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Shipworm (*Bankia setacea*) Host Selection Habits at the Port of Everett, Washington

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ABSTRACT: Studies were performed at the Port of Everett, Washington, and the associated Snohomish River Estuary, to establish settlement patterns of veliger of the shipworm, *Bankia setecea*. Estuarine waters at the Port of Tacoma also were sampled for shipworm activity. Veliger settlement patterns at the Port of Everett indicated settlement took place all year, with major activity during August–October. This also was a period of reduced Snohomish River flow; therefore, logs stored in the estuary during 1989 at 1.9–3.0 km up river from the river's mouth were attacked by *B. setacea* as the salinity of these log-storage sites increased. In contrast, major movement of veligers at the Port of Tacoma was in early summer; high water temperatures were thought to prevent midsummer settlement. The upper side of wooden samplers were significantly more infested by shipworms than the under side. Veliger settlement increased evenly with depth down to the mudline discontinuity. Veligers attacked fresh wooden samplers at a significantly higher rate when these samplers were placed next to wood that had been exposed previously to shipworm attack for over 8 wk. There was proportionally less attack on fresh wooden samplers when these samplers were placed next to material exposed to attack for 4 wk; the least attack on fresh wooden samplers occurred when they were placed adjacent to unnattacked wood that had been exposed to marine water for a month (screening prevented this material from being infested). These results suggested that there were waterborne cues emanating from previously-attacked material that attracted veligers. There were significantly more *B. setacea* attacks on wooden samplers that were half-covered with Douglas-fir bark as compared with samplers half-covered with foam plastic. These data confirmed observations that shipworms severely attack Douglas-fir logs at sites where the bark has been peeled off, an indication that settling veliger larvae may respond to host-mediated chemical cues.

Introduction

The log export trade with Pacific Rim countries is a three billion dollar component of the Pacific Northwestern economy. The Port of Everett, Washington, serves as a major hub for transshipment of timber products and logs. An advantage this port has over neighboring facilities is its protection of stored logs against attacks by the shipworm, *Bankia setacea* (Tryon). Historical lack of *B. setacea* infestations occurred because log rafts were handled and stored in the estuarine waters of the Snohomish River, and the biochemical oxygen demand (BOD) of the local marine waters was high; BOD levels represent the degree of toxic organic pollutants in the water associated with effluents from two local pulp mills.

Shipworm infestations are correlated with salinity, water temperature, turbidity, and pollution (Blum 1922; White 1929; Tabata and LeBrasseur 1956; Quayle 1956; Turner 1966; Haderlie 1972; Santhakumari 1985; Turner and Culliney unpublished data). Of these, low salinity and pollution have been crucial factors limiting shipworm activity in the cold waters of Puget Sound (Johnson and Miller 1935; Quayle 1973). However, since 1980 the BOD of the Snohomish River Estuary has decreased by 98% (Fig. 1). This decrease was mainly due to installation of pollution control equipment at the two pulp mills (Ford 1985). Low salinity remains as the main factor limiting shipworm activity around the port.

Protection against shipworm infestation is based upon decreases in salinity from river inputs into salt wedge estuaries (Miller 1926; Duxbury 1987). Both full grown and immature *Bankia* can survive

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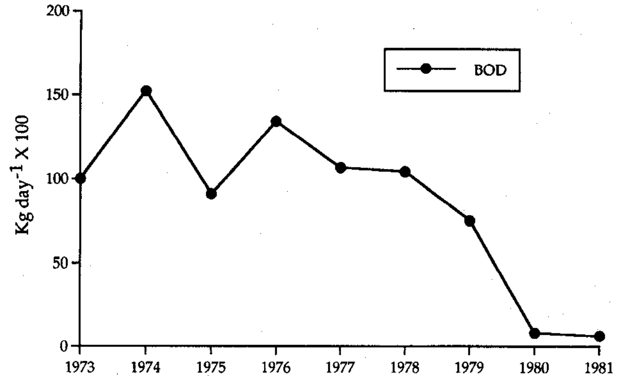

Fig. 1. Biochemical oxygen demand at the Port of Everett from 1973 to 1981 (data from Port of Everett files).

about 10 at 20% of normal marine water salinity and about 40 at 30% (Lance 1962; Turner 1966; Haderlie 1972). In addition, *B. setacea* and other Teredinidae that extrude eggs and spermatozoa, which fuse and develop into free swimming veligers, need a salinity of $\sim 20.0 \times 10^{-3}$ for successful fertilization and settling (Turner 1966; Morse 1991).

