Report on the Commercial Mussel Diver Fishery and Mussel Population Surveys in Harrington Sound

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Summary

The last surveys of the mussel population in Harrington Sound were carried out in 1988. Since that time, the dredge-based fishery for mussels has ceased, the population has had time to recover, and a new diver-based commercial fishery for mussels has been initiated, with two divers currently operating. Mussels are also exposed to varying levels of recreational harvest, but this has not been quantified. Research was carried out between 2008 and 2011 to acquire data on the composition of the mussel harvest and the status of mussel populations in Harrington Sound to assist with the sustainable management of the new commercial fishery. The landed catch of one of the commercial mussel divers was assessed to produce sex-specific size-frequency histograms. Exploratory surveys of the mussel population in Harrington Sound were conducted at the six sites studied in 1988 and at three additional sites where the licensed commercial mussel divers are known to operate. More detailed sampling was conducted at four sites: two where harvesting was known to occur, one within an area where commercial fishing for mussels was, and still is, prohibited, and a fourth site which is open to harvesting but at a depth where free-diving harvest would not be practical. The data from these assessments suggest that there has been a substantial recovery of mussels in the deeper areas of Harrington Sound, although the slow growth rate of this species means that large individuals are still scarce. Further validation of the age structure and growth rates in this population is recommended. Heavy harvesting by divers at shallower depths is keeping numbers low in these areas, therefore a commercial mussel fishery limited to free-diving harvest appears to be fully exploited at this time. The introduction of a daily bag limit for recreational harvesters is recommended as a means to reduce exploitation and illegal sales.

Introduction

The turkey wing mussel (*Arca zebra)* is a common bivalve found in shallow, coastal waters of the Atlantic ocean at tropical and subtropical latitudes (Sarkis 1993). It is the most abundant bivalve species in Bermuda waters, and is found from the shoreline to depths of 27 m (Sterrer 1985). After settlement, adults are generally found attached to hard substrate, including rocks, corals and the shells of other mussels. They are most abundant in sheltered waters at depths of 10-14 m, but this apparent depth preference may be an artifact of high harvesting levels in shallower areas. Harrington Sound has traditionally been known as an area where these mussels occur in high abundance. Turkey wing mussels are filter feeders that enhance water quality and which are an important food source for invertebrate feeders such as hogfish. Mussel shells are also an important settlement substrate for recruits of the hard branching coral *Oculina spp.*

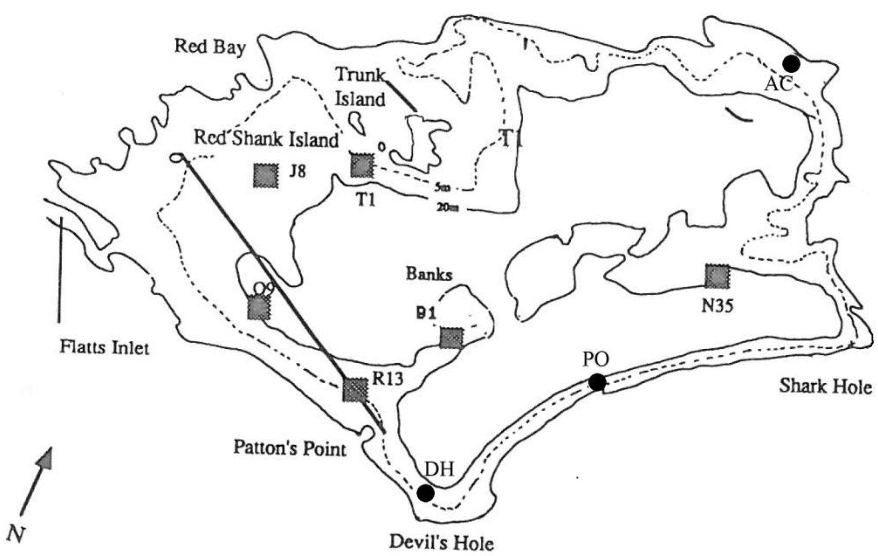
The tendency of individuals of this species to attach to the shells of conspecifics produces a clumping effect, and these mussels are often found on soft bottoms in clusters of 5 – 10 individuals. These ‘bundles’, as they are known, are thus relatively easy to harvest while free-diving. Mussels attached to rocks in the intertidal zone and shallow sub-tidal areas can also be readily harvested by people wading and using simple tools to prise them off the substrate. Mussel populations across Bermuda have therefore been exposed to varying levels of recreational harvest over time. Anecdotal observations suggest that this activity is once again becoming popular, but the current extent and impact of recreational harvesting have not been quantified. There are no restrictions on recreational harvesting at present.

Historically, there was a dredge-based fishery for mussels in Harrington Sound, and this was a traditional activity for some half dozen fishermen from the area. However, it became apparent that this fishing method was damaging the benthic habitats of the sound, most notably stands of branching corals from the genus *Oculina* that occurred at depths of 30-50 feet (10-17 m) ('Marine Resources and the Fishing Industry in Bermuda' Green Paper). In fact, it was these corals that provided much of the hard substrate that the mussels were attached to. Those fishermen using this gear type were allowed to continue until retirement but no new licences were issued, and dredging ceased in 1993.

The first permit for commercial mussel diving was issued in 2008, after a 15-year hiatus from commercial-scale harvesting. At present, there are two commercial mussel divers operating in Harrington Sound. These divers are limited to free-diving only and may not use SCUBA when harvesting mussels. Reported harvests were 217 quarts in 2008, 346 quarts in 2009, 292 quarts in 2010 and 347 quarts in 2011. This compares to harvest levels of 2,500 – 4,500 quarts per year during the height of the dredge fishery in the 1970s and more recent levels of 1,000 – 2,000 quarts per year during the early 1990s as the fishery was winding up (Department of Agriculture and Fisheries Report for the Year 1994).

In 1973, a reserve area where no dredging was permitted was designated to the west of a line from Red Shank Island to Patton's Point (Figure 1). This reserve area has been kept off limits to the current diver-based fishery. However, it does not apply to recreational harvesters.

Figure 1. Map of Harrington Sound, with 5 m (dashed line) and 20 m (solid line) depth contours, showing original sites surveyed in 1988 (squares) and additional sites surveyed in 2010 (circles). Adapted from Sarkis 1992.



