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THE DELTA FORESHORE ECOSYSTEM: PAST AND PRESENT STATUS OF GEOCHEMISTRY, BENTHIC COMMUNITY PRODUCTION AND SHOREBIRD UTILIZATION AFTER SEWAGE DIVERSION

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THE FRASER RIVER ESTUARY AND ITS INTERTIDAL REGION

Of the various ecosystems that together describe the Fraser River and its estuary, the most understudied but ecologically important is its mudflat/intertidal region. The intertidal region of the estuary provides vital habitat for a diverse macro and meiofauna, which in turn supports, during winter months, the highest densities of waterfowl, shorebirds and raptors in Canada. Furthermore, this intertidal area provides habitat for numerous fish species, as well as serving as the point of entry and exit for five salmon species. Not surprisingly, the Fraser River Estuary is one of the most biologically productive systems in Canada (Kennett and McPhee 1988). It is also adjacent to Canada's third largest urban region which is the source of much of the pollution stress in the estuary. Despite its ecological importance, little is known about the fundamental biochemical and ecological response of the estuary's intertidal zone to this pollution. Given that anthropogenic pressures are increasing, it is critical that comprehensive knowledge on the impacts of present and future contaminant exposure be obtained to effectively protect and conserve this unique habitat.

As present loading is predominantly delivered via the river, an overview of the distribution of flow is described below. Approximately 25 km upstream from the mouth, the river bifurcates into the North Arm and the Main Arm (Fig. 1). The North Arm, which carries approximately 16 per cent of the total river discharge, bifurcates again at Sea Island where about 30 per cent of the flow (~5% of the total Fraser River flow) exits via the Middle Arm onto Sturgeon Bank while the remaining 70 per cent (9% of the total flow) exits just north of Sturgeon Bank through the North Arm (Feeney 1995). The Main Arm carries the majority of the flow (>80%) and exits onto Roberts Bank between Westham and Lulu Island. A small portion of the flow goes through Canoe Pass, south of Westham Island (Kennett and McPhee 1988). The maximum discharge occurs in June (~10,000 m^3/s) and the minimum in February/March (~750 m^3/s).

The tidal cycle is a major factor influencing biological and biogeochemical processes in the intertidal zone through its control of the period and range of inundation and exposure. The maximum tidal range (~5 m) occurs in June and December, during spring tides, and the lowest range (~3 m) occurs in March and September.

The Fraser River delta, an area of ~337 km^2, lies between the North Arm of the Fraser River and Boundary Bay (Kistritz 1978). This area can be divided into six relatively distinct ecosystems: (1) Iona Island sand flats between the Iona Island Jetty and the North Arm; (2) Sturgeon Bank; (3) Roberts Bank; (4) the inter-causeway, between the coal port terminal and the ferry terminal; (5) south of the ferry terminal to Point Roberts peninsula; and (6) Boundary Bay. None of the foreshore habitats are undisturbed as diking has cut off much of the original high marsh from the sand flats. The sediment texture is variable and sandy areas dominate over finer-grained substrates.

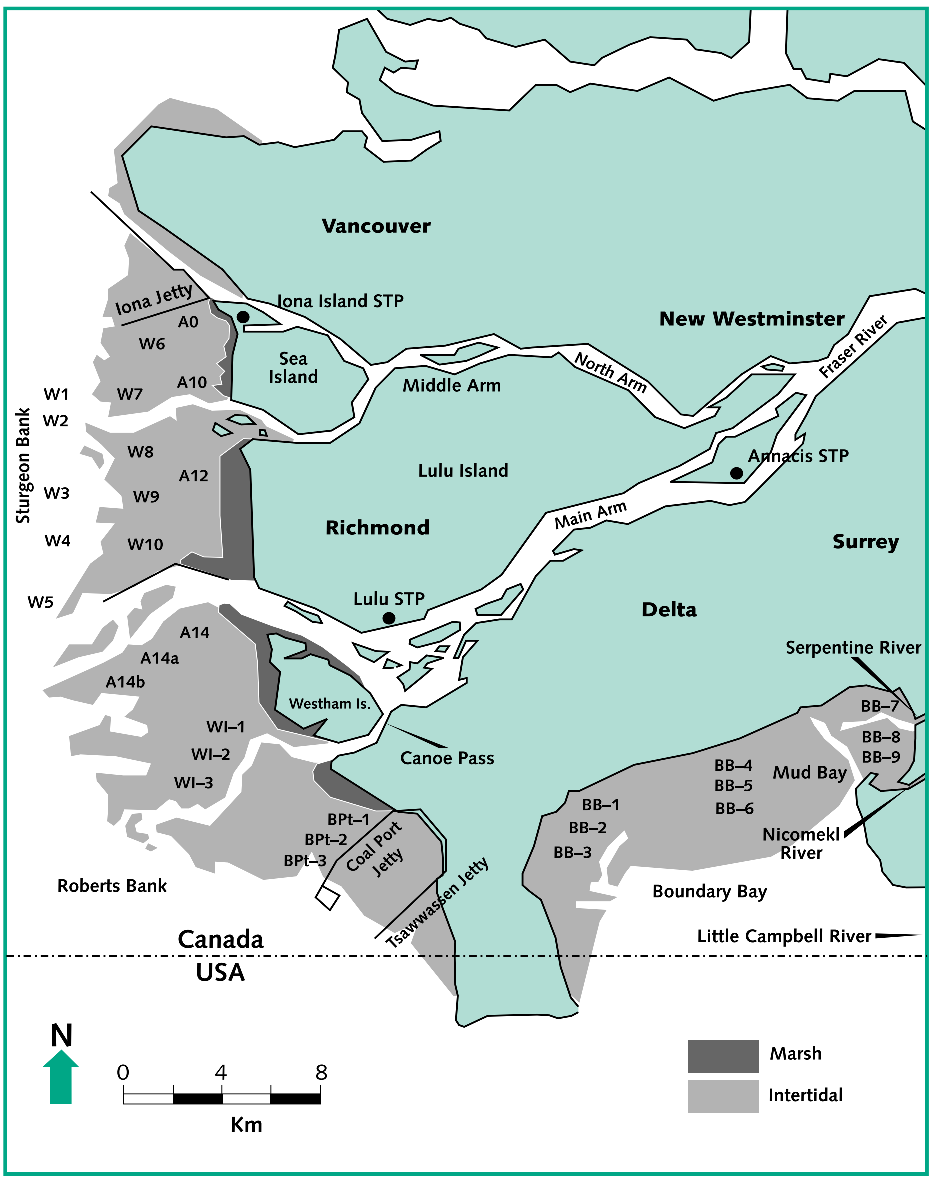

Figure 1. Map of the study area showing sampling sites on Sturgeon Bank, Roberts Bank and Boundary Bay.

The estuary has abundant fauna and flora. The shoreline of Sturgeon Bank is bordered by a marsh composed primarily of sedges (*Carex* sp.) and bullrushes (*Scirpus* sp.) (BC Research 1975). The main primary producers are benthic microalgae (*e.g.* diatoms) on top of the sediment, but benthic macroalgae such as *Ulva* and *Enteromorpha* are occasionally present. The intertidal area has a diverse invertebrate infauna dominated by polychaete worms, bivalves, amphipods, isopods, decopods, harpacticoid copepods, nematodes and oligochaetes (Otte and Levings 1975; BC Research 1975). In addition, 27 species of fish, including commercial species of salmon, have been reported on Sturgeon Bank (Birtwell *et al.* 1983). Young salmon migrate down the Fraser River and feed extensively in the nearshore areas of the estuary and undergo osmoregulation changes before moving out to sea.

The estuary supports internationally important populations of birds, including some threatened species. In particular, the vast intertidal flats from Iona Island to Boundary Bay provide critical habitat for millions of migratory waterfowl (*e.g.* snow geese) and shorebirds. The shorebirds, in particular, depend on benthic invertebrates during their migration or while they overwinter. Despite international recognition of the importance of these intertidal flats to birds, the flats and connecting foreshore continue to be altered by industrial port development and urbanization, and are exposed to contaminated water and sediments.

The Fraser River transports contaminants introduced to the river from industrial and municipal discharges, non-point source runoff from agricultural and urban land and, in the case of metals, from natural geological erosion and leaching. The contaminants are carried in solution, colloidal phases, and adsorbed to suspended organic and inorganic sediments. Some portion of all these phases can end up being deposited in the estuarine sediments of the delta's extensive intertidal sand and mudflats (approximately 150 km^2 to the 10 m deep shelf break and about 50 km^2 to lowest tide depth).

While the rest of the delta front has been receiving seasonally variable inputs of contaminants, Sturgeon Bank, particularly the northern part off Iona and Sea Islands, received direct inputs of sewage through the outfall from the Iona Island wastewater treatment plant (WWTP) from 1962–1988. During this time, the plant served a population of approximately half a million people. In 1988, sewage was redirected to discharge into the Strait of Georgia at a depth of 90 m.

