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A nitrogen budget for the Strait of Georgia, British Columbia, with emphasis on particulate nitrogen and dissolved inorganic nitrogen

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Abstract. Balanced budgets for dissolved inorganic N (DIN) and particulate N (PN) were constructed for the Strait of Georgia (SoG), a semi-enclosed coastal sea off the west coast of British Columbia, Canada. The dominant control on the N budget is the advection of DIN into and out of the SoG via Haro Strait. The annual influx of DIN by advection from the Pacific Ocean is 29 990 ($\pm 19\,500$) Mmol yr⁻¹. The DIN flux advected out of the SoG is 24 300 ($\pm 15\,500$) Mmol yr⁻¹. Most of the DIN that enters the SoG ($\sim 23\,400$ Mmol yr⁻¹) is converted to particulate N (PN) in situ by primary production. However, most of the PN produced by primary production is remineralized ($\sim 22\,000$ Mmol yr⁻¹) back into DIN within the top 50 m. The PN budget for the SoG was further constrained by nitrogen isotope composition ($\delta^{15}\text{N}$) that indicated regional differences in the source of PN. The southern strait receives a much higher proportion of terrigenous PN, relative to marine PN, than does the northern strait. The difference is due to the influence of the Fraser River, which discharges 1950 Mmol yr⁻¹ of PN and 1660 Mmol yr⁻¹ of DIN into the southern strait. The overall anthropogenic contribution of PN and DIN to the SoG is minimal relative to natural sources ($> 30\,000$ Mmol yr⁻¹). It is unlikely that the strait will be affected by eutrophication in the near future, although anthropogenic N sources, such as wastewater outfalls, may have significant local effects.

1 Introduction

The nitrogen (N) cycle is a crucial underpinning of marine biological productivity (Gruber and Galloway, 2008). During the past 150 yr, the global N cycle has been dramatically changed by human activities that have loaded reactive N into ecosystems in amounts that rival natural sources (Rabalais, 2002; Galloway et al., 2004). Two main anthropogenic sources, the burning of fossil fuels and the fixation of atmospheric N via the Haber–Bosch process to produce fertilizer, have clearly altered the terrestrial N cycle globally (Galloway et al., 2004). While most anthropogenic N stays in the terrestrial ecosystem, a small component makes its way into the ocean (Gruber and Galloway, 2008). Anthropogenic N loading to the natural environment occurs predominantly along populated and industrial coasts, where it may lead to eutrophication, harmful algal blooms, and hypoxia as shown by studies of the Adriatic Sea (Justic et al., 1987), the Baltic Sea (Andersson and Rydberg, 1988; Conley et al., 2009), the East China Sea (Chen et al., 2007) and the Gulf of Mexico (Turner and Rabalais, 1994). In effect, humans have initiated an ocean N fertilization experiment. Although the experiment has not yet affected the open ocean's N cycle, it is already affecting some of the ocean's most productive locations – continental shelves.

Coastal seas receive N both from the open sea and from land. They are already disproportionately productive for their size due to natural nutrient sources, but additional N added by human activity can put them at risk of eutrophication. The likelihood that eutrophication will occur in any given location depends on site-specific characteristics like the natural

supply of N, the rate of exchange with the open ocean, and other potential controls on primary production such as phosphorus and solar radiation (light). An important foundation to assess the risk posed by human-derived N loadings at any given location is the production of a N budget that puts local sources into context.

In a global context, N budgets for coastal systems have been well-studied, particularly on the east coast of North America (Nixon et al., 1995; Boynton et al., 1995; Castro et al., 2003; Schaeffer et al., 2007). To date, coastal N budgets only exist for a few locations on the west coast of North America. These include the following: Tomales Bay (Smith and Hollibaugh, 1997), Elkhorn Slough (Caffrey et al., 2003; Chapin et al., 2004), Yaquina Bay (Kaldy, 2006), the Gulf of California (Sanchez-Carrillo et al., 2009), San Francisco Bay (Smith and Hollibaugh, 2006), and the Salish Sea (including Juan de Fuca Strait, Strait of Georgia (SoG), and Puget Sound; Mackas and Harrison, 2007). Only two (of the aforementioned six) study locations, San Francisco Bay and the Salish Sea, are sites likely to be affected by elevated N loadings due to human activity. As such, the remaining four locations are not suitable proxies to compare and evaluate the influence of human-derived N. Further, it is difficult to compare the influence of human-derived N between San Francisco Bay and the Salish Sea since their basin shape (e.g., depth and length) and exchange rates with the open ocean are very different (Mackas and Harrison, 1997; Smith and Hollibaugh, 2006). Nonetheless, the available data presented in the aforementioned studies suggest that advected Pacific Ocean water is the dominant source of dissolved N to coastal systems on the west coast of North America. In addition, the available data suggest that eutrophication, due to increases in N loading from human activities, is unlikely to occur on the west coast of North America.

The Strait of Georgia, a semi-enclosed coastal sea off the south-west coast of Canada (Fig. 1), receives N both from an increasing local human population of over 2 million residents (Statistics Canada, 2013), and from nutrient-rich, upwelled Pacific Ocean water that enters the strait through highly mixed tidal passages (Thomson, 1981; LeBlond, 1983; Masson, 2006). A concern that N loadings from local agriculture and wastewater discharge might lead to eutrophication of the strait led Mackas and Harrison (1997) to develop a budget for dissolved inorganic N (DIN) using available data for Juan de Fuca Strait, Puget Sound and the southern Strait of Georgia. They concluded that eutrophication due to anthropogenic loadings was unlikely, partly because the overwhelming input of DIN from the Pacific Ocean produced surface waters replete in N and partly because local primary production was generally light-limited. However, there is also a strong particulate N (PN) component for the cycle in the Strait of Georgia. To date, we have lacked a complete understanding of how the PN and DIN components interact, and the relative importance of processes like burial in sediments, or consumption and recycling in the water column. Furthermore, the northern

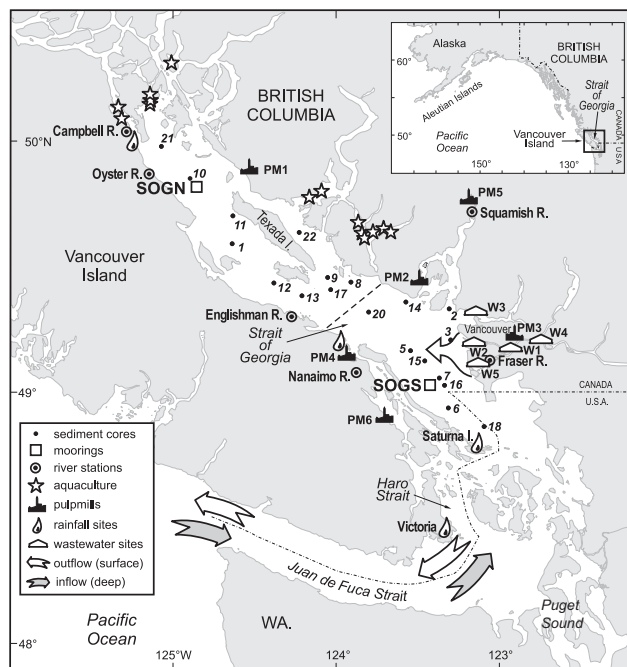


Fig. 1. Sampling locations in the Strait of Georgia for sediment box cores (small filled circle), sediment trap moorings samples (SOGS & SOGN; open square), river samples (large open circle surrounding small, filled, black circle), aquaculture (open star), pulp mills (factory), atmospheric sampling stations (raindrop), and wastewater facilities (structure). The exact latitudes and longitudes for the sampling locations of the sediment box cores are given in the Supplement Table S1, and all other sampling locations are provided in Supplement Table S2. Pulp mill locations are identified by PM # (PM1: Catalyst Paper; PM2: Port Mellon; PM3: New West Minister; PM4: Nanaimo; PM5: Squamish; and PM6: Crofton). Wastewater treatment plants are indicated by a W# (W1: Annacis Island; W2: Iona Island; W3: Lions Gate, W4: Northwest Langley; W5 Lulu Island). The dashed line denotes the boundary between the northern and southern SoG.

reaches of the Strait of Georgia, which contain roughly half of the surface area and volume for the entire strait, have been neglected.

Here, we present new data for N from river sampling, water-column profiles, vertical flux in sediment traps, and dated sediment cores. These data, together with data from other sources, are used to construct budgets for particulate and dissolved N for the whole Strait of Georgia while distinguishing between marine and terrigenous components. We further constrain the PN cycle using isotopic ($\delta^{15}\text{N}$) composition and discuss differences and connections between the northern and southern basins of the strait. Finally, we re-examine the potential for local human activities to produce eutrophic conditions within the Strait of Georgia.