A survey conducted n 1985 found no effect of fishing on turkey-wing mussel populations (Couper 1985). Yet Sarkis (1992) found that by 1988, just three years after those initial surveys, populations were dramatically reduced. Density at site O9 (Figure 1) averaged 32 mussels / m^2 in 1985, but dropped to 12 mussels / m^2 in 1988. Despite O9 being within the reserve, it is found near the eastern limits and may have been impacted by boundary effects. Density at other sites in the dredged zone also averaged less than 15 mussels / m^2. This indicated a significant effect of dredging on mussel populations in Harrington Sound. Conversely, at a site within the reserve area, mussel density rose by an average of 15 mussels / m^2 to 50 mussels / m^2 during that period. At near shore locations, Sarkis (1992) observed that mussel density was lower where recreational fishing had consistently occurred. 1988 was the last year this population was evaluated.

In Bermuda, Turkey wing mussels reproduce in the summer (June / July), utilizing stored carbohydrates, and in early fall (September), relying on large amounts of available food in the summer. Their growth appears strongly linked to food supply, being faster in the summer than in the winter at least in early life (Sarkis 1992). Growth is sigmoidal over the lifespan of the individual, with rapid growth and shell extension occurring during the summer(s) before the individual reaches maturity and slower growth with smaller incremental increases in shell length thereafter (Sarkis 1992). The maximum recorded shell length for the species is 80 mm.

Bivalve age may be estimated by counting pallial lines present either on the outside or inside of the shell, or by slicing through the shells and counting the lines present in the slice (Neves & Moyer 1988). These lines are laid down by the animal usually during periods of slower growth that are related to environmental conditions that are region-specific, and may be driven by reproductive activity, temperature variation, changes in salinity, or changes in diet. Pallial line deposition and intervals record different conditions and seasons depending on the species and location (Haag & Commens-Carson 2008), so no assumptions can be made about the seasonality and significance of pallial lines in Bermudian turkey-wing mussels. If pallial lines in local turkey-wing mussels are indeed annual and represent slower winter growth, a typical 50 mm shell would be 7 or 8 years old (J. Pitt pers. obs.), and some estimates suggest that very large individuals could be 10 years old or more (Sarkis 1992).

Given the paucity of information regarding the Turkey wing mussel and the various environmental and anthropogenic factors acting upon it, it was deemed prudent to acquire data on the composition of the harvest and the status of mussel populations in Harrington Sound to assist with the sustainable management of this fishery.

Methods

Sampling of landed harvest

The landed catch of one of the commercial mussel divers was assessed on four occasions: October 14th, 2008; July 21st, 2010; August 16th, 2010; and July 14th, 2011. All harvested mussels were sexed by the fisher at the time of processing, and measured to the nearest millimeter along the hinge by Marine Resources personnel, in accordance with the protocol described in Sarkis 1991, in order to produce sex-specific size-frequency histograms. The mussels sampled on these occasions were harvested from three separate collection sites. Mussels harvested on October 14th, 2008, and July 21st, 2010, were collected from the area near the Harrington Sound post office, in the vicinity of our site PO. Mussels harvested on August 16th, 2010, were collected in the vicinity of Patton's Point, near site R13 but just outside of the closed area. Mussels harvested on July 14th, 2011 were collected from the area around Abbott's Cliff, in the vicinity of site AC. This provides for an element of temporal and spatial comparison.

Surveys of the abundance and distribution of mussels in Harrington Sound

As an initial assessment of the mussel population in Harrington Sound, the six sites from the 1988 survey (squares in Figure 1), along with two sites where commercial mussel divers are known to harvest (circles in Figure 1), were visited on August 20th 2010. These sites were evaluated using snorkel or SCUBA depending on the depth. Sites DH, PO, R13 and T1 were in water 5-7 m deep (15-20 feet), and were surveyed on snorkel. Sites J8, O9 and B1 were 10-13 m deep (30-40 feet) and site N35 was 16 m deep (53 feet), so these sites were surveyed using SCUBA. Depth, substrate type and a qualitative visual assessment of mussel abundance and distribution were recorded for each site. Mussels were categorized as abundant, uncommon, rare or absent, and distribution remarks noted whether the mussels were attached to rocky substrate, on soft bottom or a combination of the two.

Based on this initial assessment of the sites, two sites were selected for further investigation of mussel density and population structure in 2010. On August 25th, 2010, more detailed population surveys were conducted at one site where harvesting is known to occur (PO) and a second, slightly deeper site which is theoretically open to harvesting but is beyond the depths at which free-divers can actively collect (J8). Following the sampling of commercial catch from the Abbotts Cliff area in the summer of 2011, on October 21st, 2011, additional detailed population surveys were conducted in the Abbott's Cliff area (site AC) and also at site O9 from the 1988 survey. Site O9 was included to provide a comparison from an area that had, at least in principle, been closed to commercial fishing for 38 years.

At each of these four sites, 5 x 1 m^2 quadrats were haphazardly placed at 5 - 6 m intervals along a transect line, and all mussels within the quadrat were collected and placed in individually numbered storage bags. The number of mussels in each quadrat was counted in order to calculate an average density per square metre for each site. Bycatch species associated with the mussel bundles were recorded at this time. The mussels from each site were then pooled, steamed and opened, sexed and measured in order to provide a size-frequency histogram for the population at each site. In some cases, it was not possible to determine the sex of a mussel because the gonad was damaged during opening. These mussels were included in the density estimates, but were not included in the size-frequency histogram. Obviously immature mussels, with intact flesh and no visible gonad, were recorded as such and are presented separately in the histograms. There were some individuals from the sample in October, 2011, where a gonad was present but sex could not be determined and these were recorded as unknown and included with the immature individuals.

Investigation of pallial lines relative to size

The pallial lines visible on the internal surface of 50 shells of varying size were counted in order to relate this presumed proxy for age to the hinge length of the shell, since this is the measurement generally used to construct size-frequency histograms. To investigate pallial line deposition, a sub-sample of shells were selected for sectioning (described in Neves & Moyer 1988). Shells were filled with epoxy resin, and small shells were embedded in blocks of epoxy resin using a mould. Once set, shells were cut twice using a diamond-bladed low power saw through the umbo and along the direction of maximum growth in order to acquire a 1 mm thick slice of shell appropriate for aging. Slices were fixed onto slides for microscopy using Crystalbond thermoplastic cement. Once set, slices were polished on a rotary polishing wheel using alumina powder on felt polishing cloth. Slices were examined and photographed under a low power dissecting microscope, and also examined under a high power compound microscope.

