

Appendix 3: Characterizing nutrient loadings and transformations/losses through mass balance

Prepared by:

Emily Novick, Rusty Holleman and David Senn

San Francisco Estuary Institute
Richmond, CA 94804

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3.1 Introduction

3.1.1 Motivation

The Sacramento-San Joaquin Delta receives high nutrient loads, mainly from wastewater and agriculture, which travel along a series of channels and shallow islands, and ultimately are delivered to downstream subembayments of San Francisco Bay. Initial investigations of water quality data suggest significant transformations or losses of nutrients in the Delta, but there has been limited systematic study of this to date. A detailed study of nutrient processing was needed to quantify the relative importance of nutrient transformation, removal and uptake within the Delta, which has bearing on nutrient loads delivered downstream to Suisun Bay and the rest of the San Francisco Bay. Understanding these processes is important to provide a baseline before planned wastewater treatment upgrades take effect in 2020.

3.1.2 Goals

The goal of this study was to characterize nitrogen transformations and losses within the Delta through large-scale mass balances for the Delta and Suisun Bay. The specific goals of this effort were to:

1. Estimate nitrogen transformation on a whole-Delta scale
2. Identify transformative “hot spots” within the Delta by performing smaller-scale mass balances
3. To the extent possible, use isotope or water quality data to identify the dominant processes in the “hot spot” regions identified in the mass balance

3.2 Methods

3.2.1 Box models for the Delta and Suisun Bay

A Delta-scale, one-box mass balance was calculated for ammonia (NH_4), nitrate and nitrite (abbreviated to NO_3), dissolved inorganic nitrogen (DIN , = $\text{NH}_4 + \text{NO}_3$) and total nitrogen (TN , = $\text{DIN} + \text{organic N}$), adopting a method used previously to estimate organic matter loads into and out of the delta (Jassby and Cloern, 2000) (Figure 3.1). This method makes use of flow data from the California Department of Water Resources (DWR) DAYFLOW program and DWR monthly water quality data to estimate loads into the Delta, out of the Delta to water exports and out of the Delta to Suisun Bay. When available, the analysis included internal loads from wastewater treatment plants (also known as publicly owned treatment works, POTWs) that discharge within the Delta or from internal agricultural returns. The mass balances were calculated for summer months (June to October), when transformations are expected to be the greatest and when lower flows create conditions that are closer to steady-state. While the Jassby and Cloern (2000) mass balances did not include Suisun Bay, we also were interested in the fate of nutrients once they entered this region. Therefore, a similar one-box model for Suisun Bay was developed that included loads from the Delta, wastewater treatment plant loads to Suisun Bay and exports to San Pablo Bay.

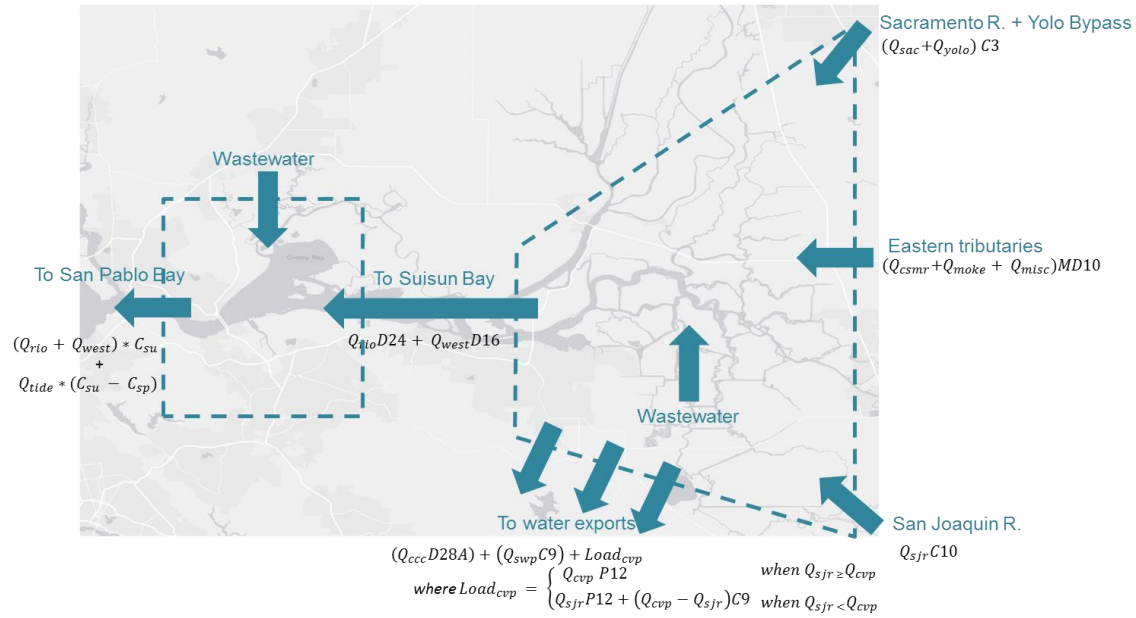


Figure 3.1 Schematic for Delta and Suisun Bay mass balances. For the first period modeled (1975-1995), Delta POTW loads were not included and the Suisun Bay model was not performed, both due to limited data availability. For the second period modeled (2006-2011), we included large Delta POTWs (City of Stockton and City of Tracy) as well as performed the mass balance for Suisun Bay (including POTW discharges from Central Contra Costa Sanitation District, Delta Diablo Sanitation District and Fairfield Suisun Sanitation District). In both cases, loads from Sacramento Regional Sanitation District were accounted for by water quality monitoring at station C3, downstream of the treatment outfall. Some of the water quality stations used in this model were discontinued in 1995. For the 2006-2011 model, new stations were substituted for the discontinued stations (see Table 3.1 for details). For both periods, there was insufficient data to include agricultural withdrawals and returns in the mass balances, but output from the Delta Simulation Model (DSM2) suggests that withdrawals and returns are comparable across all N species considered and therefore do not affect the net balance (see Table 3.2). For both periods, the mass balances were calculated for the months of June-October.

Mass balances were calculated for two periods: 1975-1995 and 2006-2011. The first period was chosen because some of the stations used in this approach were discontinued after 1995. The second period was chosen to represent more recent conditions because nutrient loads into the Delta changed between 1995 and 2005, mainly due to changes in wastewater treatment loads at Sacramento Regional Sanitation District (Sac Regional). During the first period (1975-1995), there was insufficient data to estimate direct POTW loads within the Delta. Similarly, the Suisun Bay mass balance covered only the period 2006-2011 because of limited historical POTW data availability.