OBJECTIVES

The objectives of our research program were the following: (1) to increase the knowledge of the nutrient dynamics, and of primary and secondary production of the benthic community in this unique estuarine ecosystem; (2) to identify food web links between benthic biota and shorebirds; (3) to assess metal contamination in sediments and biota and identify their sources, sinks and potential impacts; (4) to quantify the extent of recovery of the area near the original site of sewage discharge; and (5) to establish a baseline of biological and chemical characteristics to measure the response of the delta ecosystem to the WWTP effluent treatment upgrade, which will be completed by 1999 at two major plants. Prior to their upgrade, these plants discharged primary treated effluent from approximately 800,000 people and associated industrial/institutional discharges into the Main Arm of the river.

POLLUTION STRESS

The benthic community on the intertidal zone is exposed to high levels of natural environmental stress caused by tidal fluctuations which control the light climate, wave energy and inputs of fresh water and associated suspended sediments from the three arms of the Fraser entering the delta front. In addition, there have been alterations to the way the river interacts with the delta through the construction of dikes and training walls and the dredging of navigation channels. Most importantly, there has been a long history of pollution with metals (Bawden *et al.* 1973; McGreer 1979), PAHs, heavy wood preservatives, chlorinated phenols (Carey and Hart 1988), pesticides (Hall *et al.* 1991), and sewage effluents containing organic matter and nutrients (Otte and Levings 1975; Birtwell *et al.* 1983). Our studies focused on the impact of past discharges of nutrients and metals from the Iona Island WWTP and on a general assessment of metal contamination in the whole area including Boundary Bay.

SAMPLE SITES

Sites along the intertidal zone of the lower Fraser River Estuary were chosen to obtain data on the influence of the Fraser River, past pollution from the Iona Island WWTP discharge, and the composition of sediment (grain size and per cent organic matter) on the distribution of metals (all sites, Fig. 1) and of nutrients and productivity (sites labeled A, Fig. 1).

Three areas of the foreshore region were sampled: (1) the most northerly area, Sturgeon Bank, is estimated to receive 15 per cent of the industrial and municipal wastes discharged into the Fraser River (Fraser River Estuary Study 1979; Feeney 1995) and, before 1988, it received primary treated sewage effluent directly onto its foreshore. This effluent contained trace metals, such as copper, iron, lead, mercury, nickel and zinc (Tevendale and Eng 1984); (2) the Roberts Bank area receives approximately 80 per cent of the total flow of the Fraser River and is estimated to receive 60 per cent of the municipal and industrial effluent discharged into the Fraser River including the increasing discharges from the Annacis and Lulu Island WWTPs (Fraser River Estuary Study 1979); and (3) Boundary Bay, which is influenced by the Serpentine, Nicomekl and Little Campbell rivers which drain a combination of agricultural and residential areas. In addition, drainage from the agricultural areas surrounding the bay is discharged at five pump stations along the west and north shores (Swain and Walton 1990). Both Roberts Bank and Boundary Bay had nine sampling locations, whereas Sturgeon Bank had eight for a total of 26 sampling locations.

ASSESSMENT OF METAL CONTAMINATION

Spatial variability in sediment texture and associated contaminants within the intertidal area is high. To obtain a representation of metal levels in sediments from the study areas, several locations from each site were sampled, as indicated above. Boundary Bay, in most respects, can be considered a control area for comparison.

Mathematical normalization to eliminate the effect of sediment grain size was not performed for bulk trace metal data in our study because the fine sediment fraction (grain size of less than 0.05 mm) represented less than 60 per cent of the sediment samples. Horowitz and Elrick (1988) suggest that grain size normalization should only take place when the fine fraction of the sediment represents at least 50 to 60 per cent of the sample.

Sturgeon and Roberts banks had higher concentrations of metals (*e.g.* mercury [Hg], copper [Cu], zinc [Zn] and nickel [Ni]), except cadmium (Cd), which was higher in Boundary Bay, and possibly linked to use of a fungicide on golf course greens in the area (Swain and Walton 1990). In general, the highest concentrations of metals were observed in Roberts Bank, followed by Sturgeon Bank; Boundary Bay had very low metals levels, except for Cd. While the southern part of Sturgeon Bank is cleaner than Roberts Bank, the northern portion near Iona Island WWTP (Station AO) is still a metals “hot spot” and it had the maximum observation for Cu, Cd, lead (Pb), Zn and Hg (Table 1). Silver (Ag) is very high as well, as reported in the following section on sewage tracers.

The bioavailability of a metal is related to its association with the various geochemical components present in the sediment (Bendell-Young and Harvey 1992). Metals associated with the lattice framework of the sediment, particularly in the sand and possibly the larger sizes of the silt fraction, are not considered

Table 1. *Summary of maximum concentrations of metal in the total (aqua regia extract) and labile fractions of bed sediment from the Fraser delta in the spring (spr) and summer (sum), as well as the site at which the maximum occurred. Corresponding salinities for each location are presented in parentheses. Refer to Figure 1 for site locations.*

METAL	SEASON	MAXIMUM 'TOTAL' (µg/g dry wt)	REGION	MAXIMUM LABILE (µg/g dry wt)	REGION	LOEL (µg/g dry wt)	
						MARINE	FRESH
Copper	spr	54.1	SB-A0 (10‰)	25.9	SB-A0 (10‰)	70	16
	sum	45.4	SB-A0 (10‰)	32.1	RB-BPt-2 (10‰)	70	16
Cadmium	spr	0.43	SB-A0 (10‰)	0.43	SB-A0 (10‰)	5.0	0.6
	sum	0.25	BB-BB-9 (32‰)	0.21	BB-BB-9 (32‰)	5.0	0.6
Nickel	spr	44.7	RB-WI-1 (3‰)	20.0	RB* (3-10‰)	30	16
	sum	49.0	RB-WI-1 (3‰)	31.3	RB-BPt-2 (10‰)	30	16
Lead	spr	19.0	SB-A0 (10‰)	12.7	SB-A0 (10‰)	35	31
	sum	18.7	SB-A0 (10‰)	13.9	SB-A0 (10‰)	35	31
Zinc	spr	95.8	SB-A0 (10‰)	65.2	SB-A0 (10‰)	120	120
	sum	100.8	RB-BPt-2 (10‰)	64.3	RB-BPt-2 (10‰)	120	120
Hg	sum	0.22	SB-A0 (10‰)	-	-	0.15	0.2

SB Sturgeon Banks
RB Roberts Bank
BB Boundary Bay
LOEL Lowest Observable Effects Level (Nagpal, 1994)
** found at several locations*

available for uptake by an organism as they are tightly bound within the sediment. However, metals associated with iron (Fe) and manganese (Mn) oxides and organic matter can either be taken up by organisms or not, depending on environmental factors such as redox conditions, other metal complexes and salinity (Luoma and Bryan 1981).

The Fraser River was found to be an important source of Mn oxides and trace metals to estuarine sediments. This has important implications, given that metals associated with Mn oxides have an enhanced bioavailability. Hence, the Fraser River could be contributing significantly to the bioavailable fraction of metals in the intertidal region. In contrast, iron, which is primarily supplied from some of the pore waters, reduces metal bioavailability. It acts as a modifier of metal uptake, either through a protective or competitive effect, with the potential of reducing metal uptake in an organism. The results of this study suggest that while greater than 50 per cent of each metal supplied by the Fraser River is in a bioavailable form (*i.e.* in the labile fraction of the sediment associated with Mn oxides), once they settle in the intertidal region, in areas where Fe is generated by diagenesis in the pore waters, this Fe modifies metal uptake and reduces or even prevents bioaccumulation.

The metal availability to organisms was tested by measuring the amount of various metals in the tissue and shell of the most common clam, *Macoma balthica*. In most cases, there was a strong correlation between the amount of a metal in the tissues of *Macoma* and the amount of the biologically available fraction of that metal in the sediment as measured by the easily reducible (ER) metal analysis.

Cadmium in bivalve tissues was negatively correlated with reducible (RED) Fe and positively correlated with easily reducible (ER) Cd—Cd associated with Mn oxides (r=0.59). Hence, higher tissue concentrations of Cd in *M. balthica* are predicted to occur at sites where concentrations of RED Fe are low and ER Cd is high. The negative correlation between Cd tissue concentrations and RED Fe suggests that this component is modifying what Cd is available for uptake, possibly through a 'protective' or 'competitive' effect. An explanation for this inverse dependence could be: (1) RED Fe (presumably as Fe oxides) that enters the gut competes with uptake sites on the intestinal tract for solubilized metals; (2) RED Fe becomes solubilized in the gut and, as a result, the Fe itself competes with trace metals for uptake sites; and (3) RED Fe adsorbs dissolved trace metals in the external phase such as on the gill or mantle tissue.

The strongest correlation was found between Pb in tissue and Pb in the ER phase (r=0.78). Luoma and Bryan (1978) found that the biological availability of Pb to *Scrobicularia plana* (a deposit-feeding estuarine bivalve) was controlled mainly by the concentration of Pb in the sediment extracted with a weak acid digestion similar to that used for the RED Fe fraction. It is important to note, however, that the extraction scheme in the Luoma and Bryan study did not include an ER phase.

Nickel concentrations in the tissues did not correlate significantly with any of the sediment parameters; however, concentrations in the shell correlated positively with per cent loss on ignition and negatively with total Ni concentrations (r=0.52). This suggests that higher concentrations of Ni in the shell are found at locations with higher organic matter and low total concentrations of Ni.

