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A Particle Conveyor Belt Process in the Columbia River Estuary: Evidence from Chlorophyll *a* and Particulate Organic Carbon

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ABSTRACT: Us ng both the photosynthet cally act ve chlorophyll (chl) content of the organ c carbon fract on of suspended part culate matter (chl /POC) and the percentage of photosynthet cally act ve chl n fluorometr cally measured chl plus pheophyt n (% chl), we determ ned that under spec fied hydrodynam c cond t ons, neap-spr ng t dal d fferent at on n part cle dynam cs could be observed n the Columb a R ver estuary. Dur ng summert me neap t des, when r ver d scharge was moderate, bottom chl /POC rema ned relat vely unchanged from r ver ne chl /POC over the full 0–30 psu sal n ty range, suggest ng a ben gn trapp ng env ronment. Dur ng summert me spr ng t des, bottom chl /POC decreased at m d range sal n t es, nd cat ng resuspens on of chl -poor POC dur ng flood-ebb trans t ons. Bottom % chl dur ng neap t des tended to average h gher than that dur ng spr ng t des, suggest ng that neap part cles were more recently hydrodynam cally trapped than those on the spr ng t des. Such d fferent at on supported the poss - b l ty of operat on of a part cle conveyor belt process, a process n wh ch low-ampl tude neap t des favor select ve part cle trapp ng n estuar ne turb d ty max ma (ETM), wh le h gh-ampl tude spr ng t des favor part cle resuspens on from the ETM. Untrapped r ver-der ved part cles at the surface would cont nue through the estuary to the coastal ocean on the neap t de; dur ng spr ng t de some part cles eroded from the ETM would comb ne w th unsettled r ver ne part cles n trans t toward the ocean. Because ntens fied b ogeochem cal act v ty s assoc ated w th ETM, these neap-spr ng d fferences may be cr t cal to ma ntenance and renewal of populat ons and processes n the estuary. Very h gh r ver d scharge (15,000 $m^3 s^{-1}$) tended to overwhelm neap-spr ng d fferences, and s gn ficant ocean c nput dur ng very low r ver d s- charge (5,000 $m^3 s^{-1}$) tended to do the same n the estuar ne channel most exposed to ocean nput. Dur ng heavy spr ngt me phytoplankton blooms, development of a th ck bottom fluff layer r ch n chl also appeared to negate neap- spr ng d fferent at on because spr ng t des apparently acted to resuspend the same r ch bottom mater al that was la d down dur ng neap t des. When photosynthet c ass m lat on numbers [$\mu gC\ (\mu gchl)^{-1} h^{-1}$] were measured across the full sal n ty range, no neap-spr ng d fferences and no r ver d scharge effects occurred, nd cat ng that w th n our su te of measurements the compos t onal d st nct on of suspended part culate mater al was ma nly a funct on of chl /POC, and to a lesser extent % chl . Even though these measurements suggest the ex stence of a conveyor belt process, proof of actual operat on of th s phenomenon requ res scalar flux measurements of chl propert es n and out of the ETM on both neap and spr ng t des.

Introduct on

The Columbia River is the second largest river in the coterminous nited States, and its discharge influences a large area of the northeast Pacific Ocean (Small and Ramberg 1971; Barnes et al. 1972; Small and Curl 1972; Landry et al. 1989). Even though the river has been greatly altered along its entire length by dams, irrigation projects, and dredging, the lower stretch, including the 419 km^2 estuary, remains a good example of a drowned river valley created as the sea level rose to its present position after the last glaciation (Lara-Lara et al. 1990). In spite of the human alterations, the estuary (Fig. 1) is dominated by two features: variable river discharge (averaging about 7,500 $m^3 s^{-1}$ but ranging between about 4,000 and 17,000 $m^3 s^{-1}$ with peaks exceeding 20,000 $m^3 s^{-1}$ during periods of heavy rainfall and snow melt) and a large tidal prism of about 680×10^6 m^3 (Jay et al. 1997). Compared to a few other well studied estuaries, these two features largely control different distributional patterns and salient characteristics of the total estuarine field of suspended particulate matter (SPM), including the strength and positioning of estuarine turbidity maxima (ETM; Fain et al. 2001). ETM appear to be important loci for biological, biochemical, and sedimentological transformations (Baross et al. 1994; Reed and Donovan 1994; Simenstad et al. 1994b; Small and Morgan 1994; Klinkhammer and McManus 2001).

The primary mechanism for creation of ETM in the Columbia River estuary is internal tidal asymmetry; i.e., the interaction between landward-directed, near-bottom, residual currents generated by stratification (Jay and Musiak 1996). As a consequence of this asymmetry and ETM formation, we postulated that under conditions of low to mod-

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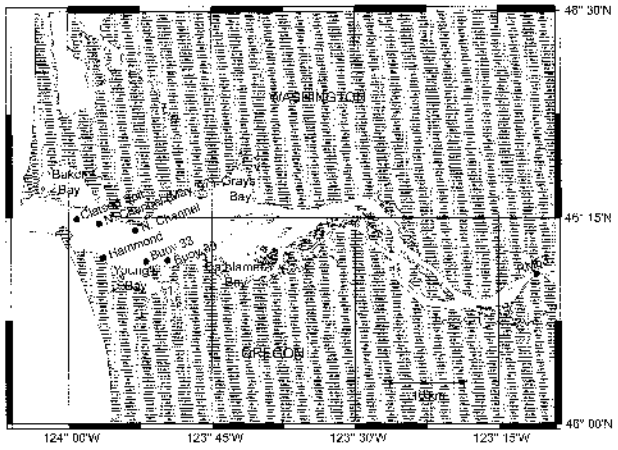

Fig. 1. Map of Columbia River Estuary showing sampling stations.

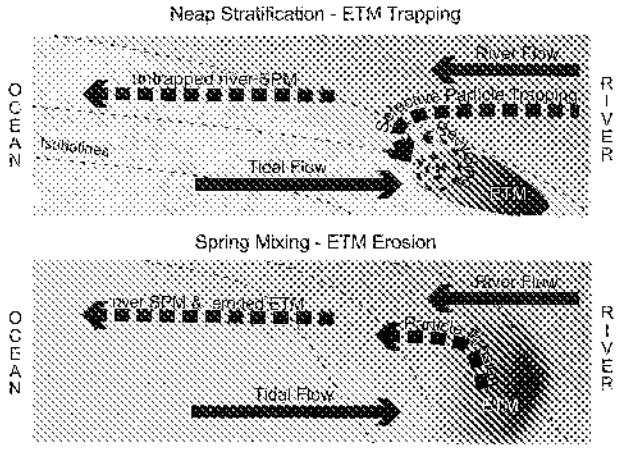

Fig. 2. Schematic of hypothesized particle conveyor belt operation.

erate river discharge the lower amplitudes of neap tides would allow net settling of riverborne particles, with subsequent selective trapping in ETM, while the higher amplitudes of spring tides would erode particles from the ETM trap. Most particles within the estuary might be visualized as moving through the ETM as if on a conveyor belt (Fig. 2; see Simenstad et al. 1994a). Representative plots of optical backscatter (a surrogate for SPM) over time gave some credence to the conveyor belt hypothesis in that a general increase in intensity and height of the ETM was almost always observed on spring tides relative to neap tides (Fig. 3). Certain characteristics of particles within spring and neap tide ETM also might be expected to differ as a result of the contrasting erosional and depositional characteristics of the two tidal phases. Such differences in particle composition would demonstrate the strong probability of conveyor belt operation in the Columbia River system.

Rudiments of the conveyor belt hypothesis have been brought out by other researchers working in various-sized tidal estuaries with ETM often generated by means other than internal tidal asymmetry, and sometimes showing seasonality (Cloern et al. 1983; Fisher et al. 1988; Moon and Dunstan 1990; ncles et al. 1998; Cancino and Neves 1999). Noted neap-spring differences in ETM, with consequences to sediment characteristics, changes in particulate organic carbon (POC), and phytoplankton populations in particular, have been noted in our own work and that of others, both as a result of seasonal and interannual changes in river discharge (Pocklington and Tan 1987; Cloern 1991a; Small and Morgan 1994; Sullivan et al. 2001; Sellers and Bukaveckas 2003), and as a result of neap-spring tidal mixing (Sinclair et al. 1981; Cloern 1991b). There was no attempt to examine potential conveyor belt operation in these studies. In this paper, we present a detailed study of changes in organic particle composition as a possible key to understanding neap-spring patterns of particle movement in the context of a conveyor belt.

