Use of Tethered Prey for Estimating the Impact of The Invasive European Green Crab

by

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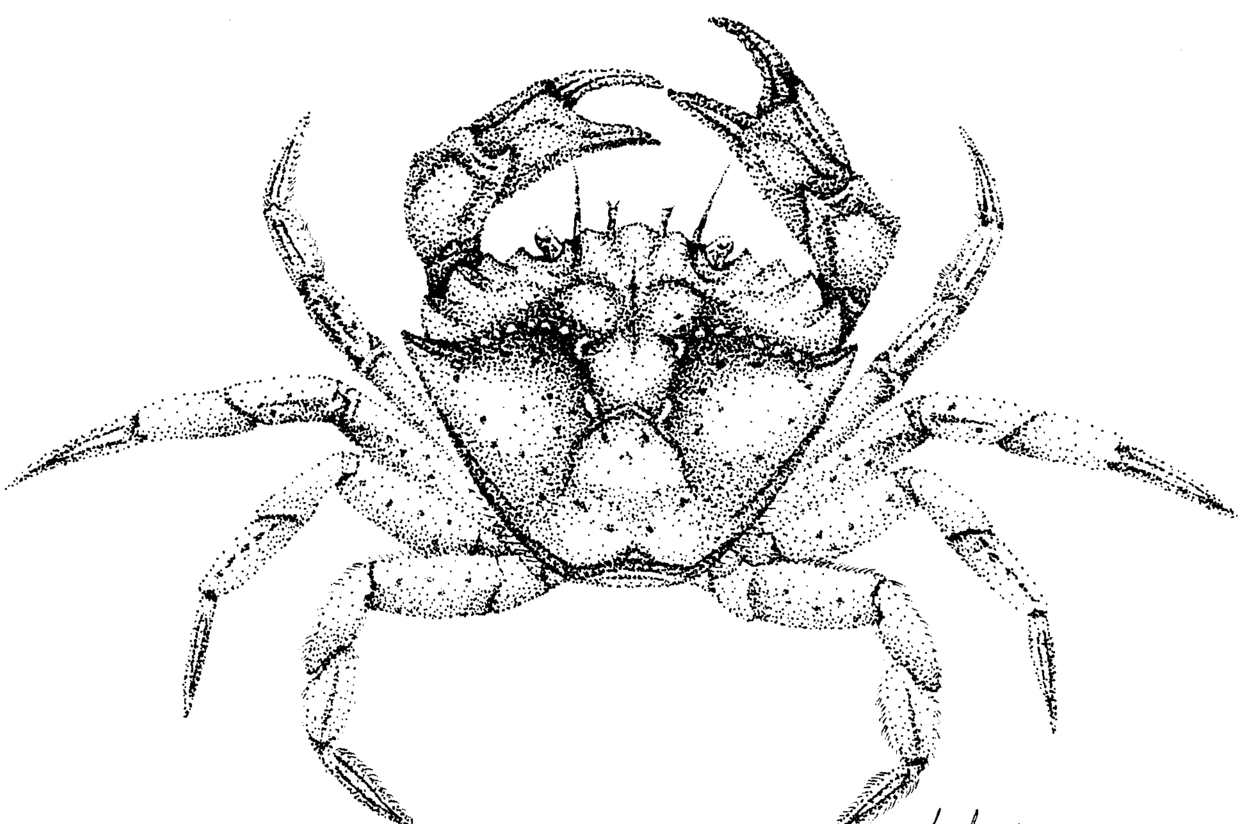

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ABSTRACT

Various mollusks, including small bivalves and gastropod snails, are a common food source for intertidal crabs. Prey opening techniques used on hard-shell prey are dependent on claw size and morphology. For example, large, strong claws can crush a snail outright while smaller, weaker claws leave characteristic peels, pulls and upper whorl peels. It is therefore often possible to identify the predator responsible for a specific breakage pattern. A feeding study was conducted to "fingerprint" the shell opening techniques of the European green crab and five common native Pacific Northwest crab species on three size classes of the intertidal snail *Littorina sitkana*. A multiple linear regression analysis utilizing a statistical program resulted in an odds ratio that identified the crab species most likely to perform a given technique. For example, the green crab was 19 times more likely to utilize the pulling technique than a Dungeness crab, while the Dungeness crab primarily relied on crushing. The green crab was the only crab species to utilize an upper whorl peel technique.

Shell breakage patterns found on snails tethered to predation lines at various sampling sites in Coos Bay and Yaquina Bay, Oregon, were then used to identify the size and species of foraging crab predators at those sites. A predation line is a tool designed to quantify the foraging impact upon small gastropod snails by various crab species in the intertidal zone. A given number of *Littorina sitkana* snails are attached to monofilament line with marine epoxy. These lines are then tied to metal rebar rods and left in the intertidal for one full tidal cycle. The fate of the snails on the lines is then scored as: live, attempted peel, peeled, pulled or crushed. The final results yield the overall crab foraging rate and indicate the most likely crab species responsible for the predation. This information can be very useful when comparing predation rates between sampling sites that host the invasive European green crab, and those sites that have not yet been invaded.

1. INTRODUCTION

Many crab species make their home in the intertidal zone of the Pacific Northwest. Crabs of the genus *Hemigrapsus* tend to seek shelter under rocks and boulders during the low tide and forage on green algae, diatoms, desmids, mollusks and other animal material during high tide (Garth & Abbott, 1980). Larger crabs, of the genus *Cancer*, shelter in the subtidal and ride the high tide into the intertidal to forage on bivalves, snails and worms (Robles *et al*, 1989) as well as on smaller *Hemigrapsus* crabs as they venture out from their sheltering rocks (Daly, 1981). Competition for food and shelter can be intense in the intertidal, and most native crab species have adapted to exploit different regions of the environmental resource spectrum. Various traits such as size, predation techniques, desiccation and salinity tolerances, and the ability to survive low oxygenated (silty) water are all factors that help to distribute the competing crab species along habitat gradients. When a new predator species is introduced into this delicately balanced community, the impact could potentially be very detrimental.

1.1 Our Native Species

Five different native crab species are included in this study. They are *Hemigrapsus oregonensis*, Hemigrapsus *nudus*, *Pachygrapsus crassipes*, *Cancer magister* and *Cancer productus*. These crabs represent the species most common at our chosen sampling sites. Two of the grapsids, *Hemigrapsus oregonensis* and *Hemigrapsus nudus*, are recognizable by their box shaped carapace. Their distribution ranges from Alaska to Baja California, and they often coexist in many locations (Garth & Abbot, 1980). When comparing the differences in their specific traits we begin to see that they appear to coexist in a perfectly balanced manner, in a competitive equilibrium (Harger, 1972). This balance is perhaps the result of competitive adaptation. Fossils of both *H. nudus* and *H. oregonensis* found, in San Pedro California, date back to the Pleistocene epoch (Garth & Abbot, 1980). This means that these two crabs have had approximately 2 million years to evolve adaptations for coexistence. Each has specific traits that make it more suited to exploit resources from opposite ends of the habitat spectrum.

The habitat in which *H. nudus* and *H. oregonensis* is found is a reflection of the species' ability to tolerate certain conditions and/or the result of competition with each other forcing certain conditions to be tolerated. When found in the same location the species are often mixed, even sheltering under the same rock, but in general the population peaks are found at different tidal heights (Daly, 1981). These tidal height zones are separated from each other by habitat criteria. Both crabs have the same omnivorous feeding habits with diets consisting of diatoms, desmids and small green algae as well as a small amount of animal material and they each have similar tolerances to temperature. The individual traits of each species are discussed below.

H. nudus tends to compete with interference, in that they grow larger by delaying maturity and reproducing less frequently thus applying more energy to increasing size for a competitive edge (Daly, 1981). The male carapace width ranges up to 56.2 mm and that for females up to 34 mm, but very seldom reaching over 26 mm. The female produces only one brood per year (on average 13,000 eggs) (Garth & Abbot, 1980). Habitat selection for *H. nudus* tends to be under large, fairly stable rocks in the middle to high rocky intertidal zone. Large stable rocks are the optimum shelters for shore crabs, and *H. nudus* successfully uses its size advantage to displace *H. oregonensis* from the larger rocks. It is also more tolerant to desiccation than *H. oregonensis* and thus better suited for survival in the high tidal zone. In a desiccation experiment conducted by Wan (1990) in an incubator with 84% humidity at 10°C *H. nudus* survived an average of 34 hours while *H. oregonensis* only survived an average of 23.

H. oregonensis, on the other hand, is smaller in size then *H. nudus*. The carapace width ranges up to 34.7 mm while the female ranges to 29.1 mm. It reaches sexual maturity more rapidly and at a smaller size and reproduces frequently (Daly 1981). About 70% of females produce two broods per year (Wan, 1990). Each brood, however, is smaller than that of *H. nudus* and averages 4,500 eggs with the brood size increasing with female size (Garth & Abbot, 1980). The strategy for *H. oregonensis* follows the life history of a ruderal species. Its smaller size forces it to live in marginal habitats with a greater rate of mortality. In order to compete it must do so with sheer numbers, replacing its losses as soon as it can and using less resources for growth and more for reproduction. *H. oregonensis* lives on mudflats in the lower rocky intertidal zone, but, in the absence of *H. nudus*, will occupy larger rocks in the middle zone (Daly, 1981). *H. oregonensis* is specially adapted to survive in the less optimal silty water of the low intertidal and mudflats. It has a dense mat of setae in the openings to the branchial chambers, which allows it to burrow into the mud without its gills clogging with sediment (Harger, 1972). When both species are exposed to muddy, oxygen poor water, *H. oregonensis* survives an average of 6.8 hours longer than *H. nudus* (Low, 1970). Wan (1990) demonstrated that *H. oregonensis* is also more tolerant to low salinity than *H. nudus*. This study yielded no difference in the species mortality rates at the gradients of 31.5‰ to 16‰ but a significant difference at 4‰. This means that *H. oregonensis* can live in bays with a large amount of freshwater runoff. *H. nudus* is less tolerant & consequently does not penetrate estuaries as high up as *H. oregonensis*.

Pachygrapsus crassipes is another native species included in this study. It makes it's home in the upper rocky intertidal among large boulders, and can sometimes be found on hard muddy shores in burrows. Its range extends from Ecola State Park, Oregon to the Gulf of California (Jensen, 1995), but in some years can be found as far north as southern Washington. The northern distribution fluctuates with changing current patterns. During El Niño years the larvae is transported farther north, thus expanding the northern distribution. In subsequent non-El Niño years, however, no further recruitment takes place and these northern populations die out.

P. crassipes, like *H. nudus* and *H. oregonensis*, is also a member of the family *Grapsidae* and also has a carapace that is box-like in shape. The male carapace width ranges up to 47.8 mm, and for females up to 40.8 mm. This crab is commonly referred to as the lined shore crab due to striated stripes that run across the carapace horizontally. The *P. crassipes* diet consists mainly of algae and diatoms, thus utilizing the same food sources as the *Hemigrapsus* crabs previously discussed. Interestingly, this species is under investigation as an invader in Asia, presumably transported via ballast water in the late nineteenth century. *P. crassipes* is potentially a very adaptive invader due to its high resistance to desiccation and it's ability to tolerate wide ranges in osmotic and temperature variation (Garth & Abbot, 1980). This crab is actually suited to a largely terrestrial life, spending half of its time out of the water.

Cancer magister and *Cancer productus* are the most dominant sub-tidal crab species encountered within the parameters of this study. *C. magister* populations range from Tanaga Island, Alaska to Pismo Beach, San Luis Obispo County; and *C. productus* can be found from Kodiak Island, Alaska to San Diego, California (Garth & Abbot, 1980). As cancrid crabs they are much larger, and mostly found sub-tidally due to their limited tolerance to desiccation. As previously mentioned, these crabs follow the tide in to forage in the intertidal. As the tide recedes, *C. productus* often seeks shelter on rocky shores under large boulders in the intertidal. During the winter, when risk of desiccation is low, *C. productus* remains in the intertidal to forage on the smaller crabs, displacing *H. nudus* from the preferred shelter of the intertidal. This series of events in turn affects *H. oregonensis*. *H. oregonensis* can actually benefit during episodes of competition when *H. nudus* numbers are low or in a state of transition due to *C. productus* remaining in the intertidal rather than leaving with the tide. The benefit to *H. oregonensis* comes in the form of relieved competition for shelter. During times of *C. productus* retention in the intertidal *H. nudus* numbers decrease and the population moves to shelter higher up on the shore. When *C. productus* is forced back into the subtidal zone due to low salinity and desiccation, *H. nudus* stays higher up on the shore for a while. *H. oregonensis* benefits from the preferred habitat that is then vacated (Daly, 1981).

In contrast, during its movements in with the tide, *C. magister* usually stays on sandy bottoms burying itself in the sand and generally moves back to the subtidal as the tide recedes. This crabs concealing behavior of burying in the sand is possible due to the fact that *C. magister* also has physical adaptations that prevent sand from entering the branchial cavity (Hart, 1982). The size range for *C. productus* is up to 180 mm for males and 158 mm for females and *C. magister* is generally larger with males ranging up to 230 mm and females up to 170 mm (Hart, 1982). *Cancer* crabs are carnivores; the common food sources for *C. productus* and *C. magister* consist primarily of small crustaceans, clams and oysters, worms, and even fish.

In light of the unique competitive arrangement between *H. nudus* and *H. oregonensis*, and the careful movements of cancrid crabs in and out of this relationship with the tide, we must now consider how an exotic such as *C. maenas* will effect such a balanced community. What happens when a species that possesses many competitively advantageous traits moves into the neighborhood? It can be assumed that all other crabs previously coveted competitive edges are lost, and that the bigger and/or hardiest crab shall prevail. We have observed that when the two dominant species fight it out the little guy can actually thrive, as was the case for *H. oregonensis* in Daly's study (1981). The only thing about this situation is the fact that *C. productus* must eventually leave the intertidal due to physical limitations regarding desiccation and salinity. Remember that its exit is the advantage to *H. oregonensis*. Because *C. productus* is unable to survive the exposure of the intertidal for long periods it does not pose a constant threat to the populations of the shore crabs that it temporarily displaces. *C. maenas*, on the other hand, could come in and stay; possibly disturbing the distribution of shelter and upsetting the balance between the native species. What we have in *C. maenas* is a voracious predator that could potentially out-compete the native species along most of the habitat spectrum due to traits discussed below.

1.2 The Invasive Species

The European Green Crab, *Carcinus maenas*, is a very successful invader. It was first introduced into San Francisco Bay in the early 1980's. The exact year is not known because when its presence was first confirmed in 1989 it was already represented by a well-established breeding population (Cohen *et al*, 1995). *C. maenas* has subsequently traveled up the northwest coastline, likely aided by El Niño driven currents, as far north as Lemmens Inlet near Tofino, British Columbia (Jamieson, personal communication). This versatile crab can tolerate a wide range of environmental factors. It can live in salinity as low as 5 ppt., can tolerate over winter temperatures as low as 0° C, and is even highly tolerant of desiccation – surviving up to two months out of water when covered with damp algae (Carlton, 1998). Such a crab could have the potential to exploit every habitat in the intertidal bay communities of Oregon - unless the larger native species are able to use their size as a competitive edge in the sub-tidal and higher salinity habitats.

What makes this crab even more of a potential threat is his wide diet selection and vast array of prey opening techniques. Over 150-recorded genera of animals and plants are documented as food sources for *C. maenas* (Cohen, Carlton & Fountain, 1995). The Green Crab has also repeatedly proven itself to be a very clever predator in a number of feeding studies. A study conducted by Cunningham et al (1984) indicates that *C. maenas* is capable of rapidly learning a variety of techniques for opening prey more efficiently and to exploit different prey sources. This learning behavior increases the ability of *C. maenas* to be an efficient invader by allowing it to adapt predation techniques to the variety of prey found in the invaded territory. This learning capacity also allows for a crab species to switch rapidly between prey sources as one source becomes depleted. A study by Moody et al (1993) displayed this crab's propensity for versatility in prey opening techniques. Predation behaviors of 4 species of decapods from the shallow subtidal zones of the Gulf of Maine were observed preying upon the blue mussel (*Mytilus edulis*). The decapods studied included 1 astacid lobster (*Homarus americanus*), and 3 brachyuran crabs, one portunid (*Carcinus maenas*) and two cancrids (*Cancer irroratus* and *Cancer borealis*). Of all the observed species, *C. maenas* utilized the highest number of techniques, opening the mussels with a total of seven predation tactics (Moody & Steneck, 1993).