2 Materials and methods

2.1 General approach

The N budget was constructed using a combination of newly collected data (sediment cores, sediment traps, and nutrient measurements in rivers and seawater), previously published values, and unpublished data (atmospheric, wastewater, pulp mill, riverine, aquaculture, and population density) obtained from various government agencies. The uncertainty associated with each estimate is expressed as the standard deviation unless otherwise indicated.

2.2 Sediment core data and the burial of total PN

2.2.1 Sample collection

Twenty sediment cores were collected throughout the Strait of Georgia between 2002 and 2007 (Fig. 1) using a box corer or Pedersen corer at water depths of 76 to 388 m (Supplement S1). Cores were sub-sectioned on board the ship into 1 cm slices for the top 10 cm, 2 cm slices for the 10–20 cm section of the core, and 5 cm slices for the remainder of the core (20 to \leq 50 cm). Each slice was homogenized in a glass jar with a stainless steel spatula and stored in darkness at -20°C prior to analysis. The sample collection, treatment, and analytical methods are detailed elsewhere (Johannessen et al., 2008).

2.2.2 Radioisotope analysis and sedimentation rate

A sub-sample from each depth interval was analyzed for ^{210}Pb and ^{226}Ra activity by Flett Research Ltd. (Winnipeg, Manitoba, Canada) following the procedures of Eakins and Morrison (1978) and Mathieu et al. (1988). Sufficient counts were accumulated to maintain counting errors less than 3%. Excess ^{210}Pb activity was calculated by subtracting the activity of ^{226}Ra . Sedimentation velocities (cm yr^{-1}) and sediment accumulation rates ($\text{g cm}^{-2}\text{yr}^{-1}$) for each sediment core were determined from the core profiles of ^{210}Pb , by solving advective–diffusive equations, as described by Johannessen et al. (2003).

To extrapolate sedimentation rates to the entire Strait of Georgia, the sediment accumulation rate for each core was assigned to the depositional portion of the surrounding area (Fig. 1), which was estimated based on grain-size distribution. Specifically, mud and silt were taken to indicate deposition, and rock, gravel or sand to indicate erosion, except on the Fraser delta, where sand actively accumulates (Hill et al., 2008).

2.2.3 Total PN and $\delta^{15}\text{N}$ analyses

Total PN was measured in all particulate samples (core sediments, filters, sediment trap samples) at the University of British Columbia using a Carlo Erba CHN analyzer, follow-

ing the procedure of Calvert et al. (1995). The analytical precision for this method was $\pm 3\%$.

The N isotope compositions were measured using a VG PRISM IRMS equipped with an inline Carlo Erba CHN analyzer. The $\delta^{15}\text{N}$ was calculated according to the following formula:

$$\delta^{15}\text{N} = 1000[(R_x - R_{\text{std}}) / R_{\text{std}}], \quad (1)$$

where R is the atomic ratio of heavy (^{15}N) and light (^{14}N) isotopes of N ($^{15}\text{N}/^{14}\text{N}$), x refers to the particulate samples and std is the atomic ratio of the heavy and light N isotopes of air. The N isotope composition is reported as $\delta^{15}\text{N}$ (‰), relative to air, with an analytical precision of 0.3 ‰.

2.2.4 Nitrogen sediment surface flux, burial flux and remineralization rates

The PN burial and remineralization rates in SoG sediments (Table 1) were calculated based on the methods described for organic carbon by Johannessen et al. (2003). Briefly, the burial flux for each core was calculated by multiplying the sediment accumulation rate (SAR, Table 1) by the concentration of PN ([PN]) in the deepest part of the core (Fig. 2). The surface flux was not calculated from the measured surface [PN] due to bio-mixing within the upper layers of the sediment cores. Instead we assumed that PN was converted to dissolved forms of N according to first-order kinetics, and thereby lost to the sediments. This loss was estimated by setting the integrated area under a theoretical exponential decay curve equal to the integrated total PN measured above the burial depth (the depth at which the [PN] becomes approximately constant). The rate of N remineralization for each core was calculated as the difference between the calculated surface flux and the burial flux. For reference, the in situ concentrations of N ([N]), surface flux, burial flux, and oxidation flux are shown graphically in Fig. 3.

2.3 Sediment trap data and total PN flux at 50 m

Total PN fluxes at 50 m were used to anchor the budget at mid-depth. Sinking particles were collected over 2008–2011 in the southern and northern Strait of Georgia (stations SOGS and SOGN; Fig. 1) using Baker sequential sediment traps (Baker et al., 1985) moored at 50 m depth. The cylindrical traps are 1 m high, with an internal diameter of 0.2 m, and are baffled at the top to reduce mixing (Johannessen et al., 2005). Samples were sieved at sea (500 μm mesh) to remove swimming zooplankton, and the $< 500 \mu\text{m}$ fraction was stored frozen for later analysis. Sediment trap flux and composition data are shown in Table 2. Annual fluxes of PN were calculated for the 50 m isobath using surface areas of 3975 km^2 and 3760 km^2 estimated for the southern and northern parts of the strait, respectively.

Table 1. Estimates of total PN fluxes derived from dated and modeled sediment box cores from the Strait of Georgia. The sediment accumulation rate is shown as SAR and PN concentration as [PN]. The depositional portion of the surrounding area, as described in Sect. 2.2.2, is denoted as “Area”. Collection date, location, station, longitude, latitude, and water depth are provided in the Supplement S1.

Station	Area (km ²)	SAR (g cm ⁻² yr ⁻¹)	[PN] (%)	PN flux – surface		PN flux – final burial		PN flux – remineralization	
				($\mu\text{mol cm}^{-2} \text{yr}^{-1}$)	(Mmol yr ⁻¹)	($\mu\text{mol cm}^{-2} \text{yr}^{-1}$)	(Mmol yr ⁻¹)	($\mu\text{mol cm}^{-2} \text{yr}^{-1}$)	(Mmol yr ⁻¹)
GVRD 1	352	0.08	0.49	27	95	23	82	4	13
GVRD 2	114	0.26	0.15	28	31	16	18	12	14
GVRD 3	195	1.30	0.12	109	213	73	143	36	70
GVRD 5	385	0.64	0.20	91	351	71	274	20	77
GVRD 6	529	2.70	0.17	319	1 689	243	1 285	76	404
GVRD 7	216	0.32	0.13	29	63	18	40	11	23
GVRD 8	250	0.10	0.24	17	43	12	29	6	14
GVRD 9	123	0.17	0.26	31	38	24	30	7	8
GVRD 10	212	0.05	0.43	15	33	12	26	3	7
GVRD 11	393	0.12	0.41	35	137	29	113	6	24
GVRD 12	219	0.12	0.33	28	62	24	53	4	9
GVRD 13	117	0.12	0.31	27	31	22	26	5	5
GVRD 14	571	0.23	0.21	35	200	23	129	12	71
GVRD 15	255	1.73	0.20	243	620	186	473	57	146
GVRD 16	179	0.98	0.18	126	225	104	186	22	39
GVRD 17	98	0.21	0.27	40	39	30	29	10	10
GVRD 18	437	0.30	0.09	18	80	14	61	4	19
GVRD 20	293	0.10	0.21	15	43	12	34	3	9
GVRD 21	307	0.11	0.45	35	107	21	64	14	43
GVRD 22	157	0.23	0.35	57	89	45	70	12	18
North	2225				676		523		153
South	3174				3515		2643		872
Total	5399				4191		3165		1025

2.4 Water data for DIN and total PN in the SoG and rivers

Seawater samples for DIN (only nitrate + nitrite measured for seawater) analysis were collected as a part of a field program established by the Department of Fisheries and Oceans and further described by Masson et al. (2006). Seawater DIN concentration data ([DIN]) were used in this study to calculate the advected DIN flux into and out of the SoG (see Sect. 2.6). Seawater samples were collected at 18 depths (0 m to >400 m below surface) from 20 stations extending from Juan de Fuca Strait to the northern SoG. Sampling was quarterly (April, June/July, August/September and December/January) for 10 yr (2001 to 2011). Samples were collected using Niskin bottles mounted on a rosette, subsampled into cleaned plastic tubes and frozen immediately. River samples were collected directly into plastic tubes from surface water away from the shore, and then immediately frozen. Samples were analyzed unfiltered using a Technicon AutoAnalyzer™ II at the Institute of Ocean Sciences, following the method described by Barwell-Clarke and Whitney (1996). The analytical precision for this method was $\pm 2\%$.

