CSIRO PUBLISHING

Marine & Freshwater Research

Volume 51, 2000

A journal for the publication of original contributions in physical oceanography, marine chemistry, marine and estuarine biology and limnology

www.publish.csiro.au/journals/mfr

All enquiries and manuscripts should be directed to
Marine and Freshwater Research
CSIRO PUBLISHING
PO Box 1139 (150 Oxford St)
Collingwood
Vic. 3066
Australia
Telephone: 61 3 9662 7618
Facsimile: 61 3 9662 7611
Email: ann.grant@publish.csiro.au

Published by **CSIRO** PUBLISHING
for CSIRO and
the Australian Academy of Science

Mar. Freshwater Res., 2000, **51**, 601–12

Impact of mortality, possibly due to herpesvirus, on pilchard *Sardinops sagax* stocks along the south coast of Western Australia in 1998–99

D. J. Gaughan, R. W. Mitchell and S. J. Blight

Research Division, Fisheries WA, Western Australian Marine Research Laboratories,
PO Box 20, North Beach, WA 6020, Australia. email: dgaughan@fish.wa.gov.au

Abstract. During progression of a mass mortality of Australian pilchards in late 1998 and early 1999, quantities of dead pilchards on the sea-surface, sea-floor and along beaches were estimated in three regions along southern Western Australia (WA) by use of transects. Total mortality was estimated at 17 590, 11 193 and 144.4 t for Esperance, Bremer Bay and Albany respectively. Mortality rates at Esperance and Bremer Bay were similar at 74.5% and 64.7% respectively, with a mean of 69.6%. In contrast, estimated mortality at Albany was only 2.4%. Although the difference in total mortality between regions is probably related to differences in stock size, as determined by simulation models, the much lower estimate for Albany is probably an artefact of an over-estimated pilchard biomass and not due to large differences in actual mortality rates. Variability in estimates of both pilchard biomass and quantities killed resulted in a wide range of estimated mortality rates, with lower estimates for Esperance and Bremer Bay of 28.0% and 22.9% respectively. This represents a significant decline in the breeding stock of WA pilchards. If the impact was closer to the mean (69.6%), then pilchard stocks in WA are severely depressed.

Introduction

A mass mortality of *Sardinops sagax* Jenyns in 1995, which originated near the Eyre Peninsula in South Australia (SA) (Fig. 1) then progressed east and west around southern Australia, was probably due to a herpesvirus (Fletcher *et al.* 1997; Griffin *et al.* 1997; Hyatt *et al.* 1997; Jones *et al*. 1997; Whittington *et al.* 1997). The focal origin, fast rate of spread, apparently high mortality rate and lack of previous mortality events of comparable magnitude led those authors to suggest that the disease agent was probably an exotic pathogen to which Australian pilchards were naïve. A second mass mortality of *S. sagax* originated in South Australia in early October 1998 and also spread across this species' range through southern Australia, over a period of seven months; pathological assessments again suggest that a herpesvirus was responsible (B. Jones, personal communication). Following the 1995 event there were concerns that the impact of the outbreak was sufficient to seriously affect the size of pilchard stocks in Western Australia (WA) (Fletcher *et al.* 1997). Fletcher *et al.* estimated that in 1995 the quantities of pilchards killed in each of the four primary pilchard-fishery management zones in southern WA (on the south and lower west coasts, Fig. 1) were relatively similar at 1500–2500 t, with a total for WA across all four zones of ~8000–10 000 t. This equated to a decline in the overall spawning biomass of *S. sagax* in WA of ~10–15%.

In this study, we estimate the effect of this second mortality event on the biomass of pilchard stocks in southern WA by using estimates of quantities of dead pilchards and of the vulnerable biomass of pilchards (N. Hall and D. Gaughan, unpublished) in each of three management zones on the south coast. Because of sampling and statistical problems, any estimates were likely to be imprecise (Cochrane 1999). Despite this, there was an urgent need to obtain peer-reviewed information on the magnitude of the second mass mortality event.

Materials and methods

Estimates of quantities of *S. sagax* killed in the 1998/99 mortality event followed methods similar to those adopted in WA during the 1995 event (Fletcher *et al.* 1997). Counts were made of dead *S. sagax* on the sea surface, sea floor and beaches, and total mortality was estimated for each management zone: there is evidence for the existence of separate adult assemblages at each of these zones (Edmonds and Fletcher 1997). Predation and scavenging on moribund and dead pilchards has not been factored into the estimations, which therefore represent the minimum within each region.

Beach counts

The progress of the pilchard mass mortality in WA waters was monitored from mid November by a network of opportunistically placed observers on land and at sea. Fisheries WA also chartered three flights to undertake aerial reconnaissance east of Esperance to Israelite Bay (Fig. 1). However, the irregular nature of progression of observed pilchard deaths prohibited detailed forward planning of this study, which was also hampered by the remoteness and sparse human population of the region east of Esperance. Beach counts eventually began at Duke of Orleans Bay, 60 km east of Esperance (Fig. 1), on 2 January 1999. The mortality event was then tracked as it moved west through the Bremer Bay and Albany regions.

