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Variation in the Relationship between Shell Length and Meat Weight for Blacklip Abalone (*Haliotis rubra,* Leach, 1814) with Implications for Compliance in New South Wales, Australia

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Abstract

The relationships between shell length and the weight of a shucked and bled meat (final meat weight (FMW)) and a completely desiccated dry meat weigh (DMW) were investigated to provide guidelines for a minimum meat weight restriction (MMW) for blacklip abalone (*Haliotis rubra,* Leach, 1814) in New South Wales (NSW), Australia. Quantile regression was used to predict FMW and DMW for specific shell lengths with various levels of probability. The expected FMW and DMW for an abalone with a minimum legal shell length of 115 mm was 78 g and 20 g respectively. There was a 5% probability that the same abalone could weigh 59 g (FMW) and 15 g (DMW) and a 1% probability that it could have a FMW of 50 g and a DMW of 13 g. This allows predictions to be made about shell lengths of abalone using their FMW or DMW alone. For example, a MMW regulation could be set at the 5% probability of FMW for the current minimum legal shell length, and an allowance of no more than 5% of a seized catch below that. Such a MMW regulation could then provide significant benefits to compliance operations in the NSW abalone fishery.

Introduction

Restrictions on the minimum size of individuals allowed to be harvested are used to manage many fisheries. Such restrictions are used to delay the harvest of individuals, so that long-term yield and egg production can be increased. In most abalone fisheries, a minimum legal length (MLL) is enforced, although other morphological variables are often highly correlated, and size limits relating to them may provide biological and logistical benefits (see also Worthington et al. 1995). Multiple size limits are also used in some fisheries (e.g. minimum and maximum size limits), and can also provide benefits. In some abalone fisheries, a minimum legal meat weight (MLW) is enforced in addition to a MLL (e.g. Tasmania, Australia).

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There are a range of management restrictions in the fishery for blacklip abalone, *Haliotis rubra* Leach 1814, in New South Wales (NSW), Australia. Perhaps the most important of these are the state-wide total allowable catch (i.e. TAC, 94 tonnes for 2011-12) and MLL (115 mm shell length at the time of this study, but note that the MLL has subsequently been increased to 117 mm in NSW) for the commercial and recreational fisheries. Large catches of abalone are also taken illegally by thieves, who do not respect the existing management arrangements, and particularly target the abundant abalone less than the MLL. Considerable resources are utilised in an attempt to prevent or apprehend such offenders, and following apprehension large numbers of illegally caught abalone are often confiscated and can be used as evidence for prosecution. For example, the number of abalone caught may be greater than proscribed possession limits and the size of the shells may be less than the MLL. In many cases, confiscated abalone have been removed from the shell, making it difficult to determine their original shell length and its relationship to the MLL.

The maximum penalties for possessing abalone under the MLL or exceeding the recreational bag limit (two abalone) in NSW stand at $88,000 (AUD) and/or 18 months imprisonment for an individual and $440,000 for corporations for each offence. Individuals or corporations found guilty of trafficking illegal catch face penalties up to 10 years imprisonment and fines up to 10 times the market value of the catch (New South Wales Fisheries Management Act 1994 No. 38).

Currently, in most cases, offenders caught with abalone meats can only be charged with offences relating to exceeding legal bag limits, as the shells have usually been discarded prior to seizure making determination of legal length difficult. If alleged offenders can be charged with offences relating to the size of abalone landed as well as exceeding bag limits, more successful prosecutions and greater penalties are likely to lead to a greater deterrence.

Evidence of the relationship between the length of abalone shells and the size or weight of meat can be used to support an argument about the shell length, particularly relative to the MLL, of confiscated meats. Such information forms the basis of minimum legal weights enforced in some fisheries. Unfortunately, a variety of factors can combine to complicate the relationship between abalone shell length and the weight of its meat. When abalone are removed from the water, they immediately begin to lose weight through loss of water and body fluid (Gorfine 2001). When the meat of abalone is removed from the shell and other viscera, the weight loss is increased as they bleed profusely through severed arteries, as there is no clotting agent in the haemolymph of abalone (Armstrong et al. 1971, Gibson et al._2002). After bleeding has ceased, the meat may continue to lose further weight through desiccation. Further, all these factors that may cause the weight loss of the meat can also be influenced by the ambient environmental conditions (Gorfine 2001; Gibson et al. 2002). Consequently, there can be considerable variation in the relationship, which because of the unknown timing and handling prior to confiscation, has implications for the evidence used to support prosecution.

