SAN FRANCISCO BAY
NUTRIENT MANAGEMENT STRATEGY

Determining relationships of loads, production and observed nutrients: Designing monitoring for planned load reductions

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Introduction
San Francisco Bay is one of the most nutrient-rich estuaries in the world, largely due to the input of treated wastewater, which serves as a nitrogen subsidy that could potentially fuel the growth of phytoplankton to eutrophic levels (Cloern et al., 2020; Senn and Novick, 2014). Despite these nutrient-replete conditions, phytoplankton abundance has been repressed by intensive benthic grazing, rapid tidal flushing, and attenuation of light by high concentrations of suspended sediment. In more recent years, the NMS has reported a gradual decrease in observed DIN at several Bay stations, which was attributed to enhanced primary production and load reductions (Figure 1)(Foley et al., 2025). In 2022, this trend was underlined by the occurrence of an unprecedented harmful algal bloom event caused by the raphidophyte plankton, *Heterosigma akashiwo*, which fully utilized nitrogen across the South and Central Bays (Kudela et al., 2024; Nardelli et al., 2026). Work began on a new nutrient management permit, which mandated the collective reduction of dissolved nitrogen loads by 40% across Publicly Owned Treatment Works (POTW) members of the Bay Area Clean Water Agencies (BACWA).

This reduction in source nutrient loads will require continuation of the current monitoring program, as well as possible changes in future monitoring strategy, to identify changes from baseline concentrations in nutrient availability and levels of production. Identifying past connections between loads, production, and observed dissolved inorganic nitrogen (DIN) concentrations is crucial to be able to identify how past variability can inform our ability to anticipate future changes.

Additionally, while loads and observed DIN are known to display positive relationships, it is also important to account for the influence of phytoplankton production itself. Phytoplankton production can be expressed in units of carbon per unit area per day (Cole and Cloern, 1987), which can also be converted to nitrogen units based on the known Redfield ratio of C:N in phytoplankton (Redfield, 1934). This calculation of gross primary production (GPP) is a function of the observed chlorophyll concentration, solar radiation (monthly means), suspended particulate matter concentration (used to calculate light attenuation), among other constants (Cole and Cloern, 1987). Calculating phytoplankton biomass allows us to account for the assimilation of nitrate or ammonium, allowing for a more complete nitrogen budget for each subembayment.

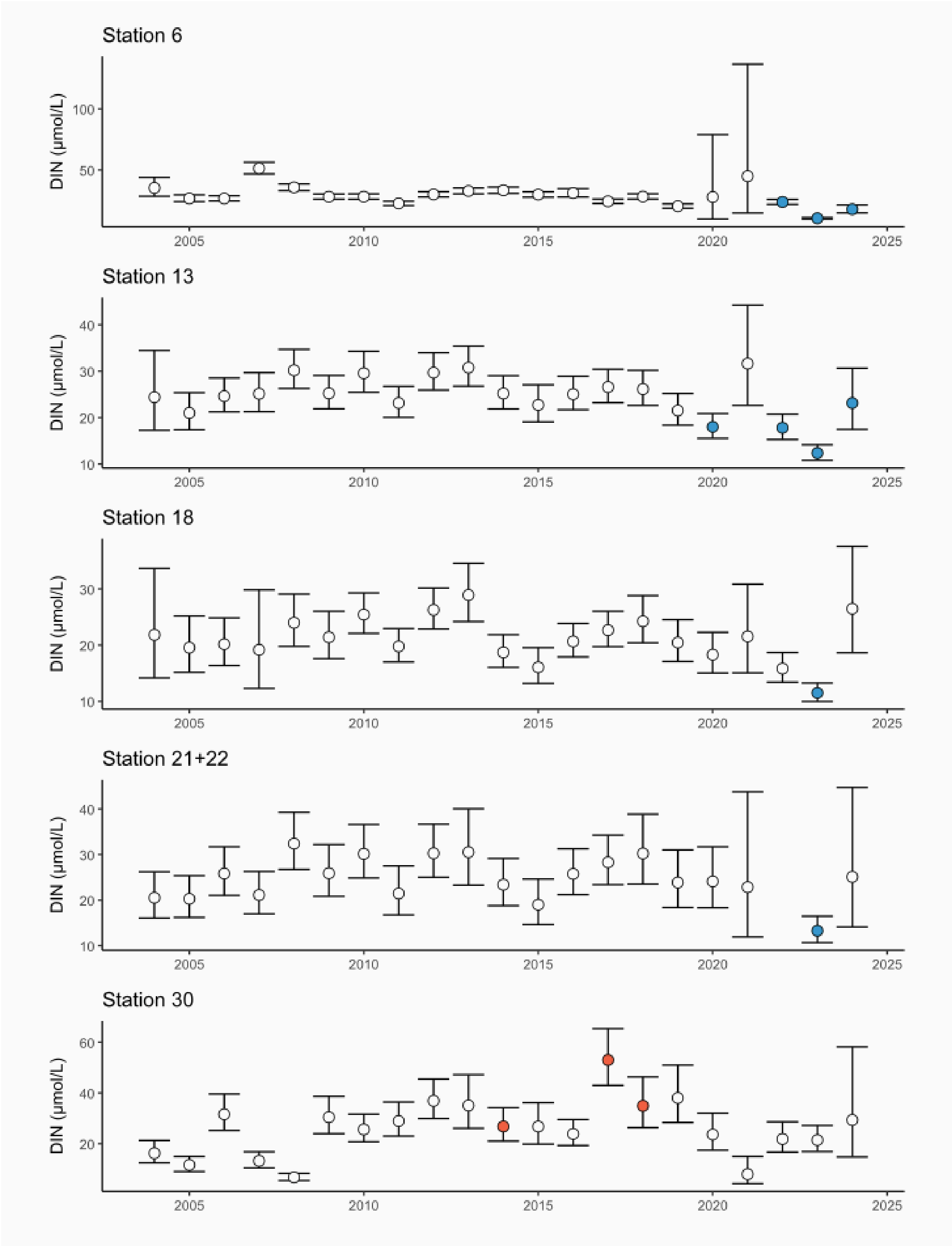

Figure 1: Trends in annual mean DIN observed at several USGS Peterson stations ranging from Suisun Bay (Station 6) to the southern end of South Bay (Station 30). Blue dots indicate significant negative 5-year preceding trends in DIN, while red dots indicate positive trends (Foley et al., 2025; San Francisco Estuary Institute, 2025).