The most obvious reason for technique usage variability between crab species is claw morphology. Portunids, such as *C. maenas*, have one large and one small cheliped. The difference in the two claw sizes allows for a larger variety of techniques to be executed than could be used by a crab with two size-matched claws. The larger cheliped tends to have more strength, allowing for crushing techniques, while the smaller cheliped can be more dexterous, allowing for cutting and pulling techniques. Behrens Yamada and Boulding (1998) measured the ideal mechanical advantage (IMA) for the claws of male specimens from decapod species indigenous to the Pacific Northwest. This knowledge was then applied to the classifying of the crab species as mollusk generalists or specialists (See Table 1.1). Prey variety selection, prey size selection (of *Littorina sitkana)* and prey handling efficiency were also observed. The three species with broad stout chelipeds and high IMA ratios (two cancrid crabs, *Cancer oregonensis* and *Cancer productus*, and a Xanthid crab, *Lophopanopeus bellus*) are specialists that could easily crush the model prey. The two crabs with more slender chelipeds and smaller IMA ratios (two grapsid crabs – *Hemigrapsus nudus* and *Hemigrapsus oregonensis)* were classified as mollusk generalists.

In light of this information it is not surprising that a crab with claws of two different sizes could exploit a large variety of prey. The IMA for the master claw of *C. maenas* is 0.33, which is comparable to that of the master claw of *Lophopenopeus bellus* and the claws of *Cancer oregonensis*. These IMAs are larger than those of the smaller *Hemigrapsus* crabs, allowing for crushing of thicker shells, but still smaller than the IMA of the most efficient mollusk predator *Cancer Productus*. The IMA for the minor claw of *C. maenas* is 0.24, which is comparable to the minor claw of *Lophopenopeus bellus* and to the IMA of *C. magister*, but less than the IMA for the *Hemigrapsus* crabs (Behrens Yamada and Boulding, 1998). This IMA ratio allows for more delicate predation techniques. The combination of these IMA ratios effectively place *C. maenas* (and *Lophopenopeus bellus)* in two slots in the hierarchy of crab species predators; its small claw makes it a generalist and its larger claw places it in the category of mollusk specialist. These classifications may explain why *C. maenas* exploits such a large variety of food sources.

Table 1.1: Correlation of claw characteristics and diet in Northeastern Pacific crab species. The ranking of crabs is based on the ideal mechanical advantage of the claws' lever system (IMA). Claws with low IMA have long slender fingers, while those with high IMA have stout, short fingers. Since many species exhibit sexual dimorphism in claw size, only males were used. Lack of an entry in the minor claw column indicates that both claws are similar. (See Behrens Yamada and Boulding, 1998, for more detail.)

Species	Max. Carapace Width (mm)	IMA Master Claw	IMA Minor claw	Claw shape and Dentition	Diet	Mollusk Specialist	Source
Dungeness Crab *Cancer magister*	190	0.25		Slender, sharp, fine denticles	Clams, Crustaceans, Fish	Yes	This Study
Oregon shore crab *Hemigrapsus oregonensis*	33	0.28		Fine denticles, Blunt tips abut	Omnivore	No	Behrens Yamada and Boulding 1998
Purple shore crab *Hemigrapsus nudus*	35	0.28		Fine denticles, Blunt tips abut	Omnivore	No	Behrens Yamada & Boulding 1998
Black-clawed mud crab *Lophopenopeus bellus*	30	0.34	0.24	Blunt broad molars, Sharp tips cross	Mollusks, Crustaceans	Yes	Behrens Yamada & Boulding 1998
European Green Crab *Carcinus maenas*	90	0.36	0.26	Major: blunt broad Minor: slender claw with fine sharp denticles	Omnivorous Mollusks, crustaceans, worms, plants	Yes	This Study, Warner et al 1982.
Pygmy Rock Crab *Cancer oregonensis*	50	0.36		Blunt, broad molars, Sharp tips cross	Mollusks, Barnacles, Crustaceans	Yes	Behrens Yamada & Boulding 1998
Red Rock Crab *Cancer productus*	160	0.39		Blunt, broad molars, Sharp tips cross	Mollusks, Barnacles, Crabs	Yes	Behrens Yamada & Boulding 1998

1.3 The Research Objectives

Monitoring the effects of a voracious invading predator such as *C. maenas* is certainly important. That is why various sampling techniques are currently being used along the Oregon coast, Washington coast, and British Columbia in an effort to gauge the status of the current invasion. Unfortunately, the stand-by sampling procedure of trapping can be misleading when quantifying crab population abundance and predation rates. The bait that is used in traps; usually salmon scraps such as heads, fins and backbones, is difficult to standardize because researchers often use whatever bait is available to them. Furthermore, bait broadcasts a very strong signal that is dispensed throughout the surrounding water by tidal currents. To foraging crabs this chemical signal is like a dinner bell ringing and they all come to eat. As a result, the final trapping data could lead to an inflated estimate of population density and predation rate. Other downfalls to trapping include the natural self-preserving tendency of smaller crabs to avoid the presence of larger crabs, and the absence of *C. maenas* foraging when the temperature drops below 8° C (leading to a population underestimate if trapping is conducted during the winter).

A more realistic method for estimating crab predation in the field is the use of tethered snail predation lines (Behrens Yamada and Boulding, 1996). A predation line consists of gastropod prey tethered to a stationary object that is then left at a sampling site for one full tide cycle. As indicated in the Behrens Yamada and Boulding study of 1996, *Littorina sitkana* snails are a natural prey source for foraging crabs, which makes the use of these snails as the tethered prey an appropriate indicator of a natural predation rate for a given location. *L. sitkana* snails also broadcast a relatively small signal when compared to the fish bait used in traps. In order to detect the snails on a predation line a crab would need to be foraging nearby. In this way the amplification of the predation rate found in trapping studies is avoided and more accurate predation picture can be developed. In using a hard-shell prey like *L. sitkana* there is also a second benefit. Crabs will utilize different prey opening techniques on hard-shell prey due to claw size and morphology. It is therefore often possible to identify the predator responsible for a predation event by the specific shell breakage pattern left behind.

The goals for this study were threefold. The first objective was to gather baseline data on the crab populations in both Yaquina and Coos Bays. This data was gathered by employing several sampling procedures including rock turning, trapping, molt searches and predation lines. Students in the Zoology 401 course at Oregon State University collected much of this baseline data, specifically the rock-turning data, in the fall of 1997 and 1998. Other portions of this data were collected by myself during the summer of 1999. The second objective was to establish the efficacy of predation lines in estimating the natural predation rate due to crabs at various sampling sites in the intertidal zone. By accomplishing this it would become possible to compare predation rates among various sites, particularly between sites that do, or do not, host the invasive green crab; as well as establish a baseline predation rate that will be useful in future comparisons. As the population numbers of *C. maenas* rise, comparisons of predation rates will allow researches to quantify the predation impact of the invader. The final objective was to fingerprint, by technique usage, each potential crab predator that might prey upon our tethered snails in the field. Our intent here was to identify hallmark techniques, those used primarily by one species. Such techniques would allow us to identify the foraging crab species most likely responsible for hitting a predation line. This information would be very valuable in documenting the relative impact of the invasive *C. maenas* and native crabs on the marine community in which they live.

2. METHODS AND MATERIALS

2.1 Study Sites

Field experiments in this study were carried out at several sampling sites within two Oregon bays: Yaquina Bay and Coos Bay (see Figures 2.1, 2.2 and 2.3). Yaquina Bay served as the experimental control due to the large quantity of background and species information available for each of the four sites. Each site was chosen along a salinity gradient, and each reflected particular habitat characteristics. Sawyer's Landing and Northwest Natural Gas Tank (NW Natural Gas) sites are located in the northern portion of the bay, while Idaho Point and Hatfield Marine Science Center (HMSC) are locate on the southern shore (see Figure 2.2). Sawyer's Landing has a gradually sloping shore with larger stable rocks at the mid and upper intertidal levels and consolidated mud

Figure 2.1: **Oregon Coast**
Proximity of Yaquina Bay and Coos Bay to one another

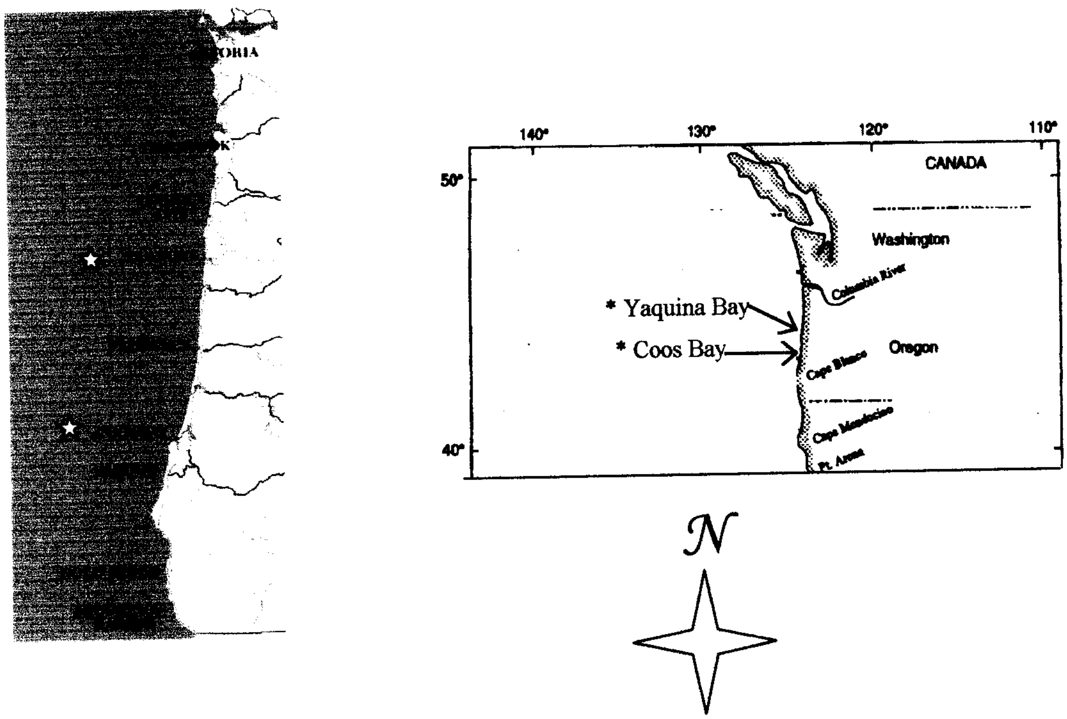


Figure 2.2: **Yaquina Bay**
Geography and Study Sites

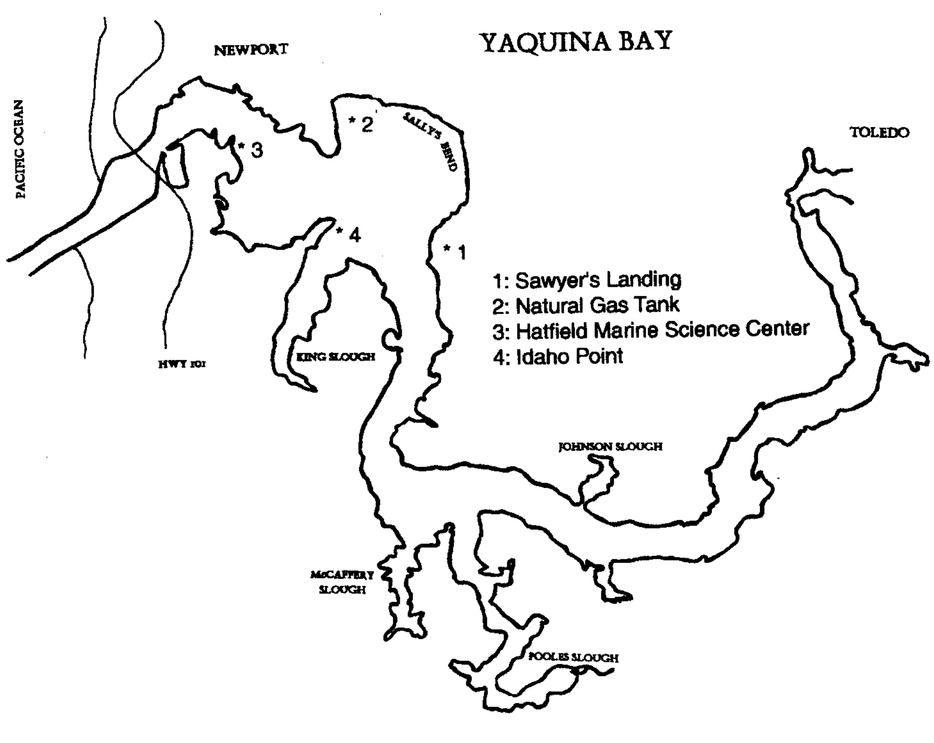
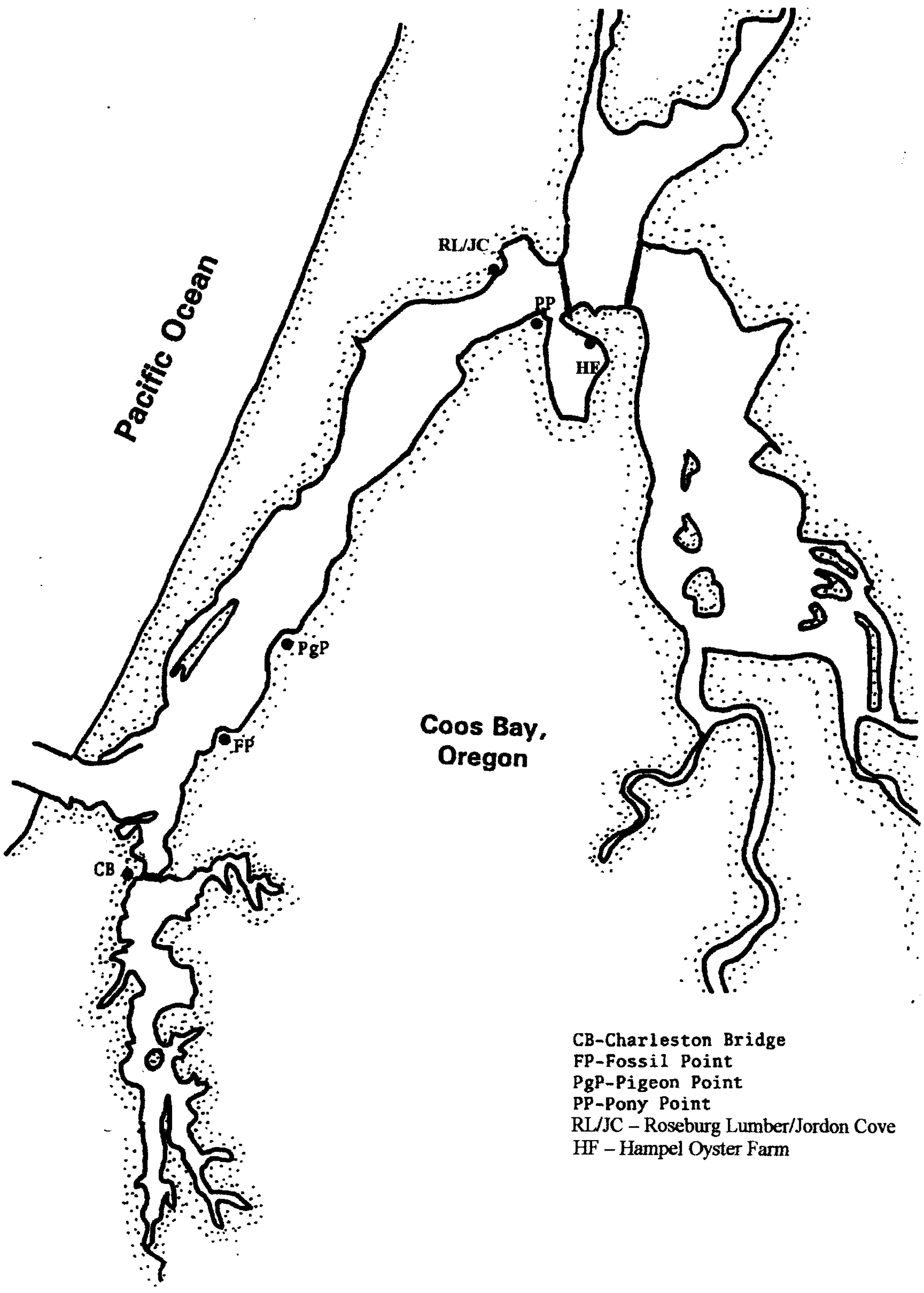


Figure 2.3: **Coos Bay**
Geography and Study Sites



CB-Charleston Bridge
FP-Fossil Point
PgP-Pigeon Point
PP-Pony Point
RL/JC – Roseburg Lumber/Jordon Cove
HF – Hampel Oyster Farm

and gravel at the lower zone. The NW Natural Gas site also slopes gradually and has large to medium rocks arranged along the upper intertidal zone and mud flats in the middle to lower zones. HMSC is a very steep shore with many boulders in the upper and middle intertidal and some mid-sized and smaller rocks in the middle to lower zones. Idaho Point is also a steep shore with soft mud flats dominating the mid and lower tidal zones and boulders mixed with large rocks covering the upper zone.