A weak correlation was found between shell Hg concentrations and total Hg in the sediment (r=0.34). A regression was not attempted for Hg in the tissues as there were insufficient sample numbers. Few studies have addressed the relationship between Hg in shells and sediment-bound Hg, although, previous studies have shown a strong relationship between total Hg in the sediment, normalized for organic matter, and tissue concentrations for *M. balthica* in British estuaries (r=0.80, r=0.74) (Langston 1982; 1985). Organic matter in sediment is believed to be the most important factor influencing Hg concentrations in these tissues (Langston 1985; Rae and Aston 1982). Nickel and Hg were the only metals for which either a negative or a positive correlation between shell concentrations and total sediment metal was found.

Copper concentrations in the tissue and the shell were correlated positively with both RED and ER Cu, that is, Cu associated with Fe and Mn oxides (r=0.65, r=0.71). Hence, high concentrations in the tissue and the shell are more likely to occur at sites high in both RED and ER Cu. Tissue and shell Zn concentrations correlated positively with concentrations of ER Mn recovered from the sediment (r=0.62, r=0.39). Therefore, high Zn concentrations in *M. balthica* occurred at locations high in ER Mn.

To provide a general assessment of the potential impact of the observed metal levels, these concentrations can be compared with B.C. working and approved sediment criteria for the protection of freshwater and marine life (Nagpal 1994). This comparison is not straightforward, however. There is high spatial variability in metal concentrations in sediments and, therefore, a very large number of sediment samples must be collected to truly assess the spatial extent and significance of any exceedances of the criteria. In addition, the criteria are based on the assumption that all the metal is in a bioavailable form, so the bioavailable concentrations should be used if available. Also, the sediment type influences the metal concentration and availability, with metal concentrations being generally higher in silt and clay than in sandy sediments. Finally, salinity affects the availability of the metal. Therefore, when salinities in the estuary are below that of sea water, freshwater criteria as well as marine criteria should be used.

The maximum total concentration of each metal in the spring and summer is presented in Table 1. In addition, the maximum concentration of each metal in the labile fraction is presented to illustrate the discrepancy in some cases between what is potentially available to an organism and the concentration of the total metal. While it was expected that the station nearest the old WWTP discharge (A0) could still exhibit metal concentrations approaching criteria, this was not always the case. For instance, sediments off Brunswick Point (the point just south of Westham Island on the Main Arm, Fig. 1) approached the criterion for Zn and exceeded it for Cu, and off Westham Island, the criterion for Ni was exceeded. Considering that salinity is an important factor governing the availability of metals (Luoma 1983) and that salinity varied from freshwater levels (nearest the outflow of the Fraser River) to marine levels (Boundary Bay and sites farthest offshore), sediment quality criteria for both marine and freshwater systems are also presented. For example, Cu did not exceed the criterion for marine systems but exceeded that for freshwater systems by two times at A0 and at BPt-2 (located in Roberts Bank) (Table 1). The corresponding salinities at these locations near the outflow of the Fraser River were more characteristic of a freshwater environment (salinity of 10‰), indicating that freshwater criteria are more appropriate in some situations.

Nickel and Cu were the only metals that exceeded sediment quality criteria at more than one location (Hg did exceed criteria values but only at one location). Concentrations of Ni at over half of the sampling locations were in exceedance of both the marine and freshwater sediment quality criteria, while Cu exceeded the freshwater criterion at greater than half of the locations. Brewer *et al.* (1998) found that chromium (Cr), Mn, Fe, Ni and Cu exceeded the provincial criteria for the protection of freshwater life at all up-river reference sites, indicating that background levels of these metals are naturally high (see Schreier *et al.* [1999] for a discussion of natural sources of Ni in the Sumas watershed). However, both Ni and Cu are also released from small industrial plants, municipal WWTPs and wood preservation facilities, indicating that considerable inputs from industrial and municipal activities plus high background levels are contributing to the elevated levels measured.

Compared to levels reported in the few previous studies that have measured metal concentrations in the Fraser River intertidal area (Table 2) (Bindra and Hall 1977; McGreer 1979; Swain and Walton 1990), levels of all metals measured in our study have decreased or remained constant, except for Cd which increased in Boundary Bay. On Sturgeon Bank, near the original sewage discharge area, Cu, Pb, Ag, Hg and Cd have decreased from 12 to 56 per cent during the period 1977–1995; Zn has remained fairly constant. In addition, total organic carbon has decreased by 69 per cent (Thomas 1997) which could explain part of the decrease in metal concentrations because metals can be incorporated or sorbed to organic matter. In addition, McGreer (1996, pers. comm.) found that burrowing rates of *Macoma* in 1995, were normal compared to 1977 when rates were almost zero. This can be taken as an indication that the sediments are no longer toxic.

While concentrations of some metals (Cu and Ni) were higher than the LOEL (lowest observable effects level) in sediment, metal concentrations (except for Cu) in the Fraser River intertidal area are equal to or lower than levels observed in other estuaries (Table 2).

The common clam (*Macoma*) is an important link between primary producers and fish and shorebirds in the intertidal area. It has been used as a biomonitor of metal contamination because it feeds directly on deposited sediments and acts as a bioaccumulator and integrator of temporal fluctuations of metals in the sediment. However, there is usually high variability in tissue levels, which is associated with factors, such as age, size, season and sediment composition. Metal concentrations in tissues were measured only once in previous studies and only at the sewage discharge site on Sturgeon Bank in 1979 (McGreer 1979). Comparing McGreer's values to those in 1996 (Thomas 1997) indicates that tissue concentrations in the clam have decreased by two-fold for Cu and Zn, and 10-fold for Hg (Table 2). Since Zn in the sediments has remained relatively constant, but tissue concentrations of Zn in the clam have decreased by two times, this suggests that there has been a decrease in the bioavailability of Zn during this 17-year period. Comparing

Table 2. Ranges of total metal concentrations (μg/g dry wt) in various estuarine surface sediments and in the tissues of Macoma balthica.

LOCATION/AUTHOR	ESTUARY	Cd	Cu	Ni	Pb	Zn	Hg
Sediment - Fraser River Estuary							
Thomas 1997	Sturgeon Bank	0.03–0.43	10.7–54.1	30.0–41.3	5.3–19.0	46.6–95.8	0.02–0.22
	Roberts Bank	0.04–0.18	17.3–52.8	33.7–44.7	3.2–12.3	14.3–100.8	0.02–0.09
	Boundary Bay	0.06–0.25	4.4–23.4	8.0–23.0	1.3–7.8	21.2–53.0	0.01–0.04
Swain & Walton 1990	Boundary Bay	<0.10–0.17	4.3–26.6	-	1.7–14.2	21.0–96.4	0.008–0.05
McGreer 1979	Sturgeon Bank	<0.4–3.0	12.4–234	28–49	3–166	41–264	0.03–0.89
Bindra & Hall 1977	Sturgeon Bank	-	21.8–302		41.7–219	67.3–301	-
Grieve & Fletcher 1976	Sturgeon & Roberts banks	-	17.2	43.4	5.1	52.7	-
Sediment - Fraser and Other Estuaries							
Thomas 1997	Fraser River, Canada	0.03–0.43	4.4–54.1	8.0–49.0	1.3–19.0	21.2–100.8	0.01–0.22
Luoma *et al.* 1990	Suisun Bay/Delta, USA	0.2–0.8	12.0–95.0	-	16.0–120.0	50.0–245.0	-
Bryan & Uysal 1978	Tamar, U.K.	<0.1–5.4	111–521	33–64'	112–697	195–1150	-
Macoma *Tissue - Fraser R. Estuary*							
Thomas 1997	Fraser River, Canada (average)	0.15–1.5 (0.65)	9.5–308.4 (84.8)	4.2–26.9 (12.9)	0.5–13.5 (2.8)	86–527 (287)	0.15–0.27 (0.27)
McGreer 1979	Sturgeon Bank (near Iona Island)	D.L.	49–314	-	D.L.	392–743	0.74–6.76
Macoma Tissue - British Estuaries							
Bryan *et al.* 1985	Tees	0.2	152	0.3	5	414	1.03
	Mersey	0.2	134	1.7	7	747	-
	East Looe (upper)	0.7	208	7.7	36	1164	0.97
	Loughor (mid)	0.2	32	1.6	2	396	0.12
	Severn	9.4	224	12.7	19	1510	-
	Dovey (mid)	0.9	33	2.6	17	771	-
	Solway	0.6	35	1.5	5	365	-

- = metal not measured
D.L. = detection limit

the present tissue concentrations in the clam from the Fraser River intertidal region to other estuaries reveals that Pb and Zn are low, Cd and Hg are average, Cu is average to high, and Ni is high (Table 2).

