A comparison of the ecology and effects of two species of thalassinidean shrimps on oyster aquaculture operations in the eastern North Pacific

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Abstract

Two species of thalassinidean shrimps, the mud shrimp *Upogebia pugettensis* and the ghost shrimp *Neotrypaea californiensis*, inhabit intertidal areas in estuaries along the west coast of North America where commercial aquaculture of the Pacific oyster *Crassotrea gigas* also occurs. Despite their important ecological role in estuaries, both species are treated equally as "pests" by the shellfish industry due to their general ability to disrupt and cover oysters with sediment. We found distinct differences in their life history characteristics and amount of sediment produced that should be considered in the control plan that the shellfish industry implements.

U. pugettensis is a filter feeder, builds a well defined mucous lined burrow, produces only a moderate amount of sediment (4.1g/shrimp/day) and reproduces during the winter, releasing larvae into the water column in the spring. *N. californiensis* is a deposit feeder, produces a much more expansive but less defined burrow as it feeds, and therefore more sediment (49.1g/shrimp/day) and reproduces during the late spring, releasing larvae in summer which recruit to the estuary after shrimp control operations have occurred. Results of experiments confirmed that *N. californiensis* is therefore a much more significant threat to oyster aquaculture operations than *U. pugettensis* and less susceptible to control via the current carbaryl pesticide application program. We also present data on long term recruitment of both species to Willapa Bay, Washington (where over 50% of the state's oyster aquaculture takes place) and suggest strategies to be incorporated in the control program.

1. Introduction

Two species of decapod thalassinidean shrimps of the family Callianassidae are common inhabitants of estuaries along the Pacific coast of North America (Swinbanks and Murray 1981; MacGinitie 1930, 1934). The ghost shrimp *Neotrypaea californiensis* and mud shrimp *Upogebia pugettensis* (hereafter referred to by generic name only) inhabit the middle to low intertidal zone and are particularly abundant in estuaries like Willapa Bay, Washington, where the slope of the intertidal area is gradual and broad areas of the estuary consist of mud and sand tideflat (>50% in Willapa Bay). These estuaries are also well suited to oyster aquaculture and the Pacific oyster (*Crassostrea gigas*) was introduced to many of them including Willapa Bay during the 1920's for commercial culture (Sayce 1976; McKenzie et al. 1997). *Neotrypaea* and *Upogebia* adversely affect oyster aquaculture by greatly increasing turbidity and sediment deposition rates and reducing the compaction of the sediment which causes the oysters to sink or rapidly be covered with sediment and die. This is particularly a problem for juvenile oysters which are typically planted as spat on a larger cultch shell making them more susceptible as the cultch is covered by sediment and sinks below the surface (Dumbauld et al. 1996, 1997). The commercial oyster aquaculture industry in Washington State found a solution to this problem in the early 1960's when researchers discovered that application of the pesticide carbaryl (brand name Sevin, 1 napthyl n-methyl carbamate) to the surface of the substrate at low tide was effective at killing shrimp (Washington Department of Fisheries (WDF) 1970, Buchanan et al. 1985). This chemical inhibits activity of the enzyme acetylcholinesterase at the nerve synapse, resulting in hyperactivity, paralysis and death of the shrimp (Estes 1986). Carbaryl was chosen because it was known to have very low toxicity to mammals and breaks down relatively rapidly in the estuarine environment. It was widely used for pest control in terrestrial agriculture and even used in flea powders for pets for these same reasons. Nonetheless, the pesticide application program in Washington State continued to attract attention due to its uniqueness as one of the only pesticide application programs in marine waters and because carbaryl was shown to kill other non-target species, particularly the commercially valuable Dungeness crab (Buchanan et al. 1985). An environmental impact statement (EIS) and supplemental environmental impact statement (SEIS) were completed on the pesticide application program in Washington State, summarizing existing knowledge and initiating a large body of new research on the effects of the pesticide on non-target species, persistence of the chemical in the environment, and the life history of the shrimp themselves (Washington Department of Ecology (WDOE) and WDF 1992, Feldman et al. 2000). Although mortality of Dungeness crab was shown to be virtually 100% for YOY crab found on the sprayed beds, over the long term, the habitat provided by oysters placed on these beds and left there to grow for several years was found to provide superior habitat for these crab, thereby mitigating the initial loss (Doty et al. 1990; Feldman et al. 2000).