Methods
We synthesized previously collected discrete nutrient measurements from several sources including USGS Peterson cruises (1969-present)(Schraga and Cloern, 2017), NMS supported high-frequency mapping cruises (2021-present), NMS sonde servicing nutrient discrete samples (2013-present), and samples from marinas and other marginal environments surrounding the South and Central Bays collected during NMS mussel toxin sampling, 2018-2020 (Art et al., 2020) (Figure 2). All data points were bound to their respective subembayment, including Lower South Bay, South Bay, Central Bay, San Pablo Bay, and Suisun Bay (Jassby et al., 1997). These samples include nitrate+nitrite and ammonium concentrations, which were pooled to produce mean subembayment-level DIN concentrations (Figure 3). Sonde-based measurements from moored stations and mapping cruises have been collated, but are currently excluded to control for methodological differences which could confound trend-based analyses.

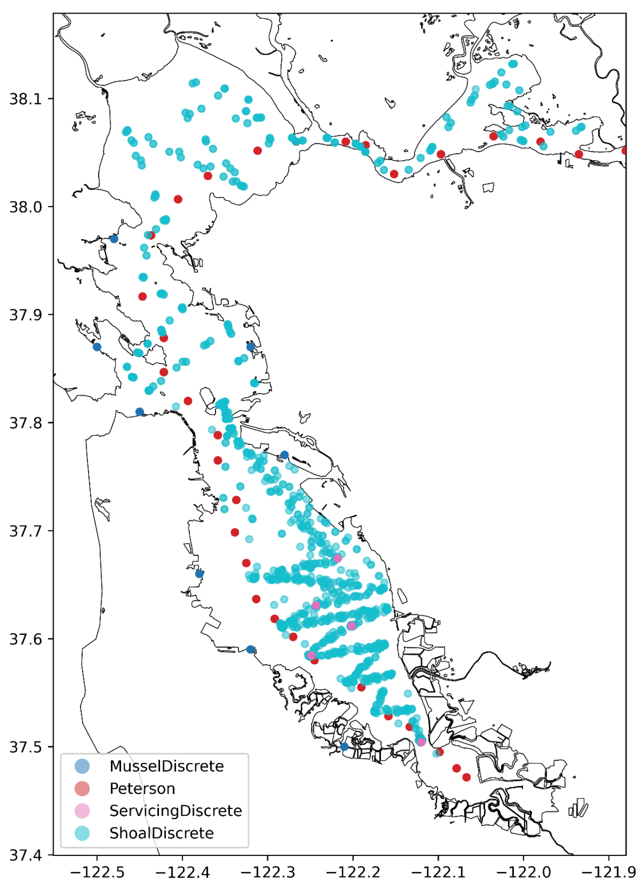

Figure 2: Discrete sampling data used in this report

As a forcing variable, we used POTW loading data gathered by HDR in partnership with BACWA since 2012. This dataset provides monthly resolution loading data in terms of nitrate+nitrite, ammonium and total DIN for each POTW. Subembayment-level monthly sums of loads were constructed by adding the total loadings of all POTWs in each subembayment

(Figure 4). Loads were categorized as dry season (May-October) or wet season (November-April).

GPP was calculated based on the approach of Cole and Cloern, 1987. For chlorophyll-a and light attenuation data needed for GPP calculations, data from the Peterson cruise were used, where light attenuation coefficients were calculated based on measured suspended particulate matter. For the long-term monthly averages of solar radiation used in the GPP calculations, data was measured by the Polaris cruises, which has been used previously in our estimates of GPP as consistent with modern-day seasonal insolation patterns (Cloern et al., 2007; Killam et al., 2023). GPP units of carbon per square meter per day were converted to nitrogen units using the standard Redfield C:N ratio of 106:16 (Redfield, 1934), and then converted to nitrogen masses by multiplying by subembayment area.

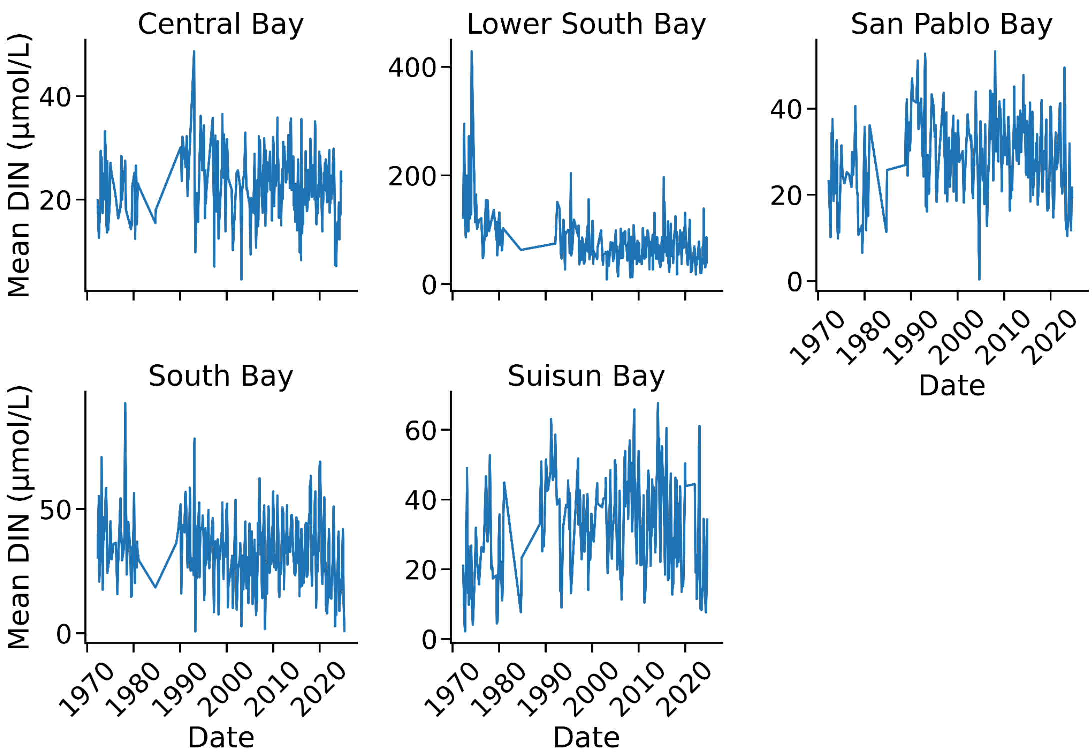

Figure 3: Time series of monthly mean DIN (µmol/L) for different subembayments. Note that comparisons in this progress report only use data back to 2012 when the monthly loading data started.

