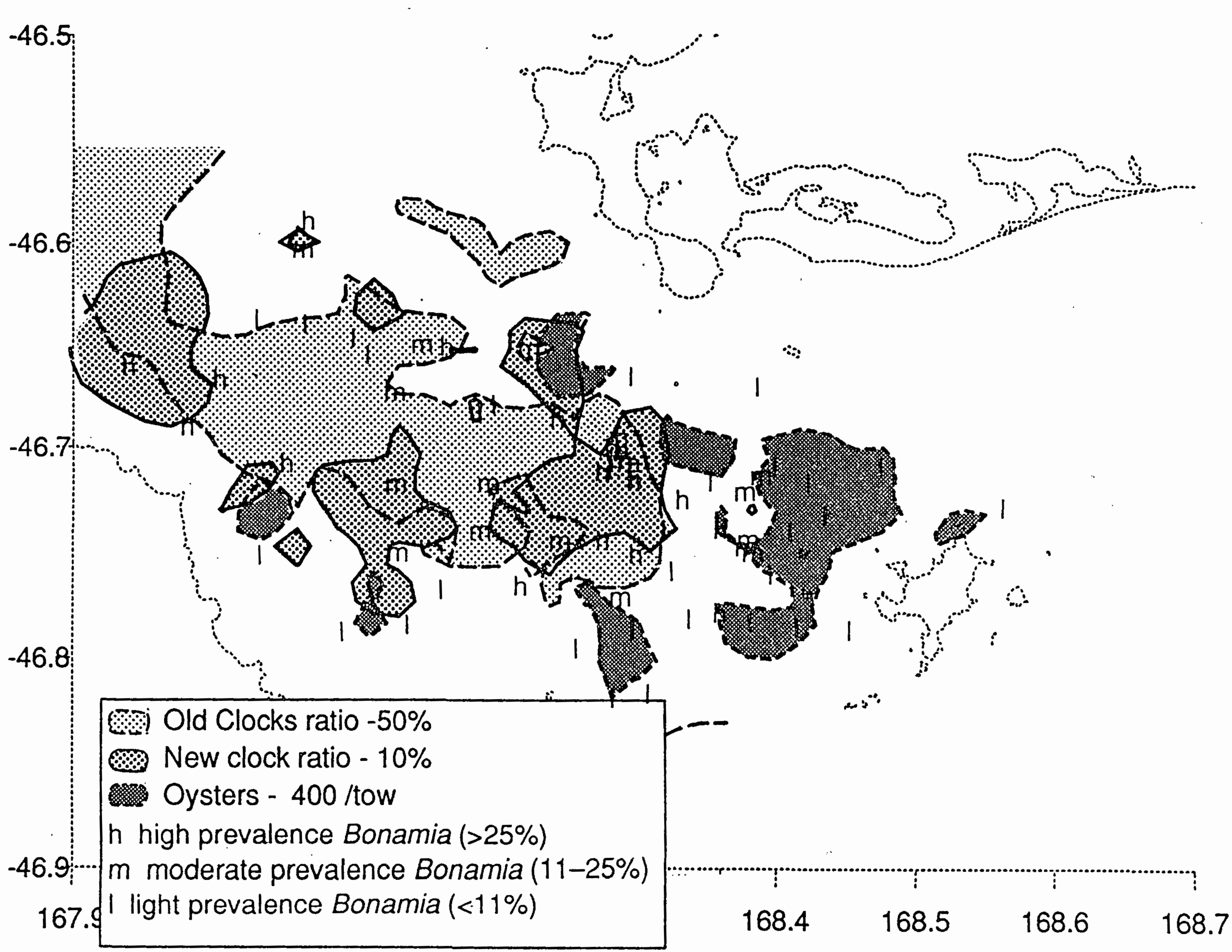

10%
2%
-46.5
-46.6
-46.7
-46.8
-46.9
167.9
168.0
168.1
168.2
168.3
168.4
168.5
168.6
168.7

Figure 10



-46.5
-46.6
-46.7
-46.8
-46.9
167.9
168.4
168.5
168.6
168.7
Old Clocks ratio -50%
New clock ratio - 10%
Oysters - 400 /tow
h high prevalence Bonamia (>25%)
m moderate prevalence Bonamia (11–25%)
l light prevalence Bonamia (<11%)