The Seven sites in Coos Bay, also chosen along a salinity gradient, served as the experimental test sites. Very little background information, including species diversity, was available for any of the sites. This allowed for testing of the predation line with no bias, and also provided for different habitats to be explored. Of the Coos Bay sites only four; Roseburg Lumber, Pony Point (airport), Hampel Oyster Farm and Fossil Point; were successfully utilized for all the sampling procedures. Roseburg Lumber site is located on the northern shore, directly across the bay from Pony Point and next to Jordon Cove. Pony Point is across the slough from Hampel Oyster Farm, and, along with Fossil Point and Charleston Boat Basin, is located on the southern shore of the bay. Charleston Boat Basin is closest to the mouth of the bay with Fossil Point midway between the basin and Pony Point (see Figure 2.3). Roseburg Lumber site is a sandy, gradually sloping shore that has large boulders in the upper zone, mid-sized rocks in the middle zone and mud mixed with eel grass patches in the lower intertidal zone. Jordon Cove is primarily reeds and mud on a gradually sloping shore. Pony Point actually hosts two habitats and thus two sampling sites. The first is located in the slough and the second is further out toward the bay near the North Bend airport. The slough is very muddy and gradually slopes out. The only rocks are rather small and located at the very upper intertidal. The airport side is also gradually sloping and goes from sandy to muddy, with eelgrass stabilizing the lower intertidal. Some smaller rocks are found in the very upper intertidal zone. Riprap slopes down, perpendicular to the shore, from the upper intertidal to the water line. The riprap and eelgrass presumably provides most of the shelter for this portion of Pony Point. Hampel Oyster Farm site is an oyster farm established on a gradually sloping mud flat located on the other side of the slough from Pony Point. Patches of eelgrass can be found among large oyster clusters across the flat. Fossil Point has a consistently high salinity measurement as it is located near the mouth of the bay. It is a pebbly shore at the upper zone that slopes down into sandstone flats and tide-pools. There were few medium or large rocks at this location for shelter. The Charleston Boat Basin was sampled at two locations. The predation lines were set under the Charleston bridge on gradually sloping mudflats while the rock turning was conducted at the other end of the basin on a steeper slope that consisted of large boulders in the upper intertidal changing to smaller rocks at the mid and soft mud in the lower zone.

2.2Feeding Study

In order to interpret the predation lines by technique it was necessary to conduct an in-lab feeding study that recorded prey size selection and technique usage for each of our common intertidal native crabs and the green crab. *L. sitkana* snails were collected from Siletz Bay, Oregon and sorted into size groups using metal wire sieves and further by hand with vernier calipers. The three size groups were: 5 - <8mm, 8 - <11mm, and 11- <14mm. The large and medium size groups combined represent the snails used in the predation line study. These results were therefore combined when the analysis was conducted for interpretation of the lines.

Trapping and rock turning at the study sites yielded the crabs used in the study. The widest possible size range within each of the crab species was chosen, and at least five representatives for each species were used totaling 37 study crabs (see Table 2). Mostly male specimens were used, as claw size tends to differ between the two sexes (especially in *Hemigrapsus*), but a couple of females were included because they represented sizes that were not available in male specimens. Each crab was confined to it's own numbered container. The containers consisted of modified Tupperware containers that varied in size from 15 x 15 x 4 cm to 25 x 25 x 11 cm, depending on the size of the crab. The containers had large "windows" cut out of two of the four sides in the small containers and all four sides in the larger containers. The "windows" were then covered with fine 2 mm mesh screen that was hot-glued into place. The mesh cover holes allowed for water flow through the containers while still retaining all snails and shell fragments for observation.

The crab containers were then divided into two groups: Predatory Crabs, which consisted of *C. maenas*, *C. productus*, and *C. magister*; and Small Shore Crabs, which encompassed the remaining three crab species. These two groups were placed in separate water tables measuring 318 x 118 x 30 cm. The two groups were formed because chemical signals emitted from larger *Cancer* crabs could inhibit the feeding activities of the smaller crabs. This is due to the fact that small shore crabs are often food sources for the larger predatory crabs. By dividing the test subjects into two groups, and keeping them in separate water tables, we avoided this possible interaction. Another factor that could have hindered the results is light exposure. Crabs feed at higher levels at night under the cover of darkness (Robles, 1987). Due to this fact, both tanks were covered with thick black plastic to optimize the feeding rates of the crabs in the study. The water flow in each tank was maintained between .49 and .51 L/min. The temperature ranged between 13.5° C and 14° C, and the salinity varied between 34 and 37ppt during the course of the experiment.

Table 2.1: **Feeding Study Participants**

Species → Subject # ↓	*Carcinus maenas*	*Hemigrapsus nudus*	*Hemigrapsus oregonensis*	*Cancer productus*	*Cancer magister*	*Pachygrapsus crassipes*
1	F, CW = 47.15	M, CW=28.85	M, CW=23.06	M, CW=94.13	M, CW=18.5	M, CW=20.72
2	F, CW = 35.59	M, CW=24.53	M, CW=22.91	M, CW=145.64	M, CW=27.3	M, CW=21.93
3	F, CW = 31.80	M, CW=24.00	M, CW=20.24	M, CW=94.39	M, CW=103.46	F, CW=22.72
4	M, CW = 48.52	M, CW=22.94	M, CW=22.35	M, CW=49.11	M, CW=113.16	M, CW=22.65
5	M, CW = 75.99	M, CW=22.35	M, CW=21.03	M, CW=82.95	M, CW=99.72	M, CW=20.57
6	M, CW = 42.79		M, CW=32.00	M, CW=25.32	M, CW=137.82	
7	M, CW = 68.04				M, CW=122.27	
8	M, CW = 64.89					

(Carapace Width (CW) given in mm
F = Female, M = Male)

The crabs were offered 15 snails per day: 5 small, 5 medium and 5 large. Snails in each crab container were scored at approximately the same time each day for the next seven days. The score was by predation technique in the following categories: live, crushed, upper whorl peeled, peeled, attempted peel, pulled and operculum severed (see Table 2.2 for descriptions, and Figure 2.4 for illustrations of the evidence). The scoring was also maintained within the three size classes of snails. At the end of seven days the crabs that were consistently consuming all the provided prey were eliminated from the study to preserve snails. The remaining crabs were kept in the study for another six days and scored every other day. See the Results (section 3.1) for data analysis information.

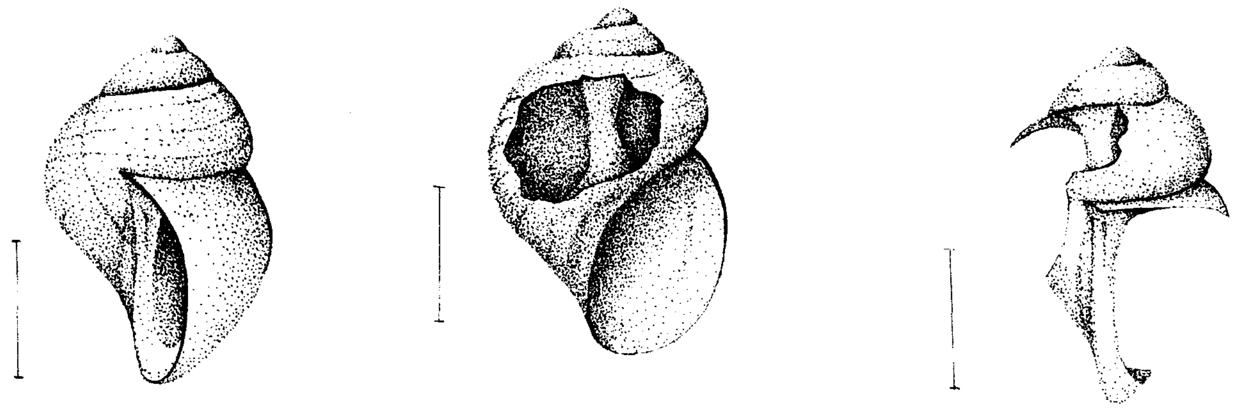
Table 2.2: **Predation Techniques**
(This table is adapted from Elner and Rafaelli, 1980, and Hughes and Elner, 1979; the modifications are based on the evidence found in this feeding study).

Predation Technique	Description	Evidence	Chelal Gape to Snail Size	Chelal Strength to Shell Strength
Live	No predation event.	Undamaged shell, live snail	--	--
Outright Crushing	Snails are indiscriminately crushed in any plane.	Non-diagnostic shell fragments, columella broken.	Large	Very Strong
Upper Whorl Peel	Tips of chelae bore holes into shell.	Puncture/peel in upper whorl of shell, lip of shell and columella intact.	Small	Medium
Peel	Chelae progressively chip away at the shell lip.	Intact columella with whorl remnants.	Small	Medium
Attempted Peel	Snail withdraws deep into the shell during an unsuccessful attempt at peeling.	Snail is still alive, but lip is chipped in a peel pattern.	Small	Weak
Pull	Chelae grasp and pull intact animal out of shell.	Empty intact shell, with little or no lip damage.	Small	Weak (slender, fast claw)
Operculum Severing	Chelae pull off all or part of operculum. This would be an attempted pull.	Intact shell with little or no lip damage. Live or dead snail, lacking operculum, still inside.	Small	Weak

2.3 Predation Lines

The first predation line trial that we conducted utilized *Mytilus trossulus* mussels as the bait. The mussels ranged in size from 30 to 50 mm and were collected off the floats and pilings by the Newport fishing docks. They were then attached near the umbo by marine epoxy glue to five-kilogram test monofilament line that was knotted on the attachment end. Twenty-five of the baited monofilament lines were then tied to five-meter lengths of leadline taken from fishing nets and two of the baited leadlines (50 mussels total) were then stretched out along the lower intertidal for one full tide cycle

Figure 2.4: **Predation Technique Diagrams**



(5 mm size bar)

Pull (un-chipped lip) | ***Upper Whorl Peel** (Green Crab Hallmark) | **Peel** - started at lip (Common technique)

(approximately twenty-four hours). They were then scored for predation hits. While we were successful in obtaining predation rates from our use of tethered mussel predation lines, we encountered some difficulties along the way. Some of the small, smoother shelled mussels became unattached on their own. This was due to the fact that there was little 'tooth' on the shell surface for the marine epoxy to adhere to. There were also some tangling problems when the five-meter leadlines were coiled for transportation. During coiling the mussels would wrap around each other, which posed some difficulties during line setting. A final drawback to using the mussel predation lines came from the fact that crabs preying on mussels do not leave behind an incriminating technique signature. This made it impossible to determine which species was responsible for attacking the line. To circumvent these problems we decided to use the grazing snail *Littorina sitkana* as the tethered model prey and four-foot sections of metal rebar as the anchor.

Medium and large *L. sitkana*, ranging in size from 9 – 14 mm (apex to bottom of lip), were collected at Siletz Bay, Oregon. Each snail was then attached at the apex of the shell to pieces of monofilament line, each about 45 cm in length, with marine epoxy. Rather than tie the baited lines to the five meter leadlines that we used previously, we chose to use a number of 91 cm sections of rebar as our anchors, attaching 10 tethered snails per section, 5 medium and 5 large. The rebar sections were much easier to handle, and tangling was greatly minimized by this change. Five of the baited rebar sections, 50 snails total, were then left at each site for one tidal cycle and scored. The scoring was done by technique usage in the same categories as specified in the feeding study: live, attempted peel, peeled, attempted pull, pulled or crushed. The predation rates were then calculated as an overall rate and by technique (see Figures 3.1 and 3.2).

2.4 Trapping

Following each predation line run we used trapping as a means by which to verify the presence of crabs expected from the predation line results. We employed folding style Aquatic Ecosystem box traps (24 x 18 x 8 inches, with 2 cm mesh) as well as minnow traps. The purpose for using two styles of traps was to get a good cross-section of the crab populations. Larger crabs cannot enter the minnow traps, and smaller crabs avoid traps that contain larger crabs that might see them as prey. Our bait consisted of salmon or tuna scraps, which were placed in egg-shaped commercial baiters (15 x 8 cm wide) pierced at regular intervals with 1 cm holes.

2.5 Rock Turning

In addition to trapping, rock turning was conducted to estimate the shore crab population size and distribution. Most of the rock turning data for Yaquina Bay was collected between September and November of 1997 and 1998. Ten Similar sized rocks, ranging between 30 and 50 cm in diameter, were randomly selected in each zone based on suitability. Suitability was determined by location (zone) and setting - only rocks resting on sediment and not deeply imbedded in the substrate were chosen. The crabs found beneath the rocks were carefully collected and placed in a bucket. The crabs were then identified, sexed and measured across the carapace. Carapace widths were measured with calipers and rounded to the lowest mm. Specimens smaller than 5mm posed difficulties in sex identification and species determination between the two *Hemigrapsus* species. The use of a small magnifying glass, however, allowed us to search for leg hairs with reasonable success and thus identify the appropriate *Hemigrapsus* species if not the gender. The data were then plotted as size frequency distributions. Graphs of the 1998 data, and graphs comparing the 1997 data with that of 1998, were then prepared for analysis.

Rock turning in Coos Bay was conducted in a slightly different manner. All sampling took place from 12 – 18 July 1999. Only five rocks were selected per site, using the same criterion as described above. The reason for the reduction in sample size selection was due to time restrictions. The data collected were therefore used as more of a qualitative rather than a comparative quantitative analysis for Coos Bay.

2.24 Molt Searches

In an effort to determine the presence of a new-year class, molt searches were conducted along the flotsam line in several locations.

3. RESULTS

3.1 Feeding Study

The data from the feeding study were run through a multiple linear regression analysis utilizing Statistical Analysis Software (SAS), a powerful statistical analysis tool. The program used was designed specifically for this particular study, and accounted for crab species, size, and status as adult or juvenile. The results of the analysis yielded an odds-ratio that represented the most likely culprit to use the technique being analyzed, followed by the number of times that the following species are **less likely** to use the technique than the other crabs being tested. The results of predation on the medium (8 - <11mm) and the large (11 - <14mm) size classes of snails were combined for the analysis because they encompass the size range of snails used on the predation line when pooled. The statistical results are presented below by technique.

Table 3.1: Odds Ratio Values for the **Crush** Technique

Species	**P-Value** (α = .05)	*Odds Ratio*	**Comparative Odds** (number of times ***less*** likely to perform Technique)
Cancer magister			Most Likely to perform Technique
Cancer productus	**.0611**	.7323	*1.3
Carcinus maenas	.0325	.7082	1.4
Hemigrapsus nudus	.0001	.0065	154
Hemigrapsus oregonensis	.0001	.0057	175
Pachygrapsus crassipes	.0031	.0031	323

* Not statistically significant, P-value above α)

Table 3.2: Odds Ratio Values for the **Upper Whorl Peel** Technique

Species	**P-Value** (α = .05)	*Odds Ratio*	**Comparative Odds** (number of times ***less*** likely to perform Technique)
Carcinus maenas			Most Likely to perform Technique
Pachygrapsus crassipes	*	0	N/A
Hemigrapsus nudus	*	0	N/A
Cancer magister	*	0	N/A
Cancer productus	*	0	N/A
Hemigrapsus oregonensis	*	0	N/A

* Program unable to determine P-value due to lack of data. This technique was not used by any other species on a large or medium sized snail. It is therefore a hallmark technique for *C. maenas*.