Integrated pest management was identified as the preferred alternative in the SEIS and this remains the goal of the shrimp control program in Washington State today (Booth 2003). In addition to the mandate to integrate several different control techniques, integrated pest management explicitly involves monitoring the population of the shrimp as pests and incorporating this knowledge into the control program. In this paper we briefly review some of the studies completed as part of the SEIS as they pertain to the ecology and life history of the two thalassinidean shrimp as pests, discuss some experiments we have conducted to examine one potential non-chemical alternative for controlling shrimp, and present data we have collected on the shrimp populations over time in Willapa Bay. We also provide a brief update on the current status of the control program in Washington State, and suggest strategies to be incorporated into this program based on the cumulative knowledge we have gained about these two species of shrimp.

2. Shrimp Ecology and Life History

Both species of thalassinidean shrimp have a complex life cycle with pelagic larvae being released into the estuary, then flushed into the nearby coastal ocean and, after developing through several intermediate stages, returning to the estuary and settling as post-larvae (Hart 1937; Johnson and Gonor 1982). Dumbauld et al. (1996) demonstrated that the seasonal timing of these events is different for each species: *Upogebia* extrude eggs in fall (October – December), eggs hatch and larvae are released in early spring (February – March), and post-larvae settle in late spring/early summer (May – July); *Neotrypaea* extrude eggs in spring/early summer (April – June), larvae hatch and are released in summer (June – August) and post-larvae return and settle to the substrate in late summer and fall (August – October). Feldman (2001) conducted a series of experiments to examine the settlement behavior of these post - larvae and their subsequent susceptibility to predation by juvenile Dungeness crab and trends suggest that *Neotrypaea* post-larvae actively select open mud substrate over shell in the laboratory while *Upogebia* post-larvae select shell covered substrate. Juvenile Dungeness crab were capable of preying on newly settled shrimp and did so in the laboratory (Feldman et al. 1997). Settlement experiments conducted in the field using small trays confirmed the difference in settlement behavior between the two species with a greater density of *Upogebia* post-larvae settling to shell-covered sediment than open sediment (ANOVA, p=0.002), while density of *Neotrypaea* was highest in the open trays (p=0.02) (Figure 1). No significant predation effect was observed in this short term field experiment. Finally, measurements of sediment produced by each species of shrimp in Willapa Bay confirmed the difference in their burrows and feeding behavior noted by other authors. *Neotrypaea*, a deposit feeder, produced significantly more sediment (49.1g/shrimp/day) than *Upogebia* (4.1g/shrimp/day) which is a filter feeder building a well defined mucous lined burrow (MacGinitie 1930, 1934; Dumbauld et al. 1997).

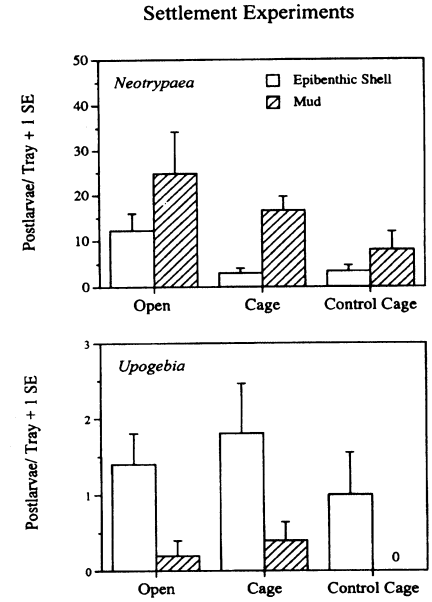

Fig. 1. Results from settlement experiments conducted in *Neotrypaea* colonies (top) and *Upogebia* colonies (bottom). The density of postlarvae of each species that settled to trays with either mud or mud and shell present are compared for three treatments (open = no cage, complete cage= no predation, and cage with no sides = no bird and large fish predation). Results suggest *Neotrypaea* preferred mud treatments while *Upogebia* selected shell-covered mud trays. No short-term predation effect was detected.