The salinity structure and dynamics of the Snohomish estuary have not been examined in detail, but studies of other estuaries offer some clues as to its possible nature. It has been suggested that the Snohomish River has a seasonal salinity stratification similar to that of the Duwamish River (Officer 1976). During periods of high freshwater flow (November to May) the Duwamish river displays a salt-water wedge stratification, but during periods of low river flow (July to September), only partial stratification is observed. The supposition of a seasonal transition from salt wedge to partial stratification, or even a well-mixed estuary condition in the case of the Snohomish River, finds support in Pritchard (1967). Pritchard notes that the movement from high stratification to well-mixed conditions occurs with decreasing river flow, increasing tidal velocity, increasing width, and decreasing depth. All of these factors favor reduced stratification during the late summer and fall months, particularly in the lower reaches of the Snohomish estuary.

During most of the year a salt-wedge stratification provides a less salty layer that is deep enough to provide floating logs with a salinity environment inimical to shipworm development. However, during periods of reduced freshwater flow and high tidal fluctuation, this protection is no longer available.

In practice, the Port's operating procedure was not to keep log rafts in deep marine waters (a cove area where the vessels are loaded) for longer than 3 wks: a time thought to be too short for shipworm damage (Crisp 1953; Quayle 1956; Haderlie 1972). Rafts to be kept longer than this period were moved into the estuary and associated sloughs where shipworm development was restricted by low salinity. However, as noted, vertical saltwater mixing can occur within this type of estuary under certain conditions. Low riverflow due to long-term droughts will also reduce freshwater input. In fact, during 1987, and in spite of the raft-storage policy, logs kept in the estuary were infested and damaged with shipworms. Gara and Greulich (1995) found that uncommonly low riverflow for 1987 created estuarine conditions favorable for shipworm activity in the normally safe log storage areas and that there was a predictable relationship between seasonal riverflow patterns and shipworm attacks. Moreover, Harr (1983) established that continued removal of high elevation old-growth forests will lead to higher run off in spring and reduced flows in fall. If this trend continues for the next decade, we predicted that the mean monthly flow of the Snohomish River during October will drop by a third; this implies continued yearly *B. setacea* attacks of logs stored in the estuary (Gara and Greulich 1995). In anticipation of continuing shipworm problems we are developing a shipworm settling model based on salinity patterns of the estuary and seasonal settling patterns of the veligers. When this model is operational, the Port would use it to move log rafts when shipworm problems are imminent. A log raft management plan also would include information on log-species preference of shipworms; whether veligers settle preferentially on previously-attacked substrates; and, as shipworm attacks traditionally occur on debarked log surfaces, the influence of Douglas-fir [*Pseudotsugae menziesii* (Mirb.) Franco] bark on preventing infestations (Nair and Saraswathy 1971).

The objectives of this study were as follows: to describe the baseline settlement pattern of *B. setacea* at the Port of Everett as well as to compare these patterns with those of neighboring ports; to establish relationships between seasonal river flow, subsequent estuary salinity patterns, and *B. setacea* infestations; to ascertain species preferences and the influence of bark on settlement, and to verify putative settlement preference for pre-attacked substrates (Crisp and Meadows 1962, 1963; Nair and Saraswarthy 1971).

Materials and Methods

Settlement Patterns

Starting in October 1988 and continuing through April 1991, we suspended strings of wooden sampling blocks from pilings located in the mouth of Everett Harbor and up the Snohomish

River to a distance of about 2.5 km. This sampling zone encompasses essentially marine conditions at the harbor's cove to brackish conditions in the log-raft storage sites (storage areas that prior to 1987 were mostly free of shipworm problems). Each sampling rope was anchored at mud line with an iron weight and each had five, equally spaced wooden blocks. Individual blocks were 10 × 9 × 1.8 cm, clear (no knots), vertical-grained and planed Douglas-fir sampling units. The first block was 30 cm up from the bottom and the remaining blocks were 60 cm apart. In this manner the blocks extended from mudline to at least mean lower low water (MLLW is the 0 datum). Each sampling location had two strings of blocks. Each string was left 4 wks. Our sampling protocol called for one of the strings to be removed every 2 wks, thus ensuring that there was a 2-wk overlap between sampling intervals. In this manner, a line of blocks was removed from the water fortnightly, and replaced with fresh material. The extracted blocks were then taken to the laboratory and the number of attacks per block estimated. As described by Quayle (1953), attacks were easily seen under a stereoscopic microscope by noting the round depression on the wood surface usually containing a spherical mollusk or a calcareous cone. The number of attacks per cm^2 was determined by placing a 1-cm grid over each block-face and counting the number of attacks in 10 of the 1-cm squares. The location of the 10 squares was ascertained from coordinates taken from a random-number generator. Total settlements counted per block were divided by 10 to determine average attack per cm^2.