River samples were analyzed for [DIN] and [PN] between 2008 and 2009 for the Fraser, Squamish, Campbell, Oyster, Englishman and Nanaimo rivers (Fig. 1; Table 3). Additional river data were obtained from Environment Canada for the Fraser River (at Hope, 1979–2006 and at Gravesend Reach, 2008–2011) and Squamish River

(2005) (Environment Canada’s water quality website; Environment Canada, 2013b). The measured DIN concentrations were multiplied by each river’s discharge (monthly and annual), while the concentration of N on the filtered particles was multiplied by the river’s total particulate load to calculate the flux of PN (Table 3). River discharge data were provided by Environment Canada (2013b) for stations Englishman (08HB002), Fraser at Port Mann Pumping Station (08MH126) and Fraser at Hope (08MF005), Nanaimo (08HB034), Oyster (08HD011), Quinsam (08HD005, as a proxy for Campbell River), and Squamish near Brackendale (08GA022) (Fig. 1). Published values were used for the total annual particle load data for the Fraser (Thomas and Bendell-Young, 1999) and Squamish rivers (Hickin, 1989). The estimated particulate load for the other rivers was based on the remainder of a particulate budget constructed by Johannessen et al. (2003), the discharge rates of the rivers, and the known relationship between the particulate load and discharge rate for the Squamish River (Hickin, 1989).

2.5 Atmospheric deposition of N to the SoG

Precipitation, atmospheric concentrations and N flux data (Table 4) were provided by Environment Canada (2013a). Rainwater NO₃ and NH₄ concentrations ([NO₃] and [NH₄]) are available from several locations adjacent to the SoG (Campbell River, Nanaimo, Victoria, Saturna). Dry deposition (PN) data, available only for the Saturna Island site

Table 2. Flux-weighted average daily N and total and annual flux of sinking particles in the Strait of Georgia based on sediment traps deployed between 2008 and 2011. Sediment accumulation rates at the two sites are based on box cores collected at GVRD 16 and GVRD 10, respectively. The data are represented as weighted averages (range) or \pm standard error.

	SOGS – 50 m ^a		SOGN – 50 m ^b	
N daily flux (g m ⁻² d ⁻¹)	0.03	(0.002–0.20)	0.017	(0.0005–0.071)
[N] (%)	0.3	(0.10–2.2)	1.0	(0.06–3.1)
N annual flux (Mmol yr ⁻¹)	3020	(196–19 605)	1776	(52–7358)
Total, annual trap flux (g m ⁻² yr ⁻¹)	4122	(2102–7346)	701	(101–1140)
Sediment fluxes (g m ⁻² yr ⁻¹) at same location	9800		500	
$\delta^{15}\text{N}$ (‰)	6.6	± 0.2	8.2	± 0.2

^a Strait of Georgia south station (Fig. 1); ^b Strait of Georgia north station

Table 3. Discharge rates, $[\text{NO}_3] + [\text{NO}_2]$ and particulate nitrogen [PN], and calculated fluxes for DIN and PN from rivers entering the SoG. Numerical values for each flux are represented as the weighted-average (range). The range of values represents the min and max of the concentration data collected over a one-year period. The $\delta^{15}\text{N}$ composition is represented by the average \pm standard deviation. Data not available: na.

Station	Monthly discharge (m ³ s ⁻¹)	$[\text{NO}_3] + [\text{NO}_2]$ ($\mu\text{mol L}^{-1}$)	DIN (Mmol yr ⁻¹)	PN ($\mu\text{g L}^{-1}$)	PN (Mmol yr ⁻¹)	PN – $\delta^{15}\text{N}$ (‰)
Fraser	3620 (1780–8590)	4.5–11.2	1662 (1184–2252)	213–266	1954 (1737–2171)	1.7 \pm 0.2
Squamish	242 (87.5–492)	3.4–6.0	37 (21–41)	920–1210	561 (502–656)	–0.5 \pm 1.5
Campbell	8.54 (2.2–16.7)	2.9–5.2	0.8 (0.2–1.1)	1177–1279	22.7 (21.7–23.7)	3.4 \pm 0.3
Oyster	13.9 (3.1–18.2)	1.9–3.5	1.0 (0.6–1.2)	567–634	19.0 (18.0–19.9)	na
Englishman	13.1 (1.4–27.0)	2.1–3.4	0.7 (0.5–0.9)	680–727	20.8 (20.1–21.4)	na
Nanaimo	39.8 (5.9–76)	1.7–5.3	4.0 (1.0–6.8)	980–1072	92.0 (87.7–95.9)	na

(Fig. 1), were extrapolated to the whole Strait of Georgia. In support of this extrapolation, the [DIN] data for all of the sites adjacent to the SoG during the year 2003 are also provided in Table 4. There are clearly regional differences in the atmospheric [DIN] (34.7–89.7 Mmol yr⁻¹), but the values are all of the same order of magnitude and are negligible in the context of the whole N budget.

2.6 Advection

The advective transport of DIN into the SoG was determined based on salt balance, following the methodology described in detail by Gordon et al. (1996), and using the following equation:

$$V_{\text{In}} = \frac{S_{\text{O}} V_{\text{Fw}}}{S_{\text{In}} - S_{\text{O}}}, \quad (2)$$

where V_{In} and S_{In} are the volume flux and salinity of the deep shoreward estuarine flow into the SoG, V_{Fw} is the volume flux of freshwater to the SoG, and S_{O} is the salinity of the out-flowing surface layer. The volume flux of the estuarine circulation (V_{In}) was estimated to be $7.8 \times 10^9 \text{ m}^3 \text{ day}^{-1}$ ($\pm 5.0 \times 10^9 \text{ m}^3 \text{ day}^{-1}$) based on a freshwater volume flux (V_{Fw}) of $0.43 \times 10^9 \text{ m}^3 \text{ day}^{-1}$ ($\pm 0.01 \times 10^9 \text{ m}^3 \text{ day}^{-1}$), seaward salinity (S_{O}) of 31 (± 0.6) and shoreward salinity (S_{In}) of 32.7 (± 0.9). The freshwater flux was based on the Fraser

River contributing 73 % to the freshwater budget (Johannessen et al., 2003) at $3620 \text{ m}^3 \text{ day}^{-1}$. The input of DIN to the SoG is then simply calculated as

$$\text{DIN}_{\text{In}} \times V_{\text{In}}, \quad (3)$$

where DIN_{In} is the mean $[\text{NO}_3]$ ($29.8 \pm 4.2 \mu\text{mol L}^{-1}$, S.D.) of incoming deep water ($> 50 \text{ m}$ depth from the Juan de Fuca Strait). This provides an estimate for the advective transport of DIN into the Salish Sea ($85\,300 \pm 55\,700 \text{ Mmol yr}^{-1}$). According to Mackas and Harrison (1997), only 35 % of this advected dissolved NO_3 will reach the SoG.

Similarly, the advective transport of DIN out of the SoG is calculated as

$$V_{\text{Out}} = V_{\text{In}} + V_{\text{Fw}}, \quad (4)$$

where V_{In} and V_{Fw} are estimated based on Eqs. (2) and (3). V_{Out} was determined to be $8.3 \times 10^9 \text{ m}^3 \text{ day}^{-1}$ ($\pm 5.0 \times 10^9 \text{ m}^3 \text{ day}^{-1}$) using Eq. (4) and based on the estimates of V_{In} (Eq. 5). The output of DIN to the SoG is then simply calculated as

$$\text{DIN}_{\text{Out}} \times V_{\text{Out}}, \quad (5)$$

where N_{Out} is the mean $[\text{NO}_3]$ ($23.0 \pm 4.6 \mu\text{mol L}^{-1}$, S.D.) of outgoing surface water ($< 30 \text{ m}$ depth) from the Juan de Fuca Strait. This provides an estimate for the advective transport

Table 4. Atmospheric dissolved inorganic nitrogen concentration [DIN], particulate nitrogen concentration [PN], and total annual atmospheric deposition to SoG for years between 2002 and 2009 for Saturna Island and Vancouver Island stations (Environment Canada, 2013c). Data not available: na.

