doi:10.1111/j.1365-2761.2011.01241.x

Survey estimates of fishable biomass following a mass mortality in an Australian molluscan fishery

S Mayfield[1], R McGarvey[1], H K Gorfine[2,3], H Peeters[4], P Burch[1] and S Sharma[1*]

1 South Australian Research and Development Institute, Henley Beach, SA, Australia
2 Zoology Department, University of Melbourne, Vic., Australia
3 Department of Primary Industries, Queenscliff, Vic., Australia
4 Western Abalone Divers Association, North Geelong, Vic., Australia

Abstract

Mass mortality events are relatively uncommon in commercially fished populations, but when they occur, they reduce production and degrade ecosystems. Observing and documenting mass mortalities is simpler than quantifying the impact on stocks, monitoring or predicting recovery, and re-establishing commercial fishing. Direct survey measures of abundance, distribution and harvestable biomass provide the most tenable approach to informing decisions about future harvests in cases where stock collapses have occurred because conventional methods have been disrupted and are less applicable. Abalone viral ganglioneuritis (AVG) has resulted in high levels of mortality across all length classes of blacklip abalone, *Haliotis rubra* Leach, off western Victoria, Australia, since May 2006. Commercial catches in this previously valuable fishery were reduced substantially. This paper describes the integration of research surveys with commercial fishermen's knowledge to estimate the biomass of abalone on AVG-impacted reefs. Experienced commercial abalone divers provided credible information on the precise locations of historical fishing grounds within which fishery-independent surveys were undertaken. Abalone density estimates remained low relative to pre-AVG levels, and total biomass estimates were similar to historical annual catch levels, indicating that the abalone populations have yet to adequately recover. Survey biomass estimates were incorporated into harvest decision tables and used with prior accumulated knowledge of the populations to determine a conservative harvest strategy for the fishery.

Correspondence *Dr Stephen Mayfield, SARDI Aquatic Sciences, PO Box 120, Henley Beach, SA, 5022, Australia. (e-mail: Stephen.Mayfield@sa.gov.au)*
**Present address: Carbon Planet Ltd, Level 4, 172 North Terrace, Adelaide, SA 5000, Australia.*

Keywords: abalone, commercial fishery, disease, mass mortality, stock collapse, survey.

Introduction

Large-scale, mass mortality events can alter ecosystems (Dadon 2005; Miner, Altstatt, Raimondi & Minchinton 2006), influence conservation status (Fiori & Cazzaniga 1999), decrease production and reduce trade opportunities (Bunn 1993), thereby causing financial hardship through lost income (Moyer, Blake & Arnold 1993; Balcom & Clemetson 2006). Consequently, the effects of such events tend to be far-reaching (Beale, Fairbrother, Inglis & Trebeck 2008). High levels of mortality are a relatively frequent occurrence in aquaculture, where high stocking densities, atypical of wild populations, allow diseases to proliferate (Dixon, Hecht & Brandt 1991; Friedman, Beattie, Elston & Hedrick 1991; Davis & Barber 1994; Chi, Lo, Kou, Chang, Peng & Chen 1997; Tomaru, Kawabata & Nakano 2001; Maeno, De La Pena & Cruz-Lacierda 2004; Cai, Chen, Thompson & Li 2006). In contrast, mass mortality events in commercial, wild-harvest fisheries are comparatively rare. Observing and documenting these mass mortality events is considerably easier than quantifying the impact on stocks, monitoring or predicting their recovery, and re-establishing commercial fishing. This is because the costs associated with managing diseases are often high (Agtrans Research 2005).

Despite being uncommon in commercially fished populations, mass mortality events have been documented for a diverse range of harvested stocks that include fish (Ward, Hoedt, McLeay, Dimmlich, Kinloch, Jackson, Mcgarvey, Rogers & Jones 2001; Smith, Norriss & Brown 2009), rock lobsters (Cockcroft 2001; Valente & Cuomo 2005), scallops (Stokesbury, Harris, Bradley, Marino & Nogueria 2007) and abalone (Lester 1986; Goggin & Lester 1995; Miner *et al.* 2006; Liggins & Upston 2009). The primary cause of mass mortality in many wild populations is disease (Harvell, Kim, Burkholder, Colwell, Epstein, Grimes, Hofmann, Lipp, Osterhause, Overstreet, Porter, Smith & Vasta 1999; Daszak, Cunningham & Hyatt 2000), although alternative, probable causes have been identified. These include changed environmental conditions (Cockcroft 2001; Valente & Cuomo 2005), such as water temperature and dissolved oxygen levels, and parasites (Mullen, Russell, Tucker, Maratea, Koerting, Hinckley, De Guise, Frasca & French 2004).

The impact from mass mortality events can be substantial. For example, lobster deaths in western Long Island Sound in 1999 were estimated to exceed 10 million individuals, resulting in a 99% reduction in lobster landings and the collapse of the local fishery (Mullen *et al.* 2004; Valente & Cuomo 2005; Balcom & Clemetson 2006). Similarly, off South Australia, the spawning biomass of sardines declined by over 100 000 tonnes ($>70\%$) in both 1995 and 1998 (Ward *et al.* 2001). Losses of $\sim$5000 tonnes, valued at $\sim$US$100 million, have been reported for scallops (Moyer *et al.* 1993; Stokesbury *et al.* 2007). For the sardine and scallop cases, survey data were vital to determining the impact of the mass mortalities and estimating reliable reductions in biomass (Ward *et al.* 2001; Stokesbury *et al.* 2007). There are few reported cases of stock recovery from mass mortality events. Perhaps the most rapid, large-scale recovery was that observed following the 1995 sardine mass mortality in South Australia (Ward *et al.* 2001), which was probably driven by the low mortality levels in juvenile sardines (Ward *et al.* 2001; Murray & Gaughan 2003). This suggests that the biology of the affected species, differing mortality levels among age classes, and the spatial and temporal extent of the mass mortality event will be key determinants of any potential recovery.

Abalone (family Haliotidae, genus *Haliotis*) are gastropod molluscs that support valuable fisheries in many of the world's temperate seas (Hamasaki & Kitada 2008). In comparison with patterns elsewhere, where well documented declines in abalone production have been recorded (Prince 2004), abalone fisheries in Australia have been comparatively resilient. Recent estimates indicate these fisheries currently provide about 50% of the global wild-harvest production (Gordon & Cook 2004). Consistent with abalone fisheries elsewhere in Australia, the Victorian abalone fishery began in the early 1960s (Gorfine, Day, Bardos, Taylor, Prince, Sainsbury & Dichmont 2009). Management arrangements for the fishery have evolved since its inception including geographic subdivision of the commercial fishery into three zones (Prince & Shepherd 1992; Fisheries Victoria 2002; Fig. 1). The Western Zone (WZ) has 14 licence holders, and the quota season extends from 1 April to 31 March of the following year. A total allowable commercial catch (TACC) of 280 tonnes (approximately Australian $10 million) per annum was implemented from 1988–89 to 2002–03 (Prince & Shepherd 1992; Fisheries Victoria 2002; Department of Primary Industries 2008). This TACC did not differentiate between blacklip abalone, *Haliotis rubra* Leach, and greenlip abalone, *H. laevigata*, the two commercially important species. Catches were dominated ($>99\%$) by blacklip abalone.

Abalone viral ganglioneuritis (AVG) is caused by a virus that infects the abalone cerebral, pleuropedal and buccal nerve ganglia, causing tissue necrosis and haemocyte infiltration lesions (Hooper, Hardy-Smith & Handlinger 2007). This disease is highly infectious (Crane, Fegan, Corbeil & Warner 2009) and results in high levels of mortality across all length classes (Gorfine *et al.* 2009; M.R. Deveney & M.S. Doroudi, personal communication). Mass mortalities of wild abalone were first observed off Port Fairy in May 2006 and followed high levels of mortality from AVG in a local, land-based, flow-through abalone farm that was discharging water adjacent to productive natural populations (Appleford 2007; Hooper *et al.* 2007). Following the initial mortalities in the wild, the virus spread through abalone populations to the east and west of Port Fairy. To date, it has impacted abalone populations across >280 km of coastline that encompasses almost the entire WZ and a large proportion of the Central Zone of the Victorian abalone fishery. The observed high levels of mortality caused by the virus and the sequential closure of exposed populations to fishing, in combination with modelled biomass outputs (Gorfine *et al.*

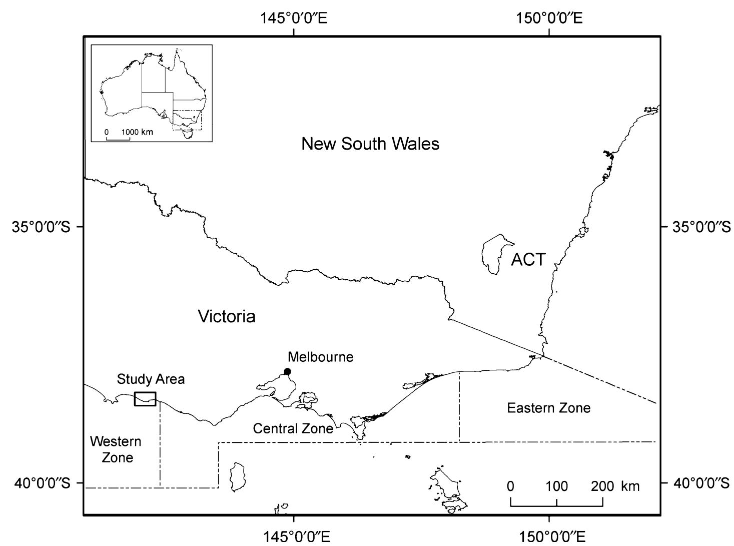

Figure 1 Map showing the location of the study area in the Western Zone of the Victorian abalone fishery. Port Fairy is located at the eastern end of the study area.