Results

Structure of the harvested population

On October 14th, 2008, 203 mussels were harvested from the vicinity of Harrington Sound Post Office by one of the commercial mussel divers. Mussels collected from this site ranged in size from 21 mm hinge length to 76 mm hinge length, with a mean hinge length of 51.6 ± 0.7 mm and a mode covering the 50 mm and 60 mm size classes (41 – 60 mm). This sample was comprised of 185 male and 18 female mussels, as identified by the fisher at the time of processing, suggesting that males dominate this area by a ratio of approximately 10:1. When the histogram is constructed for males and females separately (Figure 2), the mode for the males remains at 41 – 60 mm, but the modal class for females is 61 – 70 mm. Mean size was 50.2 ± 0.7 mm for males and 65.7 ± 1.0 mm for females. In examining the extremes of the distribution, no immature individuals were identified in this sample but 20.7 % of individuals were larger than 60 mm, the upper limit of the mode.

On August 16th, 2010, 390 mussels were harvested from the vicinity of Harrington Sound Post Office by the same commercial mussel diver. Mussels ranged in size from 20 mm hinge length to 71 mm hinge length, with a mean hinge length of 52.0 ± 0.4 mm, and the mode once again covered the 50 mm and 60 mm size classes (41 – 60 mm). This sample was comprised of 287 male and 102 female mussels, as identified by the fisher at the time of processing, or approximately 2.8 males for every female. When the histogram is constructed for males and females separately (Figure 3), the mode for the males remains at 41 – 60 mm, and the modal class for females is 51 – 60 mm. Mean size was 50.9 ± 0.5 mm for males and 55.3 ± 0.7 mm for females. Only one immature individual was identified in this sample, much less than 1 % of the collection, and 15.1 % of individuals were larger than the modal classes.

On July 21st, 2010, 477 mussels were harvested from the vicinity of Patton's Point by the same commercial mussel diver. Mussels ranged in size from 20 mm hinge length to 71 mm hinge length, with a mean hinge length of 53.0 ± 0.4 mm, with a strong mode in the 60 mm size class (51 – 60 mm). This sample had a fairly equal sex ratio, with 247 male and 230 female mussels identified by the fisher at the time of processing. When the histogram is constructed for males and females separately (Figure 4), the mode for the males still covers the 50 mm and 60 mm size classes (41 – 60 mm), but the modal class for females is 51 – 60 mm. Mean size was 50.0 ± 0.6 mm for males and 56.2 ± 0.5 mm for females. This collection contained 5 immature individuals 15 – 19 mm in length, slightly more than 1 % of the total. At the other end of the size range, 16.4 % of individuals were larger than the modal classes.

On July 14th, 2011, 712 mussels were harvested from the vicinity of Abbott's Cliff by the same commercial mussel diver. Mussels ranged in size from 23 mm hinge length to 75 mm hinge length, with a mean hinge length of 47.8 ± 0.3 mm, with a strong mode in the 50 mm size class (41 – 50 mm). This sample also had a fairly equal sex ratio, with 328 male and 380 female mussels identified by the fisher at the time of processing. When the histogram is constructed for males and females separately (Figure 5), the mode for both males and females remains in the 41 – 50 mm size class. Mean size was 47.6 ± 0.4 mm for males and 48.3 ± 0.3 mm for females. This collection contained 4 immature individuals 8 – 19 mm in length, less than 1 % of the total. At the other end of the size range, 30.8 % of males and 32.4 % of females were larger than the modal class of the sample. However, only 4.0 % of individuals had hinge lengths greater than 60 mm.

Figure 2. Population structure of the commercial harvest collected near Harrington Sound Post Office (in the vicinity of site PO) on October 14th, 2008.

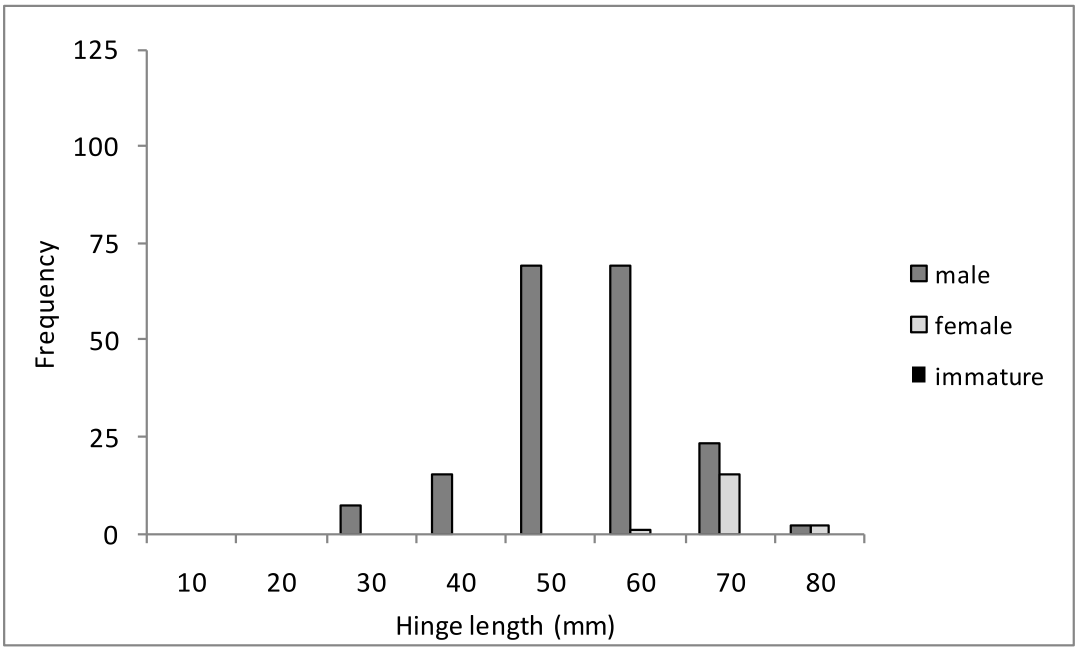


Figure 3. Population structure of the commercial harvest collected near Harrington Sound Post Office (in the vicinity of site PO) on August 16th, 2010.