Table 3.3: Odds Ratio Values for the **Peel** Technique:

Species	**P-Value** (α = .05)	*Odds Ratio*	**Comparative Odds** (number of times ***less*** likely to perform Technique)
Pachygrapsus crassipes			Most Likely to perform Technique
Carcinus maenas	**.4593**	.85877	*1.2
Cancer productus	**.4419**	.84979	*1.2
Hemigrapsus nudus	.0009	.45428	2
Cancer magister	.0001	.17482	6
Hemigrapsus oregonensis	.0001	.08397	12

* Not statistically significant, P-value above α)

Table 3.4: Odds Ratio Values for the **Attempted Peel** Technique:

Species	**P-Value** (α = .05)	*Odds Ratio*	**Comparative Odds** (number of times ***less*** likely to perform Technique)
Pachygrapsus crassipes			Most Likely to perform Technique
Hemigrapsus nudus	.0001	.38492	3
Hemigrapsus oregonensis	.0001	.16431	6
Carcinus maenas	.0001	.10954	9
Cancer magister	.0001	.05556	18
Cancer productus	.0001	.02453	41

Table 3.5: Odds Ratio Values for the **Pull** Technique

Species	P-Value (α = .05)	*Odds Ratio*	Comparative Odds (number of times *less* likely to perform Technique)
Carcinus maenas			Most Likely to perform Technique
Pachygrapsus crassipes	**.0950**	.60910	*2
Hemigrapsus nudus	.0001	.17586	6
Cancer magister	.0001	.05162	19
Cancer productus	.0001	.03562	28
Hemigrapsus oregonensis	.0004	.02626	38

* Not statistically significant, P-value above α)

Table 3.6: Odds Ratio Values for the **Operculum Severing** Technique:

Species	P-Value (α = .05)	*Odds Ratio*	Comparative Odds (number of times *less* likely to perform Technique)
Pachygrapsus crassipes			Most Likely to perform Technique
Hemigrapsus nudus	.0415	.20502	5
Hemigrapsus oregonensis	.0235	.09263	11
Cancer productus	*		N/A
Cancer magister	*		N/A
Carcinus maenas	*		N/A

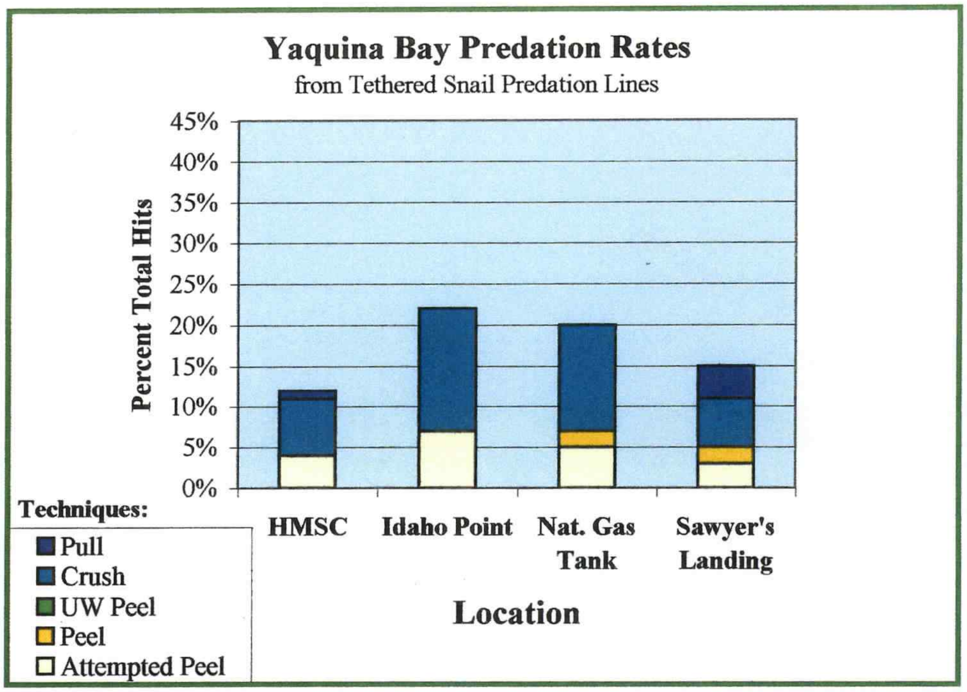
* Program unable to determine P-value due to lack of data. This technique was not used by (*) species on a large or medium sized snail. It is not likely that they will perform this technique.

3.2 Predation Lines

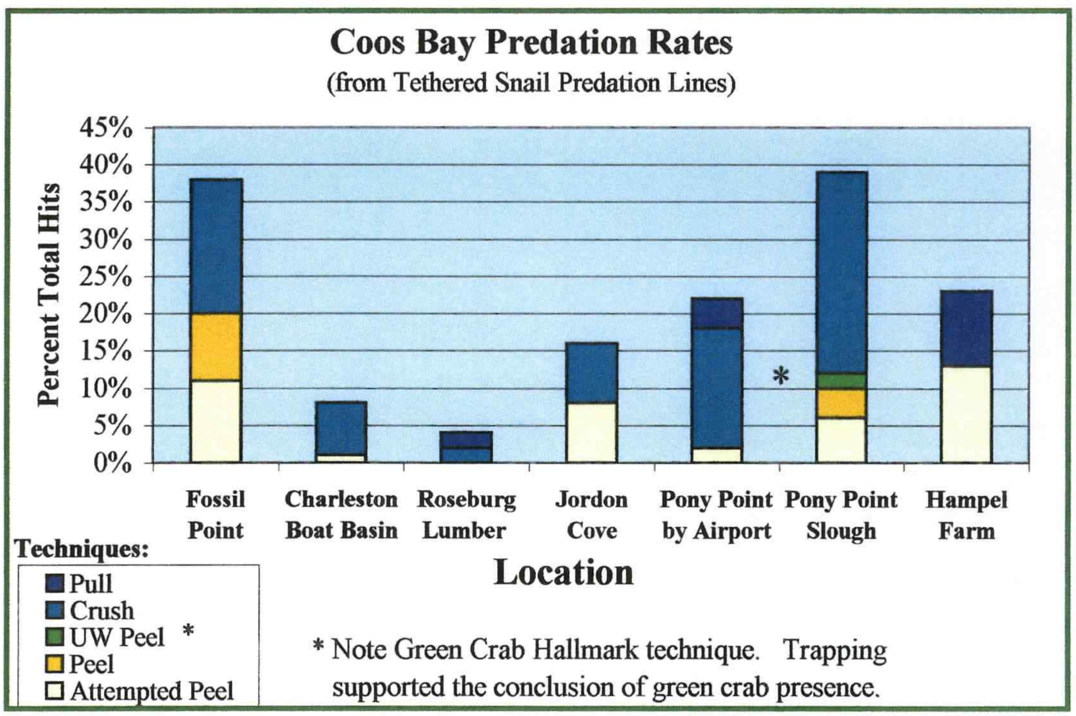
The predation line data were incorporated into bar graphs that portray the overall predation rate, and a breakdown by technique for the overall predation rate (see Graph 3.1 and 3.2).

3.3 Trapping

The trapping was conducted for qualitative rather than quantitative analysis. The data are provided in box and whisker plots showing species distributions by carapace width, with no individual number counts (Graphs 3.3 – 3.10), as well as in table format displaying individual numbers and catch per unit effort (Table 3.7 and 3.8).

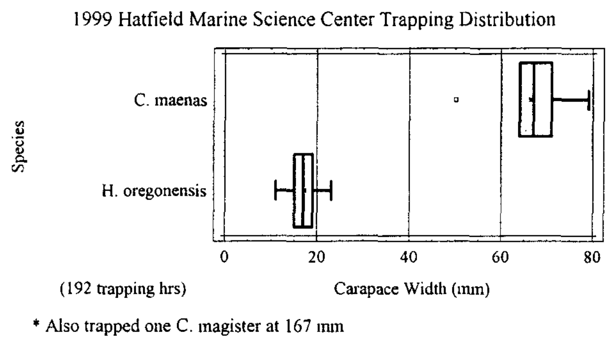


Graph 3.1: Yaquina Bay Predation Rates broken down by technique usage

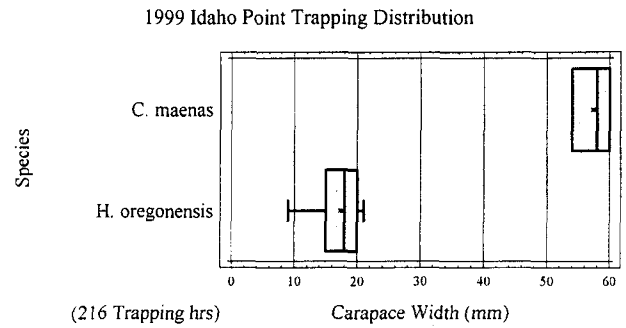


Graph 3.2: Coos Bay Predation Rates, broken down by technique usage.

Yaquina Bay

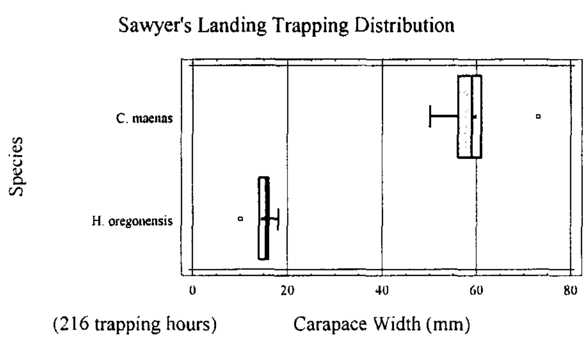


Graph 3.3: Hatfield Marine Science Center

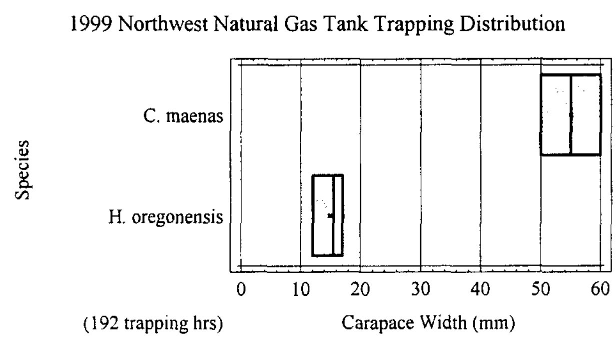


Graph 3.4: Idaho Point

These graphs are box and whisker plots that show the largest catch, the smallest catch, the median and any outliers (as separate points).

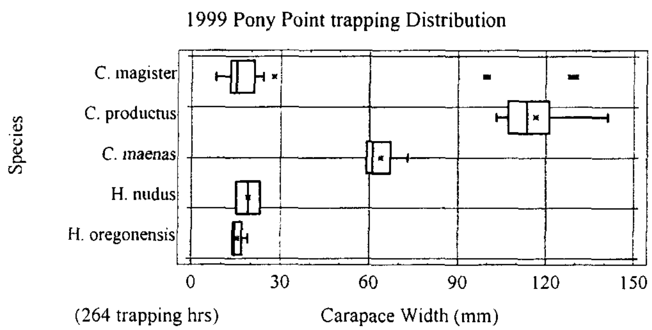


Graph 3.5: Sawyer's Landing

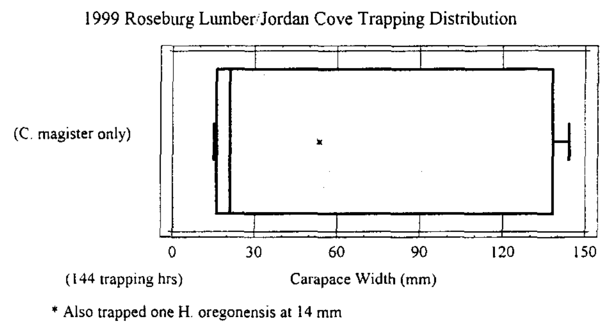


Graph 3.6: Northwest Natural Gas Tank

<u>Coos Bay</u>

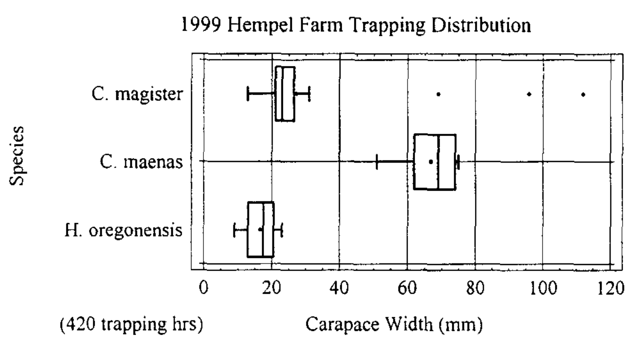


Graph 3.7: Pony Point

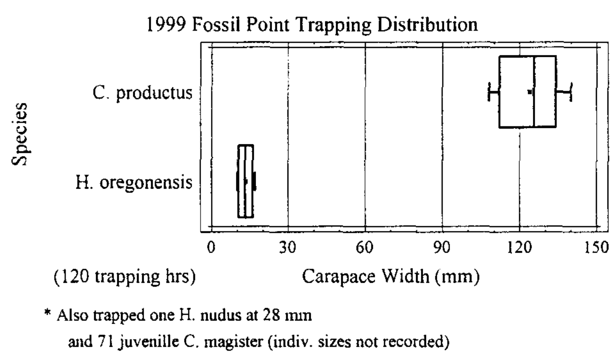


Graph 3.8: Roseburg Lumber/Jordon Cove

These graphs are box and whisker plots that show the largest catch, the smallest catch, the median and any outliers (as separate points).



Graph 3.9: Hampel Oyster Farm



Graph 3.10: Fossil Point

Yaquina Bay

Table 3.7: Trapping Specifics

Location	**# of Trap-days**	**# of Days Fished**	**Species ***	**Total Number**	**Carapace Width Size Range** (mm)	**Catch Per Unit Effort** – CPUE (#/trap/day)
Hatfield Marine Science Center	9	2	*H. oregonensis*	11	11 – 23	1.22
			C. maenas	**7**	**50 – 79**	**.78**
			C. magister	1	167	.11
Idaho Point	9	2	*H. oregonensis*	19	9 – 21	2.11
			C. maenas	**3**	**54 – 60**	**.33**
Sawyer's Landing	9	2	***C. maenas***	**7**	**50 – 73**	**.77**
			H. oregonensis	6	10 – 18	.66
Northwest Natural Gas Tank	8	2	*H. oregonensis*	6	12 – 17	.75
			C. maenas	**2**	**50 – 60**	**.25**

*Note: species are listed in order of abundance, with the most abundant species per site listed first.

Coos Bay

Table 3.8 Trapping Specifics

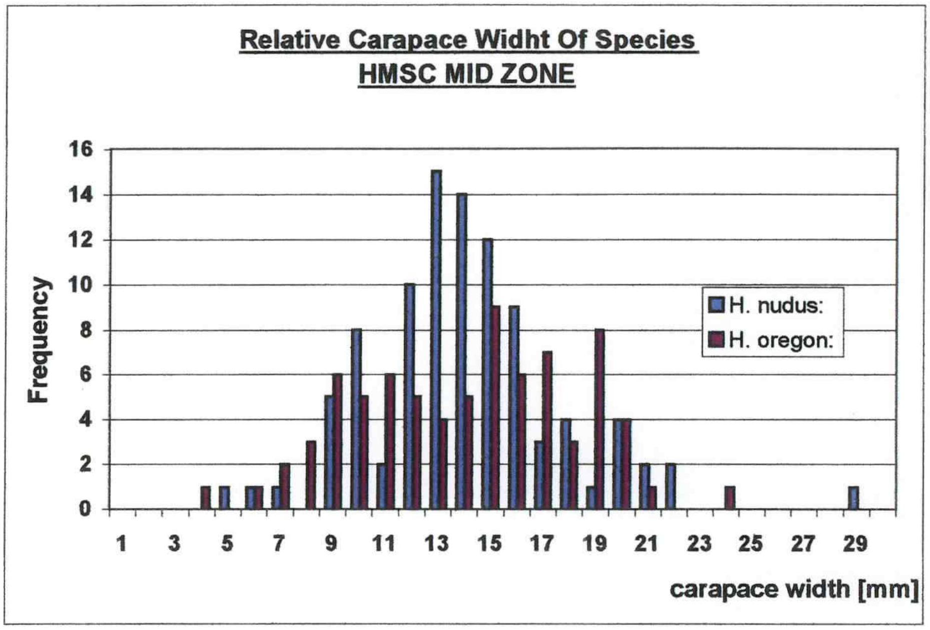
Location	**# of Trap-days**	**# of Days Fished**	**Species ***	**Total Number**	**Carapace Width Size Range** (mm)	**Catch Per Unit Effort** – CPUE (#/trap/day)
*Pony Point	11	2	*C. magister*	32	8 – 130 **mean = 27.6	2.91
			H. oregonensis	8	14 – 19	.73
			C. productus	6	103 – 141	.55
			C. maenas	**5**	**59 – 67**	**.45**
			H. nudus	2	15 – 23	.18
Roseburg Lumber	6	1	*C. magister*	7	15 – 144 **mean = 54.3	1.17
			H. oregonensis	1	14	.17
Hampel Oyster Farm	17.5	3	*C. magister*	68	13 – 112 **mean = 27.3	3.886
			H. oregonensis	12	9 – 23	.686
			C. maenas	**10**	**51 – 75**	**.571**
Fossil Point	5	1	*C. magister*	71	13 – 31 **mean = 23	14.2
			C. productus	8	108 – 140	1.6
			H. oregonensis	4	10 –17	.8
			H. nudus	1	28	.2

* *It should be noted that the trapping in Coos Bay occurred in the middle of a strong *C. magister* recruitment, which boosted the CPUE for this species. The mean size is provided to show the size skew of the new year class.