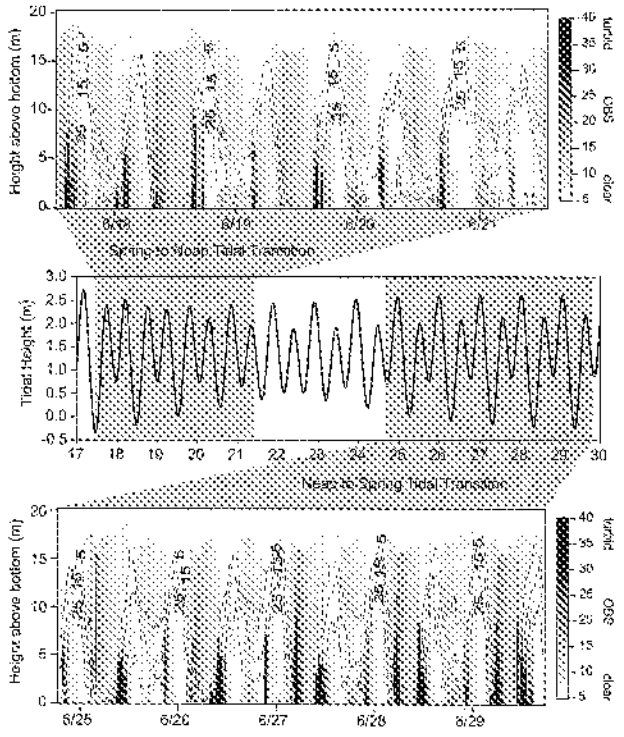

Fig. 3. Representative plot of optical backscatter, a surrogate for suspended particulate matter concentration, showing the general increase in height and intensity of estuarine turbidity maxima during tidal transitions on higher-amplitude spring tides relative to lower-amplitude neap tides.

Sampling Locations

The Columbia River estuary is essentially divided into two main channels separated by shoals in mid estuary. South Channel (the shipping channel) is contiguous between the river and coastal ocean, while North Channel is open to the ocean but basically cut off from direct connection with the river (Sherwood and Creager 1990). Sampling sites in both channels and in the river (RM53) are shown in Fig. 1. The RM53 site was occupied on every cruise. Three different South Channel sites (Buoys 39 and 33, and Hammond) and two different North Channel sites were occupied at various times of the year in an attempt to capture the maximum ETM development under different river discharge regimes. In 1997–1998, the Columbia River experienced the highest annual average discharge in over 25 yr (Jay et al. 1999), and by far the greatest discharge during our spring-summer sampling periods (up to 15,700 $m^3 s^{-1}$) occurred during May 1997. Presampling reconnaissance resulted in our establishing the most downstream sampling sites in each channel at this time. In June 1999, North Channel was sampled at the most down-estuary station because river discharge also was relatively high. All other North and South Channel sampling was done at the more up-estuary locations. Some sampling was also done near the estuary mouth at Clatsop Spit in an attempt to better assess oceanic influence separately from that in the two estuarine channels. The Clatsop Spit station was seaward of the location where South and North Channels merged into one.

Mater als and Methods

Our general approach to assessing compositional changes was to use time series of standard, relatively quickly measured attributes of collected particles, and to follow these attributes from the river to the estuary's mouth. When possible, all sampling sites were occupied over a 30-h period (somewhat greater than one flood-ebb cycle) during both neap and spring tidal phases. SPM samples from just below the surface and from near-bottom were collected every 2 h at each station using a high-volume pump and attached hose (Simenstad et al. 1994a). Detailed CTD and optical backscatter measurements were obtained concurrently on each pump cast and at intervals between each pump cast to more critically define tidal changes in temperature, salinity, and SPM concentrations at each sampling site. Immediately on shipboard, one portion of each SPM sample was filtered on preweighed polycarbonate membrane filters (90 mm diam, 1 μm pore size, Poretics) and oven-dried (60°C) for gravimetric determination of SPM concentration, and two portions were filtered on glass-fiber filters (GFF, 25 mm diam, 0.8 μm pore size, Whatman) for plant pigment and POC analyses. Pigments were extracted in the dark onboard ship in cold 90% acetone, and chlorophyll *a* (chl *a*) and pheophytin *a* concentrations were determined by a standard fluorometric assay (Strickland and Parsons 1972; 3–8% variability in replicate samples). Filtered samples for POC were frozen and transported to a shore-based laboratory where high temperature combustion analysis was done on a Perkin Elmer 240C or Carlo-Erba NA-1500 elemental analyzer (± 5–10%). Filtrate from the samples for gravimetric analysis was collected and stored frozen in acid-cleaned polyethylene bottles (30 ml) for laboratory determination of nitrate, ammonium, phosphate, and silicate concentrations using a standard AutoAnalyzer method (Strickland and Parsons 1972).

Beginning in May 1995, a fourth portion of each SPM sample was used to determine primary production rates under saturating light (primary productivity potential [PPP] as μg C l^{-1} h^{-1}), for eventual determination of assimilation number (AN, as μg C (μg chl *a*)$^{-1}$ h^{-1}). Standard experimental procedures were used; two clear polycarbonate bottles and one opaque bottle were filled (80 ml) and inoculated with 1.5 μCi $NaH^{14}CO_3$ (1 ml of solution), after which the bottles were placed in a shipboard incubator with running river or estuarine water to maintain ambient temperature, and were rotated slowly for 2 h under saturating light intensity delivered by two tungsten-halogen lamps of near-daylight spectral quality. Saturating light intensity (450 μmol quanta m^{-2} s^{-1}) was determined in precruise experiments using near-surface phytoplankton assemblages. After 2 h, the bottles were retrieved, the contents filtered in the dark through 0.45 μm pore size cellulose acetate filters, and the filters placed into vials of scintillation fluor (Opti-Fluor, Packard) for later determination of ^{14}C uptake by the photosynthetic fraction of the particles in each bottle. As each set of bottles was removed for filtration, inoculated bottles from the following 2-h sampling period were placed in the shipboard incubator until the full time series was completed for each sampling site.

We measured ^{14}C uptake under saturating light rather than natural sunlight because our principal objective was to compare through all seasons and years the potential photosynthetic capabilities of each particle sample whether it was collected day or night, bottom or surface, estuarine channel or river, flood or ebb tide, and neap or spring tidal stage. Lara-Lara et al. (1990) had already demonstrated that light and chl *a* largely control in situ primary productivity throughout the year in the

TABLE 1. Summary of mean values (± 1 SD) of suspended particulate material (SPM) and particulate organic carbon (POC) concentrations, POC as a weight percentage of SPM (wt % POC), and mean river discharge rates during all sampling dates and both neap and spring tidal phases (when available) at RM53 in the Columbia River. Values for each of these properties measured at a given time in surface and near-bottom waters were always equivalent, so depth data were combined.

Date	Tidal Phase	SPM (mg l^{-1})	POC (mg l^{-1})	wt % POC	River Discharge (m^3 s^{-1})
May 1992	Spring	18.24 (3.85)	1.26 (0.20)	6.69 (0.94)	6,598
May 1995	Spring	18.13 (3.12)	1.22 (0.13)	7.16 (1.07)	8,368
	Neap	17.63 (3.38)	1.38 (0.12)	8.27 (2.07)	8,920
May 1997	Spring	29.92 (5.05)	1.21 (0.23)	4.11 (0.74)	14,526
	Neap	32.57 (4.79)	1.23 (0.21)	3.89 (0.34)	15,716
June 1992	Neap	32.64 (11.78)	1.19 (0.21)	4.51 (1.76)	6,046
June 1999	Spring	15.70 (2.73)	0.84 (0.33)	4.70 (1.29)	10,436
	Neap	18.73 (3.13)	0.86 (0.34)	4.28 (0.70)	10,592
July 1991	Spring	28.33 (4.89)	1.20 (0.16)	4.34 (1.14)	8,495
	Neap	21.96 (6.20)	0.92 (0.14)	4.40 (0.74)	5,408
July 1996	Neap	21.77 (7.29)	1.14 (0.15)	5.72 (1.17)	7,787
July 1997	Neap	24.77 (3.08)	1.14 (0.19)	4.43 (0.74)	8,707

Columbia River and its estuary (cumulative r^2 = 0.92 in both main channels and shallows), with water temperature and SPM concentration exerting only tiny effects and nutrient concentrations very seldom if ever limiting. In our studies, major nutrient concentrations were never limiting, with nitrate and nitrite between 5–25 μM, orthophosphate between 0.3–2.8 μM, and silicate between 110–180 μM, essentially the same ranges measured by Lara-Lara et al. (1990) and Sullivan et al. (2001) during spring and summer, regardless of sampling site or depth. By controlling light at saturating levels, temperature in our flow-through incubator, and nutrients to a reasonable degree by running short-term incubations, we assumed the major effect on PPP and AN would be differences in chl *a* concentration.