 10.1071/MF99176 1323-1650/00/060601

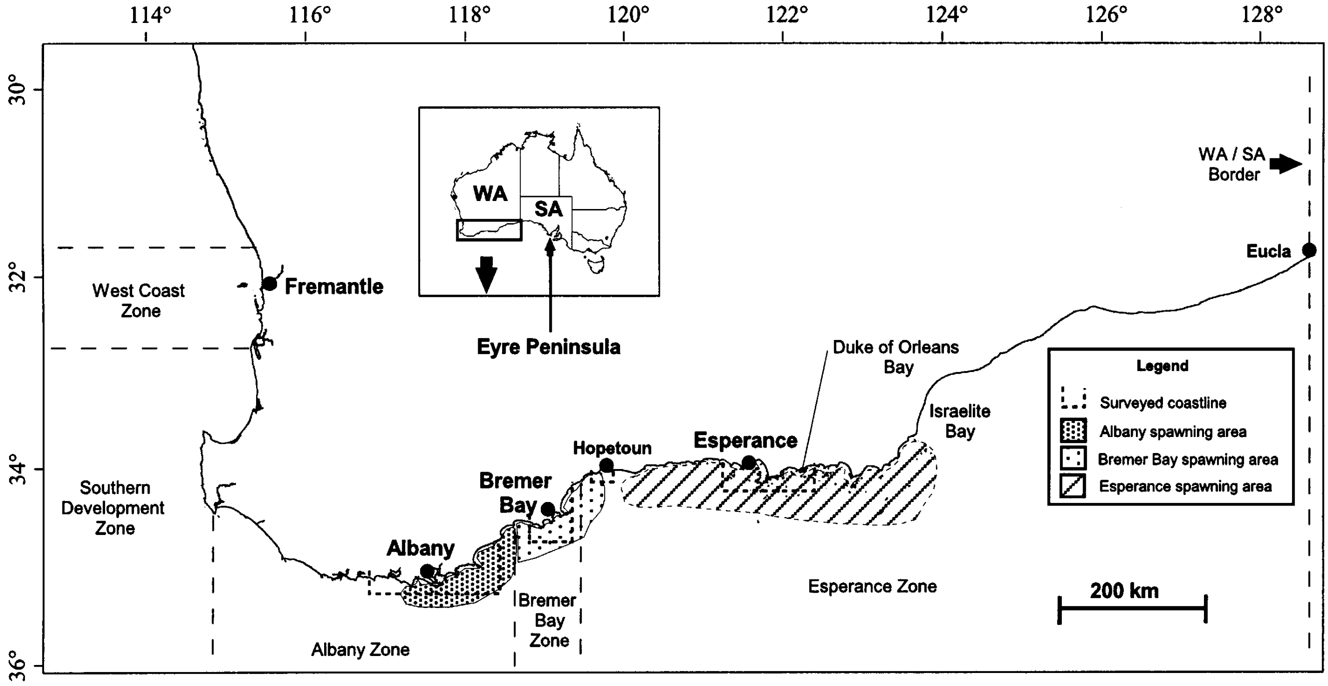

Fig. 1. Map of study region showing purse-seine management zones in southern Western Australia (WA). The three south coast zones and the West Coast Zone are the primary fishing regions. The regions within each south coast zone where beach counts were made are shown, as are the regions occupied by the exploited adult assemblage in each zone. Pilchards also occur east of Israelite Bay, but little is known about the stocks in this eastern sector of the Esperance zone. Both the 1995 and 1998/99 mass mortalities of Australian pilchards began near the Eyre Peninsula in South Australia (SA).

Preliminary observations showed that densities of dead pilchards were often greater towards the downwind end of a beach. Sampling was therefore stratified by placing transects at each end of a beach and also, where possible, along the 'middle' of the beach, which was dependent upon access. In most cases, two to three transects at any one beach were sampled, with each transect running parallel to the shore and covering the entire width of the beach. Transect length ranged from 5 to 200 m, depending on the densities of dead pilchards encountered. For example, whereas a 5 m transect at a heavily covered beach (Plates I*A*, I*B*) took several man-hours to count, a light scattering over 100 m took only minutes for a single person. This method thus takes into account differing densities along the length of the beach due to geographical (i.e. aspect) and environmental (i.e. wind direction) influences.

The density of dead pilchards was calculated by counting along the transects, from which the mean number of pilchards per linear metre of beach (or coastline), as opposed to per metre^2, could be estimated. The total length of each beach surveyed was precisely measured from an electronic chart using GIS software; this allowed the mean number of pilchards per metre along transects to be extrapolated to the total number per surveyed beach. All pilchards within each transect were removed after counting (Plate I*C*). Transects were subsequently inspected over a series of days, and newly deposited pilchards were likewise counted and removed. Numbers of dead pilchards could then be estimated at individual beaches over successive days, a necessary precaution against seriously underestimating quantities of dead fish (Anon. 1992). Dead fish were visually assessed as being either fresh (physically intact), old (e.g. signs of decay and/or lightly desiccated) or very old (substantial decay and desiccation). Subsequent to the first day of counts, only fresh pilchards were counted, thereby reducing bias due to re-deposition of dead pilchards on cleared transects. Numbers of beaches surveyed in the Esperance, Bremer Bay and Albany regions were 17, 14 and 20 respectively (Table 1). The total numbers of counts along transects, including repeat visits, within each of these same regions were 119, 57 and 73.

At most localities with dead pilchards, both on beaches and at sea, samples of 50–100 were retained and frozen for measurement of biological parameters, with 985 kept from the Esperance zone, 895 from Bremer Bay and 615 from Albany. Fresh specimens were used to determine weights of dead pilchards at Esperance (mean 35.7, s.d. 5.27), Bremer Bay (mean 34.2, s.d. 5.46) and Albany (mean 42.7, s.d. 7.41).

Because surveys accounted for only a fraction of the coastline within each region (Fig. 1), extrapolation was required to account for pilchard deposition along unsurveyed coastline. Furthermore, it was not possible to count dead pilchards at the base of cliffs and rocky areas because of inaccessibility. However, because of several reported observations by divers of large concentrations of pilchards on the sea floor adjacent to rocky habitats, these areas were included in the estimates of coast length for each zone prior to extrapolation of mean densities. The eastern and western boundaries used to determine the length of coastline (also measured by using GIS software) for each of the Esperance, Bremer Bay and Albany regions were based on distributions of pilchard eggs and, thus, spawning areas for adult assemblages of *S. sagax* in each region, as reported by Fletcher *et al.* (1996*a*).

The overall mean number of pilchards m^{-1} in each region was multiplied by both the regional mean pilchard weight and the length of coast adjacent to the area occupied by the regional adult assemblage to derive an estimate of the total mass of dead pilchards on beaches.

Sea-surface counts

Sampling procedures. Because of logistical constraints, surface counts of dead pilchards were conducted at only two regions, Esperance and Albany, and only within one-half of a day's steaming from port,

Table 1. Density of dead pilchards within each zone along the south coast of Western Australia

Zone	No. beaches	No. transects	Density (no. m^{-1})	
			Range	Mean (s.d.)
Albany	20	73	0–8.4	2.23 (6.34)
Bremer Bay	14	57	0–10 000	244.72 (1290.1)
Esperance	17	119	0–3300	125.27 (468.9)

which in both cases extended well beyond the fishing grounds. An extensive survey was conducted in the Esperance zone aboard PV *Walcott*. The transects examined off Albany used local industry vessels. Given the fact that few pilchards were observed on the sea surface in the Albany zone, transects were not continued after the first day. Instead, a second day of searching was conducted using a single-engine aircraft.

The survey transects (Fig. 2) followed various directions depending on the most recent information available at the time regarding the location of dead pilchards. A standard search area of 20 m width was scanned on one side of the vessel, with observations, i.e. counts of pilchards, made away from the direction of the sun. Transect width was kept uniform by viewing through a calibrated sight situated on the fly bridge of the vessel. The vessel followed a heading, and a GPS instrument was used to mark the end of one transect and the start of the next, with each transect ~1.8 km long. Surface density (pilchards m^{-2}) was calculated for each transect based on counts and the area represented by each transect.

To obtain estimates for total quantities of floating pilchards in each region, mean surface densities were extrapolated to account for the total surface area, with the latter estimated by using GIS software. Surveys off southern WA between 1989 and 1995 found few pilchard eggs in the plankton of waters offshore of the 200 m isobath, and hence little evidence of pilchards (Fletcher *et al.* 1996*a*). The total surface area for each zone was therefore based on an offshore limit at the 200 m isobath and the same eastern and western boundaries used to estimate coast length adjacent to spawning areas.