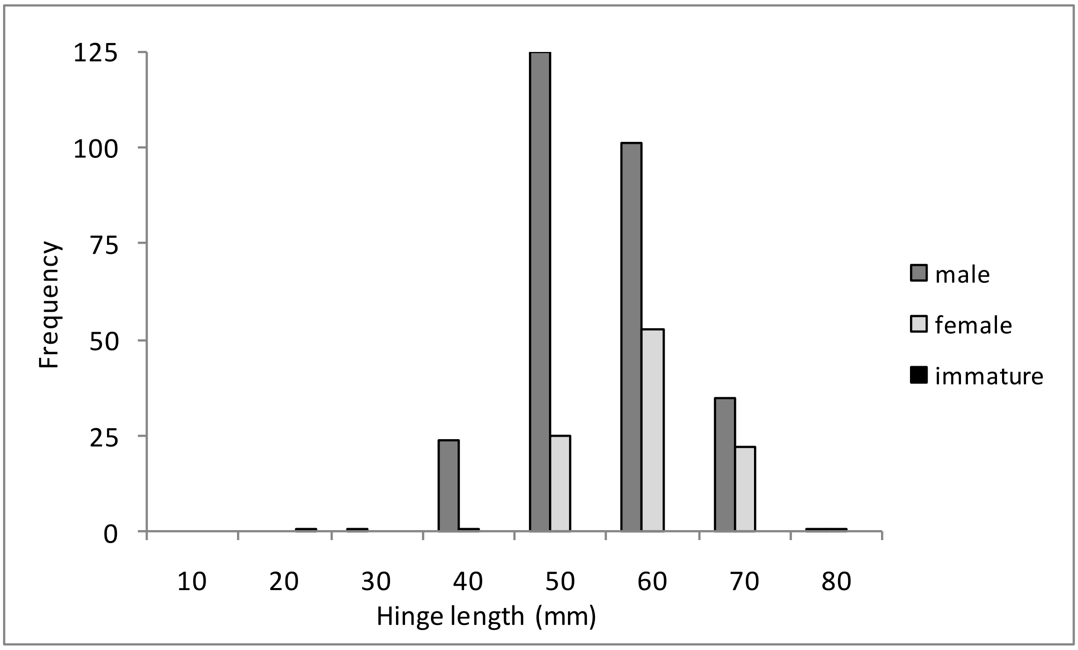


Figure 4. Population structure of the commercial harvest collected near Patton's Point (in the vicinity of site R13) on July 21st, 2010.

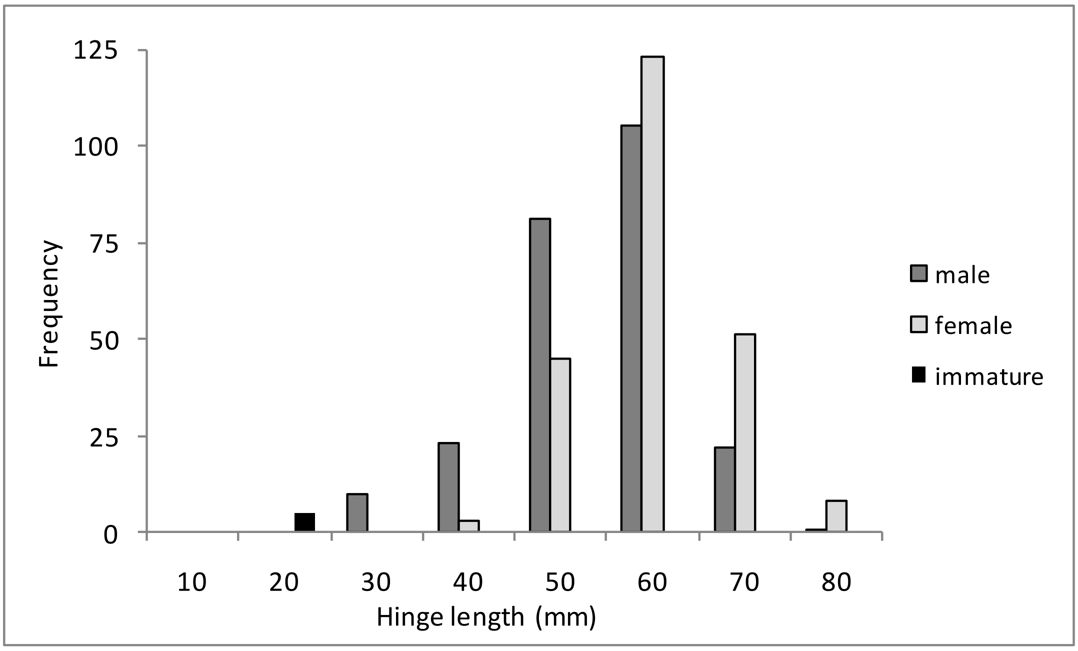
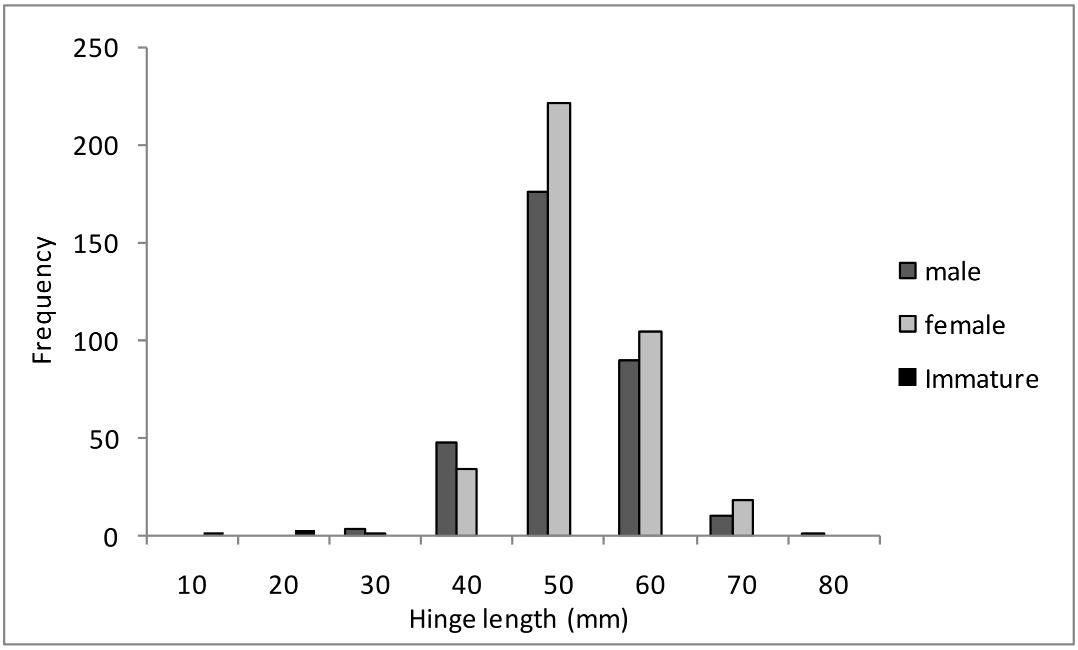


Figure 5. Population structure of the commercial harvest collected near Abbott's Cliff (in the vicinity of site AC) on July 14th, 2011.