Here, we attempt to estimate variation in the relationships between various measures of meat weight and shell length for blacklip abalone, associated with the fishery in NSW, Australia. We also investigate the potential variation in these relationships that can be caused by different methods of handling. The methods of handling were chosen to simulate the range of handling methods that may be encountered by meats that are later confiscated and used as evidence in prosecutions. Finally, the information collected to detail a more probabilistic method of describing the likelihood of a given abalone meat, or catch of abalone meat, coming from individuals below the MLL was used. All the information presented here can be used to help determine the most preferred method for dealing with confiscated abalone meat, and increasing the successful prosecution and penalties for offenders.

Materials and Methods

Variation in weight loss and morphology

To investigate variation in the weight loss and morphology of abalone, 50 individuals between 95 and 140 mm in shell length were randomly sampled from each of 12 sites between June and September 1999 (Fig. 1). Two sites were randomly chosen within each of six locations, which were selected to represent the geographic range of the fishery in NSW, Australia. The morphology of abalone in NSW is known to be related to their rate of growth (Worthington et al. 1995), and the sites selected for sampling were likely to be representative of the range in growth and morphology within the state. For example, populations of stunted and very fast growing individuals were included in the sample. All individuals were carefully removed from the reef in an attempt to minimise any damage, and only a few, minor injuries to the foot were observed (minor grazes, see Gibson et al. 2002). To investigate temporal variation in morphology, sampling was repeated at three of the six locations during March and April 2000. The morphology of abalone in NSW is also known to be related to their spawning condition, with the first and second samples likely to be coincident with maximum and minimum gonad development, respectively (see also Worthington and Andrew 1997).

Following collection, the total weight (TW) (blotted wet in g) and shell length (SL) (in mm) of each individual were measured. Abalone were then removed from their shells, sex was recorded, then the meat was separated from the viscera and immediately weighed (blotted wet in grams, and referred to as initial meat weight, IMW), then placed on racks in the shade to drain. Ten abalone were selected to represent the size range sampled from each site, and used to investigate variation in weight loss through time. The meats from these were weighed every 5 min after removal from the shell for 90 min, and then every 15 min until 2 hr after removal. Meats from all other abalone sampled were weighed every 30 min for 2 hr (the final meat weight is referred to as FMW). All meats (900 in total) were then placed in a 225 L laboratory oven at 60 ^{o}C for 48 hr to completely desiccate, and again weighed (in g, referred to as dried meat weight, DMW). Preliminary sampling suggested there was negligible further weight loss in draining meat after 2 hr or desiccated meat after 24 hr.