3. Oyster Shell Pavement Experiments

Extensive work conducted on the use and value of intertidal shell as habitat for juvenile Dungeness crab in Grays Harbor, Washington led to a large scale program where oyster shell has been placed in the intertidal of that estuary to create habitat and mitigate for the loss of crab due to channel dredging operations (Dumbauld et al. 1993, 2000). Based on results from the above investigations into settlement behavior of thalassinid shrimp larvae and juvenile crab as predators, we hypothesized that a similar shell layer might be used as an alternative control measure for these shrimp and act to stabilize the substrate and enhance predator abundance in oyster aquaculture areas.

3.1. Methods and materials

A field experiment was initiated in July 1994 in Willapa Bay, Washington using 16 small ($64m^2$) experimental field plots which were constructed at each of two locations where *Neotrypaea* (Nahcotta site) and *Upogebia* (Cedar River site) were abundant. Plots were assigned to one of four treatments: untreated mud (U) and shell (US) without carbaryl, and mud (T) and shell (TS) with carbaryl treatment (Figure 2). The plots were arranged in a randomized block design with 4 replicates per treatment. The effect was to remove larger adult shrimp from those treatments treated with carbaryl (T, TS), but retain them on the untreated plots (U, US). Four unreplicated large plots ($900m^2$) were also constructed at the Nahcotta site for *Neotrypaea* and at a separate Nemah site for *Upogebia*, to examine any differences that might arise due to spatial scale (Figure 2). Carbaryl (9 kg/ha) was applied by hand to the treated (T, TS) plots in July 1994 (*Neotrypaea*) and July 1995 (*Upogebia*). Oyster shell was spread on the shell treatments (S, US) and raked to a uniform thickness (approximately 2 shell layers ca. 10cm thick) at low tide approximately 2 weeks following carbaryl treatment. Measurements of remaining shell cover were taken at monthly intervals for 2 years following treatment using a $1m^2$ quadrat to estimate percent cover at 9 locations within each of the small shell plots and at 30 locations in each of the large plots. Once shell was covered with sediment, depth below the surface (cm) was measured at each location using a small plastic ruler inserted into the substrate until the first hard shell was encountered. Recruitment of young-of-the-year (YOY hereafter) shrimp was assessed utilizing a core (26.5 cm diameter x 15 cm depth) and the contents rinsed through a 0.5mm screen. Recruitment samples were taken in October, February and June (1994/95) for *Neotrypaea* and October, February, June, and October (1995/96) for *Upogebia*. Live oyster seed