Station	Year	Rainfall (cm yr ⁻¹)	Dissolved (Mmol yr ⁻¹)		Particulate (Mmol yr ⁻¹)		Dissolved (Mmol yr ⁻¹)		Particulate (Mmol yr ⁻¹)		Total (Mmol yr ⁻¹)
			NH ₄	NO ₃	NH ₄	NO ₃	NH ₄ +NO ₃	NH ₄ +NO ₃	NH ₄ +NO ₃	NH ₄ +NO ₃	
Saturna Island	2002	60	30.8	55.0	8.6	14.5	85.8	23.1	108.9		
Saturna Island	2003	81	29.6	60.1	8.6	14.8	89.7	23.4	113.0		
Saturna Island	2004	79	37.5	78.6	8.8	14.0	116.1	22.8	138.9		
Saturna Island	2005	76	27.5	54.8	10.4	15.0	82.3	25.3	107.7		
Saturna Island	2006	88	32.0	65.2	6.0	12.5	97.2	18.5	115.7		
Saturna Island	2007	93	42.1	76.4	6.6	11.9	118.5	18.5	137.0		
Saturna Island	2009	81	29.7	54.1	na	na	83.8	na	> 83.8		
Campbell River	2003	46	30.1	50.0	na	na	80.1	na	> 80.1		
Nanaimo	2003	48	21.5	42.5	na	na	64.0	na	> 64.0		
Victoria	2003	41	9.0	25.6	na	na	34.7	na	> 34.7		

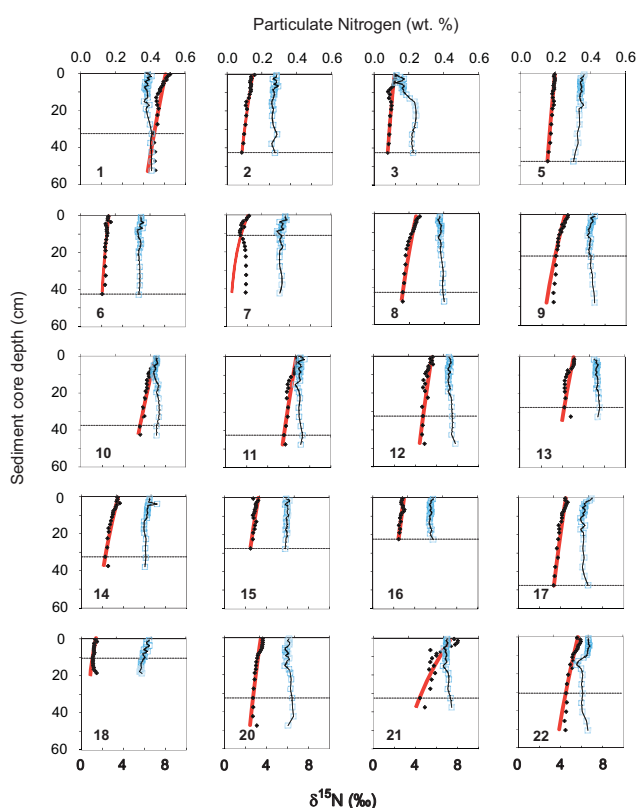


Fig. 2. Depth profiles for total particulate nitrogen concentration ([PN]) measured as weight % (wt. %, black solid diamond) and $\delta^{15}\text{N}$ composition of sediment (blue open square connected by solid black line) for all 20 box cores used in this study. The horizontal dashed line for each sediment profile represents the burial depth (the depth at which the [PN] becomes approximately constant). The solid red line that follows the [PN] depth profiles represents the theoretical exponential decay curve described in Sect. 2.2.4.

of DIN out of the Salish Sea ($69\,500 \pm 44\,200 \text{ Mmol yr}^{-1}$). However, only 35 % of this advected dissolved NO_3 is from the SoG (Mackas and Harrison, 1997).

2.7 Primary production in the SoG (conversion of DIN to PN)

Primary production (PP) converts DIN to marine particulate nitrogen (PN_{Mar}) within the water column of the SoG. The PP rate for the SoG was previously assessed by Harrison et al. (1983) to be $\sim 280 \text{ gC m}^{-2} \text{ yr}^{-1}$. This PP rate was converted to PN_{Mar} using a C:N ratio of 6.6:1 (Redfield et al., 1963). The calculated PN_{Mar} implies a total production of $23\,400 \text{ Mmol yr}^{-1} \text{ PN}_{\text{Mar}}$ for the entire strait assuming a surface area of 7735 km^2 . There are other estimates of PP for the Strait of Georgia that range from 120 to $>400 \text{ gC m}^{-2} \text{ yr}^{-1}$ (Parsons et al., 1970, 1980, 1981; Stockner et al., 1979; Pawlowicz et al., 2007). However, the particulate nitrogen budget could only be balanced if the PP rate was constrained to 260 to $300 \text{ gC m}^{-2} \text{ yr}^{-1}$ (see below for constraints in Sect. 3.1). The flux of PN_{Mar} at 50 m (the location of the sediment traps) and at the bottom (variable depths) as a result of this surface PP was estimated using an empirical relationship accounting for the remineralization of N with depth (Pace et al., 1987):

$$\text{PN}_{\text{Mar}} = 0.432(z^{-0.843} \cdot \text{pp}^{1.123}), \quad (6)$$

where z is the depth (m) in the water column.

2.8 Wastewater effluent

The input of total N (PN and DIN) from Vancouver wastewater into the SoG was estimated from the effluent loadings at the Lions Gate and Iona wastewater facilities (Table 5). Loadings for Annacis, Lulu and Northwest wastewater treatment facilities were not included in this budget, since these

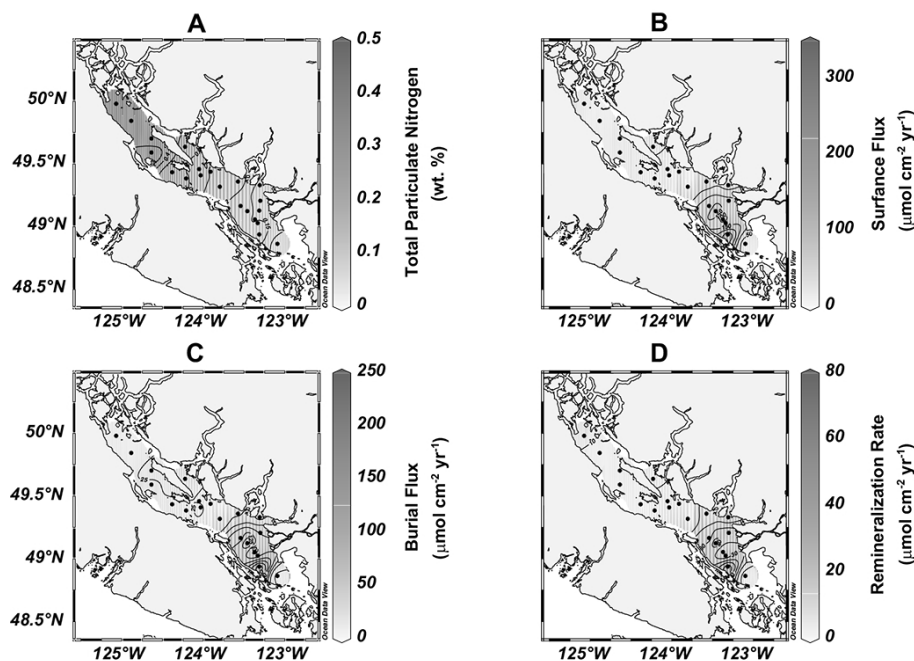


Fig. 3. A contour plot of sediment core data for the Strait of Georgia showing (a) total particulate nitrogen (PN) concentration (%) for surface sediment; (b) surface flux of PN ($50 \mu\text{mol cm}^{-2} \text{yr}^{-1}$ interval); (c) burial flux of PN; and (d) remineralization rate of PN.

facilities discharge into the Fraser River upstream of the sampling sites. Similarly, the mean input of total N (PN and DIN) from the 2 largest wastewater facilities on Vancouver Island (Clover Point and Macaulay Point) is less than 100Mmol yr^{-1} and was not included in this budget. These two Vancouver Island facilities are unlikely to influence the N flux to the Strait of Georgia, since they discharge into Juan de Fuca Strait and would be overwhelmed by the advected DIN flux.

2.9 Pulp mill effluent

Pulp mill effluent loading data were obtained from the Environmental Monitoring System Web Reporting website administered by the British Columbia Ministry of Environment (2013). The input of total N from pulp mill activities adjacent to the SoG was calculated from the reported effluent loadings for the facilities at Powell River (Catalyst Paper; $84 \pm 18 \mu\text{mol L}^{-1}$, $6.5 \times 10^{10} \text{L yr}^{-1}$; Table 5) and Port Mellon (Howe Sound Pulp and Paper; $56 \pm 18 \mu\text{mol L}^{-1}$, $2.9 \times 10^{10} \text{L yr}^{-1}$; Table 5). Although there are other active, or recently active, pulp mill operations adjacent to the SoG, including sites in New Westminster (Kruger Products LP), Nanaimo (Nanaimo Forest Products), Squamish (Western Woodfibre – closed) and Crofton (Catalyst), there is no requirement to collect DIN or PN data. Consequently, the pulp mills lacking PN and DIN data were assigned the average of the Powell River and Port Mellon fluxes.

