A biological index to predict pulp mill pollution levels

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ABSTRACT: The species diversity of mid to low rocky intertidal beaches along the protected coast of British Columbia, Canada, increases significantly as exposure to pulp mill effluent decreases. Species were categorized according to hardiness and ranked as either pollution tolerant, sensitive, or intolerant. Indicator species whose presence or abundance is highly correlated to exposure to mill effluent were discovered. A biological index (Bioindex) was developed to predict a rocky shore's exposure to mill effluent by analyzing the hardiness of the resident biota. The Bioindex is useful to evaluate the environmental stress from pulp mills, to pinpoint depleted beaches for cleanup, and to evaluate pristine areas to be protected.

The Howe Sound mills were found to have the most detrimental and widespread effect on rocky shore beaches of all regions surveyed, followed, in order of decreasing severity, by the Crofton mill, the Prince Rupert mill, and the Powell River mill. *Water Environ. Res.*, **70**, 108 (1998).

KEYWORDS: pulp mill pollution, biological index, environmental monitoring, intertidal diversity.

Introduction

This study surveys the marine environmental impact of five British Columbia, Canada, Kraft pulp mills with marine outfalls: Howe Sound Pulp and Paper's Port Mellon mill and Woodfibre mill in Howe Sound, Fletcher Challenge's Crofton mill on Vancouver Island, MacMillan Bloedel's Powell River mill, and Skenna Cellulose located near Prince Rupert.

Kraft mills create three varieties of marine environmental problems: settleable wood fibers, increased biochemical oxygen demand (BOD), and toxic effluent (Waldichuk, 1983). The effluent may contain wood fibers that settle to form a fiber mat around the diffuser pipe. The fiber mat can be from several centimetres to 15 m thick, produce toxic hydrogen sulfide gas, and smother benthic organisms surrounding the pipe's mouth (Waldichuk, 1983). Fibers can also diffuse into the water column and combine with free-floating green algae to form a fibrous mass, which can wash ashore to smother intertidal organisms (Bard, 1991, and Colodey *et al.*, 1990).

Biochemical oxygen demand, a property of pulp effluent wastewater, occurs when organic nutrients deposited in the marine environment decompose and consume oxygen. If the amount of organic nutrients in the effluent is large and little tidal flushing occurs, the BOD may cause all of the dissolved oxygen to be depleted. When dissolved oxygen levels decrease, the toxicity of Kraft mill effluent increases. This situation causes both lethal and sublethal responses in both benthic and pelagic organisms (Sprague and Colodey, 1989).

The pulping chemicals and bleaching agents used in the mills are themselves extremely corrosive and toxic (Parsons, 1972). In 1990, the average British Columbia mill, producing 750 t/d of pulp, released 1 125 kg/d of organochlorines to the marine environment (West Coast Environmental Law Research Foundation, 1990). Approximately 300 of the estimated 1 000 organochlorines present in mill effluent have been identified. The most toxic chemicals are polychlorinated dibenzo-para-dioxins and polychlorinated dibenzofurans (Health and Welfare Canada, 1990). Exposure to 2,3,7,8-tetrachlorodibenzoparadioxin (2,3,7,8-TCDD), for example, causes a number of adverse health effects in laboratory animals including impaired immune systems and liver function, cancer, reproductive failure, and birth defects (Health and Welfare Canada, 1990). Sublethal effects and reproductive failure of fish and birds after long-term exposure to organochlorine-contaminated effluent, as well as fish and invertebrate kills resulting from spills, have been reported in the literature (Colodey and Wells, 1992; Colodey *et al.*, 1990; Elliott *et al.*, 1988; and Waldichuk, 1983).

Elevated dioxin levels in sediments and organisms near British Columbia pulp mills were first discovered in 1980 by the Council of Forest Industry of British Columbia (British Columbia Research, 1980). Environment Canada first publicly announced the dioxin contamination in November 1988 and issued widespread fishery and duck hunting closures surrounding the mills. Simultaneously, Health and Welfare Canada published seafood consumption warnings. Environment Canada initiated an annual dioxin testing program in conjunction with more stringent pollution abatement programs for the mills. In response, the pulp mill industry installed more efficient effluent treatment facilities, switched to uncontaminated defoamers and wood chips for hog fuel, and began new pulp bleaching and washing practices to improve effluent quality.

The current detection limit for 2,3,7,8-TCDD is 10 parts per quadrillion (ppq). Some dioxins and furans are fat soluble and can bioaccumulate; these compounds can be accumulated to dangerous levels in organisms further along the food chain even if the toxins in the effluent are below the detection levels (Pulp, Paper, and Woodworkers of Canada, 1990). Although the government reported in 1992 and 1993 that the levels of dioxins have decreased in sediments and marine organisms, fishery closures have remained in effect (DFO, 1990, 1991, 1992, and 1993.)

The goal of this study was to determine and monitor the effects of these pulp mill effluents on intertidal community structure from 1990 to 1993. The species diversity of mid to low rocky intertidal beaches along the protected coast of British Columbia increases significantly as the distance to pulp mills, and therefore potential exposure to effluent, decreases. Intertidal species were found to vary enormously in their tolerance to exposure to mill effluent. Species whose abundance was directly correlated to exposure to mill effluent were designated "indicator species."

Although biological indices are well established in the literature, none is appropriate for monitoring the effect of pulp mill pollution on the benthic macroflora and macrofauna of the mid to low rocky intertidal zone of British Columbia. Consequently, the Biological Index for Intertidal Communities (Bioindex) was developed to correlate a beach's biodiversity with exposure to a constant level of mill effluent. The Bioindex was developed from 1990 and 1991 diversity data and was tested successfully with data from 1992 and 1993. This index provides an inexpensive means to evaluate a rocky, mid to low intertidal site's exposure to mill effluent based on the resident biota. Researchers can use the Bioindex to map the protected coast of British Columbia according to environmental stress from pulp mills. Pollution levels are expected to continue to decrease in the coming years as a result of additional environmental protection programs initiated by the government and mill operators. The Bioindex will be useful to monitor recolonization of formerly depleted sites surrounding the mills.

Methodology

Location and Date of Surveys. Twenty-eight beaches surrounding British Columbian Kraft pulp mills were studied in four regions: Howe Sound, Crofton, Prince Rupert, and Powell River. In each region, five to ten rocky-shore beach sites situated at increasing distances from each mill's marine outfall were chosen for study. The relatively remote Hornby Island, located 40 km from the nearest pulp mill, was chosen as the reference site for Howe Sound and Powell River; Ruckle Park on Saltspring Island was designated the reference site for Crofton (33 km distance); and Butze Rapids (11 km) and Fairview (13 km) were the reference sites for the Prince Rupert mill. The pristine sites were selected based on Department of Fisheries and Oceans (DFO) oceanographic data, which suggested that mill effluent was unlikely to be carried by currents to these reference sites (Thomson, 1981).

All of the beach sites surrounding each mill region were examined on 7 to 9 consecutive days during low tide. Within that time, at each individual beach site, one 3 m × 3 m quadrat plot as described in the following section was examined over a period of 1 to 3 consecutive days. Each mill region was examined annually at approximately the same time. Six Howe Sound quadrat plots were surveyed in June from 1990 to 1993: Darrel Bay (6 km), Port Mellon A (1 km), Port Mellon B (1 km), Porteau Cove (13 km), Lions Bay (22 km), and Tunstall Bay (20 km). Four Crofton quadrats were surveyed in late July of 1990, 1991, and 1993: Crofton Dock (2.3 km), Wilson Beach (11 km), Stone Beach (11 km), and Southey Point (11 km). Seven Prince Rupert beach sites were studied during August of 1992 and 1993: Ridley Channel (1 km), Ridley Lighthouse (2 km), Wolf Creek (3.6 km), Wainwright Basin (4 km), Inverness (4.8 km), Ridley Trail (5 km), and Grain Ridley (6.8 km). Finally, six Powell River sites were studied in early July of 1993: Westview (4 km), Site A (9 km), Texada Ferry (9.8 km), Site B (20 km), Texada Highway (27 km), and Keays Cove (28 km). Refer to the maps in Figures 1 to 5 for locations of pulp mills and survey sites.

Criteria for Site Selection. Sampling sites measuring 3 m × 3 m were established in the mid to low intertidal zone (0.5 to 1.0 m tide height) of rocky shore beaches at increasing distances from each mill. Each site contained rocks 15 to 50 cm in diameter that could be overturned to allow examination of the species underneath. This tidal zone was chosen for the high diversity of marine organisms it harbors and because it is frequently uncovered during the low summer tides. In addition, beach research sites were selected for long-term accessibility in the form of, for example, a park or the beach front of a local resident's home. To help locate the best sites, historical information about the region and its marine plants and animals was solicited from long-time community residents, local biologists, fishermen, mill workers, and divers.

Rocky intertidal sites that appeared by eye to have similar substrate, climate, and oceanographic features were selected for the survey. All regions are frequently visited by people, and the level of damage caused by souvenir hunters and shellfish harvesters is assumed to be equal among all sites. Such physically similar beaches are reported in the literature to contain approximately the same variety of species (Snively, 1983). Sites with these physical similarities were assumed to contain similar community structures if no other factors existed.

The ideal study would survey isolated sites unaffected by human activities. Some of these sites could be systematically exposed to increasing pulp mill effluent over time, whereas others would remain reference sites. Any changes in community structure would be noted regularly over the course of the long-term monitoring study and compared to the unexposed reference sites. Unfortunately, the pulp mills were built 50 to 100 years ago, and no data exist that describe which species lived at the survey sites before industrialization.