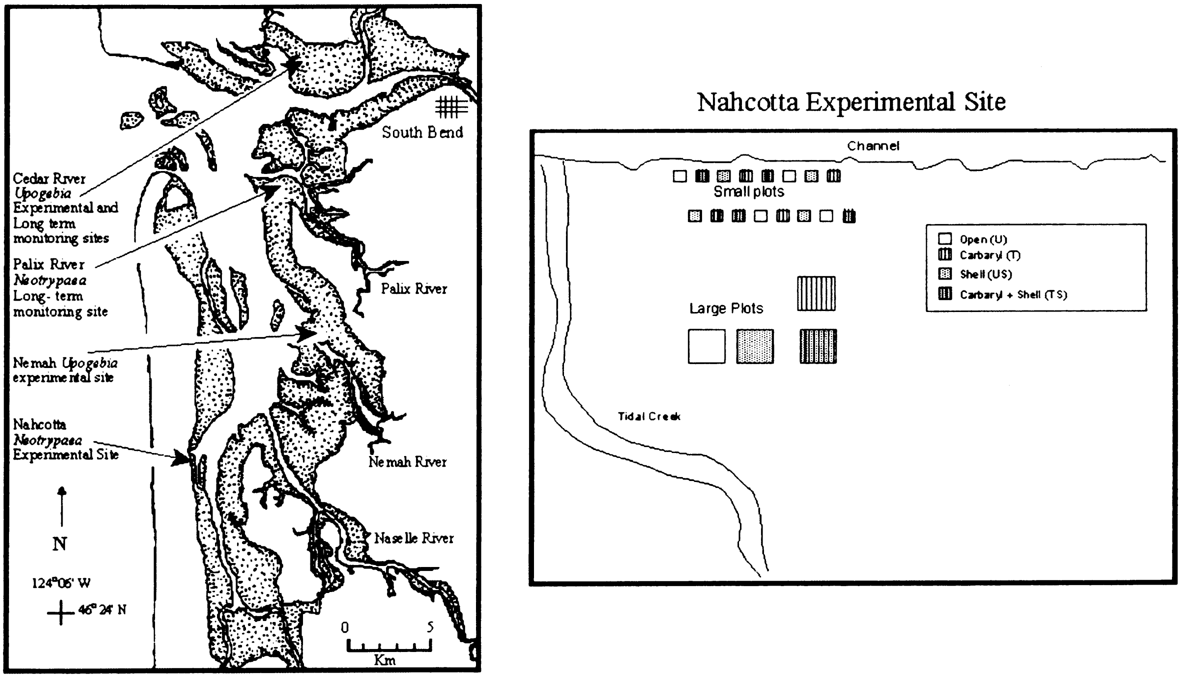

Fig. 2. Map showing locations of collections and experiments in Willapa Bay, Washington. Detail shows shell pavement experiment design at the Nahcotta site where *Neotrypaea* was abundant. Small ($64m^2$) plots with four treatments were arranged in a replicated and randomized block design. Large (900 m^2) unreplicated plots were used to test for scale effects. An identical design was employed for *Upogebia* at the Cedar River site except the large plots were located at a separate site (Nemah).

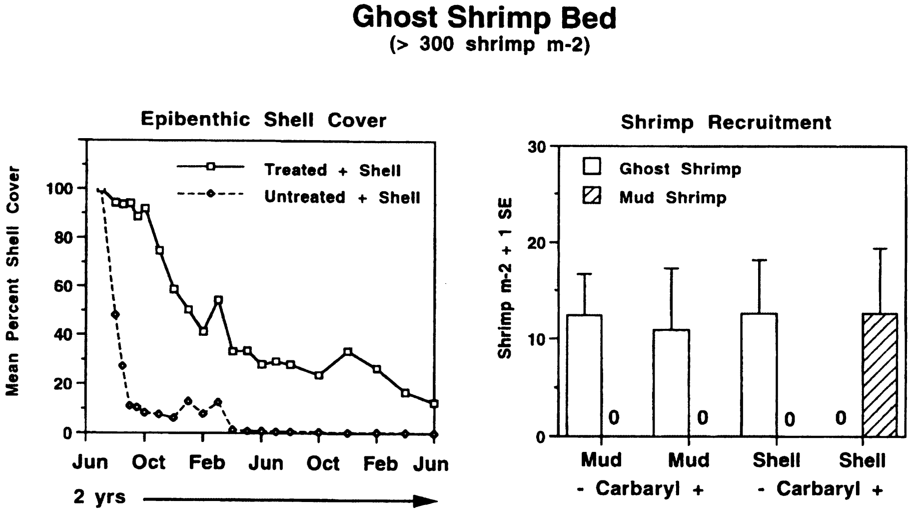

Fig. 3. Results of the shell pavement experiment for *Neotrypaea* at the Nahcotta site. Mean percent shell cover observed on the surface (left) rapidly declined in the first year to less than 20% on the carbaryl treated plots and to zero cover on untreated plots. The average density of *Neotrypaea* postlarvae that recruited to each treatment plot is shown on the right (bars represent 1SE). *Neotrypaea* recruited to all treatments except the carbaryl + shell (TS) plots where no *Neotrypaea* postlarvae were found, but *Upogebia* recruits were present.

(spat on cultch) was planted on each plot in the spring following treatment. Seed was spread by hand at a density of approximately 10 shells m^{-2} on the small plots and 20 shells m^{-2} on the large plots. The density of remaining cultch was monitored at monthly intervals thereafter by counting pieces of oyster cultch (eventually noted as oyster clusters as the oysters grew) after estimating percent shell cover using a 1m^2 quadrat in each plot as noted above.