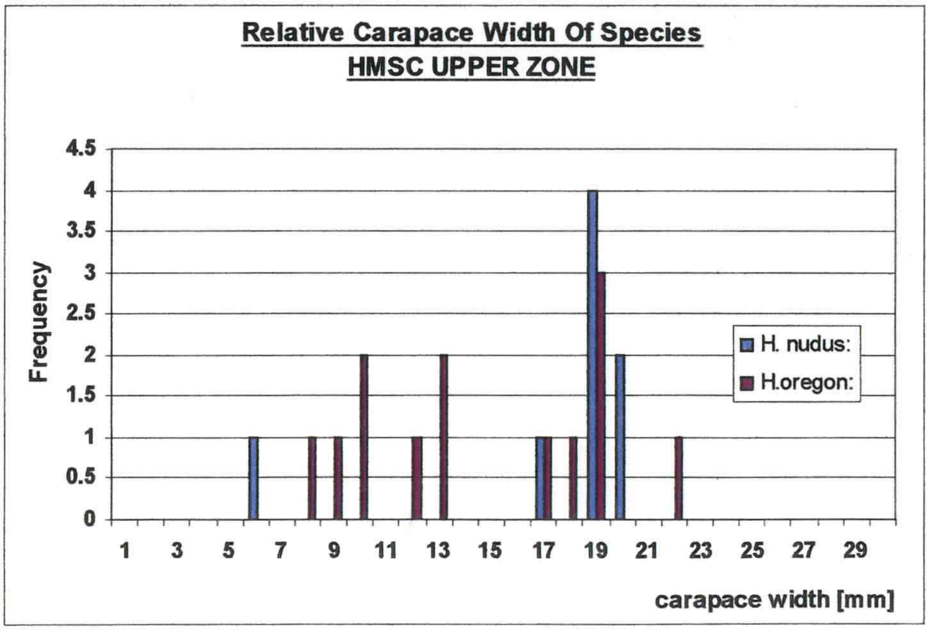
3.3 Rock Turning

Yaquina Bay

Hatfield Marine Science Center Site –

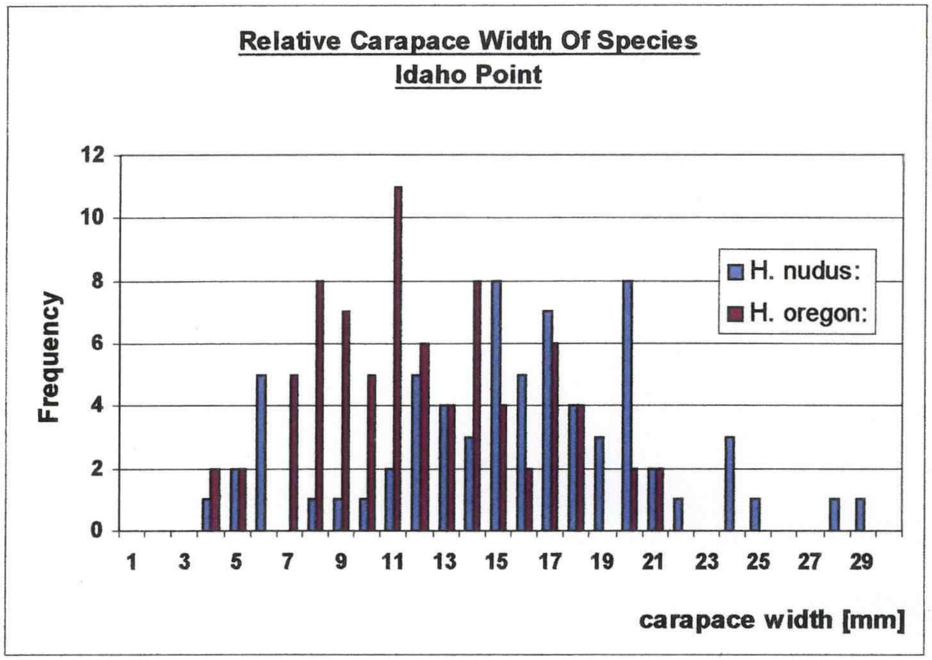


Graph 3.11: Hatfield Marine Science Center, Mid-Zone



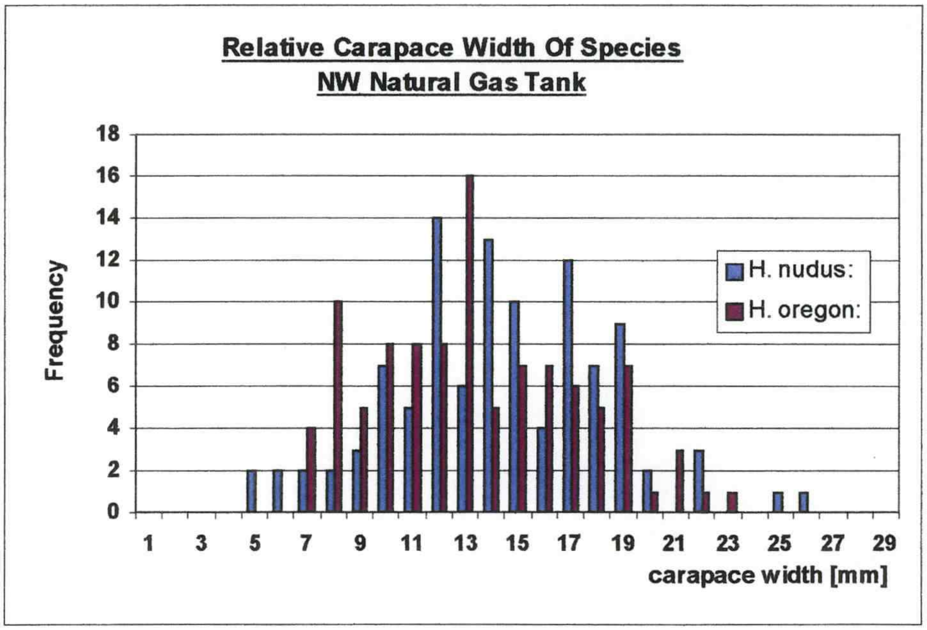
Graph 3.12: Hatfield Marine Science Center, Upper-Zone

