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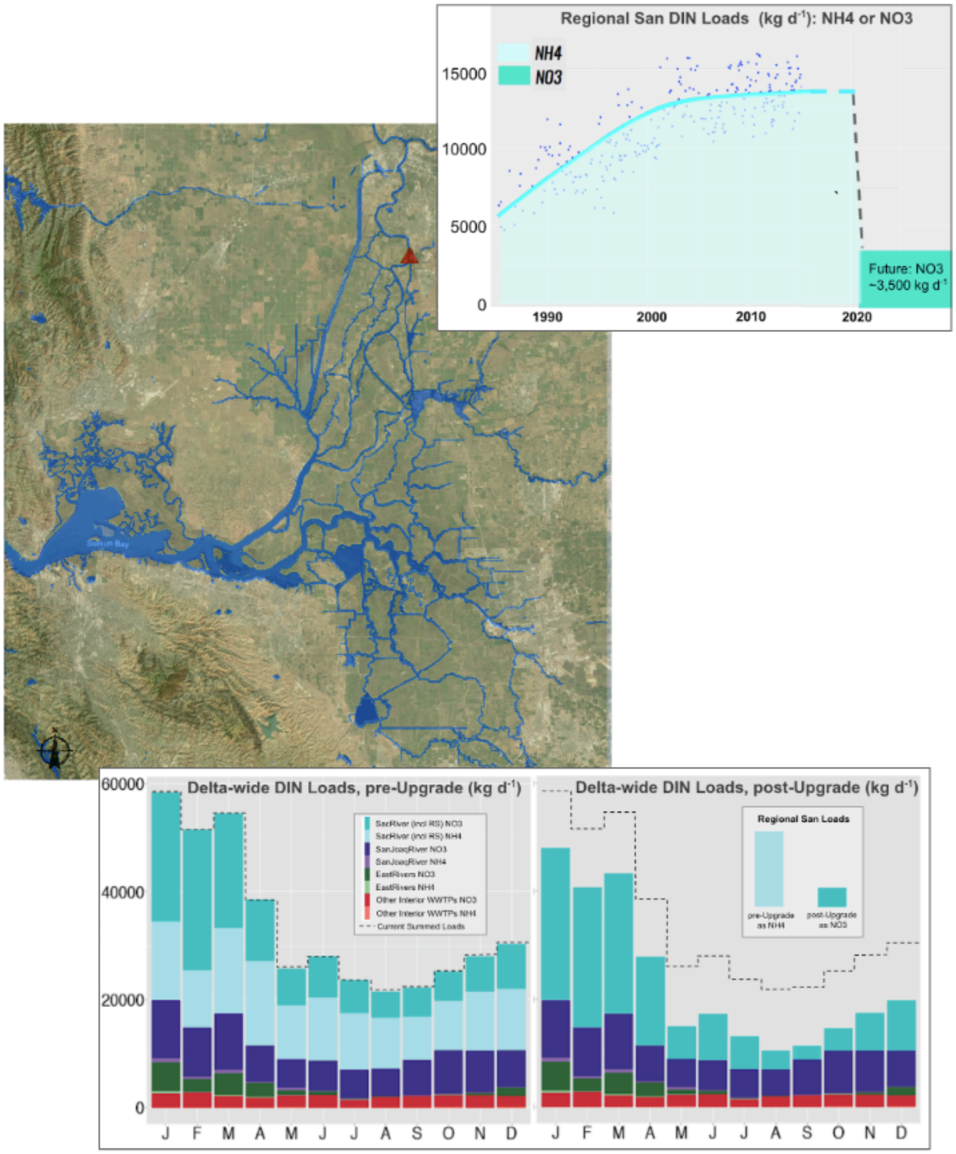

David Senn, Tamara Kraus, Amy Richey, Brian Bergamaschi, Larry Brown, Louise Conrad, Christopher Francis, Wim Kimmerer, Raphael Kudela, Timothy Otten, Alexander Parker, April Robinson, Anke Mueller-Solger, Dylan Stern, and Janet Thompson

SFEI Contribution #973

Changing nitrogen inputs to the northern San Francisco Estuary: Potential ecosystem responses and opportunities for investigation

DB Senn[1], TEC Kraus[2], A Richey[1], BA Bergamaschi[2], LR Brown[2], JL Conrad[3,4], CA Francis[5], W Kimmerer[6], RE Kudela[7], TG Otten[8], AE Parker[9], A Robinson[1], A Mueller-Solger[2], D Stern[4], and JK Thompson[2]

ABSTRACT

Anthropogenic activities have resulted in elevated ambient nitrogen (N) and phosphorus (P) concentrations in many regions of the Sacramento-San Joaquin Delta and Suisun Bay (northern San Francisco Estuary, nSFE). The Sacramento Regional wastewater treatment plant (SRWTP WWTP) currently acts as the largest N point source to the system, discharging 13,000-15,000 kg/d of ammonium-N (NH4) near the nSFE's northeastern boundary. By end of 2021, SRWTP will complete major upgrades that will reduce its effluent dissolved inorganic nitrogen (DIN) loads by >65% and release the remaining DIN as predominantly nitrate (NO3). This major change in nitrogen inputs provides a unique opportunity to study ecosystem-scale responses to an altered nutrient regime. While, in general, the nSFE has not experienced some classic symptoms of nutrient over-enrichment typical in other estuaries—e.g., large phytoplankton blooms and hypoxia—other concerning nutrient-related impacts have been hypothesized, including: occurrence of harmful algal blooms (HABs) and the production of cyanotoxins; excessive growth of invasive aquatic vegetation; and declines in the abundance and nutritional quality of phytoplankton. These impacts have repercussions for the system's food web, and habitat quality, as well as the way we manage for transportation, recreation, water conveyance, and drinking water quality. This report develops and applies a framework for i) identifying and examining ecosystem response scenarios to the forthcoming decreased N loads; and ii) identifying opportunities, and constraints or considerations, for investigating those responses, including key data needs or knowledge gaps. Through applying this framework, we identify a set of plausible response scenarios, and evaluate the feasibility of studying or observing those responses along with key study considerations and data and knowledge gaps.

[1]San Francisco Estuary Institute; [2]United States Geological Survey (USGS); [3]CA Department Water Resources; [4]Delta Science Program; [5]Stanford University; [6]San Francisco State University Estuarine & Ocean Science Center; [7]UC Santa Cruz; [8]Bend Genetics, [9]CSU Maritime Academy

ACKNOWLEDGEMENTS

This report benefitted from input shared by numerous stakeholders, regulators, and scientists working in the northern San Francisco Estuary. This project was primarily funded by the Delta Science Program's Operation Baseline initiative, with additional support from the San Francisco Bay Nutrient Management Strategy.

1. INTRODUCTION

Nutrient enrichment of aquatic ecosystems ranks among the most impactful and challenging anthropogenic water quality issues worldwide in terms of affects on freshwater, estuarine, and coastal systems; the areal extent and severity of those impacts; and the costs associated with mitigation (NRC, 2000; Cloern 2001; Statham 2012; Pearl et al. 2014). Aquatic systems draining urbanized or agricultural watersheds are often the most substantially impacted (NRC 2000), with excess nutrient loading leading to varied adverse responses, including eutrophication (increased organic matter production), hypoxia, harmful algal blooms (HABs), alteration of food webs, and reductions in fisheries (NRC 2000, Bricker et al. 2007; Diaz and Rosenberg 2008).