3.2. Results and Discussion

Shell cover on untreated (US) plots declined rapidly at the Nahcotta site where *Neotrypaea* dominated, falling to and leveling out at about 10% remaining cover throughout the first winter and then declining to zero when shrimp became active the following summer (Figure 3). Shell cover on the treated plots (TS) also declined steadily for the 2 year experimental period after treatment, but remained present on the surface for the entire period. Shell was buried to an average depth of 15cm below the surface in the untreated plots after 2 years, but remained less than 5cm below the surface on treated plots (Figure 4). Shell cover on untreated (US) plots at the Cedar River site where *Upogebia* dominated did not decline as rapidly as it did at the *Neotrypaea* site, remaining above 60% for the first year and then declining to 40% in year 2 (Figure 5). There was no apparent carbaryl treatment effect for the first year at this site, but more shell was found at the surface on the treated plots in year 2. Shell remained near the surface and there was little difference in shell depth between treated and untreated plots for the first 2 years after treatment (Figure 4). There was no significant effect of carbaryl or shell on recruitment of

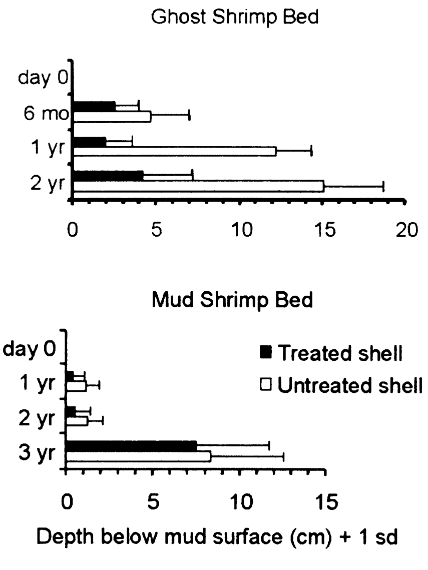

Fig. 4. Depth of the shell pavement layer for the *Neotrypaea* experiment at Nahcotta (top) and *Upogebia* experiment at Cedar River (bottom). Shell disappeared below the sediment surface on both carbaryl treated and untreated plots in the *Neotrypaea* experiment but continued to sink to 15cm on the untreated plots two years after the experiment was initiated while shell remained within the top 5 cm of the sediment in the *Upogebia* experiment and treatment with carbaryl did not make a significant difference.

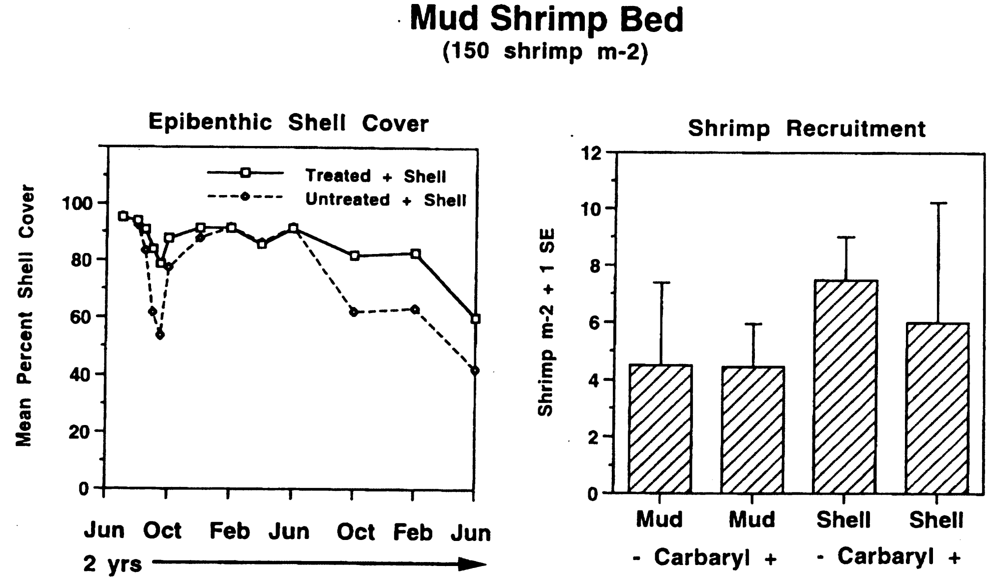

Fig. 5. Results of the shell pavement experiment for *Upogebia* at the Cedar River site. Mean percent shell cover observed on the surface (left) declined gradually to 40 – 60% after two years. The average density of *Upogebia* postlarvae that recruited to each treatment plot is shown on the right (bars represent 1 SE). No significant treatment difference is present although numbers were slightly higher in shell treatments.