Sewage Tracers

One metal that deserves special attention is silver. It is typically the most enriched metal relative to Cu, Pb and Zn in domestic sewage waste. For instance, the enrichment factor for Ag in sewage sludge is 200, which is several times higher than the factors for Cu, Pb and Zn. Hence, in the absence of metal smelter discharges, Ag is an excellent tracer for sewage contamination of sediments. It comes primarily from the photographic industry's discharges to the sanitary sewers. At present there is a Ag-enriched zone that extends several km north of the present-day submerged outfall diffuser (Fig. 2). It is similar to the northward-flowing bottom currents and the pattern observed for a dye tracer study of the effluent plume discharged from the outfall diffusers (Hodgins 1988). High Ag values extend further to the north (6 km) than to the south (1 km) of the diffuser and the highest values (~700 ppb) are found about 1 km north of the outfall. As a reference point, Ag values in average shale are ~70 ppb and would represent a pristine area. In contrast, the highest surface Ag values were ~1,300 ppb on Sturgeon Bank (at A0), the site of the pre-1988 sewage discharge. Ag concentrations rapidly decrease seaward and southward along the intertidal area (Fig. 2); in the latter case, this is due to the marked increase in sandy sediments south of the sewage discharge site. The lowest Ag concentrations were found in the course-grained sediments of A12 (Gordon 1997).

Plotting the ratio of metals to aluminum (Al) in a sediment core and comparing the ratio to that observed in shale gives a relative scale of enrichment or contamination. Figure 3 shows that Ag, Cu, Pb and Zn are enriched in the 2-10 cm interval. In fact, at 4 cm Ag is ~3,200 ppb, about three times the surface concentration. The peaks in metal concentrations and ratios may indicate the zone of deposition from 1962–1988, before the sewage discharge was moved offshore. This indicates that the sediments relatively close to the surface are considerably contaminated with metals and these contaminated sediments could be released by dredging in the area.

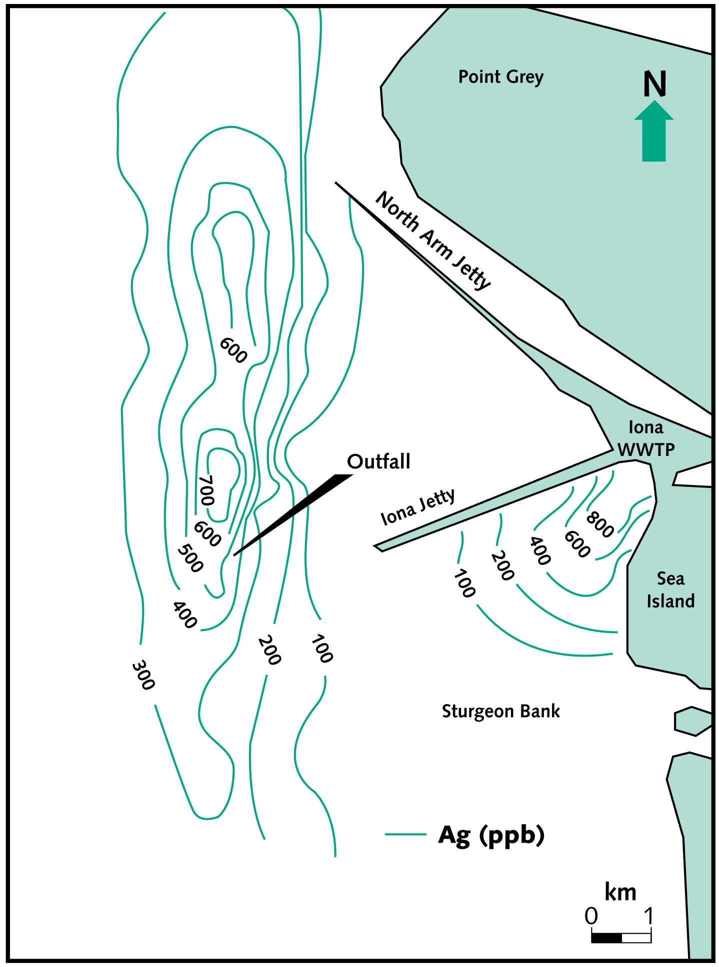

Figure 2. Distribution of Ag in surface sediments near the present Iona Island municipal WWTP deep-sea outfall and on Sturgeon Bank in the vicinity of the previously contaminated intertidal area (from Gordon 1997).

NUTRIENT DYNAMICS AND BENTHIC PRODUCTION

Nutrient Dynamics

In the Strait of Georgia and the Fraser River Estuary, nitrogen (N) concentrations may limit primary productivity (Harrison *et al.* 1983), in contrast to limitation by phosphorus in the river. Average daily nitrogen inputs to the Strait of Georgia include 1,500 tonnes from estuarine circulation which brings water of marine origin into the strait; 22 tonnes from sewage discharged in marine outfalls; 50 tonnes from the Fraser River (which includes N in sewage and in agriculture, urban and natural runoff) and 8 tonnes from atmospheric deposition (Mackas and Harrison 1997). While these values provide a general account of the annual sources of N loading to the offshore areas of the strait, the processes which control nitrogen uptake and recycling in any given season in the sand flats are as important and are discussed below.

Primary producers prefer to take up inorganic nitrogen sources such as nitrate (NO_3) and ammonium (NH_4), but some organic nitrogen compounds such as urea can also be utilized. When organic matter is deposited on or in the sediments, it is broken down (remineralized) by bacteria to NH_4, which is later oxidized to NO_3 by bacteria in the presence of dissolved oxygen. Thus the sediments usually have very high concentrations of NH_4 (several hundred times greater than the overlying water), which are usually correlated with the organic matter concentration of the sediments. Studies on nutrient cycling and dynamics showed that the concentrations of NO_3 and NH_4 in the water column on flood tides were lower than values on ebb tides, indicating that nutrients are released from the sediment during their immersion by sea water (Fig. 4). At the same time, phytoplankton chlorophyll *a* was higher on flood tides than on ebb tides, indicating phytoplankton biomass is lost to the sediment. Therefore, Sturgeon and Roberts banks represent an important nearshore nitrogen source for phytoplankton productivity in the Strait of Georgia, especially when ambient nitrogen in surface waters is low during summer, but represent a sink for phytoplankton production in the water column.

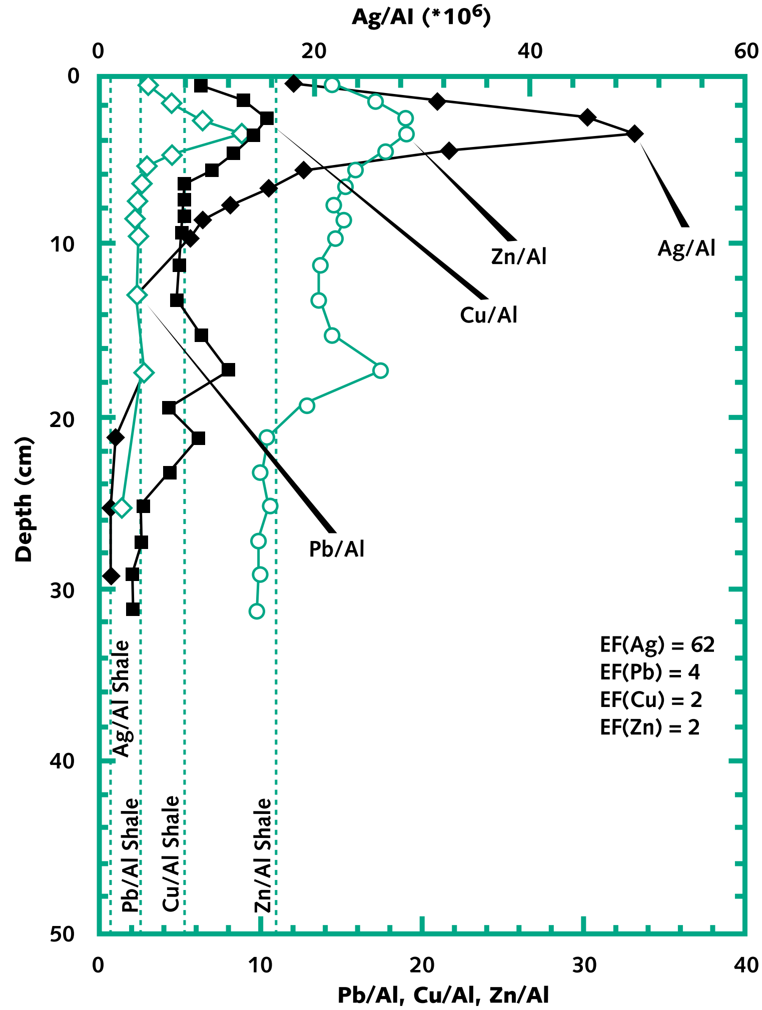

Figure 3. Vertical distribution of Ag/Al, Pb/Al, Cu/Al and Zn/Al in a 30 cm core from A0. The value of the ratios in average shale is indicated for comparison. Enrichment factors (EF) represent the maximum metal to Al ratio in the core normalized to the ratio in average shale (from Gordon 1997).