Comparing the number of mussels measured when the harvest was sampled to the number of quarts reported by the fisher for that day, a qualitative estimate is that a quart equals approximately 212 mussel meats. The calculations for this estimate are shown in Appendix I, and an examination of these numbers illustrates how variable a quart may be. With the reported harvest averaging 276 quarts over the past four years, this translates to anywhere between 30,000 and 75,000 individual mussels being harvested annually by the two commercial divers.

Mussel abundance and distribution

During initial site assessments, sites T1, DH, PO and AC were found to be fairly similar, with fine to medium sand and some large rocks in water 15 to 20 feet deep (5 – 7 m). All of these sites are known to be heavily harvested by commercial divers. Some mussels were present, primarily attached to rocks where they were more difficult to access, and there were occasional small clusters on the soft bottom. The main difference among the sites in this group was that site PO was on a steep slope, with the mussels occurring in a relatively narrow depth band. Sites J8, B1 and O9 also formed a group, with fine sand on a flat bottom 30 - 40 feet deep (10 – 12 m). These sites were too deep for free-diving harvest and mussels were abundant, occurring in large clusters that were widely distributed on the soft bottom. Site O9 lies within the area that is officially closed to the commercial mussel divers, and was closed to dredging in the past. Small colonies (<35cm diameter) of the branching coral *Oculina spp.*, were relatively abundant this site, occurring at a density of two to three per m^2. Site B1 was distinctive in that it was on top of a flat, isolated mound, surrounded by much deeper water. Site R13 had medium sand on a flat bottom that was approximately 20 feet deep (7 m). This site lies on the edge of the area that is officially closed to the commercial mussel divers, and was closed to dredging in the past. However, no mussels were found in the area that was investigated. Site N35 was 53 feet deep (16 m), and was very silty with poor visibility. Large numbers of *Cassiopeia spp.* jellyfish were present on the bottom, together with some long dead mussel shells, and approximately 6 live mussels.

Table 1. Results of initial site assessment.

Site	Depth (m)	Substrate	Mussel abundance	Mussel distribution
R13	7	Flat, Medium sand	absent	-
O9	12	Flat, Fine sand	abundant	soft bottom
T1	5	Flat, Medium sand, rocks	uncommon	mostly rocks, some soft bottom
J8	11	Flat, Fine sand	abundant	soft bottom
B1	10	Isolated mound, Fine sand	abundant	soft bottom
N35	16	Flat, Silty	rare	soft bottom
DH	6	Flat, Fine sand	uncommon	mostly rocks, some soft bottom
PO	7	Steep slope, Fine sand	uncommon	mostly soft bottom, some rocks
AC	5	Flat, Fine sand	uncommon	some soft bottom

At site PO, a total of 57 mussels were collected from the 5 survey quadrats, and density averaged 11.4 ± 3.9 mussels per m^2. Mussels at this site ranged in size from 20 mm to 63 mm hinge length, with a mean hinge length of 47.7 ± 1.0 mm, and there was a strong mode in the 50 mm size class (41 – 50 mm). This sample consisted of 37 male and 19 female mussels, as determined by Marine Resources personnel, with males outnumbering females by a ratio of approximately 2:1. When histograms are constructed for males and females separately (Figure 6), the modal class for the males remains at 41 – 50 mm, but the modal class for females is 51 – 60 mm. Mean size was 46.6 ± 1.0 mm for males and 51.3 ± 1.3 mm for females. There was only one 20 mm long immature individual in this sample, representing less than 2 % of the individuals. Mussels larger than the modal class comprised only 5.2 % of the sample.

At site J8, a total of 295 mussels were collected from the 5 survey quadrats, and density averaged 59.4 ± 8.5 mussels per m^2. Mussels at this site ranged in size from 16 mm hinge length to 73 mm hinge length, with a mean hinge length of 46.3 ± 0.6 mm and a modal size class of 41 – 50 mm. Again, males outnumbered females by a ratio of approximately 2:1. When histograms are constructed for males and females separately, the modal class for the males remains at 41 – 50 mm, but the modal class for females is 51 – 60 mm (Figure 7). Mean size was 45.8 ± 0.6 mm for males and 52.0 ± 0.7 mm for females. The 16 immature individuals in this sample ranged from 16 mm to 31 mm hinge length and represent 5.4 % of the total number of individuals sampled. Mussels larger than the modal class comprised only 5.1 % of the sample.

At this site there were 7 mussels between the sizes of 27 mm and 34 mm whose gender could not be ascertained because of damage to the tissue. These individuals are included in the density estimate but not in the size-frequency histogram.

At site O9, a total of 259 mussels were collected from the 5 survey quadrats, and density averaged 52.2 ± 8.1 mussels per m^2. Mussels at this site ranged in size from 13 mm hinge length to 65 mm hinge length, with a mean hinge length of 41.4 ± 0.6 mm and a modal size class of 41 – 50 mm. Males and females were fairly equally represented in this sample (1.2:1), but there were 73 immature and unknown individuals, including 33 with hinge lengths > 30 mm. When histograms are constructed for males and females separately, the modal class for both sexes remains at 41 – 50 mm (Figure 8). Mean size was 44.3 ± 0.7 mm for males and 47.5 ± 0.8 mm for females. The immature and unknown individuals in this sample, which ranged in size from 13 mm to 45 mm hinge length, represented 28.2 % of the total number of individuals sampled. However, the 40 individuals ≤ 30 mm hinge length, a more typical size range for immature individuals, represented 15.4 % of the sample. Mussels larger than the modal class (> 50 mm) comprised 18.5 % of the sample, and included 17.0 % of the identified males and 36.0 % of the identified females. However mussels larger than 60 mm hinge length made up only 1.5 % of the sample.