The three reconnaissance flights east of Esperance reported dead pilchards distributed over a large area both inshore and offshore in the sea south of Israelite Bay. Reports from commercial and recreational fishers provided further evidence that pilchards were not restricted to inshore areas at the time of the kill. On 19 November a commercial fishing vessel reported very large quantities of dead pilchards on the surface 81 km south-west of Eucla. On 21 November crew of a demersal-trawler operating 108 km south of Eucla observed large amounts of relatively fresh pilchards in their nets and in the stomachs of captured flathead (Platycephalidae). Closer to Esperance, recreational fishers and divers reported dead pilchards at the Mart Islands, about 10 km offshore of Duke of Orleans Bay. This information was important in gauging the extent of the mortality event in areas that were not covered by this survey and thus assisted us in extrapolating our survey data to broader regions.

Drift estimate. We assumed that wind-induced drift of dead pilchards across the surface of the water would influence the quantities of dead *S. sagax* observed. A single estimate of drift rate was calculated by tracking a group of floating pilchards for a period of 15 min in an onshore wind (22 km h^{-1}) off the coast of Albany. Positions of the vessel were recorded from GPS to determine the start and end points of the drift. No tidal or current influences were taken into consideration. Wind direction and strength at half-hourly intervals during the period of the mortality event in each region were obtained from the Bureau of Meteorology. The wind data corresponding to Bremer Bay were collected at Hopetoun (Fig. 1).

During this exercise, 15 of the floating pilchards were collected and kept in a bucket of sea water to determine how long they remained afloat. As with the estimate of drift rate, this estimate was not replicated. Despite this shortcoming, in both cases the estimates have been used to direct post-stratification of data collected.

Aircraft search. A single-engine aircraft was used to search the inshore waters west of Albany on 18 February 1999. The aircraft travelled west of Albany to Parry Beach (Fig. 2*lower*) following the coast at a height 150–200 m above sea level. Two observers during the flight used binoculars to search the surface of the water and beaches.

Sea-floor counts

To assess the numbers of pilchards on the sea floor, a JVC colour video camera (model TK-1280E) coupled with a Fujinon (1:1.2/6 mm) lens in an underwater housing and attached to a sled was towed behind the PV *Walcott* at a speed of 2–4 knots. This was done only off Esperance, so data collected in that region were subsequently also used to derive estimates for the Bremer Bay and Albany zones. The images were relayed to a monitor on the vessel and recorded for later analysis in the laboratory. The field of view (i.e. transect width) was calibrated to 1 m, using the average size of pilchards as a scale (Fletcher *et al.* 1997). As with the pilchards on the surface, counts along the sea floor were made over transects of known length and expressed as numbers of pilchards m^{-2}.

Estimation of confidence limits (CLs)

The extent of the geographical area covered during this study allowed neither consistent replication nor random sampling on beaches or at sea. Along with inconsistencies in the intensity of sampling, these factors subsequently hampered the estimation of variances using standard parametric techniques. However, in order to provide 95% confidence levels, distributions of the estimates of mass of dead pilchards were constructed using boot-strapping. For regional beach counts the approach was to resample, with replacement, from the entire suite of individual counts (pilchards m^{-1}), apply the mean regional pilchard weight to calculate an overall mean mass of pilchards m^{-1}, and then extrapolate to the entire length of coastline for that region. Each distribution was produced by 1000 recalculations of the total mortality derived from counts on beaches, thereby allowing the 2.5% and 97.5% CLs to be determined from the left and right tails of the distribution. The data-set for sea-surface counts in Esperance was likewise treated to derive 95% CLs. The 95% CLs of the total mortality estimate for the Esperance region were obtained by summing the 2.5% and 97.5% values for each of the subtotals. Because the at-sea components of mortality for Bremer Bay and Albany were extrapolated from results obtained at Esperance, and thus had no or few data with which to conduct boot-strapping, CLs were not calculated for these components of total mortality. Therefore, 95% CLs for total mortality at Bremer Bay and Albany reflect the variability in beach counts at these localities.

Results

Drift speed and proportion of floating-sinking pilchards

The single sample of pilchards that were collected as they floated to the surface under natural conditions (i.e. at sea),

(A)

(B)

(C)

Plate I. *(A)* Tagon Beach (Esperance zone), 7 January 1999; *(B)* Point Anne beach (Bremer Bay zone), 27 January 1999; *(C)* Reef Beach (Bremer Bay zone) showing a cleared transect and a sample of 100 pilchards, 4 February 1999.

