NATURAL RESOURCES

Technical Report

Ghost shrimp: commercial harvest and gray whale feeding, North Puget Sound, Washington.

June 16, 2016

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Peter Goldmark - Commissioner of Public Lands

Cover Photo: Ghost shrimp photo credit: Joe Smillie.

Ghost shrimp and gray whale feeding: North Puget Sound, Washington

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EXECUTIVE SUMMARY

The Washington Department of Natural Resources (DNR) manages 2.6 million acres of aquatic land in Washington State. DNR is challenged with determining if the commercial harvest of shrimp (*Neotrypaea californiensis*) (also referred to as burrowing shrimp or sand shrimp) is affecting the yearly feeding on these shrimp by the spring resident population of gray whales (*Eschrichtius robustus*) in Puget Sound's Whidbey Basin. Every spring, during an annual migration from warm birthing waters in the Gulf of California to feeding waters in the North Pacific, a subset of the gray whale population (annual average ~ 10 individuals) stopover in Whidbey Basin to suction feed on benthic invertebrates (Calambokidis 2010, Calambokidis et al, 2002). Burrowing ghost shrimp are thought to be a main food source for the whales during this stopover (Weitkamp et al, 1992). An investigation was conducted to estimate a standing stock of ghost shrimp (in number and biomass), as well as to estimate the quantity of ghost shrimp fed on by gray whales in Whidbey Basin. To measure the number of ghost shrimp fed on by the whales, whale feeding pit size was measured and 0.10 m diameter sediment cores were taken to 0.7 m depth to count density of ghost shrimp present inside and outside of those pits. Total feeding pit numbers were counted from May, 2015 (corresponding to whale feeding season) with low tide aerial imaging. Shrimp densities per square meter were assessed at twelve different sites, classified into one of three categories:(1) 'whale feeding', (2) 'commercial harvest', and (3) 'no whale-no harvest' sites. All shrimp found were collected, brought back to the laboratory and preserved by freezing. Carapace length, total length, sex, and wet weight were recorded for all samples. Estimated stocks were compared to commercial harvest data from the past five years. Comparisons between estimates of the total stock of ghost shrimp available to gray whales, and the number of shrimp taken yearly by harvest and whale foraging were explored. Results indicated that neither shrimp density nor biomass were significantly different across the three site types. Annual whale feeding and harvest combined account for only a small portion of the total shrimp stock available.

1 Introduction

The ghost shrimp *Neotrypaea californiensis* is a benthic crustacean that inhabits sandy substrates of North American Pacific coast estuaries. These shrimp construct complex burrow systems up to 70 cm deep in the mid to low intertidal zone of the beach. As vigorous bioturbators they turn over the sediment regularly, often making the beaches where they reside soft and soupy. These elaborate burrows contain multiple turnarounds and openings, the number of which varies seasonally (Griffis and Chavez 1988). The shrimp can live up to ten years or more (Cassidy 2008), are deposit feeders, and reside post planktonic larval phase in their burrows for their entire lives (MacGinitie 1930). Larval recruitment and settling in Washington and Oregon estuaries occurs in late summer/early fall (August to October), after a larval planktonic period of 6-8 weeks in mid-summer (Dumbauld, et. al. 1996).

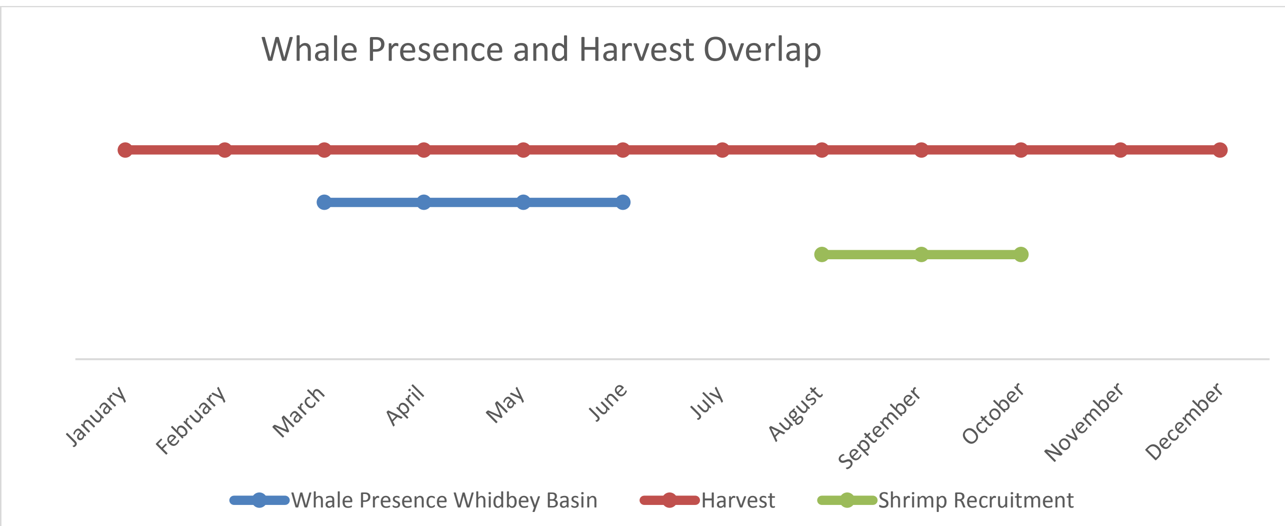

Figure 1. Timeline indicating approximate time gray whales, harvest operations, and ghost shrimp larval recruitment occurs in Whidbey Basin, Puget Sound

Each year, gray whales complete one of the longest known migration of any mammal. They travel over ten-thousand miles round trip from their birthing grounds in the Gulf of California, to their feeding grounds in the Arctic. Halfway through this migration, from approximately the last week of February to the first week in June, gray whales travel down the Strait of Juan de Fuca, (the Strait that forms the border between Canada and Washington State), into the Whidbey Basin to suction feed on benthic invertebrates (Figure 1). Ghost shrimp are thought to be a main food source for the whales over this time period (Weitkamp et. al., 1992). At high tide, the whales come in very close to shore, turn over on their side, and suction feed for invertebrates in the sediment. Suction feeding involves sucking up benthic material, and straining the material through baleen plates to expel fine particles (Nerini 1984). Evidence of feeding can be identified by shallow oblong depressions or "feeding pits" on the beach. These pits are anywhere from two to four meters in diameter, ranging from ten to thirty cm deep and remain on the beach for days to weeks of time. Pits are numerous and densely patterned enough that they are easily identified at low tide –even from aerial photos (Figure 2).

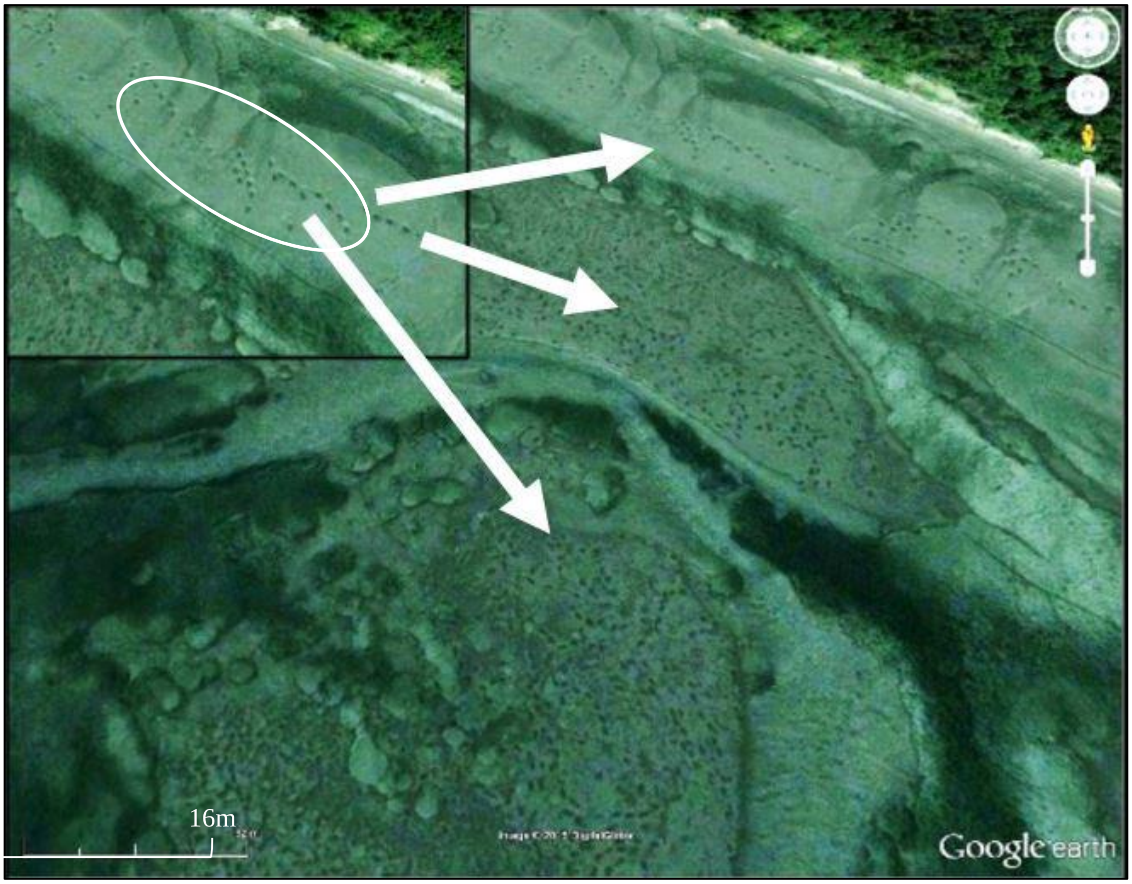

Figure 2. Aerial image of Snohomish river delta at low tide, May 2015. Arrows indicate gray whale feeding pits.