At site AC, although several bundles of mussels were observed on the sandy bottom, only 3 mussels were present in the 5 sampling quadrats, a density of less than 1 individual per m^2. No further analysis was possible.

Figure 6. Population structure of the sample taken at site PO, near Harrington Sound Post Office, on August 25th, 2010.

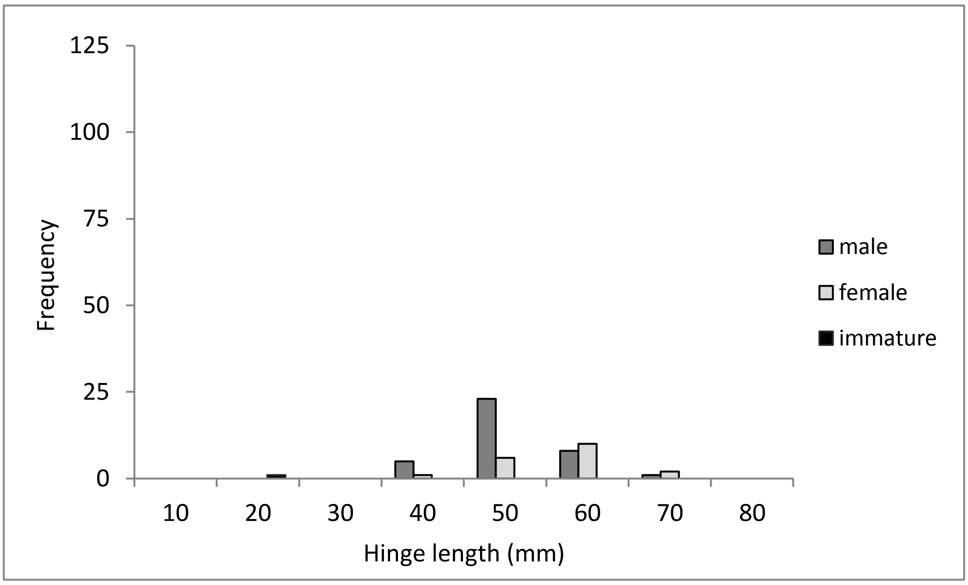


Figure 7. Population structure of the sample taken at site J8 on August 25th, 2010.

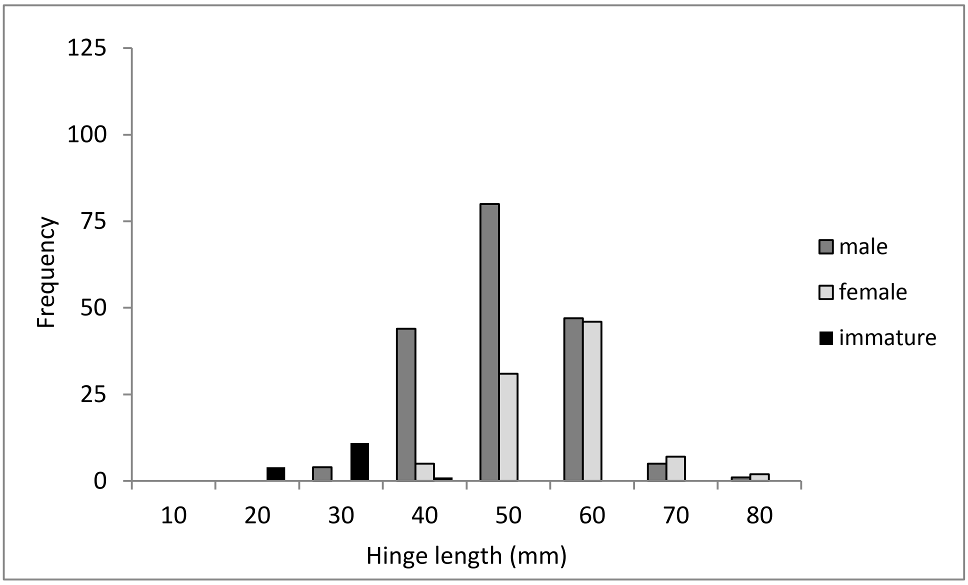
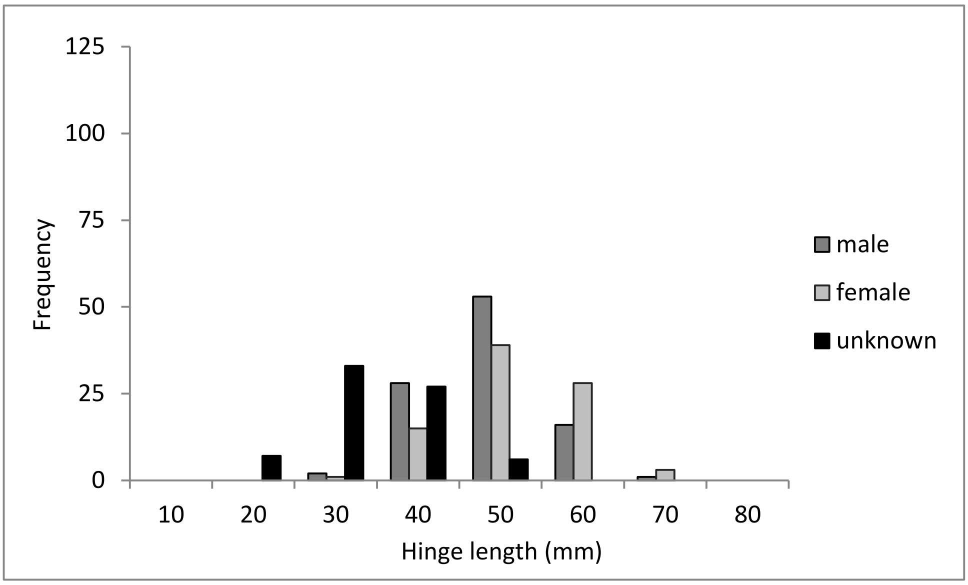


Figure 8. Population structure of the sample taken at site O9 on October 21st, 2011.