Pore water NH_4 concentrations in the top nine centimetres of sediment fluctuated between about 100 and 700 µM (1.4 and 9.8 mg NH_4-N/L) at A0 and between 20 and 700 µM (0.28 and 9.8 mg NH_4-N/L) at A14 (Fig. 5). In general, NH_4 concentrations in the pore waters were higher at A0 (near the previous sewage discharge site) than at A14 (on Roberts Bank). This is due to the higher organic matter content of the sediment at A0 and its subsequent decomposition and release of NH_4. In contrast, NO_3 concentrations in the pore waters were lower at A0 than at A14. Vertical profiles of pore water NH_4 at A0 showed various distribution patterns during the three-year study: an increase with depth or a decrease with depth, or a decrease in the top few centimetres and then an increase with depth. In contrast, at A14, the vertical distribution mostly showed a decrease with depth. Particulate organic nitrogen generally decreased with depth at both A0 and A14. These results indicate that particulate organic matter is deposited at the surface of the two banks and remineralized at the surface. Higher NH_4 concentration at the sediment surface suggests that NH_4 generated during remineralization could be released into the water column during flood tides, and it could also move downwards by diffusion because of the high concentration gradient. However, there is little accumulation of NH_4 in deeper pore waters and this suggests that denitrification (bacterial conversion of inorganic nitrogen to nitrogen gas) occurred in the sediments. The significance of denitrification to the nitrogen cycle on these tidal flats needs further study.

Chlorophyll *a* and Primary Productivity

The results show that the yearly average of benthic microalgal biomass, as measured by the amount of chlorophyll *a* (chl *a*), was lowest at A0 (84 mg chl a/m^2) and highest at A10 (2044 mg chl a/m^2), with A14 less than A12 and intermediate in biomass (235 and 882 mg chl a/m^2, respectively) (Fig. 6).

There are indications of the recovery from sewage pollution at A0 when benthic microalgal chl *a* biomass in this study is compared with biomass data from other studies at muddy sites on Sturgeon Bank. On the northern side of the Iona Jetty (see Fig. 1), Bawden *et al.* (1973) reported chl *a* values of 26–61 mg/m^2 in 1972; higher values (62.7 to 424 mg/m^2) were measured by Harrison (1981) in 1978–79. The latter higher values may be due to extracting chl *a* from a 5 cm sediment core instead of the top 1 cm extracted in the former case. Their sites were separated from the sewage discharge by the jetty and were not directly exposed to sewage effluents. A study conducted in 1974 by Otte and Levings (1975) showed very high chl *a* concentrations (up to 1,000 mg/m^2) at a site close to A0 and the algal biomass mainly consisted of dense blue-green algal mats. As blue-green algae commonly dominate the algal community in nutrient-rich lakes (Laws 1993) and estuaries (Jaworski 1990), the presence of blue-green algal mats was not surprising in this area close to the "freshwater" sewage discharge. The Otte and Levings (1975) study results agreed with those of another investigation in the same region and in the same year (BC Research 1975). The latter study observed the highest chl *a* concentration, 772 mg/m^2, at sites near the outfall and dominance by green algae. Chl *a* values in our study are comparable to Bawden *et al.*'s (1973) and Harrison's (1981) values on the northern side of the Iona Jetty, but were lower than those measured in the other two studies (Otte and Levings 1975; BC Research 1975). These comparisons suggest that A0 has recovered to the level comparable to the sites on the other side of the Iona Jetty, which were at least 2 km farther offshore than A0 and may have been partially influenced by dispersed sewage effluent which drifted with tidal cycles. Another indication of the recovery is that the dominance by blue-green algae or green algae was not observed in our study; instead, diatoms were the main component of the benthic microalgae (Ross 1998).

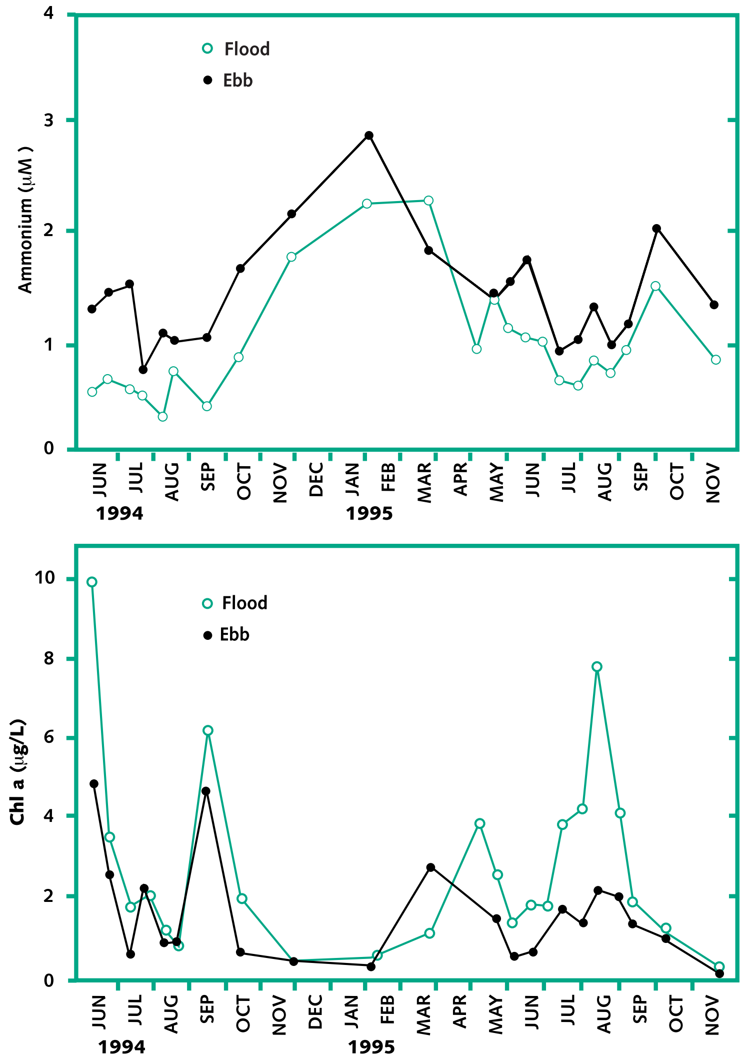

Figure 4. *Ammonium and chlorophyll* a *in the water column during flood and ebb tides in 1994 and 1995 (from Bendell-Young* et al. *in press).*

Another sign of the recovery is that temporal fluctuations in benthic chl *a* biomass appeared to be parallel between A0 and A14 and between A10 and A12. The parallel fluctuations in chlorophyll between A0 and

A14 indicate that the two sites were subject to common environmental forcing, such as effects of the light period during tidal exposure and the influence of Fraser River discharge. This suggests that A0 has partially recovered to a level that responds to natural factors. However, in comparing our four sites, the lowest chl *a* level was found at A0. Whether this low chl *a* level indicates inhibition by contaminants (*e.g.* high levels of Cu, Ag, Hg or some organic chemicals, such as herbicides) or grazing pressure cannot be resolved with our data.

Chlorophyll *a* values in the sediment column at A10 and A12 were very high (1,000 to 3,000 mg/m^2), over one order of magnitude higher than those reported for other intertidal areas (*e.g.* ~300 mg/m^2 for Netarts Bay, Oregon [Davis and McIntire 1983] and ~120 mg/m^2 for North Inlet, S. Carolina [Pinckney and Zingmark 1993]). The vertical distribution of chl *a* showed large quantities of chlorophyll present below the surface of the sediment (up to 10 cm) and a low content of phaeopigments (initial breakdown products of chlorophyll), indicating that chlorophyll in the deeper sediments was recently buried. About 50 per cent of the chl *a* was in the top 1 cm at the muddier A0 and A14 sites, while only about 20 per cent of the chl *a* was in the top 1 cm at

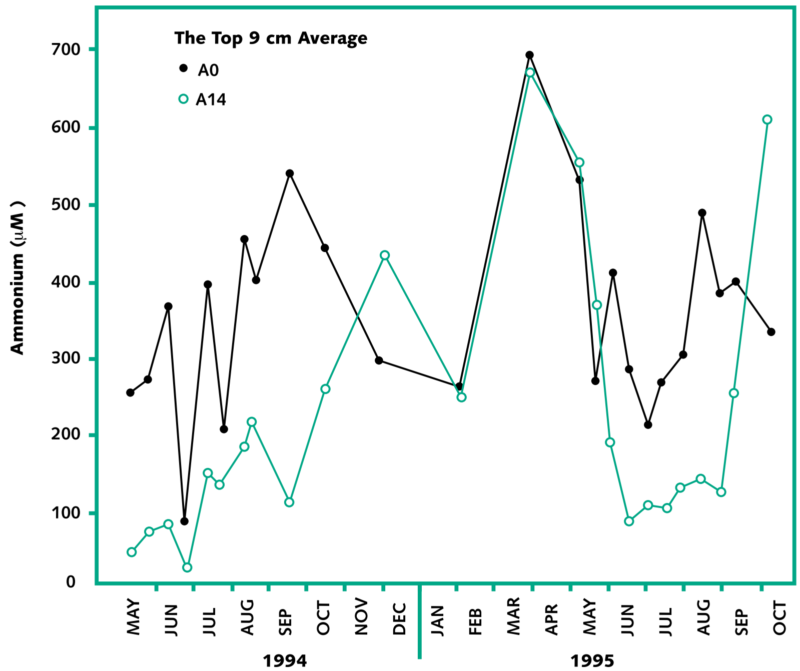

Figure 5. *Average pore water ammonium concentration from a 9 cm sediment core at stations A0 and A14.*