Along with being a main food source for transient gray whales, ghost shrimp are purchased as bait for recreational sturgeon and steelhead fishing along the West Coast USA. There is a commercial fishery in Washington State with harvest tracts in both Whidbey Basin and Willapa Bay. Harvest occurs year round, and is performed by liquefying tracts of beach from approximately zero mean lower low water (0 MLLW) to ordinary high water (OHW) by pumping seawater through a plastic PVC wand. Shrimp in the sediment float to the surface and are skimmed with a net. Harvesters provide monthly harvest logs to the Washington Department of Fish and Wildlife (WDFW). Harvest is constrained by the number of low tides in the year, and usually occurs on tides from 0 to -2 ft. (J. Linard, personal communication, October 14, 2015). Concern that gray whales were being impacted by commercial harvest prompted DNR to shut down all commercial ghost shrimp harvesting operations on state owned aquatic lands (SOAL) in April 2014 until an assessment of gray whale feeding could be made. In this study whale pits were observed no higher than the 0 ft. tidal line on the beach, and harvest occurs primarily above the -2 ft. tidal line, indicating that the area of competition is a relatively narrow strip of the beach from -2 to 0 ft. (Figure 3).

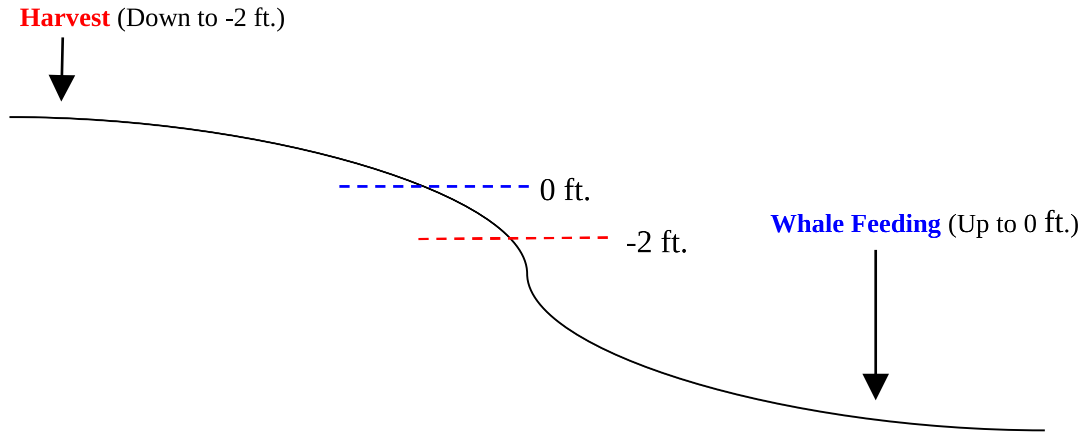

Figure 3. A cross-section of beach depicting whale feeding and shrimp harvest zones

The Tulalip Tribes also conduct shrimp harvest on beaches in Port Susan, and have continued harvesting their beaches throughout the moratorium on SOAL. Tribal and non-tribal harvest operations are relatively similar in size. Information regarding the stock of ghost shrimp in North Puget Sound and estimates of the quantity of shrimp that gray whales feed on is sparse. To our knowledge, the only study of gray whale feeding on ghost shrimp in Puget Sound was conducted and published by Weitkamp et al (1992). DNR's Aquatic Assessment and Monitoring Team (AAMT) was tasked with designing and implementing a study to determine the current total ghost shrimp stock available to both commercial harvest, and gray whales in Whidbey Basin. Study results would be used to make an assessment of the sustainability of commercial harvest in the region and inform management decisions.

For this study, we surveyed twelve separate beaches distributed around Whidbey Basin. Four of these beaches were previously authorized for harvest, three were beaches with gray whale feeding but no harvest present, and five were absent of both harvest and gray whale feeding (Figure 4). We hoped to survey equal replicates of the three beach types, but under further scrutiny, one of the whale feeding sites was classified as no whale no harvest beach. The area that gray whales fed on in 2015 encompassed 4 of the 5 state owned harvest leases in Port Susan. Focus sampling was also performed within and outside of feeding pits to estimate shrimp consumption by whales when surveying these twelve sites.

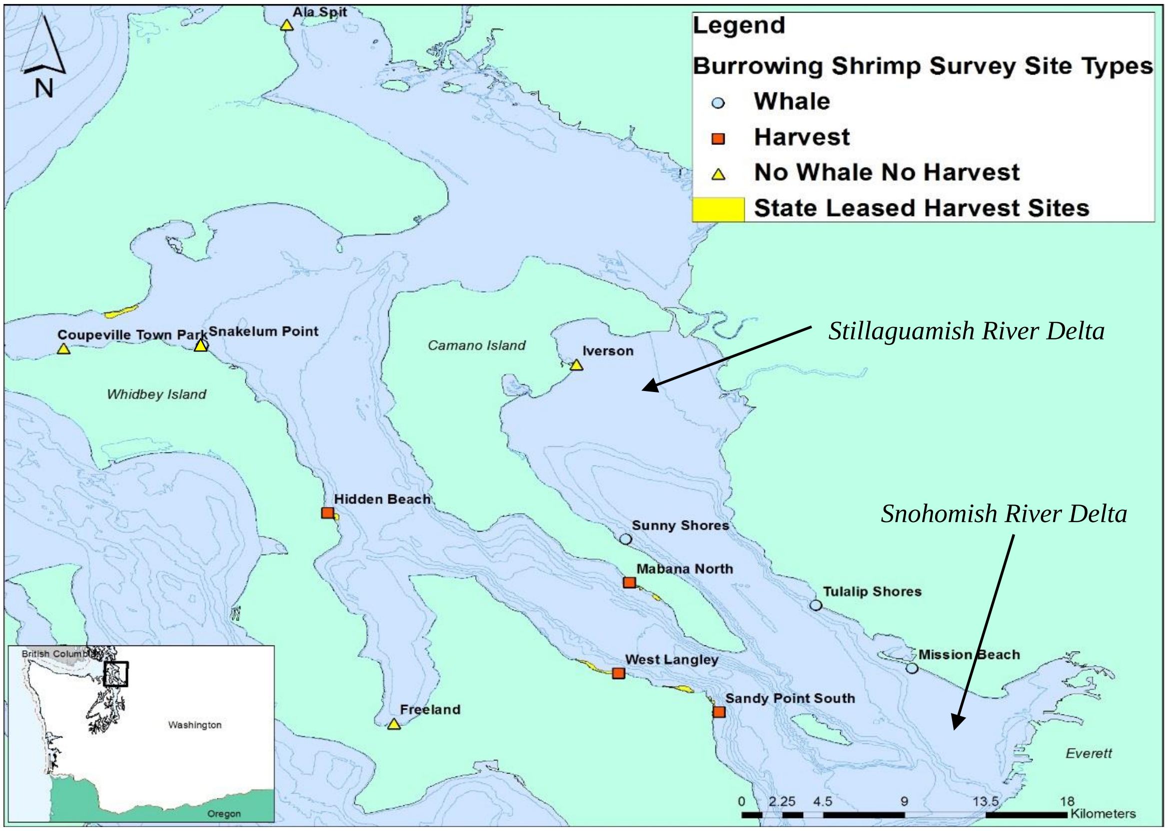

Figure 4. Map of Whidbey Basin indicating the twelve sites surveyed

1.1 Overall goal

Determine if total Whidbey Basin shrimp stock is sufficient for sustainable harvest and gray whale feeding

1.2 Specific objectives

1) Estimate total available shrimp stock available to gray whales.
2) Evaluate temporal distinction between gray whale feeding and harvest areas.
3) Estimate shrimp stock taken by gray whales and harvest.
4) Compare biomass estimates of ‘harvest’, ‘whale feeding no harvest’, and ‘no whale feeding no harvest’ sites in Whidbey Basin. Evaluate spatial distinction between gray whale feeding areas and harvest areas.
5) Resource management recommendations.

2 Methods

2.1 Assessment of ghost shrimp stock and distribution available

2.1.1 Population characteristics

All shrimp collected were frozen immediately and later measured for carapace length (mm), total length (mm), sex, and wet weight (g). Ovigerous females were noted as well as any shrimp with isopod parasites or lipid-like fatty deposits.

2.1.2 Ghost shrimp densities

Quantifying ghost shrimp densities involved several steps. Sites were designated into one of the three site types based on data collected by the volunteer-based whale observation groups; the Orca Network and the Washington State University (WSU) Beach Watchers. Representative sampling was conducted by manual coring at the reported high density sites. Follow-up liquefaction sampling of unit volume of sediment was conducted to calibrate the representative values obtained through manual coring.