A similar sampling system was established at the Port of Tacoma's Hylebos Waterway. The Hylebos Waterway is located at the outflow of the Puyallup River and at the confluence of other streams that empty into Puget Sound. Starting in January 1990 and continuing through April 1991, sampling lines were hung from a piling within a log storage area of the waterway.

Snohomish River Monitoring

Water salinity and temperature were measured with a YSI model 3310 conductivity-temperature probe and recorded on a Campbell Scientific CR10 datalogger. The probe was installed at a finger pier about 1.9 km upriver from the cove (the Nord Door Co. pier). The datalogger recorded water salinity and temperature every 5 min. Every hour the average of the last 12 observations was placed in long-term storage in the datalogger's memory. We retrieved these averages monthly on a Toshiba T1000 portable PC and uploaded the data to a mainframe computer for statistical analysis. This data recording began on April 28, 1989, and continued through December 19, 1989.

Continuous daily riverflow data were obtained from the United States Geological Survey; this agency maintains a gauging station upriver near the town of Monroe. Daily tide information was acquired from tide tables for the area.

Species Preference

To determine if *B. setacea* preferentially settle on Douglas fir, western red cedar (*Thuja plicata* Donn ex D. Don), red alder (*Alnus rubra* Bong.), western hemlock [*Tsuga heterophylla* (Raf.) Sarg.], and Alaska cedar [*Chamaecyparis nootkatensis* (D. Don) Spach], sampling lines containing blocks of these species were suspended from April 1989 to July 1989 in the cove area of the Port. A Latin square method with randomly permuted numbers was used as an experimental design. Five lines, each line with one, 10 × 9 × 1.8 cm, block of each species at a different depth were used. The depths, sampled from the bottom, were 0.3 m, 0.9 m, 1.5 m, 2.1 m, and 2.7 m. Attacks per cm^2 were calculated from the average number of larvae on a random sample of 20 cm^2 on the top and bottom surfaces of each block.

While analyzing these blocks, we observed continually that the upper surface of the samplers were more densely colonized than the lower surface. At the conclusion of the species-preference trials we analyzed this occurrence by applying the one-tailed sign test (described in Hollander and Wolfe 1973).

Substrate Preference

The possibility that shipworm-infested wooden blocks attract settling larvae was tested in the Port's cove area. From May through October 1990, a comparison was made between the number of larvae that settled on fresh wooden blocks placed next to blocks already exposed to *B. setacea* attack and next to unattacked, control blocks. The shipworm-exposed blocks consisted of the following: sets of blocks were placed in the cove's waters for 8–24 wk prior to the experiment (termed long exposure); sets of blocks were placed similarly and exposed for 4 wk (termed medium exposure), and sets of blocks were placed in cove waters for 4 wk but were protected from shipworm infestations as these blocks were encased in a fine mesh net lined with cotton sheeting (termed exp.-unattacked). At the time of the experiment, all blocks were placed on a hardwood dowel so that a block of long exposure was placed 2.5 cm from a fresh block; 30 cm away on the dowel, a block of medium exposure was placed 2.5 cm from a fresh block, and; 30 cm away on the dowel, a block of exp.-unattacked