For the 2006-2011 period, it was necessary to substitute newer water quality stations for old stations that were discontinued (Table 3.1). Substitutions occurred at 4 stations: two which were used to account for loads out of the Delta → water exports and two which were used to account for loads out of the Delta → Suisun Bay. A discussion of the uncertainty introduced by these substitutions is included in the results section. For one of the terms accounting for Delta → Suisun loads, we were able to substitute a co-located USGS station (USGS 657 for D24), and therefore we do not expect there to be much error introduced here. With the exception of 2006, loads estimated with D24/657 were comparable to or larger than loads estimated with D16, C9 and P12 combined, so any error at the three later stations will small by comparison. For example, substitutions for NH₄ had the highest % standard error, ranging from 40% at

D16 to 70% at P12. However, loads estimated using these stations are only about 1/5th of the total loads out of the Delta and even smaller in comparison to total loads *into* the Delta, so error is unlikely to have a large effect on our mass balance results. Standard error in regressions for other forms of N were smaller, about 20% on average.

Table 3.1 Regression equations used to estimate concentrations of NH₄, NO₃, and TN for the 2006-2001 period at water quality stations that were discontinued in 1995. Regressions were developed for the time period when all stations were monitored (1975-1995), with the exception of USGS station 657, which did not have a monitoring overlap with DWR station D24 but is located so close to D24 that a direct substitution is warranted. TN data is not available at USGS 657, so a regression was developed using DWR stations. DIN was estimated as NH₄ + NO₃, so a separate regression was not performed for that variable.

Discontinued station	Substitution used...					
	NH ₄	r ²	NO ₃	r ²	TN	r ²
C9	0.43 x D19 + 0.03	0.16	0.76 x D28A + 0.13	0.44	0.73 x D28A + 0.30	0.34
P12	0.84 x C10 + 0.04	0.48	0.70 x C10 + 0.15	0.63	0.64 x C10 + 0.57	0.66
D24	USGS station 657	--	USGS station 657	--	0.37 x D26 + 0.36 x D4 + 0.09	0.47
D16	0.49 x D19 + 0.02	0.23	0.64 x D19 + 0.25 x D4 + 0.03	0.91	0.35 x D19 + 0.41 x D26 + 0.12	0.69

As a way to assess the validity of our Delta-scale mass balance, we compared our results to a few other mass-balance, including a previous TN mass-balance for the Delta (TetraTech, 2006) and results from the DSM2 model.

3.2.2 Finer-scale mass balances

In order to explore in more detail the broad transformations identified in Section 3.2.1, we applied an existing a 1-D hydrodynamic and water quality model for the Delta (DSM2, QUAL) to quantify N transformations/losses on finer spatial-scales, identify zones of greatest and least transformation/losses, and develop mechanistic interpretations of N transformations/losses. Details of DSM2 and QUAL can be found in Appendix 6. Output from model, which has more than 100 nodes, was aggregated into 6 Delta regions and one additional region for Suisun Bay, and inputs, exports, and transformations/losses were quantified within each of those zones, and at the scale of the whole-Delta to provide an independent check on the 1-box model results. The DSM2 model is well-calibrated for flow, originating water source, and flow routing, because one of its applications is as a water resource management decision-support tool for the Delta¹. The water quality module includes a number of boundary condition inputs (flow, concentrations, etc.), and within the model domain is calibrated to nitrogen and phosphorous concentrations at a number of locations within the Delta (see Appendix 6). Although the water quality model has some limitations, it was the best available model and its capabilities are suitable for our goals of obtaining higher spatial and temporal resolution estimates of NH₄, NO₃ and Organic-N transformations and TN transport and net loads within and through the Delta. Nitrification is well-parameterized, and the model calibration for NH₄ concentrations is well-calibrated throughout the system. Water quality measurements used to calibrate and validate the model were generally monthly, although at some locations they were more frequent. Measurement stations are located throughout the Delta at hydrologically-important locations that also experience a diversity of nutrient conditions,

¹ <http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/models/dsm2/dsm2.cfm>

providing sufficient data resolution to support the regionally-aggregated estimates of transformation and loss rates.

Model skill was assessed for each modeled constituent at each location and also as a Delta-wide average with three statistical parameters (see Appendix 6 for details). For the purposes of this study, the most important model skill was Model Bias. NO₃ was generally overestimated by the model, Organic-N was underestimated while NH₃ had a mixed bias. On a Delta-wide basis, model bias was rated as very good for TN, NO₃, and Organic-N, and good for NH₃. Most stations had generally good Model Skill, although a couple of stations (P8 and MD10) had generally poor results for all statistical measures. Model skill for TN was calculated using the average of statistical measures for the three nitrogen-bearing constituents at each measurement location.