To remedy this drawback, beaches surrounding five mills were examined to detect trends in species tolerance to mill effluent and to identify bioindicators common to all mill regions. In addition, reference sites that were located up to 40 km from the mills and appeared to be minimally affected by pollution were selected. The observed diversity at the reference site was assumed to be of the same magnitude as the "potential diversity" of all surveyed sites. Therefore, assuming sites were similar in all other aspects, if pulp mill pollution had no effect on intertidal diversity and community structure, all sites would be similar to the reference site.

Quadrat Survey Technique. With the help of volunteers from local environmental and community groups, including the Save Georgia Strait Alliance, Western Canada Wilderness Committee, and Environmental Youth Alliance, surface-cover quadrats were surveyed at the majority of the sites in two ways. First, with the aid of quadrat frames, the 3 m × 3 m survey sites were divided into a grid consisting of 10 cm × 10 cm squares. The 0.5 m × 0.5 m wooden square quadrat frames were strung with string at 10-cm intervals to form this grid. A total of 36 frames was used to survey the 9-m^2 quadrat plot at each study beach.

The organism located directly below each string intersection of the grid was located using a plumb bob and recorded. If several species overlapped each other, for example algae growing on top of a limpet's shell, only the top species touched by the plumb bob would be recorded. Once the species found at each intersection of the first quadrat frame were recorded, the frame was moved to a neighboring unsurveyed area and the procedure was repeated. From these data, the "species richness" (that is, number of species) and the "percent cover" [(number of intersections in which species A is recorded)/(total number of intersections) × 100%] of each above-rock species were calculated.

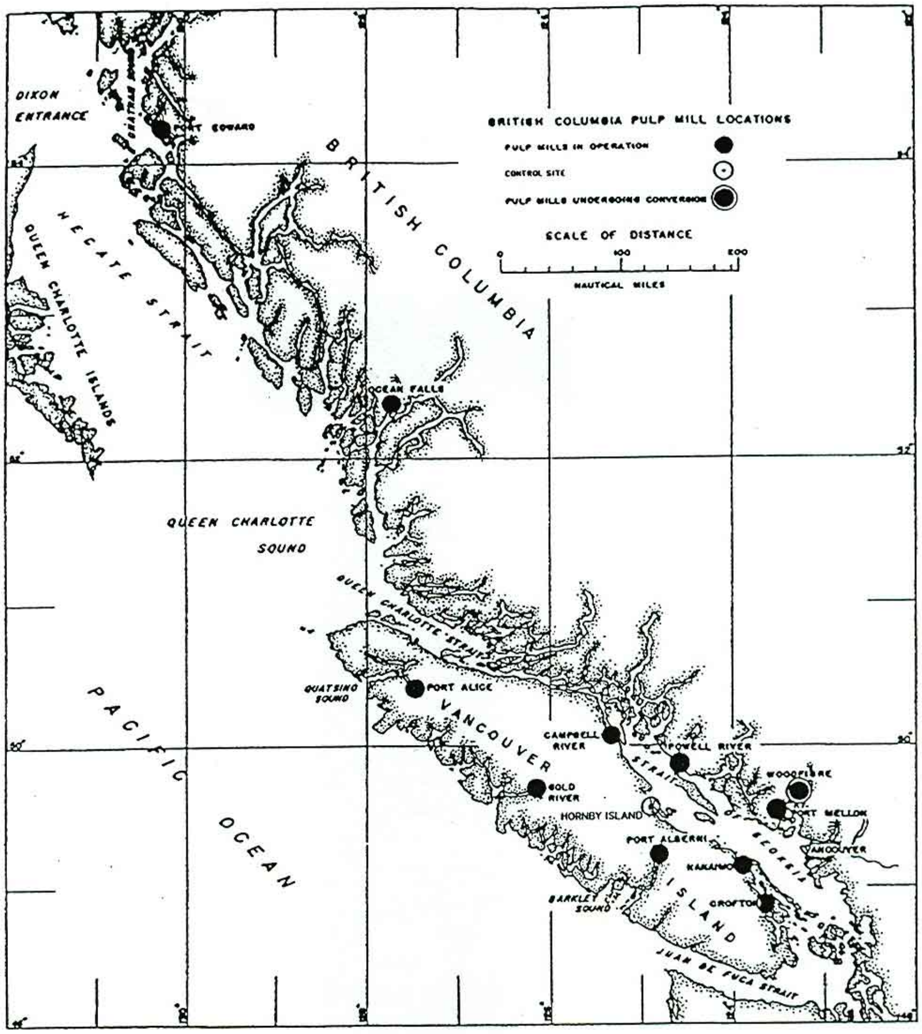

Figure 1—Coastal British Columbia.

For the second part of the survey, the frames were put aside and the quadrat plot was divided into a grid with squares of 0.5 m × 0.5 m. Each rock within the quadrat was overturned, and the number of each species observed was recorded. The presence or absence of sessile organisms under each rock was assessed. The rocks were all returned to their original positions.

Algae, invertebrates, and fish were identified in the field with the help of reference books (Barnes, 1987; Gotshall and Laurent, 1980; Harbo, 1980; Hewlett-Paine, 1993; Knopf, 1990; Lamb and Edgell, 1986; Meinkoth, 1981; and Snively, 1983). Invertebrates and fish that were unidentifiable at the species level in the field were preserved and identified at the Khoyatan Marine Laboratory in Cowichan Bay, Vancouver Island, Canada. Seaweeds were pressed on herbarium paper and later identified at the University of British Columbia and at Simon Fraser University. Unfortunately, a small number of seaweeds and worms, as well as one shrimp, were identified only to the genus level, and the amphipods were identified only to the family level. In future studies, all organisms should be identified to the species level because members of the same genus may differ in ecological requirements and possibly in tolerance to effluent exposure.

Exposure to Mill Effluent. To measure the effect of pulp mill effluent on the rocky intertidal shore, two tracers, pulp fibers and organochlorine compounds, were used to determine the amount of effluent washing ashore. The occurrence of these mill waste components at beach sites in 1990 and 1991 was used to define three effluent exposure zones: high, moderate, and low. The species richness and pollution tolerance data were used to develop a biological index to predict a site's exposure to mill effluent. The Bioindex was tested on 1992 and 1993 data for Howe Sound, Crofton, Powell River, and Prince Rupert. Bioindex-predicted exposure rankings for these years were compared with exposure rankings by tracers.

The 1990 and 1991 study sites in Howe Sound and Crofton that had observable deposits of pulp fibers and, according to Environment Canada, were contaminated with organochlorines were deemed high-exposure zones. Intertidal pulp fibers accumulated at Darrel Bay up to 6 km from the Woodfibre mill in Howe Sound. The two sites adjacent to Port Mellon (see Figure 2), Howe Sound's second mill, showed heavy deposits of pulp fibers. These findings are corroborated by the literature, which cites zones of benthic degradation from solid wood waste rang-

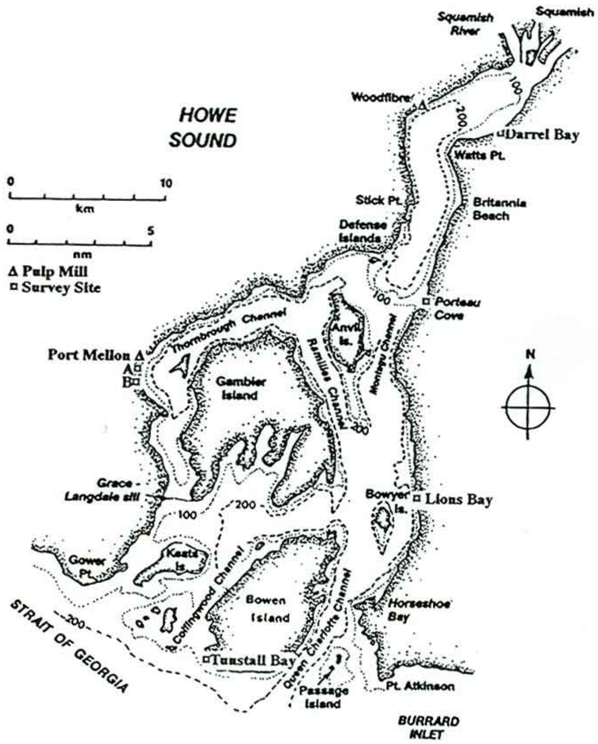

Figure 2—Howe Sound.

ing up to 5 km from Howe Sound mills (Colodey *et al.*, 1990). In addition, pulp fibers washed ashore at the Crofton government dock adjacent to the Crofton mill. During the same period, in these two mill regions, the high-exposure zone extended up to 10 km from the mill outfalls.

The 1990 and 1991 beach sites in Howe Sound and Crofton that did not have pulp fiber deposits but whose sediments or resident organisms were contaminated with organochlorines at levels greater than 10 ppq were defined as moderate-exposure zones. Organochlorine analysis was conducted by the Dioxin Testing Program of the Pollution Abatement wing of Environment Canada. Unfortunately, the exact dioxin levels for each site were not publicly disclosed, only information on whether samples were greater or less than the 10 ppq threshold.