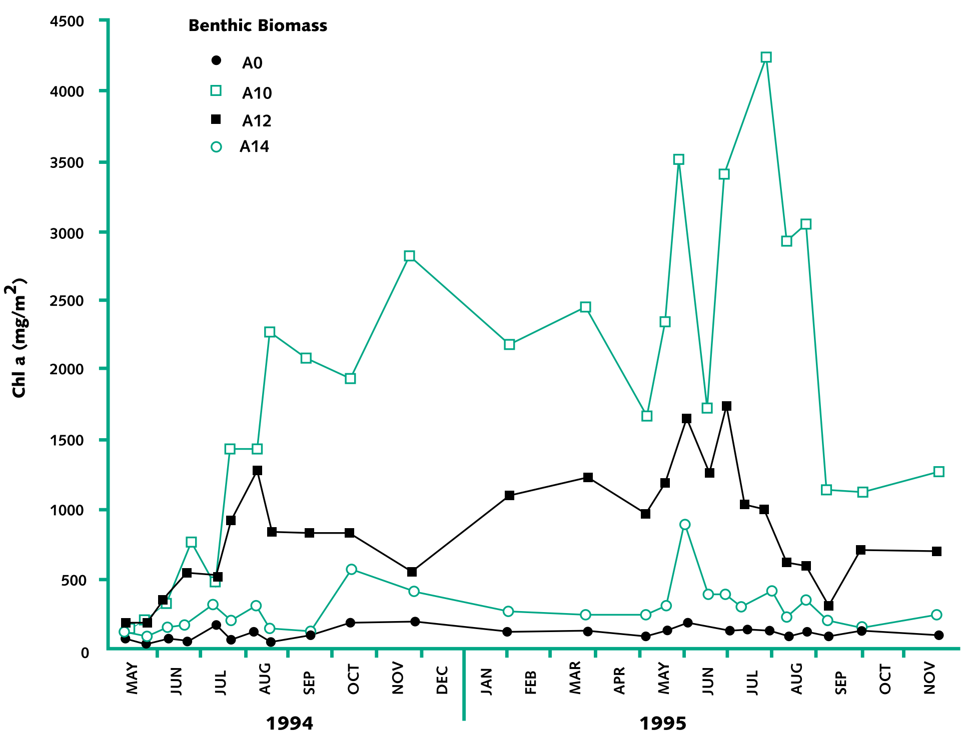

Figure 6. *Seasonal changes in sediment chl* a *at stations A0, A14, A10 and A12 (from Yin* et al. *submitted).*

the sandier A10 and A12 locations. Tidal drainage was most likely the major mechanism responsible for high chl *a* values at the two sandy sites; these sites experience tidal exposures at least once a day. The hypothesis is that microalgae grow in the benthic photic zone (usually the top 1–3 mm) and are drawn down through the large interstitial spaces of the well-sorted sandy sediment during drainage, which occurs during the ebbing tide. This process repeats over several daily tidal cycles and contributes to the accumulation of chl *a* in the deeper sediments. Large quantities of buried algal biomass indicated by these levels of chl *a* offer abundant food for benthic fauna and provide a source of NH_4 after remineralization by grazers and bacteria. In addition, it is important to stress the overall impact of the benthic algae reservoir in the sand flats for the whole delta-front secondary production: the muddy areas are not as rich in chl *a*, on a per square metre basis, and these muddy areas are only found in the upper intertidal zone.

Although sediment chl *a* (mainly benthic microalgal biomass) was lowest at A0, primary productivity per unit chl *a* was high, suggesting that perhaps grazing pressure was controlling the chl *a* standing crop more than inhibition by residual metals contamination in the sediments. The summer oxygen concentration in the water above the sediments at this site is near normal as opposed to the very low summer concentrations observed in the early 1980s (Birtwell *et al.* 1983). Reflecting these improved conditions, the top centimetre of the sediment column now exhibits the characteristic tan/brown colour of oxygenated sediments.

Secondary Production

Sturgeon Bank has exhibited several ecological changes stemming from the era of sewage deposition. These changes have included the alteration of population structure in dominant groups such as bivalves, amphipods, nematodes and polychaetes (Otte and Levings 1975; McGreer 1979), changes in sediment particle size (Grieve and Fletcher 1976) due to increased levels of organic carbon, and decreased oxygen concentration in the water overlaying the sediments (Birtwell *et al.* 1983). These were primarily due to the discharge of effluent onto the bank, compounded by physical habitat changes which caused the cessation of oxygen-rich and silt-laden freshwater flow from the North Arm over northern Sturgeon Bank. (The construction of the Iona to Sea Island causeway and the Iona Jetty breakwater also impaired effluent dispersion by sheltering the area from mixing during westerly and northwesterly winds, or by concentrating the plume against the jetty during southeasterlies.) Dissolved oxygen depletion occurred during the flood tide due to the high oxygen demand of the accumulated organic-laden sediment which was deposited when effluent was frequently pushed out of the channel and onto Sturgeon Bank by the heavier incoming seawater.

Benthic invertebrates in the area between the severely polluted zone and the contaminated zone include the polychaete worm *Manayunkia aestuarina* (Levings and Coustalin 1975; BC Research 1975), the polychaete *Eteone longa*, the common clam *Macoma balthica* (biomass up to 10.7 g/m^2 [Levings and Coustalin 1975]), the amphipods *Corophium salmonis* (biomass up to 2.9 g/m^2 [Levings and Coustalin 1975]) and *Corophium insidiosum,* and large numbers of harpaticoid copepods. The polychaete worm *Capitella capitata*, normally an indicator of organic pollution, occurred relatively infrequently when compared to other invertebrates in the area (approx. 2,200 individuals/m^2 at a distance 1,500 m southwest of the head of the effluent channel [BC Research 1975]). It was hypothesized that toxicity from heavy metals or chlorination, in combination with seasonal patterns of circulation, temperature, pH, dissolved oxygen and salinity, may have resulted in this distribution (BC Research 1975; Otte and Levings 1975).

Our objective was to monitor invertebrate production and population dynamics in the intertidal areas of Sturgeon and Roberts banks and to assess changes in these variables related to the cessation of sewage discharge onto the intertidal Sturgeon Bank. The analysis of invertebrate production, including measurements such as growth rates, secondary production and production to biomass ratios, is an important tool in estimating the availability of invertebrate food resources to their predators, and in assessing the health of an environment following an anthropogenic disturbance. Benthic invertebrates are better indicators of environmental quality than vertebrates (*e.g.* fish) because the post-larval stages of most invertebrates are relatively immobile and, therefore, must possess the inherent ability to survive in a contaminated location (Albright 1982).

Two suitable indicator species were selected based on previous research conducted by Levings and Coustalin (1975) at sites on Sturgeon and Roberts banks. The amphipod *Corophium salmonis*, and the clam *Macoma balthica* clearly fit within the guidelines of "moderate density" set forth by Pearson *et al.* (1983). Furthermore, these species form part of the basis of the food web for higher organisms in the area. For example, *C. salmonis* and *M. balthica* are common food sources of juvenile salmonids and flatfish (Cranford *et al.* 1985) and birds (Boates and Smith 1989).

When the sewage discharge was diverted in 1988, there were no animals living in the sediment at A0 (*i.e.* an azoic state). Several years later (Rebele 1994), various species of animals, such as the sewage tolerant polychaete *Manayunkia*, and *Corophium* and *Macoma*, began to recolonize this area. Another change that undoubtedly occurred was a reduction in organic matter through oxidation and the dispersal or dilution of the organic matter by sand or silt through sediment transport mechanisms. Such a reduction in sediment organic matter was even observed in the last three years (by about two-fold). This was attributed to a recent increase in sand content, and perhaps to the occurrence of less frequent sewage discharges onto the intertidal area during heavy rainstorms (due to the implementation of better control of stormwater flows in the sewerage system). Such sewage overflows are still occasionally discharged onto the old intertidal sewage channel during heavy rains or upsets at the treatment plant.