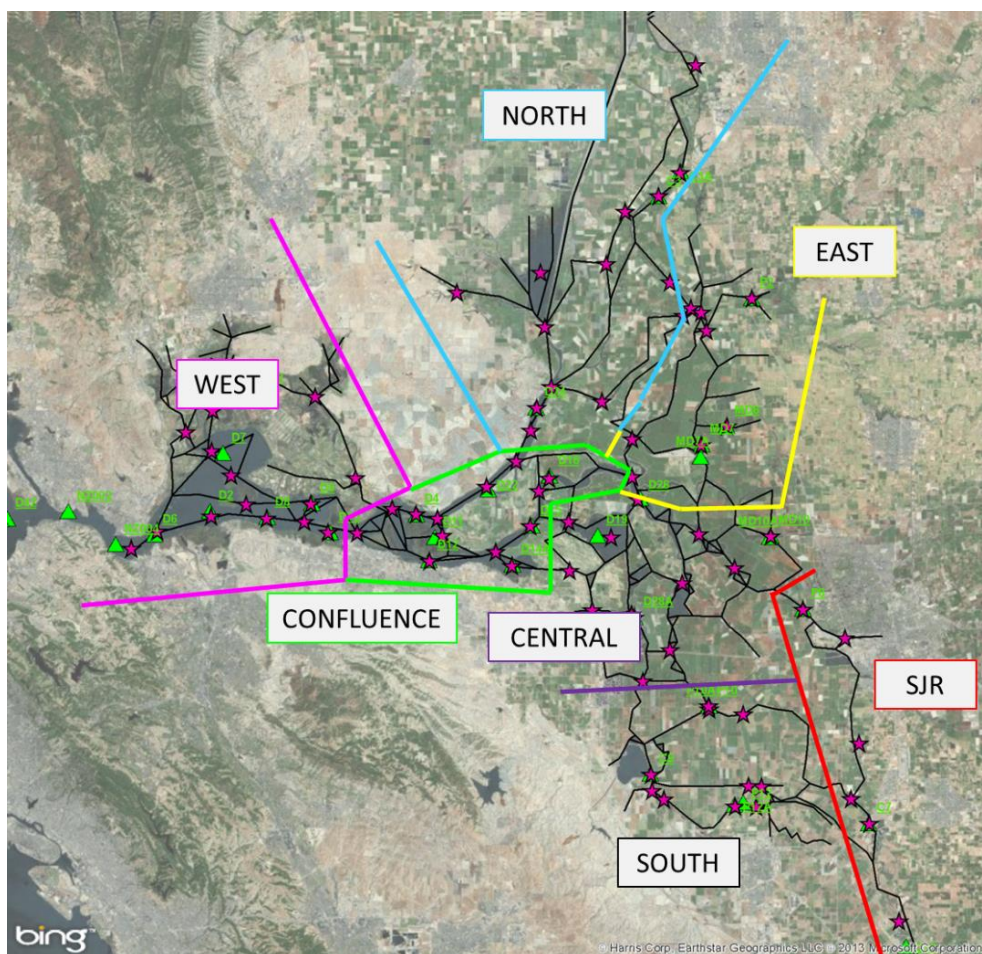


Figure 3.2 The six Delta subregions, plus Suisun Bay, used in the finer-scale mass balance. The DSM2 model grid is shown in black lines and stars and DWR monitoring stations are shown in green triangles

3.3 Results

3.3.1 Box models for Delta and Suisun Bay

1975-1995 Delta Mass Balance

For the period 1975-1995, the mass balance calculation shows NH₄ losses of approximately 70% and NO₃ gains of 15% in the Delta during summer months (Figure 3.3). It is likely that at least some of the NH₄ was simply being converted to NO₃, rather than truly lost from the system. For DIN and TN, the mass balance indicates 20% and 15% losses, respectively. Therefore, some of the nitrogen entering the Delta does seem to be permanently removed through denitrification or burial. There was insufficient data on wastewater dischargers for the 1975-1995 mass balance, and without this source term, losses have been underestimated.

The mass balance showed that, in 1975-1995, most of the NH₄ and the majority of TN entered the Delta via the Sacramento River and the majority of NO₃ entered the Delta via the San Joaquin River, likely due to agricultural activity in the watershed (Kratzer et al 2011). Loads from the Sacramento River accounted for 95%, 35%, 60% and 60% of the NH₄, NO₃, DIN and TN entering the Delta from the Central Valley, respectively (Figure 3.4). Large NH₄ discharges from the Sac Regional wastewater treatment plant just upstream of the Delta explain the NH₄ signal. NO₃ loads along the San Joaquin River are nearly twice those along the Sacramento River, despite having roughly 20% of the flow, due to high NO₃ concentrations in agricultural runoff in this region. Despite the difference in dominant form (NH₄ vs NO₃), about 60% of the nitrogen loading from both the Sacramento River and the San Joaquin River was in inorganic form.

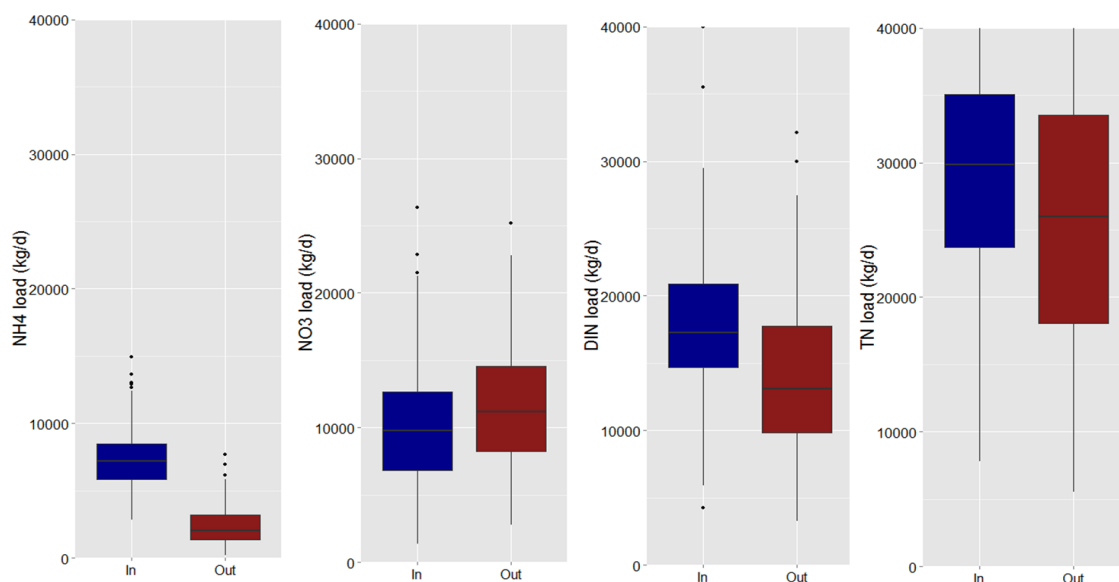


Figure 3.3 Summer (Jun-Oct) Delta-scale mass balance results (loads into and out of the Delta) for NH₄, NO₃, DIN and TN for the period 1975-1995. Boxplots show the median and 25th/75th percentile, and the whiskers extend to 1.5x the interquartile range.

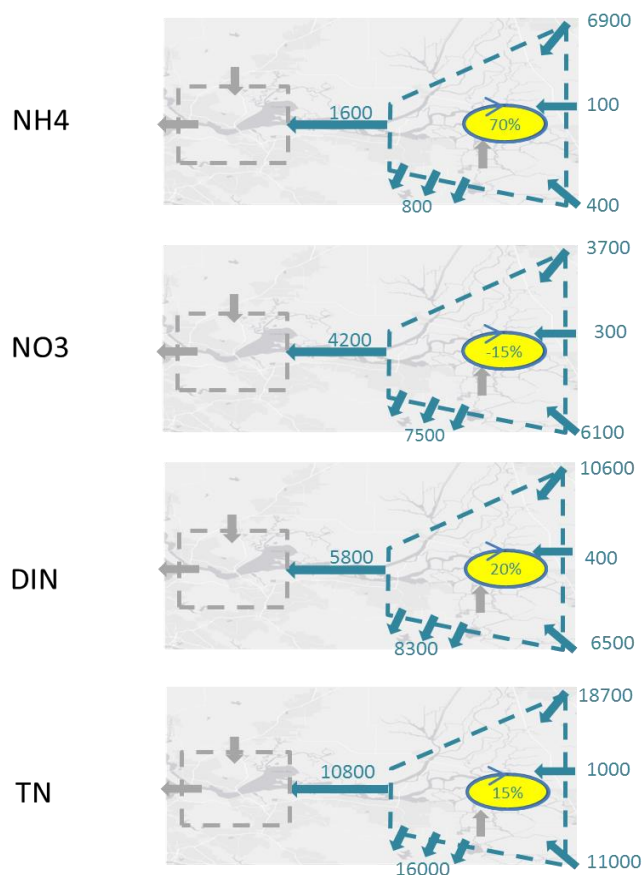


Figure 3.4 Summer (Jun-Oct) Delta-scale mass balance results for NH₄, NO₃, DIN and TN for the period 1975-1995, by component. POTW loads to the Delta were not estimated for this period due to limited data availability, nor were losses in Suisun Bay. All loads are kg-N/d. Negative loss of NO₃ suggests NO₃ production, from the transformation of NH₄ to NO₃.