2.1.3 Manual coring

Shrimp surveys were conducted March to May 2015, with the exception of Freeland Park which was surveyed in December. At all twelve sites, ghost shrimp densities were sampled along two transects that each measured three hundred meters (m) parallel to the shore. The lower transect was at the MLLW tidal line and the upper transect was spaced forty meters up (shoreward) on the beach. The point-intercept method of sampling was used, placing a one square meter quadrat every twenty five meters along each transect. Within each quadrat, a ten centimeter diameter, seventy centimeter long clam gun was used to core five haphazardly selected representative spots within the quadrat. Shrimp were separated from the sediment and any shrimp that floated to the water surface inside the cored hole were collected, bagged, and frozen. GPS points for each of the thirteen quadrat placements were taken with a handheld Trimble GPS unit.

The total number of burrows in each quadrat placement was recorded, as well as burrow system connectivity inside and outside of the quadrat. Burrow system connectivity was indicated by burrows that expelled water when moving the clam gun up and down in the sediment at a selected burrow opening. All burrows where water seeped out while moving the clam gun were counted, inside and outside of the quadrat, and recorded.

2.1.4 Liquefaction

To calculate a shrimp density estimate per beach area, the representative sampling core method was calibrated by counting all the shrimp present in a unit area of beach for a sub sample of sites using a liquefaction method. After the five standard cores were sampled within a quadrat, a 0.8m diameter core (0.5 m^2 surface area) was inserted 0.7 m into the sediment within the quadrat and water was pumped in until the sediment liquefied. The core was constructed with perforated sides so liquefied sediment flowed out while water was pumped in. Shrimp within the liquefied sediment in the core interior were too large to flow out of the perforated sides. Shrimp floated to the surface where they were scooped up, counted, and bagged for freezing. A total of ten haphazardly placed calibrations were performed, three at mission beach (whale feeding), three at Freeland park (no whale no harvest), and four at hidden beach (harvest). Calculated estimates of total shrimp per unit area were based on this regression.

2.1.5 Ghost shrimp biomass

Weighed shrimp were classified into four size classes: (Large > 6.9 g > Medium >2.4 g > Small >.63 g > Extra Small). These size classes were relevant because while whales are not likely to discriminate size of shrimp taken, commercial harvesters will predominantly focus on the larger two size classes (J. Linard, personal communication, October 14, 2015). Proportions of each size class collected from all sites were quantified. The four size classes found was similar to previous studies on population characteristics for *N. californiensis* (Dumbauld et al 1996, Bird 1982). The proportions for each size class from each site were applied to their related average mass (Large = 9.9 g, Medium = 3.8 g, Small = 1.0 g, and Extra Small = .23 g) to calculate total biomass. Biomass per square meter was then calculated based on the number of shrimp estimated using the relationship derived from the liquefaction calibration approach described above.

2.2 Mapping ghost shrimp distribution

2.2.1 Shrimp area per site delineation

The upper and lower boundaries of ghost shrimp burrows were delineated in the field at all twelve sites. Along each three hundred meter stretch of beach sampled, the upper boundary of ghost shrimp area was identified by a transition of substrate from sand/mud to shell/cobble and the abrupt absence of shrimp burrows. The lower boundary was demarcated when the continuous presence of the native eelgrass *Zostera marina* occurred, as ghost shrimp have been found to have a significantly lower density in seagrass (Castorani 2014). While walking along these upper and lower ghost shrimp area boundaries, points were recorded every ten meters with a handheld Trimble GPS unit.

2.2.2 Shrimp stock area available to whales in 2015

In addition to the directly sampled sites, the estimated extent of ghost shrimp stock area was delineated along shores of Whidbey, Camano, and Port Susan - where there was evidence that whales fed in 2015. Habitat delineation was accomplished by inspecting aerial imagery from May of 2015 – (the peak of whale feeding in Saratoga Passage). Whale feeding locations were clearly evident from obvious pits in the photos (Figure 2). At these locations, where it was evident the shrimp stock was available and utilized by whales, the lower edge; (characterized by either eelgrass, or the -10 ft. bathymetric line), and the upper edge; (identified by cobble, or where mud substrate merged into sand and gravel) were hand digitized. Characteristics of these upper and lower area bounds were consistent with ghost shrimp habitat at all sites surveyed in the field.

2.3 Estimate of shrimp biomass eaten by whales

2.3.1 Temporal feeding data

Orca Network sighting data from 2002 to 2015 was analyzed to determine the mean return and departure dates for whales to and from Whidbey Basin.

2.3.2 Whidbey basin whale feeding data

Gray whale feeding habitat in 2015 was designated using three different datasets:

1) *Scientific observation and tagged whales*. Cascadia Research Collective was contracted to tag a subset of whales with suction cup attached GPS - accelerometer enabled video cameras. Along with determining X, Y coordinates for the whales, the tags track the depth at which the whales are in the water column. Additionally, Cascadia Research personnel conducted dedicated boat surveys to observe and track the whales.
2) *Feeding pits evident in aerial images*. Whale pits around Whidbey Island, Saratoga Passage, and Port Susan were counted with use of 2015 aerial imagery. Using imagery and tools on Google Earth, polygons were made around all visible pit groupings from the upper limit of the pits to the tidal water level, where water started obscuring pits. It was assumed that the density of shallow underwater pits would be similar to the density of the pits counted in the visible, lower intertidal area. A density above the tidal line was determined per region, and this pit density was applied to the lower regions of utilized shrimp stock areas where water was covering and it was not possible to accurately count pits. The highest shoreward presence of pits indicated the shallowest areas the whales came into shore to feed.
3) *Orca Network sighting data categorized by gray whale behavior and location*. In regions where the water level was too high to observe pits in aerial images, Orca Network archives (2013-2015) were analyzed to identify sites where reported sightings documented feeding activity.

2.3.3 Surveys inside and outside pits

Whale pits are large, oval depressions (approximately 3 x 2 meters in size) in the surface of the low intertidal and subtidal beach (Figure 2). These features remain after gray whales have suction sieved sediment to feed on ghost shrimp. In the field, length, width and depth of each pit were measured, and sediment cores were sampled within and outside the whale pits. The same manual coring methods to estimate shrimp density as described above were applied to sampling within and outside of whale feeding pits. Five cores were sampled per square meter quadrat placed within then outside each pit. The number of quadrats sampled at each pit was limited by the particular size of each pit - an equal number of quadrats were made inside and outside each pit. The number of shrimp and shrimp biomass were calculated using the liquefaction vs. coring relationship. The total shrimp biomass (grams per square meter) eaten by gray whales in Whidbey Basin was calculated as the average difference biomass measured inside and outside of each pit extrapolated to the surface area of pits. The area of each pit was calculated as an ellipse given by the equation: $A = \pi(0.5W \times 0.5L)$, where W= width of the ellipse and L= length of the ellipse. This biomass per pit was then applied to the 2015 area estimate for the total number of pits in Whidbey Basin.

2.4 Estimate of shrimp biomass taken by harvest

2.4.1 Temporal harvesting data

Harvest intensity was estimated throughout the year by reviewing monthly WDFW catch records for both tribal and non-tribal harvest. Data included in the analysis was tribal data from 2010 - 2015, and non-tribal data from 2010 – Dec. 31, 2013.

2.4.2 Mean biomass harvested

Yearly commercial tribal and non-tribal ghost shrimp harvest data was provided by the Tulalip tribe and the Washington State Department of Fish and Wildlife (WDFW). The commercial harvest of ghost shrimp is reported to the WDFW in units of 'dozens of shrimp' collected. To determine biomass from this, the WDFW assigns an average measured weight per shrimp to the number of dozens reported. To avoid an overestimate of shrimp biomass, we used our community composition proportions of large and medium shrimp found at harvest sites surveyed to determine the total biomass harvested. As extra-small, and small shrimp are unlikely to be harvested (J. Linard, personal communication, October 14, 2015), we excluded these size-classes from the biomass calculation estimates. Because of the moratorium on non-tribal harvest in 2014/15, harvest data after Dec. 31, 2013 was not included in the calculation for mean yearly non-tribal harvest.

2.5 Comparison of available shrimp stock biomass and total biomass extracted

The five authorized harvest sites were delineated with Google Earth using shoreline coordinates, and specific areas were determined for each lease. This combined 'harvest area' was compared to the total estimated ghost shrimp area available to whales. Areas harvested by the Tulalip tribe were not available, but it is estimated that this harvested area is roughly the same as non-tribal. The total biomass of ghost shrimp reported taken by harvest from the past five years (both non-tribal and tribal harvest), and the amount estimated to have been removed by gray whales in 2015 was compared to the available stock estimated in all areas with gray whale feeding pits. Recommendations for ghost shrimp management are made after reviewing these findings.

3 Results

The results are presented in the same general order as the methods. First the population characteristics of all shrimp that were sampled from Whidbey Basin are presented. Next, calibration of manual coring to liquefaction, and resulting estimates for shrimp density and biomass are provided. Available ghost shrimp stock, and temporal and spatial patterns of whale feeding and harvest are presented. Finally, estimates of the total extracted shrimp stock are compared to the total available shrimp stock from all of Whidbey Basin.