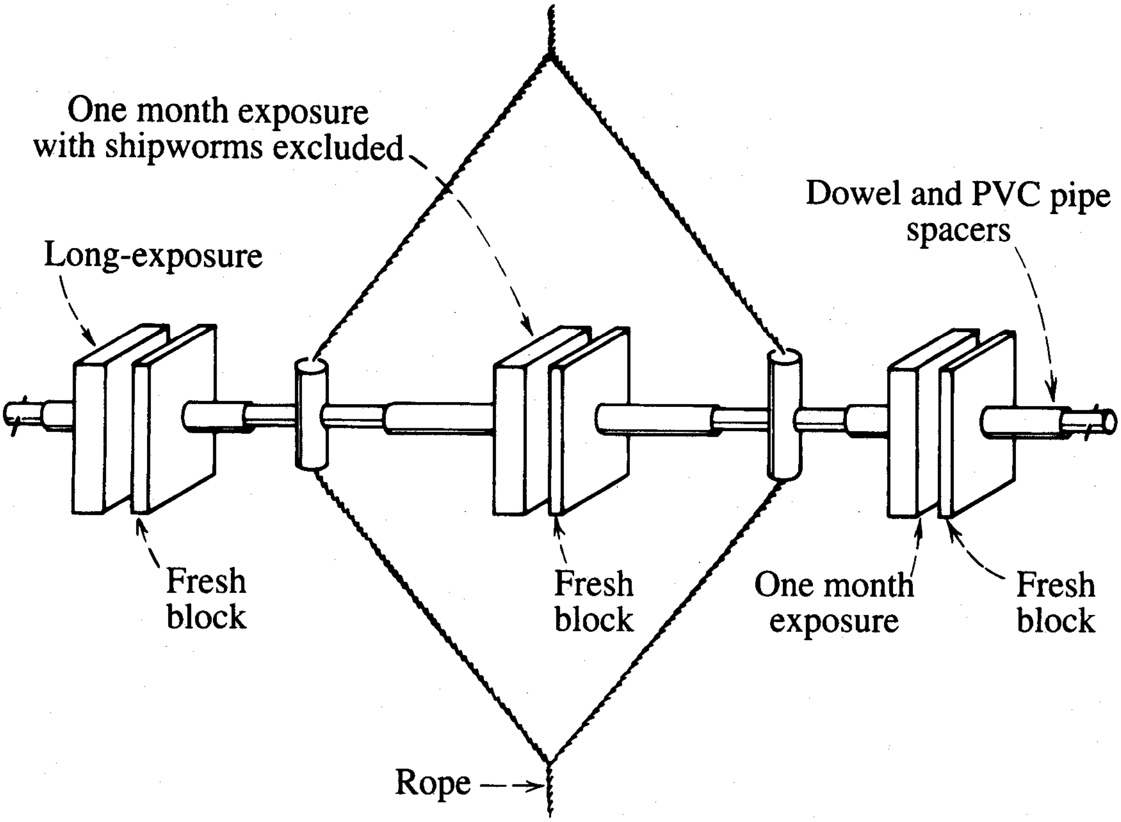

Fig. 2. Sampling unit for studying the effects of shipworm-infested wood on the settlement of *Bankia setacea* larvae at the Port of Everett: long exposure refers to wooden blocks exposed previously to shipworm attack for 8–24 wk; 1-mo exposure are wooden blocks exposed previously to shipworm attack for 1 mo (medium exposure); and wooden blocks termed exp.- unattacked are blocks that have been exposed to marine waters for a month but protected from *B. setacea* attack. The putative attractiveness of these wooden blocks is tested by counting shipworm attacks on adjacent fresh blocks.

was placed 2.5 cm from a fresh block. All the blocks were held in position on the dowel by PVC pipe spacers and cotter pins (Figure 2). The PVC spacers also reduced the chances that veligers would settle on the dowels. Ten of these test-units were suspended in the cove's waters, 2.1m above the mud line for a 4-wk period. Subsequently, all blocks were taken to the laboratory, where they were rinsed, air dried and examined under a stereo microscope in the manner previously described. This experiment took 6 mo, and because of the variation in *B. setacea* settlement patterns during this time, the data was analyzed with the Friedman two-way ANOVA nonparametric statistical method (Hollander and Wolfe 1973).

We conducted tests to see if veligers preferentially settled on Douglas-fir wood adjacent to bark. During July and again in August 1990, two lines of sampling blocks, as previously outlined, were hung from a pier at the cove. The sampling blocks of each line were randomly selected to be half covered with a strip of Douglas-fir bark or a strip of bubble-plastic packing material. At the end of 30 days the blocks were retrieved, cleaned, air dried, and the number of shipworm attacks on the uncovered half of the blocks was determined by microscopic inspection. Results of these experiments also were analyzed by the Friedman two-way ANOVA nonparametric statistical method (Hollander and Wolfe 1973).