2.10 Aquaculture

The maximum input of TN (PN + DIN) from aquaculture production affecting the SoG (Table 5) was calculated from the licensed total maximum production for every aquaculture facility located within or adjacent to the SoG (Department of Fisheries and Oceans, 2013). The license numbers reviewed include AQ 137, AQ 138, AQ 216, AQ 221, AQ 304, AQ 332, AQ 408, AQ 412, AQ 547, AQ 572, AQ 746, AQ 1697, AQ 1698 and AQ 1770. TN input to the surrounding environment was estimated to be $\sim 10\%$ (dissolved 6.7% and particulate 3.4%) of the total aquaculture production (79Mmol yr^{-1} ; Hall et al., 1992). Although the PN (26Mmol yr^{-1}) in aquaculture is not produced autochthonously, the fish meal used to feed fish would carry a marine signature ($\delta^{15}\text{N} = 10\%$; Sutherland et al., 2006). Therefore, we consider PN from aquaculture to be PN_{Mar} . Furthermore, we assume that the PN_{Mar} due to finfish aquaculture would remineralize to DIN with depth at the same rate as PN produced by PP (Sect. 2.7).

2.11 Isotopic mass balance

As an additional constraint of the PN budget, we weighted particulate fluxes by the associated stable N isotope compositions ($\delta^{15}\text{N}$) thereby ensuring that the system was isotopically balanced. In addition to our measured $\delta^{15}\text{N}$ composition of particulate matter from sediment trap and riverine samples, we were provided $\delta^{15}\text{N}$ composition data for the Iona wastewater treatment facility (2008–2012). We also incorporated published values available for pulp mill effluent

Table 5. Summary of dissolved inorganic nitrogen (DIN), particulate nitrogen (PN) and total N (TN) inputs to the SoG from terrigenous and marine sources. Data not available: na.

Source	DIN (Mmol yr ⁻¹)	DIN ^a (Mmol yr ⁻¹)	PN (Mmol yr ⁻¹)	TN (Mmol yr ⁻¹)
Terrigenous				
Fraser River	1662	1304	1954	3616
Other major rivers	37	na	716	753
Atmosphere	85	188 to 256	21.9	120
Pulp mills	20	na	5	25
Groundwater	130 to 391 ^a	130 to 391	na	na
Marine				
Advection via Haro Strait	29 900 ± 19 500	27 840	260	30 160 ± 19 500
Total PP		~ 25 100	23 400	23 400
Wastewater ^b	160 (133–188)	522 to 574	38 (37–39)	198 (170–227)
Aquaculture	53	na	26	79

^a Mackas and Harrison (1997) estimates; ^b data from Metro Vancouver, Iona outfall

(0 ‰; Oakes et al., 2010), atmospheric deposition (~ 6 ‰; Freyer, 1991; Garten, 1996; Elliott et al., 2009), and aquaculture (~ 10 ‰; Sutherland et al., 2006). We lacked data to do the same for DIN.

Estimates of $\delta^{15}\text{N}$ composition were determined for components of the PN_{Terr} and PN_{Mar} budgets that were not directly measured or assigned a value by the literature (e.g., PN_{Mar}). The $\delta^{15}\text{N}$ composition for these estimates was determined by mass balance. The constraints placed on these estimates of $\delta^{15}\text{N}$ composition are described in detail in Sect. 3.1.

2.12 Calculation of propagated uncertainty

The uncertainties (standard deviations) for budget terms determined from a calculation, such as the advective transport of DIN into and out of the SoG, were determined by propagating their uncertainties. Uncertainties were propagated onto the final calculated results using a linear approximation (a first-order Taylor series expansion). This is the standard method for propagating uncertainties through a function onto a derived quantity (e.g., Bevington and Robinson, 2003; JCGM, 2008).

3 Nitrogen budgets for the SoG

3.1 Constraints on the PN budget

We have created N budgets independently for the southern and northern basins of the strait (Fig. 4a) because the Fraser particles contribute a significant portion of bottom sediment only for the southern basin, south of Texada Island (Hill et al., 2008). Much of the Fraser River particulate material trav-

els southward in a plume extending from the delta, then enters Haro Strait where it is mixed throughout the water column by the strong tidal currents (Johannessen et al., 2005). A portion of this material returns to the strait at depth and travels northward near the bottom (Johannessen et al., 2005). The re-entry of PN by this pathway (1709 Mmol yr⁻¹) explains why the flux of particles to bottom sediment in the southern Strait of Georgia is so much higher than that captured by the 50 m sediment trap moored close to the center of the southern strait (Fig. 1). The PN_{Terr} associated with this returning transport, therefore, does not represent an exclusively external source, but rather a longer transport pathway for Fraser River particulate N with the addition of some material from outside.

The following constraints enabled the flux estimates of PN_{Terr} and PN_{Mar} to be determined within the water column and in sediment.

1. The $\delta^{15}\text{N}$ composition of PN_{Mar} must be heavier than PN_{Terr} (Sigman and Casciotti, 2001). The heaviest $\delta^{15}\text{N}$ signature for a mixture of PN_{Mar} and PN_{Terr} will reflect the lightest possible value for PN_{Mar} . Therefore, the $\delta^{15}\text{N}$ composition for PN_{Mar} must be greater than 8.2 ± 0.2 ‰ (standard error, $n = 75$); the flux-weighted average $\delta^{15}\text{N}$ composition of particulate samples from the SOGN sediment trap (Table 2).
2. The total PN flux to the sediment is 676 Mmol yr⁻¹ and 3515 Mmol yr⁻¹ for the northern and southern SoG, respectively (Table 1). Therefore, the PN_{Mar} flux to the sediment must be less than or equal to 676 Mmol yr⁻¹ and 3515 Mmol yr⁻¹ for the northern and southern SoG, respectively.
3. The $\delta^{15}\text{N}$ composition of the sediment is 6.9 ± 0.1 ‰ (standard error, $n = 10$) and 5.3 ‰ ± 0.1 ‰ (standard