2009) and industry assessment of reef scale, sustainable catches (Prince, Peeters, Gorfine & Day 2008), have resulted in the TACC being progressively reduced from 280 t in 2001–02 to 16 t in 2008–09 [Dallas D'Silva, Fisheries Victoria, Department of Primary Industries (DPI), personal communication]. Although some additional commercial harvest is permitted elsewhere, current total catches in the WZ are < 50 t.year (Dallas D'Silva, personal communication). This represents a decrease of > 80% from that harvested during 2001–02.

Importantly, AVG spread as a concentrated front (Appleford 2007) with no evidence of re-infection in previously affected areas. As of September 2009, the disease has not been observed in the WZ for > 2 years. Thus, the first wild abalone stocks to be impacted by the disease have had about 3 years to 'recover' from this mass mortality event. Similar mass mortality events have previously been documented for abalone and have mostly been caused by bacterial disease such as withering syndrome (Haaker, Parker, Togstad, Richards, Davis & Friedman 1992; Friedman & Finley 2003; Miner *et al.* 2006) or parasites such as *Perkinsus* and sabellid worms (Lester 1986; Goggin & Lester 1995; Liggins & Upston 2009). In contrast to some other commercial stocks, there are no documented recoveries of abalone from mass mortality or overexploitation (Gorfine *et al.* 2009).

Reductions in blacklip abalone biomass observed in the WZ fall outside historical experience and, although the mass mortality has been observed and documented (see Appleford 2007), understanding the impact on stocks, monitoring and predicting recovery, and re-commencing commercial fishing in areas of closure is considerably more challenging. This is because the use of more conventional methods to determine sustainable yields, such as the use of catch and catch rate, has proved inappropriate, and monitoring the wild stock is reliant on expensive, weather-dependent, diver surveys (Agtrans Research 2005; McGladdery & Zurbrigg 2006). Despite the higher costs, direct survey measures of abundance, distribution and harvestable biomass provide the most tenable approach to inform decisions about future harvests in cases where stock collapses have occurred.

The aim of this paper is to describe the integration of commercial fishermen's knowledge with research surveys to estimate the blacklip abalone biomass on disease-impacted reefs between Port Fairy and The Crags in the WZ of the Victorian abalone fishery. Our primary objectives were to (1) map historically important commercial fishing grounds, (2) measure the density of blacklip abalone within those fishing grounds and (3) estimate harvestable blacklip abalone biomass. The information was used to inform decisions about managing the recovery of this population, including the design of future structured fishing surveys and setting TACCs in this fishery.

Methods

This study focussed on providing estimates of the biomass of blacklip abalone on AVG-impacted reefs between the Crags and Port Fairy, in the WZ of the Victorian abalone fishery. Historically, these reefs produced an average reported catch of 65t. year

(Dr Harry Gorfine, unpublished data) and were the first abalone stocks to be impacted by AVG. The study involved the integration of commercial fishermen's knowledge with research surveys; the former provided essential information for the design of the latter, greatly improving the overall survey precision. Commercial fishermen identified the locations of the abalone-producing reefs across this area, which were then surveyed by research and commercial divers. Harvestable biomass was estimated for blacklip abalone larger than four alternate minimum legal lengths [MLLs; 120, 125, 130 and 135 mm shell length (SL)] for each of the four surveyed regions and for the entire survey area overall. The regulated MLL in the WZ is 120 mm SL, but fishermen currently harvest at 130 mm SL under an agreement with the management agency, DPI.

Study area

The study area was confined to four statistical reporting blocks, termed 'reef codes', in the WZ. These four reef codes cover near-shore waters along 20 km of coastline and were Lighthouse Reef, Water Tower, Burnet's and the Crags (Fig. 2). Blacklip abalone inhabit rocky, often highly rugged reefs, principally in shallow water.

Survey design

Fishery-independent estimates of blacklip abalone abundance and biomass were obtained inside a bounded, stratified, discontinuous survey region (i.e. the survey frame) spread across the four reef codes (Fig. 2). The survey design combined a modified version of the current Victorian fishery-independent, diver survey method using radial 30-m transects about each sampling location (Gorfine, Forbes & Gason 1998) with the systematic distribution of sampling locations that underpins the leaded-line survey method (McGarvey, Mayfield, Byth, Saunders, Chick, Foureur, Feenstra, Preece & Jones 2008). The latter provides estimates of absolute abalone population density at each sampling location, from which total population biomass can be inferred. The leaded-line survey method is used to estimate greenlip abalone biomass in South Australia (Mayfield, McGarvey, Carlson & Dixon 2008) with a related method adopted for use in Western Australia (Hesp, Loneragan, Hall, Kobryn, Hart, Fabris & Prince 2008). Harvestable biomass is estimated by combining survey estimates of population density with length–frequency samples and a derived relationship of whole weight to SL.

Stratification and systematic sample allocation

During November 2008, five experienced WZ commercial divers identified the locations of the productive abalone grounds between the Crags and Port Fairy, by collectively drawing the boundaries of these grounds onto a large-scale aerial photograph of the coastline. These divers also provided information on mean historical catch and 'accessibility' of each of

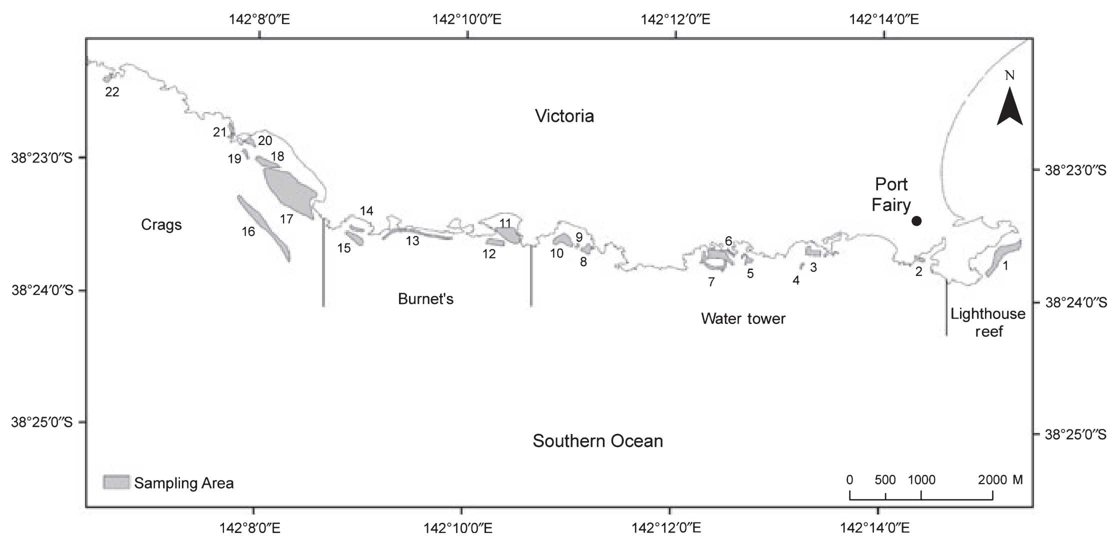

Figure 2 Map showing the 22 numbered survey blocks comprising the survey region across the Lighthouse Reef, Water Tower, Burnet's and Crags reef codes.

these abalone grounds. A copy of the aerial photograph was uploaded into ArcGIS V9.3 (ESRI) and orthorectified. Boundaries of the abalone grounds identified by the commercial divers were then drawn and numbered in ArcGIS, and the resultant maps returned to the commercial divers. This process enabled confirmation that the productive abalone grounds had been correctly identified.

The commercial abalone divers identified 22 productive abalone grounds (hereafter termed survey blocks) spread across the four reef codes (Figs 2, 3a & 3b). The 22 survey blocks ranged in area from 0.002 to 0.265 km^2, but most were small (mean area = 0.033 km^2). As sampling was limited to 40 locations, sampling effort was targeted to the most productive and more accessible survey blocks (Table 1). Two exceptions were survey blocks 13 and 16: survey block 13 was excluded because it comprises a long narrow band, within which it would have been difficult to place sampling locations, and survey block 16 was excluded because it lies in deep water, reducing dive time, and its exact location was poorly known. For these reasons, and because we required at least two samples from each survey block, 10 of the 22 survey blocks, representing 22% (by area) of the productive grounds identified by the divers, were not sampled. Consequently, the survey region comprised 12 survey blocks (1, 5–8, 10–12, 15, 17, 18 and 20) that, cumulatively, comprised a 0.5561-km^2 area from which 73% of the diver-estimated, mean historical catch had been harvested (Table 1).