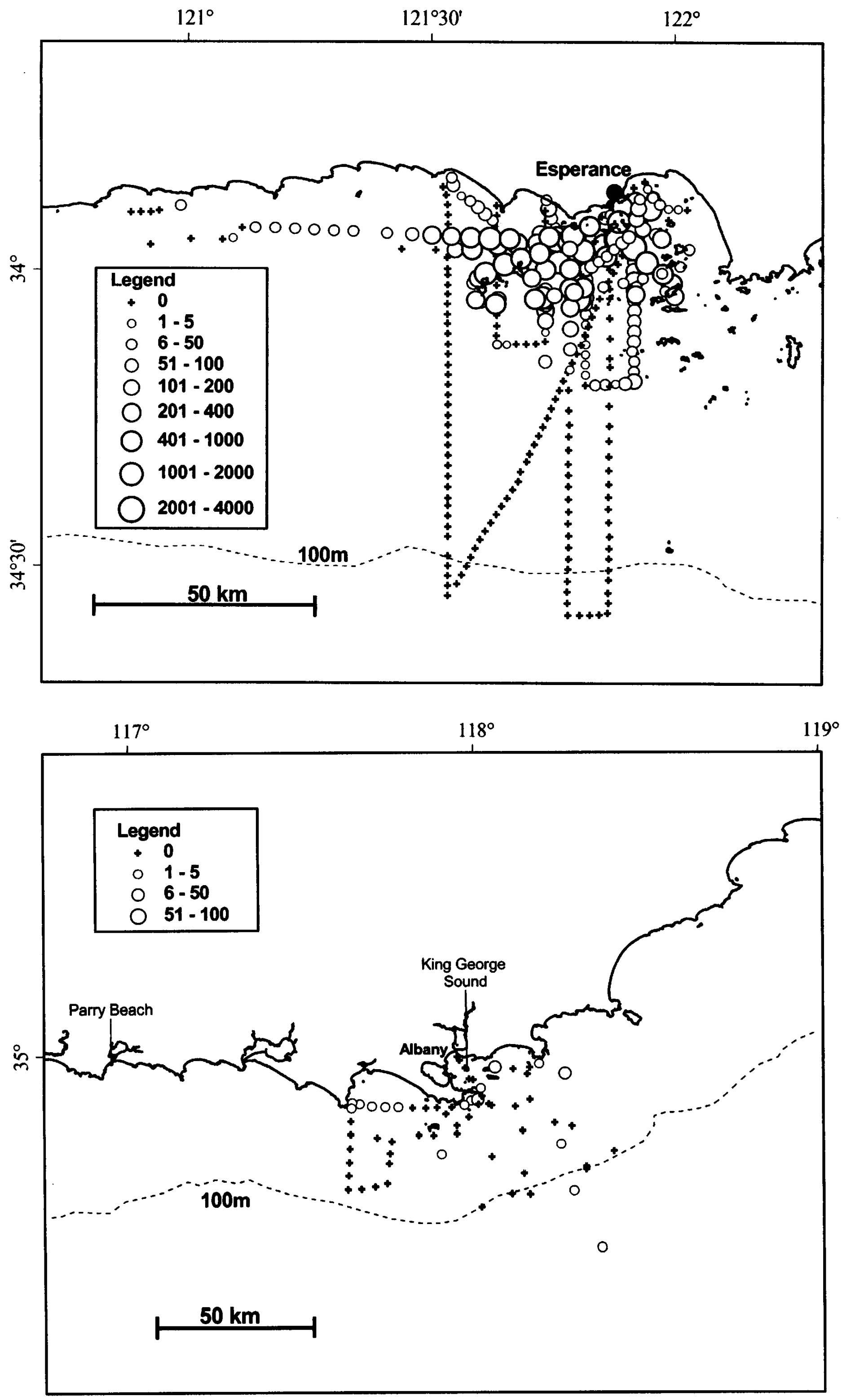

Fig. 2. Distribution of dead pilchards observed along sea-surface transects: *(upper)* Esperance zone, transects ~1.8 km long × 20 m wide; *(lower)* Albany zone.

subsequently sunk to the bottom of the experimental bucket after 28 h. Similarly, Fletcher *et al.* (1997) concluded that most pilchards floated for ~1–2 days before sinking. Although conditions in the bucket were different to those at sea we have assumed, in the absence of other information, that pilchards that rose to the surface then floated for 28 h.

Drift speed of the dead pilchards on the sea surface in a 22 km h^{-1} wind was 5.8 m min^{-1} (~350 m h^{-1}), which would transport floating pilchards 10 km in a 28 h period. Because average winds along the south coast of WA during the period of mass mortalities, coincidentally, ranged from 18 to 25 km h^{-1} from the south-east quadrant (i.e. onshore), we assumed that a certain proportion of pilchards floating within 10 km of the coast would wash ashore and therefore be included in the beach counts. We arbitrarily assumed that this proportion was 50%, but have also performed the calculations using values between 1% and 99% to assess the influence of this assumption on the estimates of total mortality for the Esperance region.

During the 1995 (Whittington *et al.* 1997) and 1998/99 mortality events, moribund pilchards were observed swimming listlessly near the surface and many dead pilchards floated to the surface at these times. However, an underwater observation of dying pilchards in Wellington Harbour, New Zealand, during the 1995 mass mortality noted that many fish also sank to the bottom (Whittington *et al.* 1997). Furthermore, it is also possible that some pilchards that sink after death may later rise to the surface. Variations in the relative proportions of pilchards that sank or floated are not understood and represent a potential source of error in this study. However, the data collected over a period of nine days during the sea-floor survey off Esperance allowed us to partially circumvent this lack of knowledge. Thus, concurrent sea-surface and sea-floor counts enabled us to determine that pilchard densities averaged 11.45 times higher (n = 14, s.d. 19.2) on the sea-floor than on the sea-surface, a relationship that does not require any assumptions about relative rates of sinking or floating. When estimating this mean ratio, only transects that had >0 pilchards m^{-2} on the surface could be used, because a ratio can not be calculated when the denominator is zero.

Multiple sampling – passage of the mortality event

Tracking the mortality event as it moved through an area was possible by multiple sampling at a particular locality. For example, on the first day of sampling at Le Grande Beach near Esperance, no dead pilchards were found (Fig. 3). Two days later, the first mortalities at this locality were recorded, with a mean density of 280 (s.d. 140.0) pilchards m^{-1}. This decreased to 31.4 (s.d. 14.0) pilchards m^{-1} the following day then to 1.8 (s.d. 0.9) pilchards m^{-1} the day after. No dead pilchards were recorded on the three days after this time, in spite of similar wind conditions during this entire period; we therefore concluded that the mortality event had finished in this area. Densities of dead pilchards on various beaches within each region generally showed this same pattern of increasing and then decreasing during the sampling period (Fig. 3). However, at Twilight Cove and Fourteen Mile Beach west of Esperance there appeared to be distinct waves of deposition of pilchards on 13 and 15 January, with a lull on 14 January. Similarly, there appear to have been two waves of deposition at Short Beach in Bremer Bay (Fig. 3). In none of these cases was there any change in the prevalence of moderate onshore winds, so we suspect that the waves of deposition resulted from the behaviour of either the infection or the pilchards, thereby causing a second peak in deaths adjacent to, or upwind of, those beaches.

Generally, pilchards were washed ashore in a single area over a period of 1–5 days. The peaks in deposition, and continued deposition over several days, at many of the beaches indicate that an intensive sampling strategy was a prerequisite to adequately account for those pilchards that washed ashore. This strategy was undertaken; although volunteers contributed substantially to the beach surveys in all regions, core staff were required at all times to ensure a rigorous standard of data collection.

Estimates of quantities killed

Esperance. Densities of dead pilchards in all three regions varied markedly between beaches (Table 1) and between days on individual beaches (Fig. 3), and several of the beaches examined in each zone had few or no dead pilchards. The highest concentration in the Esperance region was at Tagon Beach east of Esperance (mean 3300 pilchards m^{-1}, s.d. 1100) (Plate I*A*). Mean density along beaches in the Esperance region was 125.27 (s.d. 468.9) pilchards m^{-1} (Table 1) and the extrapolated mortality along the coastline for this region was 2486 t (Table 2).

Counts of dead pilchards on the sea-surface in the Esperance zone were made from 416 transects over a nine-day period which began on 11 January. The survey extended 99 km to the west of Esperance, 21 km to the east and 83 km offshore (Fig. 2*upper*). The area inside the 10 km stratum was 6189 km^2 and, with a mean density of 0.0041 (s.d. 0.009) pilchards m^{-2}, the estimated mortality within this area was 906 t. Of this total, 453 t (i.e. 50%) was used in the final surface mortality estimate for the 10 km stratum. All pilchards outside the 10 km stratum were included in the mortality estimate, which equated to 1476 t in an area of 10 087 km^2. Total surface mortality for the western half of the Esperance management zone (i.e. that for which a biomass estimate is available) was thus 1929 t (Table 2).

Twenty underwater transects were completed in the Esperance region between 11 and 19 January 1999, at the peak of the mortality event in this region. Locations of the underwater transects extended 87 km to the west of Esperance and 16 km to the east. The most southern transect was 21 km offshore. As a result of variable sea conditions and bottom structure, individual transect distances ranged from 406 to 5398 m.