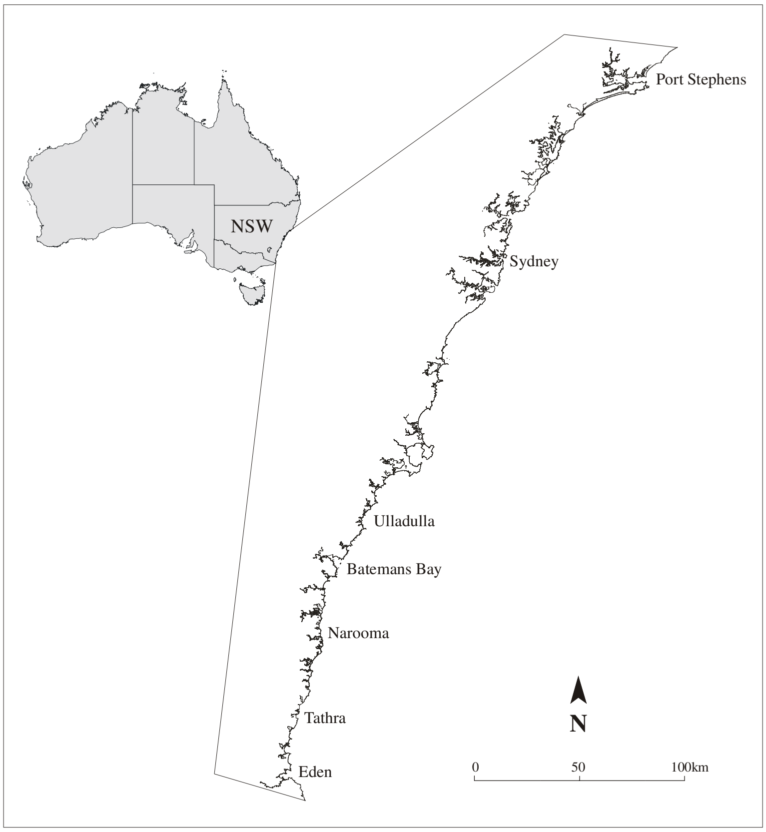

Fig. 1. Map of the New South Wales coast south of Port Stephens showing the six sampling locations. Sydney is included as a reference.

Prior to analysis, the shell length of each abalone was transformed to linearise its relationship to other allometric, morphological variables. Shell length was transformed and referred to as TSL (i.e. TSL = $SL^{2.68}$, see also Worthington et al. 1998). Separate analyses of covariance were used to investigate the effects of the random Site factor on the relationship between measures of morphology and meat weight.

Effects of handling on weight loss

An experiment was designed to investigate the effects of different handling methods on the rate of weight loss by the meat following removal from the shell and viscera. A total of 60 abalone, ranging in shell length from 86 to 122 mm, and 42 to 132 g in IMW, were sampled from one site at Port Stephens in December 2000. A size-stratified, random sample of 20 individuals, to represent the size range sampled, was selected for inclusion within each of 3 treatments. Following removal of the meat from the shell, the treatments involved storage in an ice slurry (Ice), an oven at 40 ^{o}C (heat), and on racks in the shade (ambient). The blotted wet weight of the meat was then measured every hr for 5 hr, and again after 24 hr. All meats were then placed in an oven at 60 ^{o}C for 48 hr (same as above) to completely desiccate, and were again weighed. Separate analyses of covariance were used to investigate the effects of the fixed Treatment factor on the relationship between initial and subsequent meat weights.

Implications for meat weight limits

Evidence used for prosecution will need to be based on the estimation of the probability that a meat of a particular weight came from an abalone less than the MLL. Ideally, a specific weight could be chosen, with lighter meat having a very high probability of coming from abalone less than the MLL, and a very small probability of coming from an individual greater than the MLL. Because of the observed increase in the variation of meat weight with shell length (i.e. multiplicative error structure), it is likely that such a meat weight will be most strongly influenced by individuals above the MLL. As a result, here we concentrate the description of our results on the meat weights that are expected to be associated with abalone at the MLL of 115 mm with a specific probability.

The expected probability of an abalone of a given shell length having a particular meat weight can be estimated from the observed data by fitting regression quantiles (Koenker and Bassett 1978; Cade and Noon 2003). These are estimated by minimising the sum of weighted absolute deviations between the observed data and a linear model, with no parametric assumptions about random error. This method was chosen as it is more robust to extreme values and sparseness, while providing consistent estimates of upper and lower bound slopes. In contrast, the more commonly used, parametric least squares method can be sensitive to outliers and irregularities in the distribution of the data, and can also provide inconsistent estimates of slope (Scharf et al. 1998). The regression quantiles calculated provided estimates of the meat weight expected to come from abalone of a specific shell length for a range of probabilities. For example, the meat weight expected to be associated with the lightest 1% of 115 mm abalone was calculated. Further, the probability of obtaining a 100 mm abalone with a greater meat weight was also calculated. This information can then be used in a variety of ways to provide evidence used for prosecution.