2006-2011 Delta Mass Balance

The Delta-scale mass balance was repeated for 2006-2011 to understand more recent conditions. Nutrient loading to the Delta changed considerably between 1995 and 2005, due mainly to increases in Sac Regional discharges (Jassby 2008). Also, data on wastewater discharges into the Delta were more available during this period which allowed these terms to be included in the mass balance. Similarly, data on wastewater discharges to Suisun Bay were also available during this period so a 1-box model for Suisun Bay was added into the mass balance.

Mass balance results in the Delta for 2006-2011 were generally consistent with those from 1975-1995 on a percentage loss basis (Figures 3.5, 3.6). NH₄, NO₃, DIN and TN were lost from the system on the order of about 65%, 5%, 30% and 25%, respectively (compared to 70%, 20% and 15% from 1975-1995) and loads into the Delta were still approximately 60% inorganic along all inputs. Unlike the period 1975-1995, NO₃ was practically unchanged in the Delta. Across all nutrient forms, there was about a 20-25% increase in loads into the Delta from 1975-1995 to 2006-2011. This was mainly along the Sacramento River reach (Jassby 2008). TN loads actually went down along the San Joaquin River, but because of the large increase in TN loads along the Sacramento River, overall TN loads into the Delta were still larger.

Loads out of the Delta also increased across all nutrient forms in this recent period (compared with 1975-1995), though more so for NH₄ than DIN or TN.

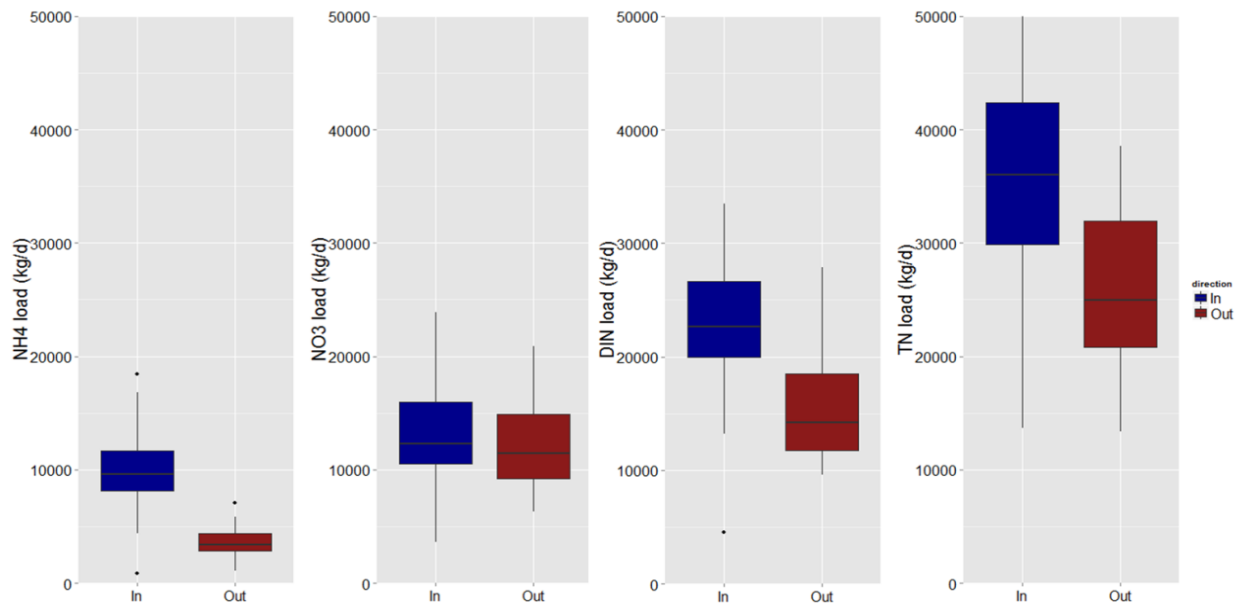


Figure 3.5 Summer (Jun-Oct) Delta-scale mass balance results (loads into and out of the Delta) for NH₄, NO₃, DIN and TN for the period 2006-2011. Boxplots show the median and 25th/75th percentile, and the whiskers extend to 1.5x the interquartile range. Mass balance calculations for Suisun Bay are not included in this graph. They are shown in figures 3.6 and 3.7

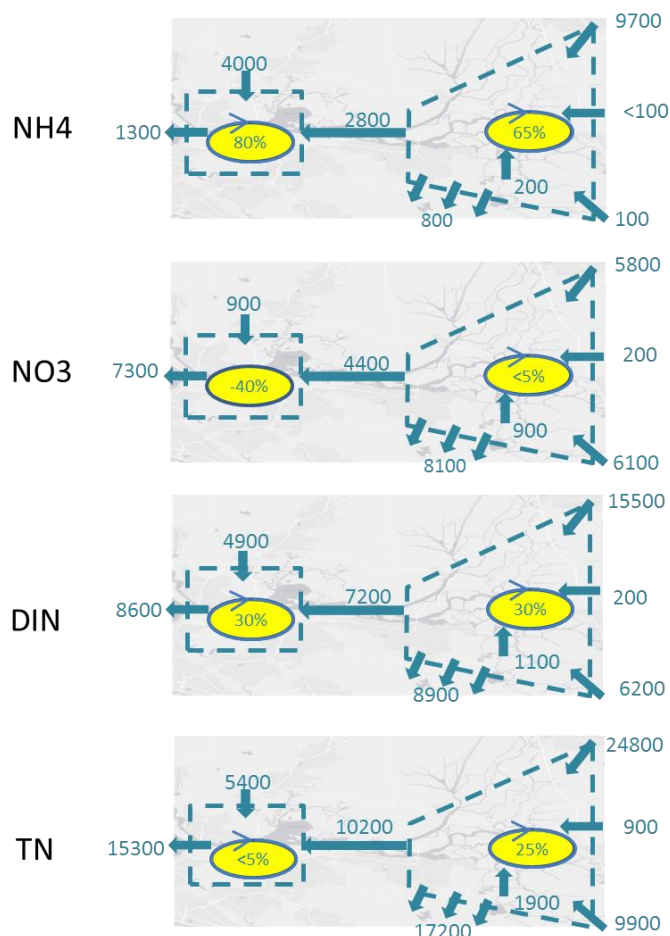


Figure 3.6 Summer (Jun-Oct) Delta-scale mass balance results for NH₄, NO₃, DIN and TN for the period 2006-2011, by component. All loads are kg-N/d. Negative loss of NO₃ in Suisun Bay indicates production of NO₃ from the transformation of NH₄ to NO₃.