Sampling locations were distributed systematically within each survey block (bubbles in Fig. 3a,b). Sample locations were allocated into each survey block in approximate proportion to diver-estimated levels of mean historical catch (Table 1). For example, eight sampling locations were allocated to survey block 17 (Fig. 3a) from which 22% of the historical catch had been obtained (Table 1). In contrast, our specified minimum of only two sample locations were allocated to survey blocks 6, 8, 11, 12 and 20 (Fig. 3a,b). GPS positions of each sampling location were provided to the research and commercial diver teams.

Diver sampling

Data were obtained for blacklip abalone located by divers inside four, 30-m long, radially aligned

Table 1 Ease of access (scaled approximately 1–20 with 1 as the easiest), mean historical catch (tonnes), % of the mean historical catch, area (km^2), number of samples obtained and survey measures of density (no m^2), biomass density (kg m^{-2}) and biomass (tonnes) of blacklip abalone recruits (i.e. ≥120 mm shell length) for each of the 22 survey blocks. Survey blocks are ordered by percentage contribution to historical catch

Survey block	Ease of access	Mean catch (t)	% of catch	Area (km^2)	No. samples	Density (no m^{-2})	Biomass density (kg m^{-2})	Biomass (t)
17	16	13.7	22.5	0.265	8	0.48	0.178	47.3
1	7	5.3	8.8	0.061	5	0.42	0.158	9.5
7	12	5.3	8.8	0.057	5	0.17	0.059	3.4
13	14	4.3	7.1	0.029	Not surveyed	–	–	–
16	Unknown	3.8	6.3	0.081	Not surveyed	–	–	–
18	4	3.3	5.5	0.024	3	0.06	0.023	0.6
10	10	2.6	4.3	0.029	3	0.61	0.227	6.6
5	15	2.5	4.1	0.009	3	0.36	0.128	1.1
15	5	2.5	4.1	0.021	3	0.35	0.122	2.5
11	2	2.2	3.6	0.048	2	0.23	0.085	4.1
8	6	2.0	3.3	0.013	2	0.19	0.071	0.9
20	18	1.7	2.9	0.010	2	0.37	0.139	1.4
6	11	1.5	2.5	0.003	2	0.15	0.047	0.1
12	13	1.5	2.5	0.018	2	0.43	0.154	2.6
22	3	1.5	2.5	0.008	Not surveyed	–	–	–
9	8	1.4	2.4	0.002	Not surveyed	–	–	–
2	9	1.4	2.3	0.004	Not surveyed	–	–	–
4	17	1.0	1.6	0.002	Not surveyed	–	–	–
14	1	1.0	1.6	0.008	Not surveyed	–	–	–
19	20	1.0	1.6	0.005	Not surveyed	–	–	–
3	Unknown	0.8	1.4	0.018	Not surveyed	–	–	–
21	19	0.2	0.3	0.005	Not surveyed	–	–	–
Total	–	60.6	100	0.717	40	–	–	–
Total surveyed	–	44.1	73	0.556	40	–	–	80.1

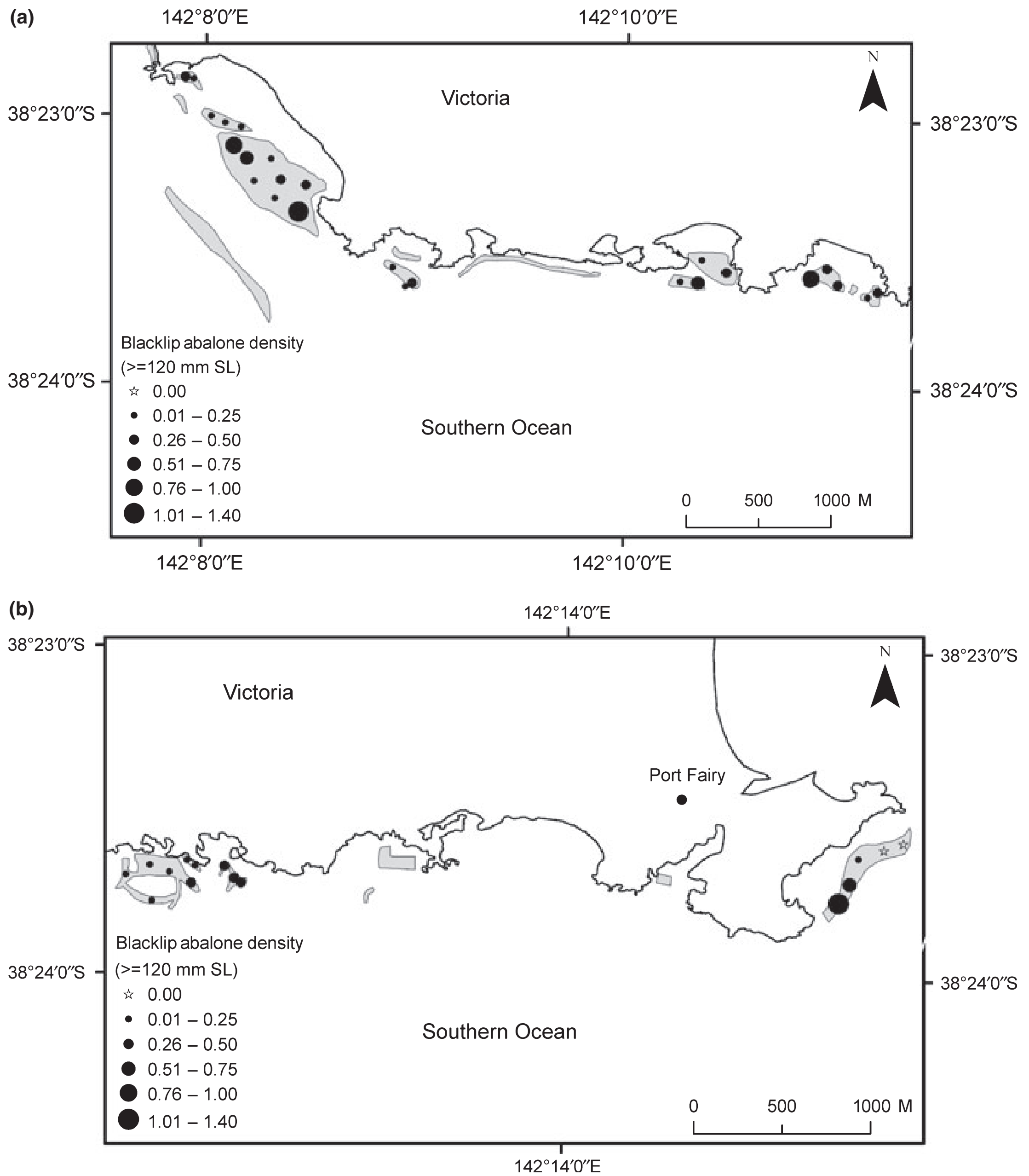

Figure 3 (a) Map showing the survey blocks and sampling locations (bubbles) in the Crags, Burnet's and Water Tower reef codes. Bubbles quantify the estimated density (no m^{-2}) of blacklip abalone recruits [≥120 mm shell length (SL); research diver counts only]. (b) Map showing the survey blocks and sampling locations (bubbles) in the Water Tower and Lighthouse Reef reef codes. Bubbles quantify the estimated density (no m^{-2}) of blacklip abalone recruits (≥120 mm SL; research diver counts only). Stars indicate sampling locations where no recruit-sized blacklip abalone were observed.

transects at each of the 40 sampling locations during May 2009. A transect was designated as the area within 1 m on one side of a line that extended north, south, east and west from the mid-point (node) of each sampling location. Thus, 0.8% of the survey region was sampled. Sampling was undertaken by paired teams of (1) research divers experienced in undertaking abalone surveys and (2) commercial divers (fishermen) that were newly trained in survey techniques.

The survey method required research divers to count all blacklip abalone observed along two of the four transects and visually classify these into three length categories. The length categories were recruits (≥120 mm SL; i.e. legal-sized blacklip abalone), prerecruits (80–119 mm SL) and juveniles (49–79 mm SL). Commercial divers were required to collect all blacklip abalone observed within the remaining two transects. The blacklip abalone collected were measured for maximum SL on board the research vessel and returned to their original locations.

Estimates of density

A paired *t*-test was used to evaluate differences between research and commercial divers in their measured mean densities of recruit-sized blacklip abalone recorded inside transects. At the majority of sampling locations (70%), counts of recruits obtained by the commercial divers exceeded those obtained by the research divers. The mean density of recruits reported by the commercial divers (0.57 ± 0.06 blacklip abalone m^{-2}) was >70% higher than that reported by the research divers (0.33 ± 0.03 blacklip abalone m^{-2}), with this difference statistically significant ($P < 0.001$). The consistent bias by commercial divers towards elevated levels of recruit-sized abalone probably reflects their (1) tendency to target and collect legal-sized abalone (e.g. non-linear transect lines) and (2) their lack of experience in undertaking surveys (e.g. sampling abalone from outside the transect areas). This conclusion was supported by research-diver observations.

Differences in the density estimates between research and commercial divers required that estimates of mean density, by reef code and for the whole survey area, be calculated (1) based on the research diver counts only and (2) using the combined research and commercial diver counts. The two estimation methods differed only in the way that density was estimated at each sampling location. For the former, only the two research diver count transects were used, whereas for the latter, all four transects were averaged at each sampling location to generate a blacklip abalone density.