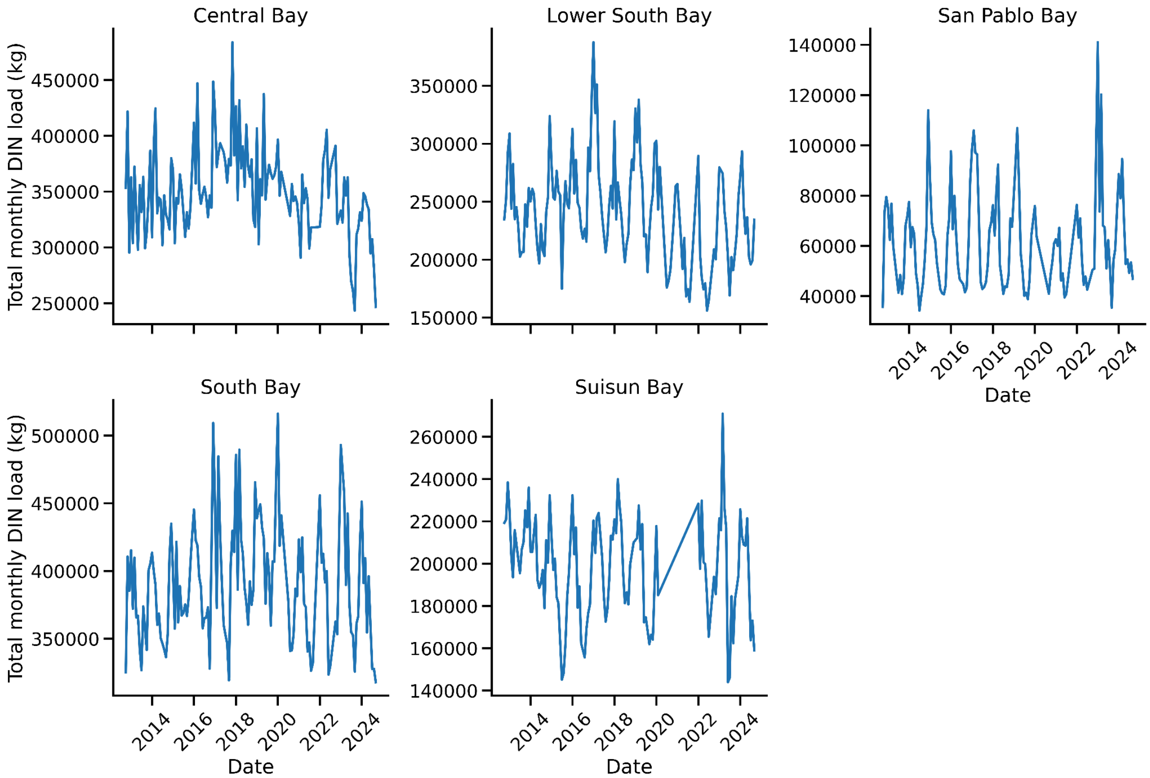

Figure 4: Time series of total DIN loading data for each subembayment.

Concentration-based DIN estimates were converted to nitrogen masses by calculating the volume of each subembayment at Mean Low Low Water, using a Dynamic Elevation Model sourced from the NOAA National Centers for Environmental Information, hosted by the California Natural Resources Agency (National Centers for Environmental Information, 2018). Mean bathymetric depth was calculated for each subembayment and multiplied by the area to obtain volumes, which were used to convert mg/L N estimates of DIN concentration to kg of nitrogen. GPP was also converted to subembayment mass by multiplying by the volume. Mass per day loads were converted to total monthly mass by multiplying by the number of days in each month.

Resulting subembayment level mean DIN mass was related to the forcing variables of decimal date, DIN load, GPP, and dry season or wet season using Generalized Additive Models (GAM) in R version 4.2.2 using the mgcv package (Wood, 2023) and the equation:

DIN mass ~ s(Decimal date) + s(Loading mass, by=Season) + s(GPP nitrogen mass)

With decimal date being transformed from the calendar date following the approach of Beck et al., 2021, and s() terminology referring to the spline smooth applied to each term, following the Restricted Maximum Likelihood method. GAMs were run separately for each individual subembayment. A gamma distribution was assumed, and the data were log-transformed, as the nutrient, loading and GPP data are all right-skewed with low values outnumbering a small number of extremely high data points. Data from the 2022 bloom event (August and September

2022) was excluded as nutrient utilization and GPP dynamics may have rendered conditions during that event structurally different from baseline conditions.

Results/Discussion:

Interannual variability in loadings and observed DIN

Both loadings and observed DIN display strong seasonality, with elevated values in the winter. South Bay generally has the greatest mass of loadings, followed by Central Bay, Lower South Bay, Suisun Bay, and San Pablo Bay (Figure 2, Figure 3). Subembayment dry season total loadings can vary by around 10% year to year, with Central Bay showing a large decline in the last five years and San Pablo Bay showing the most consistent loading values. Interannual variability in observed DIN is large, with nearly 100% differences in interannual low and high values for South Bay and Lower South Bay. Very high DIN values of 200-400 μMol were measured for Lower South Bay in the 1970s.

Generally, high variability in observed nutrient concentrations was expected due to the great number of contributing explanatory variables, including long-term weather trends, ecological variability through time, and other factors. Large variability in wet season loadings was also expected due to the influence of wetter or drier rainy seasons on POTW effluent concentrations and volumes. Dry season variability was less expected, due to the interannual variability of any individual POTW generally being modest, as it is a regulated quantity controlled by the permit. However, if we consider each POTW's loads as dependent on the others, as measures of shared population-scale trends across the Bay Area, there are parallels to other kinds of environmental data. In many environmental time series, individual stations can be subject to random variations due to noise. But when pooled, interannual signals can become detectable that are not visible in any individual POTW's loading (Bignert et al., 2014).

Relationships between DIN, loads and GPP

South Bay

Among the subembayments of SF Bay, South Bay is in many ways the optimum setting to look for loading relationships, due to its large surface area, small volume, long residence time of water and several large POTWs present. The combined relationship between date, dry/wet season loads and GPP follows some expected patterns. Coefficients for South Bay are shown in Table 1. Significant positive relationships are observed for wet and dry season loads vs observed DIN (Figure 5). GPP, by contrast, shows an inverse and significant relationship, with higher GPP being associated with lower DIN. The decimal date term is independent of the other terms, and variability in the partial effect of that term can be viewed as variance in DIN not captured by loads or GPP.