Sites up to 20 km away from the nearest Howe Sound mills, including Porteau Cove, Lions Bay, and Tunstall Bay on Bowen Island, were contaminated with dioxins and furans and closed to crab fisheries. Three sites surrounding the Crofton mill, Wilson Beach, Stone Beach, and Southey Point on Saltspring Island, were contaminated. During the same period, the moderate-exposure zone extended 10 to 25 km from the Crofton and Howe Sound mill outfalls. Reference beaches, which because of current and dilution patterns were unlikely to be exposed to mill pollution and which according to Environment Canada were not contaminated with dioxins and furans, were defined as low-exposure zones (Thomson, 1981).

Species Tolerance to Mill Effluent. Pollution tolerance categories were defined for organisms observed in 1990 and 1991 based on their presence, as defined by tracers, at high-, moderate-, or low-exposure Howe Sound and Crofton sites. Moving away from a pulp mill, pollution "tolerant" species are those that survive in high-exposure sites (0 to 10 km from the mills); "sensitive" species first appear in the moderate-exposure sites (10 to 25 km from the mills); and "intolerant" species first appear only at low-exposure sites (more than 25 km from the mills). All species observed in 1990 and 1991 were categorized based on the these criteria. Table 1 lists the species observed in their order of appearance. Common names are taken from Snively (1983). A few additional species, also included in Table 1, were observed in 1992 and 1993 at Prince Rupert and Powell River. The tolerance of these species to mill effluent was defined by the highest exposure region in which they were found. This grouping of species according to tolerance to mill effluent is corroborated by the work of other researchers who have conducted intertidal sampling around pulp mills (Hoos, 1975; Waldichuk, 1962; and Wilkes and Dwernychuk, 1991). Other scientists have demonstrated through field transplantation and laboratory pollution exposure experiments that mill effluent has both lethal and sublethal effects on marine organisms such as clams (Cooper *et al.,* 1989), blue mussels and barnacles (Wu and Levings, 1980), crabs (Cristini *et al.,* 1989), and fish (Muir and Yarechewski, 1988).

Organism presence and abundance were examined to determine which species changed the most between sites at a gradient from the mill. These species, consisting of some of the tolerant, all of the sensitive, and all of the intolerant organisms, were defined as "indicator species." Tolerant nonindicator species were those that appeared at all the sites with equal abundance. Exposure to pulp mill pollution did not seem to overtly affect survival of these species; therefore, they were not included as indicator species.

The absence of sensitive and intolerant indicator species and presence of tolerant indicator species defines a high-exposure site. The absence of tolerant indicator species and presence of sensitive and intolerant indicator species defines a low-exposure site. Finally, a moderate-exposure zone may have a mixture of species of varying tolerance. Note that a site that hosts no indicator species, only tolerant nonindicator species, is designated a high-exposure zone.

Ranking the Condition of the Intertidal Zone Surrounding Pulp Mills. A combination of two methods of evaluation was used to rank the condition of the intertidal zone surrounding pulp mills. First, the distance to the nearest low-expo-

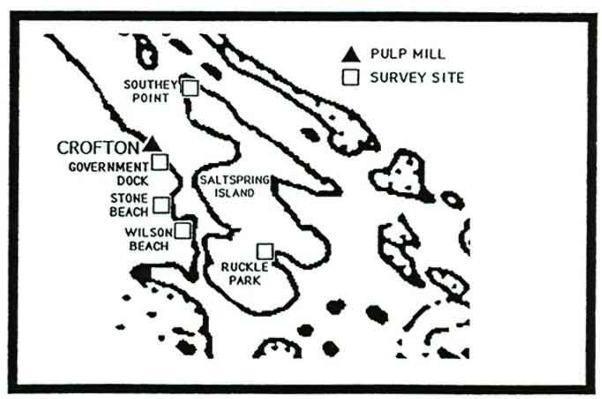

Figure 3—Crofton.

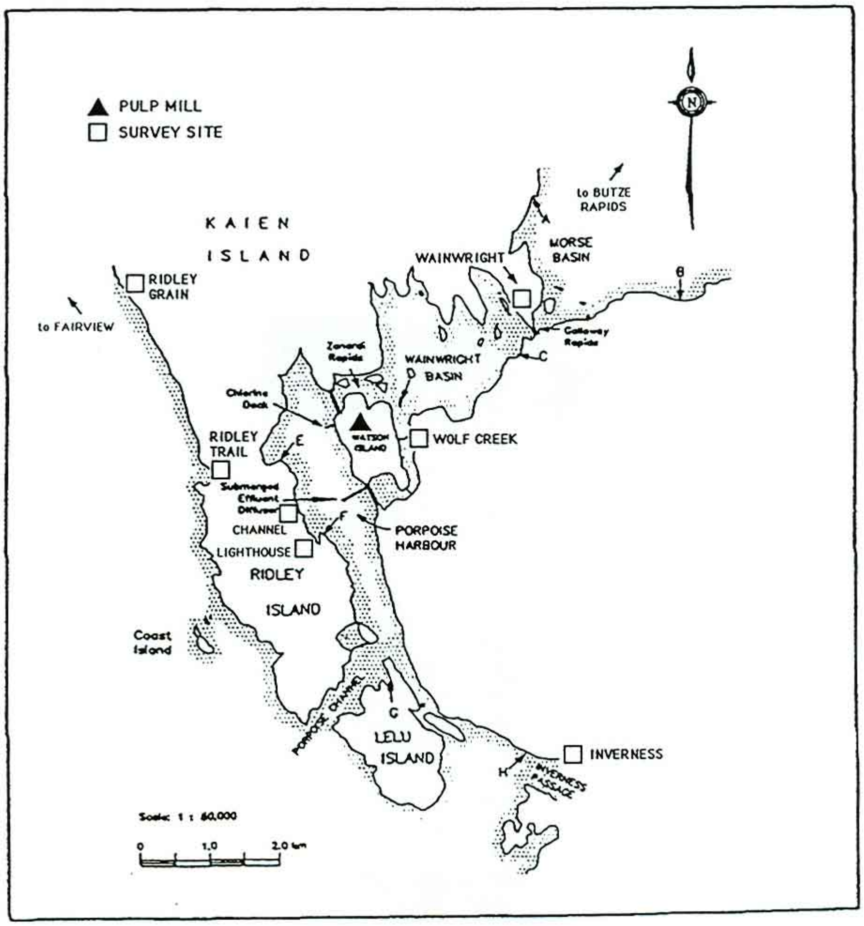

Figure 4—Prince Rupert.

sure site indicated the least polluted mill region. Second, the greatest level of depletion (that is, sites of lowest species richness) indicated the most polluted mill regions. The effect of each pulp mill's effluent on the surrounding intertidal zone was ranked from most to least polluted. This ranking is not absolute but is relative to all surveyed pulp mills.

Results

Indicator Species and General Trends. Several indicator species were found to change in abundance as exposure to mill pollution changed. The abundance of intolerant and sensitive species decreased as exposure to mill effluent increased. Similarly, the abundance of tolerant indicator species decreased in abundance as exposure decreased. One possible reason for these conditions is that the tolerant species dominated the high-exposure zones because of their hardiness but were outcompeted by pollution-sensitive and intolerant species in the moderate- and low-exposure zones. Tolerant isopods (*Idotea wosnesenskiis* and *Gnorimosphaeroma oregonensis)* and amphipods (family Grammarus) were found only at beaches with a plentiful supply of their food source pulp fibers and decomposing algae. Therefore, abundance and diversity of these species are good indicators of the volume of pulp effluent and its toxicity. Different species of algae were indicators of different exposure levels. Green algae were most abundant and diverse in high-exposure zones, and brown algae showed similar trends in moderate-exposure zones, as did red algae in the low-exposure zones. As shown in Table 2, which lists the 20% most abundant tolerant indicator species observed in the high-exposure zones, 20% most abundant sensitive indicator species in the moderate-exposure zones, and 20% most abundant intolerant indicator species in the low-exposure zones, these trends were consistent among all sites and mill regions.

Tolerance to Mill Effluent. All amphipods, barnacles, isopods, and mussels observed were tolerant species. At the opposite extreme, all scallops, sea cucumbers, sea urchins, and sponges were pollution intolerant. Anemones, chitons, fish, and worms had both sensitive and intolerant representatives. Diverse species groups whose members were tolerant, sensitive, and intolerant were the crabs, nudibranchs, sea stars, seaweeds, shrimp, snails, and tunicates. Of the 173 species observed during the study, significantly more species were sensitive (43) or intolerant (102) to the pollution than were tolerant (28) of its effects. Refer to Table 1 for scientific names of species within each organismal group.