Estimates of population size and harvestable biomass

Biomass estimates and the biomass quantile confidence intervals used in the quota decision tables were estimated using absolute density measures from only the research diver counts at each sampling location. The length samples obtained from the commercial diver transects were used to estimate both the mean weight of legal-sized blacklip abalone and the proportions of abalone that exceeded the four MLLs (120, 125, 130, 135 mm SL) for which decision-table biomass quantiles were calculated.

Survey measures of blacklip abalone density were converted to a biomass density (kg m^{-2}) by using the mean weight of blacklip abalone recruits at each sampling location. The measured blacklip abalone SLs were converted to whole weights (WW) using the published allometric relationship from nearby Boulder Point [$WW = 0.000412(SL)^{2.76}$; McShane, Smith & Beinssen 1988]. Because only the number of recruits was recorded for each research-diver transect, the biomass of blacklip abalone recruits in each count transect was calculated as the recorded number of recruits from that transect multiplied by the mean weight of blacklip abalone ≥120 mm SL obtained from the two length transects at that sampling location. For the higher MLLs of 125, 130 and 135, the biomass in each count transect was calculated as the recorded number of recruits (i.e. ≥120 mm SL), multiplied by the proportion of measured blacklip abalone in each of these higher size ranges (e.g. number ≥ 125 mm SL) as a fraction of the number ≥ 120 mm SL, multiplied by the mean weight of blacklip abalone in each of these higher size ranges. This approach was justified because mean weight and proportion legal size are ratios and should not be biased by overcounting of blacklip abalone in the commercial-diver transects.

For each survey block, a mean, legal-size density was calculated as the mean of densities from all sampling locations. The extensive quantities of total, legal-sized, population number and biomass in each survey block were calculated as the mean number density or mean biomass density (per m^2) multiplied by the area (m^2) of the block. Total, legal-size population number and total harvestable biomass in each reef code and, subsequently, for the whole survey region were calculated as the sum of the totals from the survey blocks in each reef code, and for the survey region overall. Stratified mean number densities and biomass densities, by reef code and for the survey region, were obtained by dividing the number and biomass totals, respectively, by the sum of the area covered by the blocks surveyed. This produces stratified means with weighting proportional to the area (m^2) of each survey block in each reef code and for the overall survey region. A complete set of survey estimates were computed for each alternate MLL considered (≥125, ≥130 and ≥135 mm SL).

A non-parametric bootstrap (McGarvey *et al.* 2008, Appendix B) was used to determine the confidence range around the estimates of biomass for legal-size blacklip abalone within each reef code and for the survey region overall. The bootstrap (n = 100 000 iterations) accounted for random variation at the two sampled levels of the survey design: sampling locations in each survey block (primary sampling units) and the two count transects (secondary sampling units) at each sampling location. The two levels of sampling are nested (not independent) and the bootstrap, by first re-sampling from sample locations in each block, and then re-sampling among the two transects at each selected sampling location, modelled this two-stage, survey sampling scheme. The bootstrap was implemented in R 2.9.1.

The 100 000 bootstrap iterations of legal-sized, blacklip abalone biomass were ranked and the 10%, 20%, …, 90% quantile confidence intervals (CIs) extracted. These quantiles provide lower-bound estimates of biomass for each selected confidence probability and form the base input to decision tables (e.g. Table 2). These decision tables enable fishery managers to determine harvest levels from a range of biomass confidence levels and a set of harvest fraction options. Standard errors (SE) were calculated as the standard deviation of the re-sampled estimates from the 100 000 bootstrap iterations.

Comparisons of blacklip abalone densities among sites

Estimates of density obtained for each reef code were compared with those obtained from (1) historical DPI surveys at the Crags, Lighthouse Reef and Lady Julia Percy (LJP) Island in the WZ of the Victorian abalone fishery and (2) the most recent surveys at six sites in the Southern Zone and five sites in the WZ of the South Australian abalone fishery. Data for the Crags, Lighthouse Reef and LJP Island were provided by DPI Victoria. Data for South Australia (SA) were obtained from Mayfield, Hogg, Saunders & Burch (2009) and Chick, Turich, Mayfield & Dent (2009), respectively. The MLL in SA is different from that in Victoria. Consequently, SA data were adjusted to a MLL of 120 mm SL for consistency.

Results

Surveys were undertaken over 3 days in May 2009. Three of the 40 designated sampling locations were inaccessible. Two were moved small distances without consequence, but sampling location 26, within survey block 15, was moved 100 m due south to escape breaking waves. This new location was outside the survey boundary (Fig. 3a). Data from sampling location 26 were excluded from the estimates of reef code density and biomass because only four blacklip abalone were observed at this sampling location, and the research diver advised that the sampling location was no longer on abalone reef.

Table 2 Potential blacklip abalone (≥120 mm shell length) catches (kg) under various assumed levels of (1) harvest fraction and (2) 10%, 20%, … 90% confidence for recruit size, biomass estimates in the survey region (all reef codes combined) in May 2009

	Probability (of legal biomass estimate, kg)								
Harvest fraction	90% (62 596)	80% (67 964)	70% (72 146)	60% (75 770)	50% (79 224)	40% (82 804)	30% (86 742)	20% (91 467)	10% (98 316)
0.01	626	680	721	758	792	828	867	915	983
0.025	1565	1699	1804	1894	1981	2070	2169	2287	2458
0.05	3130	3398	3607	3789	3961	4140	4337	4573	4916
0.075	4695	5097	5411	5683	5942	6210	6506	6860	7374
0.1	6260	6796	7215	7577	7922	8280	8674	9147	9832
0.125	7825	8495	9018	9471	9903	10 351	10 843	11 433	12 290
0.15	9389	10 195	10 822	11 366	11 884	12 421	13 011	13 720	14 747
0.175	10 954	11 894	12 626	13 260	13 864	14 491	15 180	16 007	17 205
0.2	12 519	13 593	14 429	15 154	15 845	16 561	17 348	18 293	19 663

The probability percentages (10%, 20%, …, 90%) are quantiles used to separate ordered values of recruit size, BMW biomass estimates from a multi-level bootstrap ($n_{iterations}$ = 100 000). They specify the probability that the true value of harvestable blacklip biomass is greater than or equal to the biomass quantile values shown in round brackets beneath each corresponding quantile percentage.

Estimates of length–frequency and density

A total of 2009 blacklip abalone were encountered and categorized into one of the three length categories (juvenile, prerecruit or recruit) on the 80 transect lines surveyed by the research divers in May 2009. Most of the blacklip abalone observed were prerecruits ($n = 1115$; 56%). Recruits comprised 40% ($n = 799$), while few juveniles were observed ($n = 95$; 4%). The low numbers of juveniles observed reflects the difficulty of sampling small blacklip abalone, which are typically cryptic, in the heterogeneous reef complex they inhabit. There were just three transects (4%) in which no blacklip abalone were observed and only 14 transects (18%) in which no recruits were observed.

The commercial divers collected a total of 1995 blacklip abalone on the 80 transect lines that they surveyed simultaneously with the research divers. These blacklip abalone ranged in length from 25 to 162 mm SL, and the mean length was 122.6 mm SL. There were few differences in the length–frequency distribution or mean length (range: 121.6–123.6 mm SL) among reef codes. In contrast with the research divers, most of the blacklip abalone collected by the commercial divers were recruits ($n = 1367$; 69%). For the whole survey region, estimates of density for the combined counts were 25% greater than those from the research divers only (Fig. 4). Although this confirms that commercial divers were overestimating densities of blacklip abalone recruits, the large number of individual blacklip collected and measured was particularly useful for determining the mean weight of legal blacklip abalone and the proportions that exceeded the range of MLLs that were considered in the estimates of biomass.

The stratified, mean estimate of the density of blacklip abalone recruits obtained from the research divers in the survey region in May 2009 was 0.39 blacklip abalone m^{-2} (Fig. 4). This mean estimate was equivalent to the mean estimate of the densities of blacklip abalone in the South Australian Southern Zone (0.39 blacklip abalone m^{-2}; Fig. 4). However, it was lower than similar mean estimates in the South Australian WZ (0.57 blacklip abalone m^{-2}) and about half that observed at LJP Island in the Victorian WZ (0.76 blacklip abalone m^{-2}) in November 2008.