YOY *Neotrypaea* to the small plots (Figure 3), but trends in the data suggest reduced densities of shrimp on plots sprayed with carbaryl and on plots covered with shell compared to open mud. By June 1995 however, shrimp densities were similar in all treatments except the treated shell plots (TS) where no YOY shrimp remained. While YOY *Neotrypaea* were absent from these plots, *Upogebia* settling in Spring 1995 successfully recruited to the treated shell plots (Figure 3). The first two sampling efforts for *Upogebia* YOY at the Cedar River site preceded the recruitment period for mud shrimp, but there was no significant effect of carbaryl or shell on recruitment by October 1996 (Figure 5). Overall densities of shrimp recruits were low however, and densities appeared to be slightly higher in plots with shell. The density of live oyster seed on the plots followed the same trend as the shell layer. Seed rapidly disappeared on the untreated plots where *Neotrypaea* was abundant (declining from 10 cultch m^{-2} to less than 2 cultch m^{-2} in the first summer and zero thereafter, Figure 6 top), but survived better on treated plots (T) and much better on treated plots with shell (TS) by the end of the experiment. Similar results were observed on the large plots where only a small shell reef was present on the surface of the untreated shell plot (US) one year after treatment, no oysters were present on the untreated plot (U), and the most oysters and shell were present on the treated shell plot (TS). A large natural spawning and set of oysters occurred in Willapa Bay in summer 1996 influencing the results of the *Upogebia* experiment causing seed counted on plots with shell present (TS, US) to increase above planted densities (Figure 6 bottom). Nonetheless, there was clearly less difference in survival of seed on treated versus untreated plots at this location with *Upogebia*

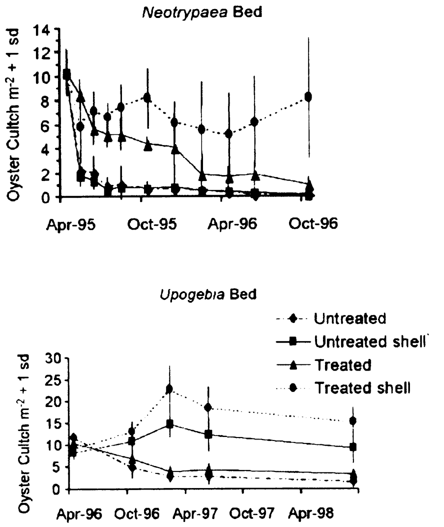

Fig. 6. Density of live oysters (measured as cultch or clusters) remaining on the sediment surface for each treatment in the *Neotrypaea* experiment (top) and *Upogebia* experiment (bottom, bars represent 1 SE). Oyster survival was highest on plots treated with carbaryl and shell.

than at Nahcotta where *Neotrypaea* was present. Results of this experiment corroborate results of previous studies (Dumbauld et al. 1997) suggesting that *Neotrypaea* causes much higher mortality of oysters due to its burrowing behavior than *Upogebia.* Without treatment, oysters cannot survive the presence of *Neotrypaea* at high density; however, with prior carbaryl treatment, the addition of a thick layer of oyster shell may as much as double survival of oyster seed. *Upogebia* poses a less significant threat, however oysters survived better on treated plots than those that were not treated and the shell layer remained on the surface of both treated and untreated plots creating a substrate for natural oyster recruitment. This shell layer could be useful in areas that are used for catching seed, but may not be an attractive alternative in areas where oysters are being harvested for market due to the presence of extraneous shell. In all cases, the presence of shell appeared to have either no effect or a slightly negative effect on shrimp recruitment and survival.