Ranking the Intertidal Zone According to Species Richness and Exposure to Effluent. Each pulp mill region was ranked according to severity of marine environmental impact using the technique outlined in the Methodology section. Howe Sound had the most depleted species richness and seemed to be most affected by pulp mill effluent, followed in order of

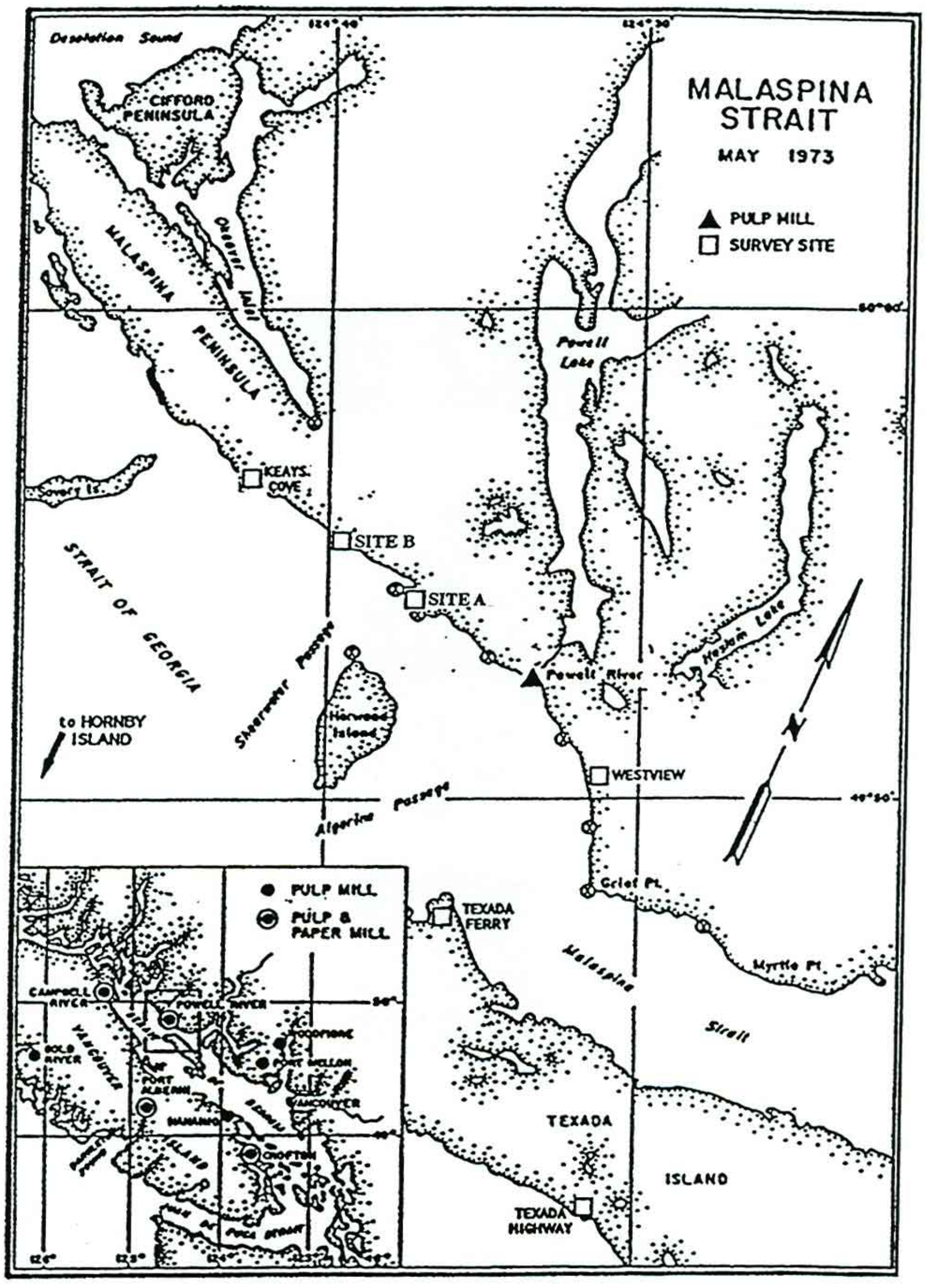

Figure 5—Powell River.

decreasing severity by Crofton, Prince Rupert, and Powell River. The following sections will describe the species richness in each survey region.

Howe Sound: Port Mellon and Woodfibre Pulp Mills. All sites were classified as high, moderate, or low exposure to mill effluent based on the criteria outlined previously in the Methodology section. Whether the number of species differed significantly between sites of different exposure for all 4 survey years (1990 to 1993) was tested. The relationship among the average number of species in each exposure zone was similar for each survey year. The species richness data were pooled from all Howe Sound sites for all 4 years, and an analysis of variance (ANOVA) and Scheffe's multiple comparison test were performed. The number of species at a survey site depended significantly on the exposure level (see Figure 6) (ANOVA: SS [sum of squares] = 15 135; $F_{[2,23]}$ [F-distribution, named for Fisher] = 3.42; and P [probability] $\ll 0.001$). There were significant differences in all pairwise comparisons among all exposure categories (high, moderate, and low) for Scheffe's test (P ≤ 0.01).

A repeated-measures ANOVA was calculated for Howe Sound sites with the most complete data (1991 to 1993 for Darrel Bay, Porteau Cove, Lions Bay, and Hornby Island) to test for an overall relationship between species richness, expo-

Table 1—Tolerant, sensitive, and intolerant mid to low intertidal species.

Common name	Scientific name	I^a
Tolerant species		
Amphipods	Family Grammarus	
Barnacles		
Common acorn	*Balanus glandula*	
Small	*Chthamalus dalli*	I
Bryozoan		
Brown	*Membranipora tuberculata*	
Crab		
Purple shore	*Hemigrapsus nudus*	
Green shore	*Hemigrapsus oregonensis*	
Granular hermit	*Pagurus granosimanus*	
Isopods		
Pill bug	*Gnorimosphaeroa oregonensis*	I
Rockweed isopod	*Idotea wosnesenskii*	I
Limpet		
Speckled	*Notoacmea persona*	
Plate	*Notoacmea scutum*	
Finger	*Collisella digitalis*	
Shield	*Collisella pelta*	
Mussel		
Blue	*Mytilus edulis*	
Nudibranch		
Cryptic	*Onchidoris bilamellata*	I
Sea star		
Purple	*Pisaster ochraceus*	
Seaweed		
Epiphyte	*Audouinella* sp.	I
Sea hair	*Blidingia subsalsa*	I
Sea moss	*Caulacanthus ustulatus*	I
Sea hair	*Enteromorpha intestinalis*	
Rockweed	*Fucus gardneri*	
Crisp lettuce	*Mastocarpus* sp.	
	Monostroma sp.	I
Brown sea hair	*Pilayella littoralis*	I
Fibrous mass	*Rhizoclonium implexum*	I
	Sarcodiotheca gaudichaudic	I
Sea lettuce	*Ulva* sp.	
Snail		
Checkered periwinkle	*Littorina scutulata*	
Sitka periwinkle	*Littorina sitkana*	
Tunicate		
Colonial	*Diplosoma macdonaldi*	I
Sensitive species		
Anemone		
Green	*Anthopleura elegantissima*	I
Chiton		
Lined	*Tonicella lineata*	I
Mossy	*Mopalia muscosa*	I
Crab		
Black-clawed	*Lophopanopeus bellus*	I
	Pachycheles pubescens	I
Fish		
Black prickleback	*Xiphister atropurpureus*	I
Rock prickleback	*Xiphister mucosus*	I
Clingfish	*Gobiesox maeandricus*	I
Tidepool sculpin	*Oligocottus maculosus*	I
Green fluffy sculpin	*Oligocottus snyderi*	I
Nudibranch		
Brown	*Acanthodoris brunnea*	I
White	*Archidoris odhneri*	I
Oyster		
Japanese	*Crassostrea gigas*	I
Jingle shell	*Pododesmus macroschisma*	I
Sea star		
Mottled	*Evasterias troschelii*	I
Six-rayed	*Leptasterias hexactis*	I
Seaweed		
	Callophyllis sp.	I
	Cladophora microcladioides	I
Sea moss	*Endocladia muricata*	I
Sugar kelp	*Laminaria saccharina*	I
Sea brain	*Leathesia difformis*	I
Red seaweed	*Gracilaria* sp.	I
Black pine	*Neorhodomela larix*	I
Red laver	*Porphyra* sp.	I
	Pterosiphonia bipinnata	I
Sargassum	*Sargassum muticum*	I
	Spongomorpha saxatillis	I
Shrimp		
Broken-back	*Heptacarpus* sp.	I
Snail		
Wrinkled amphissa	*Amphissa columbiana*	I
Worm		
Commensal scaleworm	*Glycera rugosa*	I
Armoured scaleworm	*Halosydna brevisetosa*	I
Flatworm	*Notoplana* sp.	I
Calcareous tubeworm	*Serpula vermicularis*	I
Tiny tubeworm	*Spirorbis bifurcatus*	I
Mud nemertian	*Paranemertes peregrina*	I
	Phyllodoce sp.	I
Intolerant species		
Anemones		
Buried	*Anthopleura artemisia*	I
Strawberry	*Tealia lofotensis*	I
Northern red	*Tealia crassicornis*	I
Bryozoan		
Branched	*Bugula californica*	I
Red	*Eurystomella bilabiata*	I
Chiton		
Leather	*Katharina tunicata*	I
Gumboot	*Cryptochiton stelleri*	I
Clam		
Heart cockle	*Clinocardium nuttallii*	I
Northwest	*Entodesma saxicola*	I
Bent nose	*Macoma nasuta*	I
Little-neck	*Venerupis japonica*	I
Butter	*Saxidomus giganteus*	I
Razor	*Siliqua patula*	I
Crab		
Red rock crab	*Cancer productus*	I
Decorator crab	*Oregonia gracilis*	I
Porcelain crab	*Petrolisthes eriomerus*	I
Kelp crab	*Pugettia producta*	I
Sharp-nosed crab	*Scyra acutifrons*	I

Table 1—(Continued)