Except where expressly noted in figure captions, distinct symbols have been used throughout to distinguish surface and bottom data for each sampling date, while spring and neap tidal phases are distinguished by gray (spring) and black (neap) color (Fig. 4).

Results and D scuss on

PARTIC LATE ORGANIC CARBON

In the R ver

To characterize the compositional input of riverborne particles to the estuary, we first determined relationships between POC and SPM concentrations at RM53 using all available data from all sampling periods (Table 1). Mean POC concentrations tended to vary in concert with SPM during the summer months and May 1997, so that POC as a percentage of SPM load (wt % POC) remained relatively unchanged during these periods. Only May 1992 and May 1995 showed wt % POC means elevated above 6%. Local flooding in the lower Columbia River begins when discharge reaches about 12,700 m^3 s^{-1} (Fuhrer et al. 1996), so that during the high discharge period in May 1997 substantial POC-poor mineral material was put into suspension, reducing wt % POC to summer levels. On the basis of wt % POC, river input to the estuary could only be partitioned very roughly into two categories: May 1992 and May 1995 combined, and all the summer periods plus May 1997. No neap-spring tidal differences could be discerned in the river within any given sampling date.

In the Estuary and Estuary Mouth

Relative to the river, both estuarine channels showed significant changes in the distribution of POC. Although mean surface POC concentrations (mg l^{-1}) in the two channels always approximated riverine POC concentration, bottom means in the estuary were often much greater (Table 2). Mean wt % POC usually varied little between the estuary surface and bottom within any given sampling period, so the higher bottom POC concentrations mainly resulted from higher SPM concentrations generated by suspension of bottom material into an ETM during each flood-ebb reversal. The channel bottoms at the sites of ETM development acted as SPM (and POC) reservoirs necessary for establishment and operation of a conveyor belt process. Although mean neap and spring POC concentrations along the bottom were never statistically different during any given sampling period, there was usually a tendency for spring-tide means to be higher, hinting at relatively greater erosion of bottom material during this tidal phase.

Mean POC concentrations in the mouth of the estuary at Clatsop Spit almost always tended to be smaller, sometimes much smaller near the bottom, than comparable means in the two channels (Table 2). This was largely attributable to the relatively sandy bottom at Clatsop Spit (Sherwood and

TABLE 2. Summary of mean values (± 1 SD) of particulate organic matter (POC) concentration and POC as a weight percentage of suspended particulate material (wt % POC) in surface and near-bottom waters of both channels of the Columbia River estuary and Clatsop Spit, plus estimated river discharge rates during all sampling dates and both tidal phases. POC and wt % POC values have been computed only for SPM concentrations of 200 mg l^{-1} or less (four times the smallest measurable ETM), as SPM concentrations greater than 200 mg l^{-1} always resulted from samples pumped out of the estuary bed itself, not just the ETM.

Date	Tidal Phase	POC (mg l^{-1})		wt % POC		River Discharge (m^3 s^{-1})
		Surface	Bottom	Surface	Bottom	
North Channel						
May 1992	Spring	1.34 (0.44)	3.56 (1.30)	4.92 (0.91)	4.91 (1.30)	5,890
May 1997	Spring	1.15 (0.37)	1.85 (0.47)	3.58 (1.15)	4.16 (0.68)	13,026
June 1999	Spring	0.62 (0.18)	1.08 (0.29)	4.10 (1.35)	4.06 (1.27)	11,045
	Neap	0.73 (0.20)	1.30 (0.73)	5.78 (2.91)	4.67 (2.81)	10,790
July 1991	Spring	0.75 (0.19)	3.83 (1.89)	4.64 (0.78)	4.76 (1.25)	5,720
	Neap	0.99 (0.27)	3.08 (1.63)	5.01 (1.44)	5.13 (2.16)	5,816
July 1997	Spring	0.82 (0.27)	2.26 (1.42)	4.98 (1.52)	5.01 (1.82)	8,693
	Neap	0.71 (0.16)	0.98 (0.34)	6.14 (1.20)	4.63 (1.70)	8,722
South Channel						
May 1992	Spring	1.32 (0.39)	2.72 (1.19)	7.03 (2.48)	6.11 (1.32)	6,725
	Neap	1.23 (0.15)	2.73 (1.31)	7.18 (2.38)	6.46 (1.89)	6,966
May 1995	Spring	1.33 (0.20)	2.65 (1.44)	6.90 (2.06)	6.18 (1.80)	9,019
	Neap	1.02 (0.21)	1.50 (0.54)	7.13 (1.75)	7.49 (2.30)	8,731
May 1997	Spring	1.04 (0.38)	2.83 (1.25)	3.57 (0.93)	4.15 (1.16)	13,139
	Neap	0.84 (0.23)	1.83 (1.27)	4.45 (0.98)	4.38 (1.18)	15,107
June 1992	Neap	0.98 (0.18)	2.70 (0.85)	6.84 (0.90)	6.98 (2.13)	5,338
July 1991	Spring	1.12 (0.31)	2.47 (0.77)	3.88 (1.13)	3.99 (1.09)	7,886
	Neap	0.89 (0.12)	1.71 (0.69)	6.48 (2.82)	5.52 (1.51)	5,234
July 1996	Spring	0.88 (0.13)	1.59 (0.57)	5.87 (1.47)	5.24 (0.98)	8,085
	Neap	0.91 (0.13)	1.86 (1.00)	5.49 (1.76)	6.01 (1.54)	6,782
July 1997	Spring	1.17 (0.44)	2.12 (1.12)	5.41 (1.24)	4.63 (0.92)	9,076
	Neap	0.74 (0.10)	1.24 (0.62)	6.63 (1.14)	5.83 (2.10)	8,155
Clatsop Spit						
May 1992	Spring	0.73 (0.14)	1.59 (1.38)	4.29 (0.80)	8.58 (0.80)	5,819
May 1997	Neap	0.67 (0.15)	1.31 (0.48)	3.92 (0.62)	3.77 (1.36)	12,092
June 1999	Neap	0.47 (0.10)	0.83 (0.31)	4.11 (1.51)	3.48 (1.03)	10,436
July 1991	Neap	0.70 (0.11)	1.45 (0.40)	4.45 (1.57)	4.98 (0.63)	4,701
July 1997	Neap	0.62 (0.16)	1.44 (0.85)	6.46 (1.02)	4.77 (1.70)	7,688

Creager 1990). The robust bottom POC reservoir required for separating neap and spring particle characteristics, a major feature of the channels in spring and summer, never fully materialized at the mouth. Values for POC concentrations and wt % POC at Clatsop Spit were actually most similar to those in the river, with concentration means for surface and bottom waters usually bracketing the corresponding water column mean for RM53 (Tables 1 and 2).

Chlorophyll *a* as a Function of POC

In the River

The chl *a* content of POC at RM53 varied widely in different years during May (Fig. 4). Chl *a* in May 1997 was always distinctly low, even lower than summer values in any year, presumably because high discharge disallowed development of a substantial standing stock of phytoplankton. In May 1992, very high chl *a* concentrations marked an intense phytoplankton bloom in the river. The water was visibly green. This bloom, associated with relatively low SPM and high wt % POC (Table 1), apparently did not extend in full measure to our sampling period in June 1992, 18 d later (Fig. 4). The lower chl *a* concentrations in June 1992, in concert with higher mean SPM concentrations and lower wt % POC values at this time (Table 1), suggested dissipation of the May bloom. June 1992 values appeared intermediate to those of May 1992 and summer and are viewed as transitional and plotted in context with both the spring and summer data (Fig. 4).