Among reef codes (Fig. 4), the density of recruits was greatest in the Crags and Lighthouse Reef (> 0.4 blacklip abalone m^{-2}) but about 25% lower

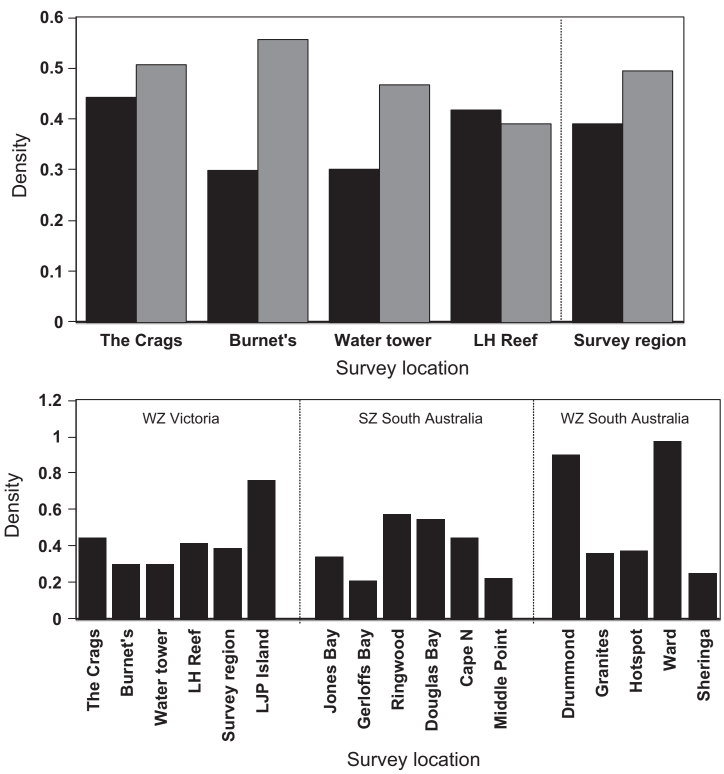

Figure 4 Top: survey estimates of the mean density (no m^{-2}) of blacklip abalone recruits [≥120 mm shell length (SL)] obtained from research diver counts only (black bars) and combined research and commercial diver counts (grey bars) in the whole survey region and in the Crags, Burnet's, Water Tower and Lighthouse Reef (LH Reef) reef codes in May 2009. Bottom: mean densities (no m^{-2}) of blacklip abalone recruits (≥120 mm SL) obtained from research diver counts only in the whole survey region and in the Crags, Burnet's, Water Tower and Lighthouse Reef reef codes in May 2009. The most recent, research-diver survey estimates of blacklip abalone recruit densities at Lady Julia Percy (LJP) Island (Victorian WZ) and at survey sites in the Southern and Western Zones of the South Australian abalone fishery, obtained by research divers, are also shown.

in Water Tower and Burnet's (0.3 blacklip abalone m^{-2}). Density estimates of blacklip abalone recruits at the Crags (survey blocks 17 and 18) in May 2009 were slightly lower than those observed in December 2008 and remained 25% below the mean level for this site between June 2000 and February 2006 (i.e. pre-AVG; Fig. 5). Although the combined estimate of juvenile and prerecruit blacklip was also low in a historical context in May 2009, it was twice that observed in December 2008. Estimates of recruit and subrecruit-sized blacklip abalone densities in the Lighthouse Reef reef code (survey block 1) in May 2009 were greater than those observed in January 2009. However, these data are more difficult to interpret when compared with the Crags because the survey locations in survey block 1 were 500 m southwest of the long-term DPI survey locations.

Estimates of the mean density of blacklip abalone recruits obtained from the research diver counts at each sampling location (Fig. 3a,b) ranged from zero at two sampling locations in survey block 1 (Lighthouse Reef reef code; Fig. 3b) to 1.4 blacklip abalone m^{-2} in the same survey block. Consistently high estimates of recruit densities were observed in survey block 17 (the Crags reef code), where they ranged between 0.1 and 1.2 blacklip abalone m^{-2} (Fig. 3a).

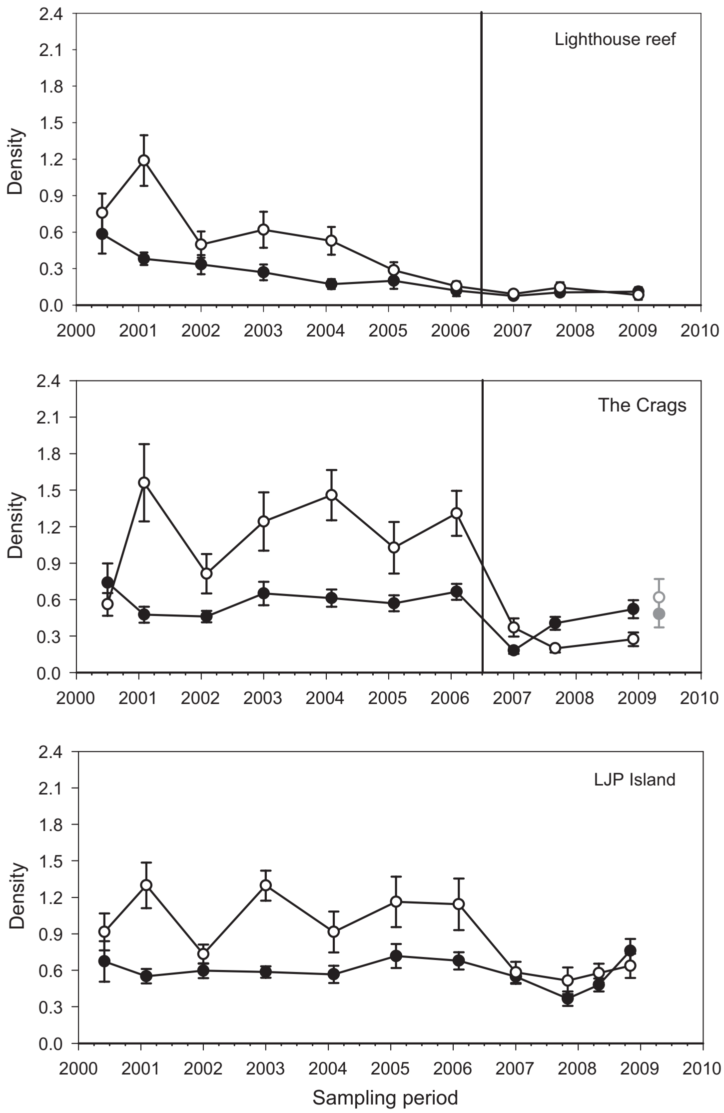

Figure 5 Density (no m^{-2}) of recruit- (solid circles) and subrecruit-sized (open circles; juveniles and prerecruits combined) blacklip abalone observed on fishery-independent surveys at Lighthouse Reef, the Crags and Lady Julia Percy (LJP) Island since 2000. The vertical line indicates the date on which mortalities owing to abalone viral ganglioneuritis (AVG) were observed at Lighthouse Reef and the Crags; AVG has not been observed at LJP Island. Only the last data point for the Crags was from the current survey (May 2009).

Estimates of population size and harvestable biomass

The stratified, mean estimate of the number of blacklip abalone recruits (≥120 mm SL) in the survey region was 215 000 individuals. Estimates of the number of blacklip abalone recruits were greatest in the Crags reef code (130 000; 61%) and lowest in the Lighthouse Reef and Burnet's reef codes (25 000; 12%). The stratified estimate of mean recruit biomass density in the overall survey region was 0.14 ± 0.03 kg m^{-2} (Fig. 6). Multiplying density by the size of the survey region (0.56 km^2), the mean estimate of the biomass of blacklip abalone recruits in May 2009 was 79.9 ± 13.9 t (Fig. 6). Across the survey region, there was a 90% probability that the biomass of blacklip abalone recruits exceeded 62.6 t, but only a 10% probability that it was > 98.3 t (Table 2). Thus, at assumed harvest fractions between 1% and 20% of the total exploitable biomass (0.01–0.2 in Table 2), and spanning the range of CIs for the minimum estimated biomass from 10% to 90%, potential levels of total catch from the survey region ranged between 0.6 and 19.7 t.

Biomass density estimates were highest in the Lighthouse Reef and the Crags reef codes (> 0.15 kg m^{-2}) and about 30% lower (0.1 kg m^{-2}) in the other reef codes (Fig. 6). Most (50%) of the biomass was contained within the Crags reef code, with comparatively much smaller levels in the remaining reef codes surveyed (Fig. 6 and Table 3).

As expected, biomass estimates and potential levels of catch decreased rapidly with the increasing alternative MLL considered (Table 3), with the estimated blacklip abalone biomass at an assumed MLL of 135 mm SL about half that estimated at 120 mm SL. For example, the median biomass estimate for a MLL of 135 mm SL in the Crags reef code was 22.0 t, while for a MLL of 120 mm SL, it was 48.3 t (Table 3).

The confidence ratio (SE/mean) for the estimate of biomass in the survey region was 17%. This was much smaller than that observed at Cowell in 2006 (24%), 2007 (23%) and 2008 (23%; Mayfield *et al.* 2008). Confidence ratios for the individual reef codes were more variable (14% at Water Tower, 25% at the Crags and Burnet's and 57% at Lighthouse Reef).

Discussion

The survey estimates of absolute population density, in combination with length–frequency samples, permitted post-disease estimates of harvestable biomass for blacklip abalone in the WZ of the Victorian abalone fishery. In concert with other initiatives – including reef scale, population models to estimate recovery trajectories (Gorfine *et al.* 2009), ongoing relative abundance surveys (Gorfine *et al.* 1998) and fine spatial scale, stock assessment and management (Prince *et al.* 2008) – these estimates provide additional information to assess the current status of the remnant blacklip abalone stocks from the Crags to Port Fairy. Importantly, these estimates provide a direct measure of the extant biomass on AVG-impacted reefs.