Idaho Point –



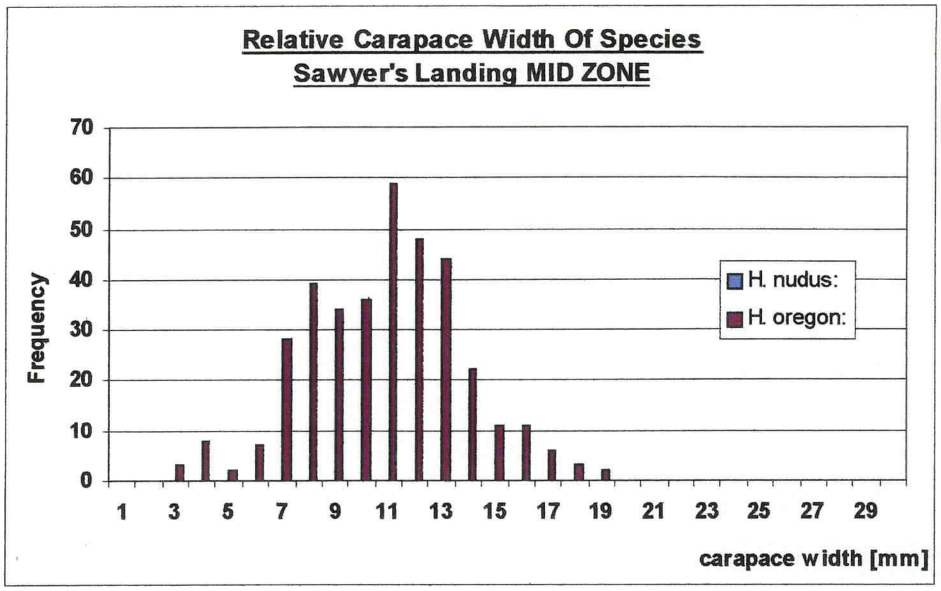
Graph 3.13: Idaho Point

Northwest Natural Gas Tank –

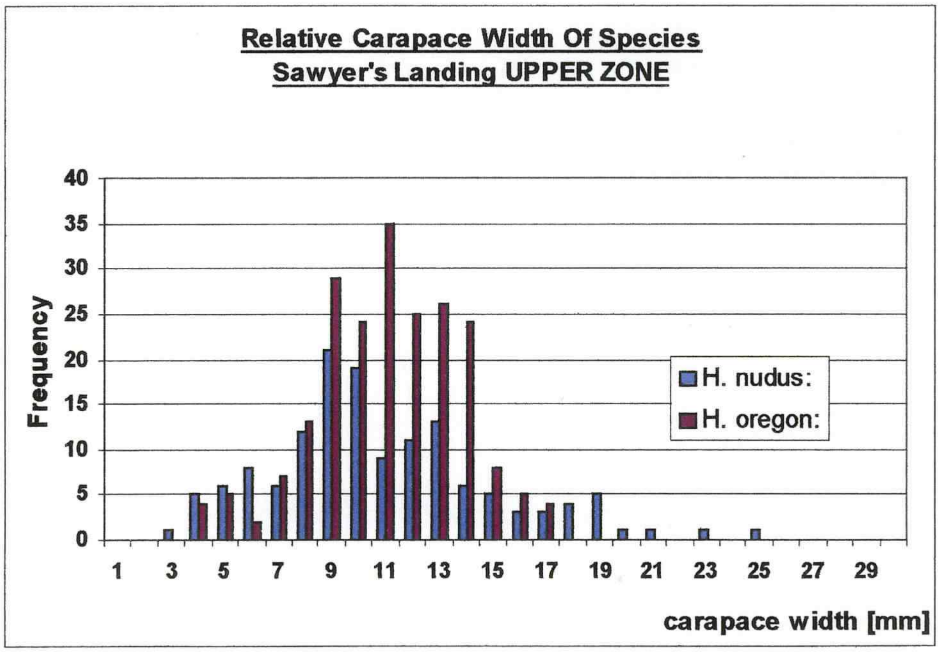


Graph 3.14: Northwest Natural Gas Tank

Sawyer's Landing –



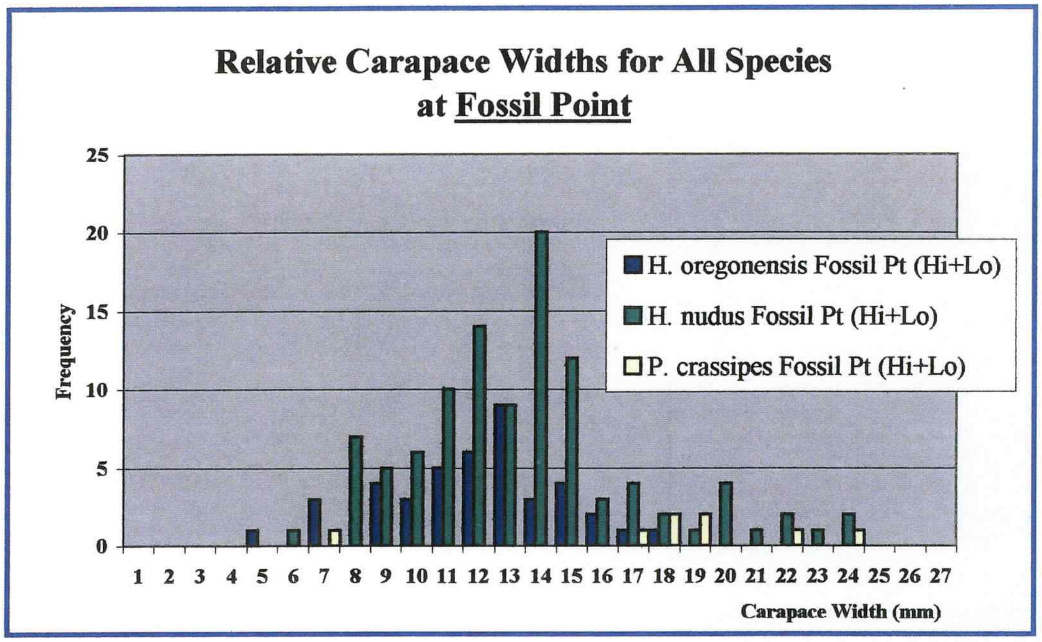
Graph 3.15: Sawyer's Landing, Mid-Zone



Graph 3.16: Sawyer's Landing, Upper-Zone

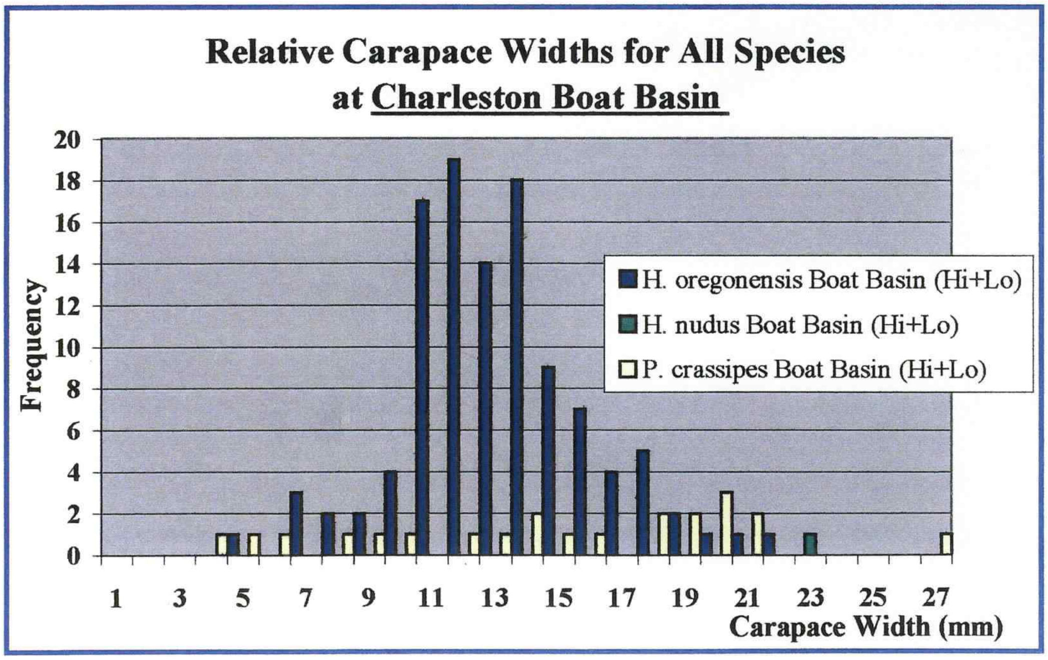
Coos Bay

Fossil Point –



Graph 3.17: Fossil Point, both sampling zones combined

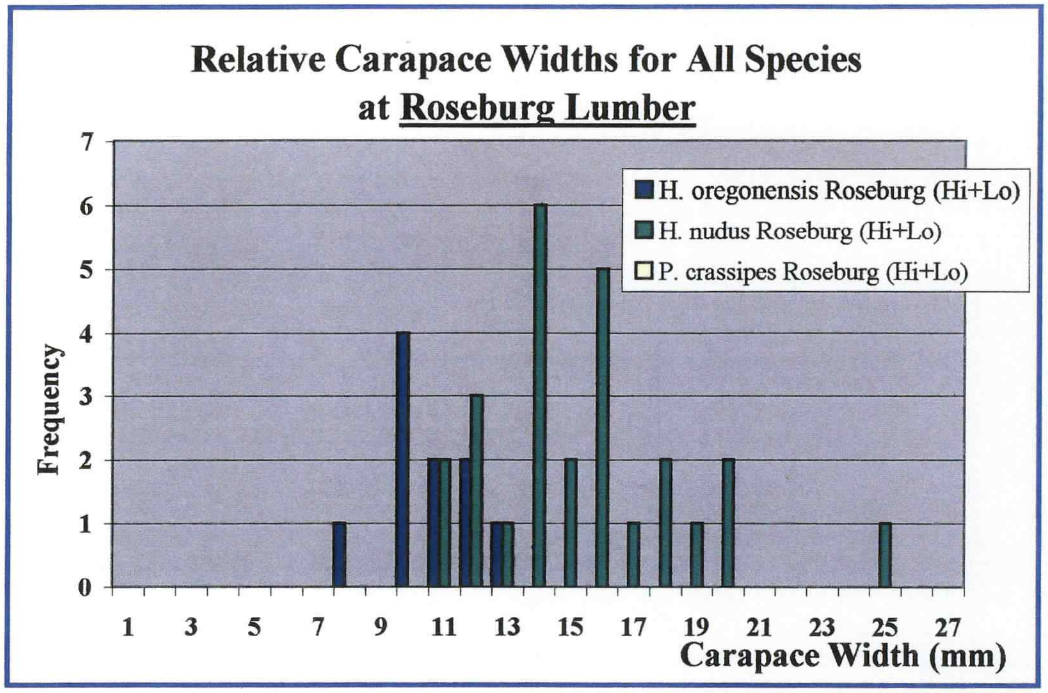
Charleston Boat Basin –



Graph 3.18: Charleston Boat Basin, both sampling zones combined

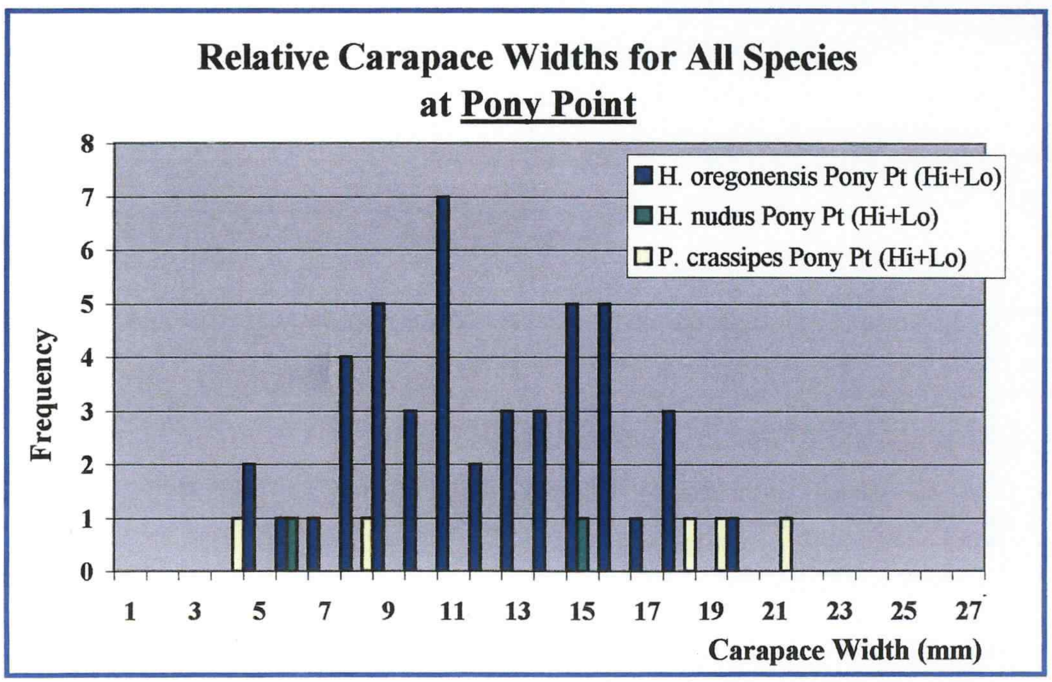
Coos Bay (continued)

Roseburg Lumber –



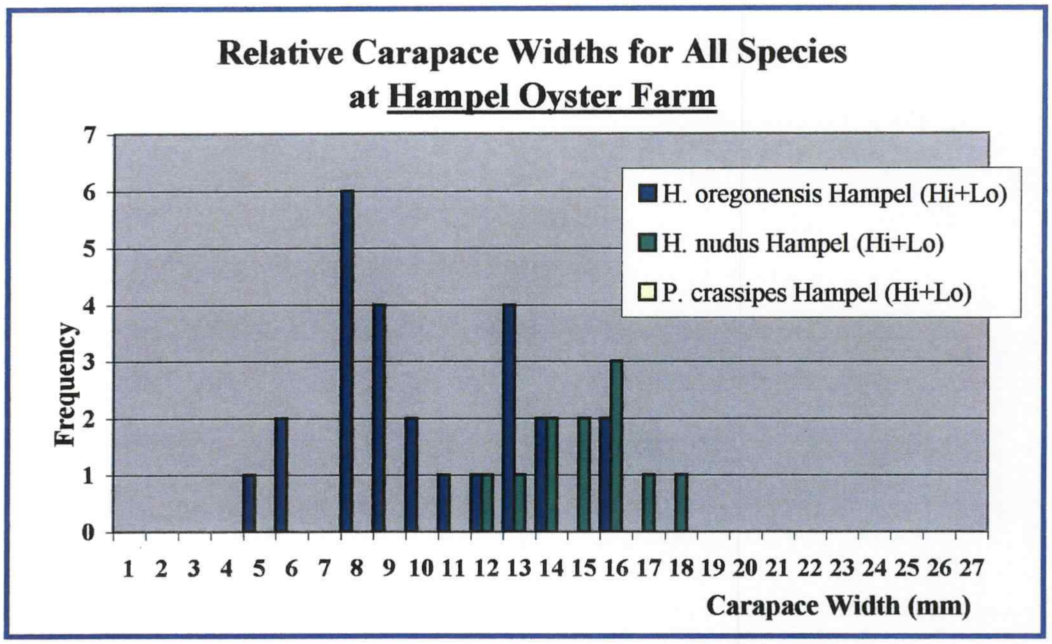
Graph 3.19: Roseburg Lumber, both sampling zones combined

Pony Point –



Graph 3.20: Pony Point, both sites, and both sampling zones combined

Hampel Oyster Farm –



Graph 3.21: Hampel Oyster farm, both sampling zones combined

3.5 Molt Searches

Yaquina Bay:

While conducting other sampling techniques at the established sampling sites searches for molts were conducted. Many large (50 – 60 mm) *Carcinus* molts were found, but no juvenile molts were recovered.

Coos Bay:

Searches were conducted as described above, during the employment of other sampling techniques. Fewer *Carcinus* molts were recovered, most of which were broken pieces, and no juvenile molts were recovered.

- **South Slough Estuarine Sanctuary Trail**, in addition to the molt searches conducted at the established sampling sites in Coos Bay, a hike was conducted within the South Slough Estuarine Sanctuary to search for molts. The following molts were found:

Table 3.9: Molt Search Results for South Slough Estuarine Sanctuary

Species	Male	Female	Unidentified	Total
H. oregonensis	34	24	74	153
H. nudus	7	4	4	15
P. crassipes			4	4
C. magister			Present (uncountable pieces)	
C. maenas	3 breast plates (one male), one claw with 18.9 propal height, and a 40 mm carapace. No juvenile *Carcinus* molts were recovered.			

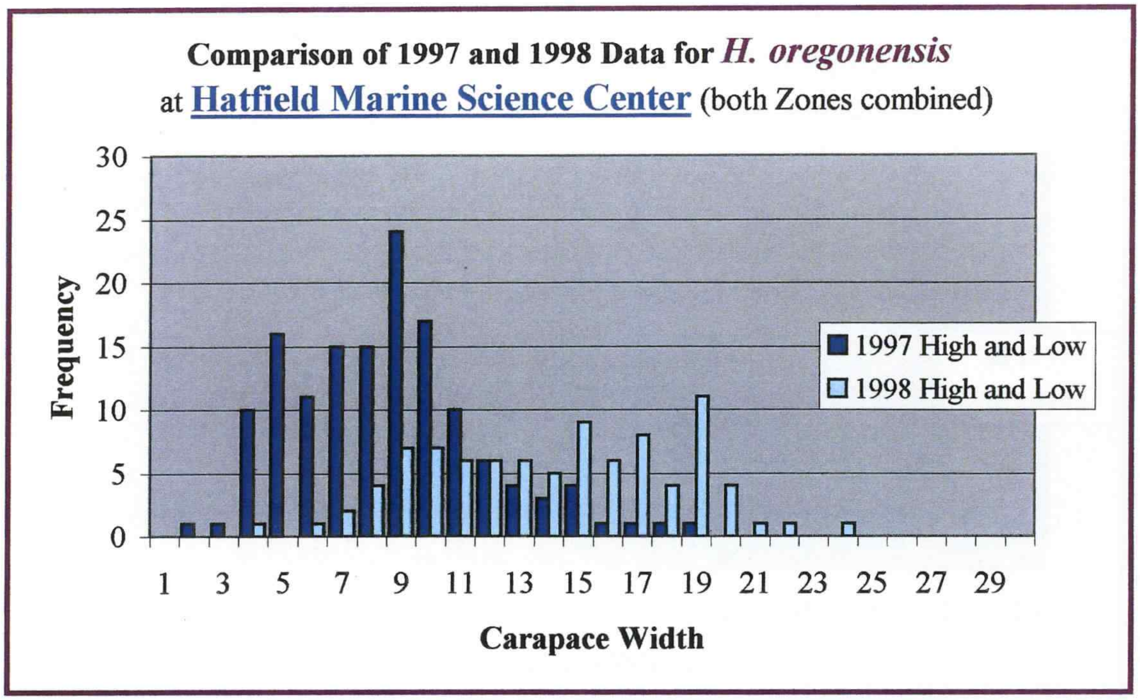
4. DISCUSSION

4.1 Rock Turning

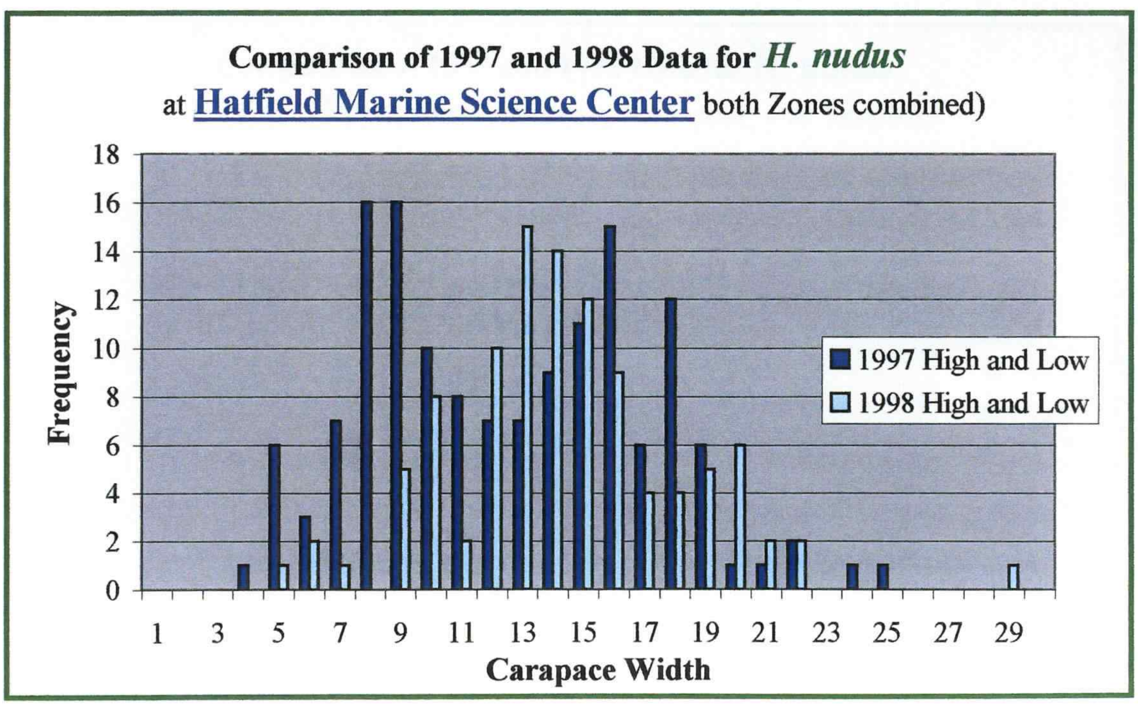
Rock turning was the best method to collect baseline data for the shore crab populations. Yaquina Bay has been consistently sampled, which allowed the opportunity to compare the data collected in 1998 with data collected in 1997. Students and faculty of the Green Crab Project, Oregon State University, collected the 1997 and 1998 data following the procedures outlined in section 2.23. The comparisons shown below encompass the reasoning behind collecting baseline data. Without knowing where a population once was it is difficult to see the changes in population dynamics that can result from an ecologically changing event, such as the invasion of a non-indigenous species. Unfortunately Coos Bay has not been consistently sampled and such comparisons were not possible.

Yaquina Bay 1997/1998 Data Comparisons

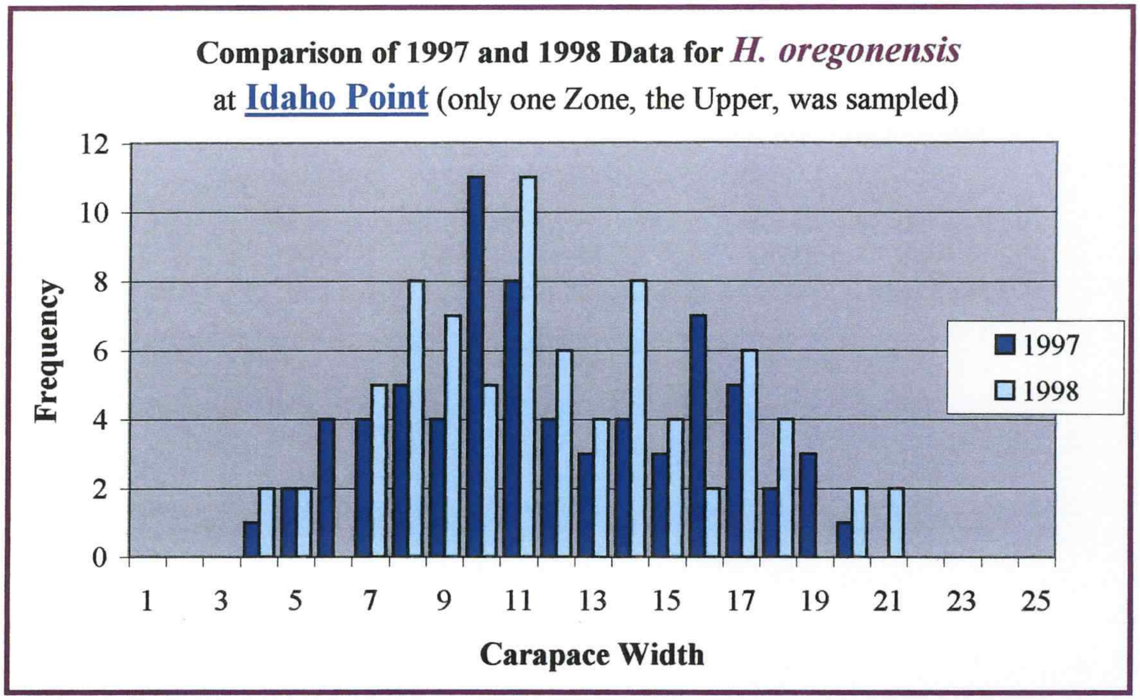
The graphs below are arranged by site, with one graph for each species. Graphs 4.1 and 4.2 show the 1997 – 1998 comparison data for the Hatfield Marine Science Center (both zones combined), 4.3 and 4.4 show the comparisons for Idaho point, 4.5 and 4.6 portray the comparisons for the Northwest Natural Gas Tank Site, and the Sawyer's Landing comparisons (both zones combined) are revealed in 4.7 and 4.8.