The northern San Francisco Estuary (nSFE; Figure 1), including the Sacramento-San Joaquin Delta and Suisun Bay, receives large inputs of anthropogenic nutrients, resulting in elevated ambient dissolved nitrogen (N) and dissolved phosphorous (P) concentrations (Novick et al. 2015; Kraus et al. 2017a) that exceed levels linked to adverse impacts in many other freshwater and estuarine systems (Elser et al. 2007; Paerl 2009; Dahm et al. 2016). Although many habitats within the nSFE are nutrient-enriched, characteristics of the nSFE – in particular high turbidity and high benthic grazing rates – have limited the occurrence of classic eutrophication symptoms of nuisance phytoplankton blooms and hypoxia (Cloern 2001; Jassby 2008; Kimmerer and Thompson 2014). In fact, large swaths of the nSFE are considered food-limited due to low phytoplankton production (Jassby et al. 2002; Jassby 2008). The nSFE's nutrient-enriched state has nonetheless remained a major concern, with environmental managers examining potential linkages between excess nutrients and other ecological concerns (DSC 2013; CVRWQCB 2015; Cooke et al. 2018), including: harmful algal blooms (HABs), in particular the toxin-producing cyanobacteria *Microcystis* spp. (Lehman et al. 2005; Lehman et al. 2017); rapidly spreading and dense invasive aquatic vegetation (iAV), which interferes with boating and water exports, traps sediment, and provides habitat for introduced predator fish species (Boyer and Sutula 2015; Ta et al. 2017); and declines in phytoplankton blooms or changes to phytoplankton community that adversely impact the pelagic foodweb (e.g., Sommer et al. 2007; Dugdale et al. 2007; Glibert et al. 2011; Parker et al. 2012; NRC 2012). Nutrient management decisions in the nSFE must also take into account potential changes in how the system responds to nutrients, due to plausible changes in physical forcings. For example, continuation of the decades-long decrease in sediment loads, and increasing nSFE water clarity (Kimmerer 2004; Cloern and Jassby 2012; Schoellhamer et al. 2016) could foster excessive phytoplankton production and low dissolved oxygen. Increases in light availability, along with anticipated increases in water temperature (Brown et al. 2016a), may also leave regions of the nSFE susceptible to more frequent and severe HAB events.

Currently, the Sacramento Regional Wastewater Treatment Plant (SRWTP), which discharges treated wastewater to the Sacramento River at the Delta's northeast boundary (Figure 1), is one of the largest nutrient sources to the nSFE, and the largest ammonium (NH4) point source to the Sacramento River (Figure 2; Jassby 2008; Saleh and Domagalski 2015; Novick et al. 2015). SRWTP's nitrogen loads have increased approximately 2-fold since the 1980s (Jassby 2008; Figure 2). Notably, SRWTP is overall the largest source of dissolved inorganic N (DIN = NH4 + nitrate (NO3)) to nSFE during non-winter months, exceeding all tributary inputs when their flows are at their seasonal minimum (Novick et al. 2015). Major upgrades to SRWTP (~$2B), with expected completion by end of 2021, will substantially alter SRWTP's N inputs to the Delta by decreasing total dissolved inorganic N loads by >65%, with the remaining discharged N occurring primarily as nitrate (NO3), as opposed to the current NH4-dominated release (Figure 2). Since nutrients have the potential to influence primary production and microbial metabolism, the upgrade could in theory have many and major effects on ecosystem function and condition. How the nSFE will actually respond, though, is highly uncertain because, in addition to nutrients, multiple other time- and space-varying factors influence those responses, e.g., physical connectivity, flow patterns, temperature, light availability, and foodweb interactions (Ward and Paerl, 2017).

This report develops and applies a framework for i) identifying and examining ecosystem response scenarios to the forthcoming decreased N loads; and ii) identifying opportunities and constraints for investigating those responses, including key data needs or knowledge gaps. Through applying this framework, we aim to provide a menu of plausible response scenarios and important considerations for use by regulators, managers, and the scientific community for prioritizing among scientific investigations that can address ecosystem management and ecosystem processes questions.

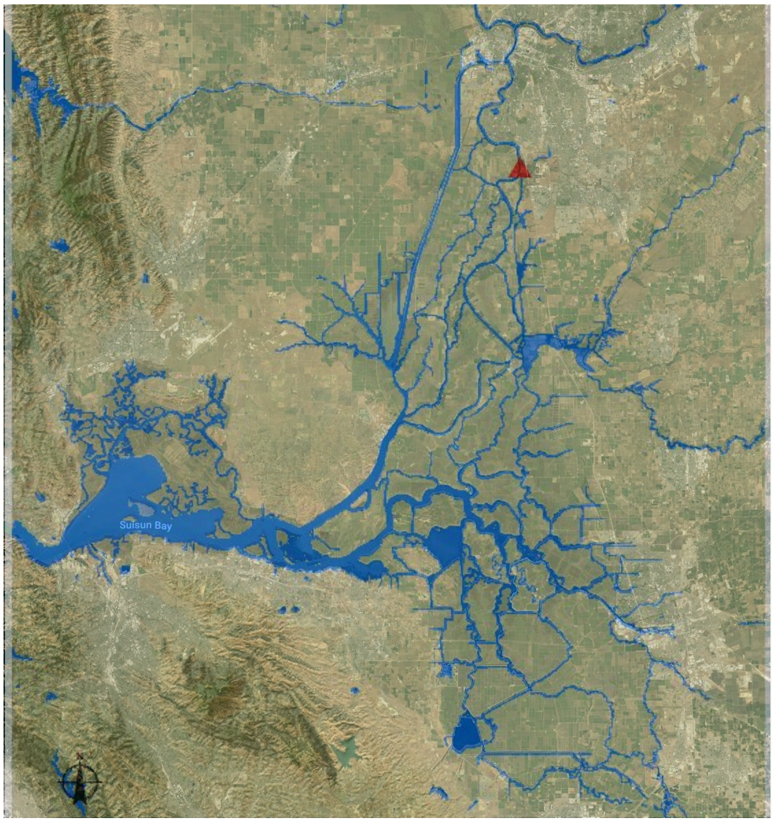

Figure 1 Map of the northern San Francisco Estuary, including the Delta and Suisun Bay. Red triangle: location of Regional San WWTP outfall, discharging to the Sacramento River.