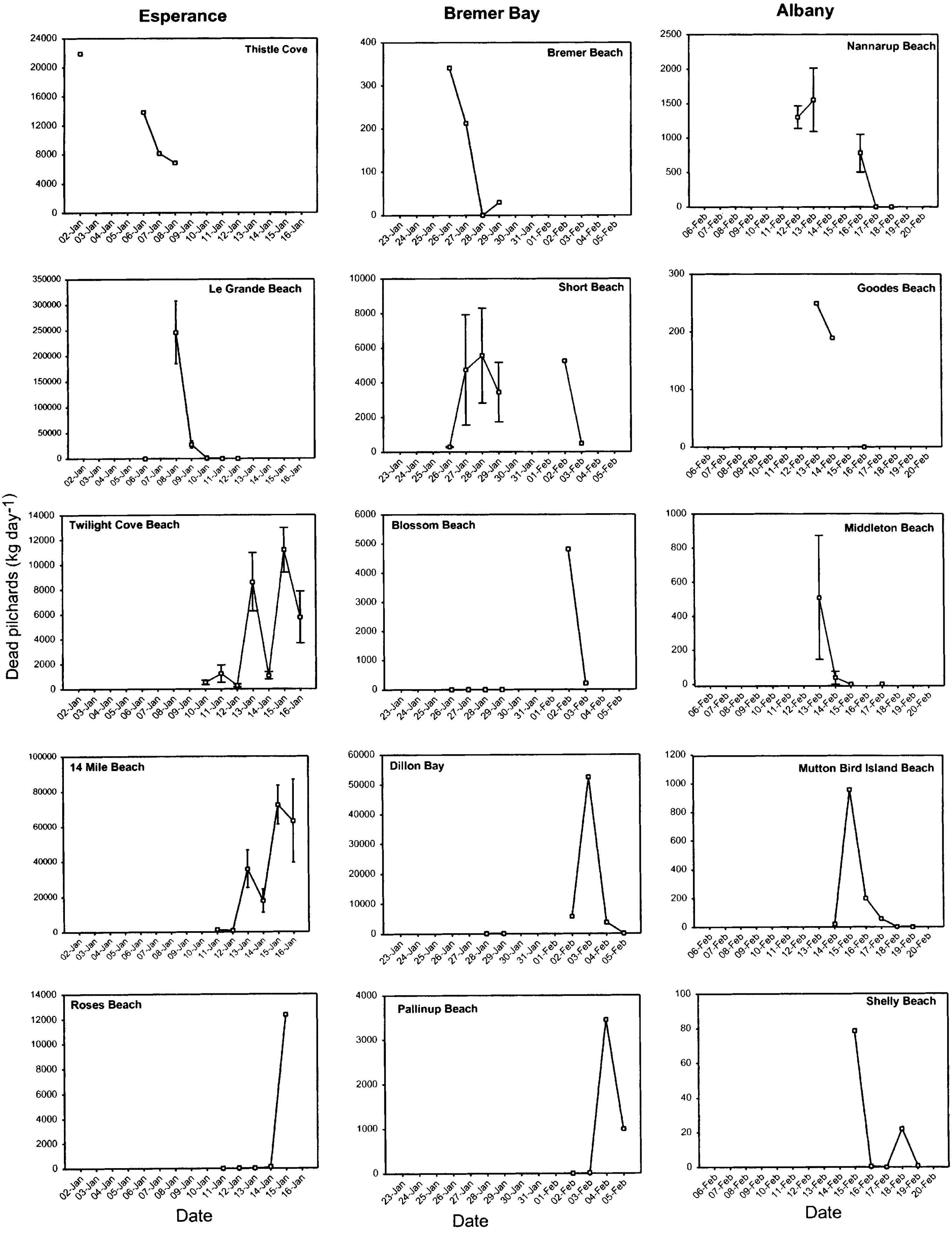

Fig. 3. Quantities of dead pilchards (mean, ± s.d. for those cases with >2 transects) deposited at daily intervals on some beaches within the Esperance, Bremer Bay and Albany zones. Only beaches surveyed on >2 days are shown. For each zone, the beaches are shown in an east-to-west direction going down the page.

Table 2. Estimates of total quantities (+95% CLs) of pilchards killed (tonnes) in each of three regions along the south coast of Western Australia based on sea-surface, sea-floor and beach counts obtained during the 1998/99 mass mortality

Because of insufficient data, the at-sea estimates for Albany and Bremer Bay were calculated from the product of their respective beach estimates and a constant derived from the at-sea:beach ratio estimated from the more comprehensive data set collected at Esperance. The 95% CLs were derived from distributions generated by bootstrapping the original data. The 95% CLs for Esperance are the sum of those for the subtotals. Because the at-sea estimates for Albany and Bremer Bay were calculated from beach counts, their 95% CLs reflect the variability in those beach counts

	Albany	Bremer Bay	Esperance
Sea surface			1929 (1299–2640)
Sea floor			13 175 (8069–19 050)
Total at sea	124	9612	15 104
Beaches	20.4 (13.4–41.6)	1581 (280–5728)	2486 (718–5335)
Total	144.4 (95.1–294.7)	11 193 (1983–40 529)	17 590 (10 086–27 025)

As found by Fletcher *et al.* (1997), the only species of fish observed dead on the bottom was pilchard. For some transects, either seagrass or silt probably obscured dead pilchards on the sea floor. Any bias in these counts is therefore likely to be downwards, tending to underestimate mortality. The density observed along these transects varied from 0.0 to 0.036 pilchards m^{-2} (mean 0.025, s.d. 0.031).

Because the mean sea-surface counts were estimated from more transects over a much wider area than the sea-floor counts, the estimate for mass of dead pilchards on the sea floor in Esperance was derived by use of the relationship described previously, i.e. multiplication of mean surface density by 11.45. Another factor to consider in applying this relationship was that it was derived only from data from transects that had pilchards on the surface. We therefore applied a correction factor of 0.483, which is the proportion of positive surface transects, to the sea-floor:sea-surface relationship. This resulted in an estimate of dead pilchards on the sea-floor of 13 175 t (Table 2). Total mass of pilchards killed in the western part of the Esperance zone during the 1998/99 mass mortality was estimated to be 17 590 t, of which 85.9% was observed at sea. The assumption that 50% of pilchards on the surface within 10 km of the coast washed ashore, and were thus accounted for in beach counts, had only a limited influence on the estimate of total pilchard mortality in the Esperance region (Fig. 4).

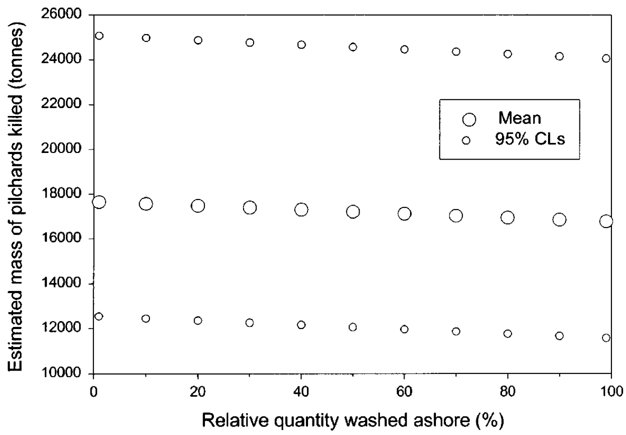

Fig. 4. Sensitivity of the total mortality estimate for Esperance to the assumption that 50% of pilchards floating within 10 km of the coast would be washed ashore and thus accounted for in the counts of pilchards on beaches. The mean (+95% CLs) were estimated from data sets derived by bootstrapping the original data for Esperance.

