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A simple, cost-effective, morphometric marker for characterising abalone populations at multiple spatial scales

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Abstract. The ability to identify and separately manage component populations is becoming increasingly important in guarding against overexploitation of many marine species. Blacklip abalone (*Haliotis rubra*) form isolated populations with variable life history characteristics as a result of the heterogenous areas they inhabit. Many of these populations are 'stunted', reaching a lower maximum size compared with those in adjacent areas. We obtained a range of morphological measurements from samples of 'stunted' and 'non-stunted' *H. rubra* collected from sites spread across broad (tens of kilometres) and fine (hundreds of metres) spatial scales in southern South Australia. The ratio between shell length and shell height showed clear and significant differences among samples from 'stunted' and 'non-stunted' sites. The morphometric collections from the sub-sites suggested that 'stunted' populations existed at smaller spatial scales (up to 400 m) compared with that for 'non-stunted' populations (at least 1000 m). The 'morphometric marker' developed in the present study has the potential to be used as a tool to identify individual populations rapidly and cost-effectively that can then be managed separately. Our approach is applicable to other species of abalone as well as other sedentary invertebrates with limited larval dispersal.

Additional keywords: fisheries management, *Haliotis rubra*, population structure.

Introduction

Fine-scale population structure is common in many inshore marine species because they are structured by static coastscapes (Sponaugle *et al*. 2002; Strathmann *et al*. 2002; Swearer *et al*. 2002; Orensanz *et al*. 2005). This is particularly the case for sedentary invertebrates with limited larval dispersal for which the stocks tend to be highly structured across small spatial scales (Sponaugle *et al*. 2002; Strathmann *et al*. 2002; Orensanz *et al*. 2005). Aggregations of such species form discrete populations, which are more or less isolated from conspecifics by reproduction and migration (Berryman 2002), often with variable life history parameters (McShane *et al*. 1988; Orensanz and Jamieson 1995; Withler *et al*. 2003; Orensanz *et al*. 2005). The high degree of population structuring in these species has been historically unrecognised in their management, leading to serial depletion of populations and, in many cases, stock collapse (Tegner *et al*. 1996; Perry *et al*. 2002; Orensanz *et al*. 2005). This is because acquiring information on the boundaries between separate populations and identifying the demographic variability among these is impeded by the difficulties of tracking minute larvae (Swearer *et al*. 2002; Gilg and Hilbish 2003) and the high costs of collecting biological information across a range of spatial scales (Prince 2005).

The study of morphometric variation among populations may offer a cost-effective tool with which to identify separate populations of marine species (Cadrin 2005). Although this approach has been commonly used (Cadrin 2000; Kong *et al*. 2007), spatial patterns in morphology may be environmentally induced and not reflect demographically isolated units (Swain and Foote 1999; Swain 2005). However, the highly localised populations formed by sedentary invertebrates with limited larval dispersal are likely to exist at similar scales to this environmental variation, making studies on morphology an extremely useful tool for population identification. In addition, morphological differences among populations are likely to indicate differences in growth and maturation (Cadrin 2005), and can potentially provide biological information to support their effective management (Cadrin and Friedland 1999).

Abalone are a typical group of sedentary invertebrate species with limited larval dispersal that have numerous discrete populations often within metapopulations across their geographical extent (Prince 2005; Morgan and Shepherd 2006). These populations often differ in their biology and morphology (Shepherd and Hearn 1983; McShane *et al*. 1988; Worthington *et al*. 1995; Worthington and Andrew 1997; Tarbath 2003; Tarbath *et al*. 2003), resulting in the presence of so-called 'stunted' areas

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of abalone that have a slower growth rate and/or a smaller maximum size compared with adjacent populations (Shepherd and Cannon 1988; Nash 1992). 'Stunted' populations typically form dense aggregations in sheltered areas with lower wave exposure (McShane and Naylor 1995*b*). It is suggested that abalone in these protected areas grow more slowly compared with individuals in more exposed habitats as a result of lower water movement providing less food in the form of drift algae (Day and Fleming 1992; Shepherd and Steinberg 1992; McShane and Naylor 1995*b*). However, density-dependent processes may also contribute to relatively lower rates of growth in 'stunted' areas (Emmett and Jamieson 1988; McShane and Naylor 1995*a*; Dixon and Day 2004) compared with other fished populations.