Contrary to May 1992, SPM, POC, and wt % POC values at RM53 in May 1995 were never matched by high bloom-level chl *a* (Fig. 4). The range of chl *a* concentrations in May 1995 almost exactly overlapped the chl *a* range in summer, over essentially the same small POC range. In terms of chl *a*/POC, the May 1995 riverine contribution to the estuary could most appropriately be combined with the summer data, while the May 1992 and May 1997 contributions stood alone as two extremes.

In the Estuary and Estuary Mouth

Chl *a* in both channels and at Clatsop Spit during most sampling periods was highly correlated

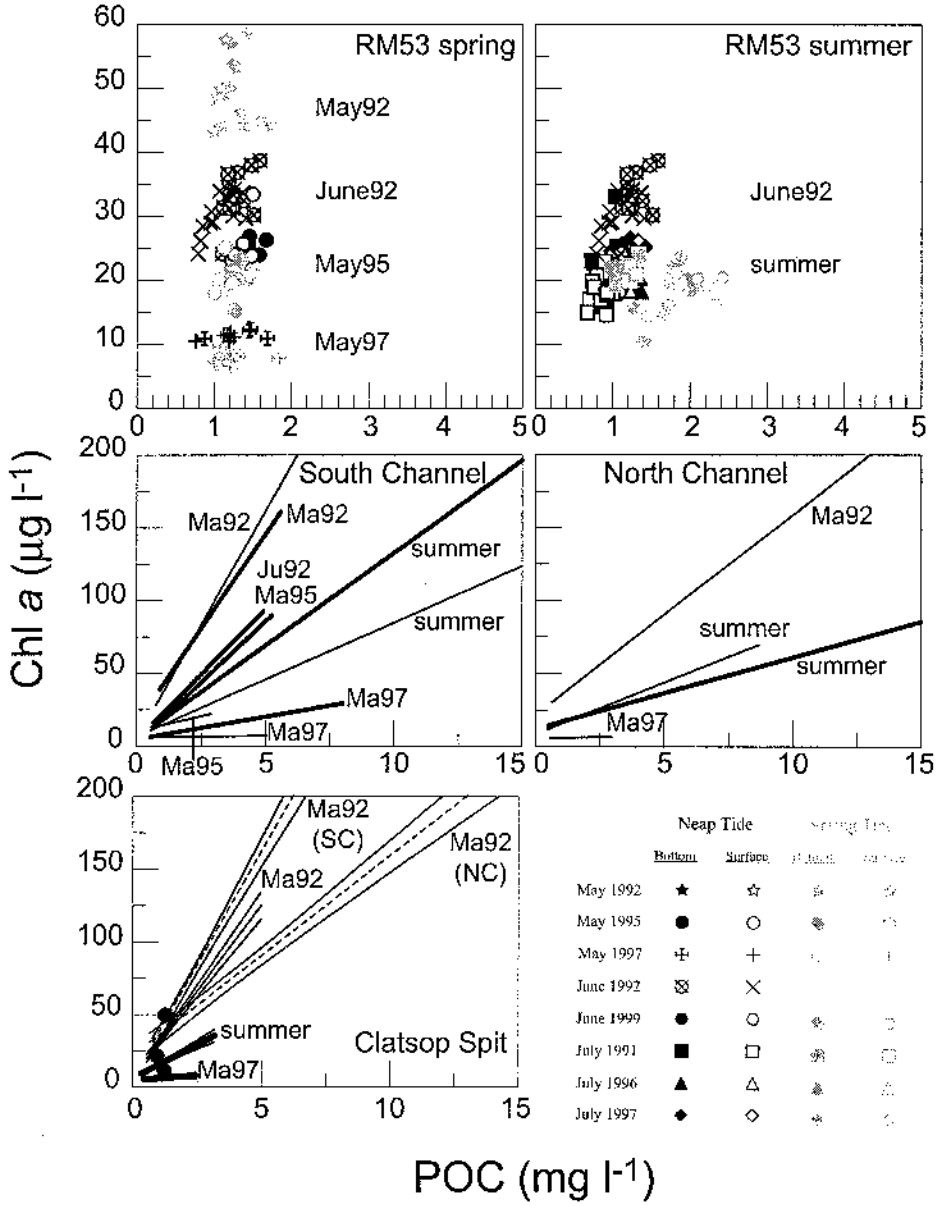

Fig. 4. Chlorophyll *a* (chl *a*) as a component of particulate organic carbon (POC) in the river (RM53) for both surface and near-bottom samples on both neap and spring tides during spring and summer. Type I linear regression analyses on combined surface and bottom data and combined summer data during neap tides (bold lines) and spring tides (fine lines) for South Channel, North Channel, and Clatsop Spit. For Clatsop Spit, the May 1992 regression (± 95% confidence interval) is compared to those for South Channel (SC) and North Channel (NC). RM53 means for May 1992, May 1997, and summer (plus May 1995) are shown as filled circles. Black open and filled symbols refer to neap tides, gray symbols refer to spring tides.

with POC (Table 3) over a range extending well into that defined for an ETM (Small and Morgan 1994). The statistics of the chl *a* versus POC concentration relationships during different summer periods were so similar within a respective tidal phase that they were combined. It was in these summer periods in South Channel that the correlation relationships showed clear neap versus spring tidal differences (Fig. 4). The more that POC increased as a constituent of an intensifying ETM, the greater the disparity in bottom chl *a* concentration between neap and spring tides. This tidal distinction was also observed in May 1995 in South Channel, but to a lesser extent apparently because of the marginal correlation on the spring tide (Table 3). It was not observed during the high discharge period in May 1997 or during the May 1992 bloom. It was also not observed during the

TABLE 3. Model I least squares statistics for linear regression analysis of chlorophyll *a* concentration (Y, μg l^{-1}) as a function of particulate organic carbon (POC) concentration (X, mg l^{-1}) in estuarine channels and Clatsop Spit, by tidal phase and date.

Location	Tidal Phase	Date	n	Regression	r
North Channel	Spring	May 1992	30	Y = 13.75X + 21.27	0.96
		May 1997	30	Y = 0.25X + 5.91	0.09
		July 1991, 1997; June 1999	87	Y = 7.13X + 7.56	0.86
	Neap	July 1991, 1997; June 1999	178	Y = 4.67X + 11.81	0.93
South Channel	Spring	May 1992	62	Y = 31.33X + 4.59	0.94
		May 1995	26	Y = 4.10X + 9.63	0.45
		May 1997	30	Y = 0.30X + 5.86	0.20
		July 1991, 1996, 1997	89	Y = 7.79X + 6.70	0.93
	Neap	May 1992	32	Y = 25.96X + 15.55	0.91
		June 1992	32	Y = 17.96X + 4.07	0.93
		May 1995	28	Y = 16.82X + 1.37	0.94
		May 1997	32	Y = 3.05X + 4.90	0.81
		July 1991, 1996, 1997	123	Y = 12.74X + 5.20	0.95
Clatsop Spit	Spring	May 1992	30	Y = 23.69X + 6.93	0.97
	Neap	May 1997	24	Y = 1.28X + 4.64	0.36
		July 1991, 1997; June 1999	53	Y = 9.65X + 5.71	0.81

combined summer months in North Channel (Fig. 4). The lack of neap versus spring tidal differences during these periods implied conditions were either unsuitable for operation of the conveyor belt process, or, perhaps more likely, the simple relationship between chl *a* and POC was an unsuitable tool for identification of the process during these periods. In no case was the neap versus spring tidal distinction for chl *a* versus POC concentration in summer (and May 1995) due to phased relationships with the diel cycle, a possibility suggested by Lucas and Cloern (2002) in a modeling study. When chl *a* as a function of POC was analyzed separately by day and night periods, no differences were found (not shown).

During the spring tide in the May 1992 bloom, the chl *a* to POC relationship at Clatsop Spit fell approximately midway between that for North and South Channels (Table 3, Fig. 4). The same is made on the neap tide during the summer months, but over a POC range greatly reduced from that in the channels (Table 3; but for clarity, not illustrated in Fig. 4). The estuary mouth at Clatsop Spit appeared to represent an approximately equal integration of chl *a* concentrations passing through the two estuarine channels, regardless of POC range or tidal stage.