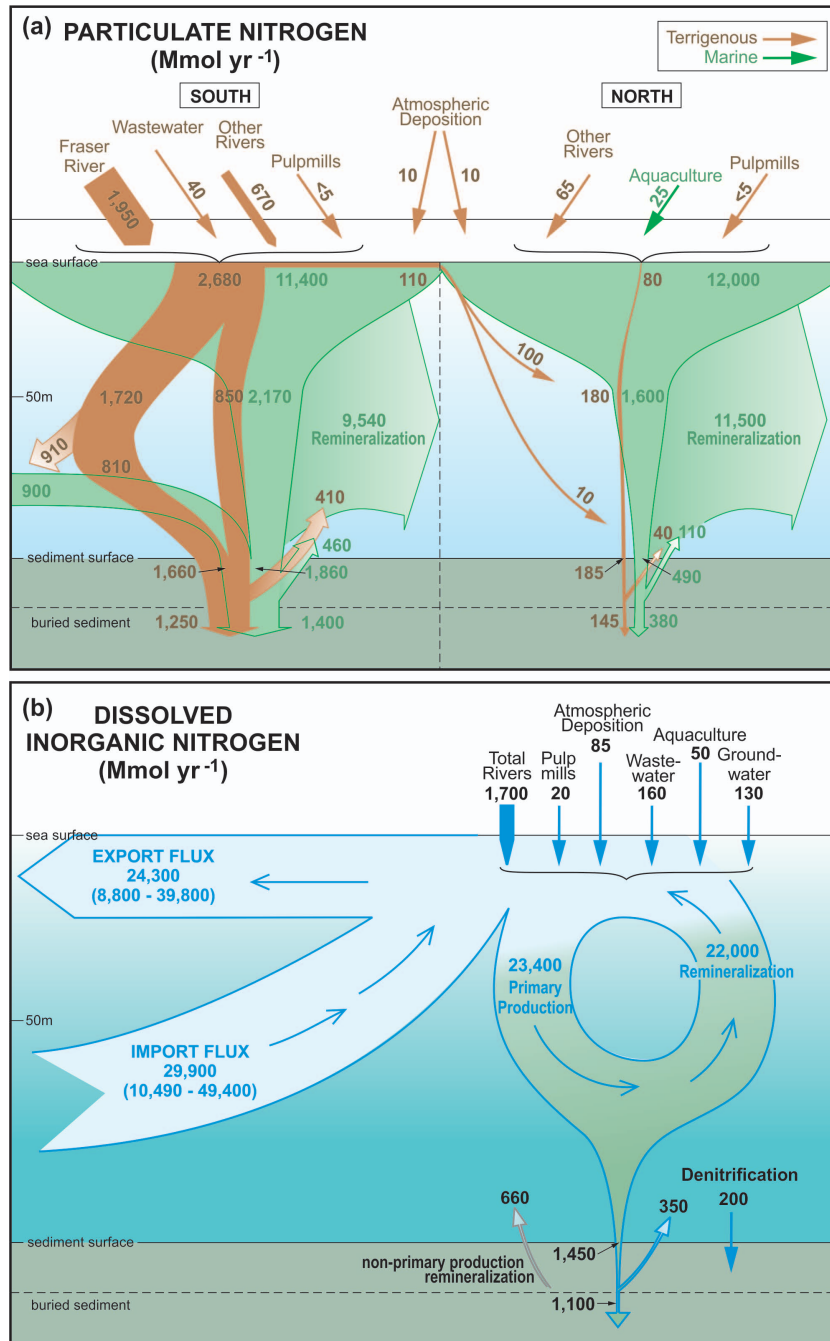


Fig. 4. Schematic diagrams of the nitrogen cycle in the Strait of Georgia (SoG) showing budgets for (a) particulate nitrogen and (b) dissolved inorganic nitrogen (DIN). Southern (left) and northern (right) regions of the strait are presented separately in (a) to highlight the large difference in the terrigenous particulate nitrogen contributions and sources between the two basins. Brown arrows indicate terrigenous particulate nitrogen (PN_{Terr}) fluxes and green arrows marine (PN_{Mar}) fluxes. Fading toward the head of an arrow indicates remineralization. Remineralization in this figure includes only the transformation of PN to DIN. Arrows show PN fluxes in $Mmol\ yr^{-1}$, as indicated by the number written beside the arrow, which also has width scaled according to the size of the flux. Fluxes of PN and DIN were estimated independently for several components within the budget including sources (e.g., rivers, wastewater, aquaculture, etc.), vertical PN flux (surface, 50 m depth) and fluxes into and out of sediments (flux to sediment surface and burial flux). For example, the net export of PN_{Terr} from southern to northern SoG is shown by the $110\ Mmol\ yr^{-1}$ pathway at the surface of the southern SoG. Of this, $100\ Mmol\ yr^{-1}$ enters the northern SoG above 50 m depth, as indicated by sediment traps, and the remaining $10\ Mmol\ yr^{-1}$ enters deeper water. Likewise, remineralization of $910\ Mmol\ yr^{-1}$ of PN_{Terr} within the shallower parts of southern SoG is partially offset by the import of $900\ Mmol\ yr^{-1}$ of PN_{Mar} from outside the southern boundary of the strait.

error, $n = 10$) for the northern and southern SoG, respectively, representing a mixture of PN_{Mar} and PN_{TERR} .

- The rate of PP for both the northern and southern SoG is the same. Although the rate of PP has only been measured in the southern SoG (Harrison et al., 1983), there is evidence that supports the assumption that PP rates are similar for both the northern and southern SoG including the following: (a) the concentration of chlorophyll (mg m^{-3}) is regionally equivalent on an annual, seasonal and depth-integrated basis (Masson and Pena, 2009); (b) water column profiles for NO_3 are regionally indistinguishable both annually and seasonally (Masson, 2006); (c) chlorophyll *a* concentrations, derived from satellite imagery, indicate that PP is equivalently active in the southern and northern SoG (Gower et al., 2013); (d) the PP rates are constrained by total organic matter and nitrogen and carbon isotope composition of particles collected in the sediment traps and sediment samples.
- The average rate of PP must be $280 \text{ gC m}^{-2} \text{ yr}^{-1}$ for the entire SoG, with a range of 260 to $300 \text{ gC m}^{-2} \text{ yr}^{-1}$. The PP rate cannot exceed $300 \text{ gC m}^{-2} \text{ yr}^{-1}$ based on constraints (1), (2) and (3) requiring PN_{Mar} to have a $\delta^{15}\text{N}$ composition greater than 8.2‰ . The total PN flux to the sediment in the northern SoG must be 676 Mmol yr^{-1} , and the $\delta^{15}\text{N}$ composition of the sediment must be $6.9 \pm 0.1\text{‰}$ in the northern SoG, respectively. A PP rate of $300 \text{ gC m}^{-2} \text{ yr}^{-1}$ yields 530 Mmol yr^{-1} of PN to the sediments in the southern SoG based on Eq. (6). This production rate leaves 176 Mmol yr^{-1} to carry a terrigenous $\delta^{15}\text{N}$ signature of $\sim 2.5\text{‰}$ (77 Mmol yr^{-1} at 3.7‰ – northern inputs; 74 Mmol yr^{-1} at 1.1‰ – advection of material from the southern SoG). A PP rate greater than $300 \text{ gC m}^{-2} \text{ yr}^{-1}$ would generate a $\delta^{15}\text{N}$ composition greater than 7.0‰ , violating constraint (3). Similarly, the PP rate cannot be less than $260 \text{ gC m}^{-2} \text{ yr}^{-1}$ because it disallows PN_{Mar} and PN_{TERR} to balance. Further, a rate of $260 \text{ gC m}^{-2} \text{ yr}^{-1}$ requires the $\delta^{15}\text{N}$ composition of PN_{Mar} to be assigned a value of 9‰ . The PN budget cannot be balanced with a PP rate of $260 \text{ gC m}^{-2} \text{ yr}^{-1}$ and a value $< 9\text{‰}$. Therefore, we conclude that PP is $280 \pm 20 \text{ gC m}^{-2} \text{ yr}^{-1}$.

Based upon the constraints mentioned above and end-member data for PN_{Mar} ($8.7 \pm 0.3\text{‰}$) from Johannessen et al. (2005), the $\delta^{15}\text{N}$ composition for PN_{Mar} was assigned a signature of 8.7‰ .

3.2 Particulate nitrogen

In situ PP is the largest term in the PN budget ($23\,400 \pm 1\,700 \text{ Mmol yr}^{-1}$; Table 5; Fig. 4). Most (94% , $22\,000 \text{ Mmol yr}^{-1}$) of this PN is remineralized to DIN within the SoG (Fig. 4). In situ PP effectively removes 720 Mmol yr^{-1} of N from the entire SoG as PN buried in the sediment. Most of the PN_{Mar} produced by phytoplankton is remineralized within the top 50 m of the water column, as evidenced by the small flux of sinking particles captured at 50 m in the sediment traps. Since there are no empirical relationships of PN_{TERR} remineralization in the literature, we assumed that loss of this material during its descent to the sediment was negligible. Consequently, the ratio of PN_{Mar} to PN_{TERR} declines with depth. By 50 m (sediment trap depth), the PN_{Mar} flux in the southern basin is of similar magnitude to that of PN_{TERR} (Fig. 4a), and in the southern basin of the strait, the burial in bottom sediments of PN_{TERR} exceeds that of PN_{Mar} (Fig. 4a). The change in the PN_{Mar} to PN_{TERR} with water column depth is also supported by the lighter $\delta^{15}\text{N}$ composition of the sediment relative to the sediment trap samples (see Sect. 3.3).

The southern SoG receives $\sim 2\,690 \text{ Mmol yr}^{-1}$ of PN_{TERR} , with most of this flux coming from rivers ($2\,627 \text{ Mmol yr}^{-1}$, Fig. 4a). The northern SoG, in contrast, receives much less PN_{TERR} (186 Mmol yr^{-1}) with 59% of this input (109 Mmol yr^{-1}) due to the advection of particles from the southern strait (Fig. 4a). The difference between the northern and southern basins in the strait reflects that most of the river-borne particles fall out of suspension close to the river mouths.

Atmospheric sources contribute $21.9 \text{ Mmol yr}^{-1}$ of PN_{TERR} , of which about two-thirds is in the form of NO_3 and the rest is NH_4 (Table 4a). We have assumed, following Mackas and Harrison (1997), that the PN_{TERR} flux from groundwater sources is insignificant ($< 1 \text{ Mmol yr}^{-1}$, Table 5).

Anthropogenic sources of PN represent $\sim 2\%$ of the PN_{TERR} flux from outside the strait, or $\sim 0.2\%$ of the total PN flux including marine and terrigenous sources. Municipal wastewater contributes 38 Mmol yr^{-1} of PN, while aquaculture contributes another 26 Mmol yr^{-1} (Table 5). The PN_{TERR} contribution by pulp mills (5 Mmol yr^{-1}) was estimated based on the ratio of DIN:PN observed by Oakes et al. (2010) for primary treated pulp-mill effluent. Most of the material dumped in the Strait of Georgia at ocean dumping sites is dredged from the Fraser River downstream of our sampling sites, and is consequently already included in the Fraser River N flux estimate. Some of the PN_{TERR} in the dredged material may be remobilized into the water during dumping, but is not likely to be significant and has been neglected in the budget.

The sinks for PN are burial in the sediment and remineralization from the sediment and within the water column. According to the Pace et al. (1987) model, 96% of the

PN_{Mar} ($\sim 22\,300\text{ Mmol yr}^{-1}$) produced by phytoplankton in the SoG would be remineralized by the time it descended to the seafloor. Since the small amount of PN_{Mar} from aquaculture (26 Mmol yr^{-1}) is also essentially of marine origin, we have assumed that it would remineralize at the same rate. Consequently, we estimate that $\sim 96\%$ of aquaculture-produced PN_{Mar} (25 Mmol yr^{-1}) is remineralized to DIN in the water column (Fig. 4a).