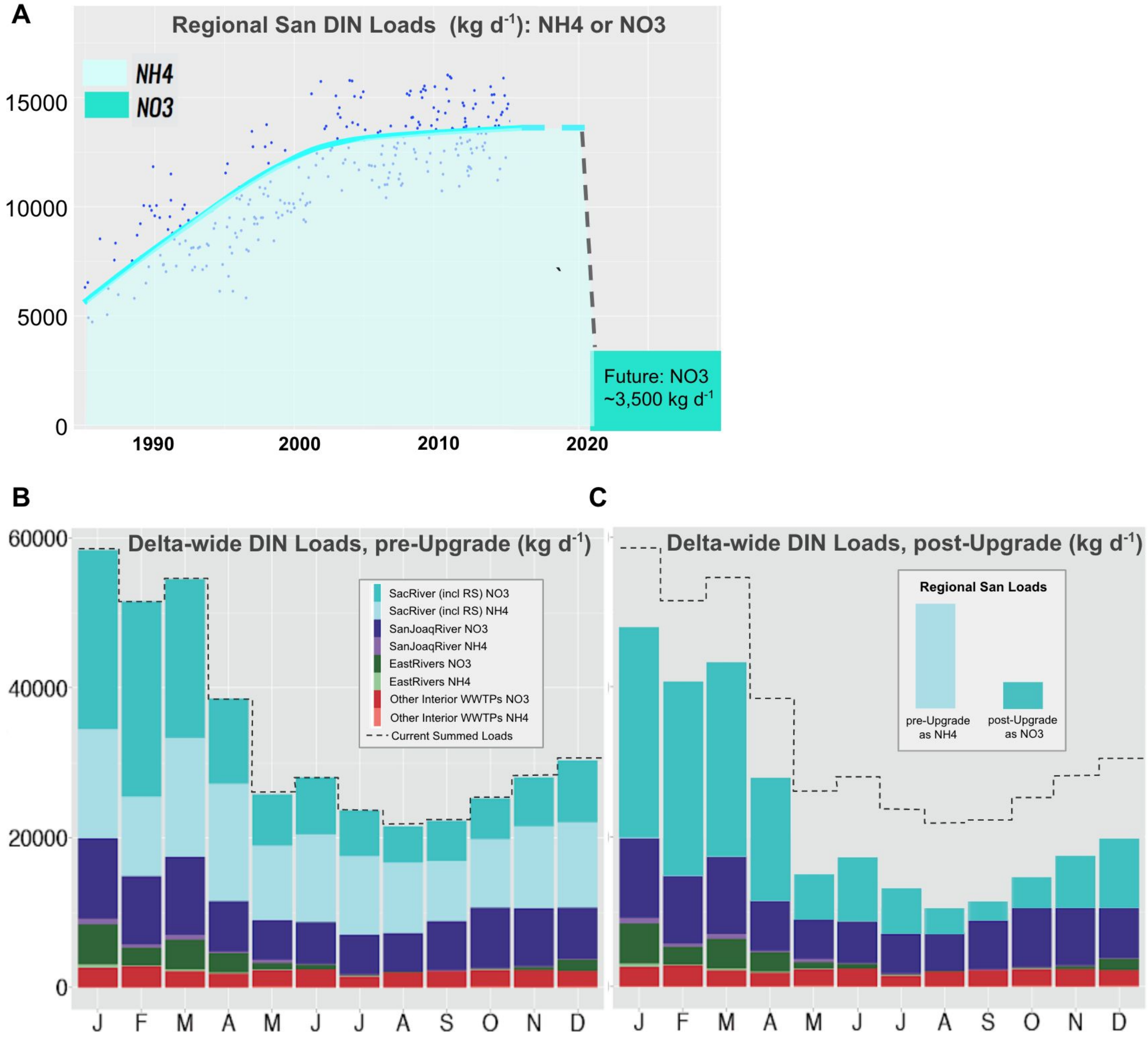

Figure 2: **A.** Time series of inorganic N loads from SRWTP, 1985-2016, and estimated post-upgrade loads. Points represent calculated load (Measured Concentration x Flow) based on monthly data (Data: pre-2005, Jassby 2008; 2008-2016, current study, using data obtained from Regional San); curve approximates annual average loads. Current N loads are predominantly in the form of ammonium (NH4). The upgrade will add nitrification and denitrification steps to the treatment plant, substantially decreasing dissolved inorganic N (DIN) loads and converting most of the NH4 to nitrate (NO3). **B**. DIN loads to the Delta as a function of month, depicting proportions entering as ammonium (NH4) and nitrate (NO3). Loads entering via the Sacramento, San Joaquin, and eastern tributaries (Mokelumne and Cosumnes) were estimated using monthly flow rate and monthly NH4 and NO3 concentration data, with monthly averages estimated for the period 2007-2013 (see Novick et al. 2015). Sacramento River loads were estimated using a site downstream of Regional San's outfall (DWR-EMP station C3, ~4km downstream of outfall), and therefore include SRWTP's contribution. Other interior WWTP loads (red) include inputs from Stockton and Tracey. **C.** Post-upgrade estimated DIN loads. Estimated by adjusting Sacramento River loads to account for Regional San's anticipated future inputs, assuming the following: Current loads: ~14000 kg N/d, ~100% of DIN as NH4; Future: ~3500 kg N/d, ~100% of DIN as NO3. These plots are presented as semiquantitative overviews. The current Sacramento River load estimates suggest that some NH4 loss had already taken place by the time water reached station C3 during summer months, which is consistent known nitrification rates (e.g., Kraus et al. 2017a). To approximate future loads, DIN was assumed to behave conservatively over the stretch from the outfall to C3, and the difference between SRWTP's current and future DIN loads (~10500 kg d^{-1}) was subtracted from Sacramento NH4 and NO3 loads.

2. BACKGROUND and APPROACH

2.1 Background

The nSFE (Figure 1) serves as critical aquatic habitat and as a vital drinking water resource for 25 million Californians and irrigation water for the agriculturally-rich Central Valley (e.g., Jassby, 2008). It is also a physically, biologically, and hydrologically complex system, receiving flows from the Sacramento and San Joaquin Rivers, which drain approximately 40% of California and then move through and merge within the Delta, a maze-like network of interconnected channels and sloughs. The Delta has undergone physical alterations over the past 150 years that have altered the system's hydrology, terrestrial and aquatic habitats, and the ecosystem services these habitats provide (e.g., Whipple et al. 2012). A substantial portion of water entering the Delta (≥25% annually) is exported for irrigated agriculture and domestic water use (Jassby, 2008). The Delta also receives considerable inputs of treated wastewater effluent and agricultural runoff, both of which contribute the nutrients nitrogen (N) and phosphorous (P) (Novick et al. 2015) and other contaminants.

Long-term observational data indicate that the nSFE is in a state of severe ecological decline (e.g., Sommer et al. 2007; Thomson et al. 2011; NRC 2012). Population collapses of several pelagic fish species, including the endemic Delta smelt, have received considerable scientific attention in terms of both extensive monitoring and targeted investigations, with results pointing to the combined impacts of multiple anthropogenic stressors contributing to the population declines (Sommer et al. 2007; Baxter et al. 2010; Hanak et al. 2013; NRC 2012), including: landscape alterations and habitat loss; species invasions; water withdrawals; declining food resources; and agriculturally- and wastewater-derived contaminants, including nutrients. While the 'endangered fish vs. water withdrawals' debate typically receives the most public dialogue and regulatory attention, there is also evidence for negative impacts on habitat quality at lower trophic levels, such as harmful algal blooms, invasive aquatic macrophytes, localized issues with low dissolved oxygen, and excessive anthropogenic nutrients (Novick et al., 2015; Dahm et al. 2016; Brown et al. 2016b). Related to these latter issues, the Central Valley Regional Water Quality Control Board (CVRWQCB) sponsored a series of white papers exploring priority nutrient management issues[1], which culminated in the Delta Nutrient Research Plan (Cooke et al. 2018). The Delta Nutrient Research Plan in turn served as a basis for this project's high-level management priorities.

The SRWTP upgrade will substantially reduce nutrient loads to the nSFE (Figure 2). Studying ecosystem-scale responses to this altered nutrient regime provides unique opportunities to inform adaptive management decisions in the nSFE, and also to advance fundamental understanding of nutrient dynamics in freshwater and estuarine systems. However, given the nSFE's size and complexity, and the numerous nutrient-related responses that have been hypothesized for this system, a structured approach was needed for systematically examining potential responses to inform prioritization of science and monitoring work.