Table 1: GAM summary table for South Bay comparison of DIN to decimal date, summary and winter loads and monthly subembayment GPP (in kg of N)

Component	Term	Estimate	Std Error	t-value	p-value
A. parametric coefficients	(Intercept)	3.408	0.030	114.895	0.0000***
B. smooth terms	s(DecimalDate)	5.835	6.986	11.496	0.0000***
	s(DINload.kg):SeasonDry Season	1.000	1.000	8.346	0.0046**
	s(DINload.kg):SeasonWet Season	1.000	1.001	7.899	0.0057**
	s(GPP.Nmonthmass)	2.057	2.608	65.688	0.0000***

Signif. codes: 0 <= '***' < 0.001 < '**' < 0.01 < '*' < 0.05

Adjusted R-squared: 0.690, Deviance explained 0.718

-REML : 484.875, Scale est: 0.0654, N: 135

Increased nitrogen loading is expected to manifest as increased observed concentrations of DIN, because phytoplankton and other life forms in the Bay cannot use the observed DIN instantaneously, instead taking days to even weeks to assimilate new dissolved nutrients (Berg et al., 2017). This temporal mismatch will be greater in winter than in summer, since phytoplankton growth and their rate of assimilation is reduced by lower solar radiation and higher light attenuation due to higher turbidity. Despite that, the GPP: nutrient relationship was stronger and more linear than expected, considering the fact that GPP has been considered more of an index integrating other various parameters influencing phytoplankton growth, rather than an empirical measure (Killam et al., 2023). GPP helps to correct for winter vs summer differences in loads through its seasonal responsiveness, leading both winter and summer loading relationships to be relatively consistent in slope for South Bay.

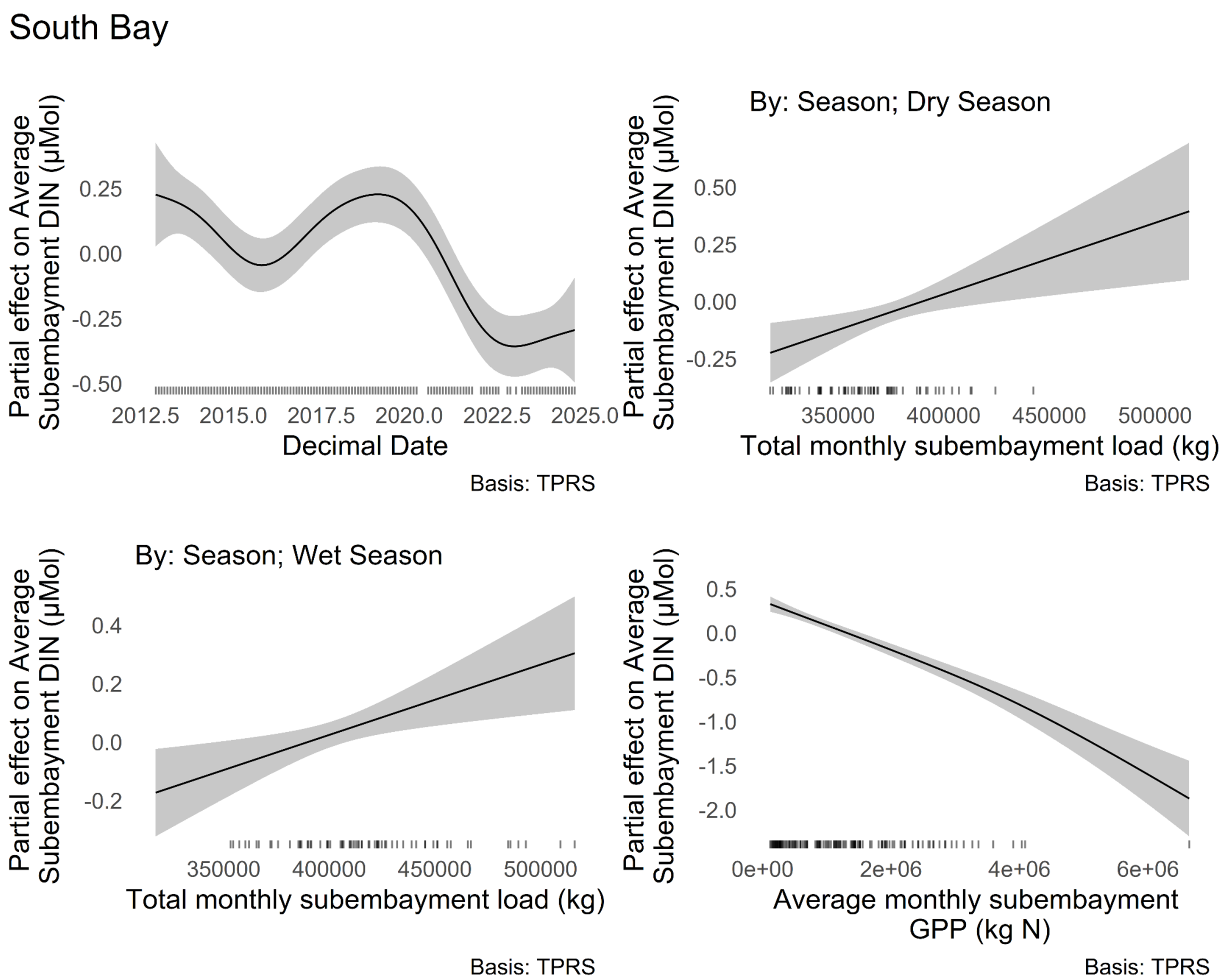

Figure 5: GAM results for South Bay (y-axis is in logarithmic units)

Other sources of variability are not fully quantified by the terms of the model, leading to the strong interannual variability observed in the time series plot. Since 2020, there has been a decline in nutrients in South Bay, which leveled off in 2022 (Figure 5). This change could be attributed to other sources of nitrogen loss, such as denitrification, which has been measured as a significant source of flux, especially in regions where the surface area of sediment is higher relative to water column volume, such as the South Bay shoals (Czapla et al., 2025).

The GPP term itself may include denitrification in the modeled slope, rather than being a pure assimilation signal, because the carbon burial associated with production fuels the later denitrification. It is possible that when independent measures of denitrification flux are developed and integrated into the GAM that the GPP-DIN slope may become less steep. But because denitrification operates on longer time scales of weeks to months, work will be needed to account for that temporal lag.