3.1 Ghost shrimp stock and distribution

	Size classes burrowing shrimp			
Measurement	***Large***	***Medium***	***Small***	***Ex. Small***
Carapace length (mm)	20.26	14.58	10.41	6.16
Total length (mm)	80.90	59.00	39.49	22.40
Total mass (g)	9.92	3.77	1.04	0.21

Table 1 Weights and length measurements for the four distinct shrimp size classes across all sites

3.1.1 Population characteristics

Of 2383 Shrimp collected and measured from all sites, 1161 (49%) were identified as male, and 1215 (51%) were identified as female. 381 (31%) of those females were ovigerous. Fecundity increases with size, and females are ovigerous from April to August - eggs hatch from June to August. It is estimated the female ghost shrimp takes approximately four years (with a growth rate of 3.3 mm carapace length (cl) per year) to reach its most fecund age (Dumbauld et. al. 1996). In our study, 50% of all larger female shrimp (cl $\geq$ 13 mm) were ovigerous, and 46% of all smaller female shrimp collected (cl < 13 mm) were ovigerous.

Within 177 (7%) of all shrimp measured, a native parasitic isopod *Lone cornuta* was present. There is some evidence to suggest this parasite has been slightly reducing the ghost shrimp population along the outer coast of the Pacific Northwest over the past ten years (Dumbauld et al 2014). From all 2383 shrimp measured, 478 shrimp (20%) were large, 359 shrimp (15%) were medium, 1068 shrimp (45%) were small, and 459 (19%) were extra small. The total biomass of all 2383 shrimps collected was 8455 grams, with 5363 g (63%) large, 1519 g (18%) medium, 1400 g (17%) small, and 175 g (2%) extra-small shrimp. Harvest and whale feeding sites contained proportionally more medium, small, and extra small shrimp than the no whale no harvest sites, where shrimp were primarily all large (Figure 5). Although the total number of shrimp were less at the no whale-no harvest sites, the greater proportion of large shrimp explains the finding of no significant difference in total biomass among sites.

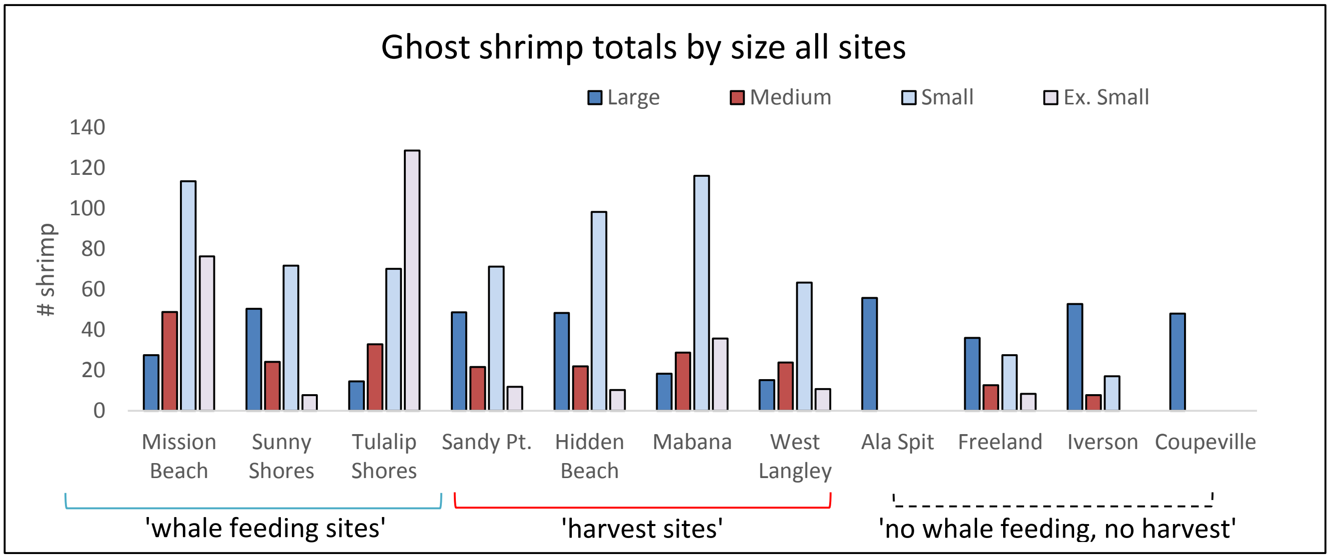

Figure 5. Size distribution per square meter

The relationship between representative manual coring and total count liquefaction is represented in the plot below (Figure 6). y = 6.08x + 21.86 with an r2 value of 0.77 indicating a fairly strong correlation between our manual coring methods, and the total amount of shrimp within 0.5 m^2 area of beach surface.

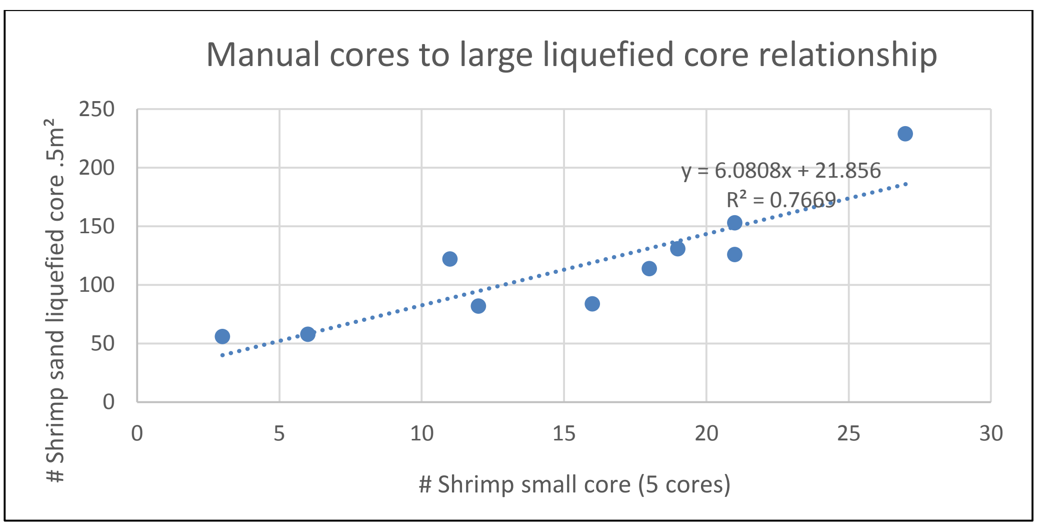

Figure 6. Relationship in shrimp counts between manual coring and liquefaction methods

3.1.2 Shrimp density

Twelve sites were surveyed; three whale feeding, four harvest, and five no harvest-no whale feeding. Whale feeding sites had the highest shrimp density with a calculated average of 222 shrimp/m^2 ± a standard deviation (SD) of 49. Harvest sites had a slightly lower average density, with an average of 161 shrimp/m^2 ± SD 32. No whale-no harvest had the lowest density, averaging 71 shrimp/m^2 ± SD 16 (Figure 7). While significant differences were detected between 'whale feeding' and 'no whale-no harvest' site densities as well as between 'harvest' and 'no whale no harvest' sites, no significant difference was detected between harvest and whale feeding site densities using the t-test statistic with unequal variance $p < 0.5$.

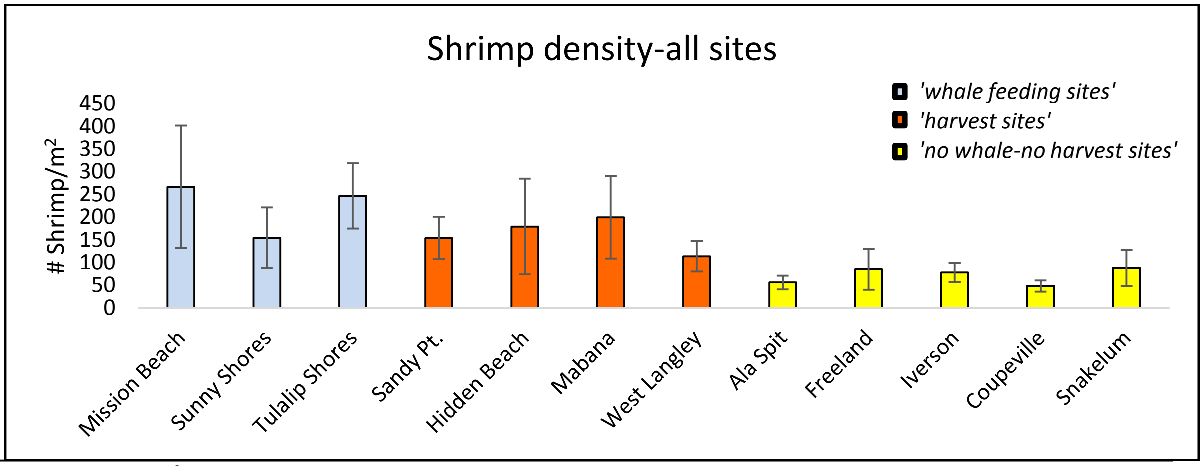

Figure 7. Density of shrimp (# shrimp m2). Error bars indicate standard deviation

3.1.3 Shrimp Biomass

Biomass averaged across the three site types for whale no harvest, harvest, and no whale no harvest were respectively 543 g/m^2 ± SD 1.28x10^5 g/m^2 ± SD 98, and 559 g/m^2 ± SD 158 (Figure 8). There was no significant difference between any of the site types with a single factor ANOVA $p < .05$.