Bremer Bay. The highest counts along beaches in southern WA were recorded at Pt Anne in the Bremer Bay zone (10 000 pilchards m^{-1}, Table 1, Plate 1*C*), which likewise had the highest estimated mass for any single beach (981 t). Mean density on the shore was 244.72 (s.d. 1290.1) pilchards m^{-1} (Table 1). Extrapolated mortality for the coastline in the Bremer Bay zone was 1581 t (Table 2).

Although there were no counts of dead pilchards at sea in the Bremer Bay region, this component had to be accounted for when estimating total mortality for this region. We therefore assumed that the relative proportions of dead pilchards at sea and on beaches in the Esperance zone were applicable to the Bremer Bay zone, particularly because wind conditions were very similar. At-sea mortality for Bremer Bay was thus estimated to be 9612 t, with the total for this zone of 11 193 t (Table 2).

Albany. Densities of dead pilchards along beaches in the Albany region were considerably lower than in the other two regions (Table 1). Extrapolated mortality for coastline in the Albany region was only 20.4 t (Table 2).

Sea transects in Albany extended 49 km east of King George Sound, 50 km to the west and 62 km offshore (Fig. 2*lower*). Only 53 pilchards were observed, resulting in a mean density on the surface of 0.00000847 (s.d. 0.0000217) pilchards m^{-2}. During the flight in the Albany region no dead pilchards were observed, either on the sea surface or on the beaches. The reconnaissance flights east of Esperance had previously shown that dead pilchards at sea and on beaches could be seen from the air. Therefore, we took the result of the aerial search to indicate that there were very few dead pilchards, either floating or washed ashore, in the area searched. Thus, the results of the aerial survey did not contradict the low numbers observed from ground level.

Total surface area within the Albany zone was 6108 km^2. The area inside the 10 km stratum was 1944 km^2 and the estimated quantity of dead pilchards within this area was 0.70 t, of which 50% (0.35 t) were assumed to have washed ashore. The sea-surface mass of dead pilchards for the area outside the 10 km stratum equated to 1.50 t in 4164 km^2. In comparison to Esperance, the region with the largest data set, this value for Albany was inordinately low compared with the estimate for pilchards deposited ashore. Therefore, rather than use the sea-surface data for Albany, the at-sea proportion estimated from Esperance was applied to Albany, giving a value of 124 t (Table 2). Total mass of dead pilchards at Albany was thus 144.4 t.

Effect on the stock

Estimates of vulnerable biomass (+ 95% CLs) for each region, where vulnerable pilchards are those older than approximately two years, were obtained from age-structured simulation models that are being developed (N. Hall and D. Gaughan, unpublished). These models incorporate all previous estimates of spawning biomass obtained with the daily egg production method within each region (Fletcher *et al.* 1996*a*, 1996*b*, 1997; Gaughan, unpublished), and thus integrate catch-at-age and fishery-independent data. Estimated effect of the mass mortality in each region had a positive relationship with the vulnerable biomass in that region, as estimated for December 1998, i.e. just before the mass mortality event reached exploited pilchard assemblages in WA (Fig. 5). Using the 'best' estimates for both the quantity of pilchards killed and vulnerable biomass, we estimated that the mortality rate at Esperance, Bremer Bay and Albany was 74.5%, 64.7% and 2.4% respectively. Similarly, expressing the estimated quantity of pilchards killed as a percentage of the 95% CLs for vulnerable biomass in each zone resulted in similar ranges for Esperance (28.0% to ~100%) and Bremer Bay (22.9% to ~100%), and a much reduced range for Albany (Table 3).

Table 3. Effect of pilchard mortalities (% killed) in each of three regions along the south coast of Western Australia during the 1998/99 mass mortality

Calculated from the estimate of quantities killed expressed as percentages of the corresponding vulnerable biomass, and of the upper and lower 95% CLs. The estimated quantity killed in Albany was 8.6% of the lower 95% CL of the biomass estimate for that same region, 2.4% at the level of the best estimate, and so on. At both Bremer Bay and Esperance estimated mortality exceeds the lower 95% CL for vulnerable biomass and is therefore assumed to be close to 100%

Region	Lower 95% CL	Vulnerable biomass	Upper 95% CL
Albany	8.6	2.4	0.9
Bremer Bay	379 (i.e. ~100)	64.7	22.9
Esperance	331 (i.e. ~100)	74.5	28.0

Discussion

Estimates of pilchard mortality

We estimated that at least 28 000 t of mature pilchards were killed on the south coast of WA during early 1999, noting that this estimate does not include those deaths east of Israelite Bay (Fig. 1). In the context of purse-seine fisheries in southern WA, this value equates to annual catches for 3–5 years being harvested in a two-month period.

The positive relationship between estimated impact and biomass levels as derived from the integrated-simulation models (N. Hall and D. Gaughan, unpublished) indicates that the differences in quantities killed between zones reflect the different stock sizes, which decrease from east to west (Fig. 5). This supports the hypothesis of Fletcher *et al.* (1997) that differences in concentrations of dead pilchards between areas in 1995 were most likely due to differences in density of adults, not to any variations in the influence of the causative agent.

Given the similarity in the estimated impact for Esperance and Bremer Bay, we contend that these rates of mortality more probably reflect the true situation than do the low values estimated for Albany. The much lower estimate of the impact at Albany suggests that either the quantities of pilchards killed were seriously underestimated or that the vulnerable-biomass estimate at that zone, as of late 1998, was seriously overestimated. Whereas quantities of dead pilchards

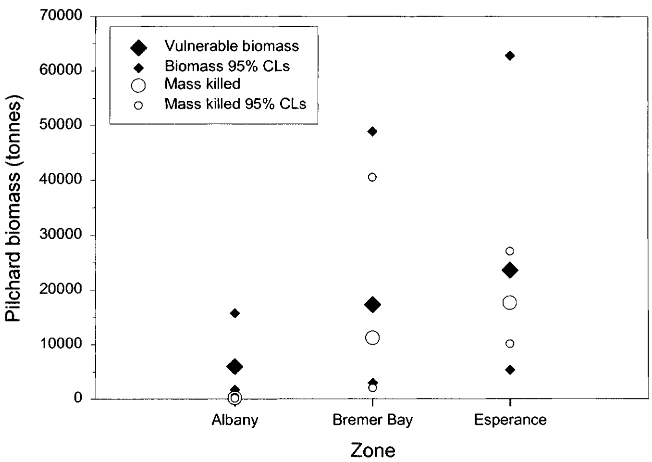

Fig. 5. Estimates of vulnerable biomass (+95% CLs) for pilchards at the Albany, Bremer Bay and Esperance zones in December 1998, along with the estimated total quantity of pilchards killed (+95% CLs) in each zone. The estimates of vulnerable biomass were obtained from a simulation model which integrates catch-at-age data with spawning biomass estimates from DEPM surveys.