4. Long Term Monitoring Data

A separate population of *Neotrypaea* (Palix River) and *Upogebia* (Cedar River) in Willapa Bay, Washington has been monitored each year since 1989 (Figure 2). Shrimp samples were taken annually between August and October with a large core (40 cm dia. by 60 cm depth). When possible 10 samples were taken at each location. Contents were sieved through a 3mm mesh screen and sorted for shrimp. All shrimp were counted, measured (carapace length, mm) and sex determined for individuals larger than 4mm CL.

Since *Neotrypaea* settle to the benthos in late summer and are often too small to be retained on the 3mm mesh when sampling for adults occurred, a smaller core (26.5 cm dia. by 15 cm depth) was used to assess recruitment of YOY *Neotrypaea* at several locations throughout Willapa Bay since. Ten samples were taken at each location, contents sieved through 0.5mm mesh screen and sorted for shrimp. Populations of both species increased to their highest levels in the mid 1990's and have since declined to the lowest levels observed to date. (Figure 7). These increases were at least generally correlated with higher levels of recruitment in the early to mid 1990's (Figure 8), although peaks in recruitment for the two species do not directly coincide.

5. Current Status of the Control Program in Washington State

With completion of the SEIS on burrowing shrimp control in Washington State in 1992, the desired outcome became integrated pest management (IPM). Little groundwork had been laid for this however, and a Burrowing Shrimp Committee, which later became the Integrated Pest Management Committee, was established to oversee accomplishment of that goal. As part of this effort, several hurdles to implementing true integrated pest management were identified (Dewitt et al. 1997): 1) development of accurate shrimp population census

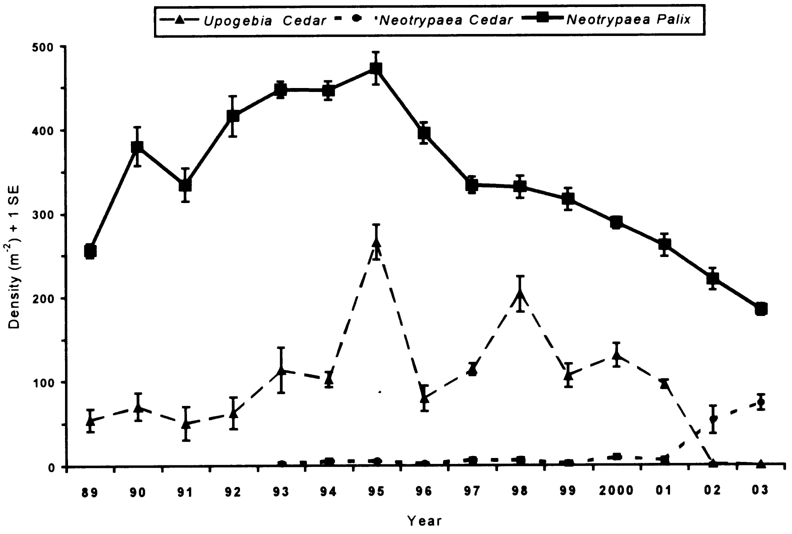

Fig. 7. Average density of shrimp present at two long term monitoring locations in Willapa Bay from 1989 – 2003 (bars represent 1SE). Note the increase in abundance of both species during the 1990's and recent decline especially for *Upogebia* which have dropped to zero and have been replaced by *Neotrypaea* at the Cedar River site.

methods, 2) characterization of a damage density threshold, 3) development of alternative methods and timing of carbaryl delivery, 4) determination of underlying reasons for increased burrowing shrimp abundance, and 5) development of objective decision-making criteria for use of control tactics. Clearly another necessary item was development of effective alternative control strategies.

The Willapa Bay-Grays Harbor Oystergrowers Association, Washington Department of Ecology, and several other state agencies signed a memorandum of agreement in 2001 to transition the industry towards IPM and agreed to address most of the tasks identified above. Application of pesticides to water bodies remains a contentious issue in the United States and in response to a decision by the Ninth Circuit Court of appeals (on herbicide application to creeks in Oregon state), WDOE required oyster growers to obtain a National Pollution Discharge Elimination System Permit in 2001. This permit placed further restrictions on the industry and required that an IPM plan be submitted to WDOE. The permit was issued, but legally challenged in 2002. In 2003, the shellfish growers signed an out-of-court settlement that reduces the amount of carbaryl applied over time and terminates its use for shrimp control by 2012. The search for alternative control measures has therefore gained momentum and integrated pest management remains the guiding principle (Booth 2003).