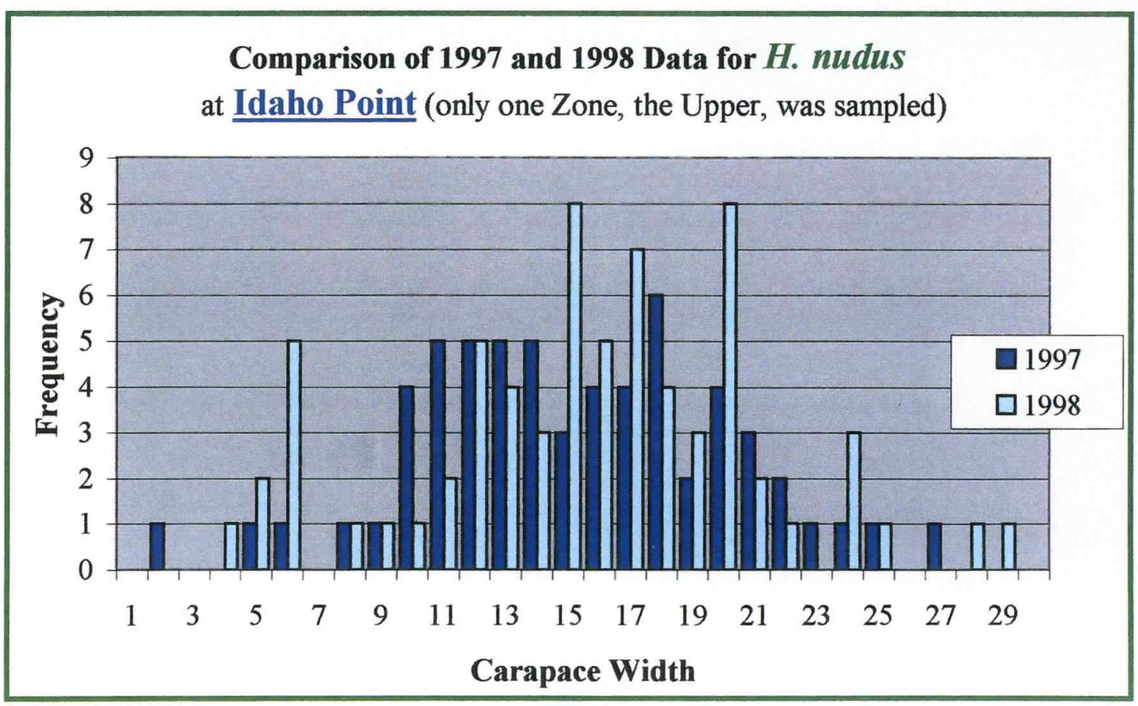
Graph 4.1: Comparison of 1997 – 1998 Data for *H. oregonensis* at HMSC



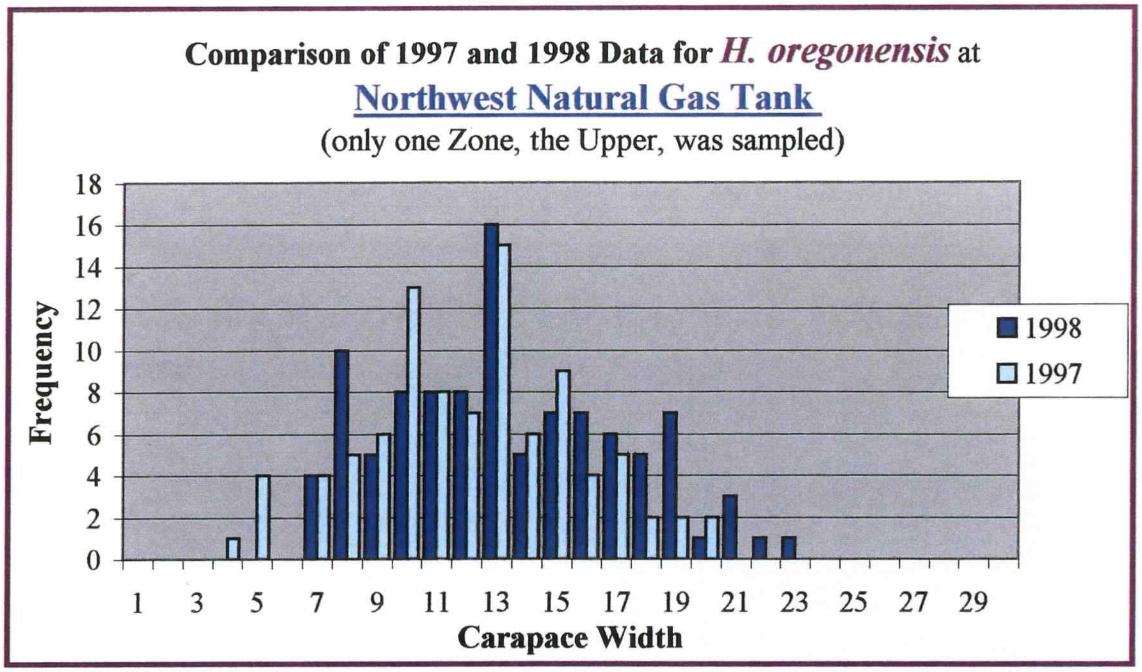
Graph 4.2: Comparison of 1997 – 1998 Data for *H. nudus* at HMSC



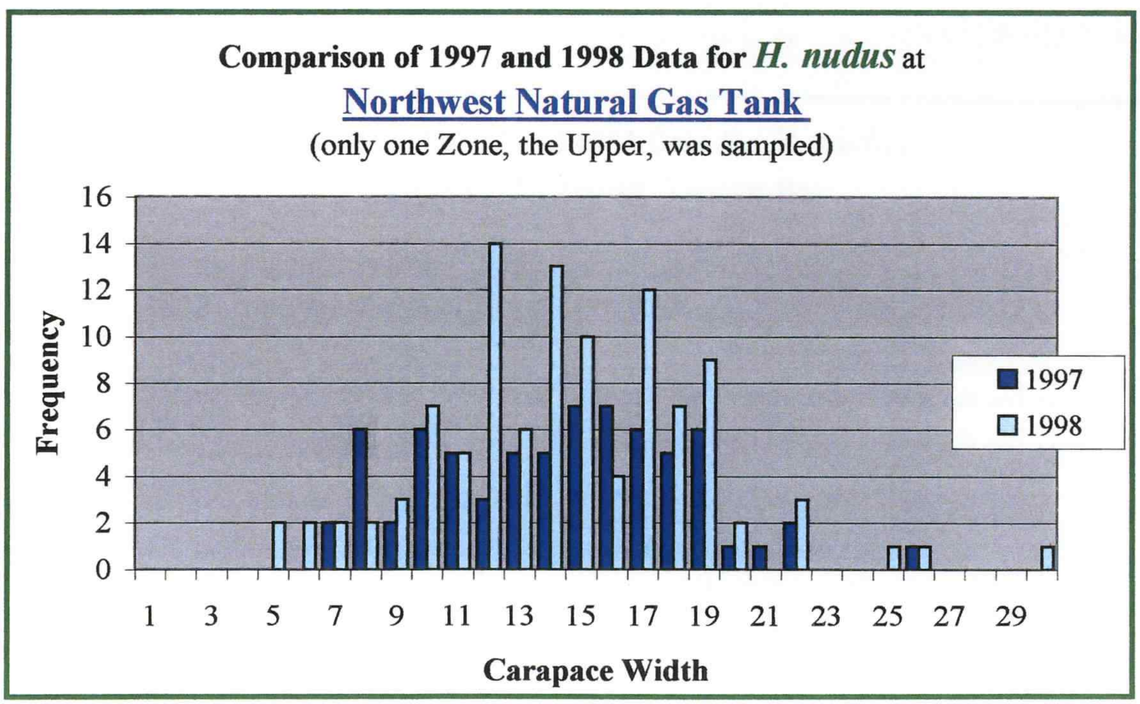
Graph 4.3: Comparison of 1997 – 1998 Data for *H. oregonensis* at Idaho Point



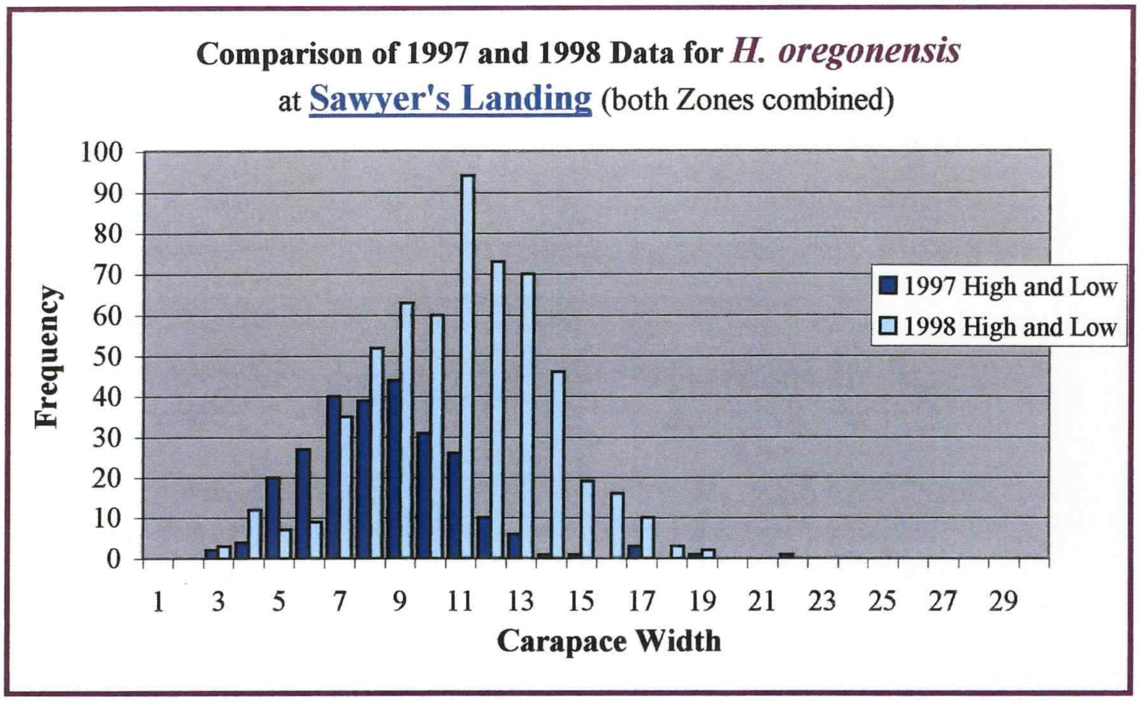
Graph 4.4: Comparison of 1997 – 1998 Data for *H. nudus* at Idaho Point



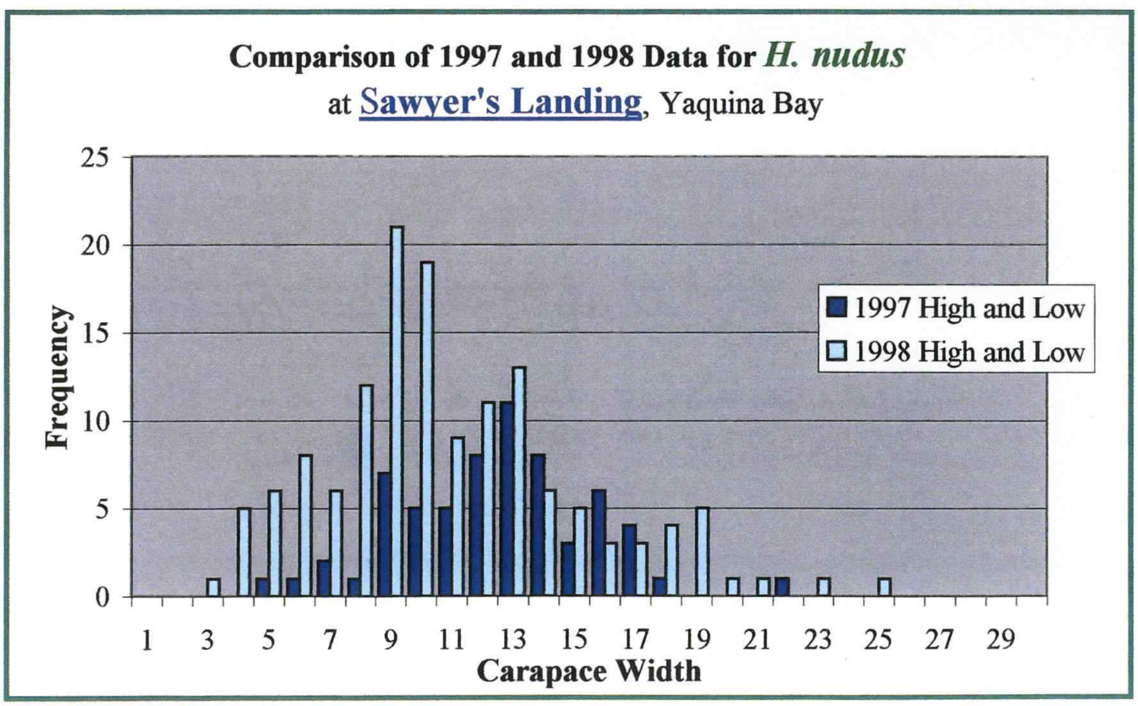
Graph 4.5: Comparison of 1997 – 1998 Data for *H. oregonensis* at the Natural Gas Tank



Graph 4.5: Comparison of 1997 – 1998 Data for *H. nudus* at the Natural Gas Tank



Graph 4.7: Comparison of 1997 – 1998 Data for *H. oregonensis* at Sawyer's Landing



Graph 4.8: Comparison of 1997 – 1998 Data for *H. nudus* at Sawyer's Landing

The comparisons for both species at Northwest Natural Gas site and Idaho Point, and for *H. nudus* at Hatfield Marine Science Center and Sawyer's Landing, portray stable populations that appear to be very close in both size and distribution. In contrast, the graphs for *H. oregonensis* at Hatfield Marine Science Center and Sawyer's Landing (Graph 4.1 and 4.7) are quite different. These graphs reveal an apparent size shift increase in the average carapace width for *H. oregonensis* populations at both sites. In order to test this possible conclusion the data was statistically analyzed using a two-sample "t" significance test. This test is used to determine if there is indeed a significant difference between the average carapace width for *H. oregonensis* between the years 1997 and 1998. A significant difference in this test proves that there is a shift in average carapace width, and that the difference is not the result of a sampling margin of error. The results of this analysis are shown in Table 4.1, and confirm the conclusion that, for some unknown reason, the average carapace width for *H. oregonensis* is increasing at these two locations.

Table 4.1: Test For Significant Difference in Carapace Width for ***H. oregonensis*** Between 1997 and 1998

Site/ Zone	**1997** Mean Carapace Width (mm)	**1998** Mean Carapace Width (mm)	**t-Statistic p-value** ($\propto = .05$)
HMSC/ High	7.92	14.54	p off chart, < .0005 **.0005 < .05**
HMSC/ Low	8.82	14.04	p off chart, < .0005 **.0005 < .05**
Sawyer's Landing/ High	7.57	11.06	p off chart, < .0005 **.0005 < .05**
Sawyer's Landing/ Low	9.19	10.76	p off chart, < .0005 **.0005 < .05**

These observations likely reflect growth of the 1997 *H. oregonensis* class at both sites, and limited recruitment from the 1998 class at the HMSC site. The limited recruitment could possibly be due to *C. maenas* predation on the new-year class, but there may be other explanations that tie *C. maenas* into the picture. Hypothetically, just the movement of a new species into the area may explain this trend. Recall that the movement of *C. productus* into the intertidal during the winter was actually a slightly positive factor for *H. oregonensis* (Daly, 1981). *C. maenas* may be moving in and out of the preferred habitat, displacing *H. nudus*, and providing *H. oregonensis* with occasional access to the preferred habitat. Such an interaction would benefit *H. oregonensis* and result in a larger average carapace width. This is all speculation, however, and continued monitoring of this baseline data is highly recommended to see if the population dynamics of the shore crabs are indeed shifting and not just varying from year to year.

4.2 Feeding Study

It should be noted that our sample sites were chosen as representations of the habitat most likely to be invaded by the green crab. Respectively, the crabs included in the feeding study are also most likely to be affected by the invasion of *Carcinus maenas.* Because of their status as 'prey' to the green crab, *Hemigrapsus* crabs represent the crabs most likely to be interfered with negatively. This is because *H. nudus* and *H. oregonensis* range from the mid to low intertidal zones and are thus very likely to encounter *C. maenas* individuals as they forage into the low and mid-intertidal when the tide rises. These crabs are also very likely to encounter a predation line left in the field at the low intertidal zone. *P. crassipes*, on the other hand, is actually more suited to a largely terrestrial life and spends half of its time out of the water in the upper intertidal zone (Garth & Abbot, 1980). Due to this lifestyle the likelihood of this species encountering a *C. maenas*, or a predation line set in the low intertidal, is unlikely. Its inclusion in the feeding study was necessary for completeness, however, because predation lines set in the mid to upper intertidal would score hits from *P. crassipes.* There is a strong likelihood that the two cancrid crabs, *C. productus* and *C. magister*, could potentially encounter and prey upon tethered snails set in the low intertidal. They are also likely to encounter *C. maenas* as it too moves in and out of the intertidal with the tide. The cancrid crabs, particularly *C. productus*, are actually our best line of defense against this invader. In a study by Hunt (2000) a pattern emerged linking *C. productus* presence to *C. maenas* absence. This may be the result of the native crab out-competing the invasive crab, and is quite promising as a population control for the green crab. This controlling factor is absent in many locations, however, due to the physical limitations of *C. productus* in withstanding desiccation and low salinity.

The emergence of the "Upper Whorl Peel" as a hallmark technique for the green crab in the feeding study was quite significant. This technique increases the value of the predation line tool tremendously when estimating the impact of this invasive species.