Subembayment	GPP relationship	Load relationship		Other DIN variability through time
		Dry season	Wet season	
Lower South Bay	**Negative**	**Positive**	No relationship	Decrease 2020-2025
South Bay	**Negative**	**Positive**	**Positive**	**Increase 2015-2020 Decrease 2020-2025**
Central Bay	**Negative**	No relationship	No relationship	**Increase 2015-2017 Decrease 2022-present**
San Pablo Bay	**Negative (flat at higher values)**	Positive, nonlinear	**Positive**	**Decrease 2022-present**
Suisun Bay	**Negative (flat at higher values)**	Positive	Positive	**Decrease 2022-present**

Table 2: Relationships between different terms and DIN for each subembayment. Statistically significant relationships are bolded.

Comparison of relationships in other subembayments

Comparison of GAM relationships for each subembayment are collated in Table 2 and Figure 6. The South Bay is in many ways the ideal setting to look for a relationship between observed nutrients, loads and GPP, because it hosts the greatest nitrogen loads, has a large surface area for production, a relatively small volume for dilution, and waters there have a long residence time of weeks to months (Smith and Hollibaugh, 2006). However, other subembayments show similar relationships (Table 2). Lower South Bay shows a significant positive relationship between loads and DIN in the dry season, but a non-significant relationship in the wet season (Figure 6). Meanwhile, as was observed in South Bay, GPP is also significantly inversely related to nutrients in Lower South Bay, which has also observed a decline since 2020, independent of the other terms. The lack of a relationship between Lower South Bay wet season loads could be due to several factors, such as those loads coinciding with high flows, increasing dilution, and reducing the residence time of those loads in Lower South Bay. In winter, the nitrogen loads may instead pass quickly through Dumbarton Bridge to the South Bay. Integration of the Dumbarton Bridge SUNA nitrate data into this analysis may help resolve questions of nutrient flux out of Lower South Bay.

Central Bay shows no significant relationship between loads and observed nutrients in either the wet or dry seasons, while the GPP relationship is still significant (Figure 6). The date trend shows a slightly later onset of decline, starting in 2022 instead of 2020 as was seen in South Bay and Lower South Bay. A lack of a strong first-order relationship between Central Bay and loads compared to the other subembayments is expected, due to the large volume producing dilution, combined with rapid tidal exchange of nutrients going out the Golden Gate, and incoming nutrients from the ocean during times of upwelling. Additionally, the Central Bay's nutrient field is a function of the loadings coming from the northern and southern directions, but our model does not yet incorporate loadings from neighboring regions.

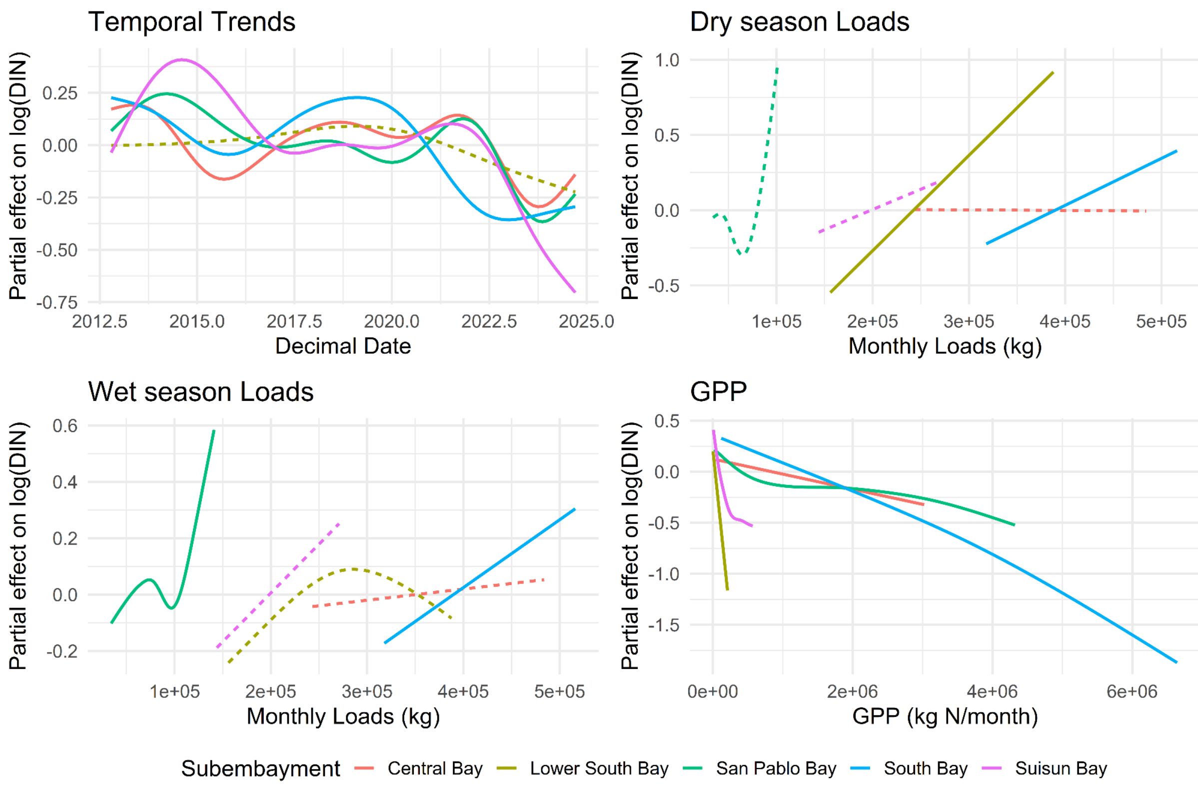

Figure 6: GAM modeled smooths for all subembayments plotted together. Note that this is not a single combined GAM with subembayment as an explanatory variable. Dashed lines are used to mark GAM relationships that are not significant. Individual GAM plots (with confidence intervals) can be viewed as supplementary figures at the end.

San Pablo Bay has the smallest total loading mass of any subembayment. The loading relationship is weak and barely significant for the wet season, and not significant for the dry season (Figure 6). Several POTWs in San Pablo Bay do not discharge in the dry season, and during the wet season, loads are likely transported out of San Pablo Bay due to higher flows. GPP has a significant inverse relationship with observed nutrients similar to the other subembayments, but there is a long tail of higher calculated GPP values with no corresponding decline in nutrients. The highest GPP values also coincide with the spring bloom, when flow is higher and the residence time of phytoplankton in San Pablo Bay is likely shorter. In San Pablo Bay, as with Central Bay, we see a decline in nutrients after late 2021/early 2022 not captured by the other terms.