The current broad-scale (100–1000 km of coastline; McShane *et al*. 1994) management of most abalone fisheries fails to account for the finer scale variability in population structure evident in abalone stocks, leaving fast-growing populations prone to overfishing and slower-growing populations underused (Strathmann *et al*. 2002; Prince 2005). In response to this localised variability, the spatial scale of management in the South Australian abalone fishery has decreased steadily since 1985. Notably, in the southern zone (SZ) of this fishery there are four separately managed, 'fish-down' areas (FDAs) within which the blacklip abalone (hereafter referred to as abalone) populations are considered stunted. These areas were formally introduced during 1994–95 following *ad hoc* fishing at a variety of minimum legal lengths (MLL) between September 1989 and October 1994 (Tyrer 1995; Mayfield *et al*. 2007). Collectively, the FDAs have a separate total allowable commercial catch (TACC) that is harvested at a MLL of 110 mm shell length (SL), 15 mm smaller than that in the remainder of the fishery. Nevertheless, despite these relatively 'novel' management arrangements, it is widely acknowledged that FDAs do not encompass all of the 'stunted' populations of abalone in this fishery and their large size ensures they also contain populations of 'non-stunted' abalone.

Studies on the spatial variability of abalone morphology have shown differences among sites separated by as little as 200 m (Breen and Adkins 1982; McShane *et al*. 1988, 1994; Worthington *et al*. 1995). Consequently, phenotypic variation in morphometric traits may be an effective method for discriminating among 'stunted' and 'non-stunted' abalone populations. In the present study, we investigate the potential of identifying a 'morphometric marker' that could be used as a tool to discriminate between 'stunted' and 'non-stunted' populations of abalone in the SZ. This was achieved by examining the spatial variability in the morphology of abalone among 'stunted' and 'non-stunted' sites at broad (tens of kilometres) and fine (hundreds of metres) spatial scales within the fishery. The 'morphometric marker' developed was applied to the fine-scale samples of abalone to assess the spatial extent of 'stunted' and 'non-stunted' populations. These data were also used to evaluate the suitability of current management arrangements, particularly in one of the current FDAs.

Materials and methods

Study site

The present study was conducted in the southern zone (SZ) of the South Australian abalone fishery. The SZ includes all coastal waters of South Australia (SA) east of Meridian 139°E, with the exception of the Coorong and waters inside the Murray River mouth. After consultation with divers and licence holders, all of the sites were distributed in the waters between Beachport and the SA/Victoria border (Fig. 1).

Broad-scale

Data to evaluate the broad-scale variation in morphology were obtained from eight sites (Gerloffs Bay (GB), Ringwood Reef (RR), Acis Reef (AR), Red Rock Bay (RB), Salmon Hole (SH), Number 2 Rocks (No2), Middle Point (MP) and Cape Northumberland (CN)) distributed along 100 km of coastline. The first four sites were located in areas with 'stunted' abalone, whereas the latter four were in areas with 'non-stunted' abalone (Fig. 1). 'Stunted' and 'non-stunted' sites were selected on the basis that they represented two common growth forms in the SZ and other abalone fisheries so the development of a 'morphometric marker' would have to at least have the ability to separate abalone from these sites. Furthermore, these sites were also chosen for the fact that they were regularly targeted by commercial fishers. Between 120 (SH) and 236 (GB) abalone were collected from each of these sites between October 2004 and January 2005 (see Table 1 for sampling details).

Fine-scale

To assess finer scale patterns in abalone morphology, GB and MP were re-sampled in conjunction with the collection of additional samples from sub-sites located ~150 (GB150, MP150), 400 (GB400, MP400) and 1000 m (GB1000, MP1000) from each of these sites (Fig. 1). GB and MP were chosen for re-sampling because abalone from these sites showed substantial differentiation in morphology. In addition, information on the spatial extent of 'stunted' populations in GB and 'non-stunted' populations in MP was important for these sites as they receive the most effort from commercial fishers. These sub-sites were determined by moving the prescribed distance along a randomly selected compass bearing from the original site whereupon divers were deployed to locate the nearest aggregation of abalone. Between 134 (MP) and 187 (GB150) abalone were collected from GB, MP and each of the six sub-sites during May 2006 (Table 1).

Morphometric sampling

At all sites, samples of abalone were collected using SCUBA within approximately a $10 \times 10\,m^2$ area. Divers moved haphazardly among aggregations of abalone and collected every individual within each of these. This methodology would have provided a relatively unbiased sample of the size range of abalone present as samples were typically collected from three to four aggregations. A strictly random approach to sampling would have relied on identifying all of the aggregations within each site and would have been difficult to achieve given the time limitations of SCUBA diving. Numerous 'morphometric measurements', including shell length, width, height, weight, volume and whole wet weight, were obtained from each abalone collected. All of the linear shell measurements were obtained using vernier callipers to 0.1 mm (Tissot 1988) and weight