Because no other crab successfully employed this technique on medium or large snails in the feeding study this signature verifies green crab foraging as a percent of the overall predation rate. In addition, although many techniques were shared, there was evidence of a hierarchy of use among the other techniques. If you consider the natural habitat ranges of the crabs involved in the feeding study it is possible to abstract the most likely culprit utilizing a shared technique with a relatively high degree of certainty. This can only be done if the species diversity at the study site is relatively low.

For example, review the feeding study results for the "Pull" technique (Table 3.2). *C. maenas* was most likely to utilize this technique, however *P. crassipes* was only two times less likely to use it. In fact, the results were so close between the two crab species that the statistical program found the difference to be not statistically significant. Knowing that in actuality *P. crassipes* would not hit a line set in the low intertidal we would disregard the likelihood of it being the culprit. The next likely predator to pull a snail out of its shell is *H. nudus* and this crab is (a statistically significant) six times less likely to use the "Pull" technique. The remaining crabs are far behind at nineteen to thirty-eight times less like than *C. maenas* to use the "Pull". We would therefore conclude that a "Pull", recorded from the low intertidal of a site where *C. maenas* has been observed, would most likely be the work of *C. maenas*. Using this type of logic the predation picture becomes quite a bit clearer when estimating the foraging impact of a specific species.

Respectively it should be noted that "Crushes" indicate *C. productus*, *C. magister*, and *C. maenas* hits by relatively equal proportions (less than a two difference), and would not reflect the presence of any of the smaller shore crabs (Table 3.3). The "Peel" technique was the least specific technique successfully employed. All the crab species, to one degree or another, peel their snail prey (Table 3.4). The only significant finding for this technique was that *H. oregonensis* was quite a bit less likely to peel than all the other crab species. This is probably due to its broad, stout chelipeds. Their morphology would make them clumsy when trying to delicately peel a shell. Surprisingly the two larger crabs, *C. productus* and *C. magister*, were relatively proficient at the technique even though their claw strength would allow them to crush the snail shells outright.

"Attempted Peels" were the work of the smaller crabs. There could, however, be factors causing these results that would offset the usefulness of this data in field application. First and foremost is the fact that the only food that these crabs were provided with was the snails. Smaller crabs have weaker claws and would thus have a more difficult time eating hard-shell prey. Given no other alternative food source, and hunger from many days of captivity, they would probably at least try to eat them even if their efforts fail. This would boost the likelihood of their utilizing an unsuccessful peel technique that would not necessarily be evident in the field. For this reason I would not recommend seeking a predator for an "Attempted Peel" technique used on a predation line set in the field based on the results in Table 3.5. "Operculum Severing", the attempted pull technique, was not a common appearance in the feeding study and was never observed in the field. This technique also portrayed the smaller grapsid crabs as the most likely culprits, and once again this may be the result of laboratory confinement. Both attempted peels and operculum severing are unsuccessful predation efforts, indicating that the crabs attempting to prey on the snails are not very proficient at consuming hard shell prey. Both of the *Hemigrapsus* crabs have an IMA of 0.28 and are generalists rather than mollusk specialists. The results of this feeding study support this conclusion by revealing them as the most unsuccessful predators on *L. sitkana* in the group.

4.3 Trapping

Trapping was conducted to confirm or deny the presence of crabs indicated by the shell fingerprints left behind on the predation lines. In most cases only one or two days of trapping was conducted immediately following the setting of the predation lines. The short number of days is unfortunate because of the inconsistent nature of the trapping method. Not only are we unable to come to any solid conclusions regarding population densities, we may also have missed trapping a species all together.

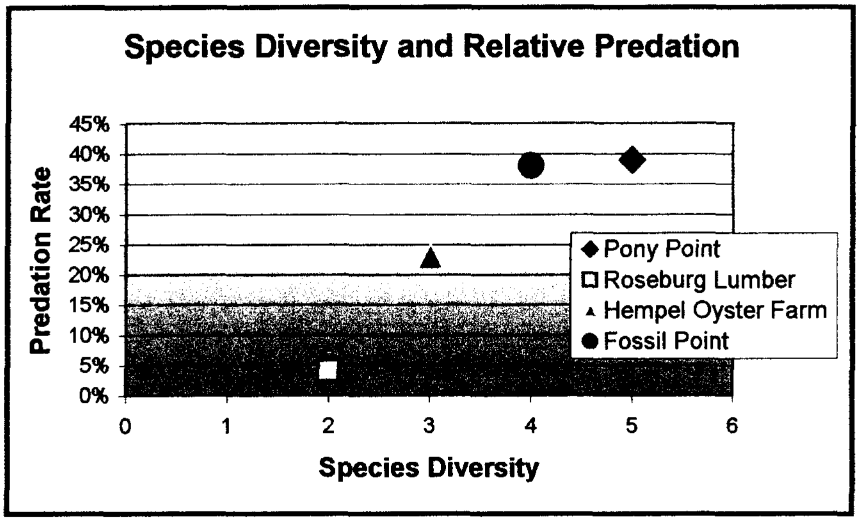
There are two trapping events for each site in Yaquina Bay. We were unable to conduct trapping at all of the Coos Bay sites, however, due to time restrictions. For this reason we cannot confirm or deny the presence of the expected crabs from the Charleston Boat Basin or Jordon Cove predation lines and will therefore not specifically discuss those results. In addition to the lack of trapping at some sites we also lost traps at the Pony Point Slough site (most likely stolen as this is a busy boat ramp). As a result of this complication it was necessary to lump the two Pony point sites into one trapping category (referred to as *Pony Point from here on). This may or may not be appropriate considering the fact that these two sites reflect to different habitat types that are approximately 800 meters apart. It is, however, likely that the crabs might move up and down the slough with the tide – which would support the sharing of the trapping data. For the purpose of discussing the predation lines the data from the two traps recovered from the slough were added to the data from the 9 traps set at the Pony Point Airport site. Overall, downfalls aside, the trapping was a good snapshot that provides an instantaneous predator picture to which we were able to compare our instantaneous predation line results – and thus test the predator identification theories behind the predation line.

4.4 Molt Searches

Molt searches and rock turning were the methods intended to reveal the presence of a juvenile green crab class. No molts for a juvenile class were recovered in either bay during this study, nor were any juvenile crabs exposed by rock turning or trapping. In September, shortly after this study was terminated, less than a dozen juvenile class crabs were discovered in Yaquina Bay during tow weeks of trapping with 10 pitfall traps. This reflects a small, but present, new-year class. Due to this late find it may be advisable, in spite of the labor intensity of employing this method, to add pitfall traps to the sampling regime outlined in this study.

4.5 Predation Lines

The first trend evident when comparing the Yaquina predation rates to the Coos predation rates is that the predation rates in Coos Bay are higher at three of the seven sites (Fossil Point, Pony Point and Hampel Oyster Farm). Reviewing the trapping data for the two bays reveals another trend. At each of the four Yaquina sites *C. maenas* was the only mollusk specialist to be trapped, except for one *C. magister* at Hatfield Marine Science Center. Conversely, Coos Bay trapping (only conducted at *Pony Point, Roseburg Lumber, Hampel Oyster Farm and Fossil Point) revealed the presence of other mollusk specialists as well. Trapping at Pony Point, where predation was highest, recovered all species from the feeding study except *P. crassipes* (the absence of which supports the conclusion that this species is unlikely to dwell in the lower intertidal). The high species diversity at this site could be the reason behind the high predation rate results (see Graph 4.6) .



Graph 4.6: Coos Bay Predation (% per day) as a Function of Species Diversity

Fossil Point also had a high predation rate. Trapping here revealed the presence of *C. productus* in a relatively high concentration, *H. oregonensis*, a large number of juvenile *C. magister* and one *H. nudus*. This is reasonably high species diversity, but only the *C. productus* could be responsible for the crushing (discussed below). This would indicate that this species must have a rather high consumption rate or has a high population density - for which we do not have reliable data. The theory of a high consumption rate is confirmed when the feeding study data are analyzed for total consumption rates (see Tables 4.1 and 4.2). Surprisingly, though, *C. maenas*, in spite of its smaller mean carapace width, had the highest consumption rates in our feeding studies – not *C. productus*. In reviewing the results from the predation rate study by Behrens Yamada and Boulding of 1996 we see again that *C. productus* is quite a proficient predator. In this study the predation rates at the zero tide level at three of their Washington sites; Roche Harbor, Lab Pier, and Lab 6; were quite high, ranging from 40% to over 70% per day for the large snail class. *C. productus* was trapped with elevated numbers at each of these sites. This concurring evidence supports the conclusion that *C. productus* is quite a voracious predator in its own right and largely responsible for the elevated predation rate found at Fossil Point.

Table 4.2: Predation Rate on Medium and Large Snails by Species

Species	# of Participants	Mean Carapace Width (mm)	# of Trials (all participants combined)	Total # of Snails Fed	Total # of Snails Consumed	Overall Predation Rate
C. maenas	8	51.8	53	530	396	75%
C. magister	7	88.9	38	380	269	71%
C. productus	6	81.9	46	460	313	68%
P. crassipes	5	21.7	50	500	89	18%
H. nudus	5	24.5	48	480	46	10%
H. oregonensis	6	23.6	53	530	40	8%

* Data taken from the feeding study, **medium and large snails** were only considered for application to field predation line data.

Table 4.3: Predation Rates on all Snails by Species

Species	# of Participants	Mean Carapace Width (mm)	# of Trials (all participants combined)	Total # of Snails Fed	Total # of Snails Consumed	Overall Predation Rate
C. maenas	8	51.8	53	795	600	75%
C. productus	6	88.9	46	690	444	64%
C. magister	7	81.9	38	570	346	61%
P. crassipes	5	21.7	50	750	164	22%
H. nudus	5	24.5	48	720	101	14%
H. oregonensis	6	23.6	53	795	85	11%

* Data taken from the feeding study, **all snail size** categories were included

4.5 Pulling it all Together

Applying the feeding study conclusions discussed above to the predation lines, and verifying the conclusions by analyzing the trapping data, is quite tricky. The only site that scored the hallmark upper whorl peel technique was Pony Point Slough, where we were unable to trap. The rest of the results must be dealt with carefully as the techniques are shared among the species. In all of the discussions below attempted peels were included as 'predation events' in the overall predation rates.

Yaquina Bay

The Yaquina Bay sites are all quite similar to one another with respect to crab species diversity and overall predation rates. These facts make Yaquina Bay optimal as a control for testing the predation lines. We know that *C. maenas* is the most likely crab to use the pull technique with *H. nudus* next in line (only 6 times less likely) when we disregard the results of *P. crassipes* as discussed previously. At Sawyer's Landing, where there were pulls, only *C. maenas* and *H. oregonensis* were trapped. Because *H.*

oregonensis is 38 times less likely to pull, *C. maenas* is most likely responsible for those predation events. This equals approximately 4%. Add the crushes at this site, which *H. oregonensis* is 175 times less likely to perform, and you can conclude that *C. maenas* is responsible for another 6%. This means that green crabs were responsible for approximately 67% of the 15% gastropod predation rate (10%) at Sawyer's Landing. Hatfield Marine Science Center also had pulls, but one *C. magister* was trapped. While *C. magister* is 19 times less likely to pull, it is more likely to crush (though not by much) which makes the reading of this predation line a little more difficult without being able to quantify the population distributions. It is safer to say that *C. maenas* and *C. magister* are both responsible for about 67% of the 12% gastropod predation rate (8%) at this site, rather than to try and divide the responsibilities. Idaho Point was another site that revealed the presence of only *C. maenas* and *H. oregonensis* in the traps. By the logic used in analyzing the predation line data at Sawyer's Landing it can be determined that *C. maenas* is responsible for the crushes, and thus 68% of the total 22% gastropod predation rate (15%) at this site. The Northwest Natural Gas Tank trapping had the same results. Accordingly, the crushing predation, equal to about 13%, is the responsibility of the green crabs trapped there. This means that *C. maenas* was responsible for approximately 65% of the 20% gastropod predation rate at this site (13%). Peels were not distributed to any particular species at any of these sites because of the wide species use of this technique. It should be noted that at sites where only *C. maenas* and *H. oregonensis* are trapped *C. maenas* is twelve times more likely to be the culprit. It should also be noted that at each site in Yaquina Bay the *C. maenas* contribution to the gastropod predation rate was between 65% and 68%. This is a remarkably narrow range, making these conclusions very consistent. This is also a significant contribution indicating that this invasive species could create quite an impact on the native snail populations.

Coos Bay

The Coos Bay sites functioned as experimental tests. The trapping in Coos Bay revealed wide species diversity at many of the sites, making drawing solid conclusions quite difficult. The only site that scored the diagnostic "Upper Whorl Peel" technique was Pony Point Slough, where we were forced to use the pooled *Pony Point trapping data for verification of our expected green crab presence. This is indeed confirmed by this pooled data, assuming that the green crabs trapped approximately 800 meters away could have foraged that far, and allow the conclusion that *C. maenas* is responsible for that 2% predation rate, equal to approximately 5% of the total predation rate of about 39%. In addition, the "Pulls" are indicative of *C. maenas* predation at the Pony Point Airport (there were no pulls at the slough). We make this conclusion because we know that *P. crassipes* is not responsible for pulls in the low intertidal, and that *C. maenas* is the most likely culprit. The next likeliest crab to pull that was actually present was *H. nudus*, and this crab is six times less likely to pull as well as less abundant in the traps, so we would contribute the 4% of pulls, which is approximately 18% of the total predation rate, to the green crab. This is a significant contribution. Both Pony Point sites also had a high number of crushes, which is supported by the presence of all three mollusk-specialists in the pooled trapping data, and a wide variety of other techniques to include pulling and peeling. This is expected by the high species diversity revealed in the traps. This high diversity, however, makes it virtually impossible to dole out responsibilities for any of the remaining techniques. Hampel Oyster Farm trapping yielded the same variety of crabs as the Hatfield Marine Science Center in Yaquina Bay, but all the *C. magister* trapped were very small juveniles. The 2 juvenile *C. magister* in the feeding study, carapace widths of 18.5 mm and 27.3 mm, performed a large number of attempted peels and also successfully employed the pull technique. There is therefore a shared responsibility for the pulls with *C. maenas* and *C. magister*, and the *H. oregonensis* presence is unlikely to be a factor in those predation events. The total pull predation was 10%, which is 43% of the total predation rate of 23%. Fossil Point predation was divided between crushes, peels and attempted peels. This site had an exceptionally high predation rate when compared to most of the other Coos Bay and Yaquina Bay sites. This is perhaps explainable by the trapping results, which revealed a dominant *C. productus* presence, as discussed above, accompanied by *H. oregonensis*, the background presence of one *H. nudus*, and a large number of juvenile *C. magister*, 71 total. The *C. magister* could be largely responsible for the attempted peels, but certainly not the crushes due to the weak status of the juvenile chelae (neither of the juvenile *C. magister* performed a crush in the feeding study). It is therefore safe to say that *C. productus* is responsible for the crushes which equals approximately 45% of the total 38 % predation rate (17%). The peels at Fossil Point are, again, non-assignable due to common technique usage. The last site that was trapped was Roseburg Lumber. This site had a very low predation rate, and only the presence of *C. magister* and the background presence of one *H. oregonensis*. This indicates that the field consumption rate for *C. magister* is relatively low at this site, and that this species would be responsible for the full 4.5% predation rate here because the only techniques used were pulling and crushing and it has already been concluded that *H. oregonensis* is not likely to perform these techniques.

4.6 Conclusion

The sampling protocol set forth in this document, combined with the addition of pitfall traps, is a thorough regime that would allow the monitoring of the invasive species *Carcinus maenas*. This program also documents the status of the native Northwest crab populations as the invader gains in population density. This is of significant ecological importance if we are to understand the effects of the green crab on Northwest crab species. In addition, predation lines are clearly valuable tools that allow us to quantify the impact of an individual crab species on gastropod populations. The conservative estimate of a 65% - 68% green crab contribution to gastropod predation at the Yaquina Bay sites is a red flag that should alert us to the potential impact of this voracious predator on native mollusks.

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& **RESEARCH**

Dr. Sylvia Yamada, Zoology Department, Oregon State University
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Zoology 401 Research Students, Oregon State University

1997: Tiah Angel, Brian Chipman, Kimberly Cleveland, Tammy Cronick, Janette Ehlig, Angela McGuire, Jennifer Oliver, Anja Schmelter, Jenifer Whitsett, and Zasha Bassett.

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(*Sandra put in the extra effort of organizing the raw data for 1998, which was quite an endeavor!)

To view the Zoology 401 student reports on The European Green Crab, *Carcinus maenas*, in Oregon visit the following web site: http://www.osu.orst.edu/~yamadas

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Freshest fish (and bait!) in town. Thanks for all the salmon scraps.

Pacific Coast Cannery, Charleston
Thanks for the many fish heads and scraps.

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