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[1] https://www.waterboards.ca.gov/centralvalley/water_issues/delta_water_quality/delta_nutrient_research_plan/index.html

2.2 Approach and Organization

Approach

We developed a framework that allowed for i) Identifying a broad set of potential ecosystem responses to the forthcoming decreased N loads; and ii) Systematically examining those responses and evaluating the feasibility of studying or observing those responses, including important data needs and knowledge gaps. The framework (Figure 3) consisted of three major components:

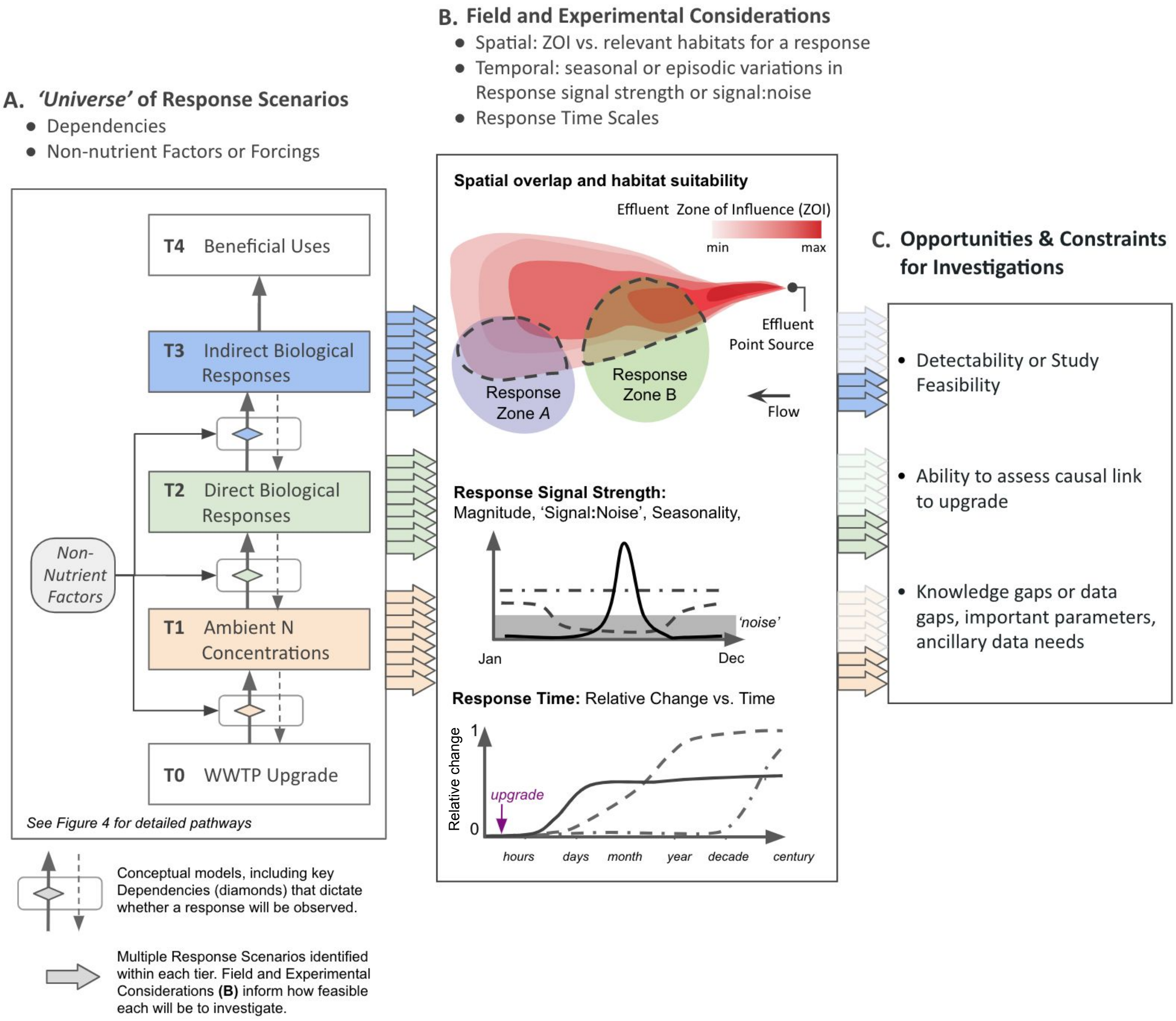
- 'Universe' of Response Scenarios (Figure 3A)
- Field and Experimental Considerations (Figure 3B)
- Opportunities and Constraints for investigations (Figure 3C)

Universe of Response Scenarios*:* Three organizing principles shaped the approach to identifying a starting set of 'response scenarios':

1. *Wide Net:* At the outset, we cast a wide net to gather a broad initial set of response scenarios from the scientific literature, nSFE technical reports, and management-related documents focused on the effects of nutrients in nSFE.
2. *Link to Upgrade along Bottom-up Pathways:* Numerous factors influence ecological responses and overall ecosystem function, including natural and anthropogenic physical, biological, and chemical forcings. The analysis here focused only on response scenarios that could be linked to the upgrade's nutrient load reductions, and adopted the basic premise that nutrients exert influence along "bottom-up" pathways by first directly influencing primary production (phytoplankton, macrophytes, aquatic vegetation) or the non-photosynthetic microbial community (heterotrophic, chemoautotrophic; referred to hereafter as microbes). Both direct and indirect responses were included; however, a key inclusion criterion for indirect responses were that they occur through a series of biological responses, initiated by a direct bottom-up response to nutrient load reductions.
3. *Management Endpoints:* Nutrient-related management priorities, identified by regulators, managers, and stakeholders (e.g., Delta Nutrient Research Plan, CVRWQCB, 2018) are the primary motivation for this analysis, and thus serve as the ultimate endpoints.

Following this approach, a diverse set of response scenarios (Figure 4, Table 4) was identified. Each response scenario falls along a complete pathway, originating from an anticipated change in nutrient loads (T0), and extending to one of seven nutrient-related management priorities (T4). Intermediate responses were grouped into three tiers: changes in ambient nutrient concentrations (T1); direct biological responses (T2); and higher-level biological responses, including food web interactions (T3). Within T1-T3, we used conceptual models to identify nutrient-linked mechanisms, influential non-nutrient physical and biological factors, and key dependencies - i.e., conditions that must be satisfied for the response to occur.

Field and Experimental Considerations: Casting a wide net yielded a large and diverse set of potential responses. While this served as a useful starting place, to identify opportunities for investigations additional criteria were needed to evaluate responses scenarios in terms of their 'study-ability' (Figure 3,



Criteria	Major Considerations
Detect? Feasibility of detecting or observing a response (or lack thereof)	1. Analytical methods (sensitivity, specificity) 2. Spatial overlap between study site(s) and ZOI (see Box 1) 3. Signal:Noise -- Effect size vs. Natural variability 4. Data density (space, time, length of record)
Test Link? Ability to attribute a response (or lack thereof) to upgrade	5. Number of steps (tiers) removed from the upgrade (T0) 6. Potential for changes in other influential factors in the system 7. Response time
Occur? Likelihood that a hypothesized response will occur, and be substantial or important at an ecosystem-scale	8. Correct conceptual model, correct mechanisms and drivers; 9. Key dependencies satisfied, relative importance of processes

Figure 3 Framework for identifying and exploring Response Scenarios. The inset table summarizes the criteria by which Response Scenario were evaluated in Step B.

inset table): 1. Will the response be detectable *(Detect)*? 2. Will a link to the upgrade be testable *(Test Link)*? 3. How likely is it that the response will occur, and be substantial at the ecosystem-scale *(Occur)*?