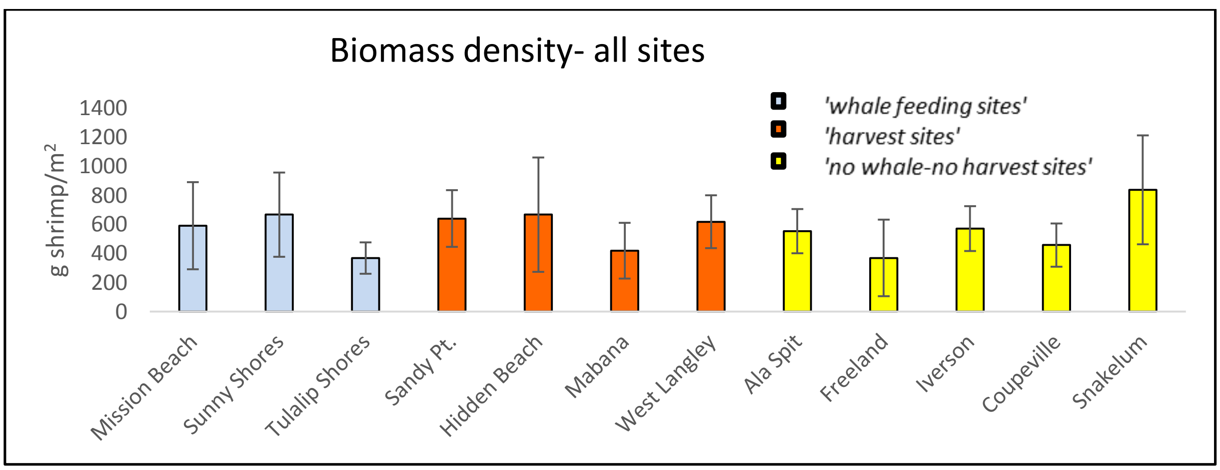

Figure 8. Average estimated biomass density (g/m2). Error bars indicate standard deviation

3.1.4 Shrimp area per site delineation

The average shrimp area for all 300 m sections of field sample sites mapped was 3.6x10^4 m^2 ± a standard error (SE) of 7,998. Iverson Spit had the greatest shrimp area, at 1.2x10^5 m^2 - this was likely due to its low, shallow slope in N. Pt. Susan, located on the leading edge of the

Stillaguamish River delta. Coupeville Town Park had the smallest shrimp area of any site, at 1,017 m^2.

3.2 *Whale feeding*

3.2.1 Shrimp area available to whales in 2015

For 2015, shrimp stock area used for feeding by gray whales was split into five different regions; 1) East Port Susan, 2) West Camano Island, 3) the Snohomish river delta, 4) SE Whidbey Island, and 5) Sandy Point Whidbey Island (Figure 9). During their time in Whidbey Basin in 2015, whales were observed feeding extensively off of the Snohomish River Delta. Satellite imagery of the delta also showed the majority of whale pits here (Figure 9). This region provided the largest extent ($1.0x10^7$ m^2) of shallow whale feeding grounds. The total available shallow (down to -10 ft.) shrimp stock area from all five regions, excluding harvested sites with whale feeding in 2015 was calculated at $1.7x10^7$ m^2. When including additional northward regions, where whales fed in the past 3 years, utilized shrimp stock area increases to $1.9x10^7$ m^2.

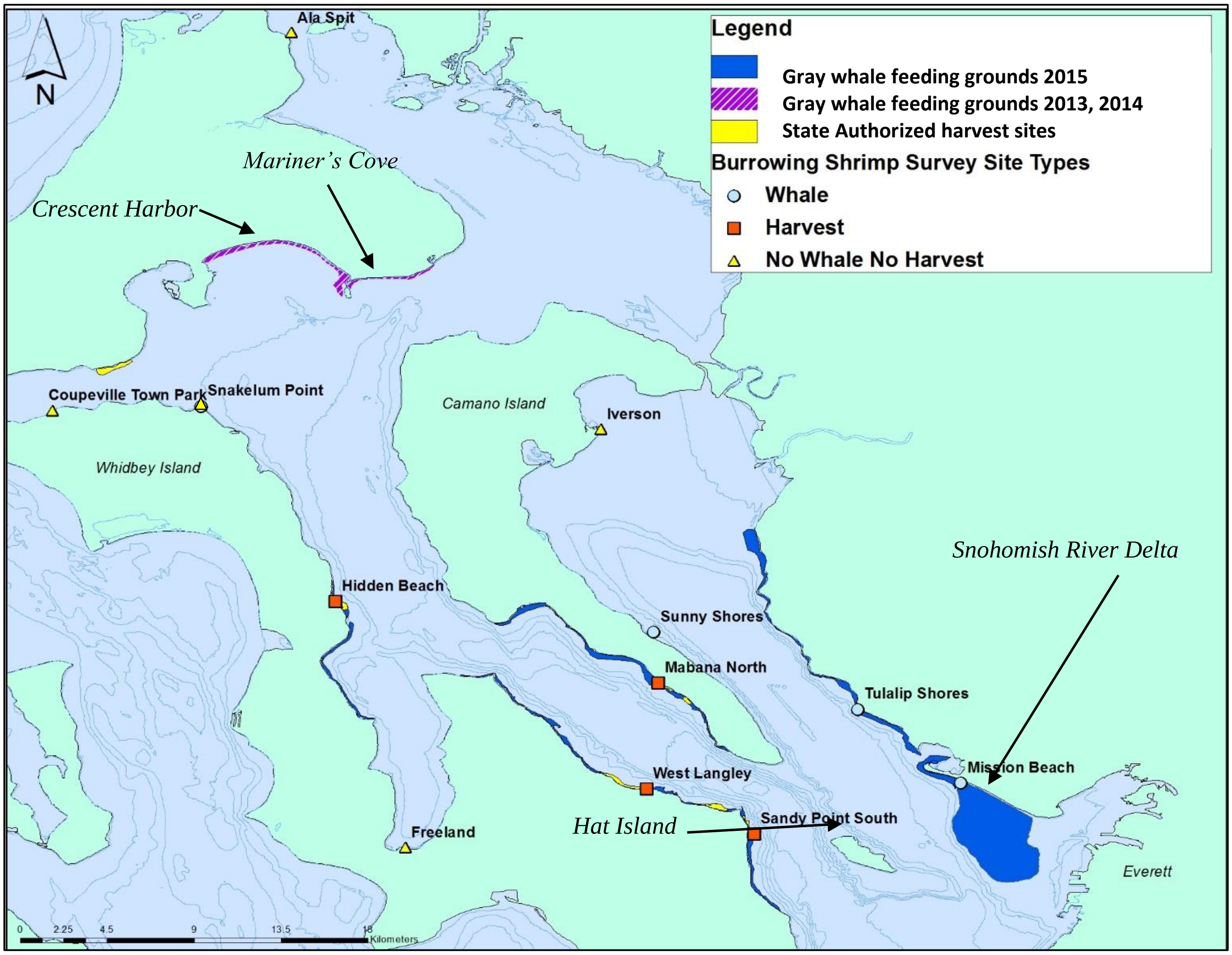

Figure 9. Whale feeding grounds, harvest areas, and shrimp sampling sites. Feeding areas indicated for 2013 and 2014 are in addition to the 2015 feeding areas.