Suisun Bay loadings show a positive but not significant relationship with nutrients (Figure 6), and a negative relationship between GPP and nutrients. As with San Pablo Bay, there are a series of high GPP values that do not coincide with any decline in observed nutrients. The integration of a flow term will likely help account for these values. When the spring bloom occurs, production may be high, but the impact on local dissolved nitrogen may be muted by the limited residence time of phytoplankton before they are transported out of the area. As with San Pablo Bay and Central Bay, we again can see a decline in 2022 of nutrients heading into later years.

For Suisun, San Pablo and Central Bays, the model would potentially be improved if Delta-sourced loadings are accounted for, due to variability in flows during recent years. Additionally, the initiation of the Echowater tertiary treatment plant by Sacramento Area Sewer District likely played a significant role in reducing local DIN supply, but is not currently accounted for by this model. As mentioned before, accounting for the flow term will also likely impact the relationships of all parameters by ensuring that residence time is accounted for, which can modulate the impacts of GPP, loads and other parameters through dilution and transport. Additionally, the dataset in this study has very good data coverage of shallow water environments in the South Bay shoals, but much less in San Pablo Bay and Suisun. It is possible that channel-biased estimates of GPP are not representative of production across the broader environment of San Pablo and Suisun Bays, where there may be large spatial variability due to the dynamic turbidity regime observed in the shallow shoals of those subembayments. Additionally, Suisun Bay and in some conditions, San Pablo Bay both host the greatest known concentrations of grazing by the invasive *Potamocorbula* clams of the studied subembayments (Hartman et al., 2024; Lucas et al., 2016; Parchaso et al., 2021). It may be that high assumed values of GPP don’t necessarily manifest as high net nitrogen assimilation, due to quick drawdown of biomass by the clams.

Future monitoring changes to detect loading changes

Next directions for this analysis

The analyses described in this report demonstrate that even at the relatively coarse subembayment-scale approach, changes in nutrient loadings can be detected in ambient DIN concentrations averaged over that subembayment. One key aspect allowing that work to be delivered was the introduction of GPP into the nutrient budget as a term in the GAM model. Interannual variability in production is a forcing rivaling and sometimes exceeding the forcing of POTW nutrient loadings, and including it as an independent term is crucial to allow for the relationship of loadings to be discerned in the interannually and seasonally noisy record. However, for some of the model outputs described above, the lack of a statistically significant relationship is not evidence of a lack of relationship. As noted, it is likely that some subembayments like Central Bay, San Pablo Bay and Suisun are heavily influenced by upstream conditions. Accounting for these influences via a term quantifying flow and Delta-sourced nutrients will likely improve model fit and the ability to predict local nutrient availability.

Similarly, accounting for downstream sinks such as the Golden Gate Strait in the case of Central Bay, or Dumbarton Bridge for Lower South Bay, could also improve predictions. Dumbarton Bridge hosts a SUNA nitrate monitoring sonde, and we could integrate this data into the model as an estimate of nutrient flux between Lower South Bay and South Bay.

We also have time-based load estimates of percent contributions of each POTW, produced through the SFEI biogeochemical model, which could be used to build more refined estimates (Figure 7). This could be accomplished by setting individual POTW zones of influence as the bounds for a series of models, similar to the subembayment-level analysis shown above, or by incorporating a percent contribution term in the model as a predictive variable tied to the known loadings for a region. Currently it is likely that the channel-based observations explain the majority of variability in the model, as they are more consistently collected, as well as having started collection further back in time. But when moving to the scale of station-based approaches, we will be able to apply the relative loadings at every point in space and time to investigate the relative impacts of loadings on the channel or shoals respectively. Doing so, we would be able to integrate the assumed DIN contributions for different POTWs in areas where POTWs might not be geographically located but still exert influence, such as Central Bay, as well as the shallowest Northeastern shoals of SF Bay.

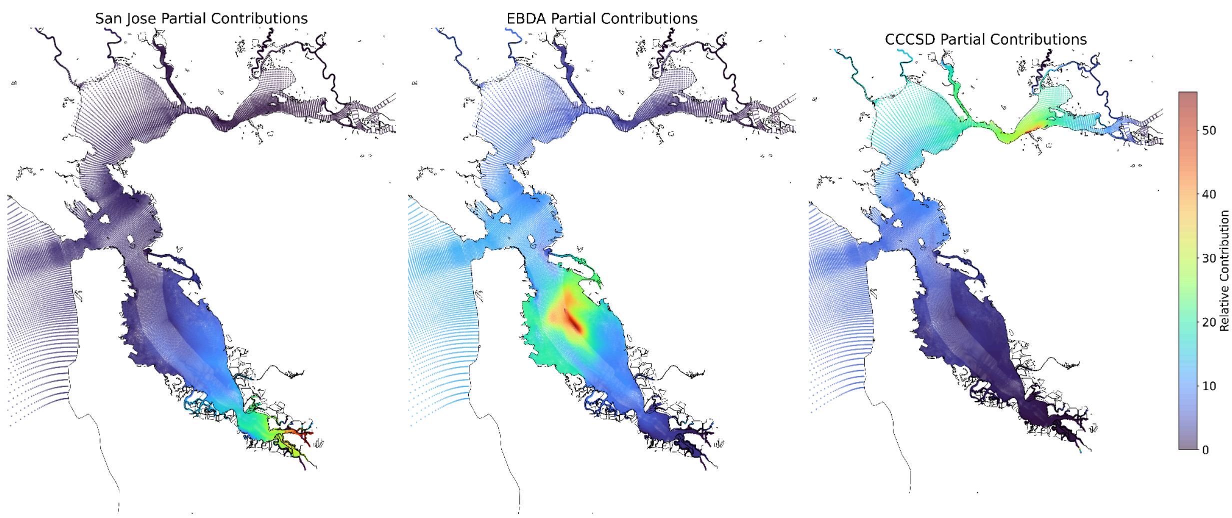

Figure 7: Examples of partial contributions (percent of observed DIN) attributed to three example POTWs in a tracer model developed by the SFEI modeling team for a snapshot on August 1, 2021. Values shown as points representing each grid cell of the model.