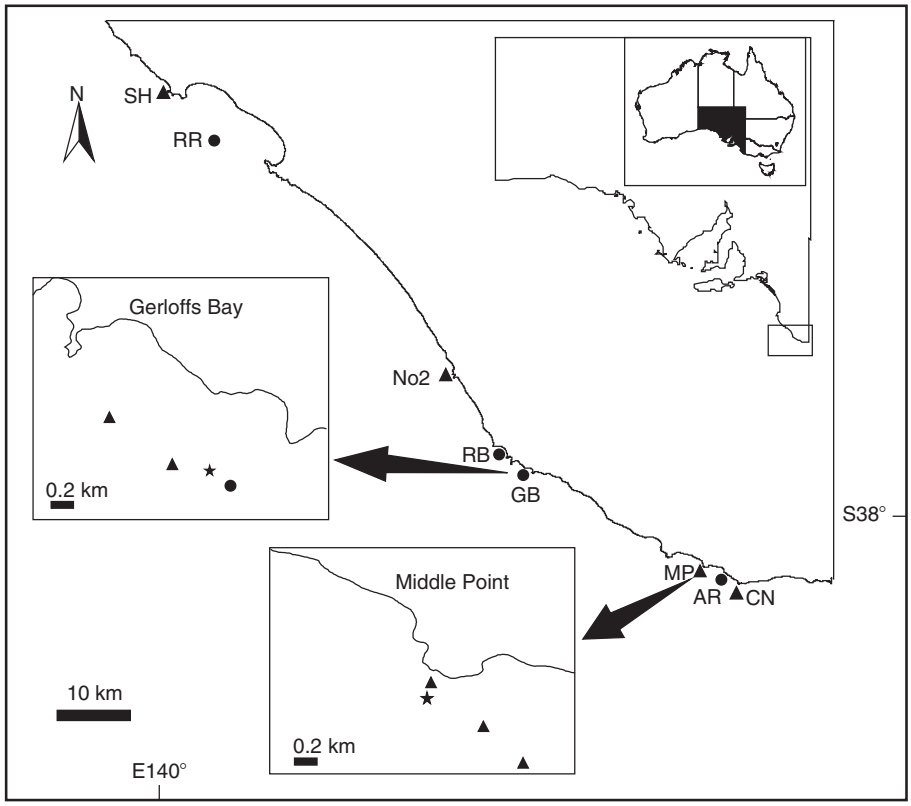

Fig. 1. Map of study area with the locations of the broad-scale sites: Acis Reef (AR), Cape Northumberland (CN), Gerloffs Bay (GB), Middle Point (MP), Number 2 Rocks (No2), Red Rock Bay (RB), Ringwood Reef (RR) and Salmon Hole (SH). Insert maps show the location of the sub-sites within GB and MP. Stars indicate the location of the broad-scale site in these areas. Circles and triangles represent 'stunted' and 'non-stunted' sites respectively.

Table 1. Blacklip abalone morphometric data collection summary from the broad and fine-scale sites in the southern zone (SZ)

Gerloffs Bay 1 and Middle Point 1 indicate the re-sampled broad-scale sites

Site	Latitude	Longitude	Date	*n*	Size range (mm)
Acis Reef	38°02.8′S	140°37.9′E	31/10/2004	215	15–147
Cape Northumberland	38°03.6′S	140°39.7′E	31/10/2004	173	39–159
Gerloffs Bay	37°55.7′S	140°24.4′E	11/02/2005	236	27–122
Middle Point	38°02.5′S	140°37.0′E	31/10/2004	128	30–170
No 2 Rocks	37°48.8′S	140°19.5′E	27/11/2004	168	11–158
Red rock Bay	37°54.6′S	140°23.2′E	28/11/2004	131	28–148
Ringwood Reef	37°31.9′S	140°02.6′E	17/10/2004	203	37–141
Salmon Hole	37°29.2′S	139°59.8′E	17/10/2004	120	51–167
Gerloffs Bay 1	37°55.7′S	140°24.4′E	23/05/2006	153	49–124
Gerloffs Bay 150	37°55.8′S	140°24.2′E	23/05/2006	187	53–130
Gerloffs Bay 400	37°55.7′S	140°24.5′E	23/05/2006	162	49–160
Gerloffs Bay 1000	37°55.4′S	140°23.9′E	23/05/2006	167	48–145
Middle Point 1	38°02.5′S	140°37.0′E	21/05/2006	134	54–156
Middle Point 150	38°02.4′S	140°37.0′E	26/05/2006	164	50–151
Middle Point 400	38°02.6′S	140°37.3′E	21/05/2006	138	74–153
Middle Point 1000	38°02.9′S	139°37.5′E	26/05/2006	161	71–158

measurements were obtained using an electronic balance to 0.1 g. Shell volume was measured by sealing the respiratory pores with a latex glove, filling the shell with water and then weighing the water from the shell.