3.2.2 *Temporal feeding data*

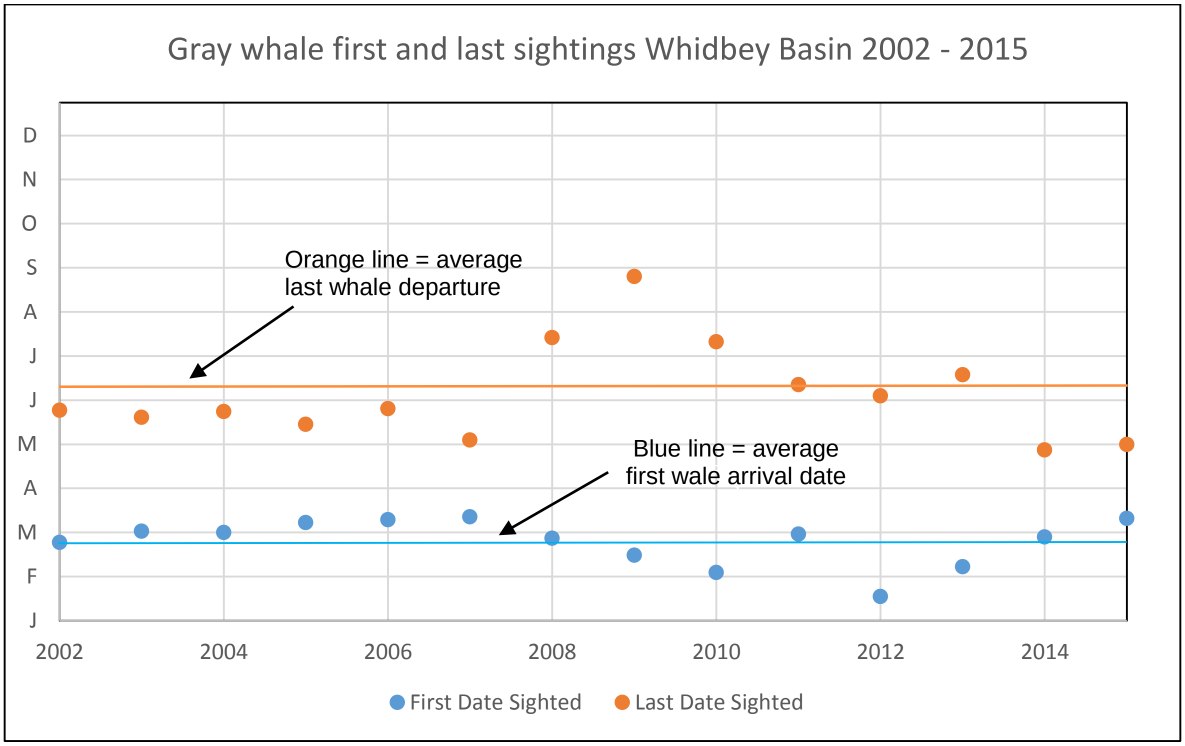

Figure 10. Timing of first and last individual gray whales sightings, Orca Network Data 2002-2015

From the Orca Network sighting data going back to 2002, the mean date of the first whale sighting is February 25, with a standard deviation (SD) ± 16 days. The mean date the last gray whale sighting occurs is June 8 ± SD 33 days (Figure 10). The average amount of time spent in northern Puget Sound is 104 days ± SD 44, with the longest amount of time, 196 days, spent in 2009, and the shortest in 2015, at 52 days. There also seems to be a positive trend associated with the amount of time the whales spend in Whidbey Basin, and the number of whales that enter in the spring. The average number of gray whales that have entered northern Puget Sound over the past 24 years is 7, SD ± 2.73, with the most whales present (12) in 2009 and 2010, and the least (2) in 1990 and 1994 (Calambokidis 2015). Overall, the number of whales coming into Whidbey Basin every year has been steadily increasing since 1990 (Calambokidis 2015).

3.2.3 *Scientific observation of whales feeding*

A dedicated tagging effort by Cascadia Research Collective from the 17- 19th April 2015, resulted in two whales being successfully tagged and tracked (gray whale ID's 22, and 383). The tags gathered valuable video of the whales, and they were seen to display a higher level of social interaction underwater than previously thought. A third tag was deployed, but it was damaged due to a whale-to-whale collision. The whales were observed spending a greater amount of time on the Snohomish River delta, and a lesser amount of time in NE Port Susan than had been recorded in years past (Calambokidis 2015). Also noteworthy, the tagged data displayed a pattern of long deep dives off the fringes of the Snohomish river delta and Hat Island during low tides, and a transition up onto the delta combined with a shift to short shallow dives during high tide (Figure 11). This indicated that there is a good chance whales are feeding constantly throughout the day - but for a large portion of the time in water deeper than 10 meters, far deeper than where intertidal shrimp harvest occurs.

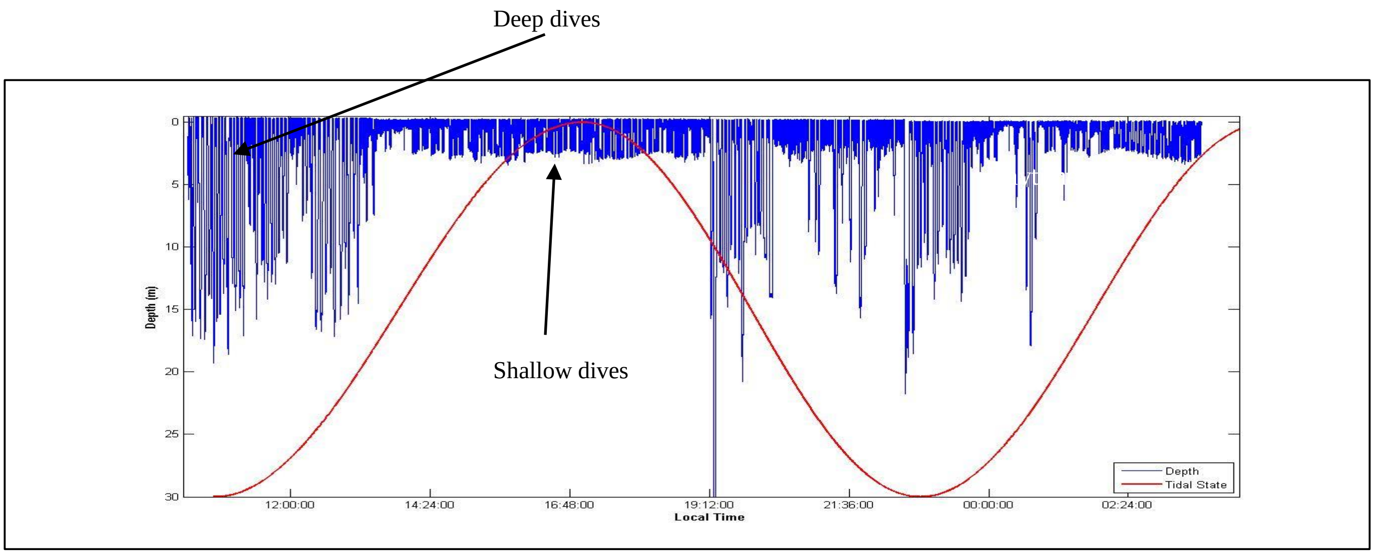

Figure 11. Depth and duration of whale dives from acoustic tag deployment March 17, 2015 (from Cascadia Research Collective 2015) overlain with tide stage data.

3.2.4 Feeding pits evident in aerial images

Low tide aerial images from Whidbey Basin were analyzed for presence of gray whale feeding pits. Pits were delineated and counted. Figure 2 is an example of a photo where feeding pits are easily observed. The density of pits above water line was assumed similar to the pit density below the water to the -10 ft. bathymetric line. Below this point visual confirmation of pit presence was obstructed.

Feeding pits in Whidbey Basin were most prevalent on the Snohomish River Delta, where total counts were estimated at 4.18×10^4 pits (34% of all pits estimated). All other regions in Whidbey Basin where feeding pits were observed totaled to 8.08×10^4 pits (66%), making the total estimated pits in Whidbey Basin 1.23×10^5. Just 2 %, or 2,607 of those pits are estimated to be located inside of DNR authorized ghost shrimp harvesting areas. For 2015, the total area inside feeding pits for Whidbey Basin is estimated at 1.04×10^6 m^2; this estimate comes from the total number of feeding pits extrapolated by the average area per feeding pit (8, SD ± 5.14 m^2, n = 24).

3.2.5 Shrimp density surveyed inside and outside pits

From a total of twenty four pits surveyed, outside quadrats of whale feeding pits proved to have a higher calculated density at 250 ± SD 108 shrimp/m^2, and lower inside of surveyed pits with an average of 130 ± SD 58 shrimp/m^2 (Figure 12). A significant difference was detected with a t-test statistic assuming unequal variances ($p < .05$). Although we attempted to survey beaches as quickly after whales were observed feeding as tides allowed, the large error is likely due to shrimp rapidly recolonizing feeding pits in the time between whales feeding and our surveys.

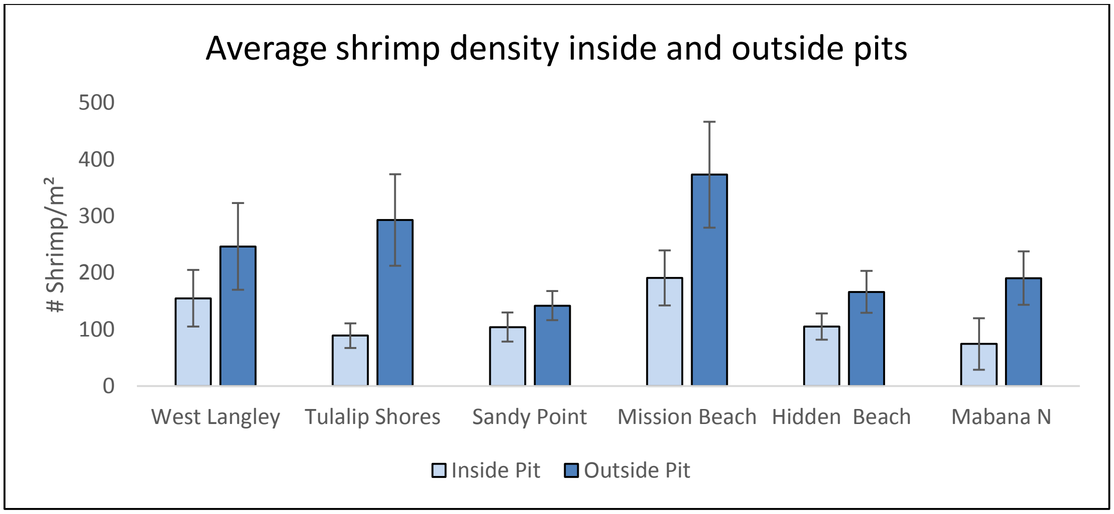

Figure 12. Shrimp densities inside and outside of whale pits, n=24, error bars indicate standard deviation

3.2.6 Shrimp biomass density inside and outside feeding pits

From the twenty four feeding pits surveyed, mean biomass was higher, 628 ± SD 207 g/m^2, outside feeding pits, and lower, 355 ± SD 158 g/m^2 inside feeding pits. A two sample t-test indicated this difference was significant (assuming unequal variances $p < .05$) (Figure 13).