Percent of Chl *a* and Chl *a*/POC

In the River

When the percentages of photosynthetically active chl *a* (% chl *a*) relative to the fluorometric measurement of total pigment *a* (i.e., chl *a* plus pheophytin *a*) were determined for all sampling dates at RM53, it was found that the values in May 1997 were no different from those in the summer months, even though most chl *a*/POC was below 10 μg mg^{-1} in May 1997 (Fig. 5). High river discharge, while acting to reduce concentration of total pigment *a*, did not reduce chl *a* and pheophytin *a* disproportionally. Only in May 1992 did % chl *a* in the river differ significantly from the other dates, registering 90–100% on most occasions, and indicating that the bloom was composed of almost pure photosynthetically active chl *a*.

In the Estuary and Estuary Mouth

Patterns of % chl *a* as a function of chl *a*/POC in the estuary were similar in both channels, but distinctly different from the pattern at RM53 (Fig. 5). As an aid for interpretation, these plots were annotated with horizontal lines representing one standard deviation around the RM53 mean for % chl *a*, and with vertical lines bracketing the chl *a*/POC range (10–30 μg mg^{-1}) that is considered reasonable for healthy phytoplankton assemblages (Eppley 1972; Welschmeyer and Lorenzen 1985; Harris 1986; Prahl et al. 1997). The chl *a*/POC ranges in May 1992, May 1997, and the summer months (plus May 1995) were fairly distinctly separated from one another, as noted in the river. Only the % chl *a* pattern changed markedly from that in the river. For comparative purposes, % chl *a* was treated as a linear function of chl *a*/POC between 10–30 μg mg^{-1}, even though the relationship is more than likely curvilinear between 0% and 100% chl *a* over the full range of chl *a*/POC. Within the 10–30 μg mg^{-1} range, there were no statistical differences among the four estuarine regression slopes ($p = 0.05$) for the summer (plus

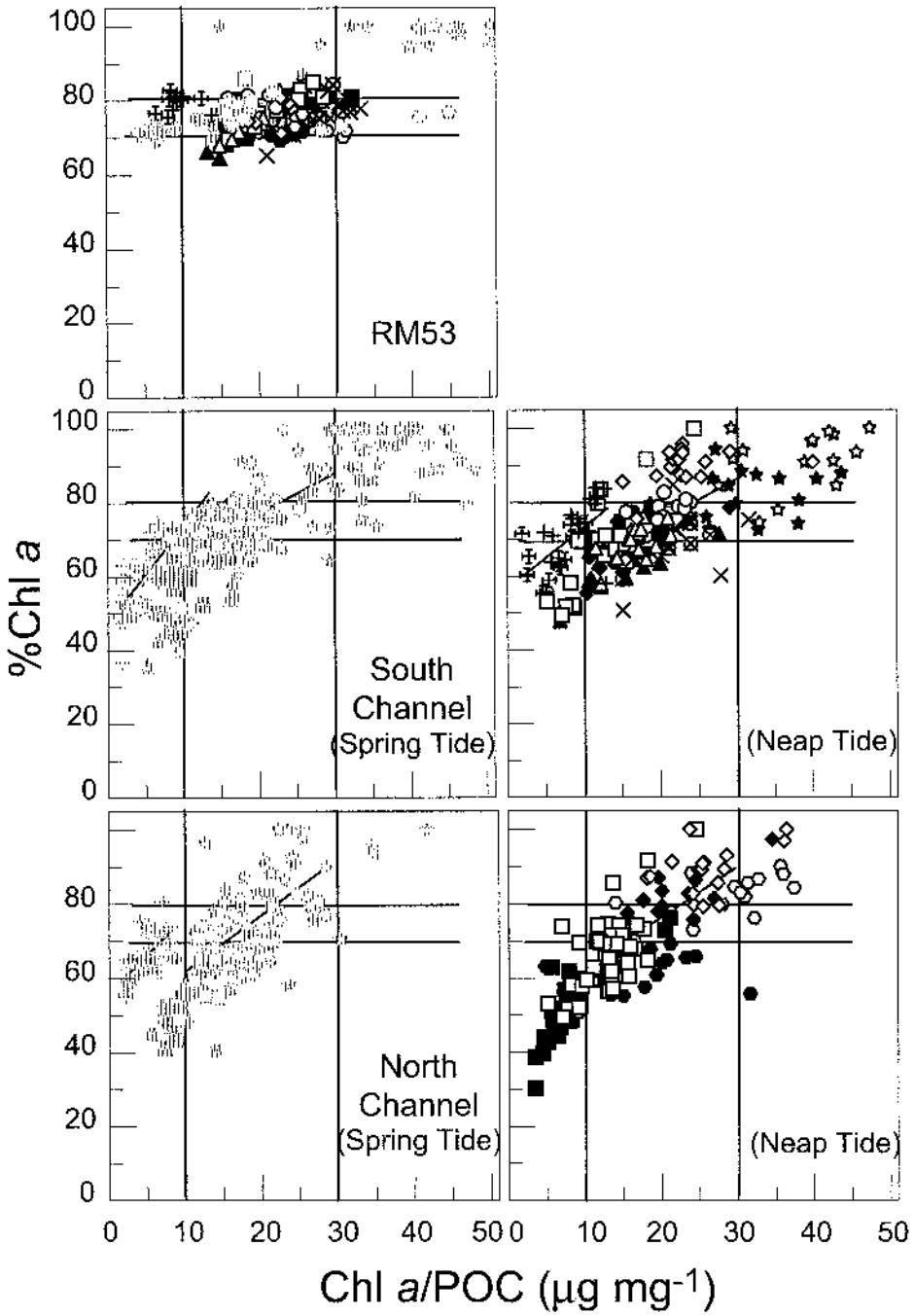

Fig. 5. Percentage of fluorometrically determined photosynthetically active chlorophyll *a* (% chl *a*) as a function of chl *a*/POC in the river (RM53), during spring and neap tides in South Channel, and during both tidal phases in North Channel. Horizontal lines in all plots represent one standard deviation around the mean for % chl *a* in the river (except May 1992), and vertical lines bracket the 10–30 µg •mg^{-1} range of chl *a*/POC considered to be a reasonable range for healthy phytoplankton; symbols as in Fig. 4.

May 1995) data. Some differences were noted in the distribution of the summer data when viewed by channel, sampling period, tidal phase, and sampling depth. Most of the surface samples on both neap and spring tides in both channels had % chl *a* signatures ≥ 70% (i.e., values equal to or above those delivered by the river), while most of the bottom values were equal to or below 70%. A major exception was the preponderance of surface values in July 1991 that were quite low and still within the

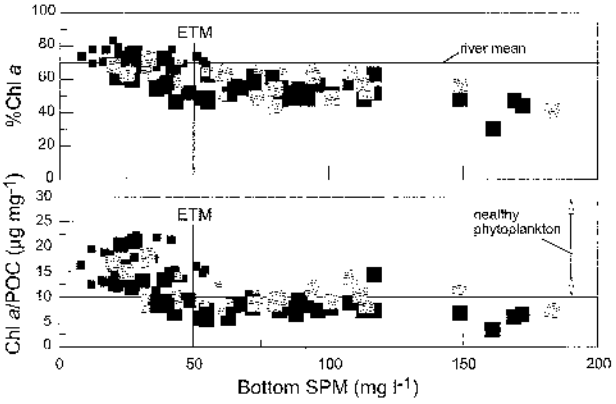

Fig. 6. chl *a*/POC and % chl *a* as functions of total suspended particulate matter (SPM) along both channel bottoms in July 1991. Particularly note the preponderance of low values during both neap (black) and spring (gray) tides in North Channel (large squares) relative to South Channel (small squares) during robust estuarine turbidity maxima (ETM).

10–30 μg mg^{-1} chl *a*/POC range, particularly in North Channel. When the chl *a*/POC range was extended to include values less than 10 μg mg^{-1}, both the surface and bottom % chl *a* in both channels in summer reached their lowest levels, with July 1991 values continuing to be prominent.