The period 2006-2011 consisted of two years of above-average flows (WY 2007 and WY 2011). It was hypothesized that the rate of nutrient transformations in the Delta would be lower during these high flow years as compared to average or below average flow years due to decreased residence time. The average loads into and out of the Delta during these different flow conditions are summarized in Table 3.2. The results support the original hypothesis of decreased transformation rates during high flow years. While loads into the Delta were lower during average or low-flow years, mass N lost was still greater across all N species considered. (Table 3.2).

Table 3.2 Comparison of nitrogen losses in the Delta between high flow years (2007, 2011) and low flow years (2006, 2008, 2009, 2010). All loads are in units of kg-N/d. Loads in and loads out of the Delta are averages for the years indicated. Differences in mass balances for Suisun Bay were not considered here

	High flow years				Average/low flow years			
	Loads in	Loads out	Mass loss	% loss	Loads in	Loads out	Mass loss	% loss
NH ₄	10700	4700	6000	55%	9600	3100	6500	70%
NO ₃	14900	15100	-200 (gain)	-1% (gain)	11900	11300	600	5%
DIN	25600	19900	5700	20%	21500	14400	6200	35%
TN	39700	32700	7000	15%	36200	24800	11400	30%

As mentioned above, some of the stations used by Jassby and Cloern (2000) were discontinued in 1995. In order to continue to use this approach past this point, some estimates of water quality concentration needed to be made (Table 3.1). Substitutions occurred at 4 stations: two which were used to account for loads out of the Delta → water exports and two which were used to account for loads out of the Delta → Suisun Bay. A discussion of the uncertainty introduced by these substitutions is included in the results section. For one of the terms accounting for Delta → Suisun loads, we were able to substitute a co-located USGS station (USGS 657 for D24), and therefore we do not expect there to be much error introduced here. With the exception of 2006, loads estimated with D24/657 were comparable to or larger than loads estimated with D16, C9 and P12 combined, so any error at the three later stations will small by comparison. For example, substitutions for NH₄ had the highest % standard error, ranging from 40% at D16 to 70% at P12. However, loads estimated using these stations are only about 1/5th of the total loads out of the Delta and even smaller in comparison to total loads *into* the Delta, so error is unlikely to have a large effect our mass balance results. Standard error in regressions for other forms of N were smaller, about 20% on average.

2006-2011 Suisun Bay Mass Balance

For the 2006-2011 time period, there was sufficient wastewater data in Suisun Bay (Central Contra Costa Sanitary District, Delta Diablo Sanitary District, Fairfield-Suisun Sanitary District) to also perform a rough mass balance for Suisun Bay (Figure 3.7). The mass balance indicates substantial losses of NH₄ and DIN (80% and 30%, respectively), a modest increase in NO₃ (40%), but very little TN loss (<5%).

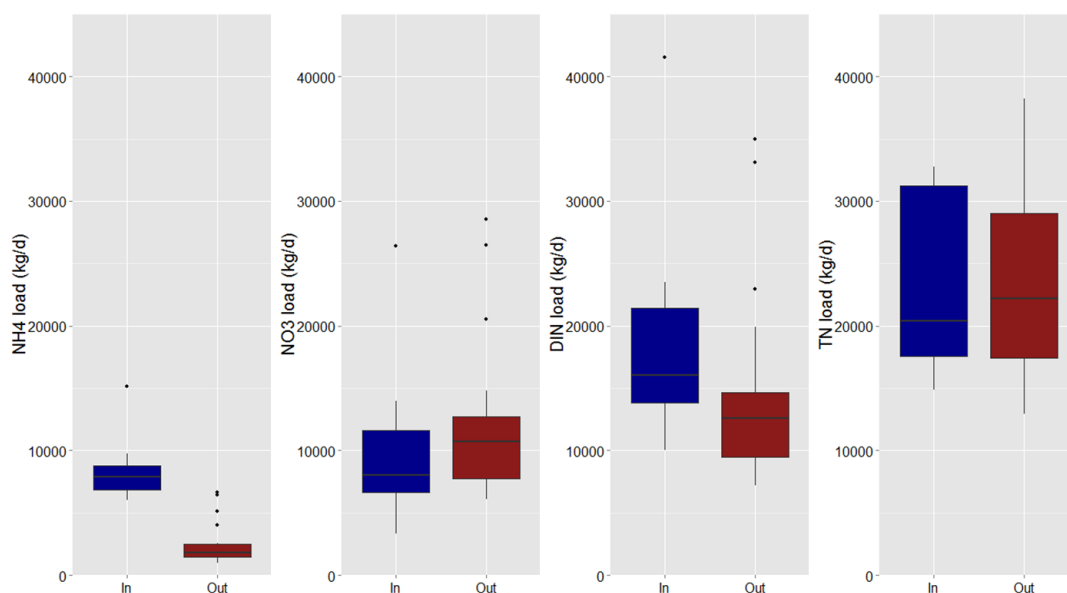


Figure 3.7 Summer (Jun-Oct) Suisun Bay mass-balance results for NH₄, NO₃, DIN and TN for the period 2006-2011. Boxplots show the median and 25th/75th percentile, and the whiskers extend to 1.5x the interquartile range.

Comparison of One-Box Mass Balances with Other Methods

A large component of this collaborative project was updating and refining the DSM2 water quality model for the Delta (see Appendix 6). The output from this model can be used to corroborate the mass balance calculations as well as explore transformations and losses on smaller spatial scales (see Section 3.4 below,

as well as main manuscript). DSM2 model output was aggregated on a whole Delta scale to compare inputs, outputs and losses to the results of the one-box mass balance calculations for the Delta (Table 3.3). The DSM2 model does not explicitly characterize TN, so we estimated it as DIN + orgN + 0.08 x algal biomass, since orgN in the model is detritus, not viable phytoplankton. In spite of the considerable differences in approach, as well as the uncertainty in the one-box model approach, the two methods produced remarkably similar results. Both the one-box model and the DSM2 model predict significant losses of NH₃ in the Delta and Suisun (60-80%) and moderate losses of TN in the Delta (25% in both methods). For Suisun Bay, The one-box model predicts minimal TN losses in Suisun Bay, while DSM2 shows losses as high as 25%.