The likelihoods with which response scenarios satisfied each criterion were scored categorically from Likely to Unlikely, based on a set of 9 basic considerations summarized in Figure 3's inset table. That assessment helped identify or further clarify dependencies, important data and knowledge gaps, and study requirements, for example: What components of a study would maximize the likelihood of detecting change(s)? What observations are needed to unambiguously determine whether upgrade-related nutrient decreases caused (directly or indirectly) the response? What work is needed to target unresolved science questions, competing hypotheses, or critical data gaps?

Opportunities & Constraints: The results from the above evaluations were distilled down to set of opportunities and constraints related to the potential for investigating response scenarios, including identifying data and knowledge gaps, and key dependencies or study design requirements. A key aspect of this distillation was integrating across the individual response scenarios to identify shared data and knowledge gaps and synergies among study requirements. In addition to the integrated discussion, the major outputs for this step include two tables providing at-a-glance overviews, one compiling the relative likelihoods of successfully testing the full set of response scenarios (Table 2), and the second capturing the compiled data and knowledge gaps (Table 3).

Organization

The Results and Discussion section is structured to allow the reader to jump straight to the take-home messages, with main observations distilled into summary materials (Figure 4, Tables 2-3), and deeper dives into technical topics consolidated within six technical Boxes. Each Box (Box 1-Box 6) follows a similar structure, beginning with basic background and each topics ecological importance and management relevance. Next, conceptual models are used to describe the set of mechanisms that shape ecosystem responses and lead to one or more response scenarios occurring, along with important unknowns or uncertainties. Each Box ends with an Overview, consisting of four components: suitability of nSFE regions or habitats for studying responses; anticipated response times; dependencies, or prerequisites, that will influence whether a scenario occurs; and a summary of response scenarios' study-ability (based on criteria in Figure 3).

Note: Although the term 'nutrients' is used throughout, the discussion below focuses primarily on changes to N loads to the nSFE, as opposed to changes to phosphorus (P). Phosphorus cycling, while taken into consideration, receives no explicit discussion since P loads are not expected to change as a result of the SRWTP upgrade. In addition, since this study focuses exclusively on potential effects from SRWTP's N loads, nutrient-related issues in areas outside SRWTP's zone of influence are not considered here.

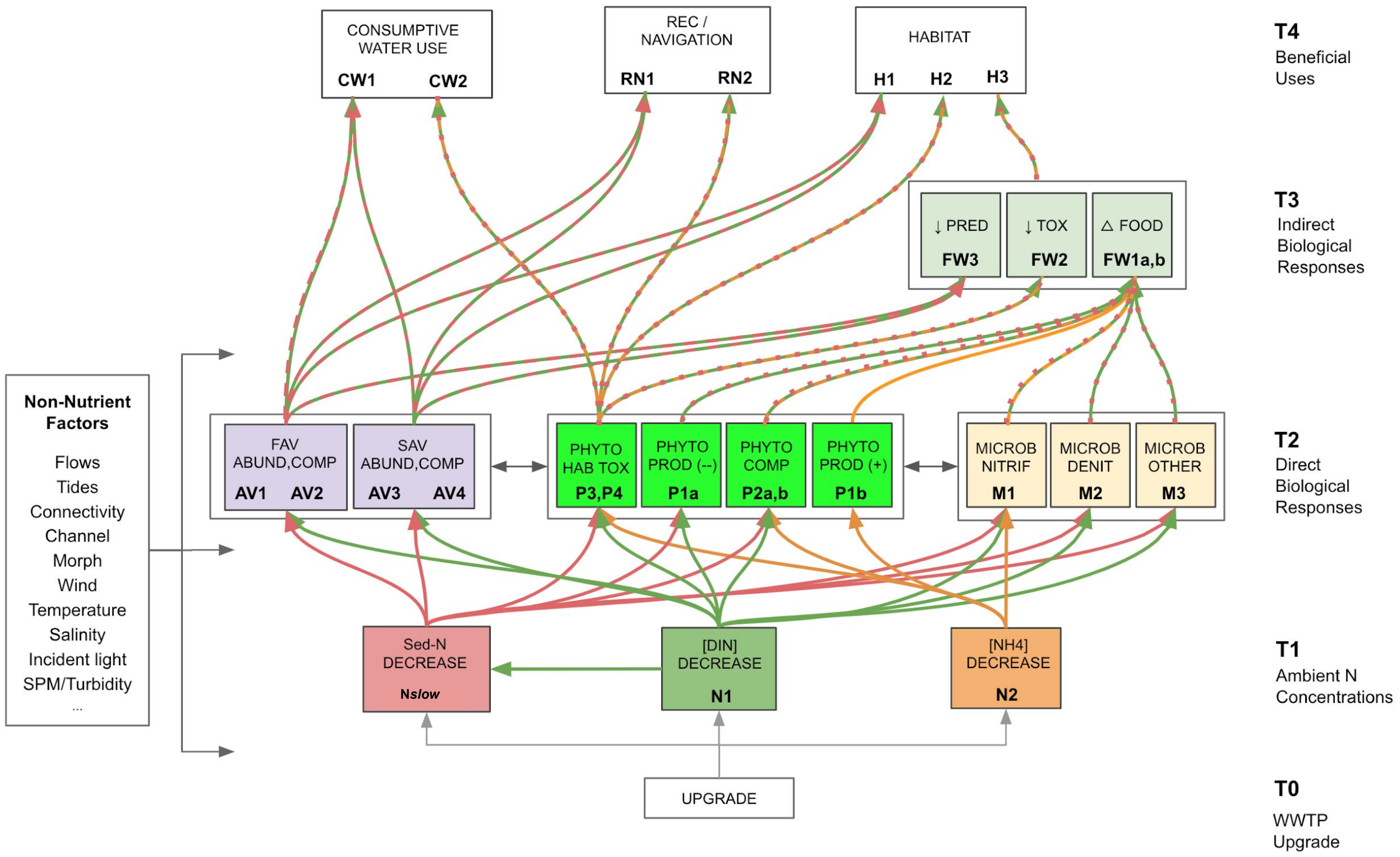
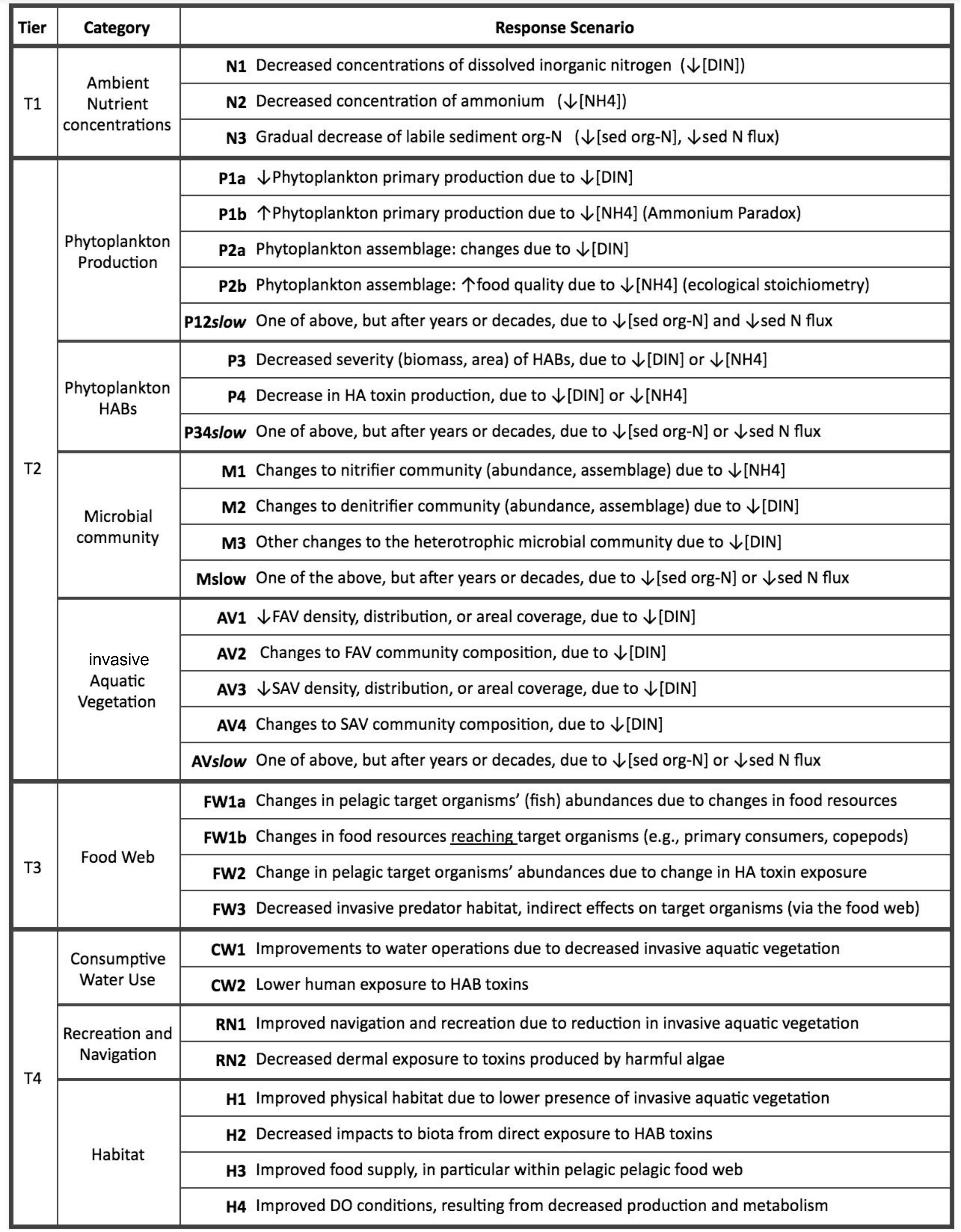