Results

Variation in weight loss and morphology

There were significant correlations among all the measures of morphology and meat weight both within and among all sites (Table 1 and Fig. 2). In general, closely related variables, such as TW and IMW (i.e. prior to major weight loss), and FMW and DMW (i.e. after weight loss), were most strongly correlated. Of the different measures of meat weight, IMW was the most strongly correlated with TSL. The correlation of FMW and DMW with TSL was slightly reduced, presumably through variation in the loss of meat weight following removal from the shell.

Table 1. Pearson correlation among five morphological variables (transformed shell length (TSL), total weight (TW), initial meat weight (IMW), final meat weight (FMW), dried meat weight (DMW)) of 50 abalone sampled from within each of 12 sites. Values in the top section of the matrix show the range of within site correlations, and below are correlations among all abalone sampled. All correlations are significant with P<0.01.

	TSL	TW	IMW	FMW	DMW
TSL		0.65-0.93	0.53-0.91	0.43-0.88	0.51-0.88
TW	0.84		0.84-0.97	0.59-0.93	0.64-0.93
IMW	0.79	0.89		0.79-0.96	0.78-0.95
FMW	0.70	0.75	0.87		0.72-0.97
DMW	0.72	0.78	0.86	0.88	

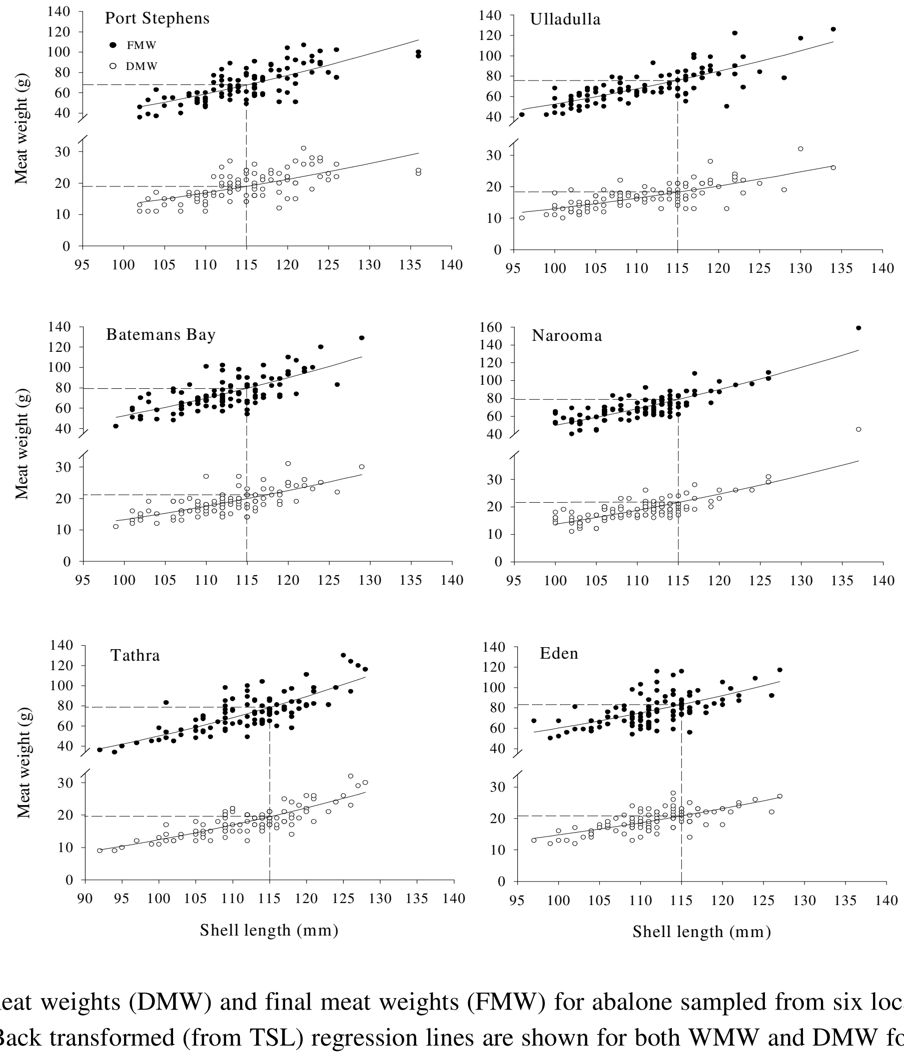

Fig. 2. Dry meat weights (DMW) and final meat weights (FMW) for abalone sampled from six locations along the NSW coast. Back transformed (from TSL) regression lines are shown for both WMW and DMW for each location. Dashed lines indicate predicted MW at MLL (115mm).