The one-box mass balance calculations were also compared to a previous EPA-funded study (TetraTech, 2006) that looked at TN loads in/out of the Delta (not Suisun Bay). The EPA study only considered annual-average results, not the summer season, so the methods aren't entirely comparable to this study. However, results from the EPA study for dry year annual averages from this study should more closely resemble the June-Oct time period considered for the one-box mass balance and the DSM2 model. The EPA study showed TN losses of 35% in the Delta (due mostly to higher estimated loads in from tributaries), which is higher than but still within reasonable agreement with the one-box mass balance and DSM2 model (15-25%).

Table 3.3 Comparison of mass balance results by SFEI box-model (adapted from Jassby and Cloern, 2000) for the period June-Oct 2006-2011, DSM2 model output for the period June-Oct 2006-2011 and a results of an EPA study (Tetra Tech, 2006) for a number of dry years. All loads are kg/d. Terms omitted from the mass balance calculation for each method are shaded grey.

		SFEI box model (this report)	DSM2 output	EPA box model (Tetra Tech, 2006)
NH ₄	Loads into Delta— rivers	9800	12700	
	Loads into Delta – DICU		800	
	Loads into Delta - POTW	200	400	
	Loads out to exports	800	700	
	Loads out to islands		800	
	Loads out to Suisun	2800	800	
	<i>Loss in Delta</i>	65%	85%	
	<i>Loss in Suisun</i>	80%	55%	
TN	Loads into Delta— rivers	35000	38900	48200
	Loads into Delta – DICU		7800	4500
	Loads into Delta - POTW	1900	2100	
	Loads out to exports	17200	16200	16400
	Loads out to islands		7200	
	Loads out to Suisun	10200	13000	18300
	<i>Loss in Delta</i>	25%	25%	35%
	<i>Loss in Suisun</i>	<2%	20%	

3.3.2 Finer scale mass balances

We hypothesize that, in reality, nutrient transformations or losses do not happen uniformly throughout the Delta, but instead that specific areas may be responsible for greater amounts of transformations or losses due site-specific or system characteristics. The 1-box model was a useful tool for an initial whole-Delta estimate, but that approach (or a several-box model) is not well-suited for the spatially-resolved question because of the system's complex hydrology and limited nutrient data. To examine N transformations and losses at higher spatial resolution, we used DSM2 model output and aggregated estimates to 6 sub-regions

of the Delta (Table 3.4, Figures 3.8-3.9), and estimated losses of NH₄ loss and TN. As a first step, we compared the results from the 1-box model to DSM2 model output over the whole Delta (same years), and found that the losses were of similar magnitude (i.e., 85% loss of NH₄ with DSM2, compared to 65% loss with 1-box model; 25% loss of TN estimated with both methods; See Appendix 3 for more information)

Within the Delta, 4 of the 6 regions had NH₄ loss >50%; losses were ~20% and 40% in the South and the Confluence regions, respectively. The greatest NH₄ loss (mass and percentage) occurred in the North region, followed by the East. TN losses were greatest in the North (10%), Central (25%) and South regions (15%), and smaller in the East, San Joaquin and Confluence regions. Although not described here, a similar set of mass balances for Suisun Bay (using 1-box and DSM2) yielded the highest % losses of all N species compared to the Delta regions (see Appendix 3 for more details).

Table 3.4 Loads into and out of each DSM2 subregion, in kg/d, and the % of loads in that are lost within each region.

	NH ₄			TN		
	In	Out	Loss	In	Out	Loss
North	12700	5000	61%	28500	25600	10%
East	3400	1700	50%	11700	11300	3%
Central	1600	700	56%	20800	15300	26%
Confluence	2800	1700	39%	23700	23000	3%
South	900	800	11%	20400	17800	13%
San Joaquin	500	200	60%	13700	13500	1%
West	4000	1700	58%	18000	14700	18%