in Esperance and Bremer Bay obviously far exceeded those that scavengers could consume (e.g. Plates I*A*, I*B*), this source of removal may have had a pronounced effect on counts of dead pilchards in the Albany region, thus contributing to the low numbers observed. However, even having considered this factor, we suspect that because both sampling intensity and wind conditions were similar in Albany to those in the other regions, it is unlikely that the quantities of dead pilchards washed ashore were underestimated to the extent that the mortality rate was only approximately 1/30th of that observed in the other two regions. An over-estimation of vulnerable biomass in the period before the mortality event thus appears more likely. Although this was not a welcome conclusion, in retrospect it was not particularly surprising. The most recent fishery-independent estimate of spawning biomass of pilchards off Albany before the 1998/99 mass mortality event, which was used in the integrated-simulation model, was obtained from a DEPM (daily egg production method) survey conducted in July 1997. Because there were very high egg counts at two sampling stations and low counts at the remaining stations, the July 1997 estimate was recognized as having a high variance, and the 'best' estimate of spawning biomass was most likely too high; however, in the interest of maintaining objectivity, this 'best' estimate was integrated into the simulation model. The further evidence provided here that the pilchard biomass at Albany has recently been over-estimated will be used as a basis for refining the integrated-simulation model for the Albany zone.

Immediate effect on pilchard stocks

Following this study, a series of DEPM surveys were conducted along the south coast of WA to estimate the size of the remaining spawning biomass of *S. sagax* in the commercial fishing areas and thus further assess the short-term effect of this mortality event. Use of this method in South Australia (Ward and McLeay 1999) suggested that the outbreak killed at least 60% of the stock in that State, which is similar to the mean of best estimates for Esperance and Bremer Bay found in the present study (i.e. 69.6%). Considering even the lower estimates for Esperance (28.0%) and Bremer Bay (22.9%), and our contention that such mortality rates also apply to Albany, the effect of the outbreak was substantial. If the 'best' estimates for WA and the independently derived estimates for SA are considered as appropriate (i.e. 60–70%), then the mass mortality should be viewed as disastrous for Australian pilchard stocks. Indeed, major losses over a very short period indicate that the status of these stocks should be considered to be depressed and, at best, in a period of regrowth if the combined effects of the variables able to influence recruitment strength have been favourable.

Fletcher *et al.* (1997) found that the total mass of pilchards killed in each of the four adult assemblages in 1995 were relatively similar at 1500–2000 t, which represented a decline in the entire spawning stock in south-western Australia of 10–15%. As variations in the pilchard biomass of 10–15% can occur frequently as a result of normal variations in recruitment levels, no long-term effects on the pilchard stocks were anticipated following the previous mortality event, unless it recurred (Fletcher *et al.* 1997). Considerably higher proportions of pilchards were killed along southern WA in the 1999 event. The short-term effects are already evident for purse-seine fisheries off southern WA. Annual catches of pilchards from the south coast during 1999 amounted to only 730 t, considerably less than the expected catch of 4000–5000 t. Subsequent to the 1998/99 mass mortality of pilchards, unusually high water temperatures coincident with La Niña conditions may have caused shifts in distribution of pilchards away from warm water and thus could be contributing to an ongoing lack of pilchards for both the Albany and Bremer Bay fisheries, as well as for the purse-seine fleet in the West Coast and Southern Development zones.

Potential ecosystem effects

It is possible only to hypothesize on the long-term effects of this second mortality event on the stocks of *S. sagax*. Thus, besides the negative effects on the purse-seine fisheries in WA, the potentially disastrous effects on the ecosystem of losing a huge quantity of a dominant clupeoid (e.g. Berdnikov *et al.* 1999) also need to be considered. The loss of 60–70% of the pilchard stock over a very short period is cause for concern since pilchards occupy a pivotal position of energy transfer in food webs in which they occur (e.g. Cole and McGlade 1998). This trophic position has been termed the 'wasp's waist' since pilchards feed on many species and are eaten by many species but have few (in terms of both species and numbers) comparably sized planktivorous, pelagic counterparts that share this position in the food web. In regions were they occur, pilchards thus constitute a major conduit between primary production and a variety of predators from the molluscan, teleost, avian and mammalian groups (e.g. Cole and McGlade 1998; Ward and Jones 1998).

A modelling exercise aimed at assisting in the development of management principles for exploited pelagic ecosystems suggested that a large decrease in stock size of small pelagic fish was likely to result in increased biomass of their food and competitors, and a decrease in the population of their predators (Mackinson *et al.* 1997). Furthermore, the higher trophic levels took the longest time to recover. In consideration of a 60–70% loss of pilchard stocks, it would not be surprising if populations at higher trophic levels whose members are known to at least periodically consume pilchards, such as those of southern bluefin tuna (SBT) and western Australian salmon (Serventy 1956; Cappo 1987), are negatively affected by the mass mortality of pilchards off southern Australia.

There is a range of potential effects on other species that share the pelagic and inshore habitats of pilchards from southern Australia, but few of these have been quantified. An increase in mortality and decrease in breeding success of little penguins (*Eudyptula minor*) in Victoria during 1995 has been linked to the mass mortality of pilchards in that year

(Dann *et al*. 2000). Likewise, Bunce and Norman (2000) expect a decrease in both survival and reproductive success of Australasian gannet (*Morus serrator*) because of a dietary change from predominantly *S. sagax* to less nutritious food following the passage of the 1998/99 mass mortality event through Victorian waters. Finally, although modelling exercises, such as that by Mackinson *et al.* (1997), and application of general ecological principles can provide a broad view of expected effects of a decrease in abundance of a dominant small pelagic fish, many of the more localized effects will probably remain poorly understood (Bunce and Norman 2000).

Is there a risk of another mass mortality of pilchards?

The origin of the infectious agent in Australia is still unknown, although studies of the 1995 mass mortality contended that the agent was new to Australian and New Zealand pilchards (Fletcher *et al.* 1997; Griffin *et al.* 1997; Hyatt *et al.* 1997; Jones *et al.* 1997; Whittington *et al.* 1997). Whittington *et al.* (1997) hypothesized that herpesvirus may have been introduced via ballast water, sea birds or imported baitfish, and they noted at that time that >10 000 t per annum of *S. sagax* were being imported annually from California, Peru, Chile or Japan without quarantine inspection to feed sea-caged SBT near the southern extremity of the Eyre Peninsula in SA (Fig. 1). The caged-SBT industry in SA has expanded since 1995, and increasingly larger quantities of *S. sagax* have subsequently been imported into Australia, with only limited disease testing.

Both Griffin *et al.* (1997) and Whittington *et al.* (1997) recognized that imported frozen pilchard was a potential source of the introduced pathogen. There have now been two outbreaks; when each mass mortality started, the largest quantities of imported *S. sagax* were fodder for caged fish in South Australia, and both the 1995 and 1998/99 mortality events started in that State. Although the first sightings of dead pilchards were not in the immediate vicinity of SBT cages, our hypothesis is that these imports were the most likely source of both the outbreaks.