There was significant spatial variation in the morphology and weight loss of abalone (Table 2 and Fig. 2). The relationship between TSL and TW varied significantly among sites. That is, the weight of an abalone of a given length varied among sites. Increases in TSL were generally associated with smaller increases in TW at sites in the south of the state, although there was also significant variation among sites within a location. For example, for a given increase in TSL, there was a 3.16-3.99 times increase in TW at the four southern most sites, and a 4.28-4.46 times increase at the four northern most sites. Within one location, for a given increase in TSL, the increase in TW differed among sites by 1.55 times (i.e. 31% of the average for that location), and this was associated with a stunted, slow-growing population.

Table. 2. Summary of analyses of covariance in five morphological variables of abalone from a) 12 sites during one season and, b) 6 sites during two seasons. Tabled values show the *F*-ratio for each factor with associated significance (i.e. significant factors are shown by 1 for 0.05<*P*<0.01, 2 for 0.01<*P*<0.001 and 3 for *P*<0.001), and the mean square associated with the residual. See Table 1 for explanation of abbreviations.

	Covariate:	TSL				IMW	FMW
	Independent:	TW	IMW	FMW	DMW	FMW	DMW
Source	df						
a)							
Covariate	1	395.9^{3}	313.0^{3}	447.9^{3}	188.4^{3}	804.0^{3}	328.04^{3}
Site	11	0.8	0.9	1.0	0.8	0.5	0.6
Site*Covariate	11	3.5^{3}	2.8^{2}	1.3	2.8^{2}	2.2^{1}	7.4^{3}
Residual	576	632.0	162.0	119.6	7.3	58.2	2.7
b)							
Covariate	1	482.5^{3}	338.5^{3}	419.6^{3}	310.2^{3}	3488.0^{3}	552.8^{3}
Season	1	-	-	-	-	-	-
Site	5	1.1	1.2	1.4	0.5	1.1	0.5
Season*Site	5	1.0	1.4	0.9	0.8	0.4	0.6
Season*Covariate	1	8.9^{1}	12.1^{1}	14.0^{1}	13.5^{1}	0.2	6.0
Site*Covariate	5	3.4^{2}	2.9^{1}	1.7	1.9	0.6	5.4^{3}
Season*Site*Covariate	5	1.2	1.0	0.7	1.6	3.2^{2}	5.2^{3}
Residual	576	557.4	153.3	113.4	8.4	55.1	2.7

The relationship between TSL and two of the measures of meat weight (i.e. IMW and DMW) also varied significantly among sites (Table 2 and Fig. 2). For example, the estimated DMW of an abalone of 100 mm in shell length varied among sites from 12.1-15.9 g, and for a 115 mm abalone the DMW varied among sites from 17.7-22.3 g (Fig. 2). There was no significant variation among sites in the relationship between TSL and FMW, presumably because of greater within site variation, but the expected FMW for an abalone of 115 mm SL still varied among sites from 66.4-83.4 g (Fig. 2).

The pattern of weight loss by the meats through time, following removal from the shell, was generally similar among sites. That is, there was rapid weight loss by the meat in the first 10 min, followed by the gradual slowing of weight loss through time. After 10 min, the expected meat weight had dropped to 82% of the initial weight (i.e. range among sites 73-93%), but differences in weight loss among sites were not significant. After 30 min, the expected meat weight had dropped further to 77% of the initial weight, and there was significant variation among sites in its relationship to the initial weight (i.e. range among sites 69-90% for a meat of initially 80 g). Individuals and sites that experienced a high weight loss in the first 10 min generally remained below subsequent expected meat weights.