Common name	Scientific name	I[a]	Common name	Scientific name	I[a]
Fish			Sea grapes	*Halosaccion glandiforme*	I
Midshipman	*Porichthys notatus*	I		*Halymenia schizymenioides*	I
Limpet			Iridescent	*Iridaea cordata*	I
Keyhole	*Diodora aspera*	I	Iridescent	*Iridaea splendens*	I
Nudibranch			Split kelp	*Laminaria setchellii*	I
Sea lemon	*Archidoris montereyensis*	I	Rock crust	*Lithothamnium philippi*	I
Yellow-edged	*Cadlina luteomarginata*	I		*Microcladia coulteri*	I
Ringed	*Diaulula sandiegensis*	I		*Odonthalia floccosa*	I
Alabaster	*Dirona aurantia*	I	Black sea tar	*Petrocelis middendorfii*	I
Red	*Rostanga pulchra*	I		*Plocamium cartilagineum*	I
Scallop				*Polyneura* sp.	I
Free swimming	*Chlamys hericia*	I	Red sea hair	*Polysiphonia hendryi*	I
Sea cucumber			Lacy porphyra	*Porphyropsis* sp.	I
Orange	*Cucumaria miniata*	I	Red kelp	*Prionitis* sp.	I
Black-speck white	*Cucumaria piperata*	I		*Ptocamium cartilagineum*	I
White	*Eupentacta quinquesemita*	I		*Rhodoglossum* sp.	I
California	*Parastichopus californicus*	I		*Scinaia confusa*	I
Sea star			Shrimp		
Small brittle	*Amphipholis squamata*	I	Ghost	*Callianassa californiensis*	I
Leather	*Dermasterias imbricata*	I	Snail		
Blood	*Henricia leviuscula*	I		*Alia carinata*	I
Vermillion	*Mediaster aequalis*	I		*Alia gausapata*	I
Daisy brittle	*Ophiopholis aculeata*	I	Leafy hornmouth	*Ceratostoma foliatum*	I
Pink	*Pisaster brevispinus*	I	Wrinkled slipper shell	*Crepidula lingulata*	I
Sunflower	*Pycnopodia helianthoides*	I		*Fartulum occidentale*	I
Sun	*Solaster stimpsoni*	I		*Platynereis bicanaliculata*	I
Sea urchin			Spindle whelk	*Searlesia dira*	I
Green	*Strongylocentrotus droebachiensis*	I	Wrinkled whelk	*Thais lamellosa*	I
Red	*Strongylocentrotus franciscanus*	I	Sponge		
Seaweed			Red	*Plocamia karykina*	I
Alaria kelp	*Alaria marginata*	I	Crumb of bread	*Halichondria panicea*	I
Coral leaf	*Bosiella* sp.	I	Tunicate		
	Branchioglossum bipinnatifidum	I		*Clavelina huntsmani*	I
	Bryopsis hypnoides	I	Red	*Cnemidocarpa finmarkiensis*	I
	Ceramium sp.	I	Warty tunicate	*Pyura haustor*	I
	Coramium pacificia	I	Worm		
Graceful coral	*Corallina vancouveriensis*	I	Commensal scale	*Arctonoe vittata*	I
Seersucker kelp	*Costaria costata*	I	Bamboo	*Axiothella rubrocincta*	I
	Cryptopleura sp.	I	Sand nemertian	*Cerebratulus* sp.	I
	Cryptosiphonia woodii	I	Green nemertian	*Emplectonema gracile*	I
	Gastroclonium subarticulatum	I		*Lumbrineri* sp.	I
	Gelidium purpurescens	I		*Micrura verrilli*	I
	Gigartina sp.	I		*Nereis* sp.	I
	Grateloupia pinnata	I		*Platynereis bicanaliculata*	I
			Hairy gill	*Thelepus crispus*	I
			Orange nemertian	*Tubulanus polymorphus*	I

[a] Indicator species.

sure, and sampling year. There were no significant differences related to overall species richness and sampling year, nor any interaction between sampling year and exposure.

For each Howe Sound site that was surveyed for 3 or 4 years, a linear regression was performed to determine whether the number of species varied over time (1990 to 1993). Only those sites that showed a significant trend in number of species over time are presented here. The number of species increased significantly over time at the moderate-exposure sites of Lions Bay (regression coefficient = 3.61, r^2 [coefficient of determination calculated from the square of the correlation coefficient] = 0.739, and $P < 0.05$) and Tunstall Bay on Bowen Island (regression coefficient = 8.29, $r^2 = 0.869$, and $P < 0.05$).

Crofton Pulp Mill. The Crofton pulp mill is situated on the east coast of Vancouver Island. Oceanographic features predict that mill waste will be discharged in a south-southwesterly plume through Sansum Narrow, concentrating in Maple Bay. In late 1989, a large toxic spill occurred at Crofton. According to residents of Maple Bay and Saltspring, the surrounding coastal region was visibly bathed in mill foam and chemical discharge for a number of days. A barnacle and mussel kill resulted, and most of the organisms encrusted on the dock pilings peeled off.

Table 2—Tolerant, sensitive, and intolerant indicator species.

Tolerant, high exposure		Sensitive, moderate exposure		Intolerant, low exposure	
Common name	**Scientific name**	**Common name**	**Scientific name**	**Common name**	**Scientific name**
Pill bugs	*Gnorimosphaeroma oregonensis*	Black prickleback	*Xiphister atropurpureus*	Red bryozoan	*Eurystomella bilabiata*
Isopods	*Idotea wosnesenskii*	Rock prickleback	*Xiphister mucosus*	Leather chiton	*Katherina tunicata*
Sea hair	*Blidingia subsalsa*	Sculpin	*Oligocottus maculosus*	Red rock crab	*Cancer productus*
Sea moss	*Caulacanthus ustulatus*	Jingle oyster	*Pododesmus macroschisma*	Porcelain crab	*Petrolishes eriomerus*
Brown sea hair	*Pilayella littoralis*	Mottled star	*Evasterias troschelii*	Orange cucumber	*Cucumaria miniata*
Fibrous mass	*Rhizoclonium implexum*	Six-ray star	*Leptasterias hexactis*	Leather star	*Dermasterias imbricata*
		Sea moss	*Endocladia muricata*	Brittle sea star	*Ophiopholis aculeata*
		Black pine	*Neorhodomela larix*	Alaria	*Alaria marginata*
		Seaweed	*Pterosiphonia bipinnata*	Coral leaf	*Bosiella* sp.
		Tubeworm	*Spirorbis bifurcatus*	Sea moss	*Ceramium* sp.
				Gigartina	*Gigartina* sp.
				Snail	*Alia* sp.
				Snail	*Fartulum occidentale*
				Green urchin	*Strongylocentrotus droebachiensis*
				Sea grape	*Halosaccion glandiforme*
				Iridescent seaweed	*Irideae* sp.
				Split kelp	*Laminaria setchii*
				Hairy gill worm	*Thelepus crispus*
				Orange nemertian	*Tubulanus polymorphus*

The foam was later analyzed by the DFO and found to contain several compounds, including the toxin 2,4,7,8-TCDD (Wilson, R. [1989], personal communication, Maple Bay Conservation, Vancouver Island, British Columbia, Canada).

Whether the number of species differed significantly between sites of different exposure to Crofton mill effluent for all 3 survey years (1990, 1991, and 1993) was tested. The relationship among the average number of species in each exposure zone was similar for each survey year. The species richness data were pooled from all Crofton sites for all 3 years, and an ANOVA and Scheffe's multiple comparison test were calculated. The number of species at a survey site depended significantly on the exposure level (see Figure 7) (ANOVA: SS = 2 028; $F_{[2,8]} = 4.46$; and $P \ll 0.001$). There were significant differences in all pairwise comparisons among all exposure categories (high, moderate, and low) for the Scheffe's test ($P \leq 0.05$).

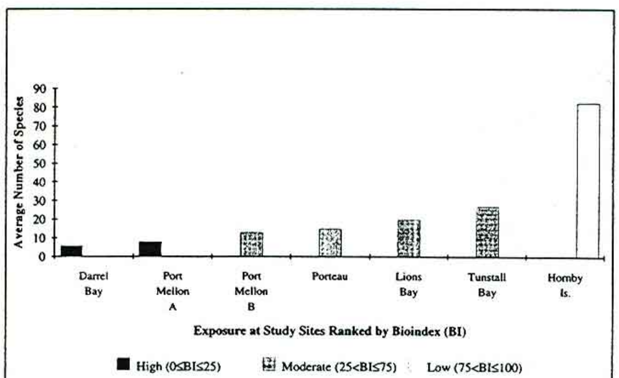

Figure 6—Average species richness (1990 to 1993) versus exposure to Woodfibre and Port Mellon pulp mill effluent (Howe Sound, British Columbia, Canada).

For each Crofton site that was surveyed during 3 years, a linear regression was performed to determine whether the number of species varied over time (1990, 1991, and 1993). Only those sites that showed a significant trend in number of species over time are presented here. The number of species increased significantly over time at the high-exposure site of Crofton government dock (regression coefficient = 2.29, $r^2 = 0.988$, and $P < 0.001$) and at the moderate-exposure site of Stone Beach in Maple Bay (regression coefficient = 3.29, $r^2 = 0.994$, and $P \ll 0.001$).

Prince Rupert. Whether the number of species differed significantly between sites of different exposure to Prince Rupert mill effluent for both survey years (1992 and 1993) was tested. The relationship among the average number of species in each exposure zone was similar for each survey year. The species richness data from all Prince Rupert sites for both years were pooled, and an ANOVA and Scheffe's multiple comparison test were performed. The number of species at a survey site depended significantly on the exposure level (see Figure 8) (ANOVA: SS = 2 801; $F_{[2,10]} = 4.10$; and $P \ll 0.001$). There were significant differences in all pairwise comparisons among all exposure categories (high, moderate, and low) for Scheffe's test ($P \leq 0.05$.)