Results

Settlement Patterns

Shipworm settlement on logs can occur all during the year with major activity from August through December (Fig. 3). This settlement pattern, however, varies throughout the Puget Sound Region. As seen in Fig. 4, peak *B. setacea* activity in the Port of Tacoma (about 90 km south of Everett) is in early summer, while major shipworm settlement in Friday Harbor (about 84 km northwest of Everett) is a late winter occurrence, as shown by Johnson and Miller (1935).

We found that the principal *B. setacea* settlement period at Everett was particularly hazardous to log

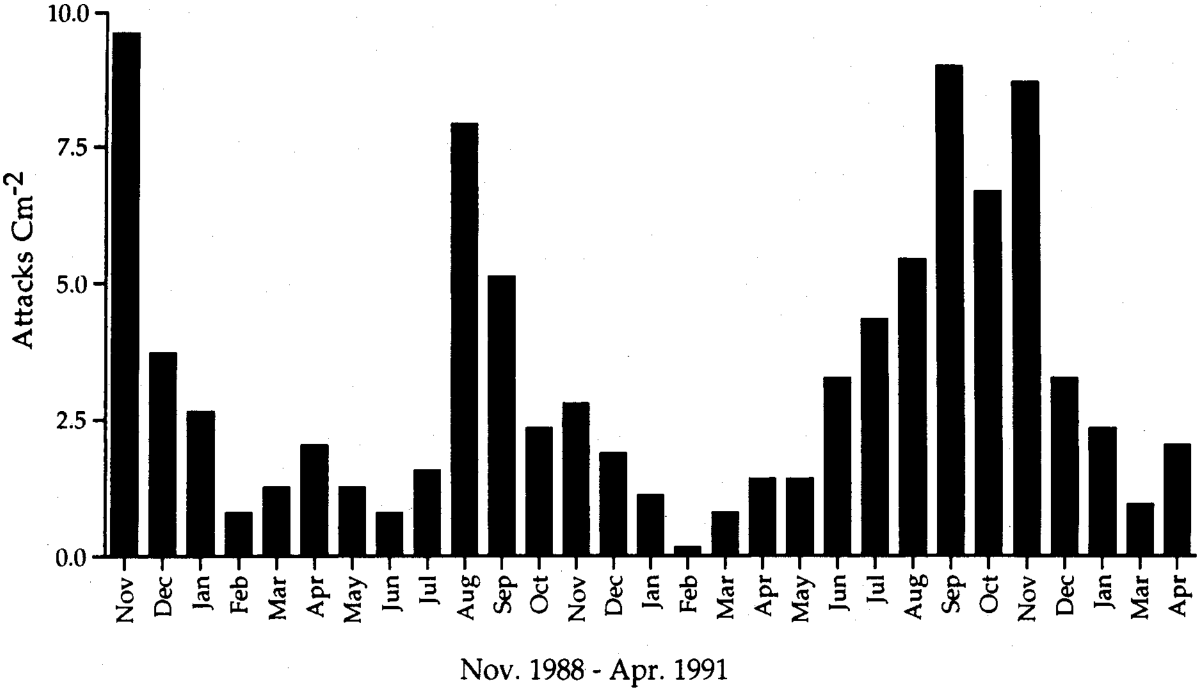

Fig. 3. Settlement patterns of *Bankia setacea* at the Port of Everett from November 1988 to April 1991, as determined by shipworm attack of suspended wooden test blocks.

rafts stored within the Snohomish River Estuary as peak settlement corresponded to minimum river flow and maximum estuarine salinity levels. In fact, during 1989, log rafts stored at three sites, 1.9, 2.4, and 3.0 km upriver, respectively, from the cove were infested by shipworms (Figure 5). We observed an increase in settlement with water depth; as seen in Fig. 6, intertidal flats and areas at 0.6 m. below MLLW had minimal shipworm activity.

Wood Species Trial

Shipworms did not have a discernable preference for a particular host species. However, confirming our earlier observations, veligers larvae did preferentially settle upon the upper surface of all wood species used as test blocks ($p = 0.03$) (Fig. 7).