Despite a similar general pattern of weight loss through time, there was significant variation in the relationship between the three measures of meat weight (i.e. IMW, FMW and DMW) among sites (Table 2). For a meat that was initially 80 g, FMW and DMW ranged among sites from 64-73% and 16-20% of the IMW. The rate of weight loss by the meat was also related to the initial morphology of the abalone. At sites where weight increased more slowly with shell length, there was a greater increase in FMW for a given IMW. That is, there was reduced weight loss, presumably from bleeding, at sites where abalones were light for their shell length. This also extended to the relationship between FMW and DMW, where there was reduced weight loss from desiccation at sites where abalones were light for their shell length.

There was significant variation among sampling times in the morphology and weight loss of meat following removal from the shell (Table 2). The significant differences among times did not vary among sites for the relationship between TSL and TW, IMW, FMW and DMW. That is, for a given increase in TSL there was a greater increase in all measures of weight during the period of maximum gonad development during spring. There was no significant difference in this seasonal effect between male and female abalone. Differences among sites in the rate of weight loss from IMW to FMW and DMW did vary significantly among sampling times, but absolute changes were small.

Effects of handling on weight loss

Before and 2 hr after treatment, there was no significant difference in the weight loss of meats exposed to the different handling treatments (Fig. 3). From 3 hr, there was a significant difference among the treatments in the relationship between meat weight and its initial weight. That is, the rate of weight loss among treatments varied among meats of different weights. After 5 hr, a meat that was initially 60 g was expected to have reduced to 59% of its initial weight in the Heat treatment and 71% in the Ice treatment. After 24 hr, this had reduced further to 34% in the Heat treatment and 70% in the Ice treatment. At the same time, a meat that was initially 100 g was expected to have reduced to 38% and 57% of its initial weight, respectively. That is, the Ice treatment reduced weight loss of small abalone more than large abalone, while the Heat treatment increased weight loss of small abalone more than large abalone. When all meats were dried, there was no significant difference among treatments in the relationship between the dry meat weight and its initial weight. In other words, after drying, meats had lost a very similar weight regardless of how they were treated.

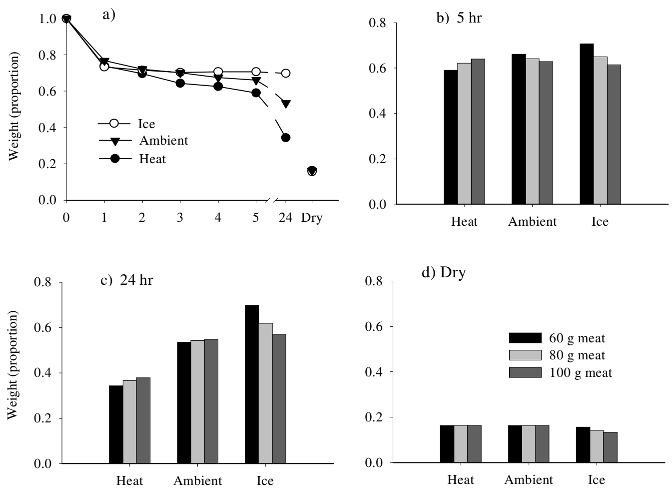

Fig. 3. Effects of handling treatments on the estimated weight as a proportion of initial meat weight for a) a 60 g meat through time and after drying b-d) 60, 80 and 100 g meats at 5 and 24 hr and after drying.

Implications for meat weight limits

The average expected FMW and DMW for an abalone with a shell length of 115 mm (MLL) were 78 g and 20 g, respectively. There was a 5% probability that the same abalone could weigh 59 g (FMW) and 15 g (DMW) and a 1% probability that it could have a FMW of 50 g and a DMW of 13 g (Table 3, Fig. 4).

Table. 3. Dry meat weight (DMW) and final meat weight (FMW) ranges in grams for abalone with shell lengths of 100 mm and 115 mm for a range of quantile percentages.