Powell River. Powell River was quantitatively surveyed in 1993 but only qualitatively surveyed in 1992. Therefore, no quantitative temporal changes could be measured. Whether the number of species differed significantly between sites of different exposure to Powell River mill effluent in 1993 was tested, and Scheffe's multiple comparison test was performed. The number of species at a survey site depended significantly on the exposure level (see Figure 9) (ANOVA: SS = 1 848; $F_{[1,5]} = 7.00$; and $P < 0.05$). There were significant differences in

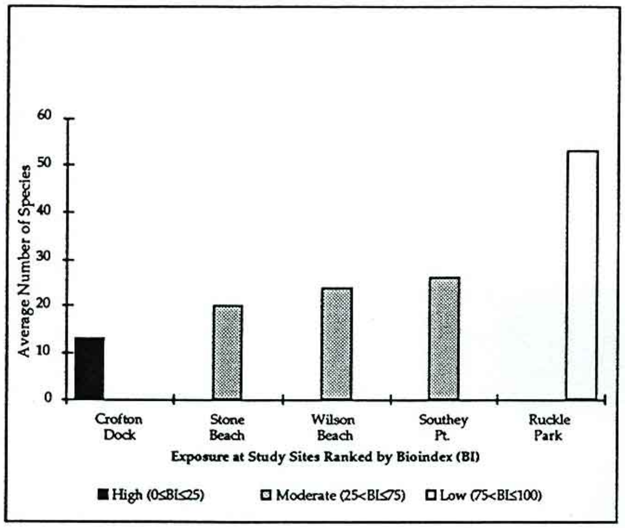

Figure 7—Average species richness (1990, 1991, and 1993) versus exposure to Crofton pulp mill effluent (Vancouver Island, British Columbia, Canada).

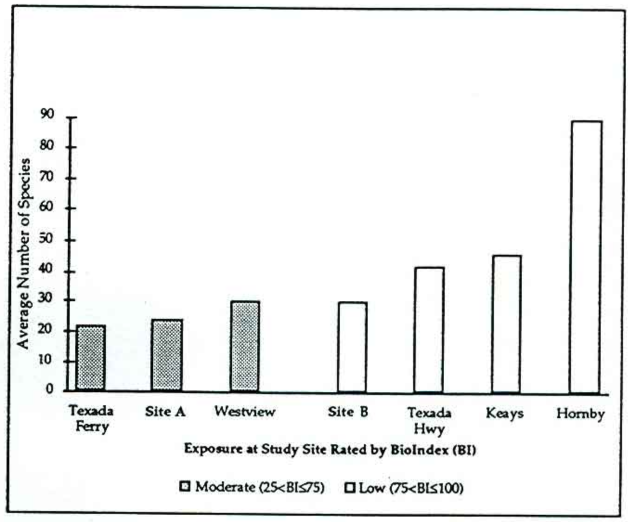

Figure 9—Species richness (1992) versus exposure to Powell River pulp mill effluent (British Columbia, Canada).

all pairwise comparisons among all exposure categories (high, moderate, and low) for Scheffe's test ($P \leq 0.05$.)

Bioindex for Intertidal Communities. A sensitive index is needed to allow economical and easy determination of a site's exposure to mill effluent without requiring that the accumulation of organochlorines or pulp fibers be evaluated. The 1990 and 1991 data at Howe Sound and Crofton, which noted three distinct levels of intertidal community structure in each exposure zone, were used to define the relationship between exposure and intertidal diversity. This relationship is described by the Bioindex for Intertidal Communities (refer to Figure 10). The Bioindex exposure ratings for the 1990 and 1991 sites in Howe Sound and Crofton (on whose data it was based) concurred with the original exposure rating based on tracers. The Bioindex was tested with diversity data from 1992 and 1993 sites at Howe Sound, Crofton, Prince Rupert, and Powell River. The Bioindex was used to detect temporal changes in exposure to mill pollution at each site. In the following sections, the Bioindex exposure ranking will be compared to the exposure rating based on tracers.

The Bioindex was designed to determine the extent to which a protected Pacific Northwest rocky-shore beach is exposed to pulp mill pollution based on its resident mid to low intertidal biota. This index applies to beaches that are affected by effluent from pulp mills only. Beaches that are exposed to large amounts of other types of pollution, for example oil spills, cannot be evaluated by the Bioindex. This index makes three assumptions. First, the Bioindex assumes that the beaches are exposed to a stable amount and toxicity of mill pollution. Second, the index assumes that similar types of species will occur over time at a site if the pollution level remains constant. Third, the index assumes that the resident species have adjusted to any change in exposure and have reached an equilibrium state of diversity.

The Bioindex is a 100-point scale that defines exposure zones based on the proportion of sensitive and intolerant indicator species among the total number of indicator species (tolerant, sensitive, and intolerant) found at a site. A site's point value is calculated by the following formula: [(proportion of tolerant indicator species) $\times$ 0] + [(proportion of sensitive indicator species) $\times$ 0.5] + [(proportion of intolerant indicator species) $\times$ 1.0] = Bioindex score.

Zero Bioindex points are assigned to a site hosting 100% tolerant indicator species (or 100% tolerant nonindicator species); 50 points are assigned to a site hosting 100% sensitive species; and 100 points are granted for 100% intolerant species. High-exposure sites are those assigned up to 25 points, moderate-exposure sites gain from 25 up to 75 points, and low-exposure sites are awarded 75 to 100 points. In the moderate-exposure range, a scoring of 25 to 50 points indicates a mix of tolerant and sensitive species, whereas the 50- to 75-point range

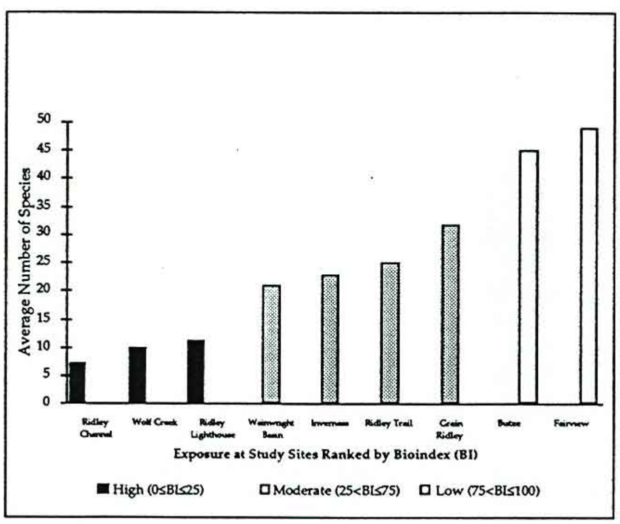

Figure 8—Average species richness (1992 to 1993) versus exposure to Prince Rupert pulp mill effluent (British Columbia, Canada).

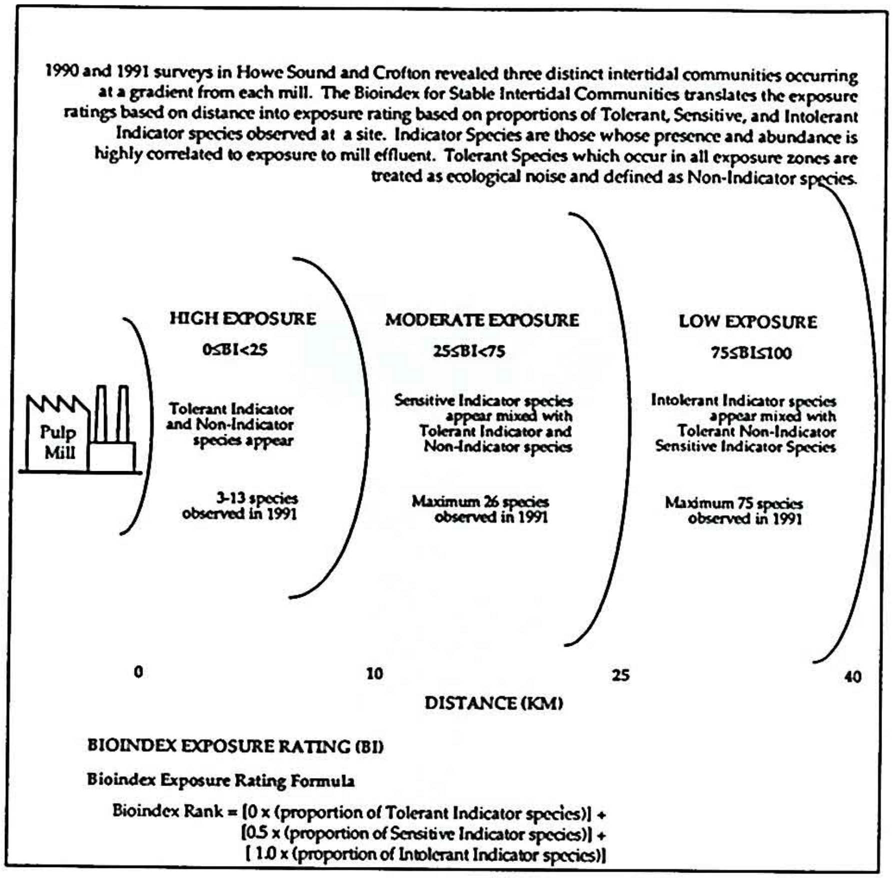

Figure 10—Exposure, tolerance, and the Bioindex exposure rating (BI).

represents a mix of sensitive and intolerant species. Note that a condition of 100% intolerant species at a site was never observed and is unlikely because sensitive species can survive at moderate- and low-exposure sites even though their numbers may be limited by competition from intolerant species.