<u>Directions for future monitoring</u>

Currently planned improvements

The data and analyses described in this report are the result of years of iterative improvements in monitoring methods, and some improvements have already been planned for deployment as part of the NMS's existing 5-year plan. The Peterson cruise data has previously been demonstrated to be crucial to the understanding of nutrients and production across San Francisco Bay, which is confirmed in this work. Maintaining the long-term temporal continuity of the dataset will be important to capture as POTW upgrades come online, for comparison to the pre-upgrade baseline.

It is unclear whether the lack of ability to predict total DIN mass for Central Bay is due to a genuine lack of relationship with loads, or simply because we don't have a full characterization of DIN in that deeper subembayment. One way to determine if a deep reservoir of DIN is present in Central Bay, outside the photic zone, is through observations of DIN at depth.

Previous estimations of nutrient masses have assumed full vertical mixing, acknowledging that there were times of year when vertical structure could begin to appear in nutrient concentrations, and also pointing out that there was a potential that such assumptions could be broken in the future (Cloern et al., 2020; Smith and Hollibaugh, 2006). Measuring whether the development of vertical structure of nutrients has occurred in recent years could help resolve whether loads are influencing nutrients in Central Bay, but are not completely resolved by surface samples.There are current plans to measure nutrients at depth from the Peterson, from an additional Golden-Gate adjacent site, at bottom water, and also through more high-frequency profiles collected via SUNA casts.

There are some suggestions from these analyses that the North Bay estimates of production and nutrients may be skewed by a lack of coverage in shallow environments. NMS is seeking to fill this gap through the recent deployment of a measurement sonde on the San Pablo Bay shoal (EXO sonde is already deployed, and a SUNA nitrate-measuring sonde is planned), and through the expansion of high-frequency mapping cruises to the North Bay. Through these efforts, we will gain more granular data to calculate GPP and nutrient flux in the shallower regions of North Bay. Similarly, for shallower areas of Central Bay, sondes have been deployed near Emeryville and Seaplane Lagoon in Alameda to address similar shallow area data gaps. All of these ground-based observations can in turn be used to validate remotely sensed estimates of chlorophyll, turbidity and solar radiation, culminating potentially in whole-bay calculations of GPP via remote sensed data from Sentinel-2 and other satellite products.

Denitrification is a key source of nutrient flux that NMS will prioritize measuring in the coming years, with planned efforts from Martin Volaric to quantify the magnitude of potential flux, building on empirical measurements undertaken by Ariella Chelsky and colleagues (Czapla et al., 2025). The SFEI NMS modeling team has also prioritized reconstructing the relationship between GPP and denitrification, which could assist in resolving how much of the GPP term in the above model may be attributable to denitrification rather than assimilation by phytoplankton.

Potential special monitoring projects to pursue

There are several projects which could be pursued as part of this project's limited funding for pilot monitoring work. For example, the Grizzly Bay nutrient monitoring station was used by NMS in model validation work, and we intend to pull that dataset in here to improve our understanding of Delta transport. But that station is currently offline due to the loss of USGS funding for their Delta monitoring sonde network. There are plans to resurrect the sensor under new management, but it should be a priority for NMS to evaluate the continuity of that dataset going forward, in case methodological changes lead to offsets in observations. Interim data collection could help bridge the gap.

Work to improve our GPP calculations could also help refine the models shown in this report. GPP is seen as an index, using standardized relationships for calculating light attenuation coefficients. It also uses a literature-based Carbon:Chlorophyll ratio which may not account for seasonal variations in chlorophyll content known from phytoplankton in other regions (Cloern et al., 1995; Jakobsen and Markager, 2016). Another pathway for study could be refining these two constants to produce more empirical calculations of GPP that can serve as less of a loose index and more as a representative absolute value for models of ecosystem production.

Supplementary figures:

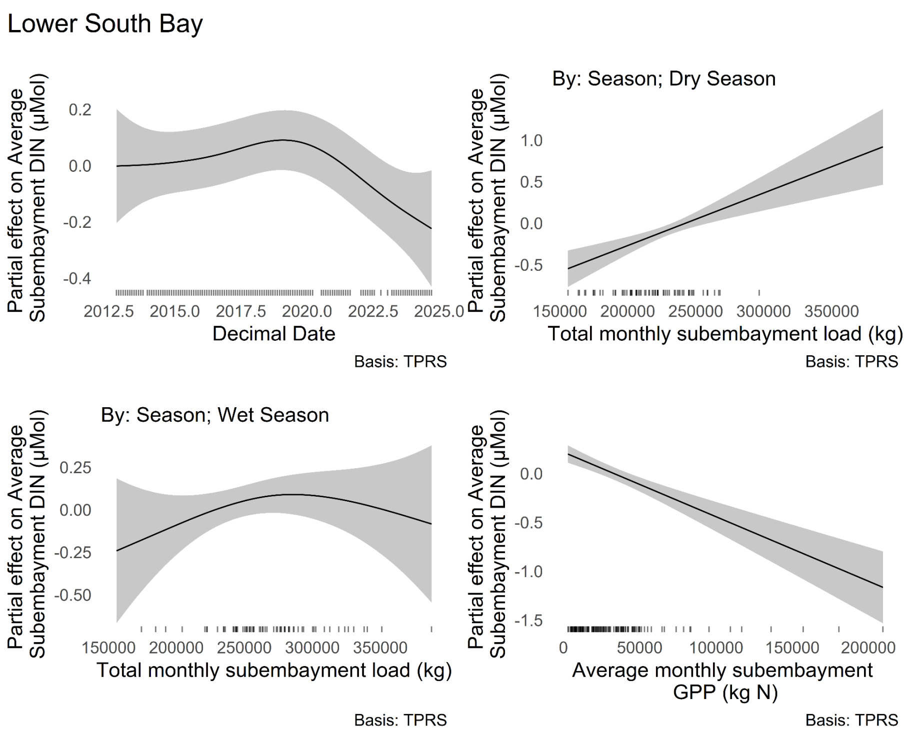

Figure S1: GAM output for Lower South Bay (y-axis is in logarithmic units)