At the control station (A10), the density of *C. salmonis* was similar to that observed prior to the cessation of direct sewage discharge onto the intertidal zone (Arvai 1997). In terms of secondary productivity, values observed for *C. salmonis* (a maximum level of 0.78 g ash-free dry weight (afdw)/m^2/yr) in this study were lower than those observed for this and other species of the same genus in other research. The average productivity over the three years was similar at A0 and A14 (Fig. 7). At these two stations, which are still under the influence of past (A0) or present (A14) WWTP effluent disposal, high winter density, biomass, and productivity were observed. (Station A14 is exposed to WWTP discharges from Main Stem Fraser River WWTPs). It is likely that food availability (some in the form of organic matter

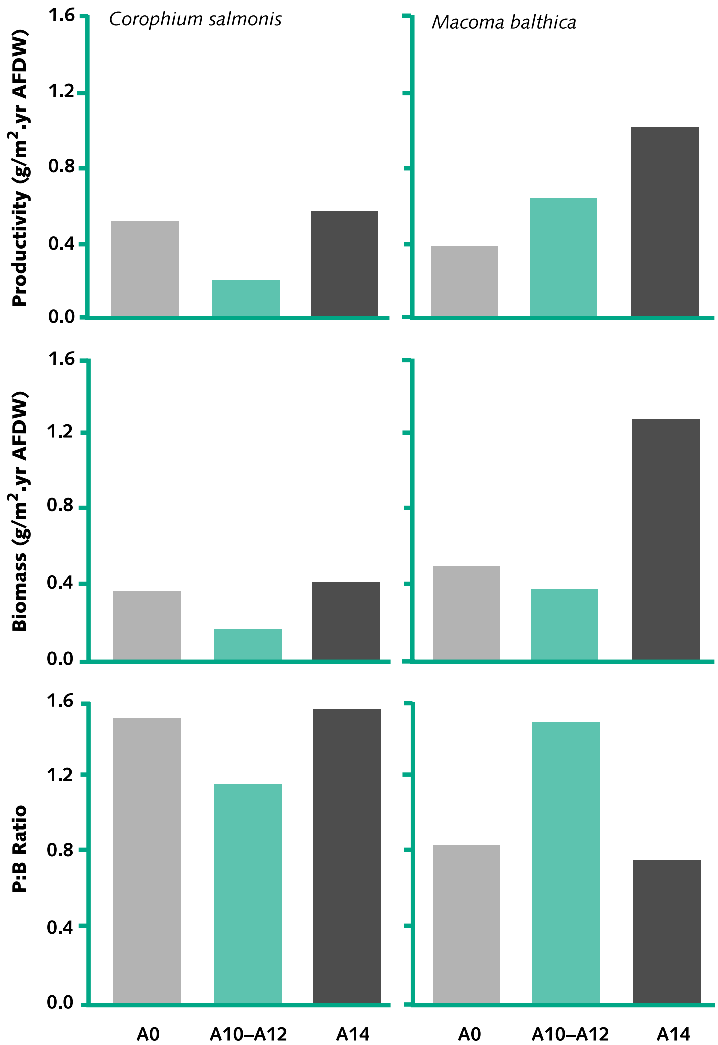

Figure 7. Three year averages of secondary productivity (g afdw/m^2/yr), mean biomass (g afdw/m^2/yr), and Productivity: Biomass (P:B) ratio for Macoma balthica *and* Corophium salmonis*. afdw=ash free dry weight (from Arvai 1997).*

from the WWTPs), longer potential feeding times and sediment-grain preference contribute to this finding at these stations. In general, densities observed at contaminated sites exceeded values found in previous studies at the same locations (BC Research 1975; Otte and Levings 1975).

Succession in the invertebrate community is complex, and can be affected by several interacting factors. For example, when sewage discharge is decreased, several factors such as the organic carbon, metal and nutrient contents in water and sediment change simultaneously and the importance of these individual factors may have different "weightings" in driving the biological community structure. For example, the preference of *Corophium* for fine grain sediments may be more important than a decrease in metal concentrations in the sediment (Arvai 1997). However, for station A0, the change from the original state of frequent anoxia was probably the most important factor influencing invertebrate recolonization of the area.

Secondary production of *M. balthica* (a maximum level of 1.9 g afdw/m^2/yr on Sturgeon and Roberts banks; Fig. 7 shows average of three years) was similar to values observed in other areas around the world (Beukema 1981; Cranford *et al.* 1985). Therefore, it was concluded that the *M. balthica* population and productivity have recovered dramatically from the previous azoic condition since effluent diversion. While most of the recovery is probably related to the reduction in contaminants and restoration of dissolved oxygen, some of the recolonization may be due to an increase in sand content or the decrease in organic matter. It is important to note, however, that in contrast to the situation with *Corophium*, both productivity and biomass values at A0 were less than half as high as those at A14, a site with similar sediment characteristics.

SHOREBIRD FEEDING ECOLOGY

Foraging conditions on the intertidal flats influence the time required for shorebirds to accumulate or replenish energy stores and this has a major influence on their survival and breeding success (Alerstam 1990), whether they are just passing through or spending the winter there. Until now, conservation has been hindered by a lack of understanding of intertidal food webs and the specific habitat and prey requirements of these birds.

In the Fraser River delta, two important shorebird species, Western Sandpiper and Dunlin, are potential indicators of coastal ecosystem health because the former uses the flats intensively in spring and late summer and the latter stays all winter.

Despite the extensive geographical range of Dunlin (*Calidris alpina*), populations of several subspecies of Dunlin worldwide (including our local subspecies, *pacifica*) appear to have declined in recent decades (Goss-Custard and Moser 1988; Paulson 1993). In Europe, studies on the wintering grounds have related these declines to human encroachment into wetland habitats and contaminated estuaries (Goede and De Bruin 1985a; 1985b). A possible explanation for their declining numbers in North America comes from Warnock and Gill (1996) who estimate the loss of Dunlin wintering habitat is between 30–91 per cent. Due to these concerns related to this species—35,000 to 60,000 of which overwinter in the Fraser River delta—Dunlin was selected for study in the Fraser delta. The behaviour and feeding of overwintering Dunlin were studied to evaluate this species' suitability as an indicator of ecosystem health of the intertidal flats and adjacent uplands (Shepherd 1997).

To understand what factors need to be considered when making inferences about the links between the health of the species and its food web, the feeding distribution in time and space was examined. By attaching radio transmitters to birds, information on site fidelity, habitat use, home ranges and activity budgets of male and female adult and juvenile Dunlin were obtained. Dunlin foraged both by day and night, as expected, but, surprisingly, they regularly fed at nearby agricultural fields at night. Males frequented these fields more than females. This was unexpected because a great deal more, and a greater diversity of, mudflat was available at night than during the day. Dunlin were rarely located in the fields during the day, likely due to the huge numbers of diurnal wintering raptors in the area. Hence, using Dunlin for monitoring toxic substances in the Fraser River delta would be complex since they forage in both marine and terrestrial areas and to differing degrees depending on their gender. This behaviour will add a layer of complexity to assessing the sources of contaminants in their diet. For example, contaminants in adult females would generally reflect uptake from the food web in the intertidal marine habitats, whereas males would reflect more of a mixture between marine and terrestrial sources.

This new information clouds the interpretation of the limited historical analyses of contaminants in Dunlin that were not separated into male and female samples. For example, in the late 1980s when the dioxin and furan discharges from upstream pulp mills were at their highest, a pooled sample of 18 Dunlin livers from both sexes was collected in December/January, 1989/90 (Whitehead 1997 pers. comm.). This analysis resulted in a concentration of 6.3 ng/kg of the most toxic dioxin congener, 2,3,7,8-tetrachlorodibenzo-*para*-dioxin, but it may have been higher in the females. Further, since all age classes were pooled, juveniles fresh from their arctic breeding grounds (where presumably exposure to these toxins is much lower) may also have lowered the concentrations. The eventual concentration accumulated by the end of the winter feeding would have likely been higher. However, as the levels of dioxins and furans in other wildlife (*e.g.* great blue heron) have declined dramatically (see Wilson *et al.* 1999), this threat should no longer exist for Dunlin.

In contrast to Dunlin, which reside on the delta for up to six months, Western Sandpiper (*Calidris mauri*) only utilize the delta tidal flats during spring and late summer migration. Predator/prey interactions of the Western Sandpiper were studied in order to determine the habitat requirements of a "typical" migratory shorebird and, also, the potential use of the species as a bioindicator of environmental health of the delta.

Western Sandpipers are one of the most common shorebirds in the western hemisphere. On the Pacific coast of North America, they migrate in large flocks between breeding grounds in Alaska and coastal wintering areas from California to Peru (Wilson 1994). The primary Pacific coast migration route is defined by a chain of critical stopover sites, including the Fraser River Estuary. Here, the northward migration is characterized by a peak in numbers from mid-April to late May (Butler *et al.* 1987), with maximum weekly numbers exceeding 500,000 shorebirds. On the Fraser River Estuary, the greatest overall densities of Western Sandpiper are found on Roberts Bank, west Boundary Bay and Sea Island (Butler 1994). In comparison, the southward migration is less intense and spread over a longer period, late June to early October, because of sex- and age-segregated movements by the shorebirds. In either migration, an individual might spend days to weeks on the delta.

Given their vast numbers and feeding demands, the expectation is that Western Sandpipers remove a high proportion of the available benthic production in the form of epibenthic and infaunal invertebrates from intertidal areas during their stay. Indeed, the arrival of migratory shorebirds on temperate mudflats in the Bay of Fundy has been associated with the decline in numbers of invertebrates (Daborn *et al.* 1993). In this context, the intense feeding pressure provided an opportunity to examine the link between the benthic community and at least one species of shorebird. This information will be useful in assessing the contaminant exposure risks this species and others at a similar trophic level might experience in the delta.

However, establishing the food web link quantitatively is difficult because of the spatial variability of invertebrates and difficulties in experimental design and analyses. Both factors have confounded quantitative interpretation and few studies have detected significant reductions in invertebrate numbers due to shorebird presence (Sewell 1996). Although Western Sandpipers are known to feed on invertebrates such as crustaceans, polychaete worms and clams living in or on the sediment, information on their natural diet is limited because of the difficulties in either observing what they eat or identifying prey remains in stomach contents. Taxonomic identification of the invertebrates and the lack of statistically valid sampling techniques are further problems. However, without a quantitative understanding of the distribution and abundance patterns of prey, coupled with an understanding of predator/prey relationships, actual prey and, thus, feeding habitat requirements cannot be ascertained. As a result, understanding the consequences of threats to habitat and subsequent provision of habitat conservation advice have been hindered.