Obtaining these survey measures overcomes the difficulties of assessing these stocks by more

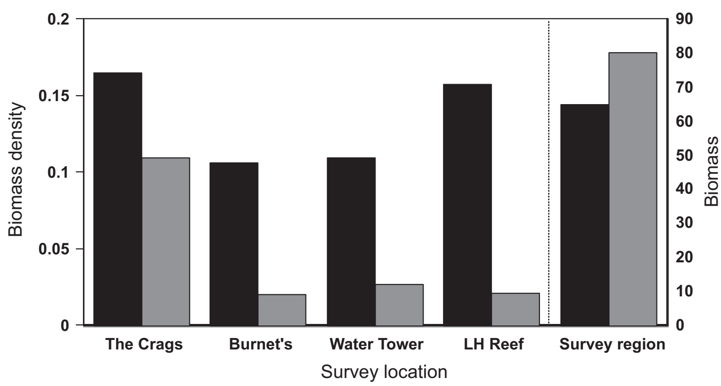

Figure 6 Survey estimates of mean biomass density (kg m^{-2}; black bars) and mean biomass (t, grey bars) of blacklip abalone recruits (≥120 mm shell length) obtained from research diver counts in the whole survey region and in the Crags, Burnet's, Water Tower and Lighthouse Reef (LH Reef) reef codes in May 2009.

Table 3 Probability percentages (10%, 20%, …, 90%) of blacklip abalone biomass for four alternate minimum legal lengths [120, 125, 130 and 135 mm shell length (SL)] in the whole survey region (all reef codes combined) and separately for the Crags, Burnet's, Water Tower and Lighthouse Reef reef codes in May 2009

Location (reef code)	Minimum legal length (mm, SL)	Probability (of legal biomass estimate, kg)								
		90%	80%	70%	60%	50%	40%	30%	20%	10%
Survey region	120	62 596	67 964	72 146	75 770	79 224	82 804	86 742	91 467	98 316
	125	55 190	59 875	63 473	66 554	69 511	72 522	75 835	79 712	85 344
	130	41 066	44 491	47 056	49 308	51 463	53 650	55 967	58 804	62 814
	135	27 659	29 879	31 513	32 935	34 311	35 708	37 238	39 083	41 729
The Crags	120	33 619	38 304	41 924	45 117	48 257	51 534	55 105	59 464	65 709
	125	31 096	35 171	38 315	41 072	43 729	46 457	49 474	52 957	58 094
	130	22 913	25 815	28 038	29 985	31 845	33 745	35 855	38 373	41 923
	135	16 503	18 294	19 626	20 835	22 006	23 184	24 497	26 097	28 404
Burnet's	120	6223	7116	7808	8429	9043	9623	10334	11122	12267
	125	4506	5442	6029	6627	7146	7722	8331	9038	10079
	130	2985	3646	4129	4584	5037	5497	5963	6518	7250
	135	1418	1978	2296	2548	2849	3166	3475	3849	4363
Water Tower	120	10 007	10 689	11 208	11 656	12 080	12 515	12 979	13 526	14 285
	125	8567	9090	9475	9816	10129	10453	10793	11201	11761
	130	6567	6907	7151	7363	7563	7763	7981	8242	8598
	135	3973	4171	4325	4464	4601	4744	4901	5093	5375
Lighthouse Reef	120	2757	4512	6388	7846	8995	10 375	12 129	14 235	16 743
	125	2397	3898	5547	6854	7870	9010	10 490	12 374	14 520
	130	2175	3527	4637	5629	6536	7483	8754	10 005	11 858
	135	1430	2369	3122	3890	4480	5166	6049	6976	8220

The probability percentages are quantiles used to separate ordered values of biomass estimates from a multi-level bootstrap ($n_{iterations}$ = 100 000). They specify the probability that the true value of blacklip biomass is greater than or equal to the biomass quantile values shown beneath each corresponding quantile percentage.

conventional methods, such as the use of catch and catch rate, that are now less applicable to this fishery. Consequently, these direct survey measures of abundance, distribution and harvestable biomass provide the most tenable approach to informing decisions about future harvests in cases where stock collapses have occurred. The current biomass estimates are, therefore, particularly useful for informing potential harvest strategies for these stocks, including possible levels of catch, as has been undertaken elsewhere (Mayfield *et al.* 2008). This approach also enables rapid re-commencement of commercial fishing, with controlled risks of overexploitation through use of a risk-based (decision table) framework (Punt & Hilborn 1997; McGarvey *et al.* 2008), and alleviates some of the pressure on fishery managers required to manage stocks and fishermen through this process (Perry, Walters & Boutillier 1999). Indeed, measures of harvestable biomass are among the most useful estimates that can be provided to fishery managers, particularly when there is some prior knowledge regarding acceptably conservative risk levels and exploitation rates. Acceptable values will depend on the target species and the development stage in the exploitation history of the fishery.

Two key strengths of our approach were (1) selecting a survey method that measures absolute population density (Woodby, Kruse & Larson 1993; McGarvey *et al.* 2008) and (2) using information provided by commercial fishermen to identify those previously productive reefs where the survey could be targeted. The low proportion of transects (4%) in which no blacklip abalone recruits were observed and the high precision of the survey estimates provide convincing evidence of the ability of commercial fishermen to identify productive fishing grounds. Despite the usefulness of this information, these data are seldom available because, in our experience, commercial fishermen are seldom forthcoming about information concerning fishing location. The reliability of the spatial information provided by the divers was also validated by the low confidence ratios, which were much smaller than those obtained in other surveys using similar methodology (Hesp *et al.* 2008; Mayfield *et al.* 2008).

Density estimates of blacklip abalone recruits at the Crags were lower than those observed previously and remained 25% below the mean, pre-AVG level for this site. The estimate of subrecruit-sized blacklip abalone was similarly low in a historical context. Although these data are from only a small section of the coastline, they provide evidence that the blacklip abalone stocks in these areas remain in a weak position as they have yet to fully recover from the mortalities caused by AVG. Furthermore, the mean estimate of the density of blacklip abalone recruits in the survey region was about half that observed at LJP Island in November 2008 and lower than similar mean estimates from the South Australian WZ.

Few large blacklip abalone were observed on the surveys. Almost half the sample comprised recruits between 120 and 130 mm SL and $<15\%$ were >140 mm SL. While these are similar proportions to those observed in the commercial catch from 2003/04 to 2005/06 (Dr Harry Gorfine, unpublished data), only a small number appeared fouled and domed – characteristics typical of older, mature abalone – with the majority being flat and clean shelled (Dr Harry Gorfine, personal observation). For several years, rapid visualization of abalone shells has been used to infer population fecundity in the WZ (Prince *et al.* 2008). Application of this principle to this sample suggests that few of the blacklip abalone observed were fully mature and that current levels of egg production are low. Additionally, although the ecosystem effects of the abalone mortalities are poorly understood, there is anecdotal evidence of changes in community structure. Consequently, recruitment levels may be further compromised by these ecosystem changes (Miner *et al.* 2006). It is also possible that the low levels of recruitment observed at LJP Island since 2007 may reflect environmentally driven, lower recruitment levels across the WZ. In conjunction with the low density estimates observed here that will probably reduce fertilization success (Babcock & Keesing 1999), recruitment levels may remain depressed, with further recovery of the population slower than currently anticipated. Consequently, monitoring of future stock levels, especially recruitment, should be a high priority for the fishery.

The principal weakness of the biomass estimates provided in this report is that surveys were conducted in only 12 of 22 historical fishing grounds. However, these 12 fishing grounds represented 78% (by area) and 73% (by catch) of the 22 fishing rounds identified. Consequently, the biomass estimates excluded (1) the 10 blocks not surveyed (22% by area) and (2) areas lying outside the 22 survey blocks. These difficulties could be overcome by sampling those survey blocks that were not surveyed, particularly survey blocks 13 and 16 from which 10 t.year (13%) was traditionally harvested. This would provide additional, direct measures of biomass over a larger area that is more representative of the historical fishery. However, because commercial divers would regularly visit the unsurveyed areas, it may be possible to 'scale' the current biomass estimates to a larger area through the use of more relative measures, such as those that would be obtained through a structured commercial fishing programme.

A secondary weakness arises from the exclusion of the commercial diver density data from the estimates of biomass. Because abalone aggregate, survey estimates of mean density can be imprecise, and using additional transect measures of density increases the sample size of secondary units at each sampling location. However, survey measures of the density of blacklip abalone recruits obtained from commercial divers were at least 70% greater than those obtained from the research divers. Although it is possible that the practised research divers were 'undercounting' blacklip abalone recruits, a more plausible explanation for this difference is that the commercial divers were 'overcounting' recruits because of their more limited experience in undertaking surveys. Compared with research divers, collection of data by commercial divers is relatively inexpensive, especially if performed in conjunction with their fishing activities. Nevertheless, these difficulties illustrate the merits of adequately trained and experienced individuals undertaking data collection, as this (1) provides a high degree of confidence in the reliability and accuracy of the information and (2) avoids the need to discard potentially biased data.

Harvestable biomass estimates were strongly dependent on the choice of minimum size (MLL). Thus, selection of a MLL will be one of the determinants for the magnitude of any potential harvest. For example, the median estimate of biomass in the Crags reef code decreased from >48 to <25 t when the alternate MLL of 120 and 135 mm SL were considered. The biomass of blacklip abalone in the survey region, at a MLL of 120 mm SL, was 80 t. This biomass estimate is just 25% greater than the level of catch that the four reef codes surveyed historically produced (65t.year) and provides a further indication that these blacklip abalone populations have yet to fully recover to their pre-AVG levels.