Data analysis

As a result of the considerable variation in shell length among sites (Table 1, Fig. 2), shell width and shell height were transformed by dividing shell length with each of these variables

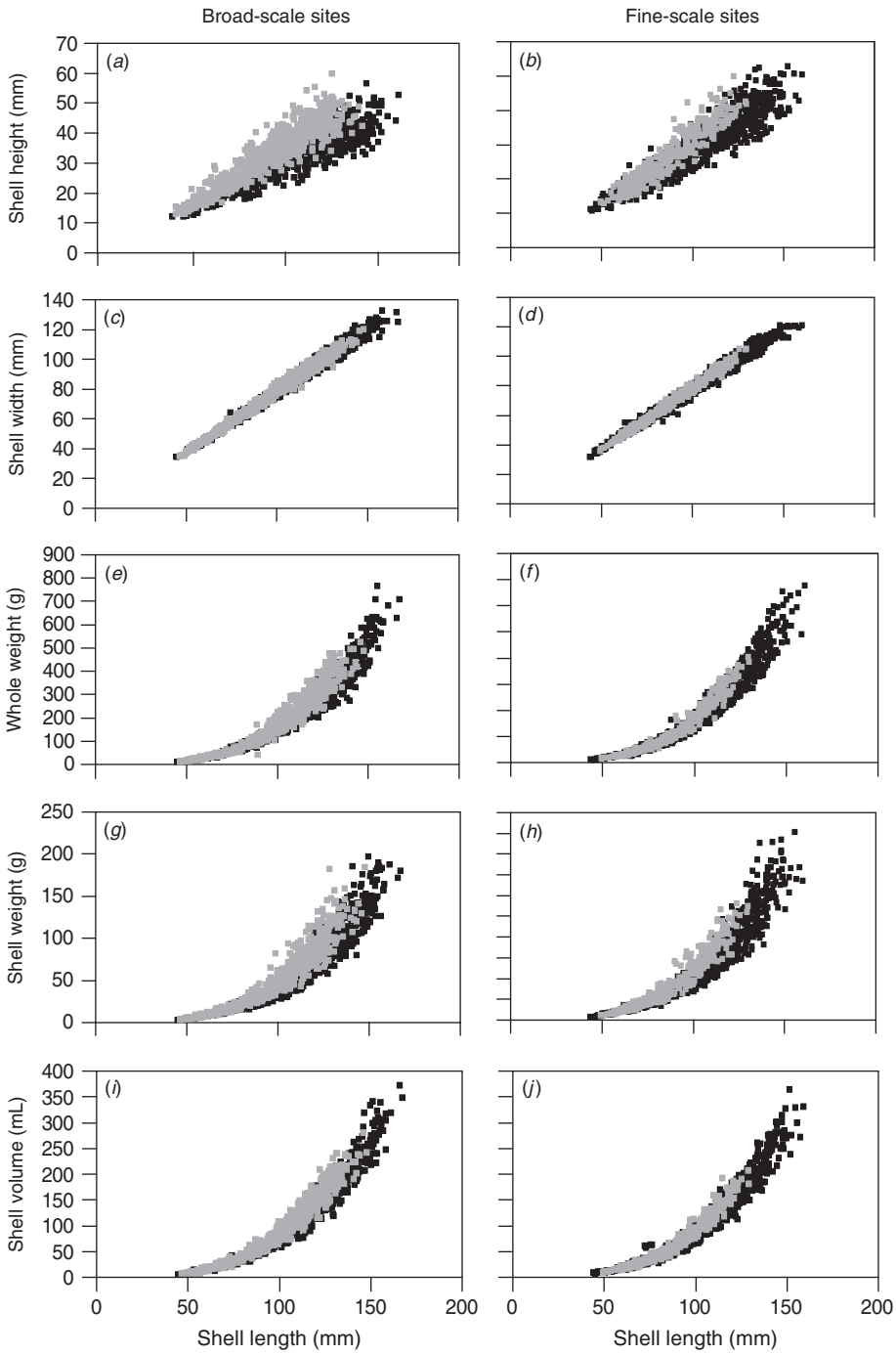

Fig. 2. Relationships of (*a–b*) shell height, (*c–d*) shell width, (*e–f*) whole wet weight, (*g–h*) shell weight and (*i–j*) shell volume against shell length for all sites. Grey: data from 'stunted sites'; black: data from 'non-stunted' sites.

to provide an index that was independent of shell length. The effect of shell length on the rest of the morphometric measures was removed by using the relationship described by Thorpe (1975) that adjusts each variable to that expected for the overall mean shell length. In addition, this transformation removed the non-linearity of these relationships, satisfying the assumptions underlying the principal components analysis (PCA) (Quinn and Keough 2002). Furthermore, only abalone greater than 90 mm in shell length were used owing to the similarity of juvenile morphology among sites (Fig. 2). The morphometric data included in the multivariate analysis were shell length to width (SL : SW ratio), shell length to height (SL : SH ratio), shell weight (SWt),

shell volume (SV) and whole weight (WW). PCA was then used to reduce the dimensionality of the transformed morphometric data.