Substrate Preference

Fresh test blocks positioned next to the long-exposure blocks were most severely infested (1563.1 larvae block^{-1}) versus 1122.0 and 1180.3 larvae block^{-1} of the medium-exposure blocks and exp.-

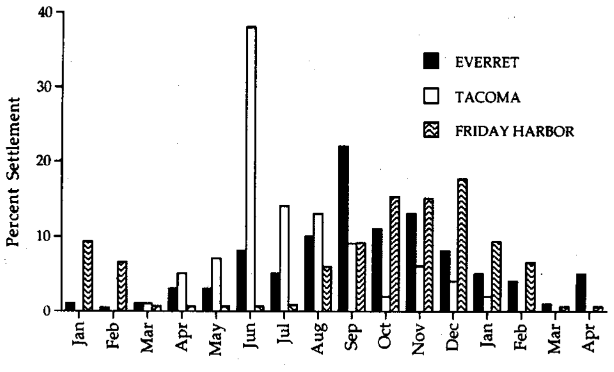

Fig. 4. *Bankia setacea* settlement patterns (as percent of yearly totals) at the Port of Everett, Port of Tacoma and Friday Harbor (Friday Harbor data from Johnson and Miller 1935).

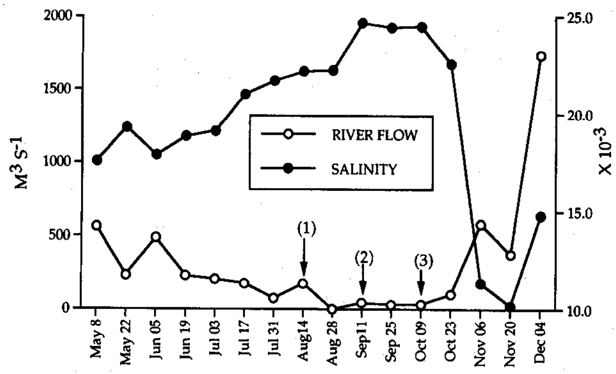

Fig. 5. Relationships at the Snohomish River Estuary during 1989 among river flow, salinity, and *Bankia setacea* infestations of stored logs. Shipworm attacks occurred at three log-storage sites: site number 1 was 1.9 km from the Port of Everett's marine water cove and sites 2 and 3 were 2.4 km and 3.0 km, respectively, from the cove.

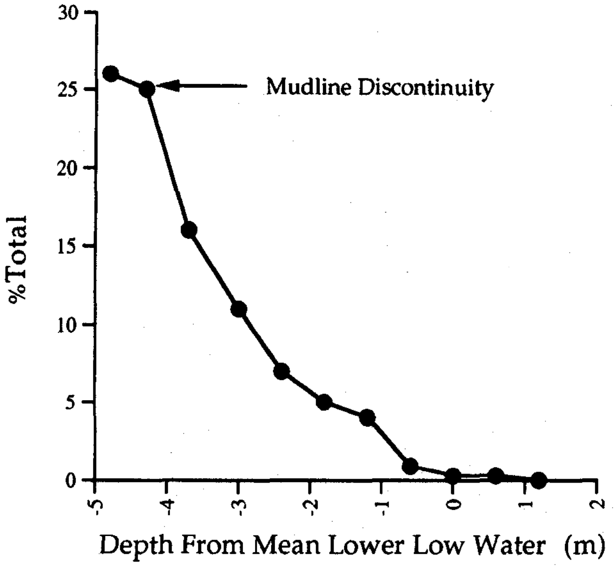

Fig. 6. Percent of *Bankia setacea* attacks of wooden sampling blocks suspended at various depths within the Snohomish River Estuary.

TABLE 1. Number of *Bankia setacea* veligers attacking fresh wooden blocks placed next to wooden blocks that had been previously exposed to shipworm attack for 8–24 wk, termed Long Exposure; or for about a month, termed Medium Exposure; or wooden blocks exposed to marine waters for a month but screened from shipworm attack, termed Exp.-Unattacked.