Measures of density and estimates of biomass were not evenly distributed among the survey blocks or across the four reef codes. For example, density estimates were highest in the Crags and

Lighthouse Reef reef codes and about 25% lower elsewhere. Similarly, half the biomass of blacklip abalone recruits was contained within the Crags reef code, notably survey blocks 17 and 18. These patterns suggest that the current fine-scale spatial management approach (Prince *et al.* 2008) should be maintained to prevent localized depletion and ensure adequate recruitment.

Higher MLL, lower harvest fractions and increased confidence in biomass estimates reduce the risk of further stock decline (Sanders & Beinssen 1998; Chu 2009). This is particularly the case here, where the abalone stocks are currently recovering from a catastrophic impact. Under these circumstances, conservative catch limits and elevated MLLs will provide the best opportunity for the stocks to continue to recover (see also Gorfine *et al.* 2009). However, determining the fraction of the available biomass that could be harvested, from a range of probabilities and alternate MLL, is challenging and will be influenced by the available biomass, its productivity and recruitment levels. Development of broader-scale harvest strategies is further complicated by the fact that (1) large areas of the four reef codes were not sampled, (2) there were no catch data to 'scale' the current estimates to a larger spatial scale and (3) there have been no documented recoveries of abalone populations that have experienced similar impacts (Gorfine *et al.* 2009). This is in direct contrast to some short-lived, highly fecund species that have shown the ability to recover rapidly from low biomass levels resulting from mass mortality events (e.g. Ward *et al.* 2001).

Our data were integrated with the wealth of accumulated knowledge and expertise on the WZ abalone fishery to explore alternative harvest strategies with key stakeholders. Recognizing the high risk of collapse in abalone fisheries (e.g. Davis, Haaker & Richards 1996; Haaker, Davis & Taniguchi 1996; Hobday, Tegner & Haaker 2000; Tegner 2000), stakeholders adopted a precautionary approach. Consequently, while it was agreed that the magnitude of the harvestable biomass was inadequate to re-commence commercial fishing, it was considered that there was sufficient stock to permit a structured commercial fishing programme with a MLL of 135 mm SL and a maximum catch of 7t (25% harvest fraction with an 90% confidence of harvestable biomass exceeding 27.7 t (Table 3)). This conservative strategy was considered appropriate for obtaining the additional information required to 'scale' the current biomass estimates to a broader area, particularly outside those areas surveyed, while not compromising the ongoing re-building policy.

Acknowledgements

This research was funded by the Western Abalone Divers Association (WADA) through a Fisheries Research and Development Corporation Tactical Research Fund grant (Principal Investigator: Harry Peeters). We thank the attendees at the WADA abalone diver-survey workshops in November 2008 and August 2009 for their suggestions regarding the survey design, analyses and interpretation. The willingness to identify productive abalone fishing grounds for survey by Jason Ciavola, David Fenton, David Forbes, Philip Plummer, Glen Plummer and Peter Riddle is gratefully acknowledged. The diving surveys were conducted by Jason Ciavola, David Forbes, David Fenton, Philip Plummer, Peter Riddle and Bruce Waters with assistance from Andrew Hogg. Bruce Taylor provided the historical survey abundance and length–frequency data. Dr Duncan Worthington, Dr Marty Deveney, Mr Cameron Dixon and an anonymous reviewer provided numerous useful comments that substantially improved this manuscript.

References

Agtrans Research. (2005) *Review of Progress on Invasive Species. Final Report to the Department of Environment and Heritage.* http://www.environment.gov.au/biodiversity/invasive/publications/review/index.html. Accessed 20 July 2009.

Appleford P. (2007) *Second Abalone Virus Scientific and Management Forum.* http://www.dpi.vic.gov.au/DPI/nrenfaq.nsf/LinkView/1861A62E385B8F83CA2573ED007FE2E585B-CE8A032C4BCE1CA2573DA0014ABEB/$file/Peter%20Appleford.pdf. Accessed 20 July 2009.

Babcock R. & Keesing J. (1999) Fertilization biology of the abalone *Haliotis laevigata*: laboratory and field studies. *Canadian Journal of Fisheries and Aquatic Sciences* **56,** 1668–1678.

Balcom N.C. & Clemetson A.O. (2006) Lobster resource failure in Long Island Sound, fisheries extension and litigation. *Fisheries* **31,** 276–284.

Beale R., Fairbrother J., Inglis A. & Trebeck D. (2008) *One Biosecurity: A Working Partnership. Report to the Minister for Agriculture, Fisheries and Forestry.* http://www.daff.gov.au/__data/assets/pdf_file/0010/931609/report-single.pdf. Accessed 19 July 2009.

Bunn C. (1993) History of exotic animal disease incursions in Australia. *The Macedon Digest: Australian Journal of Disease Management* **8,** 8–10.

Cai J., Chen H., Thompson K.D. & Li C. (2006) Isolation and identification of *Shewanella alga* and its pathogenic effects on post-larvae of abalone *Haliotis diversicolor supertexta*. *Journal of Fish Diseases* **29,** 505–508.

Chi S.C., Lo C.F., Kou G.H., Chang P.S., Peng S.E. & Chen S.N. (1997) Mass mortalities associated with viral nervous necrosis (VNN) disease in two species of hatchery-reared grouper, *Epinephelus fuscogutatus* and *Epinephelus akaara* (Temminck & Schlegel). *Journal of Fish Diseases* **20,** 185–193.

Chick R.C., Turich N., Mayfield S. & Dent J.J. (2009) Western Zone Abalone (*Haliotis rubra* & *Haliotis laevigata*) Fishery. Fishery Assessment Report for PIRSA. SARDI Aquatic Sciences Publication No. F2007/000561-3. SARDI Research Report Series No. 376. 91 pp.

Chu C. (2009) Thirty years later: the global growth of ITQs and their influence on stock status in marine fisheries. *Fish and Fisheries* **10,** 217–230.

Cockcroft A.C. (2001) *Jasus lalandii* walkouts' or mass strandings in South Africa during the 1990s: an overview. *Marine and Freshwater Research* **52,** 1085–1092.

Crane M.S.J., Fegan M., Corbeil S. & Warner S. (2009) *Development of Molecular Diagnostic Procedures for the Detection and Identification of Herpes-like Virus of Abalone (*Haliotis *spp.*). Final Report to the Fisheries Research and Development Corporation. Project Number 2007-006. Aquatic Animal Health Laboratories, Geelong, Australia. 79 pp.

Dadon J.R. (2005) Changes in the intertidal community structure after a mass mortality event in sandy beaches in Argentina. *Contributions to Zoology* **74,** 27–39.

Daszak P., Cunningham A.A. & Hyatt A.D. (2000) Emerging infectious diseases of wildlife – threats to biodiversity and human health. *Science* **237,** 443–449.

Davis C.V. & Barber B.J. (1994) Size-dependent mortality in hatchery-reared populations of oysters, *Crassostrea virginica,* Gmelin 1791, affected by juvenile oyster disease. *Journal of Shellfish Research* **13,** 137–142.

Davis G.E., Haaker P.L. & Richards D.V. (1996) Status and trends of white abalone at the California Channel Islands. *Transactions of the American Fisheries Society* **125,** 42–48.

Department of Primary Industries (2008) *Fisheries Victoria Commercial Fish Production Information Bulletin 2008*. Fisheries Victoria, Queenscliff, Victoria, Australia.

Dixon M.G., Hecht T. & Brandt C.R. (1991) Identification and treatment of a *Clostridium* and *Vibrio* infection in South African abalone, *Haliotis midae* L. *Journal of Fish Diseases* **14,** 693–695.

Fiori S.M. & Cazzaniga N.J. (1999) Mass mortality of the yellow clam, *Mesodesma mactroides* (Bivalvia: Mactracea) in Monte Hermoso beach, Argentina. *Biological Conservation* **89,** 305–309.

Fisheries Victoria (2002) *Victorian Abalone Fishery Management Plan*. Department of Natural Resources and Environment, Melbourne, VIC, Australia, 52 pp.

Friedman C.S. & Finley C.A. (2003) Anthropogenic introduction of the etiological agent of withering syndrome into northern California abalone populations via conservation efforts. *Canadian Journal of Fisheries and Aquatic Sciences* **60,** 1424–1431.

Friedman C.S., Beattie J.H., Elston R.A. & Hedrick R.P. (1991) Investigation of the relationship between the presence of a Gram-positive bacterial infection and summer mortality of the Pacific oyster, *Crassostrea gigas* Thunberg. *Aquaculture* **94,** 1–15.

Goggin C.L. & Lester R.J.G. (1995) *Perkinsus*, a protistan parasite of abalone in Australia: a review. *Marine and Freshwater Research* **46,** 639–646.

Gordon H.R. & Cook P.A. (2004) World abalone fisheries and aquaculture update: supply and market dynamics. *Journal of Shellfish Research* **23,** 935–939.