Bioindex Exposure Rating. The intertidal survey sites surrounding each pulp mill were evaluated using the Bioindex to determine effluent exposure (refer to Table 3). Bioindex exposure ratings were graphed for the survey sites in each region: Howe Sound, Crofton, Prince Rupert, and Powell River.

Howe Sound. Figure 6 illustrates the average species richness at Howe Sound sites from 1990 to 1993 versus exposure to Woodfibre and Port Mellon mill effluent. The Bioindex exposure ratings agreed with tracer exposure rankings for all sites during all survey years. The Bioindex was used to detect temporal changes in several Howe Sound sites. At the Lions Bay and Tunstall Bay sites, not only did the number of species increase dramatically, but the proportions of sensitive and intolerant species also increased. Larger proportions of sensitive and intolerant species translate into a higher Bioindex rank. Lions Bay jumped from 29 to 38 Bioindex points over 4 years because of an increase in the proportion of sensitive species (no intolerants were observed). Tunstall Bay increased from 50 to 69 points as a result of the appearance of never-before-observed intolerant species. Despite the rise in diversity and Bioindex ranking, the two sites remain rated as moderate-exposure zones. The highest Bioindex rank of all the sites was noted in 1993 at Hornby, with 91 Bioindex points. The Hornby reference site had little fluctuation in Bioindex rating over the 4 years of the study. This fluctuation could be considered the background noise from natural, nonanthropogenic causes such as recruitment or climatic fluctuations.

Crofton. Figure 7 illustrates the average species richness at Crofton sites during 1990, 1991, and 1993 versus exposure to Crofton mill effluent. During all survey years, the Bioindex exposure ratings agreed with tracer exposure rankings for all sites except the government dock site. In 1990 and 1991, the Crofton dock site hosted 100% effluent-tolerant species, was rated 0 Bioindex points, and thus was considered a high-exposure zone in corroboration with the tracer exposure ranking. However, in 1993, all of the species observed at the dock site were sensitive species, and the Bioindex rank rose to 50 points, indicating a moderate-exposure zone, although pulp chips were still present at the site. In the moderate-exposure Stone Beach and low-exposure Ruckle Park reference sites, few changes in Bioindex rating occurred over the course of the study.

Prince Rupert. Figure 8 illustrates the average species richness at Prince Rupert sites during 1992 and 1993 versus exposure to Prince Rupert mill effluent. The Bioindex exposure ratings agreed with tracer exposure rankings for all sites during all survey years. Wolf Creek, Ridley Lighthouse, and the beach site directly across Porpoise Channel from the Prince Rupert

Table 3—Table of Bioindex exposure rating.[a]

Howe Sound 1993 and 1992 data

Site	D[b]	1993	T	S	I	BI	E	1992	T	S	I	BI	E
Darrel Bay	6	7	100	0	0	0	H[c]	7	100	0	0	0	H
Port Mellon A	1	9	100	0	0	0	H	7	100	0	0	0	H
Port Mellon B	2	13	25	50	25	50	M	nc[d]					
Porteau Cove	13	14	50	50	0	25	M	15	43	29	28	43	M
Lions Bay	22	28	23	77	0	38	M	18	37	63	0	32	M
Tunstall Bay	20	43	8	46	46	69	M	nc					
Hornby Island	40	90	1	16	83	91	L	84	0	30	70	85	L

Howe Sound 1991 and 1990 data

Site	D	1991	T	S	I	BI	E	1990	T	S	I	BI	E
Darrel Bay	6	7	100	0	0	0	H	3	100	0	0	0	H
Porteau Cave	13	16	40	60	0	30	M	nc					
Lions Bay	22	18	30	70	0	35	M	16	43	57	0	29	M
Tunstall Bay	20	19	0	100	0	50	M	20	0	100	0	50	M
Hornby Island	40	75	0	31	69	85	L	qs[e]					

Crofton 1993 and 1991 data

Site	D	1993	T	S	I	BI	E	1991	T	S	I	BI	E
Crofton Dock	2.3	17	0	100	0	50	M	13	100	0	0	0	H
Wilson Beach	11	nc						24	0	100	0	50	M
Stone Beach	11	25	0	89	11	56	M	19	0	100	0	50	M
Southey Pt.	11	nc						26	0	63	37	69	M
Ruckle Park	33	53	2	42	56	77	L	53	0	38	62	81	L

Crofton 1990 data

Site	D	1990	T	S	I	BI	E
Crofton Dock	2.3	10	100	0	0	0	H
Wilson Beach	11	23	0	100	0	50	M
Stone Beach	11	15	0	100	0	50	M
Southey Pt.	11	nc					
Ruckle Park	33	qs					

Prince Rupert 1993 and 1992 data

Site	D	1993	T	S	I	BI	E	1992	T	S	I	BI	E
Ridley Channel	1	nc						7	100	0	0	0	H
Ridley Light	2	nc						11	75	17	8	17	H
Wolf Creek	3.6	11	67	33	0	17	H	9	100	0	0	0	H
Wainwright	4	21	12	44	44	66	M	nc					
Inverness	4.8	23	20	60	20	50	M	nc					
Ridley Trail	5	29	17	33	50	67	M	21	20	60	20	50	M
Grain Ridley	6.8	32	10	42	48	69	M	nc					
Butze	11	39	4	35	61	79	L	50	3	28	69	83	L
Fairview	13	56	5	37	58	77	L	42	3	29	68	82	L

Powell River 1993 data

Site	D	1993	T	S	I	BI	E
Westview	4	30	20	30	50	65	M
Site A	9	24	0	60	40	70	M
Texada Ferry	9.8	22	0	50	50	74	M
Site B	20	30	4	26	73	83	L
Texada Hwy	27	42	3	38	59	78	L
Keays	28	46	1	45	52	75	L
Hornby Island	40	90	1	16	83	91	L

[a] Refer to Table 1 for list of tolerant, sensitive, and intolerant species, which are denoted as indicator species for the Bioindex.

[b] *D* = shortest distance to nearest pulp mill measured over the water, km; *T* = proportion of tolerant indicator species to all indicator species observed, %; *S* = proportion of sensitive indicator species to all indicator species observed, %; *I* = proportion of intolerant indicator species to all indicator species observed, %; BI = Bioindex ranking = $[(0 \times T) + (0.5 \times S) + (1.0 \times I)]$; and *E* = exposure to pulp mill pollution ranking.

[c] H = high = $0 \geq \text{BI} > 25$, M = moderate = $25 \geq \text{BI} > 75$, and L = low = $75 \geq \text{BI} \geq 100$.

[d] Not conducted that year.

[e] Qualitative survey; no definitive species count made.

mill had high accumulations of pulp fibers, and according to DFO, these sites were contaminated with organochlorines. The Bioindex and tracers ranked these sites as having high exposure to pulp mill effluent. Wainwright Basin and Ridley Island sites tested positive for organochlorines but did not have washed-up pulp chips. The Bioindex and tracers deemed these sites to be moderately exposed. Finally, the uncontaminated reference sites, Butze Rapids and Fairview, were ranked as low-exposure sites by the Bioindex.

Bioindex exposure category rankings at all Prince Rupert sites were similar for 1992 and 1993.

Powell River. Figure 9 illustrates the species richness at Powell River sites during 1993 versus exposure to Powell River mill effluent. The Bioindex exposure ratings agreed with tracer exposure rankings for all sites during all survey years. No Powell River sites were evaluated to be high-exposure sites according to the Bioindex rankings, and no pulp chips were found on these beaches. The Westview, Site A, and Texada Ferry sites surrounding the Powell River mill were contaminated with toxins (DFO, 1993) and ranked as moderately exposed by the Bioindex. Finally, the reference sites at Site B, Texada Highway, Keays Cove, and Hornby Island were, according to DFO, uncontaminated by dioxins and ranked as low-exposure sites by the Bioindex.

The Bioindex is subtle enough to detect the difference in exposure at sites that have the same number of species. Westview, a moderate-exposure site, hosted 30 species, as did Site B. However, Site B's resident biota had a higher proportion of intolerant and sensitive indicator species and therefore was deemed low exposure.

Discussion

Indicator Species and Observed Trends. The abundance of tolerant individual species such as shore crabs, hermit crabs, and periwinkles remains approximately constant at all exposure sites. The diversity of crabs, chitons, intertidal fish, sea stars, nudibranchs, snails, and worm species increases as exposure decreases. The abundance of sensitive and intolerant species from the above categories was observed to increase as exposure decreased.

Sea Stars. Tolerant purple sea stars (*Pisaster ochraceus*) appear near mills as juveniles less than 3 cm in diameter. Apparently, the juveniles migrate from these high-exposure regions at the adult stage or fail to survive to maturity. A combination of juvenile and adult purple sea stars along with sensitive juvenile mottled sea stars (*Evasterias troschelii*) are observed in the moderate-exposure zone. At low-exposure sites, intolerant brittle stars (*Amphipholis squamata, Ophiopholis aculeata*), pink stars (*Pisaster brevispinus*), blood stars (*Henricia leviuscula*), leather stars (*Dermasterias imbricata*), vermillion stars (*Mediaster aequalis*), sunflower stars (*Pycnopodia helianthoides*), and sun stars (*Solaster stimpsoni*) are observed in addition to the purple and mottled stars.