6. Conclusions and Suggestions

Both *Neotrypaea* and *Upogebia* are endemic to estuaries along the west coast of North America and as such are a very important components of these ecosystems. These thalassinid shrimp are strong bioturbators however, and will continue to pose a problem for oyster aquaculture which takes place in the same intertidal environment. Results of research conducted to date suggest that there are substantial differences between the two species that should be taken into account in any program designed to control their abundance in these systems.

Neotrypaea is a much stronger bioturbator and causes much more significant damage to oyster aquaculture operations. Control programs should distinguish species and target *Neotrypaea* whenever possible. Current population trends for Willapa Bay suggest that recruitment of both species has been low for several years and that adult populations of *Upogebia* have declined substantially to near zero at one location. These trends should be taken into account in the control program and resources focused on areas where *Neotrypaea* are still abundant. Because *Neotrypaea* recruits later in the summer (August – October), where feasible, annual control

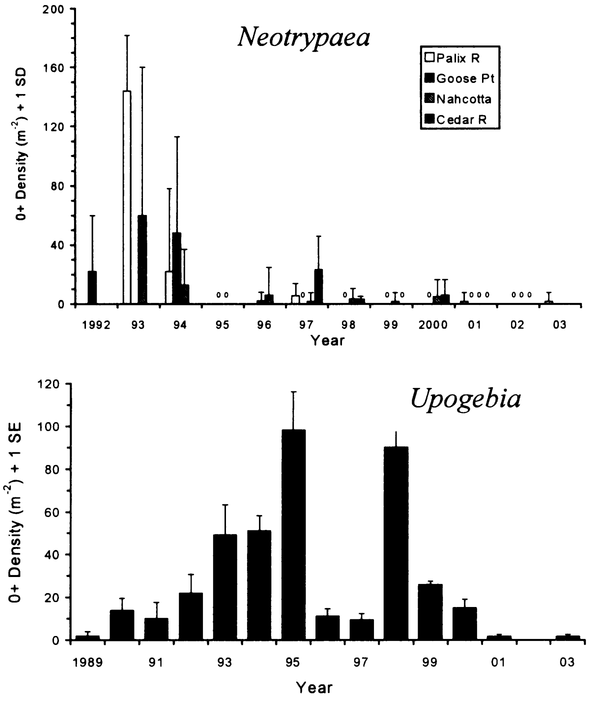

Fig. 8. Average density of 0+ shrimp sampled at several long term monitoring locations in Willapa Bay Washington. *Neotrypaea* (top) experienced relatively high recruitment in the early 1990's but recruitment has since fallen to very low levels. Recruitment of *Upogebia* (measured at one location only, bottom) also fluctuated, but remained relatively high in some years when *Neotrypea* numbers were low.

programs including current pesticide application in Washington State, should try and target efforts to proceed this period in order to remove both adults and newly recruited juveniles.

Experiments on recruitment suggest that postlarval settlement behavior for the two species of shrimp is different: *Neotrypaea* selecting open mud/sand environments while *Upogebia* may select areas covered with shell. Furthermore, areas with shell appear to attract juvenile shrimp predators such as Dungeness crab. This suggests that oyster beds should not be fallow and therefore have oyster seed or adults present on the bed at the time of shrimp recruitment (August – October) in order to prevent or reduce survival of *Neotrypaea.* Distributing a thick layer of oyster shell over oyster beds appears to have some potential for enhancing oyster survival and reducing the need for shrimp control, particularly in areas where *Neotrypaea* populations have already been reduced. While oyster shell is generally recycled and used in hatchery or seed catching operations and recognized to be a valuable resource to the shellfish farmer, continued experiments with use in selected areas to reduce shrimp populations seems warranted.

The search for alternative control measures will be difficult given the nature of the problem and the ability of these shrimp to burrow deep in the intertidal substrate. However, continued emphasis on integrated pest management as a goal which explicitly recognizes monitoring of shrimp populations as a tool has some very attractive advantages given the information on the life history and ecology of the shrimp we present here.

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