Shell length (mm)		***100***		***115***	
Meat Condition (g)		***DMW***	***FMW***	***DMW***	***FMW***
Quantile	***50%***	13.60	52.99	20.02	77.61
	25% - 75%	12.54 - 15.39	48.32 - 58.23	17.89 - 22.30	69.97 - 86.06
	10% - 90%	11.20 - 16.46	44.26 - 65.44	16.12 - 24.69	63.58 - 95.21
	5% - 95%	10.93 - 17.48	42.04 - 68.85	15.28 - 26.18	59.47 - 99.77
	1% - 99%	9.83 - 19.96	38.13 - 79.75	12.60 - 28.53	50.41 - 112.05

Sixty eight percent of abalone with a shell length of 100 mm had a higher FMW and 66% had a higher DMW than the lightest 1% of 115 mm abalone (FMW 50 g, DMW 13 g) indicating that meat weights which fall in the low end of the acceptable range for 115 mm abalone are far more likely to have originated from abalone with shell lengths less than the MLL.

The predicted meat weight for an abalone of a given shell length varied among sites along the NSW coast. For example the average DMW for a 115 mm abalone for all sites was 20 g, but varied among sites from 17 – 22 g (Fig. 2). The 5% quantile value for the same size abalone ranged from 13–17 g, while the 10% quantile value ranged from 14–20 g.

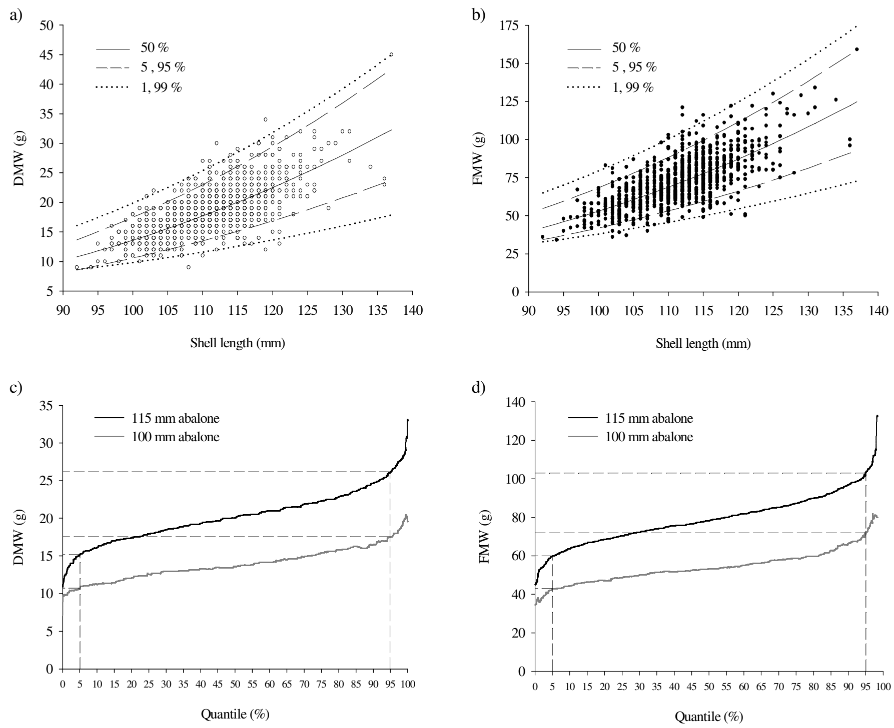

Fig. 4. a) Dry meat weight (DMW) and b) Final meat weight (FMW) with 1, 5, 50, 95 and 99 % quantile lines for all abalone sampled from 12 sites. c) Dry meat weight and d) Final meat weight for a 115 mm and 100 mm abalone versus quantile percentages. Dashed lines indicate meat weight at the 5 and 95 % quantile.

Discussion

Variation in weight loss and morphology

In this study, significant correlations, and spatial variation, among morphological variables, and variation in meat weight loss following removal of the shell were observed. While significant correlations among morphological variables has the potential to aid fishery compliance prosecutions through implementation of a minimum meat weight regulation, variation in morphology and weight loss will complicate its implementation.

There was significant spatial variation among sites for many of the morphological variables. While there were some trends between northern and southern regions, and there was also some variation between sites from the same location, most of the variation occurred at very small spatial scales, consistent with previous studies of abalone demography and morphology (McShane et al. 1986; Worthington et al. 1995; 1997). Also, despite a uniform general trend in weight loss and bleeding rates through time following removal of the shell, the spatial differences along the NSW coast were still significant.