Overall, the fluxes of PN in SoG sediments are 4191 Mmol yr^{-1} to the sediment surface, 3165 Mmol yr^{-1} buried, and 1025 Mmol yr^{-1} is remineralized (Table 5, Fig. 3). Most (93% ; 2555 Mmol yr^{-1}) of the PN is buried in the southern strait (Fig. 4a). A quarter of the PN_{TERR} entering SoG sediments is converted to DIN (453 Mmol yr^{-1}), with 91% of the sediment-based remineralization occurring in the south (Fig. 4a). Similarly, a quarter of the PN_{Mar} entering SoG sediments is converted to DIN (572 Mmol yr^{-1}), with 81% occurring in the south (Fig. 4b). There is no quantifiable evidence that PN_{TERR} remineralization occurs within the water column, and therefore we have assumed that PN_{TERR} is not lost during the settling of particles to the sediment within the SoG.

3.3 The $\delta^{15}\text{N}$ composition as a constraint to the PN budget

Particulate organic matter reflects the $\delta^{15}\text{N}$ composition of its source, with terrigenous material having a lower signature than marine-derived material $\delta^{15}\text{N}$ composition (Peters et al., 1978). The isotopic composition of particles in the SoG aids in identifying processes and sources important to PN fluxes, particularly by providing a way to distinguish between marine and terrestrial contributions. A prior study of sinking particles collected in the southern SoG reported $\delta^{15}\text{N}$ compositions of $1.5\text{--}9\text{‰}$ (Johannessen et al., 2005). Johannessen et al. (2005) suggested that there was a seasonal effect on the $\delta^{15}\text{N}$ composition of particles related to the length of the food chain, with lower values observed during phytoplankton blooms (short food chain) than during the rest of the year (long food chain). Here, we have expanded the study area to include the northern Strait of Georgia, where there is a much smaller influence of PN_{TERR} from the Fraser River.

In the northern SoG, the remineralization rate of PN_{Mar} in the water column (using the Pace et al. (1987) model and a ratio of C : N of 6.6 : 1) suggests that PP would produce a flux of PN_{Mar} at 50 m of $\sim 1670\text{ Mmol yr}^{-1}$ based on an area of 3100 km^2 (average for burial and surface areas). The measured total PN flux based on the sediment trap at 50 m depth was determined to be 1776 Mmol yr^{-1} . Given marine and terrigenous end-member $\delta^{15}\text{N}$ values of 8.7‰ and 3.7‰ , respectively, the measured $\delta^{15}\text{N}$ composition of 8.2‰ in the 50 m trap particles implies that 92% of the PN flux at that depth was PN_{Mar} with a flux of 1634 Mmol yr^{-1} . The two separate determinations of PN_{Mar} flux at 50 m are encouragingly close, both indicating that the PN flux in the north-

ern SoG at 50 m below sea level is dominated by PN_{Mar} . It is important to note that the estimated proportion and flux of marine material would vary based on the assigned marine end-member $\delta^{15}\text{N}$ value of 8.7‰ (e.g., the PN_{Mar} flux would be greater if the $\delta^{15}\text{N}$ was lighter). A sensitivity analysis was performed, based on the constraints outlined in Sect. 3.1, to determine the upper and lower limits for this end-member value for both the northern and southern SoG. It was determined that $8.7 \pm 0.3\text{‰}$ was the most reasonable value for $\delta^{15}\text{N}$ composition of PN_{Mar} .

Similarly, in the southern SoG the PN_{Mar} flux calculated from the Pace et al. (1987) model was determined to be $\sim 2150\text{ Mmol yr}^{-1}$ (over 3500 km^2). The measured total PN flux based on the sediment trap at 50 m depth was determined to be 3020 Mmol yr^{-1} . Given marine and terrigenous end-member $\delta^{15}\text{N}$ values of 8.7‰ and 1.1‰ , respectively, the measured $\delta^{15}\text{N}$ composition of 6.6‰ in the 50 m trap particles implies that 72% of the PN at that depth was PN_{Mar} with a flux of 2174 Mmol yr^{-1} . Again, the two separate determinations of PN_{Mar} flux are very similar and imply that the PN flux in the southern SoG at 50 m depth is comprised mostly of PN_{Mar} , but with a much larger terrigenous component than in the north.

The $\delta^{15}\text{N}$ composition for river particles (PN_{TERR}) was low, relative to PN_{Mar} (-1‰ to 4‰), which is typical for material of terrigenous origin (Sigman and Casciotti, 2001). For the group of rivers discharging to the northern strait (Campbell, Oyster and Englishman rivers), only Campbell River particles were measured, yielding $\delta^{15}\text{N}$ values of $3.4 \pm 0.3\text{‰}$ (Table 3). For the southern strait, the average $\delta^{15}\text{N}$ composition of PN for the Fraser River, by far the largest contributor, was $1.7 \pm 0.2\text{‰}$, while the other measured rivers (Squamish and Nanaimo) yielded a flux-weighted composition of $-0.5 \pm 1.5\text{‰}$.

The measured $\delta^{15}\text{N}$ composition of sediment, prior to ultimate burial, in the northern SoG (6.9‰ , Fig. 2, Supplement Table S3) is equivalent to the value calculated from the proportional contributions of its marine and terrigenous sources (6.9‰). In the southern strait, the measured and calculated $\delta^{15}\text{N}$ of the sediment are also equivalent (5.3‰ , Fig. 2, Supplement Table S3). The measured $\delta^{15}\text{N}$ composition of sediment in the SoG after burial is effectively the same as in the surface with a signature of 7.0‰ in the north and 5.3‰ in the south (Fig. 2, Supplement Table S3).

The transport of PN_{TERR} material in the southern SoG is more complicated than in the north. There are few data available in the southernmost SoG. As described in Sect. 3.1, particle movement in the southern SoG is dynamic and complex (Johannessen et al., 2003). Therefore, the fluxes and movement of PN were estimated using the constraints described in Sect. 3.1 and by ensuring that isotopic mass balance was achieved in both the sediments and SOGS sediment trap. Sources within the SoG were sufficient to account for all of the PN_{TERR} . However, 64% of the material that enters the SoG (1724 Mmol yr^{-1} ; assigned $\delta^{15}\text{N}$ of 1.7‰) is transported

into Haro Strait. Within Haro Strait, 915 Mmol yr^{-1} of PN_{TERR} is lost and the remaining 809 Mmol yr^{-1} is mixed with an unknown source of PN_{MAR} (assigned $\delta^{15}\text{N}$ of 8.7‰) before it re-enters the SoG.

Unfortunately, the influence of this region adjacent to the Haro Strait is the least constrained component of the PN budget. Based on the constraints on the PN budget (Sect. 3.1), the incoming particulate material from Haro Strait ($1709 \text{ Mmol yr}^{-1}$) must carry a $\delta^{15}\text{N}$ composition of 5.4‰ . Effectively, there is no loss of PN from this budget. Therefore, the PN_{TERR} originating from the Fraser River (1.7‰) must mix with an external source that carries a $\delta^{15}\text{N}$ composition that is greater than $8.7 \pm 0.3\text{‰}$. To date, the particulate dynamics for this region is not completely understood, and there is a paucity of [PN] and $\delta^{15}\text{N}$ data along the west coast of North America. For regions adjacent to the SoG, such as Puget Sound (see Fig. 1), there is one study that examines the C : N ratio (Walsh et al., 2008) but does not provide [PN], one study (Hedges et al., 1988) that examines the [PN] of a small coastal bay, and one study (Brandenberger et al., 2011) that has both [PN] and $\delta^{15}\text{N}$ data from sediment cores sampled at two locations within Puget Sound. Based on the available data, the [PN] within Puget Sound is similar to the concentrations in the southern SoG (Fig. 2) and range from 0.1 to 0.29 wt. % (Hedges et al., 1988; Brandenberger et al., 2011). Similarly, the $\delta^{15}\text{N}$ composition of four sediment core samples (two sediment cores per sampling location) collected within the Puget Sound have analogous $\delta^{15}\text{N}$ compositions to most sediment cores evaluated for the SoG (e.g., GVRD sediment cores 1, 8, 9, 10, 11, 12, 13, 14, 17, 18, 20, 21, 22, see Fig. 2). The $\delta^{15}\text{N}$ composition of the four sediment cores from Puget Sound ranged from 6.0 to 6.8‰ at the sediment–water interface but, subsequently, became isotopically heavier (6.5–7.2‰) at depths greater than 50 cm (Brandenberger et al., 2011). It would be beneficial if another study focussing on the $\delta^{15}\text{N}$ composition of PN and DIN were to identify what processes are contributing to the mixed $\delta^{15}\text{N}$ signature coming from Haro Strait.

