**Exhibit C**

# A review of the past decade of research on non-chemical methods to control burrowing shrimp

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## Biological control

- C*rab* – Dungeness Crab and Red Rock Crab were assessed for their potential to control adult burrowing shrimp. Adult crabs were placed in fenced enclosures in areas with high ghost shrimp burrow counts. Studies were conducted in both the winter and summer. Predation was observed over a 2 to 7 day period. There was a 5 to 25% to reduction in burrow counts. Total burrow counts, however, were still extremely high (>100/$m^2$) even after 7 days of enclosure. These results indicated that predation on adult burrowing shrimp was insufficient to provide any practical control.

- *Green Sturgeon* - Sturgeon were assessed for their ability to reduce adult burrowing shrimp density. Comparisons in burrow density inside and outside of areas staked to exclude green sturgeon were compared. Differences were noted, but not enough to warrant consideration for biological control. Densities of burrowing shrimp immediately within a sturgeon feeding pit and outside the feeding pit were compared. Some reduction was noted, but there were still adult shrimp remaining within the feeding pit. Comparative surveys of the densities of sturgeon feeding pits were made between commercial shellfish beds and open tideflats. There was minimal use of shellfish beds by green sturgeon compared to adjacent non-shellfish tideflats.

- *Parasitic isopods* – A bopyrid isopod parasite, *Orthione griffenis*, introduced in the 1980s from Asia, caused the collapse of west coast mud shrimp (*Upogebia pugettensis*) populations. Another isopod parasite has been noted on ghost shrimp but has had no effect on its populations.

## Mechanical and cultural control

- *Suction harvesting method:* Several suction head devices were designed and hooked up to water pumps. The premise was to create enough suction to selectively evacuate shrimp from their burrows, without removing sediment. The best design (shown in the figure below) was fashioned from 33 gallon plastic barrels cut longitudinally and attached to a sharp-edged plywood platform. We were able to apply enough suction to collapse the barrels, and could selectively pull large volumes of water out of burrows, but few shrimp were removed from their burrows. We concluded that suction is not a feasible method for shrimp control. Not only was it destructive to the benthic environment, but it failed to remove a significant number of adult shrimp.

- *Subsurface air bubble harvester*: The premise of an air bubble harvester is to put enough air below the shrimp to force them up out of their burrows into the water column, where they are then trapped in a net or other harvest device. Two devices were constructed (see picture below). One used compressed air at 10.7 CFM @ 125 psi applied through our six-wheel spikewheel unit. The other used 185.5 CFM @ 100 psi applied through a large shank system constructed by an Oysterman, Leonard Bennett. The first system was tested using WSU's spikewheel barge; the second system was tested using a commercial shellfish barge (see photo below). Based on data from underwater cameras, there was no evidence that any shrimp were raised from the substrate. Burrow counts post-treatment were temporarily reduced 39% with the high volume air bubble method (60 vs. 98 burrows/$m^2$), but this level is still well above what is required for a successful control.

- Surface cover: Thin quick drying cement layers were set over infested areas. Although these layers set quickly, they were not effective in reducing shrimp (see photo). Plastic traps were placed over areas infested with burrowing shrimp for 1, 3 and 10 days. Although the areas under the traps went anoxic, the shrimp populations were not significantly reduced. A previous effort to use a thick cover of oyster shells was also concluded to be ineffective.

- Heat: Surface areas of sediment were heated with a propane torch for 2 minutes/$m^2$. The sediment temperatures at 10 cm and 20 cm depths

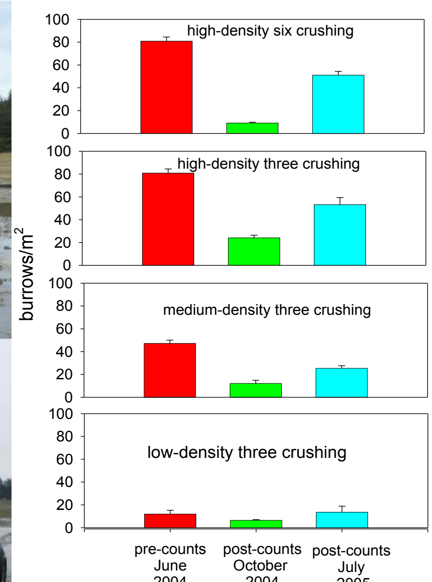
did not change sufficiently to affect burrowing shrimp. There was no effect on adult shrimp below the heated area.

- Electrofishing: Similar equipment to that used for electrofishing was assessed for burrowing shrimp control. Experiments were done in the lab by USDA. Burrowing shrimp retreated deeper into their burrows following the introduction of electric current. The treatment was not effective in removing shrimp from their burrows or killing them.

- High pressure low-volume water injection. A shanking system was designed to inject water at 1500 PSI and be dragged through the sediment (see photo). Penetration of the water jet into the sediment was not deep enough to reach shrimp. The system did not reduce shrimp densities.