Thereafter, discriminant function analysis (DFA) was used to determine which morphometric character contributed most to the observed variation among sites. This was achieved by including all of the variables in the analysis initially and then proceeding in a backwards fashion of removing the variable with the lowest 'F-to-remove' value. This value for a variable indicates its statistical significance in the discrimination between groups; that is, it is a measure of the extent to which a variable makes a unique contribution to the prediction of group membership. The discriminant function (DF) was developed from the retained variable with the highest 'F-to-remove'. The success of the discrimination among sites was assessed by determining the proportions of the various groups of abalone that were correctly assigned to their respective site of origin. The assumptions of linearity between relationships of the variables for the PCA and homogeneity of the within-group variance-covariance matrices for the DFA (Quinn and Keough 2002) were met through the above transformations of the data.

To assess the suitability of using the SL:SH ratio as a 'morphometric marker' to differentiate among sites, ANOVA was used with site being a random factor. Tukey's honestly significant difference (HSD) *post hoc* tests were conducted to assess where the differences existed. Plots of residuals against group means revealed that these data satisfied the assumptions of normality and homogeneity of variance (Quinn and Keough 2002). Statistica ver. 6.1 (StatSoft, www.statsoft.com) was used for all ANOVA and DFA, whereas PC-ORD (McCune and Mefford 1999) was used to conduct the PCAs.

Results

Broad-scale

Abalone from the 'stunted' sites tended to have higher and heavier shells compared with those in 'non-stunted' sites, whereas the rest of the morphometric measures tended to overlap between the two classifications (Fig. 2). Outputs from the PCA showed that abalone from Acis Reef and Red Rock Bay, and from Cape Northumberland, Middle Point and Number 2 Rocks exhibited similar morphometric characteristics (Fig. 2). Abalone from Salmon Hole tended to separate from the other 'non-stunted' sites, whereas abalone from Gerloffs Bay and Ringwood Reef grouped separately to the other sites (Fig. 3). Further, the PCA reduced the number of axes from five to two as the first two axes explained almost 95% of the variation.

The DF, based on the SL to SH ratio (Table 2) further supported these results. Samples of abalone from Gerloffs Bay, Salmon Hole and Ringwood Reef showed high levels of 'correct classification' (>60%; Table 3). However, lower proportions (<40%) of samples from Red Rock Bay, Middle Point and Cape Northumberland classified correctly, primarily owing to these sites overlapping with others (Fig. 3).

The SL : SH ratio differed significantly among sites ($F = 37.65$; d.f. = 772; $P < 0.0001$) with the Tukey's HSD tests revealing significant differences between 'stunted' and 'non-stunted' areas. Furthermore, within 'non-stunted' areas, Cape Northumberland had a significantly lower SL:SH ratio compared with the other sites (Fig. 4). These data suggest that a SL : SH ratio >3.25 reflects abalone from 'non-stunted' populations and <3.25 reflects abalone from 'stunted' populations.

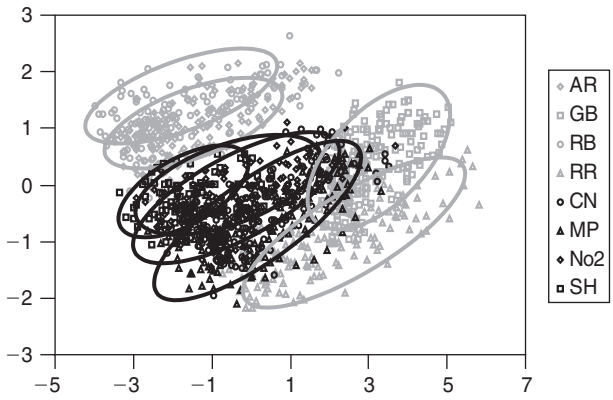

Fig. 3. Ordination of the principal components analysis (PCA) on the morphometric characteristics from each of the eight broad-scale sites. Black and grey symbols indicate abalone from 'non-stunted' and 'stunted' sites respectively. Ellipses indicate 95% confidence intervals.