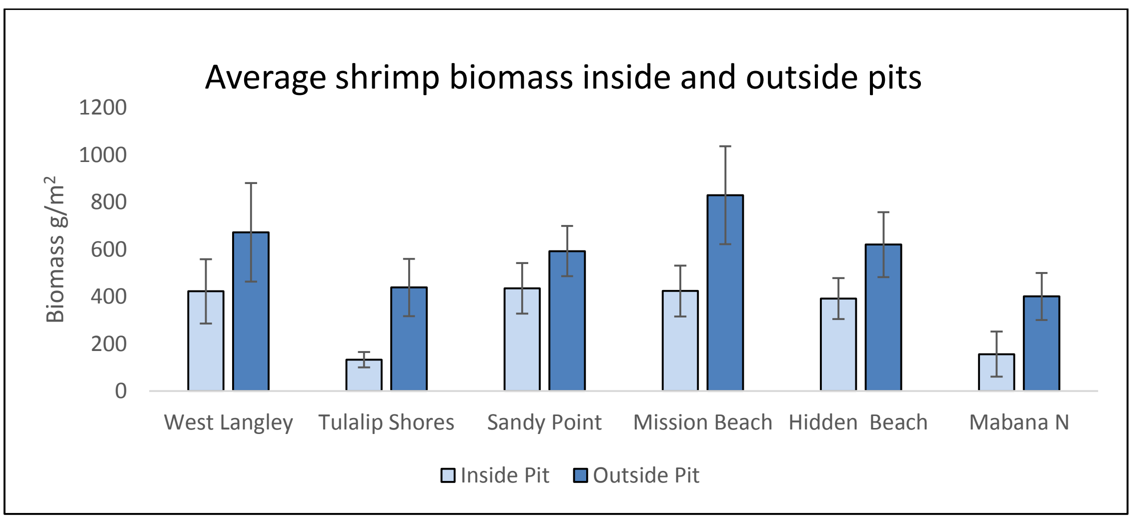

Figure 13. Shrimp biomass density inside and outside feeding pits, n=24, error bars indicate standard deviation.

3.2.7 Total number of shrimp taken by whales 2015

The estimated number of shrimp removed by whales per square meter (120.8 ± standard error (SE) of 15.09 shrimp) was multiplied by average pit size (8.4 ± SD 5.1 m^2) as well as the total number of pits counted in Whidbey Basin above the -10 bathymetric line ($1.23x10^5$ pits). Based on these calculations, the total number of shrimp estimated taken by whales for all of Whidbey basin in 2015 was $1.24x10^8$ ± SE 1,519 shrimp.

3.2.8 Total shrimp biomass taken by whales 2015

Applying the estimated shrimp biomass removed by whales per square meter (273.17 ± SE 29 g) to average pit size, and total number of pits an estimate of total biomass taken by gray whales was calculated at 286.29 metric tons shrimp ± SE 30.03.

3.3 Harvesting

3.3.1 Temporal harvesting data

Harvest occurs all year long, and is driven by sales to the recreational Sturgeon and Steelhead fishers along the West Coast. Harvest can only occur on areas of the beach that are exposed at low tides. Beaches are harvested anywhere from 90 to 130 times per year. From 2010 to 2014, harvest from both non-tribal and tribal commercial fisheries combined remained constant throughout the year with an average of 9,101 ± SD 318 shrimp harvested monthly.

3.3.2 Mean yearly number of shrimp harvested

Closure of the (non-tribal) commercial shrimp fishery in 2014 necessitated that we compare our 2015 estimates of gray whale feeding to the mean annual WDFW data for non-tribal commercial harvest from previous years (2010-2013), and tribal harvest from 2010 - 2014. Ghost shrimp harvested per tract per day is reported by the dozens of shrimp. Mean yearly tribal harvest was reported as $1.5x10^6$ ± SE $4.92x10^5$ shrimp and mean yearly non-tribal harvest was reported at $2.57x10^5$ shrimp ± SE $4.04x10^5$.

3.3.3 Mean yearly shrimp biomass harvested

The mass per shrimp size categories derived from our four sampled harvest sites were used to calculate the biomass harvested. The mean yearly harvest for tribal was calculated at 7.83 ± SE 5.46 metric tons, and the mean yearly non-tribal harvest was calculated at 12.72 ± SE 2.00 metric tons. Mean yearly biomass for all harvesting operations combined was 20.55 metric tons.

3.3.4 Harvest area comparison

In 2015, we encountered whale feeding pits at all four harvest sites surveyed. Commercially authorized harvest sites for ghost shrimp accounted for $7.29x10^5$ m^2 (4.1%) of the total shallow (shallower than -10 ft MLLW) available shrimp area in 2015. The northernmost harvest site (Blowers Bluff) was not surveyed - neither Orca Network data nor aerial images indicated any gray whale feeding in this region of Whidbey basin. Tribal harvest coordinates were not available, however, it is estimated that authorized harvest area on SOAL for tribal and non-tribal were similar - increasing the total harvest areas overlapping with gray whale feeding to 8.2%.

Comparison of available stock and total biomass extracted

Biomass Estimated Taken Yearly From:	Total Biomass (Metric Tons)	Std. Error
Mean Yearly Tribal Harvest Tulalip	7.83	2.43
Mean Yearly Harvest DNR Leases	12.72	2.00
Total Intertidal Whale Feeding 2015	286.29	30.03
Available Ghost Shrimp Stock 2015 in whale Feeding Regions	9377.31	562.49

Table 2. Annual estimates: total stock of ghost shrimp compared with shrimp taken by whales and harvesting.

To extrapolate to the total stock of ghost shrimp utilized by gray whales, each of the six regions in Whidbey Basin where whale feeding occurred were assigned an average density of shrimp/m^2 based on the densities that were found at our whale feeding sites. These densities were standardized by the 300 m long surveyed areas walked with GPS, then extrapolated to the total available gray whale feeding habitat estimated at $1.78x10^7$ m^2. From here a ghost shrimp stock of 9,377 metric tons ± SE 562 was derived. This estimate (encompassing the areas that we observed whale feeding pits in 2015), is nearly thirty times greater than the estimated yearly shrimp biomass extracted by harvest and whale feeding combined (**Error! Reference source not found.** 14). Non-tribal and tribal harvest (20.55 metric tons combined) accounts for only 7.2% of the total estimated available ghost shrimp stock biomass extracted. In 2013 and 2014, Crescent Harbor and Mariners Cove (approximately $1.41x10^6$ m^2 of available habitat), in the Northern region of Saratoga Passage, were hotspots for whale feeding and hold additional available shrimp biomass (Figure 9).