Algae. Algae are good indicators of exposure to mill effluent. Close to mills, green algae dominate the shore because of two factors: hardiness and a ready supply of fresh water. In 1992, mats of green algae (*Rhizonclonium implexum, Enteromorpha intestinalis*) up to 10-cm thick in spots and ranging for tens of square metres smothered the beach and its benthic organisms at highly exposed Port Mellon and Crofton mill sites. Moving to a moderately exposed site, the abundance of green algae decreases and the brown algae increases. Rockweed (*Fucus gardneri*) serves to shelter invertebrates from the sun, whereas sargassum (*Sargassum muticum*) and kelp (*Laminaria saccharina, Laminaria setchellii, Alaria marginata,* and *Costaria costata*) provide a nursery for juvenile fish. In the low-exposure sites, the high abundance of rockweed subsists and a host of varied filamentous red algae is observed.

Isopods and Amphipods. Rockweed isopods (*Idotea wosnesenskiis*), pillbug isopods (*Gnorimosphaeroma oregonensis*), and amphipods (family Grammarus) were found to be good indicators of the volume of pulp effluent and of its toxicity. Isopods thrive on the supply of pulp fibers provided by the mill. Amphipods eat decomposing algal mats covering some high-exposure beaches. Large populations of these species are able to survive near mills and dominate the under-rock niche because of their hardiness and the plentiful supply of food. As exposure to mill effluent decreases to a moderate level, their food supply begins to dwindle, and competitors begin to colonize their niche; consequently, population size decreases. At low-exposure sites, isopods rarely appear, and only smaller populations of amphipods survive to capitalize on the ready supply of decomposing algae.

Unfortunately, the amphipods were only able to be identified to the family level. Because species within a family or genus may have entirely different ecological requirements, in future studies, amphipods should be identified to the species level. More accurate taxonomy may allow the identification of a variety of indicator species within the group Amphipoda.

Discrepancies with Predictions of the Bioindex. The Bioindex is not adequate to explain the proportions and variety of indicator species in a community whose membership is changing because of varying effluent exposure levels. The Bioindex is only valid if exposure to toxins is constant and species diversity is not changing drastically. Discrepancies with predictions of the Bioindex, such as tolerant and intolerant indicator species coexisting, occur at a site where the level of exposure to mill effluent is changing and the community has not yet reached equilibrium.

Communities that undergo changes in exposure to mill effluent are likely to experience changes in species abundance and diversity. Assuming availability of larvae, at least three factors determine whether a species can thrive at a site of given exposure: species tolerance to effluent; preexistence of species prey and physical requirements needed for survival and reproduction; and competition and other factors.

Reasons for Temporal Change. Organochlorines were first detected in marine organisms surrounding pulp and paper mills in 1980 (British Columbia Research, 1980). By 1989, the federal DFO initiated a campaign to monitor dioxin and furan levels near pulp mills and issue fishery closures and seafood consumption warnings. In response to DFO's pollution abatement legislation and enforcement of the Fisheries Act, the Howe Sound, Crofton, Powell River, Prince Rupert, and other mills have each spent (or plan to spend) an average of $150 million to upgrade effluent treatment facilities, switch to uncontaminated defoamers and wood chips for hog fuel, and begin new pulp bleaching and washing practices. Consequently, effluent quality has improved, and the dioxin loading has decreased. From an average coastal mill dioxin loading high of 51 mg/d of 2,3,7,8-TCDD in 1989, the levels fell to 5 mg/d by 1993 (data for individual mills unavailable from DFO). Sediment testing by DFO for dioxins and furans showed that 2,3,7,8-TCDD toxicity equivalents (TEQs) decreased from an average of 214 pg TEQ/g sediment in 1990 to less than 100 pg/g by 1993. Testing of dioxin and furan levels in Dungeness crab hepatopancrease (digestive gland) collected near mill outfalls showed an average of 900 pg/g of 2,3,7,8-TCDD TEQs in 1989 dropping to less than 100 pg/g by 1993. In addition, the level of dioxins in sediments and marine organisms such as fish, mussels, oysters, and crabs declined over the same period (DFO, 1993.) However, contamination levels were still high enough to substantiate fishery closures in regions up to 25 km away from mill outfalls by Health Canada during all years of this study (DFO, 1993.)

Diversities in 1992 and 1993 at Crofton and Howe Sound were found to be significantly greater than those of 1990 and 1991. The Bioindex predicted that the exposure level at Crofton mill had changed from high in 1989 to moderately exposed by 1993. The decreased dioxin loading and presumed toxicity level of the effluent may have allowed species diversity and complexity of community structure to increase. Unfortunately, decisive conclusions cannot be made linking decreased pollution output at a particular mill to increased species richness observed at surrounding sites. Because the DFO dioxin loading effluent data were provided as an average of all British Columbia coastal mill outputs, an organochlorine analysis of intertidal organisms and sediments at individual sites of this study could not be conducted.

Drawbacks of Study and Method. This study has several drawbacks. First, no scientific records exist that describe the condition of the beach sites before the pulp mills were established nearly 100 years ago. The rocky intertidal sites close to the mills are assumed to be depleted because there are an order of magnitude fewer species present than at the reference sites. Although the number of species increases exponentially as distance from each of the five mills increases, there exist no historical data to prove that the diversity of the sites near the mills decreased because of the mill effluent. Only trends can be noted: similar types and numbers of species reside in each exposure zone at all mills. However, a causal link between the decline in biodiversity and proximity to pulp mills cannot be made decisively. And, although an increase in species richness at sites following a decrease in organochlorine loading in effluent cannot be concluded definitively, the evidence points to pulp mill pollution as an important factor in these trends, although other currently unknown factors cannot be ruled out.

Second, sites must be chosen carefully. The presence of tracers, such as fibrous mass, pulp fibers, or dioxin contamination, must be taken into account when study sites are chosen because proximity to the mill can be deceptive. Sites adjacent to pulp mills may in fact have higher diversity and a lower exposure rating than sites across the channel or downcurrent from the mill because of a shadow effect. Although some of the effluent is pumped directly to the ocean from the shore, mills have subtidal diffusers several hundreds of metres offshore and below the surface to dispose of most of their wastewater. The effluent is directed away from the mill, and therefore, the pollution may be more likely to reach, for example, a nearby island than to curl around and affect the adjacent beach.

Finally, only a small area was quantitatively examined within one tide zone at each site. However, diving surveys (data not presented) demonstrated that the condition (measured by the relative diversity) of the subtidal matched the condition of the adjacent intertidal. In other words, low-exposure subtidal and intertidal sites had greater diversity than more exposed sites. Therefore, the intertidal appears to be an accurate and appropriate monitoring medium for the marine environment.

Conclusion

Pulp mills significantly affect intertidal diversity and community structure of beaches more than 25 km from outfalls. Intertidal species richness and community complexity in a 3 m × 3 m mid to low (0.5 to 1.0 m tide height) intertidal quadrat plot were found to increase as potential exposure to mill effluent decreased. This statistically significant trend was consistently demonstrated at sites surrounding each mill in each survey year. Therefore, pulp mill pollution appears to decrease intertidal species diversity. The intertidal zone of Howe Sound was the most negatively affected by pulp mill effluent, followed by Crofton, Prince Rupert, and Powell River. Significantly depressed species richness was apparent at beaches surrounding pulp mills compared to reference sites, even at the least negatively affected pulp mill region, Powell River.

The Bioindex can be used to correlate indicator species diversity and community structure with exposure to pulp mill effluent. This new biology-based index applies to protected, rocky, mid to low intertidal summer communities of the Pacific Northwest. The Bioindex can be applied to regions of varying oceanographic features and can detect improvements in water quality. It is hoped that the index can be used to determine biologically when the effective toxicity of the pulp mill effluent changes. The Bioindex can be used to track and account for the rate of recovery of depleted sites as mill pollution decreases because of new pollution abatement programs established in response to stricter enforcement of the Canadian Fisheries Act by Environment Canada and the DFO. The Bioindex may be a useful and inexpensive monitoring technique in addition to expensive organochlorine analysis, since this study has discovered that in some regions cumulative pollution may exert a large and long-lasting effect on intertidal diversity and community structure even when current pollution decreases.

Difficulty arises when trying to determine whether population and community changes may result from an industrial source if no historical data are available. For this reason, a long-term, intertidal monitoring study was conducted in conjunction with the Save Georgia Strait Alliance and the federal Environment Canada Ministry. School and community groups adopt local beaches and conduct annual quadrat and transect surveys with the help of volunteer scientists. The information is then collected in a central data bank.

After several more years, the data can be used to detect natural oscillations and provide the basis for an understanding of what the "natural diversity" of a variety of unpolluted sites is. The data will state which species are present where—basic and vital information that is currently lacking. In addition, the information may allow researchers to map the coast according to environmental stress via the Bioindex. In this way, they can first pinpoint the areas that are most degraded and require the most "cleanup." Second, researchers will be able to identify the most fragile areas and protect them before they are touched by industrial pollution.

For sites to recover, the pollution abatement programs must successfully decrease the volume of pulp fibers in the effluent and decrease the toxicity of the effluent. Advanced biological treatment programs such as the one operated at the Prince Rupert mill have proved effective in addressing both of these problems. The goal for industry, government, and environmental agencies must be to minimize exposure ratings at beaches surrounding pulp mills to levels that will allow all sites to be recolonized to premill levels of diversity and community structure.

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