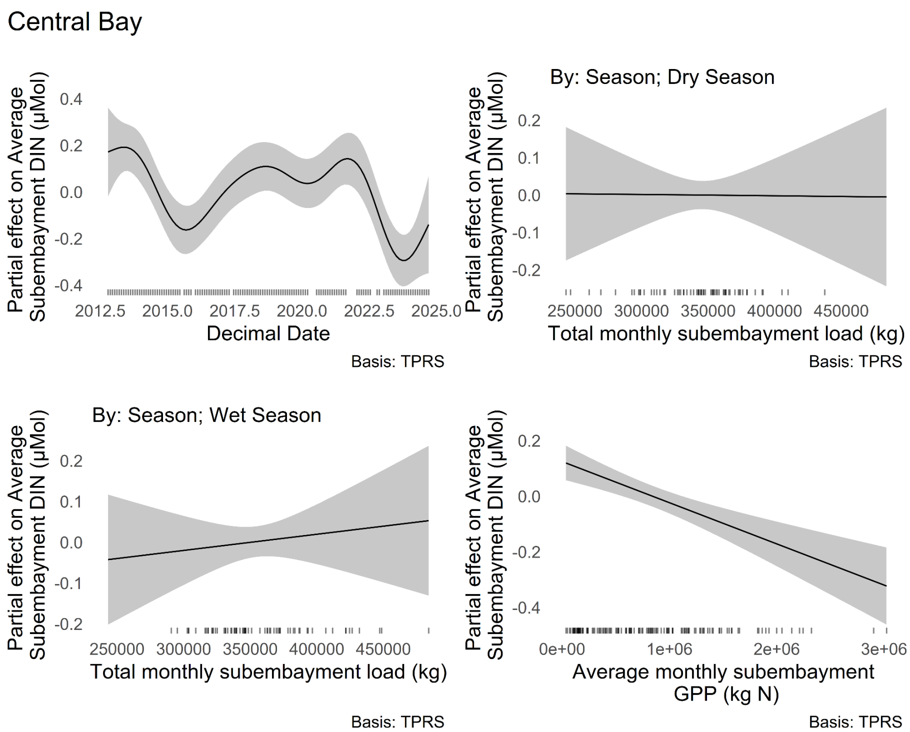

Figure S2: GAM output for Central Bay (y-axis is in logarithmic units)

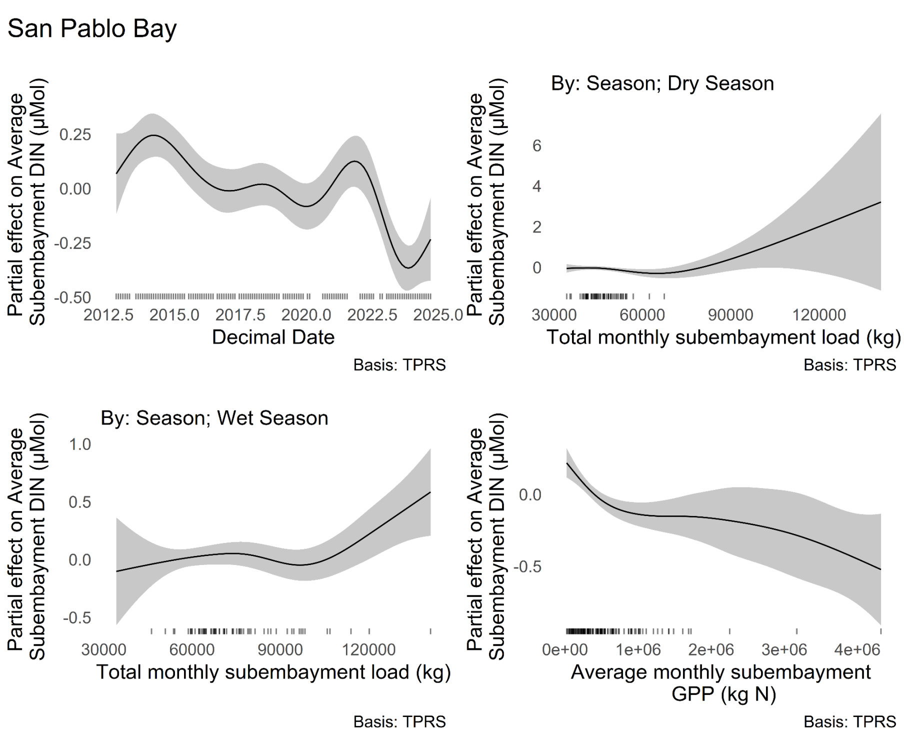

Figure S3: GAM output for San Pablo Bay (y-axis is in logarithmic units)

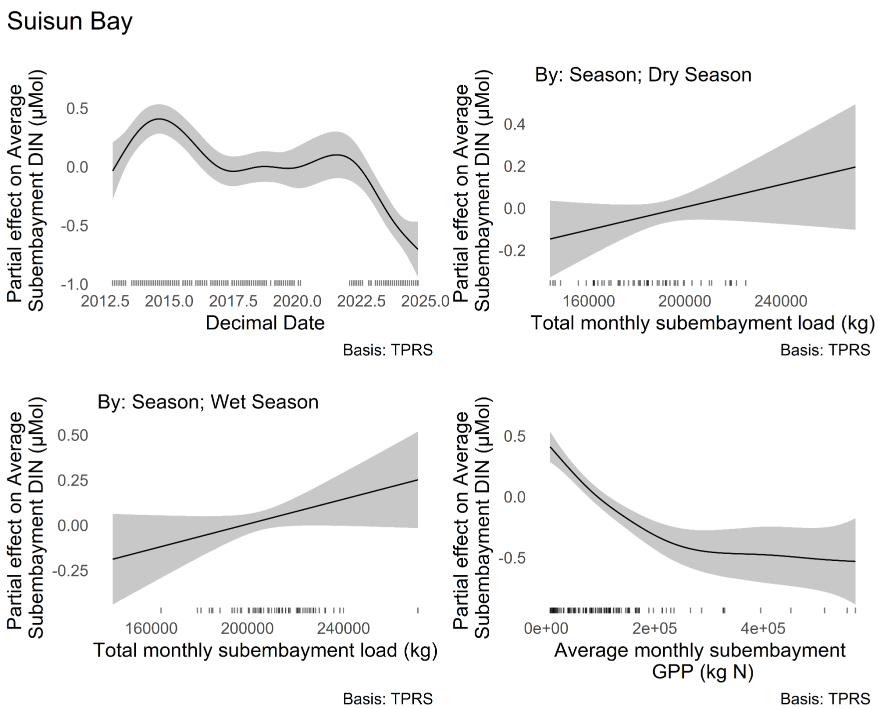

Figure S4: GAM output for Suisun Bay (y-axis is in logarithmic units)

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