The low July 1991 values were brought about by the generation of robust ETM, particularly in North Channel, as shown in plots of bottom % chl *a* and bottom chl *a*/POC as functions of bottom SPM concentration (Fig. 6). Across the full range of SPM, there was no neap-spring differentiation in either % chl *a* or chl *a*/POC in North Channel in July 1991. SPM in South Channel seldom reached ETM concentrations on the neap tide, whereas on the spring tide over half of the SPM concentrations were in the ETM range. These different distributions of bottom SPM in South Channel yielded a mean (± 1 SD) chl *a*/POC concentration of 16.1 ± 3.1 μg mg^{-1} on the neap tide, but only 10.5 ± 2.4 μg mg^{-1} on the spring tide, irrespective of the flood-ebb status of the diel tidal cycle. Bottom % chl *a* showed no measurable difference, averaging 72.7 ± 3.9% on the neap tide and 73.7 ± 3.9% on the spring tide. Results similar to those for July 1991 in South Channel were observed for the remaining summer months in both channels. By combining the North and South Channel data in these remaining summer months, five other neap-spring chl *a*/POC series pairs were created (n = 152). Grand averages for these series were 17.6 ± 5.1 μg mg^{-1} on the neap tide and 11.3 ± 4.1 μg mg^{-1} on the spring tide, again independent of flood-ebb cycles. Although standard deviations were not small, the sense from these combined summer data was that particle settling tended to occur on the neap tide, and erosion of more chl *a*-poor POC occurred on the spring tide, just as in July 1991 in South Channel. Again, % chl *a* remained essentially unchanged, suggesting that the settled particles were recently settled surface phytoplankton with characteristically high chl *a* and low pheophytin *a* concentrations.

The high % chl *a* of the May 1992 bloom in the river at high chl *a*/POC levels carried through to both channels, although no neap data were available in North Channel during the bloom (Fig. 5). By inspection, no neap-spring differences were noted in bottom % chl *a* or chl *a*/POC in South Channel during this sampling period, and plots of values as functions of bottom SPM verified the lack of difference (not shown). It is hypothesized that under bloom conditions, settling of chlorophyll-rich particles would be greatest, and these particles would tend to concentrate throughout the course of the bloom as a near-bottom fluff layer. Resuspensions would bring some of this chl *a*-rich material back into the water column, and because the source of these resuspensions would mainly be the thick, recently settled fluff layer, the same material would be resuspended in both the smaller-amplitude range of neap tides and the greater-amplitude range of spring tides. The May 1992 South Channel patterns failed to show appropriate conditions for possible conveyor belt operation. This forecast is similar to that for July 1991 in North Channel even though the patterns for the two sampling periods must have developed differently; in July 1991 the bottom neap values apparently were reduced to the level of the spring tide values, whereas in May 1992 it is suggested that the bottom spring tide values were raised to the level of the neaps.

The % chl *a* distributions in May 1997 were offset from the summer patterns, particularly if the summer patterns were extrapolated downward into the 0–10 μg mg^{-1} chl *a*/POC range of values characteristic of May 1997 (Fig. 5). Phytoplankton assemblages in May 1997 presumably retained their high % chl *a* values in South Channel in the face of low chl a/POC because they lost less of their riverine signature during rapid transit through the estuary as a consequence of high rate of river discharge. Even with the low chl *a*/POC levels there was a tendency toward separation of bottom neap and spring tide values, although standard deviations about the means were relatively large (6.7 ± 2.7 μg mg^{-1} on the neap tide versus 3.1 ± 1.6 μg mg^{-1} on the spring tide). No North Channel neap-spring comparisons could be made in May 1997 because of the lack of data on the neap tide.

Distributions of % chl *a* as functions of chl *a*/POC at Clatsop Spit (not shown) were nearly identical to those in both channels, indicating no al-

teration in chlorophyll pigment composition as the two channels merged, but we had no neap-spring comparisons by sampling date.

Chl *a*/POC as a Function of Salinity

In the Estuary

In an attempt to further refine neap-spring comparisons, chl *a*/POC data were examined not by sampling date, but by surface and bottom salinity increments in both estuarine channels during each of the two tidal phases (Fig. 7). These analyses were done mainly to examine flood-ebb effects. It was immediately apparent that surface chl *a*/POC in summer (plus May 1995) varied by channel. At all times in South Channel, and during much of the time in North Channel, chl *a*/POC in surface waters was constrained within a narrow (0–5 psu) salinity range, with values on each sampling date highest in the lowest-salinity water and generally decreasing on exposure to increasing salinity. This loss was largely due to lysing of freshwater cells on encountering brackish water (Lara-Lara et al. 1990), probably with subsequent aggregation into larger, faster-settling flocs (Reed and Donovan 1994). These phenomena are well known in tidal estuaries elsewhere (Admiraal et al. 1985; Filardo and Dunstan 1985; Painchaud and Therriault 1985; Denant et al. 1991; Fisher et al. 1998). Only in North Channel in July 1991 was strong oceanic influence registered in surface waters of the estuary, with salinities reaching 27.5 psu on the neap tide. Very weak river discharge at this time (Tables 2 and 3) likely abetted this high-salinity intrusion with its attendant high chl *a*/POC signal. As this high chl *a*/POC mixed with the high chl *a*/POC of river origin during flood-ebb transitions, lysing of both freshwater and marine cells likely occurred in conjunction with surface injection of chl *a*-poor bottom material, to yield low chl *a*/POC at mid range salinities.

The greatest effect of diel tidal excursions on chl *a*/POC was expected to occur along the bottom of the estuary. To verify this expectation, data for chl *a*/POC in bottom waters in summer (plus May 1995) were binned within successive 2.5 psu salinity increments across the full salinity range (Fig. 7). This bin size was chosen because the initial 0–2.5 psu bin reasonably coincided with the salinity range associated with most surface samples, and successive 2.5 psu bins yielded good neap versus spring tidal comparisons of chl *a*/POC patterns across the complete salinity range. If a bin contained less than three chl *a*/POC values, the bin size was increased to 5 psu or, on occasion, a single value was plotted when an expanded bin size would have exceeded 5 psu. With this data handling approach, it became obvious that chl *a*/POC in bottom waters differed by tidal phase in South Channel. Means for neap tides did not vary greatly, as previously noted, and across the full salinity range fell only slightly lower than the mean for chl *a*/POC in the river. This observation strongly suggested a relatively benign particle trapping environment. Not only did spring tide values tend to average lower than those in the river and on the neap tide across the full salinity range, but they also showed a slightly concave distribution across the full salinity range, so that at mid range salinities there was clear distinction between neap and spring chl *a*/POC in bottom waters. This distribution confirmed that increasing tidal velocities began to suspend bottom sediments so that near the apex of tidal reversal (at mid range bottom salinities), sufficient chl *a*-poor POC was vertically entrained to depress the chl *a*/POC signature of the SPM. During ebb and flood slack periods (at the lowest and highest salinities, respectively), bottom chl *a*/POC on the spring tide approached that on the neap.

In North Channel, the similarly low neap and spring bottom chl *a*/POC values in July 1991 were spread across the full salinity range, the only time North Channel neap values were so distributed (Fig. 7). Excluding data from the July 1991 neap-tide series, a case can be made that the bottom chl *a*/POC distribution in North Channel on both neap and spring tides in summer followed the same patterns as those in South Channel, albeit with less data across the complete salinity range and with generally greater variability at high salinities about each chl *a*/POC mean. The spring tide series showed the same general concave distribution as in South Channel, for example, with lowest values at mid range salinities, little differentiation between the river and estuary in the 0–2.5 psu range, and little differentiation between the two tidal phases at the highest salinity. During neap tide, two high individual chl *a*/POC values at 2.5 and 15 psu were reasonably consistent with the river mean and with estuarine means at salinities greater than 20 psu, suggesting no change in bottom chl *a*/POC during most neap tides in North Channel across the full salinity range.