Table 2. Summary outputs from the discriminant function analysis on all morphometric characters for all broad-scale and sub-sites

Morphometric characters in bold indicate the discriminant function with the highest F-to-remove value

Scale	Morphometric character	F-to-remove
Broad-scale	**Length/height**	**58.43**
Broad-scale	Length/width	6.79
Broad-scale	Whole weight	36.65
Broad-scale	Shell weight	7.23
Broad-scale	Shell volume	40.37
Fine-scale	**Length/height**	**44.63**
Fine-scale	Length/width	3.63
Fine-scale	Whole weight	33.71
Fine-scale	Shell weight	29.77
Fine-scale	Shell volume	24.57

Fine-scale

Abalone had higher shells that were heavier in both shell and whole weight in GB and GB150 compared with the other sub-sites (Fig. 2). This variability was reflected in the PCA outputs as samples from these two sites tended to group away from those of the other sub-sites (Fig. 5). Again this variability was a result of differences in the SL : SH ratio that contributed most to the variability observed (Table 2). However, the DFA showed that GB and GB150 had low levels of correct classification as a result of samples from these two sites overlapping in the PCA (Table 4, Fig. 5). MP1000 had the highest level of correct classification (62.8%) as it tended to group away from the other sites that all overlapped strongly (Table 4, Fig. 5).

The SL : SH ratio varied significantly among sites ($F = 23.5$; d.f. = 601; $P < 0.0001$). In Gerloffs Bay, the Tukey's HSD test revealed that GB and GB150 had a significantly lower SL:SH ratio compared with the other sites, whereas MP1000 had a significantly lower SL : SH ratio compared with the other sites in

Table 3. Outputs from the discriminant function analysis examining the percentage of successful discrimination among sites based on the SL:SH ratio for each of the eight broad-scale sites

AR, Acis Reef; CN, Cape Northumberland; GB, Gerloffs Bay; MP, Middle Point; No2, No 2 Rocks; RB, Red Rock Bay; RR, Ringwood Reef; SH, Salmon Hole

Site	Percentage correct	AR	CN	SH	MP	No2	GB	RB	RR
Acis Reef	47.6	70	24	9	3	11	15	13	2
Gerloffs Bay	60.2	8	16	0	0	3	59	1	11
Red Rock Bay	31.8	30	14	2	2	3	7	28	2
Ringwood Reef	63.8	2	3	0	1	3	17	3	51
Cape Northumberland	36.5	30	57	4	23	25	12	3	2
Middle Point	36.8	13	26	10	43	18	4	2	1
No 2 Rocks	27.7	0	32	13	32	38	14	0	8
Salmon Hole	64.7	3	4	55	2	17	1	2	1
Total	44.2	156	176	93	106	118	129	52	78

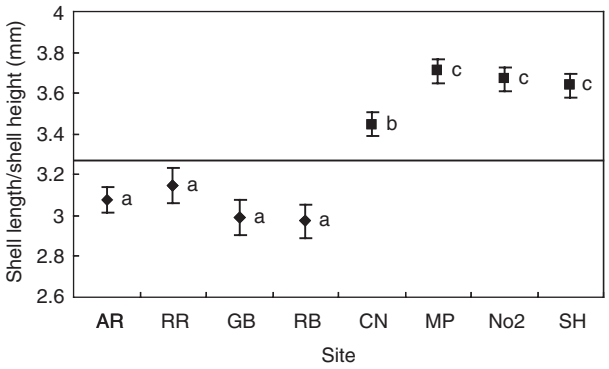

Fig. 4. Shell length to height (SL : SH) ratio for all abalone measured from the broad-scale sites. 'Stunted' and 'non-stunted' sites are represented by diamonds and squares respectively. Letters indicate groups classified by the Tukey's honestly significant difference (HSD) test. Horizontal line indicates SL : SH ratio value that separates 'stunted' from 'non-stunted' sites. Error bars are ±1 standard error.

Middle Point (Fig. 6). Application of the 3.25 SL : SH ratio value that is identified above suggests that abalone at GB and GB150 are 'stunted', whereas abalone at the remainder of these sites are 'non-stunted'. These results suggest that the spatial extent of the 'stunted' abalone population in Gerloffs Bay is up to 400 m compared with 1000 m for the 'non-stunted' population in Middle Point.

Discussion

The collection of morphometric data across both broad and fine spatial scales enabled identification of a simple 'morphometric-marker' to distinguish between 'stunted' and 'non-stunted' abalone populations. The substantial, small-scale spatial variation in morphology of abalone observed in the present study was most evident in differences in the SL : SH ratio of individuals among sites. The DFA revealed that this ratio was primarily responsible for the variation observed in the PCA among sites and was consistent across broad and fine spatial scales. The spatial differentiation in the morphology of abalone we have observed here is probably a result of spatial variability in environmental factors acting at broad and fine-spatial scales. However, abalone morphology has been shown to vary at the finest spatial scales measured (Worthington *et al*. 1995). Given that the dispersal of abalone probably only occurs at scales of tens to hundreds of metres (Prince *et al*. 1987), populations formed under these conditions, which are demographically isolated from conspecifics, exist at very fine spatial scales (Temby *et al*. 2007) and would be similar to that at which environmental variability operates. Consequently, we argue that the SL : SH ratio is likely to be a useful tool for differentiating among separate abalone populations.