Figure 4 Response Scenarios (colored boxes; see Table 1 descriptions) organized along 'bottom-up' mechanistic pathways connecting the WWTP Upgrade (T0) with Beneficial Uses (T4). The pathways and the individual Response Scenarios along each path are all hypothetical. The likelihood that a response will occur, its magnitude (relative to natural variation), and its potential to trigger responses at higher tiers depends on an array of Non-Nutrient Factors that modulate biological and biogeochemical responses and other dependencies, as discussed in the text. Arrow color represents a pathway's origin in T1 (N1=green; N2=orange; N*slow*=red; multi-colored = multiple potential origins). ↔ connotes interactions/feedbacks between T2 responses, P↔M, AV↔P, and AV↔M which are discussed in the text.

Table 1 Response Scenarios related to the Sacramento Regional Wastewater Treatment Plant upgrade. See Figure 4 for organization of response scenarios along bottom-up mechanistic pathways. The management priorities included in Tier 4 capture high priority issues identified by regulators, managers, and stakeholders over the past decade (see Delta Nutrient Research Plan, Cooke et al, 2018).



Tier	Category	Response Scenario	
T1	Ambient Nutrient concentrations	**N1**	Decreased concentrations of dissolved inorganic nitrogen (↓[DIN])
		N2	Decreased concentration of ammonium (↓[NH4])
		N3	Gradual decrease of labile sediment org-N (↓[sed org-N], ↓sed N flux)
T2	Phytoplankton Production	**P1a**	↓Phytoplankton primary production due to ↓[DIN]
		P1b	↑Phytoplankton primary production due to ↓[NH4] (Ammonium Paradox)
		P2a	Phytoplankton assemblage: changes due to ↓[DIN]
		P2b	Phytoplankton assemblage: ↑food quality due to ↓[NH4] (ecological stoichiometry)
		P12*slow*	One of above, but after years or decades, due to ↓[sed org-N] and ↓sed N flux
	Phytoplankton HABs	**P3**	Decreased severity (biomass, area) of HABs, due to ↓[DIN] or ↓[NH4]
		P4	Decrease in HA toxin production, due to ↓[DIN] or ↓[NH4]
		P34*slow*	One of above, but after years or decades, due to ↓[sed org-N] or ↓sed N flux
	Microbial community	**M1**	Changes to nitrifier community (abundance, assemblage) due to ↓[NH4]
		M2	Changes to denitrifier community (abundance, assemblage) due to ↓[DIN]
		M3	Other changes to the heterotrophic microbial community due to ↓[DIN]
		Mslow	One of the above, but after years or decades, due to ↓[sed org-N] or ↓sed N flux
	invasive Aquatic Vegetation	**AV1**	↓FAV density, distribution, or areal coverage, due to ↓[DIN]
		AV2	Changes to FAV community composition, due to ↓[DIN]
		AV3	↓SAV density, distribution, or areal coverage, due to ↓[DIN]
		AV4	Changes to SAV community composition, due to ↓[DIN]
		AV*slow*	One of above, but after years or decades, due to ↓[sed org-N] or ↓sed N flux
T3	Food Web	**FW1a**	Changes in pelagic target organisms' (fish) abundances due to changes in food resources
		FW1b	Changes in food resources reaching target organisms (e.g., primary consumers, copepods)
		FW2	Change in pelagic target organisms' abundances due to change in HA toxin exposure
		FW3	Decreased invasive predator habitat, indirect effects on target organisms (via the food web)
T4	Consumptive Water Use	**CW1**	Improvements to water operations due to decreased invasive aquatic vegetation
		CW2	Lower human exposure to HAB toxins
	Recreation and Navigation	**RN1**	Improved navigation and recreation due to reduction in invasive aquatic vegetation
		RN2	Decreased dermal exposure to toxins produced by harmful algae
	Habitat	**H1**	Improved physical habitat due to lower presence of invasive aquatic vegetation
		H2	Decreased impacts to biota from direct exposure to HAB toxins
		H3	Improved food supply, in particular within pelagic pelagic food web
		H4	Improved DO conditions, resulting from decreased production and metabolism

3. RESULTS and DISCUSSION

3.1 Overview

Twenty five response scenarios were identified across Tiers 1-3 (Figure 4, Table 1) and organized into six categories: Ambient Nutrients (Box 1); Phytoplankton Production (Box 2); Harmful Algal Blooms (HABs; Box 3); Invasive Aquatic Vegetation (iAV; Box 4); Microbial Community (Box 5); and Higher Trophic Level Food Web (FW; Box 6). Two overarching topics, Wetlands and Drinking Water Quality, receive additional discussion Appendix A, with relevant technical concepts covered in Boxes 1-6.