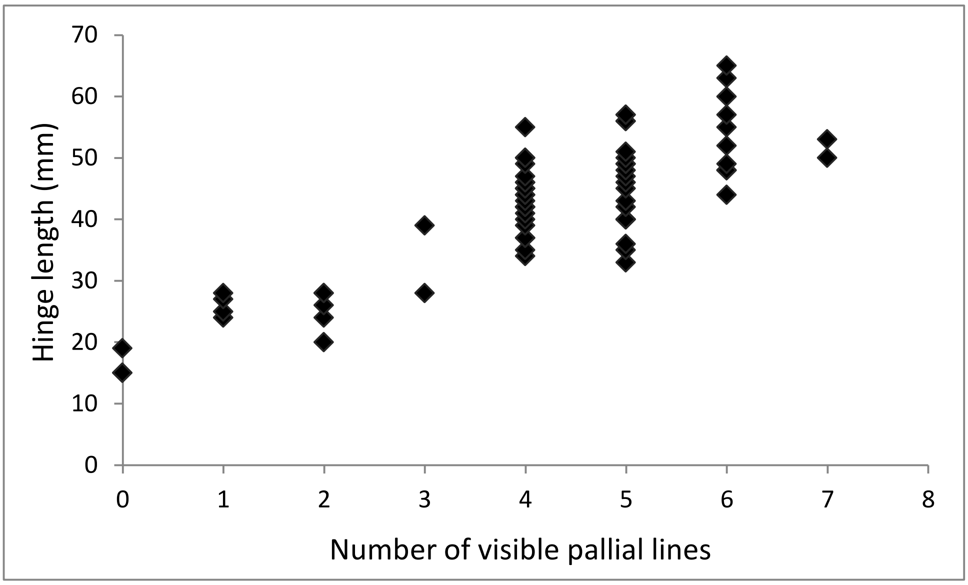


Bycatch organisms were recorded qualitatively but not quantified. The species most commonly associated with mussel bundles were worm snails, whose shells often provided an attachment substrate for the mussels, chicken liver sponge (*Chondrilla nucula*), and flat tree-oysters (*Isognomon alatus*). Small colonies of the hard corals *Siderastrea radians*, *Isophyllia sinuosa*, *Oculina spp.* and *Agaricia fragilis* were also frequently found attached to the mussel shells. Other attached organisms included a variety of other sponges (at least three different types), tulip mussels (*Modiolus americanus*) and cherry clams. Small gobies and spider crabs were also found among the bundles. All of these organisms would have been removed from the environment along with the clumps of mussels during the standard free-diving harvesting technique. Overall, however, collateral damage appeared low when mussels were collected in bundles from soft bottom habitats.

Investigation of pallial lines relative to size

The number of pallial lines visible on the inner surface of the mussel shells were poorly correlated with the size of the shell, as measured by the length of the hinge. Shells with the same number of pallial lines came in a wide range of sizes, and the size ranges were largely overlapping, such that shells with 4 pallial lines ranged in size from 34 mm to 55 mm while shells with 5 lines ranged from 33 mm to 57 mm (Figure 9). Pallial lines were less distinct and less visible in shells with hinge lengths greater than 60 mm. Further, pallial lines were often less easy to distinguish in the shells of female mussels. Microscopic examination of shell slices showed that early dark pallial lines were often covered over by additional secreted material in larger individuals, but that shells where outer lines were indistinct often did not have visible internal lines either. Transmission light microscopy showed the presence of varying numbers of thin white and translucent bands in between the darker pallial lines.

Figure 9. Relationship between hinge length of the shell and the number of pallial visible on the inner surface of the mussel shell.



Discussion

The annual commercial harvest currently averages 276 quarts, the equivalent of approximately 73,000 mussels. This compares to over 500,000 mussels being harvested annually by the dredge fishery in the 1970s, and is approximately 15 % of these historic harvest figures.

The size ranges and means for the 2008 – 2011 harvest samples and in situ surveys are similar, with means of approximately 48 – 53 mm in the harvest samples and 41 – 47 mm in the survey samples. The difference is a reflection of proportionally fewer very large individuals and, to a lesser degree, more small individuals in the survey samples. The sample with the smallest mean size was the survey sample at site O9 in October, 2011, and this was strongly influenced by the 40 individuals that were < 30 mm hinge length, a reflection of new recruits to this site during the preceding summer.

The free-diving harvesting technique depends on collecting the ‘bundles’ of mussels quickly, so there is no opportunity to select against smaller individuals, but the scarcity of small individuals in the harvest samples could be attributed to loss during processing. In any case, with the exception of the October, 2011, sample from site O9, small individuals were rare to absent in both the samples of landed harvest and most of in situ surveys, generally making up less than 5 % of sampled individuals. However such small individuals comprised up to 9 % of sampled individuals during the 1988 survey. The timing of the O9 sample in October meant that individuals recruited that summer would be included in the sample. The unusually high number of recruits in this sample may reflect overall strong recruitment in Harrington Sound during the summer of 2011 or strong recruitment at this site. Recruitment at site O9 could be enhanced by the high density of adults there, and this could operate via several mechanisms. The healthy adult population is presumably a good source of larvae, which could lead to enhanced recruitment if the larvae are retained in the immediate area. Alternatively, dispersed larvae from individuals throughout Harrington Sound might be attracted to the area by the presence of these adults or it may simply be that the large numbers of mussel shells present provide an abundance of suitable settlement substrate.

The scarcity of large individuals in the survey samples is also noteworthy. Individuals larger than the modal size classes (>60 mm) made up 15 – 20 % of the harvest samples, but only about 5 % of the survey samples. A possible explanation might be that the shallower areas where the commercial divers harvest were not impacted as heavily by the dredging activities in the past, resulting in greater numbers of older individuals at these sites relative to previously dredged areas such as site J8. Site PO was sampled under both protocols however, with proportionally fewer large individuals present in the survey samples. Although as the survey sample was taken after three summers of heavy harvesting in this area by at least one of the commercial divers, it is perhaps not surprising that large individuals were scarce. The modal classes in the samples from 2011 are slightly smaller than the modes from the samples taken at other sites in previous years, and there appear to be fewer large individuals. However, without samples from all areas in all years, it is not possible to determine whether this is indicative of a decline in mean size of individuals within the time frame of the study or of differences between the different areas of Harrington Sound.

These figures compare to typically smaller mean sizes of 35 – 46 mm found in the 1988 surveys, with the exception of site N35 which had a mean size of 64.6 mm (Sarkis 1991). However, it was noted at the time that site N35 had a very low density of 3 mussels per m^2 and an absence of smaller individuals, such that it appeared there had been no recruitment in the area for some time (Sarkis 1991). This site is comparatively isolated in the northeast corner of Harrington Sound and, assuming that the correct location was found, hardly any mussels were found here during the 2010 survey.