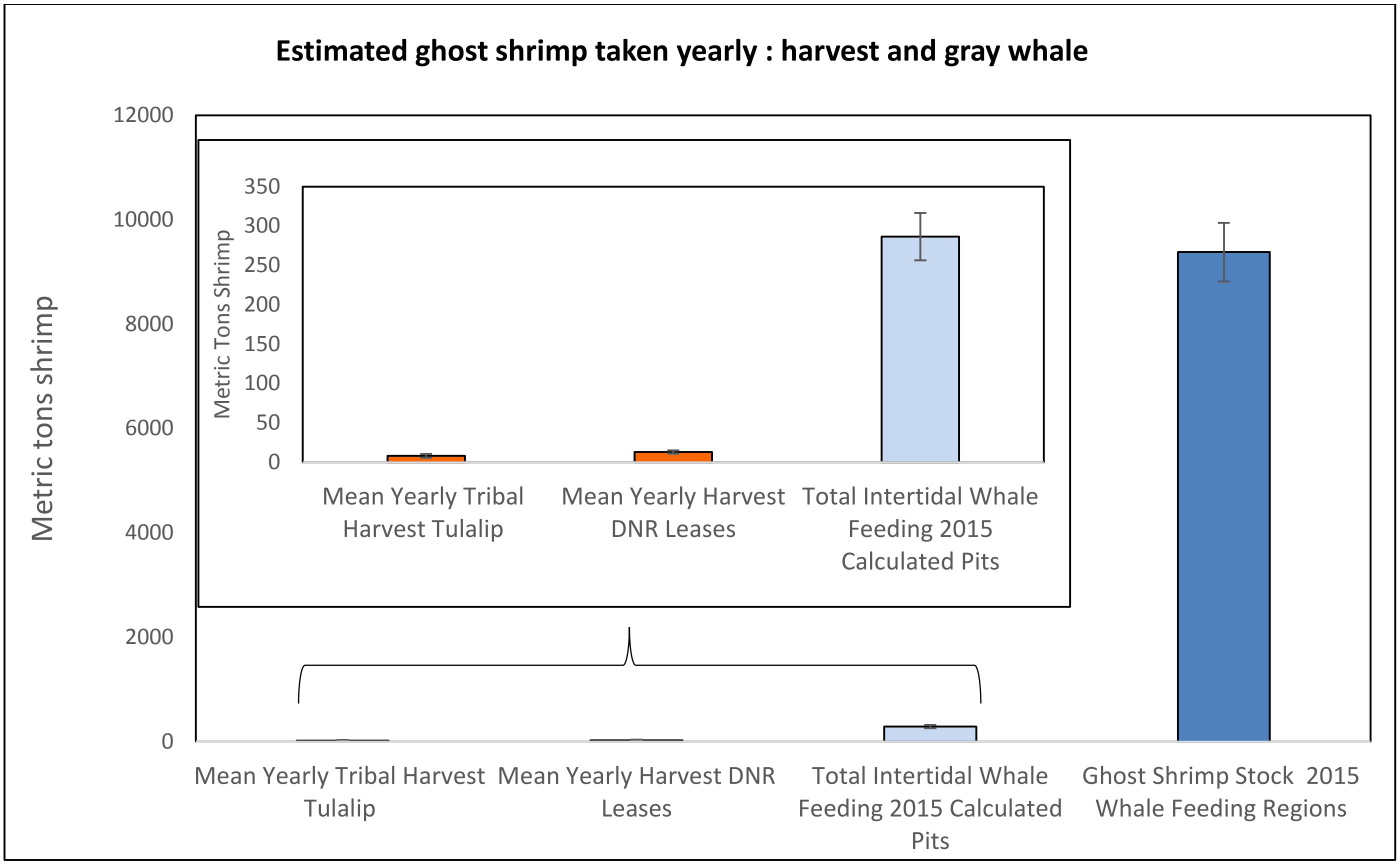

Figure 14. Comparison of ghost shrimp biomass taken yearly from commercial harvest and gray whales and total shrimp biomass available. Error bars indicate standard error
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4 Discussion

This study estimates an available standing stock of ghost shrimp in Whidbey Basin that is considerably larger than the average yearly shrimp biomass extracted from harvest and whale feeding combined. While this quantity of shrimp removed seems small, its ecological significance on shrimp population is less certain. The estimated density of shrimp inside and outside of feeding pits was not consistent with previous estimates. Weitkamp et al (1992) estimated within pit ghost shrimp density of 218 g/m^2, and outside pit density of 1058 g/m^2. Our estimates in 2015 showed within pit density of 357 ± SD 158 g/m^2, and outside density of 628 ± SD 217 g/m^2 - implying a much lower total biomass removed by whales. Measurements of pit size n = 11 (5.4 ± SD 1.2 m^2), by Weitkamp et al (1992) however, were also smaller and less variable than our measurements, (8.3 ± SD 5.1 m^2) n = 24. In 1990 the Department of Fisheries estimated the standing stock of ghost shrimp at 1325 g/m^2, averaged over 12 different sites in Whidbey Basin (Department of Fisheries unpublished data). We estimated a smaller biomass, with 725 ± SD 179 g/m^2 averaged from our twelve sites. These estimates (allowing for differences in sampling methods) may indicate that there has been a decline in shrimp standing stock over the past 25 years. Similarly, ghost shrimp surveys in Willapa Bay indicated a 48 to 67% ghost shrimp population decline from 2006 to 2009. In Yaquina Bay, declines up to 71% were observed (Dumbauld et. al 2014). Both are areas where commercial shrimp harvesting is minimal. Ghost shrimp populations in Willapa Bay increased in the early 1990's, reaching densities of 400 shrimp/m^2, and dropping to fewer than 50 shrimp /m^2 by 2010. Large fluctuations like these have been recorded previously in other crustacean and shellfish populations in Pacific Northwest estuaries, and have been hypothesized to relate to large scale atmospheric and oceanic weather patterns like El Nino. It is thought that the success of yearly shrimp settlement depends upon how oceanic conditions manipulate current direction and duration, as well as the water chemistry conditions pelagic larval ghost shrimp are exposed to (Dumbauld et. al. 2014).

The estimated available Whidbey Basin shrimp biomass greatly exceeds both whale feeding and commercial harvest biomass, indicating that ghost shrimp are unlikely to be a limiting resource for gray whales visiting northern Puget Sound. Spatially, harvested beaches account for a very small portion (~ 8.0%) of the total area that whales utilize as feeding habitat, and the total yearly amount of shrimp extracted by whales and harvest combined is estimated at ~ 3.3% of the total biomass available above -10 ft MLLW. Additionally, data from tagged whales in 2015 shows that even more feeding may occur subtidally (< -10 ft. MLLW) at depths deeper than where commercial harvest occurs (Calambokidis 2015). Temporally, gray whales feed at Whidbey basin for only a short period of time during the spring compared with the time available for commercial harvest.

4.1 Management recommendations

4.1.1 Restricted Harvest

Even if the total population of ghost shrimp is large enough to sustainably support both harvest and gray whales, there may be other factors associated with harvest (noise, disturbance of sediment) that could deter whales from feeding in certain areas. Figure 15 indicates when whales have been observed in Whidbey Basin, and when harvest has historically occurred. A potential management approach may be to suspend harvest operations from the time the first individual whale of the year is reported in the area until the last whale has left the area (Approximately February through June. Harvesting can then commence after the whales have departed Puget Sound.

It has been shown that ghost shrimp densities fluctuate with the strength of annual recruitment. Fecundity increases with size/age, and females are ovigerous from April to August with eggs hatching from June to August (Dumbauld et. al. 1996). It will therefore be important to closely monitor the number of ovigerous females in July and August, to monitor general shrimp stock and recruitment onto harvest beaches. An investigation designed to indicate the length of time required for the recovery of shrimp populations following harvest should be completed. Results from monitoring ghost shrimp population change can provide information on whether a regulated fishery might be necessary.

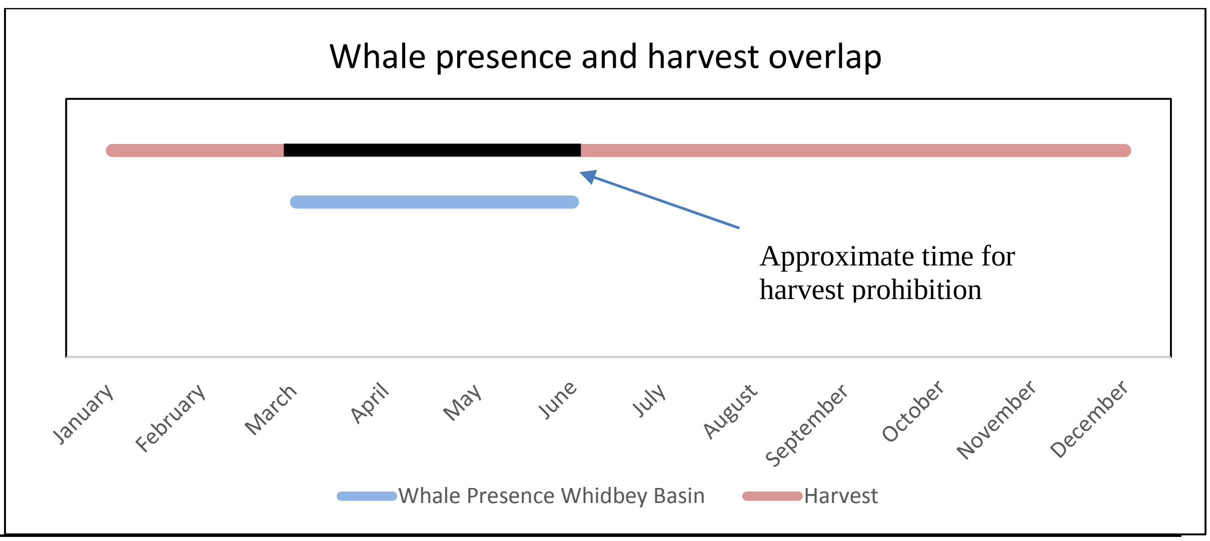

Figure 15. Approximate time gray whales are present in Whidbey Basin and when suggested harvest prohibition might occur.

4.1.2 Monitoring

The following monitoring suggestions might occur together with a restricted harvest.

Conduct surveys designed to:

1) Compare whale feeding at harvest beaches when harvest occurs compared with whales feeding in the same areas where harvest was prohibited last year.
2) Estimate shrimp population recovery rate post-harvest.
3) Compare 'harvest' and 'whale feeding' beaches to monitor shrimp population densities throughout Whidbey Basin.
4) Recruitment surveys of newly settled shrimp. This will provide information on resiliency of the shrimp population.
5) Continued involvement with Cascadia Research Collective to accomplish;
    - Whale fecal sample collection –for qPCR DNA analysis to determine what proportion of whale food is composed of ghost shrimp.
    - Additional GPS – accelerometer enabled tag deployments on gray whales to collect data on the locations and duration of gray whales feeding within Whidbey Basin.
    - Multibeam and video surveys to identify subtidal pits deeper than the -10 ft. MLLW, to confirm that when whales are diving deeper they are spending time feeding.

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