- Low pressure – high volume water injection. Taylor Shellfish designed a tow sled that injected water at ~ 10,000 gpm into the sediment. This large injection sled was very difficult to tow in a straight line and the barge was not able to maintain the plotted course of direction. An assessment of post-treatment efficacy indicated good shrimp control in the affected areas, but the entire sediment profile, vegetation and invertebrate population were also destroyed. Overall this method was not practical to implement and extremely destructive to the habitat.

- Crushing: Several amphibious platforms were assessed for compaction of sediment and killing shrimp. A four-wheeled Rolligon and a tracked unit (see photos) were repeatedly driven over affected ground and population changes of shrimp were monitored over time. Crushing reduced the number of burrows/$m^2$ in the year of treatment, but one year after treatment burrow density rebounded well above the 10 burrows/$m^2$ considered to be the economic threshold (See adjacent graph).

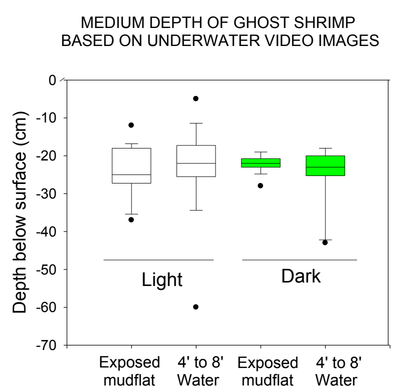


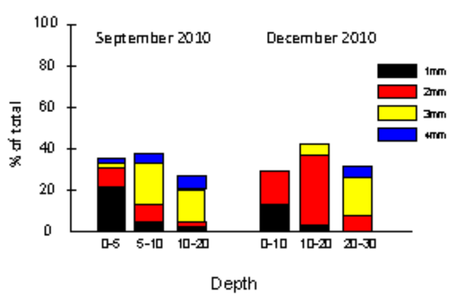
- Disking and shanking: Shallow disks and deep shanks were pulled through infected ground with either a Rolligon or ATV to control shrimp (see pictures). Neither method was effective in reducing shrimp populations. Neither method could penetrate deep enough to affect shrimp, and both methods were destructive to eelgrass, surface sediment and oysters that were present. New efforts are focused on shallow in-water harrowing as a method to reduce the populations of new recruits as they settle. Results are pending.



- Cultural methods: There has not been any recent controlled scientific research on cultural methods. However, long-lines, floating racks and flip bag cultural methods are commonly used by growers to prevent oysters sinking in affected ground. These methods are feasible in areas of production that are protected from violent storm action, and where shrimp populations are not too high to prevent effective anchoring. These condition are not very common, so these methods are really only feasible for growers with large acres to select from. Shellfish production in Willapa is 95% ground culture and 5% off-bottom. The majority of growers don't have viable options for switching their farms to off-bottom culture.

- Behavioral weak links. Assessments were made to find weak links in the biology of the pest that could help focus the mechanical control effort. Burrowing shrimp were pit-tagged, as well as filmed under the surface in their burrows to determine if there was a time when they came closer to the surface. Shrimp maintained a fairly constant depth within their burrows, 25-30 cm, regardless of the conditions. Adult burrow depth, 60 to 100 cm, is deep enough to preclude most types of mechanical control (see figure on excised burrow). The depths of new recruits were sampled as a function of time and size. New recruits were often found at depths too deep to




facilitate easy physical control.

- Trapping: Scents were tested for their attractiveness to burrowing shrimp. Several were found to be effective. Scent lures were then used in crawfish traps on the sediment surface to trap adult burrowing shrimp. Although a few large male shrimp were trapped, the traps had no impact on density of shrimp in the immediate area.

- Water injection. The traditional method to harvest shrimp is by pumping water into the sediment along a bank of drainage channel. Shrimp will float out. This method is destructive to the sediment, and is only effective on channel banks and not flat shellfish ground. A method was devised to extract shrimp from small areas on flat ground by pumping water into an 8” diameter aluminum pipe sunk 1 meter deep into the sediment (see figures). It was effective for sampling but not practical for treating large areas.

- Sound Waves. Sound waves of different frequencies were assessed to determine if shrimp were sensitive to a particular Hz. No frequencies within the normal range were found to be effective. Infrasound and ultrasound could have some potential, but have yet to be fully assessed.