Broad-scale differences in morphology were greatest between sites in 'stunted' areas compared with 'non-stunted' areas, with a SL : SH ratio of 3.25 separating all of the 'stunted' and 'non-stunted' sites. However, within the 'non-stunted' sites, Cape Northumberland had a significantly lower SL : SH ratio compared with the others, suggesting that abalone from this site may comprise an intermediate morphological classification between the two that we have presented here. The fact that the SL : SH ratio was able to identify this variability indicates that it is a sensitive measure of morphometric differentiation among populations. The morphometric samples collected at finer scales revealed that the 'stunted' population of abalone in Gerloffs Bay occupied a smaller area compared with the 'non-stunted' one in Middle Point. 'Stunted' samples of abalone were only found within 400 m of the original GB site, whereas all of the samples within 1000 m of the MP site were classified as 'non-stunted'. Consequently, these data suggest that the scale of differentiation between 'stunted' and 'non-stunted' populations ranges from up to 400 m (Gerloffs Bay) to at least 1000 m (Middle Point). These results might imply that the population at Middle Point could potentially extend from tens to hundreds of kilometres if similar values of the SL : SH ratio were observed continuously over this range. However, the mixture of 'stunted' and 'non-stunted' populations among the broad-scale sites suggests that the environmental conditions that are probably causing the variability in the ratio are acting at finer scales. In addition, the population at Middle Point is probably nearing its boundary at this distance as MP1000 had a significantly lower SL : SH ratio compared with the other sites in Middle Point. Alternatively, abalone in MP1000 could represent the beginning of a separate population within Middle Point that is an intermediate classification similar to that of Cape Northumberland above.

Table 4. Outputs from the discriminant function analysis examining the percentage of successful discrimination among sites based on the SL : SH ratio for GB and MP broad-scale sites and the six sub-sites
GB, Gerloffs Bay; MP, Middle Point

Site	Percentage correct	GB	GB150	GB400	GB1000	MP	MP150	MP400	MP1000
GB	40.0	22	25	0	3	1	0	0	4
GB150	48.5	14	32	0	14	0	3	1	2
GB400	38.5	1	1	20	15	0	6	6	3
GB1000	62.8	2	5	7	49	0	5	9	1
MP	5.6	0	3	1	6	4	19	26	12
MP150	56.1	0	2	6	5	1	46	14	8
MP400	54.1	2	1	3	6	5	13	53	15
MP1000	54.1	3	4	1	4	7	5	15	46
Total	46.3	44	73	38	102	18	97	124	91

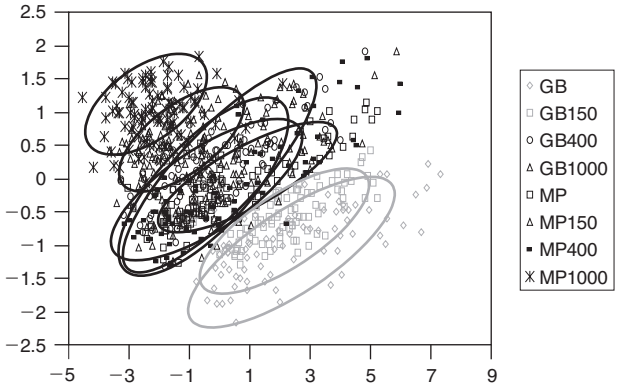

Fig. 5. Ordination of the principal components analysis (PCA) on the morphometric characteristics from Gerloffs Bay (GB), Middle Point (MP) and the six sub-sites. Black and grey symbols indicate abalone from 'non-stunted' and 'stunted' sites respectively. Ellipses indicate 95% confidence intervals.