The differences in morphology and weight loss observed between sampling times are likely to be related to variation in gonad development and spawning. It is well documented that abalone are in better condition during spring in NSW when their gonad condition is largest in preparation for spawning (McShane et al. 1986). Much of the remaining variation is probably due to environmental variables such as food availability, population density and competition with other grazers such as the sea urchin *Centrostephanus rodgersii* (Agassiz 1863) and their influence on food supply and growth of abalone. Competition is likely to affect the feeding efforts of abalone over a range of spatial and temporal scales and could contribute to the relationship between meat weight and shell length (Andrew et al. 1998; Andrew and Underwood 1992). The results of this study are limited to only two sampling times and replication of the study over 2 or more years would provide better and more reliable information on seasonal and annual variation.

Effects of handling on weight loss

The history of handling abalone meat is likely to influence its weight loss and be an important factor to consider when enforcing a minimum meat weight. This study clearly showed that handling of an abalone meat following removal from the shell can be a source of significant variation when using meat weights to predict shell length. The impact of a range of experimental handling treatments following removal of the shell varied among abalone of different sizes. The meat weight of small abalone was less affected by being chilled, but was more affected by storage in a warm environment, while the reverse was true for large abalone. Alternatively, when these meats were completely desiccated, the post shucking history became unimportant, and better estimates of shell length could be determined using dried meat weight.

It is likely that logistics will limit the total number of seized meats able to be rapidly dried to make estimates of shell length for use in prosecutions. Consequently, fresh meat weight will be more easily available and likely to be used most commonly in estimates of shell length. Shell lengths determined in this manner alone need to be used with caution and acknowledgement of the associated variation that accompanies the relationship with fresh meat weight, and particularly that caused by post shucking history. Consequently, decisions based on fresh meat weight alone are less likely to be useful for prosecution of offenders.

Implications for meat weight limits

The results presented in Table 3 provide useful guidelines for estimating shell lengths from fresh meat weight and dry meat weight at different levels of probability. For example, an absolute meat weight restriction for a MLL of 115 mm could be set at the 5% quantile of the relationship between meat weight and shell length, which are 59 g (FMW) and 15 g (DMW). This implies a <5% chance of an abalone at the MLL having such meat weights or less. Alternatively, a more conservative regulation could involve the 1% quantile making the minimum meat weight 50 g (FMW) and 13 g (DMW) for a 115 mm abalone.

Setting an absolute meat weight restriction at the 5% or even 1% quantile is complicated by the possibility of encountering the <5% or <1% of abalone that are below the predicted FMW and DMW. This study has shown that there is significant spatial and temporal variation along the NSW coast in morphological, meat weight and bleeding rate variables. Consequently, it could be argued by an offender that any abalone meat found in their possession under an absolute meat weight restriction is just unusually small and did in fact come from a legal sized abalone. An even more conservative approach would be to set a minimum meat weight at an appropriately low probability level and allow for a proportion of seized meats to be below this limit before prosecution. For the previous example, a meat weight restriction could be set at the 5% quantile (FMW – 59 g, DMW – 15 g) and then allow 5% of the seized abalone meats to be below this restriction. This approach would better allow for the spatial and temporal variation of abalone observed along the NSW coast. If a more conservative approach is preferred, then a lower quantile and its associated meat weights could be used. A restriction based on appropriate quantiles with an allowable proportion built in for error, rather than an absolute meat weight has the flexibility to be used conservatively, if needed.

Conclusion

The results of this study provide useful information that can be used to compile evidence in a prosecution of illegally caught abalone. Being able to prosecute offenders for having under-size abalone when only abalone meats are confiscated can provide useful additional information about the case. If offenders can be charged for both illegally caught and under-size abalone, then legislation allows for more severe penalties, acting as a increased deterrent to potential re-offenders. It is commonly recognised that theft of abalone is probably the most significant problem facing the fishery today and any steps taken to reduce the efforts of illegal fishing is beneficial both to profitability of the commercial industry and to the sustainability of the fishery in NSW.

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