The sandpiper study had two objectives. The first was to examine the spatial variability of invertebrate species across one area of the delta (Boundary Bay) as a prerequisite to designing sampling schemes to quantify prey density. A survey of macrofaunal invertebrates (>500 µm size) was conducted by collecting a series of 10x10 cm sediment cores across the intertidal flats of Boundary Bay. Between three and 10 invertebrate taxa per core were found with four numerically dominant taxa: gammarid amphipods (*Corophium* spp.), podocopid ostracods, polychaete worms (*Polydori ligni*) and epibenthic gastropod snails (*Batillaria zonalis*). For most taxa, there were significant differences between core densities at all scales except 1 km. With all taxa, there was considerable residual variation, suggesting patchiness at even smaller spatial scales than replicate cores collected 1 m apart.

The second objective consisted of a short-term exclosure experiment and random sampling (before/after predation) to assess reductions in invertebrate densities by Western Sandpipers at the Fraser River delta stopover during the spring migration. Surprisingly, there was little evidence for reductions in macroinvertebrate densities between the inside and outside of the exclosure cages even though several million Western Sandpipers had been feeding in the vicinity. In the exclosure experiment, a significant decline was observed only in a phyllodocid polychaete (*Eteone* spp.), but only at a site with little evidence of shorebird feeding. Thus, the decline could reflect the extreme patchiness in invertebrate distribution rather than shorebird predation. Results from the random sampling before and after shorebird migration revealed no differences that could be interpreted as being caused by shorebird foraging (Sewell 1996).

The trophic level(s) an animal feeds on and its connections as a prey itself to other trophic levels defines its place in the food web. The results of these studies have not elucidated the trophic position of Dunlin and sandpipers and highlight both the complexity of invertebrate spatial patterns and the uncertainties surrounding the feeding ecology of shorebirds. The apparent failure to detect the predatory "signature" of several million Western Sandpipers is enigmatic. One possible explanation is that the spatial variability of the macroinvertebrates is so high that the statistical power to detect effects is low (Sewell 1996). Another possibility is that Western Sandpipers may have been feeding on meiofaunal invertebrates and plants far smaller (<500 µm) than the macroinvertebrates that were assessed. Ongoing investigations utilizing a scanning electron microscope have revealed microstructures in shorebird bills that may act as sieves for meiofaunal prey. Other studies utilizing high-speed video technology have demonstrated that Western Sandpipers can indeed feed on meiofauna suspended in solution (Elner, unpub. results).

Overall, the research on the links between this species and the benthic food web has identified crucial gaps that need to be addressed before specific feeding habitat characteristics can be identified and mapped for conservation purposes. The prime question that remains is: from what prey do the Western Sandpiper and Dunlin, as well as other shorebirds, derive the bulk of their nutrition? If, indeed, meiofauna are the preferred prey, less biomagnification of contaminants by the intertidal-feeding shorebirds will occur than if the birds were feeding at a higher trophic level. Assessing contaminant accumulation in shorebird species that reside on the delta for extended periods and their prey is recommended to resolve this question.

CONCLUSIONS

While it is important to understand that the delta front comprises six fairly distinct habitats/zones differentiated by variable marine/freshwater ratio, sediment type and supply, several generalizations can be made about the status of this unique and internationally important ecosystem.

Sturgeon Bank is still influenced by the Iona Island municipal WWTP, although to a much lesser extent than before 1988, and by inputs from discharges to the North Arm upstream of the junction with the Middle Arm. Roberts Bank is directly influenced by the Main Arm and inputs from Lulu Island and Annacis Island municipal WWTPs. Boundary Bay reflects inputs delivered via the much smaller Nicomekl, Serpentine and Little Campbell rivers which carry an entirely different kind of contaminant mix. In general, metal concentrations were highest on Roberts Bank, and concentrations in Boundary Bay were much lower than those in Roberts and Sturgeon banks. However, the northern portion of Sturgeon Bank near Iona Island WWTP is still a contaminant hot spot, and it had the maximum occurrence of Cu, Cd, Pb, Zn, Ag and Hg. While greater than 50 per cent of each metal supplied by the Fraser River is in a bioavailable form, the iron generated by diagenesis in the pore waters of the estuarine sediments can reduce metals bioavailability and hence their bioaccumulation by organisms.

Nickel and copper exceeded provincial sediment quality criteria for the protection of freshwater or marine life at more than one location, and Hg exceeded the criterion near Iona Island WWTP.

On Sturgeon Bank, near the original sewage discharge area, Cu, Pb, Ag, Hg and Cd have decreased from 12 to 56 per cent during the period 1977–1995; Zn has remained approximately constant. The common clam *Macoma* was used as a biomonitor of metal contamination. Comparing 1979 with 1996 indicates that concentrations in the clam have decreased by two-fold for Cu and Zn and by 10-fold for Hg. Comparisons of *Macoma* tissue with those from other estuaries indicate that Pb and Zn are low, Hg and Cd are average, Cu is average to high, and Ni is high.

Silver proved to be an excellent tracer of the horizontal and vertical extent of contamination from the previous sewage discharge near the Iona Island WWTP. Vertical profiles of Ag in the sediments near Iona Island indicate that there are considerable deposits of contaminated sediments from about 2 to 10 cm below the cleaner sediment surface. These sediments should not be disturbed unless they can be removed without recontaminating a wider area. Thus, the proposal to reconnect McDonald Slough with the Strait of Georgia (*i.e.* dredge an opening through the artificial causeway) could cause significant trace metal contamination in adjacent areas or in dredge disposal zones.

Ammonium concentrations in the sediment pore waters at Iona Island were generally higher than at Roberts Bank (100 to 700 µM or 1.4 to 9.8 mg NH_4-N/L). This is due to the higher organic matter content of the sediment and the subsequent decomposition and release of ammonium. This supply of ammonium to the water column could help to maintain primary production through late summer when offshore levels of nitrate and ammonium are frequently near limiting concentrations for phytoplankton growth.

The yearly average benthic algal biomass was the lowest at A0—the site previously most impacted by the Iona Island municipal WWTP discharge—(84 mg chl *a*/m^2) and highest at A10—a control site (2,044 mg chl *a*/m^2)—with A14 (potentially affected by municipal WWTPs discharging to the Main Arm) and A12 (a control site) being intermediate in biomass. While the algal biomass at A0 is low, biomass has recovered to levels seen, in the past, at sites some distance from the previous sewage discharge channel. In addition, the previously observed blue-green algal mats have been replaced by benthic diatoms, which are present at lower biomass levels than the blue-green algae and are indicative of less nutrient-rich environments. Primary productivity per unit chl *a* was high at A0, suggesting that the metals in the sediments do not inhibit photosynthesis. The summer oxygen concentrations in the water above the sediments at A0 are now similar to other locations on the banks and the top centimetre of the sediment now exhibits the characteristic tan/brown colour of oxygenated sediments.

There were no animals living in the sediment at A0 when the sewage was diverted in 1988. Several years later, invertebrates such as the amphipod *Corophium*, the clam *Macoma* and the polychaete *Manayunkia* began to recolonize the area. This is likely due to an increase in the oxygen content of the sediment because of the decrease in the organic matter and a change from muddy to more sandy sediments.

As indicators of delta-foreshore ecosystem health and contamination, the use of Dunlin and Western Sandpiper was found to be somewhat problematic. Using Dunlin, which reside on the delta for up to six months, to monitor toxins in the Fraser River delta is complex since they forage in both marine and terrestrial areas (*i.e.* in nearby fields at night) depending on their gender. Contaminants in adult females, however, would generally reflect uptake from the intertidal food web. On the other hand, the Western Sandpiper, which utilize the delta tidal flats intensely during spring and late summer migrations, would possibly accumulate enough contaminants if sampled near the end of their spring migration stopover. Unfortunately, as meiofauna (*e.g.* nematodes and protozoans) are possibly the dominant food for this species, biomagnification of contaminants up the food chain would miss at least one magnification step and hence dampen the contaminant signal they could pick up in their short stay.

In conclusion, the delta foreshore is an ecosystem on the mend from about a century of contamination and habitat alteration. The sand flats are presently supporting large populations of shorebirds and waterfowl and the benthic food webs appear to be highly productive in comparison to other estuaries. However, this generality may not cover all areas as there are hot spots of past contamination. For example, a pollution episode that lasted for 26 years can still be detected a decade after it ceased. That area has now been recolonized by the former resident biota, and metals in the sediments have declined in concentration or their bioavailability. These responses should continue to improve over the next decade, especially as the frequency of combined sewer overflows at the outfall declines in response to the present program of sewer separation and management. Improvements should also be observed at the sites on Sturgeon and Roberts banks presently affected by contaminants originating in the Lulu and Annacis Island municipal WWTPs discharging to the Main Arm after secondary treatment is implemented fully in 1999. The improvements may be more subtle than those observed near the Iona discharge, however, as these sites were never exposed to the same intensity of pollution. The uncontaminated condition of Boundary Bay is noted but this could change as urban development intensifies in the Nicomekl and Serpentine River drainage basins in Surrey.

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