As in the summer months, both channels in May 1992 and May 1997 displayed highest surface chl *a*/POC in fresh water, which then predictably decreased as salinity increased on the flood tide (Fig. 7). Along both channel bottoms, the overall relationship between chl *a*/POC and salinity during the May 1992 bloom differed from patterns in summer. A rapid decline in chl *a*/POC on both neap and spring tides occurred as salinities increased from zero to about 5 psu, following the

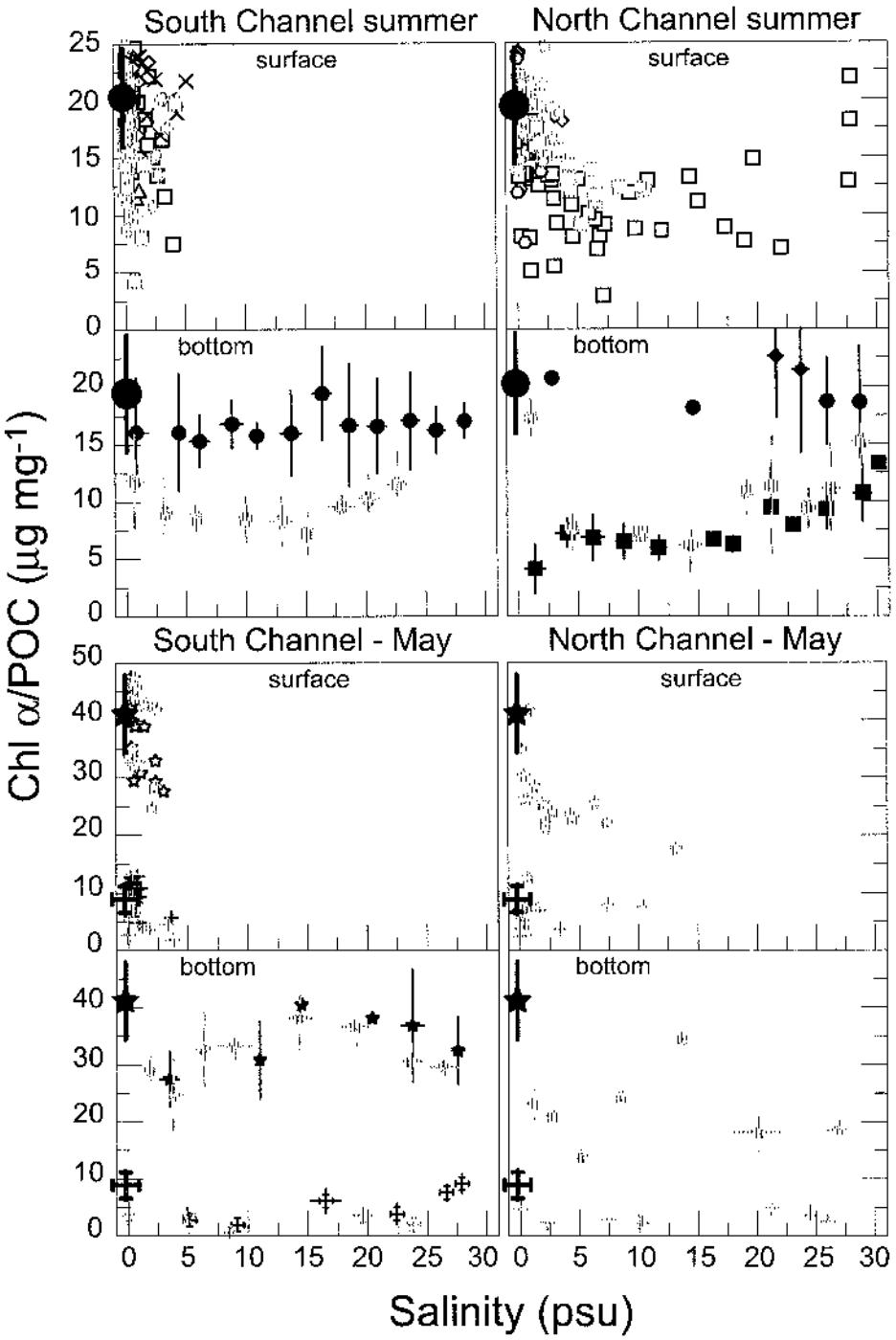

Fig. 7. Surface chl *a*/POC as a function of surface salinity during summer in South Channel and North Channel. Large filled circles are mean river chl *a*/POC (± 1 SD). Note the different July 1991 pattern (squares) in the two channels. Bottom chl *a*/POC means (± 1 SD) as a function of bottom salinity in 2.5 psu increments show distinct separation of neap and spring tide means during summer in South Channel, but not such a distinct separation in North Channel because of the preponderance of low chl *a*/POC on the neap tide in July 1991 (squares). Surface chl *a*/POC in May 1992 and May 1997, as functions of surface salinity, follow patterns similar to those during summer, but at chl *a*/POC levels both higher (May 1992) and lower (May 1997). Large filled stars and crosses are mean river chl *a*/POC (± 1 SD) for May 1992 and May 1997, respectively. Note that bottom chl *a*/POC means (± 1 SD) in May 1992 show a convex distribution with increasing salinity, and no distinction between tidal phases.

decline at the surface. This decline in low-salinity bottom water paralleled that in the summer months, particularly on the spring tide. As salinities increased beyond 5 psu, the relationship became convex during both tidal phases in South Channel, and possibly also during spring tide in North Channel. Maximum chl *a*/POC was reached at about 15 psu, near the time of maximum resuspension. This pattern mirrored that in summer months, particularly on the spring tides, and supported the notion of a thick bottom fluff layer enriched in chl *a* and resuspended maximally during each tidal reversal on both neap and spring tides.

In the Estuary Mouth

No neap-spring comparisons could be made for the mouth of the estuary because both tidal phases were never sampled at Clatsop Spit within the same time period. It was instructive to note how the chl *a*/POC patterns in the estuarine channels extended into the mouth. Surface chl *a*/POC at Clatsop Spit decreased as surface salinity increased from zero to 15 psu, mimicking both the levels and patterns of chl *a*/POC in both channels during summer and also during May 1992 and 1997 (not shown). nlike the channels, surface salinities at Clatsop Spit continued to increase beyond 15 psu during all sampling dates. Surface chl *a*/POC also began to increase in waters with salinity above 15 psu, eventually reaching levels comparable to those in the river. Bottom salinities extended to 30 psu at Clatsop Spit, and the chl *a*/POC signatures on all dates matched the bottom patterns in the estuarine channels on all dates except in North Channel on the neap tide in July 1991. High chl *a*/POC in high salinity surface and bottom water at Clatsop Spit indicated steady input of coastal phytoplankton assemblages to the mouth of the estuary. pwelling-induced phytoplankton blooms off the Oregon and Washington coasts are well documented (Anderson 1964; and many references in Pruter and Alverson 1972; Small and Menzies 1981; Landry and Hickey 1989), and conceivably some river-derived chl *a*/POC signal might also be returned to the estuary mouth from the Columbia outfall plume along the coast (Small and Ramberg 1971; Hickey et al. 2003). The lack of similarity between chl *a*/POC measurements in bottom waters from Clatsop Spit and North Channel in 1991 strongly suggested that the North Channel signal resulted almost entirely from large in situ resuspensions of chl *a*-poor POC at tidal reversals, not from direct coastal input.

Primary Prod ctivity Potential

In the R ver

Rate measurements, in the form of PPP, offered a possibility to examine neap-spring patterns beyond the concentration-based compositional properties chl *a*/POC and % chl *a*. In the river, PPP was linearly correlated (r = 0.91) over a 6–27 μg l^{-1} range of chl *a* (Fig. 8). We had no productivity measurements before 1995, so the potentials of the May 1992 bloom in the river could not be directly assessed. sing the regression equation from Fig. 8 and an average chl *a* concentration at RM53 of 50 μg l^{-1} (Fig. 4), we tentatively estimated a productivity potential of 180 μg C l^{-1} h^{-1}. This estimate must be viewed with caution, because the measurement and equation errors associated with high PPP levels during blooms in the Columbia River estuary are unknown (McArdle 2003).