	(Number of Attacks/Fresh Test Block) (Rank)		
Trial Number	Long Exposure	Medium Exposure	Exp.-Unattacked
1	(1,535) (3)	(924) (1)	(1,118) (2)
2	(1,364) (3)	(1,087) (1)	(1,360) (2)
3	(2,794) (3)	(2,660) (2)	(2,330) (1)
4	(2,592) (3)	(2,293) (2)	(2,003) (1)
5	(2,442) (3)	(659) (2)	(448) (1)
6	(338) (3)	(079) (1)	(141) (2)
7	(2,359) (3)	(2,044) (2)	(1,613) (1)
8	(1,006) (2)	(499) (1)	(1,080) (3)
9	(664) (2)	(798) (3)	(416) (1)
10	(852) (3)	(608) (2)	(548) (1)
Avg. attacks per fresh block	1,563.1	1,122.0	1,180.3
Sum of ranks	28	17	15
Mean rank	2.8	1.7	1.5

unattacked blocks, respectively (Table 1). The nonparametric analysis showed that there was a significant difference ($p < 0.01$) between mean levels of settlement on long, medium, and exp.-unattacked materials. Settlement on fresh blocks next to the medium-exposure material were not significantly different ($p > 0.25$) from fresh blocks next to the exp.-unattacked material.

In the bark influence test, the July trial was eliminated from analysis because several of the block coverings fell off. In the August trial, the number of veligers settling on uncovered halves of test blocks, whose other halves were covered with Douglas-fir bark, was discernible ($p < 0.05$) from settlement on blocks that were half covered with a plastic covering (Fig. 8).

Discussion

The bimodal settlement pattern at The Port of Everett probably is linked to the life history of *B. setacea*. In early spring, increasing light duration and high nutrient levels (stirred up by late winter-early spring storms) cause a rapid increase in phytoplankton populations (Isaac 1969). This food base increases zooplankton, including the planktonic larvae of many mollusk and crustacean species (Starr et al. 1990); a time that corresponds with the Port's March through June shipworm set-

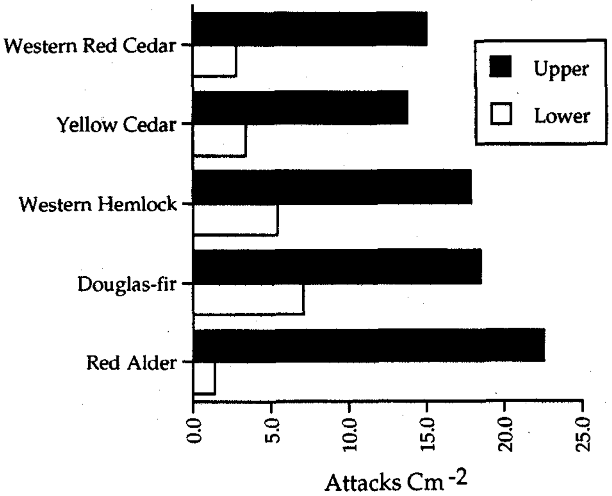

Fig. 7. Settlement of *Bankia setacea* within the Snohomish River Estuary on the upper and lower surfaces of four species of conifers and a hardwood used as sampling blocks.

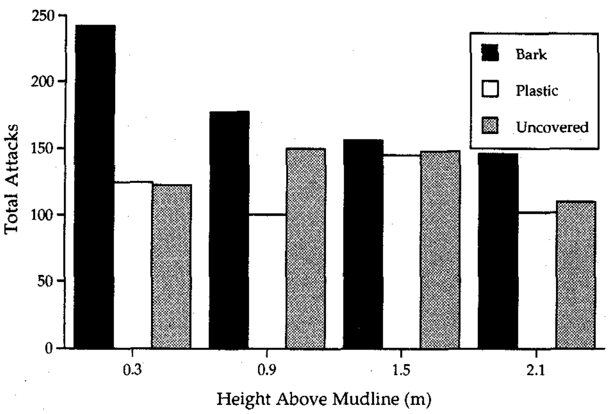

Fig. 8. Number of *Bankia setacea* attacks on wooden blocks whose surfaces were half-covered with either foam plastic or Douglas-fir bark or were left uncovered. Data was taken from the number of attacks on the uncovered-half of each test block or from half of completely uncovered test blocks.