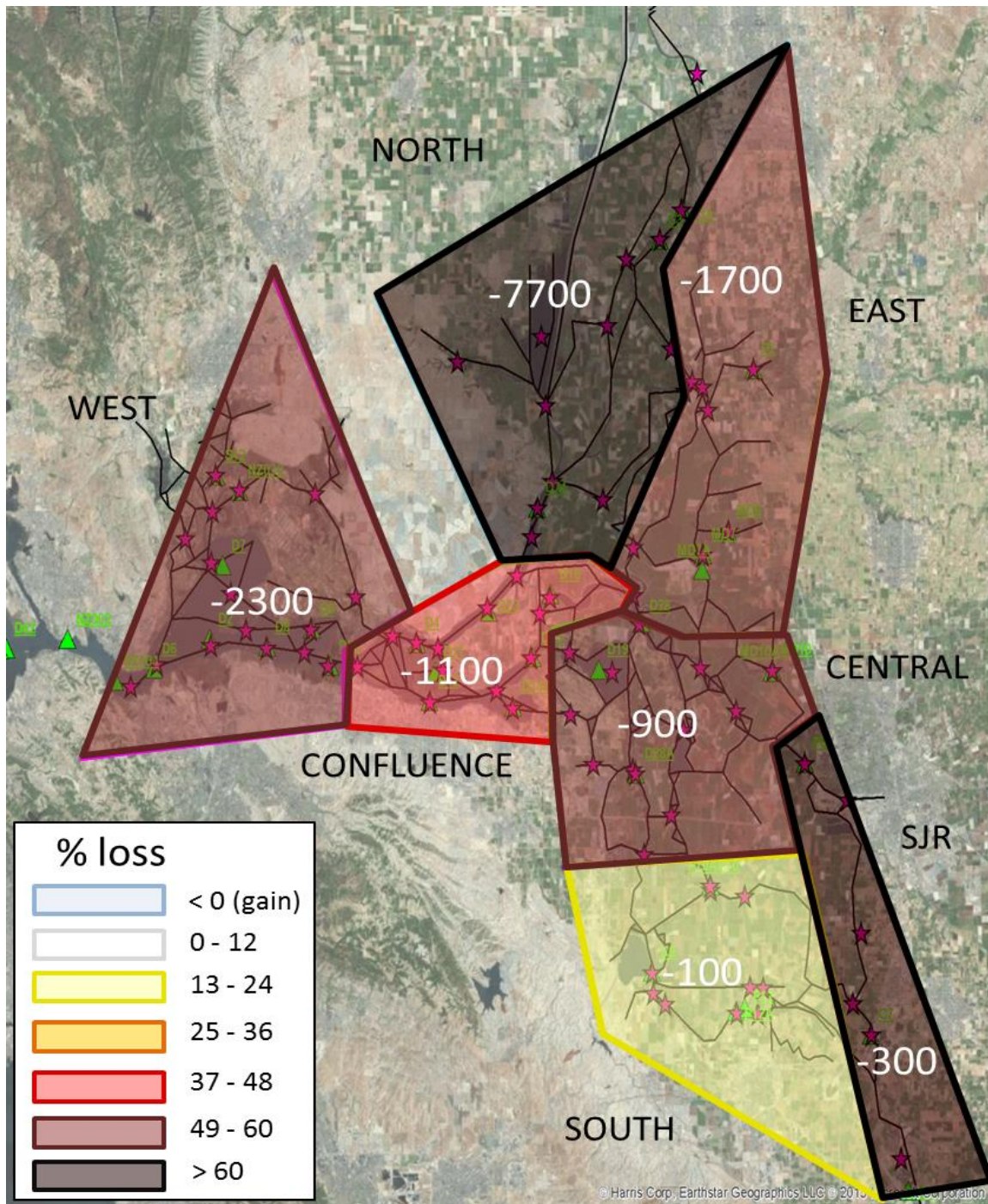


Figure 3.8 NH4 subregion mass balances. Color indicates % lost within each region. Mass losses written in text, in kg N/d.

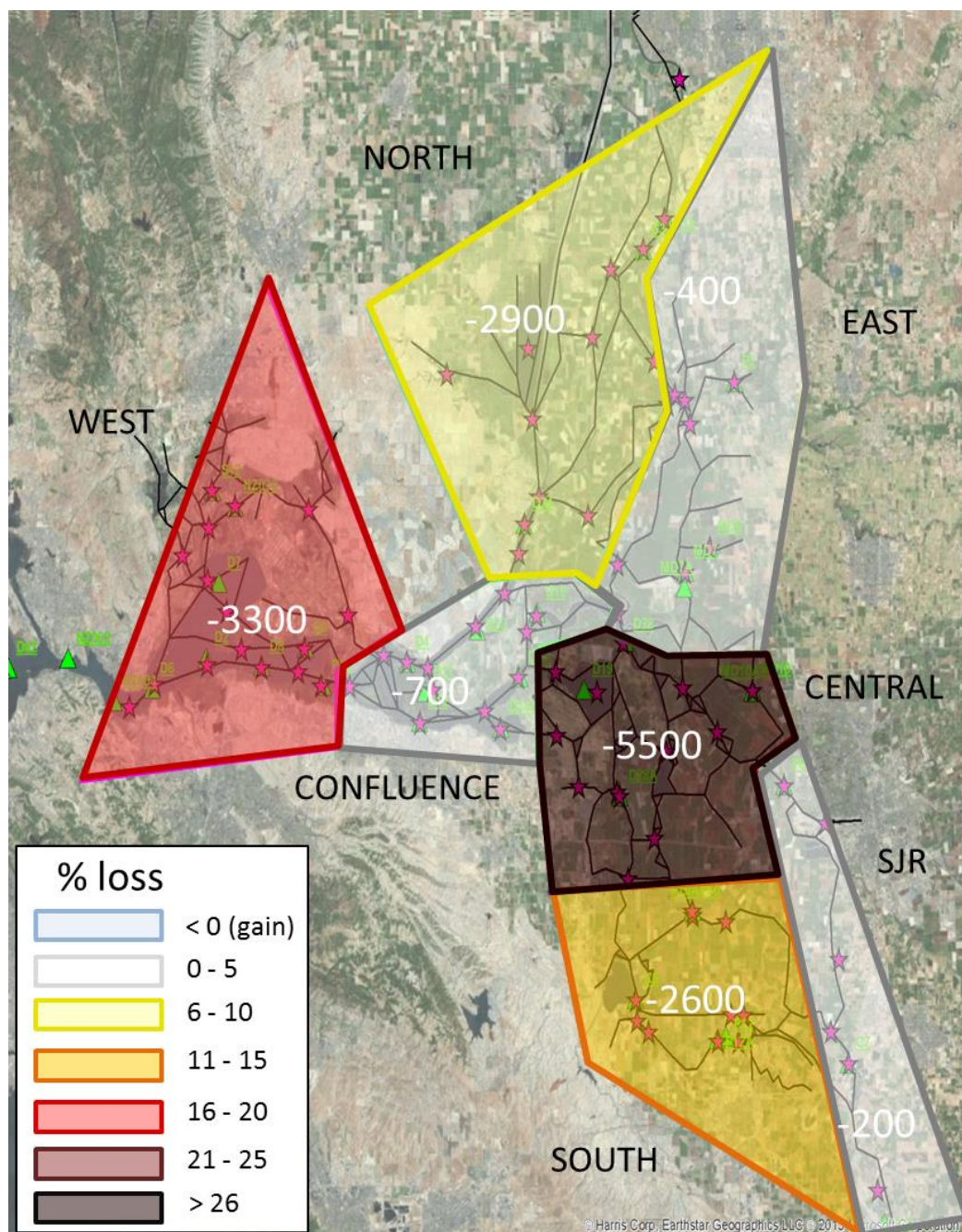


Figure 3.9 TN subregion mass balances. Color indicates % lost within each region. Mass losses written in text, in kg N/d.

4. Discussion

The two mass balance approaches, which estimate that TN loss in the Delta occurred at a rate of 10,000 – 12,000 kg N/day, provide independent quantitative evidence that losses occurred and that the losses were large relative to inputs (~30%). While N loss from a system such as the Delta is not surprising, the important role that these losses play in the overall fate of N in the Delta, and on ambient nutrient concentrations within the Delta, had not previously been quantified. The estimated losses must have occurred along one, or both, of two broad pathways (see also Figure 10):

1. N was lost from the system through denitrification (conversion of NO_3 to N_2 by heterotrophic microorganisms during metabolism of organic matter), or possibly through anamox (carried out by chemosynthetic $\text{NO}_3^- + \text{NH}_4^+ \rightarrow \text{N}_2$);
2. TN was lost from the system through temporary storage (in viable plants, or after accumulating in the sediments) and eventual permanent burial of organic matter within the system. That organic matter could have been produced internally (e.g., phytoplankton; benthic algae; aquatic vegetation); or was loaded into the system as particulate N) by upstream tributaries and buried within the Delta.