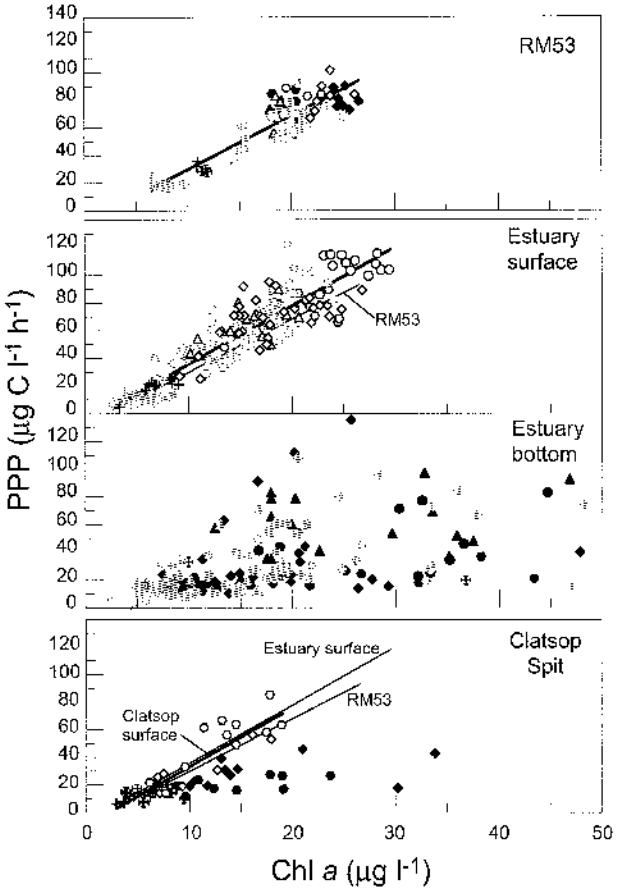

Fig. 8. Primary productivity potential (PPP) as a function of chl *a* concentration in the river, in the combined channels of the estuary at the surface and bottom, and at Clatsop Spit surface and bottom. No measurable change occurs in surface PPP from the river through the estuary and to Clatsop Spit. Great variability occurs in estuarine bottom PPP as particles are reworked and resuspended in estuarine turbidity maxima of different strengths, although there is no apparent neap-spring tide differentiation.

In the Estuary and Estuary Mouth

Productivity potential was also well correlated (r = 0.91) with chl *a* concentration in estuarine sur-

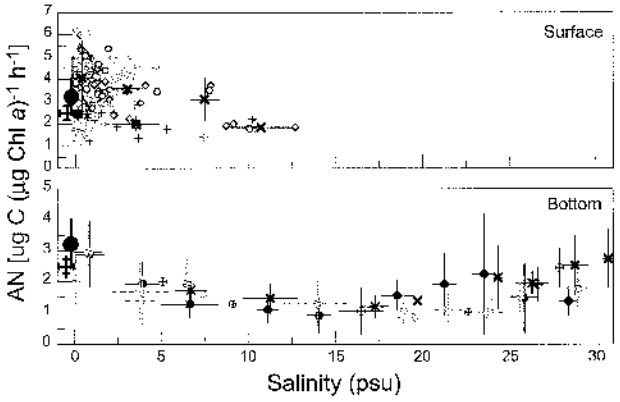

Fig. 9. Assimilation number (AN) as a function of surface salinity and bottom salinity for periods in which primary productivity data were available. Clatsop Spit AN (bold X) are plotted as means (± 1 SD) within 2.5 psu salinity increments in both surface and bottom, while combined channel means (± 1 SD) are in 2.5 psu increments only at the bottom. Large filled circles and crosses at zero salinity are, respectively, mean (± 1 SD) AN for summer (plus May 1995) and May 1997. Note the concave distribution of AN across the full salinity range, regardless of sampling date, sampling station, or tidal phase.

face waters, and the relationship was indistinguishable ($p = 0.05$) from that in the river (Fig. 8). No relationship existed in estuarine bottom waters. No general differences between channels or between tidal phases could be demonstrated for either depth. The extreme variability in bottom PPP, over a wide range of chl *a* concentrations, was likely dictated by the different strengths of the ETM and the compositional and age differences of the pigmented particles in the bottom POC reservoirs at the different sampling times. Coastal populations with high photosynthetic potential, brought into estuarine bottom waters on the flood tides and immediately sampled, would likely yield high PPP. Resuspension of older settled phytoplankton cells or allochthonous algal cells whose photosynthetic machinery would be photo-inhibited to varying degrees by the high light intensities that saturate surface populations, should yield a wide range of PPP.

The PPP relationship for surface waters at Clatsop Spit remained nearly identical to that in the estuary and the river, indicating a sustained surface potential controlled mainly by the fraction of chl *a* that never settled out of the surface (Fig. 9). Any resuspended material poor in PPP and at chl *a* levels greater than about 10 µg l^{-1} had to be in concentration low enough that it did not dilute the surface signal, a reasonable possibility during our neap-tide-only PPP sampling at Clatsop Spit.

Assimilation N mber

AN as a function of salinity was computed for RM53, Clatsop Spit, and both surface and bottom depths on neap and spring tides for North and South Channels combined (Fig. 9). Bottom data were binned by salinity increments as before, but only Clatsop Spit data (bold X) were similarly binned at the surface (principally to feature the standard deviations around each binned mean). Surface AN distributions did not differ significantly by tidal phase, and like surface chl *a*/POC distributions in summer, values tended to decrease with increasing salinity, eventually reaching lowest levels at mid range salinities. Mid range AN (2–4 µg C (mg chl *a*)$^{-1}$ h^{-1}) agreed with surface values measured in the estuary by Lara-Lara (1982) under natural light levels during spring and summer of 1980 and 1981.

Bottom AN distributions over the complete salinity range also did not differ by tidal phase (Fig. 9). The generally concave mean distributions were similar to the spring-tide chl *a*/POC pattern (Fig. 7), but not to the neap pattern (except for North Channel in July 1991). Notably, AN in bottom waters during May 1997 (crosses) followed the same concave pattern as in the summer months (Fig. 9). Depressed AN values on neap tides were attributed to selective particle trapping in which increasing numbers of riverborne phytoplankton cells began to lose photosynthetic potential and settle out on exposure to increasing salinity, and increasing numbers of marine phytoplankton cells did likewise on exposure to decreasing salinity. As there was no measurable change in chl *a*/POC (as well as % chl *a*) across the full salinity range on the neap (particularly in South Channel; Fig. 7), cells apparently lost their productive vigor, on average, faster than their chl *a* was transformed to pheophytin. On the spring tide, the similar bottom AN and chl *a*/POC patterns suggested that erosion of bottom material during tidal reversals always produced ETM characterized by low chl *a*/POC and low AN (Fig. 9).

Conclus ons

Evidence for operation of a particle conveyor belt process in the Columbia River estuary was observed during summer periods (plus May 1995) in South Channel. These were all periods of moderate river discharge to South Channel, suggesting that some balance between discharge and tidal incursion regulated ETM in such a way that selected characteristics of bottom particles could be differentiated on neap and spring tides. Differentiation could not be unequivocally demonstrated when river discharge was very high (May 1997) nor could it be demonstrated during large phytoplankton blooms (May 1992). nder appropriate conditions, generally higher values of chl *a*/POC were found in bottom waters during the lower-ampli-

tude neap tides, as opposed to the higher-amplitude spring tides. This temporal trend was attributed to increased settling of more chl *a*-rich POC from surface waters on the neap tides and resuspension of more chl *a*-poor POC on the spring tides; i.e., necessary conditions for operation of a conveyor belt process. These effects were less evident in the bottom waters of North Channel, becoming totally obscured during very weak river discharge in July 1991. North Channel is the region most directly exposed to ocean influence and most removed from direct river input. Both channels appeared to contribute equally to the chl *a*/POC signature of SPM in bottom waters at the mouth of the estuary, at least on the neap tide.

Operation of the particle conveyor belt process may have extended to bloom concentrations of chl *a*, but it is likely that settling out of copious quantities of chl *a*-rich bloom cells led to accumulation of a fluff layer at the sediment interface that was sufficiently thick to mask any % chl *a* or chl *a*/POC evidence for the process. nder these bloom conditions, ETM generated during tidal reversals would contain material from the same chl *a*-rich layer on both neap and spring tides.

Although patterns for chl *a*/POC showed differences in bottom waters on neap versus spring tides during summer (plus May 1995), the chl *a*-specific photosynthetic potential (AN) of phytoplankton stocks did not. The fact that both % chl *a* and chl *a*/POC in bottom waters remained high during neap tides but AN did not, suggested that river-borne phytoplankton began to rapidly lose their photosynthetic potential as they moved hydrodynamically from surface waters into bottom waters on the neap, but lost their chl *a* signature more slowly. Erosion of bottom materials on the spring tides injected into the water column biogeochemically aged chl *a*-poor POC with a greatly reduced photosynthetic potential. Within our suite of measurements, evidence for the conveyor belt process was mainly a function of chl *a*/POC and to a lesser degree of % chl *a*. It must be emphasized that even though distributions of chl *a*/POC and % chl *a* suggest the existence of a conveyor belt process, proof of this phenomenon's actual operation will require scalar flux measurements of these quantities in and out of the ETM on both neap and spring tides. Such measurements are not an insignificant undertaking (Jay et al. 1997), but one worth attempting in the future.

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