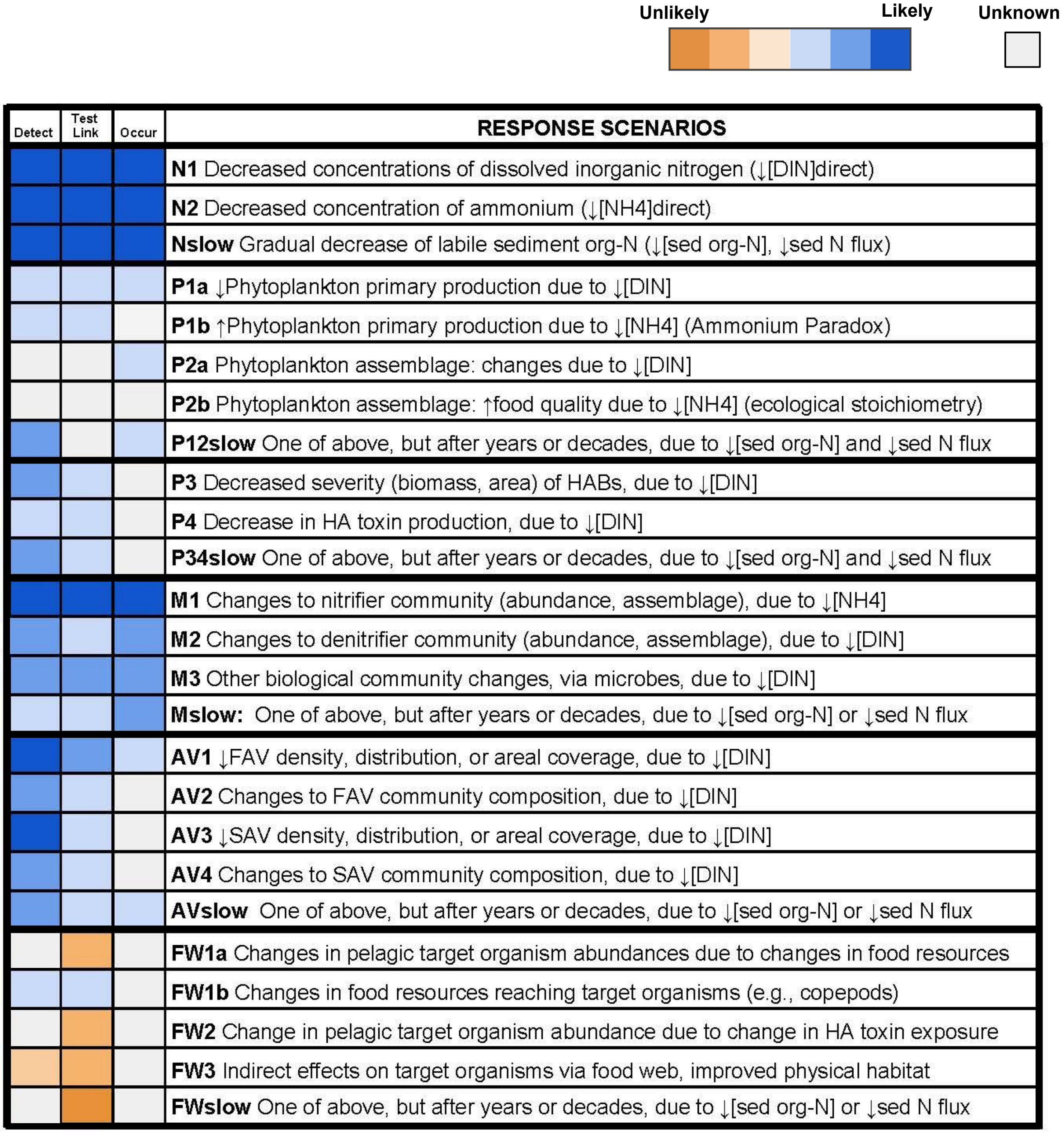
Although the response scenarios all link back to the upgrade along mechanistic pathways, they differ considerably in the ease, or feasibility, with which they can be investigated. Each response scenario's 'study-ability' (Figure 3b, including inset table) was evaluated (see Boxes for details), with an overview presented in Table 2. Changes to ambient N levels (Tier 1) can be predicted with high confidence, at least in terms of the direction(s) of change. In addition, although major data gaps need to be addressed to allow for accurate predictions of space-time variations in post-upgrade ambient N concentration, tractable studies can be designed to address those gaps.

The potential influences of the upgrade on Tier 2 responses, however, are much less certain, and will be more difficult to investigate (Table 2). Multiple other factors, in addition to nutrients, influence phytoplankton production, HAB, and iAV responses, some of which are poorly understood while others represent major data gaps that would need to be addressed in field studies. The upgrade nonetheless presents unique opportunities to, for example, test whether the form of N has a major influence on phytoplankton production (P1b), or whether nutrient load reductions decrease the frequency or severity of HABs (P3,P4) or reduce the density or spatial coverage of some iAV species (AV1, AV3).

Most Tier 3 (higher trophic level food web) response scenarios would be extremely difficult to detect or confidently establish a linkage to the upgrade (Table 2). There are simply too many steps along the mechanistic pathways, possible interactions or covariates to consider, and time lags between the upgrade and potential population-level effects to allow for a response to be unambiguously attributed to the upgrade. Changes to some indicators of copepod production (FW1a) are one notable exception.

Table 3A compiles major data or knowledge gaps (rows) identified while exploring response scenarios in Boxes 1-6, with Table 3B providing additional context. Each of the gaps G1-G18 was added initially based on its relevance to a specific response scenario (e.g., G1 and G2 were priorities for scenarios N1 and N2; G3 was a priority for N*slow*). Gaps were subsequently ranked for their priority-level related to other response scenarios. Rows containing more (and darker) red indicate data or knowledge gap that are of high relevance or high priority for investigating multiple scenarios. G18-G21 were included as priorities that broadly relevant across all (or most) response scenarios.

Table 2 Summary of categorical scores assessing response scenario ‘study-ability’ (See Figure 3 inset table): Detectable? Ability to Test Link to Upgrade? Likelihood of Occurring? See Boxes 1-6 for further discussion.