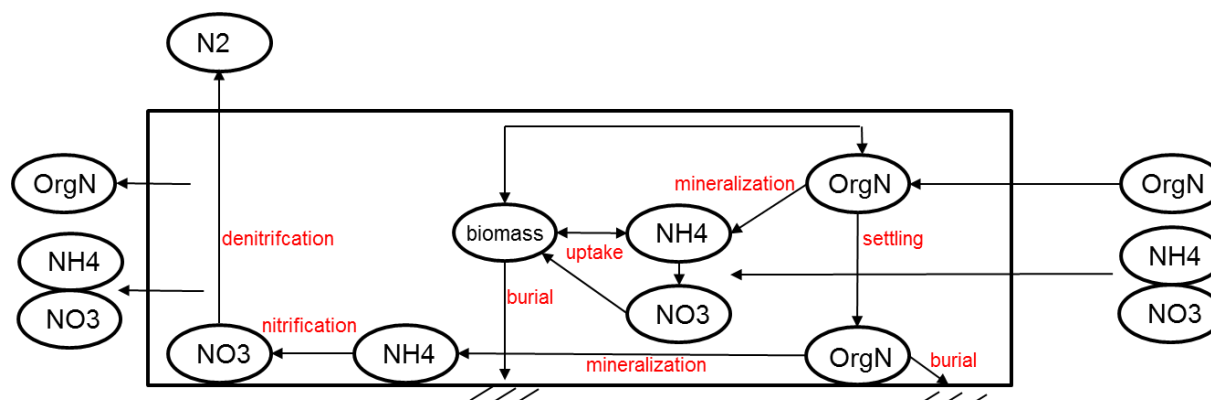


Figure 10 Conceptual model of TN loss pathways. TN can be lost via denitrification of NO_3 at the sediment/water interface or through burial/storage of TN in organic matter. Organic matter can be import into the and buried within, or can come from internal production (via phytoplankton, benthic algae or aquatic plants) and stored/buried in the system.

Since there are few measurements within the Delta to directly estimate the N losses along these pathways, we used data from a range of freshwater and estuarine ecosystems to quantify potential losses, or estimates of related processes from other Delta studies. In oxic waterways like most of the Delta, the majority of denitrification would be expected take place at low oxygen environments, such as the sediment water interface, because denitrifying organisms require low oxygen conditions ($< 5 \mu\text{M}$). Cornwell et al (2014) performed sediment incubation experiments to estimate rates for a number of processes flux estimates, including denitrification, at 8 locations within Suisun Bay and the Delta (within the Confluence and Central regions in Figure 3.8). They estimated that denitrification occurred at rates on the order of 10-12 mg N/m²-d, which fall within an intermediate range for denitrification rates estimated for a number of estuaries (Cornwell et al 2014). As a first approximation, if those rates are extrapolated to the entire area of Delta waterways ($2.7 \times 10^8 \text{ m}^2$; Jassby and Cloern 2000), denitrification losses amount to 3000 kg N/d, or 25-30% of the estimated TN lost in the Delta. Therefore, while denitrification may be one of several factors contributing to N loss, these initial estimates do not indicate that denitrification can alone explain the majority of the loss.

Burial or long-term storage of organic matter is another pathway along which N could leave the aqueous system. Similar to our estimates above, Jassby and Cloern (2000) estimated that a nontrivial amount of N enters the Delta in the form of organic N, much of it as dissolved organic N (DON, ~67%). In order for that allochthonous DON to settle and be stored or buried in the Delta, it must first be incorporated into the particulate phase through assimilation by the microbial community. Using an approach similar to the one employed by Jassby and Cloern (2000) for dissolved organic carbon (DOC), we estimate that ~40% of allochthonous DON can be incorporated into microbial (particulate) biomass. Combined with the portion of allochthonous total organic N (TON) that was already in the particulate phase, ~70% of the allochthonous TON load has the potential to settle, or be grazed by zooplankton or filter-feeding benthos and eventually settle and be stored within the Delta, or about 10,000 kg/d. Organic N is also produced within the Delta (autochthonous production) by phytoplankton, benthic algae and aquatic plants. Isotopic data in the Cache Slough/Yolo Bypass region indicates that in that area much of the available nutrient pool was converted into algal biomass (see Appendix 5). The Cache Slough / Yolo Bypass region is within the Northern region (Figure 3.8), where we estimated that 25% of the overall N loss occurred. Delta-wide, Jassby and Cloern (2000) estimated that average summertime net phytoplankton productivity in the Delta is approximately 55 t C/day or approximately 9,000 kg N/day (assuming C:N ~ 6). If all of this phytoplankton was buried within the system, it could conceivably explain the TN loss not feasible by denitrification. However, a good portion of this phytoplankton could be flushed out from the system, and that which is settled is labile and likely to be returned to the water column N pool. Nitrogen could also be stored and potentially permanently buried in aquatic plants. Jassby and Cloern (2000) estimated production from two major species of aquatic macrophytes in the Delta: the submerged macrophyte *Egeria densa* was estimated to contribute 5 t C/day (annual average) and the free-floating macrophyte *Eichhornia crassipes* contributed approximately at approximately 7 t C/day annual average, but this was based on an areal extent of macrophyte coverage of approximately 800 and 300 hectares, respectively. However, the areal coverage of both species has grown to approximately 2,000 ha for *Egeria* (Santos 2009) and 800 ha for *Eichhornia* (Boyer and Sutula 2015), which would scale up to approximately 12.5 and 18.5 t C/day (respectively), or approximately 5,000 kg N/day combined. A greater proportion of the organic matter produced by macrophytes tends to be refractory compared to phytoplankton, and therefore has a greater likelihood of being efficiently buried with less re-mineralization. Benthic microalgae productivity from Jassby and Cloern (2000) are trivial compared to these other two sources, and while it is possible that the extent of benthic microalgae has increased since the time of this earlier study, we will assume it remains small by comparison. When these potential PON terms are combined (24,000 kg/d), they reach a number that roughly 2/3 of the summertime TN loads to the Delta; in other words, it is possible that most of the TN loads that the Delta receives could conceivably move along a biogeochemical pathway through transformation to PON, and therefore be susceptible to settling and burial. If only a minor fraction (e.g., 20-30%; 5000-8,000 kg/d) of that combined PON term experienced burial as its ultimate fate, it can, in combination with denitrification, readily explain the mass balance loss term.

The main manuscript includes a more detailed discussion of results, including finer scale mass balances.

5. References

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