3.4 Dissolved inorganic nitrogen (DIN)

The largest source of DIN to the Strait of Georgia is advective transport into the strait from the Pacific Ocean, driven by estuarine circulation, which accounts for 85 % ($29\,900 \pm 19\,500 \text{ Mmol yr}^{-1}$) of the DIN flux (Table 5, Fig. 4b). The Fraser River is the next largest source of DIN ($1662 \text{ Mmol yr}^{-1}$) and contributes an order of magnitude less N than advective transport. Our estimate for Fraser River DIN flux ($1662 \text{ Mmol yr}^{-1}$) is averaged from data that range from 1184 to $2252 \text{ Mmol yr}^{-1}$, and is therefore equivalent to the $1304 \text{ Mmol yr}^{-1}$ estimated by Mackas and Harrison (1997). Remineralization of PN_{TERR} and PN_{MAR} in the surface sediment of the strait releases about two-thirds as much DIN as the Fraser River supplies ($1025 \text{ Mmol yr}^{-1}$), while the remaining streams flowing into the SoG contribute in aggregate

less than one-third of the Fraser River's DIN input, with individual fluxes of $0.7\text{--}37 \text{ Mmol yr}^{-1}$.

Atmospheric deposition, groundwater and anthropogenic sources represent negligible contributions to the DIN flux (Fig. 4b). The flux of N into the SoG from the atmosphere is primarily dissolved ($82.3\text{--}118.5 \text{ Mmol yr}^{-1}$; 76–87 % of the total atmospheric flux; Table 2), about two-thirds of which is NO_3 and one-third ammonia. For groundwater flux we have no direct measurements and have, therefore, used the Mackas and Harrison (1997) estimate of $5\text{--}15 \text{ tonnes day}^{-1}$ ($130\text{--}391 \text{ Mmol yr}^{-1}$).

Anthropogenic sources (wastewater, aquaculture and pulp mills) together contribute only $\sim 0.7\%$ of the total DIN flux into the Strait of Georgia (Table 5). Vancouver wastewater from the Iona and Lions Gate treatment facilities contributes 160 Mmol yr^{-1} of DIN. The Annacis, Lulu and Northwest wastewater treatment facilities discharge into the Fraser River just upstream from our sampling sites, and consequently their inputs are included in the estimated Fraser River N flux. The DIN flux from pulp mill activities into the SoG was estimated to be $\sim 20 \text{ Mmol yr}^{-1}$, based on the effluent loadings for the facilities at Powell River ($5.5 \pm 0.3 \text{ Mmol yr}^{-1}$) and Port Mellon ($1.6 \pm 0.2 \text{ Mmol yr}^{-1}$). No data for DIN were available for pulp mill operations in New Westminster, Nanaimo, Squamish or Crofton. Therefore, these locations were assumed to contribute a similar flux to Powell River and Port Mellon (average of the two fluxes: 3.6 Mmol yr^{-1}). The DIN flux from all the aquaculture sites in the Strait of Georgia is estimated at 53 Mmol yr^{-1} (Table 5), based on a maximum total aquaculture production of 22×10^3 metric tonnes of N over a 2 yr grow-out cycle.

The dominant sink for DIN (88 %, Fig. 4b) is advective export of surface water from the SoG to the Pacific Ocean as part of the estuarine circulation ($24\,300 \pm 15\,500 \text{ Mmol yr}^{-1}$; Fig. 4a). This value agrees with the Mackas and Harrison (1997) estimate of $19\,410 \text{ Mmol yr}^{-1}$. The uncertainties associated with the advective transports of DIN are large ($> 65\%$), mainly because of the temporal variation in salinity. Denitrification represents another potential sink for DIN. Given that the SoG is not anoxic, except within a small subsidiary fjord (Saanich Inlet), we assume that denitrification is restricted to basin sediments. Based on sediment denitrification rates for the Washington continental shelf ($50\text{--}110 \mu\text{mol N m}^{-2} \text{ d}^{-1}$; Engstrom et al., 2009), prorated to the area of accreting basin sediments in the SoG, denitrification appears to provide a negligible loss of ~ 99 to 217 Mmol yr^{-1} DIN.

The overall DIN flux into the SoG was estimated to be $\sim 32\,000 (\pm 19\,500) \text{ Mmol yr}^{-1}$ compared to an overall DIN flux out of $\sim 25\,600 (\pm 15\,500) \text{ Mmol yr}^{-1}$ (Fig. 4b). The DIN budget shows an excess source of $6400 \text{ Mmol yr}^{-1}$. The uncertainty associated with the exchange of DIN between the strait and the Pacific Ocean is easily large enough to account for the difference. Therefore, we intentionally have

not forced the sources and sinks to balance for the DIN budget.

3.5 Dissolved organic nitrogen (DON)

As in the case of the N budget by Mackas and Harrison (1997), we have not considered dissolved organic nitrogen (DON) in the dissolved component of the budget for the SoG predominantly because we lack a database to make a confident evaluation of its sources or its potential to support primary productivity. DON data are available for areas adjacent to the SoG, (Saanich Inlet, Stuart Island, Swanson Channel, Juan de Fuca Strait), but no data are available for the SoG (Wong et al., 2002). Recent papers have proposed that DON is a significant contributor to dissolved N in the ocean (e.g., Duan et al., 2010 (Gulf of Mexico); Letscher et al., 2013 (Arctic Ocean)) and may account for roughly 60% of the reactive nitrogen in the ocean (Voss and Hietanen, 2013). Based on this evidence, one might assume that exchanges of DON at Haro Strait would be similar to, and perhaps greater than, those of DIN. However, estimated DON fluxes would accrue an even larger uncertainty than the DIN fluxes given the paucity of local data. Likewise, rivers contribute DON in amounts that could be comparable to, or much greater than, DIN (Duan et al., 2010; Letscher et al., 2013; Guo et al., 2004; Dittmar et al., 2001). Even though DON concentrations in aquatic media appear to be significant, it remains very uncertain whether the DON is reactive on the timescales involved in the exchange of water in the SoG (weeks to months). Voss and Hietanen (2013) suggest that the DON may be relatively unreactive in surface waters, but that its breakdown could fuel primary production, especially in oligotrophic regions. The SoG would, accordingly, not be a favorable location for DON to play a large role in supporting primary production. Given these observations, we deem it premature to develop a DON budget at this time. However, the major implications of the DIN budget – that (1) natural supply of DIN is sufficient to support the measured primary production and consequent particle fluxes and (2) natural sources of DIN (ocean and rivers) far exceed anthropogenic sources – would, if anything, be strengthened by the addition of reactive DON to the budget.

4 Conclusions

The nitrogen cycle in the Strait of Georgia is driven primarily by the exchange of DIN with the Pacific Ocean through Haro Strait (Fig. 4). A large proportion of the DIN cycles through phytoplankton, entering the particulate cycle temporarily before being remineralized in the water column. Only a small proportion (12% for entire SoG) of the PN is ultimately buried in the bottom sediment. Since terrigenous material is re-mineralized less efficiently in the water column, the ratio of PN_{TERR} to PN_{MAR} is higher in accumulating sediment than

it is in surface water of the strait, meaning that the sediment record is not an accurate portrayal of PN cycling at the surface.

In contrast to DIN, both PN_{MAR} and PN_{TERR} owe their origins to external sources (inflow) or processes (e.g., PP) occurring within the strait. The strait appears to be a relatively homogeneous sea with respect to DIN, but the northern and southern basins differ in their sources and fluxes of PN_{TERR} , with only minimal communication of this component between basins. The far smaller flux of PN_{TERR} in the northern SoG means that its contribution to the sediment flux and burial is also smaller both quantitatively and in proportion to PN_{MAR} .

The ratio of DIN to PN is high in the Fraser River relative to that of the other, smaller rivers that are more typical streams in western Canada (Seitzinger et al., 2002). Seitzinger et al. (2002) state that a high DIN:PN ratio is a sign of anthropogenic activity. This interpretation is consistent with the large urban population in the Fraser River drainage basin (2.3 million; Statistics Canada, 2013) and the use of much of the flat area between Hope and the strait for agriculture compared with the relatively pristine drainage basins of the other rivers.

Within the Strait of Georgia, anthropogenic N fluxes are negligible for both PN and DIN compared to the natural cycle, which is supported by nutrient-rich water from the Pacific Ocean entrained into the strait through estuarine circulation. It is likely, however, that local effects occur near outfalls or at aquaculture sites, one clear example being at the core 3 site where surface sediments record a change in $\delta^{15}\text{N}$ values reflecting the installation of a nearby deep-water outfall (Macdonald et al., 2008). If present circumstances favoring light limitation of phytoplankton in the strait were relieved by a change in stratification due to a change in the Fraser River discharge (Morrison et al., 2002; Masson and Pena, 2009), anthropogenic loadings of N might then contribute to higher productivities. Otherwise, there is little potential for human activities to release sufficient nitrogen to lead to eutrophication.

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