Figure 11

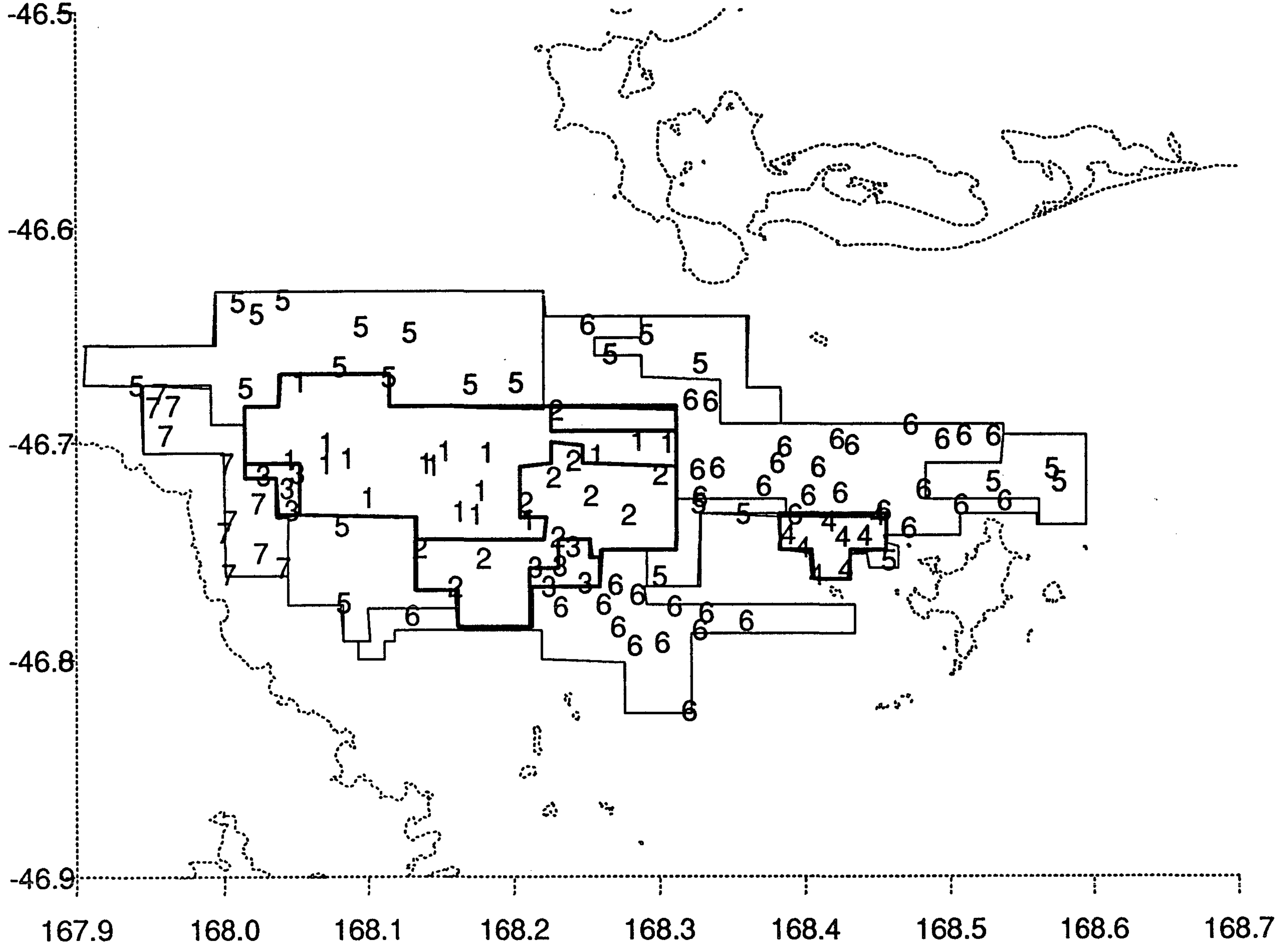
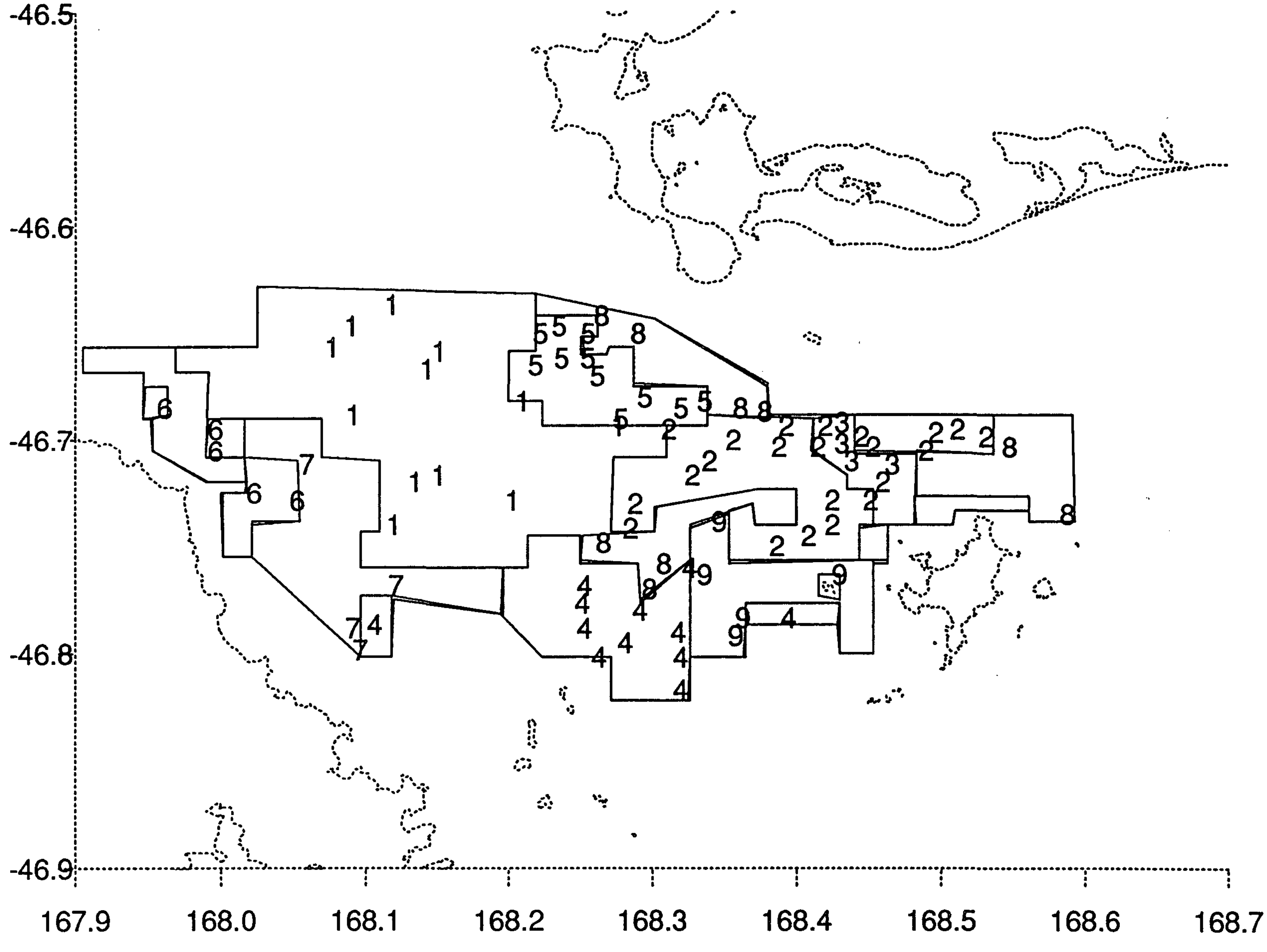
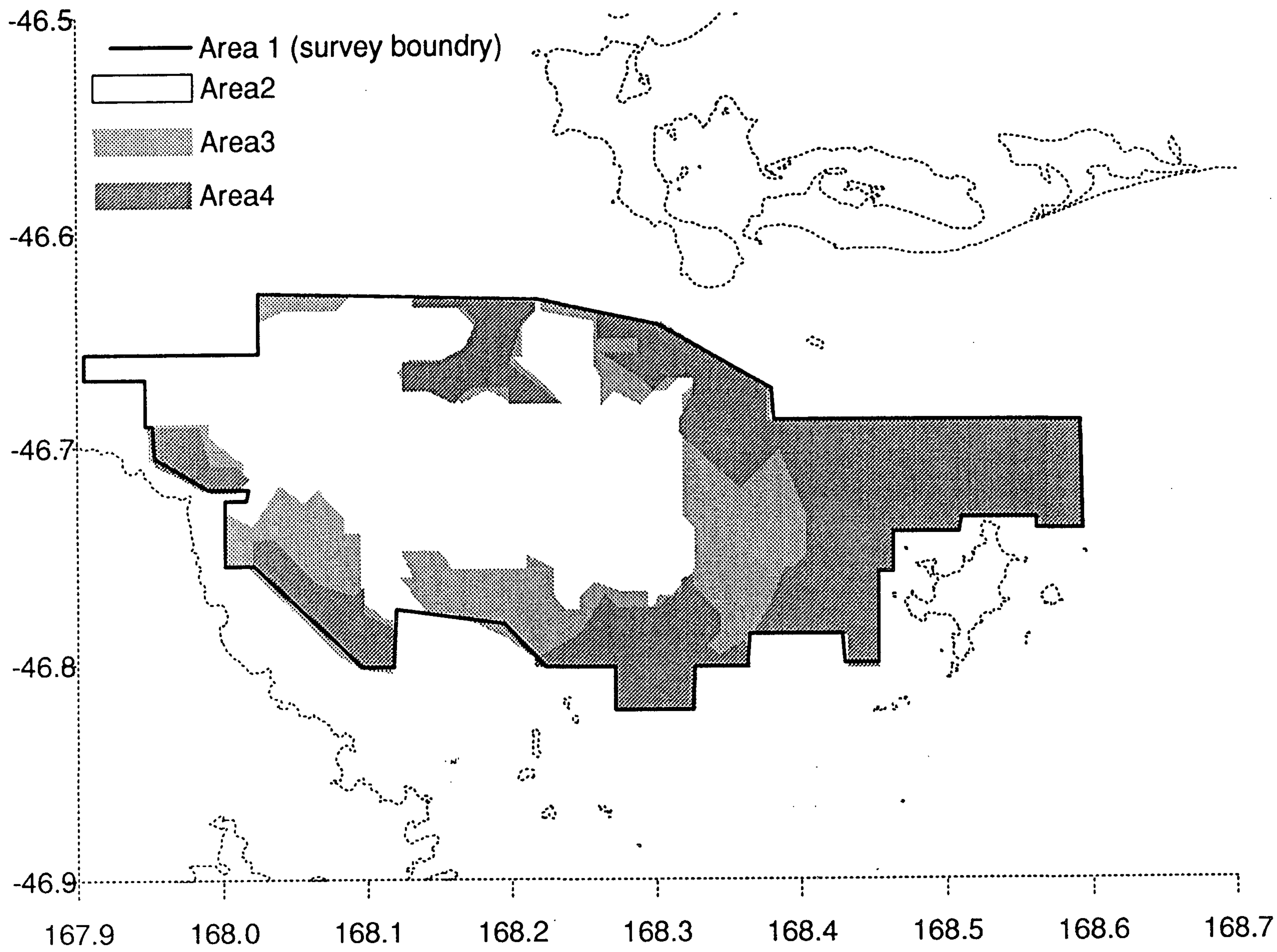

-46.5
-46.6
-46.7
-46.8
-46.9
167.9
168.0
168.1
168.2
168.3
168.4
168.5
168.6
168.7

Figure 12



-46.5
-46.6
-46.7
-46.8
-46.9
167.9
168.0
168.1
168.2
168.3
168.4
168.5
168.6
168.7

Figure 13



Area 1 (survey boundry)
Area2
Area3
Area4
-46.5
-46.6
-46.7
-46.8
-46.9
167.9
168.0
168.1
168.2
168.3
168.4
168.5
168.6
168.7