Gorfine H.K., Forbes D.A. & Gason A.S. (1998) A comparison of two underwater census methods for estimating the abundance of the commercially important blacklip abalone, *Haliotis rubra*. *Fisheries Bulletin* **96,** 438–450.

Gorfine H.K., Day R.W., Bardos D., Taylor B., Prince J., Sainsbury K. & Dichmont C. (2009) *Rapid Response to Abalone Viral Depletion in Western Victoria: Information Acquisition and Reef Code Assessment*. Final report to the Fisheries Research and Development Corporation. Project No. 2007-066. The University of Melbourne, Melbourne, Australia, 65 pp.

Haaker P.L., Parker D.O., Togstad H., Richards D.V., Davis G.E. & Friedman C.S. (1992) Mass mortality and withering syndrome in black abalone, *Haliotis cracherodii*, in California. In: *Abalone of the World: Biology, Fisheries and Culture* (ed. by S.A. Shepherd, M.J. Tegner & S.A. Guzmán del Próo), pp. 214–224. Fishing News Books, Oxford, United Kingdom.

Haaker P.L., Davis G.E. & Taniguchi I.K. (1996) Serial depletion in invertebrate diving fisheries. *Journal of Shellfish Research* **15,** 526.

Hamasaki K. & Kitada S. (2008) The enhancement of abalone stocks: lesson from Japanese case studies. *Fish and Fisheries* **9,** 243–260.

Harvell C.D., Kim K., Burkholder J.M., Colwell R.R., Epstein P.R., Grimes D.J., Hofmann E.E., Lipp E.K., Osterhause A.D.M.E., Overstreet R.M., Porter J.W., Smith G.W. & Vasta G.R. (1999) Emerging marine diseases-climatic links and anthropogenic factors. *Science* **285,** 1505–1510.

Hesp A., Loneragan N., Hall N., Kobryn H., Hart A.M., Fabris F.P. & Prince J. (2008) *Biomass and Commercial Catch Estimates for Abalone Stocks in Areas Proposed as Sanctuary Zones for the Capes Marine Park*. Fisheries Research Report No 170. Department of Fisheries, North Beach, WA, 62 pp.

Hobday A.J., Tegner M.J. & Haaker P.L. (2000) Over-exploitation of a broadcast spawning marine invertebrate: decline of the white abalone. *Reviews in Fish Biology and Fisheries* **10,** 493–514.

Hooper C., Hardy-Smith P. & Handlinger J. (2007) Ganglioneuritis causing high mortalities in farmed Australian abalone (*Haliotis laevigata* and *Haliotis rubra*). *Australian Veterinary Journal* **85,** 188–193.

Lester R.J.G. (1986) Abalone dieback caused by protozoan infection? *Australian Fisheries* **45,** 26–27.

Liggins G.W. & Upston J. (2009) *Investigating and Managing the Perkinsus-Related Mortality of Blacklip Abalone in NSW*. Final Report to the Fisheries Research and Development Corporation.

Project No. 2004-084. 182 pp. NSW Department of Primary Industries, Cronulla, Australia.

Maeno Y., De La Pena L.D. & Cruz-Lacierda E.R. (2004) Mass mortalities associated with viral nervous necrosis in hatchery-reared sea bass *Lates calcarifer* in the Philippines. *Japan Agricultural Research Quarterly* **38,** 69–73.

Mayfield S., McGarvey R., Carlson I.J. & Dixon C.D. (2008) Integrating commercial and research surveys to estimate the harvestable biomass, and establish a quota, for an unexploited abalone population. *ICES Journal of Marine Science* **65,** 1122–1130.

Mayfield S., Hogg A., Saunders T.M. & Burch P. (2009) *Southern Zone Abalone Fishery (*Haliotis rubra *and* H. laevigata). Fishery Assessment Report for PIRSA. SARDI Aquatic Sciences Publication No. F2007/000552-2. SARDI Research Report Series No. 350, 50 pp.

McGarvey R., Mayfield S., Byth K., Saunders T.M., Chick R.C., Foureur B.F., Feenstra J.E., Preece P.P. & Jones A. (2008) A diver survey design to estimate absolute density, biomass and spatial distribution of abalone. *Canadian Journal of Fisheries and Aquatic Sciences* **65,** 1931–1944.

McGladdery S.E. & Zurbrigg R.E. (2006) Canada's approach to aquatic animal biosecurity: experience and evolution. In: *Aquaculture Biosecurity: Prevention, Control and Eradication of Aquatic Animal Disease* (ed. by A.D. Scarfe, C.-S. Lee & P.J. O'Bryen), pp. 31–54. Wiley-Blackwell, London.

McShane P.E., Smith M.G. & Beinssen K.H.H. (1988) Growth and morphometry in abalone (*Haliotis rubra* Leach) from Victoria. *Australian Journal of Marine and Freshwater Research* **39,** 161–166.

Miner C.M., Altstatt J.M., Raimondi P.T. & Minchinton T.E. (2006) Recruitment failure and shifts in community structure following mass mortality limit recovery prospects of black abalone. *Marine Ecology Progress Series* **327,** 107–117.

Moyer M.A., Blake N.J. & Arnold W.S. (1993) An ascetosporan disease causing mass mortality in the Atlantic calico scallop, *Argopecten gibbus* (Linnaeus, 1758). *Journal of Shellfish Research* **12,** 305–310.

Mullen T.E., Russell S., Tucker M.T., Maratea J.L., Koerting C., Hinckley L., De Guise S., Frasca S. Jr & French R.A. (2004) Paramoebiasis associated with mass mortality of American lobster *Homarus americanus* in Long Island Sound, USA. *Journal of Aquatic Animal Health* **16,** 29–38.

Murray A.G. & Gaughan D.J. (2003) Using an age-structure model to simulate the recovery of the Australian pilchard *(Sardinops sagax)* population following epidemic mass mortality. *Fisheries Research* **60,** 415–426.

Perry R.I., Walters C.J. & Boutillier J.A. (1999) A framework for providing scientific advice for the management of new and developing invertebrate fisheries. *Reviews in Fish Biology and Fisheries* **9,** 125–150.

Prince J.D. (2004) The decline of global abalone (genus *Haliotis*) production in the late twentieth century: is there a future? In: *Stock Enhancement and Sea Ranching*, 2nd edn (ed. by K.M. Leber, S. Kitada, T. Svasand & H.L. Blankenship), pp. 427–443. Blackwell Publishing, Oxford.

Prince J.D. & Shepherd S.A. (1992) Australian abalone fisheries and their management. In: *Abalone of the World: Biology, Fisheries and Culture* (ed. by S.A. Shepherd, M.J. Tegner & S.A. Guzmán del Próo), pp. 407–426. Fishing News Books, Oxford, United Kingdom.

Prince J.D., Peeters H., Gorfine H.K. & Day R.W. (2008) The novel use of harvest policies and rapid visual assessment to manage spatially complex abalone resources (Genus *Haliotis*). *Fisheries Research* **94,** 330–338.

Punt A.E. & Hilborn R. (1997) Fisheries stock assessment and decision analysis: the Bayesian approach. *Reviews in Fish Biology and Fisheries* **7,** 35–63.

Sanders M.J. & Beinssen K.H.H. (1998) A comparison of management strategies for the rehabilitation of a fishery: applied to the fishery for blacklip abalone *Haliotis rubra* in the Western Zone of Victoria (Australia). *Fisheries Research* **38,** 283–301.

Smith K., Norriss J. & Brown J. (2009) Population growth and mass mortality of an estuarine fish, *Acanthopagrus butcheri*, unlawfully introduced into an inland lake. *Aquatic Conservation: Marine and Freshwater Ecosystems* **19,** 4–13.

Stokesbury K., Harris D.E., Bradley P., Marino M.C. & Nogueria J.I. (2007) Sea scallop mass mortality in a marine protected area. *Marine Ecology Progress Series* **349,** 151–158.

Tegner M.J. (2000) California abalone fisheries: what we've learned and where we go from here. *Journal of Shellfish Research* **19,** 626.

Tomaru Y., Kawabata Z. & Nakano S. (2001) Mass mortality of the Japanese pearl oyster *Pinctada fucata martensii* in relation to water temperature, chlorophyll a and phytoplankton composition. *Diseases of Aquatic Organisms* **44,** 61–68.

Valente R.M. & Cuomo C. (2005) Did multiple sediment-associated stressors contribute to the 1999 lobster mass mortality event in western Long Island Sound, USA? *Estuaries* **28,** 529–540.

Ward T.M., Hoedt F., McLeay L., Dimmlich W.F., Kinloch M., Jackson G., Mcgarvey R., Rogers P.J. & Jones K. (2001) Effects of the 1995 and 1998 mass mortality events on the spawning biomass of sardine, *Sardinops sagax*, in South Australian waters. *ICES Journal of Marine Science* **58,** 865–875.

Woodby D.A., Kruse G.H. & Larson R.C. (1993) A conservative application of a surplus production model to the sea cucumber fishery in southeast Alaska. In: *Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations* (ed. by G. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke & T.J. Quinn II), pp. 191–202. Alaska Sea Grant College Program, Fairbanks, Alaska, USA.

Received: 11 October 2009
Revision received: 2 August 2010; 6 September 2010
Accepted: 13 September 2010