**Summary:**

Research over the past decade has examined options for nonchemical control. The table in the appendix lists most of those projects and PI’s. No suitable biological control method has yet been found to suppress the population of ghost shrimp. None of the mechanical methods assessed provided viable options for management of burrowing shrimp populations. They all failed to permanently reduce shrimp populations below the economic threshold (10 burrows/$m^2$). Most of the methods tested were also very destructive to the habitat, as well as to any shellfish that would be present at the time of treatment. At present the only commercial production of oysters in shrimp infested ground in Willapa Bay and Grays Harbor is in the small areas of the bays that are protected from exposure to major winter storms and have low enough shrimp densities to provide for secure anchoring for off-bottom culture. None of these production methods, however, are viable for large-scale production across the major growing regions in these estuaries.

| Major research projects between 2005 and 2016 to develop alternative controls for burrowing shrimp management* | | |
|---|---|---|
| Project/ year(s) | PIs | Summary of findings, and significance to IPM |
| Monitoring and general IPM | | |
| Mapping the distribution of burrowing shrimp and their interaction with oyster aquaculture in Willapa Bay: 2006 to 2010 | Dumbauld, USDA; Wecker, UW | Shrimp populations of Willapa Bay were mapped. This is useful to trend future patterns of recruit and population shifts. |
| Monitoring larval stages of burrowing shrimp and associated water quality variables in Willapa Bay: 2007 to 2009 | Bollens, WSU Vancouver | Diurnal and tidal patterns of larvae movement in the water column were found. Could potentially help monitoring for new recruitment in the future. |
| Using molecular genetics to identify source populations of ghost shrimp in Willapa Bay and Grays Harbor Estuaries: 2005 to 2007 | Parr, San Jose State | Not successful in identifying recruit source populations. |
| Rearing of juvenile burrowing shrimp from eggs: 2006 | Dumbauld, USDA-ARS and UW | Not successful enough to provide samples for research. |
| Biological control | | |
| Macrofauna predators (crab) as biocontrol for burrowing shrimp: 2006 to 2007 | Patten, WSU | Few adult burrowing shrimp were consumed by crab under natural conditions in the wild. |
| Macrofauna (green sturgeon) as biocontrol for burrowing shrimp: 2006 to 2007 | Trimble, UW; Patten, WSU | Green sturgeon feed on significant amounts of adult burrowing shrimp. The use of this listed species is problematic for a biocontrol agent. |
| Lug worm as biocontrol of burrowing shrimp: 2006 | Booth, PSI | No effects on burrowing shrimp populations were found. |
| Identification of predators as potential biological control agents of burrowing shrimp in Willapa Bay: 2007 to 2009 | Bollens, WSU Vancouver | Numerous species were found which consumed burrowing shrimp larvae. No one predator dominated enough to be a significant management tool. |
| Augmenting the bopyrid isopod parasite *Ione cornuta* for the biological control of its ghost shrimp host *Neotrypaea californiensis:* 2006 to 2010 | Chapman, OSU | This isopod had only a minor effect on ghost shrimp. It would not be useful to manage populations. |
| Mechanical control | | |
| Examination of operational parameters for electrofishing equipment to be used to control burrowing shrimp in oyster culture, a feasibility study: 2008 | Dumbauld USDA-ARS | Not effective; shrimp moved deeper into their holes rather than out of their holes. |
| Burrowing shrimp control using sound waves: 2006, 2015 | Patten, WSU; Dumbauld, USDA-ARS | Irritation noted at some high frequencies in the lab. Use in field could be problematic. Potential management tool, but use of sound wave technology has serious implications for endangered species (whales, seals etc.) |

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|---|---|---|
| Water sled as alternative control for burrowing shrimp management : 2006 to 2008 | Johnson, Taylor Resources | Partial control provided by water jet sled, but impacts to the sediment were too significant to be a valid control method. |
| High pressure water jets for burrowing shrimp control: 2006 | Patten, WSU | Water jet penetration not deep enough for efficacy. |
| Harvest & harrowing systems for control of newly recruited burrowing shrimp: 2006, 2015, 2016 | Patten, WSU | In-water sediment disturbance to dislodge newly recruited shrimp followed by netting. Results to date have not been effective. New efforts are continuing. Method would not be useful for management of adult shrimp. |
| Mechanical compaction for control of burrowing shrimp: 2004 to 2007 | Patten, WSU | Compaction of shrimp-affected tideflats suppressed population for short term, but populations were back to pre-existing densities in the year after treatment. |
| Sediment mechanical modification for control of burrowing shrimp: 2005 to 2008, 2015 to 2016 | Liou, U of Idaho; Patten, WSU | Sediments in the bay are not suitable for achieving enough compaction to kill shrimp. Applying a thin layer of cement did not control shrimp. |
| Chemical control | | |
| Screening of alternative chemicals for burrowing shrimp control: 2004 to 2008 | Patten, WSU | Organic insecticides, GRAS compounds, salts, and dozens of other chemicals were assessed for their potential efficacy. None were effective enough to warrant registration. Only imidacloprid showed promise. |
| Evaluation of subsurface chemical delivery systems for management of burrowing shrimp populations: 2006 to 2010 | Patten & Durfey, WSU | Partial success using shanking and spikewheel technology to improve efficacy of more benign chemistries, but this methodology was too problematic to be practical. |

*This list represents only some of the major work done during this time period.