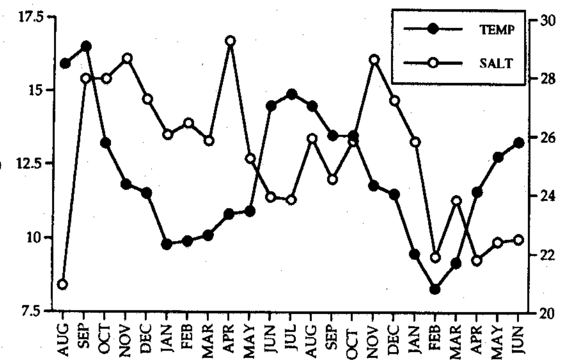

Fig. 9. Temperature and salt content fluctuations of the Hylebus Waterway at the Port of Tacoma as reported by Shoener (1983).

tling peak. The second major settlement activity corresponds with *B. setacea* gamete-production by 4-mo-old male and female shipworms that settled during spring and early summer (Quayle 1956). Accordingly, veligers that settled on test blocks in late summer and autumn were produced by winter survivors and the spring-early summer shipworm cohorts. The drop in shipworm settling in late autumn and early winter is probably due to the high rainfall and increased flow of the Snohomish River which freshens the estuarine system (Gara and Greulich 1995). Conversely, a decrease in late seasonal shipworm activity does not occur at Friday Harbor (Johnson and Miller 1935), a well-mixed estuary common to drowned river valley systems (Duxbury 1987).

In contrast to the shipworm settlement pattern at the Port of Everett, major settlement at the Port of Tacoma appeared in early summer with reduced activity during the rest of the year. Based on data collected by Schoener (1983) (Fig. 9), salinity levels of Tacoma's marine waters appear to be above 20×10^{-3}, ideal for *B. setacea* survival (Tabata and LeBrasseur unpublished data). But, the Port's high water temperatures between June and September are unfavorable for shipworm development; Tabata and LeBrasseur (unpublished data) and Johnson and Miller (1935) showed that ideal water temperatures for *B. setacea* growth are between 4–15°C and 7–12°C respectively.

That shipworm larval concentrations increase with depth is well known (Miller 1926; Owen 1953; Haderlie 1968, 1972; Crisp 1979; McKoy 1980; Santhakumari and Nair 1984). Quayle (1953) associates this behavior with *B. setacea* preference for the cold, dense and salty conditions of deep waters. The Port of Everett capitalizes on the shipworm's distribution in the water column as shallow areas of the Snohomish River Estuary, which occur from −0.6m to 1.2m (MLLW), have been located and provide ideal long-term log storage sites. These are estuarine localities and diurnally the log rafts stored in these areas are left high and dry (Fig. 6).

In laboratory tests of *B. setacea*, Harington (1921) found that settling veligers respond to humic substances in the water column. Culliney (1973) observed that swimming veligers retracted their vela and sank when in presence of wood extracts. This observation may account for the preponderance of shipworm infestations we found on the upper surface of test blocks—the swimming veliger larvae sensed the submerged woody bait and sank toward the material. An attack behavior also noted in Fig. 6. The majority, therefore, landed on the upper surface. This observation agrees with Quayle (1956); he showed that *B. setacea* manifests no spatial readjustments within the water column. Other Teredinidae, however, prefer the undersurface of sampling blocks (Isham et al. 1953; Owen 1953; Crisp 1974; Chandramohan et al. 1979), a reaction to the veliger's propensity for deep shade. Our study showed that veligers settle preferentially on wood adjacent to previously infested wood. Early studies have shown that wood exposed to marine conditions quickly absorb high molecular weight substances and become colonized by microorganisms that secrete additional materials (Zobell and Allen 1935, 1939). Chemicals eluted from these materials may be responsible for veliger settling (Scheltema 1974; Morse 1991). Gregarious settlement behavior also may be in response to attractants (Thompson 1958; Scheltema 1971; Hidu 1969); however, Crisp and Meadows (1962, 1963) argue that soluble pheromones would be so diluted that swimming veligers would be unable to respond to such minute semiochemical cues. In agreement with Bayne (1969), our observation that more *B. setacea* were caught on samplers next to previously attacked wood is a response of settling veligers to arrestants. Arrestants would detain settling larvae as a reaction to chemicals produced by a myriad colonizing microorganisms, decaying wood, and possibly byssus-derived materials exuded by previous colonizers (Sigerfoos 1907; Lynch 1947; Isham and Tierney 1953; Morse 1991). The fact that we found a distinct preference for veliger settlement next to bark reinforces this argument; Harington (1921) found that shipworm veligers accumulate near wood and bark extractives.

These findings suggest that the Port should continue to dredge and remove sunken logs and debris from the vicinity of log storage sites as these materials produce foci of shipworm populations; and to monitor the water salinity of their long-term storage sites during the maximum settlement periods of the shipworms.

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