The imported-pilchard hypothesis suggests that importation of untreated frozen pilchards carries a very high risk for Australian stocks of *S. sagax*. Research aimed at developing molecular-diagnostic techniques for the pilchard herpesvirus is underway and may answer some of the questions pertaining to the 1995 and 1998/99 mass mortalities of Australian pilchards. Meanwhile, the devastating effect of the mass mortality dictates that the imported-pilchard hypothesis be given very serious consideration in terms of trade, quarantine and resource management.

Acknowledgments

We are most grateful to the Fisheries WA staff, industry members and, particularly, many unpaid volunteers who helped during this study. These included the following: Russel Adams, Rick Allison (and for Plate I*B*), Graeme Baudains, Tim Bray, Bremer Bay Fish Processors, Bremer Bay Baits, Jan Blight, Lesley Blight, Rushton Blight, Olga Cironis, Tania Gaughan, Ken Gittins, Marcus Grey, Paul Hillier, Matt Holmes, Jerry Jenke, Kevin Johnson, Ian Keay, John Kelly, Bob Kirk, Paul Lewis, Eric Loughton (and for Plate I*A*), Stuart McDowall, Kevin McNeil, Joan Munckton, Michael Nicholas, Rod Pearn, Janine Price, Cameron Dawes-Smith, Bruce Webber, Fiona Wells, Master and crew of PV *Walcott*. We apologize for any omissions. Members of the public also provided information on when fish started appearing on beaches. Finally, thanks to our colleagues at WAMRL, particularly Mike Moran, for reviewing the manuscript.

References

Anon. (1992). Investigation and valuation of fish kills. [Prepared by The Pollution Committee, Southern Division & The Socioeconomics Section.] American Fisheries Society Special Publication No. 24. 95 pp.

Berdnikov, S. V., Selyutin, V. V., Vasilchencko, V. V., and Caddy, J. F. (1999). Trophodynamic model of the Black and Azov Sea pelagic ecosystem: consequences of the comb jelly, *Mnemiopsis leydei*, invasion. *Fisheries Research* **42**, 261–89.

Bunce, A., and Norman, F. I. (2000). Changes in the diet of the Australasian gannet (*Morus serrator*) in response to the 1998 mortality of pilchards (*Sardinops sagax*). *Marine and Freshwater Research* **51**, 349–53.

Cappo, M. C. (1987). The fate and fisheries biology of sub-adult Australian salmon in South Australian waters. Fisheries Industry and Research Trust Account Report. Project No. 84/75. 162 pp.

Cochrane, K. R. (1999). Review of the WA Pilchard Fishery 12–16 April 1999. Fisheries WA Fisheries Management Paper 129. Also available at: http://www.wa.gov.au/westfish/comm/broc/mp/mp129/index.html

Cole, J., and McGlade, J. (1998) Clupeoid population variability, the environment and satellite imagery in coastal upwelling systems. *Reviews in Fish Biology and Fisheries* **8**, 445–71.

Dann, P., Norman, F. I., Cullen, J. M., Neira, F. J., and Chiaradia, A. (2000). Mortality and breeding failure of little penguins, *Eudyptula minor*, in Victoria, 1995–96, following a widespread mortality of pilchard, *Sardinops sagax*. *Marine and Freshwater Research* **51**, 355–62.

Edmonds, J. S., and Fletcher, W. J. (1997). Stock discrimination of pilchards, *Sardinops sagax*, by stable isotope ratio analysis of otolith carbonate. *Marine Ecology Progress Series* **152**, 241–7.

Fletcher, W. J., White, K. V., Gaughan, D. J., and Sumner, N. R. (1996*a*). Analysis of the distribution of pilchard eggs off Western Australia to determine stock identity and monitor stock size. Final Report to Fisheries Research and Development Corporation. Project No. 92/95. 115 pp. (Fisheries Research and Development Corporation: Canberra.)

Fletcher, W. J., Lo, N. C-H., Hayes, E. A., Tregonning, R. J., and Blight, S. J. (1996*b*). Use of the daily egg production method to estimate the stock size of Western Australian sardines (*Sardinops sagax*). *Marine and Freshwater Research* **47**, 819–25.

Fletcher, W. J., Jones, B., Pearce, A. F., and Hosja, W. (1997). Environmental and biological aspects of the mass mortality of pilchards (Autumn 1995) in Western Australia. Fisheries Western Australia, Fisheries Research Report No. 106. 111 pp.

Griffin, D. A., Thompson, P. A., Bax, N. J., Bradford, R. W., and Hallegraeff, G. M. (1997). The 1995 mass mortality of pilchard: no role found for physical or biological oceanographic factors in Australia. *Marine and Freshwater Research* **48**, 27–42.

Hyatt, A. D., Hine, P. M., Jones, J. B., Whittington, R. J., Kearns, C., Wise, T. G., Crane, M. S., and Williams, L. M. (1997). Epizootic mortality in the pilchard *Sardinops sagax neopilchardus* in Australia and New Zealand in 1995. II. Identification of a herpesvirus within the gill epithelium. *Diseases of Aquatic Organisms* **28**, 17–29.

Jones, J B., Hyatt, A. D., Hine, P. M., Whittington, R. J., Griffin, D. A., and Bax, N. J. (1997). Special topic review: Australasian pilchard mortalities. *World Journal of Microbiology and Biotechnology* **13**, 383–92.

Mackinson, S., Vascocellos, M., Pitcher, T., Walters, C., and Sloman, K. (1997). Ecosystem impacts of harvesting small pelagic fish in upwelling systems: using a dynamic mass-balance model. In 'Forage Fishes in Marine Ecosystems. Proceedings of the International Symposium on the Role of Forage Fishes in Marine Ecosystems'. pp. 731–49. Alaska Sea Grant College Program Report No. 97–01. (University of Alaska: Fairbanks.)

Serventy, D. L. (1956). The southern bluefin tuna, *Thunnus maccoyii* (Castelanu) in Australian waters. *Australian Journal of Marine and Freshwater Research* **7**, 1–43.

Ward, T. M., and Jones, G. K. (1998). Potential effects of clupeoid fisheries on predatory fishes, seabirds and marine mammals in southern and eastern Australia. In 'A collaborative investigation of the usage and stock assessment of baitfish on southern and eastern Australian waters, with special reference to pilchards (*Sardinops sagax*)'. (Eds T. M. Ward, M. Kinloch, G. K. Jones and F. J. Neira.) pp. 29–47. Final Report to Fisheries Research and Development Corporation. Project No. 1994/029. (Fisheries Research and Development Corporation: Canberra.).

Ward, T., and McLeay, L. (1999). Spawning biomass of pilchards (*Sardinops sagax*) in shelf waters of central and western South Australia in 1999. Report to the Pilchard Working Group. (available from South Australian Research and Development Institute (Aquatic Sciences): Adelaide.) 38 pp.

Whittington, R. J., Jones, J. B., Hine, P. M., and Hyatt, A. D. (1997). Epizootic mortality in the pilchard *Sardinops sagax neopilchardus* in Australia and New Zealand in 1995. I. Pathology and epizootiology. *Diseases of Aquatic Organisms* **28,** 1–16.

Manuscript received 1 December 1999; revised and accepted 14 March 2000