The distribution of mussels observed in 2010 and 2011 varied greatly from that found in the 1988 survey, and the current forms of harvest activity appear to influence this. Mussels were uncommon at shallow sites within the depth range of free-diving commercial, and presumably also recreational, harvesters (sites T1, PO, DH and AC). Site T1 was the only one of these sites surveyed in 1988. Assuming densities at the first three sites were comparable to the 11 mussels per m^2 found at site PO, this represents little change from the density of 8 mussels per m^2 found at site T1 in 1988. The very low density of mussels at site AC in October is likely related to the large number of mussels recorded as being harvested from this area earlier in the summer. The area is also known to be popular with recreational harvesters, and the licensed fishers have complained that some of those harvesting in this area are selling their catch illegally. As a result, mussels appear to be particularly heavily exploited in the Abbott's Cliff area.

In contrast, mussels were abundant at the group of sites that were 30 – 40 feet deep, beyond the range of the free-diving harvesters (site O9, J8 and B1). The density of 59 mussels per m^2

found at site J8 in 2010 is greater than that found at site R13 in 1988 (49 mussels per m^2), in the area that was closed to dredge harvesting. Even though site O9 was officially closed to harvesting in 1988, it may have been subject to edge effects as the density of mussels there was similar to that at the dredged sites. The density of 52 mussels per m^2 at this site in 2011 represents a significant increase from the densities of between 6 and 13 mussels per m^2 found at this site and similar sites in 1988. In contrast, current investigations in the vicinity of site R13, theoretically still protected from commercial harvest, failed to locate any mussels.

The comparisons between the current and historical data are limited by the low resolution available in the site location map for the 1988 survey, on which Figure 1 is based, and latitude and longitude co-ordinates are not available. Further work is needed to confirm the locations of the original sites R13 and N35 in order to properly evaluate the apparent changes in these areas.

There is a suggestion of gender-dependent size structure in the turkey wing mussel population, with males dominating smaller size classes and females being more abundant in the larger size classes. In addition, in some samples, males outnumbered females by a ratio of 2:1, or more, although other samples displayed a fairly even sex ratio. Although there are several ecological and ecotoxicological models that might explain such a phenomenon, it may be simply that the gonads of smaller individuals are generally paler and rapid visual assessments are biased towards identifying them as males. The sparse and temporally variable sampling effort in this study has hindered our ability to investigate this further. Additional investigation during the reproductive season when the gonads are most distinct would help elucidate this, but cannot be justified at this time due to limited resources. If these patterns can be confirmed, the use of techniques to investigate gonad structure and sex-specific growth rates in this species is worth considering.

These data indicate that there has been a substantial recovery of mussels in the deeper areas of Harrington Sound over the 18 years since dredging activities ceased, although slow growth after maturity means that large individuals are still scarce. Heavy harvesting by divers at shallower depths is keeping numbers low in these areas. In theory, mussels in the deeper areas would serve as a source of larvae and new recruits for the whole of Harrington Sound. However, the low numbers of small individuals in most of the current samples may indicate that either reproductive or settlement success is being compromised.

Reproductive success might be compromised by the apparent scarcity of larger / older females as the population recovers from overexploitation, whereas settlement success might be compromised by scarcity of suitable substrate for attachment. The destruction of the *Oculina spp.* coral beds by the dredging activities has left few patches of this known substrate available for recruitment. Further work should include an assessment of how well these corals are recovering, and what role this may play in the current status of mussel populations in Harrington Sound. In addition, the tendency of larval mussels to settle onto the shells of conpecifics is being confounded by the removal of these shells when mussels are harvested. Although the shells of harvested mussels are usually returned to the water, this is done in the vicinity of the processing station rather than in suitable recruitment habitat where these shells might contribute to the settlement success of future generations of mussels.

Another consideration for the management of this fishery is that there are known problems with the harvesting of slow-growing species. Mussels are once again relatively abundant in Harrington Sound after 18 years without commercial scale exploitation, and current harvest levels reflect this. However slow-growing species require long periods of time to build up such levels of biomass, and generally are not able to replace individuals at a rate that can keep up with the rate of removal by harvesting. This usually leads to depletion of the resource. What is clear from the investigation of pallial lines and size is that the size structure of the mussel population in Harrington Sound cannot really be considered as truly representative of the age structure. Yet the use of pallial lines for ageing is very time-consuming. Further, validation of the timing and periodicity of the deposition of pallial lines in turkey wing mussels in Bermuda is necessary if this technique is to be applied with any meaning. Validation could be achieved by staining the shells of a number of individuals with one of several non-toxic bioavailable dyes used for this purpose, and then maintaining these individuals in situ in cages for a set period of time. The presence of pallial lines relative to the dye marks would then illustrate the periodicity of deposition. Such a validation of the periodicity of pallial lines in the shells of *Arca zebra* could contribute valuable information on the age structure of this stock and the growth rate of this species in Bermuda waters. Application of these methods to specimens from throughout Harrington Sound would clarify whether local conditions have differing effects on mussel growth in different parts of the Sound. Such information would provide needed insight into the risks associated with exploitation of this population.

Conclusions and Recommendations

Although mussels are more abundant in the 30' – 40' depth range than they were in 1988, low densities of mussels are found in the shallower areas of Harrington Sound where commercial and recreational mussel divers harvest. If the commercial mussel fishery is to be limited to free-diving harvest, this fishery is fully exploited at present.

It is recommended that there be no further entries into the commercial mussel diver fishery at this time.

There is no information on the level of recreational harvest, although it is suspected to be fairly high in shallow areas, particularly in the intertidal zone. There have been some complaints about the quantities of mussels being taken by some recreational harvesters, and the possibility that these mussels are being sold illegally has been raised. More data on this aspect of the fishery is therefore required.

It is recommended that a daily bag limit for recreational harvesters be established. This could be done in conjunction with a licensing scheme. The potential benefits of additional spatial restrictions should be investigated.

As a short-term, experimental measure, it is suggested that the commercial mussel divers be asked to return empty mussel shells to the areas they were collected from in order to boost the amount of hard substrate available as an attachment surface for new recruits.

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Appendix I

Table showing calculations for the estimated number of mussels per quart, based on the number of mussels counted during sampling and the number of quarts reported for that date by the fisher.

Date	Mussels counted	Quarts reported	Mussels per quart
14 – Oct - 08	203	1	203
21 – Jul - 10	477	3	159
16 – Aug - 10	390	3	130
14 – Jul - 11	712	2	356
average			**212**

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