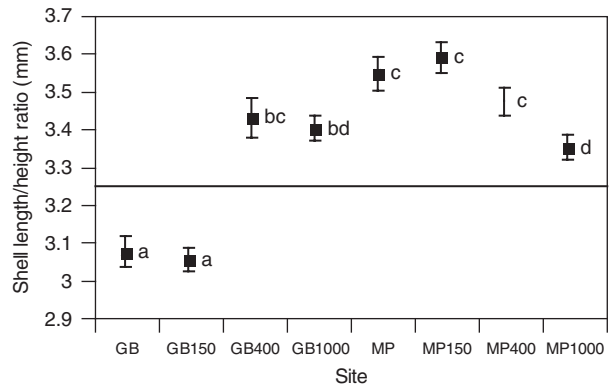

Fig. 6. Shell length to height (SL : SH) ratio for all abalone measured from Gerloffs Bay (GB), Middle Point (MP) and the six sub-sites. Letters indicate groups classified by the Tukey's honestly significant difference (HSD) test. Horizontal line indicates SL : SH ratio value that separates 'stunted' from 'non-stunted' sites. Error bars are ±1 standard error.

These results are supported by those in previous studies where abalone inhabiting areas of slower rates of growth tend to have heavier, wider and higher shells compared with those located in areas with faster growth rates (Breen and Adkins 1982; McShane *et al*. 1988; Tissot 1988; Worthington *et al*. 1995). Breen and Adkins (1982) found slower-growing *Haliotis kamatsakana* populations could be differentiated on the basis of shell height. Similarly, in New South Wales, Worthington *et al*. (1995) found that slower-growing abalone populations had significantly wider shells. In their study, shell height was not measured and could also have potentially separated these populations. However, neither of these studies collected samples of abalone at appropriate spatial scales to identify the spatial extent of separate populations. Our data, in combination with these studies, suggest that the principles underpinning the 'morphometric marker' that we have developed may be more broadly applicable to other abalone fisheries.

Although the SL : SH ratio was able to discriminate between 'stunted' and 'non-stunted' populations of abalone in the SZ, so was the variability in shell length. The abalone in all of the 'non-stunted' sites had substantially greater shell lengths compared with those in 'stunted' sites. However, using shell length as a tool to discriminate between these populations is problematic as 'non-stunted' populations that are heavily fished will have very few large abalone and the length frequencies will be similar to 'stunted' populations that are unfished. Nevertheless, length frequencies of populations in conjunction with the SL : SH ratio would be extremely useful in discriminating between 'lightly fished' and 'stunted' populations. 'Lightly fished' populations could potentially be classified as 'stunted' according to the SL : SH ratio as they tend to have many larger abalone that have reached their maximum size and have grown substantially in shell height as a result of their age (J. Prince, pers. comm.). Given that these populations will still have a higher average shell length compared with that for 'stunted' populations, length to frequency distributions for each of these populations would reveal this difference.

Patterns of morphometric variation among populations are also likely to indicate differences in growth and maturation rates (Cadrin 2005), which will determine how they respond to exploitation (Wells and Mulvay 1995). Therefore, for the purpose of fishery stock assessment, morphologically distinct populations should be modelled and managed as separate management units (Cadrin and Friedland 1999; Cadrin 2000, 2005). Although this has been attempted in the SZ with the implementation of FDAs, where stunted stocks of abalone were thought to exist, the boundaries of these fishing areas were based on ease of

geographical identification as a result of the limited information on the extent of these populations. The location and boundaries of these FDAs can now be reconsidered by using the 'morphometric marker' we have developed as a tool to ensure that they encompass only 'stunted' abalone. For example, the data presented here suggest that FDA 4, which encompasses all of Gerloffs Bay, could be reduced in size to exclude 'non-stunted' abalone. Further, two sites (Acis Reef and Red Rock Bay) not located in any of the current FDAs were classified as 'stunted', indicating the potential for additional FDAs across the SZ. In addition, our data indicate that 'non-stunted' abalone may exist as larger populations compared with 'stunted' abalone. Consequently, management units for the former could potentially be much larger in size compared with those for the latter. However, further morphometric samples of abalone are required to determine the consistency and confirm the location and extent of the 'stunted' and 'non-stunted' populations across this fishery. If individual populations of abalone can be identified using this approach, then managing these separately on this basis would assist in guarding against serial depletions of abalone stocks.

The development of this approach provides a cost-effective tool to provide a wealth of data, through the measurement and analysis of shell samples to inform changes (i.e. a reduction) in the spatial scale of abalone management. This is timely as the concept of finer scale management of abalone fisheries has effectively become the orthodox position (Naylor *et al*. 2006) but its application has been restricted by the inability to gather detailed demographic data at useful spatial scales (Prince 2005; Naylor *et al*. 2006). Thus, use of the 'morphometric marker' developed in the present study provides an opportunity to bridge the traditional disconnect between scales of ecological variation and fisheries management. Although these ideas are particularly pertinent for abalone given their history of stock collapse, fine-scale population structuring is common for most sedentary invertebrates and probably for many teleosts and chondrichthyans (Prince 2005). Consequently, developing a 'morphometric marker' may be able to assist with the conservation and management of many marine species.

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