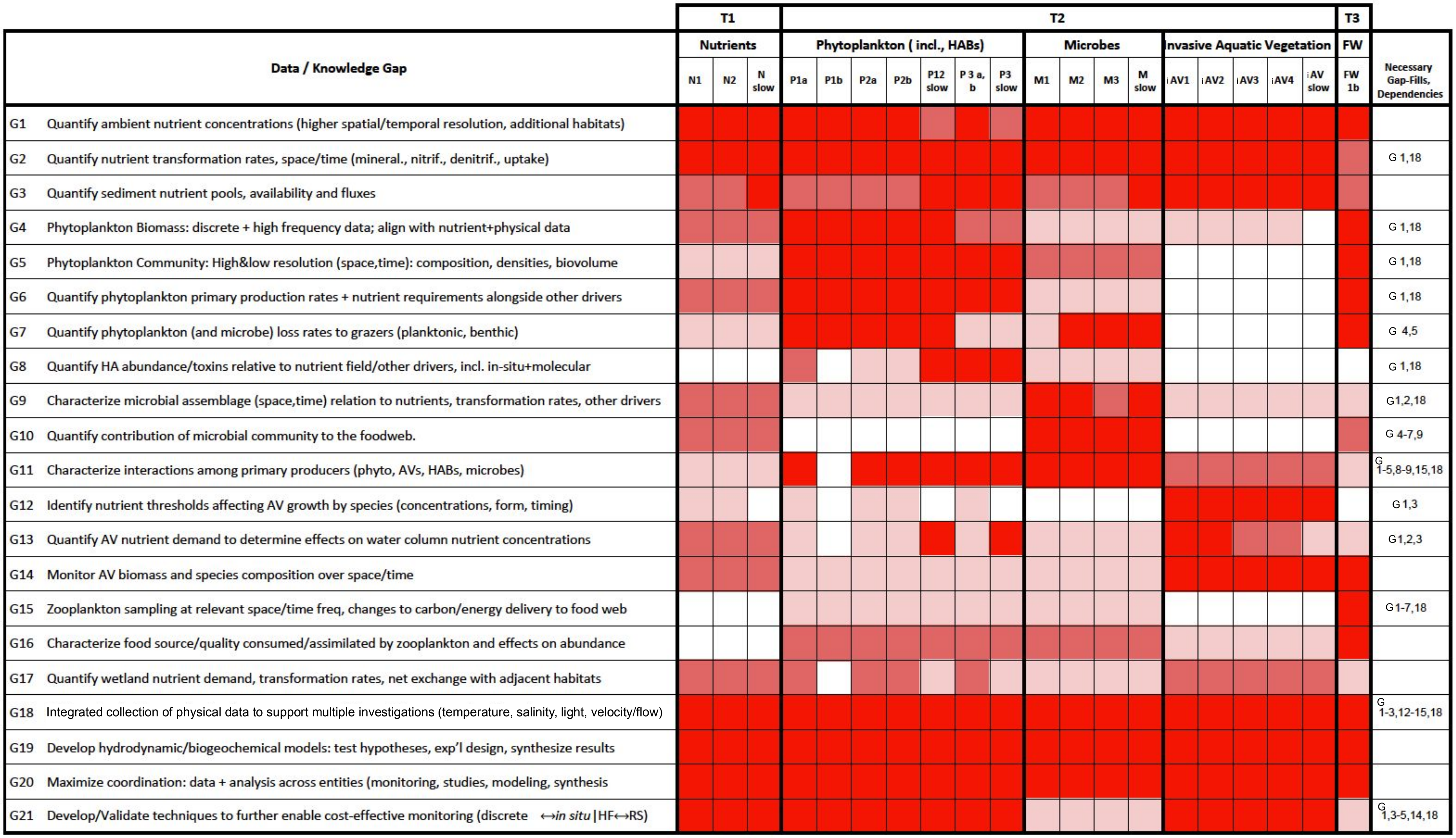


Unlikely 🟧 🔶 🔸 🔹 🔷 🟦 **Likely** **Unknown** ⬜

Detect	Test Link	Occur	RESPONSE SCENARIOS
🟦	🟦	🟦	**N1** Decreased concentrations of dissolved inorganic nitrogen (↓[DIN]direct)
🟦	🟦	🟦	**N2** Decreased concentration of ammonium (↓[NH4]direct)
🟦	🟦	🟦	**Nslow** Gradual decrease of labile sediment org-N (↓[sed org-N], ↓sed N flux)
🔹	🔹	🔹	**P1a** ↓Phytoplankton primary production due to ↓[DIN]
🔹	🔹	⬜	**P1b** ↑Phytoplankton primary production due to ↓[NH4] (Ammonium Paradox)
⬜	⬜	🔹	**P2a** Phytoplankton assemblage: changes due to ↓[DIN]
⬜	⬜	⬜	**P2b** Phytoplankton assemblage: ↑food quality due to ↓[NH4] (ecological stoichiometry)
🔷	⬜	🔹	**P12slow** One of above, but after years or decades, due to ↓[sed org-N] and ↓sed N flux
🔷	🔹	⬜	**P3** Decreased severity (biomass, area) of HABs, due to ↓[DIN]
🔹	🔹	⬜	**P4** Decrease in HA toxin production, due to ↓[DIN]
🔷	🔹	⬜	**P34slow** One of above, but after years or decades, due to ↓[sed org-N] and ↓sed N flux
🟦	🟦	🟦	**M1** Changes to nitrifier community (abundance, assemblage), due to ↓[NH4]
🔷	🔹	🔷	**M2** Changes to denitrifier community (abundance, assemblage), due to ↓[DIN]
🔷	🔷	🔷	**M3** Other biological community changes, via microbes, due to ↓[DIN]
🔹	🔹	🔷	**Mslow:** One of above, but after years or decades, due to ↓[sed org-N] or ↓sed N flux
🟦	🔷	🔹	**AV1** ↓FAV density, distribution, or areal coverage, due to ↓[DIN]
🔷	🔹	⬜	**AV2** Changes to FAV community composition, due to ↓[DIN]
🟦	🔹	⬜	**AV3** ↓SAV density, distribution, or areal coverage, due to ↓[DIN]
🔷	🔹	⬜	**AV4** Changes to SAV community composition, due to ↓[DIN]
🔷	🔹	🔹	**AVslow** One of above, but after years or decades, due to ↓[sed org-N] or ↓sed N flux
⬜	🔶	⬜	**FW1a** Changes in pelagic target organism abundances due to changes in food resources
🔹	🔹	⬜	**FW1b** Changes in food resources reaching target organisms (e.g., copepods)
⬜	🔶	⬜	**FW2** Change in pelagic target organism abundance due to change in HA toxin exposure
🔸	🔶	⬜	**FW3** Indirect effects on target organisms via food web, improved physical habitat
⬜	🟧	⬜	**FWslow** One of above, but after years or decades, due to ↓[sed org-N] or ↓sed N flux

Table 3A Data needs and knowledge gaps identified in the conceptual framework for potential nutrient-related responses to the SRWTP upgrade. Cell color indicates the relevance of the data need or knowledge gap to each response. Note that data needs and knowledge gaps were identified for Tiers 1 and 2 only, with the exception of FW1b. The priorities (color) were assigned relatively for each Response (columns); relative priorities are therefore most pertinent within columns. While color across a row indicates that Data or Knowledge Gap is broadly applicable, the relative priorities are less meaningful. The far-right column (Necessary Gap-Fills, Dependencies) identifies other Data/Knowledge gaps (rows) upon which each row depends; i.e., for row 4, also pursuing rows 1 and 19 will make the data in row 4 most

■	very high
▩	high
░	moderate
□	not relevant



		T1			T2																T3	
		Nutrients			Phytoplankton (incl., HABs)							Microbes				Invasive Aquatic Vegetation					FW	
	Data / Knowledge Gap	N1	N2	N slow	P1a	P1b	P2a	P2b	P12 slow	P 3 a, b	P3 slow	M1	M2	M3	M slow	iAV1	iAV2	iAV3	iAV4	iAV slow	FW 1b	Necessary Gap-Fills, Dependencies
G1	Quantify ambient nutrient concentrations (higher spatial/temporal resolution, additional habitats)	■	■	■	■	■	■	■	▩	■	▩	■	■	■	■	■	■	■	■	■	■	
G2	Quantify nutrient transformation rates, space/time (mineral., nitrif., denitrif., uptake)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	▩	G 1,18
G3	Quantify sediment nutrient pools, availability and fluxes	▩	▩	■	▩	▩	▩	▩	■	■	■	▩	▩	▩	■	■	■	■	■	■	▩	
G4	Phytoplankton Biomass: discrete + high frequency data; align with nutrient+physical data	▩	▩	▩	■	■	■	■	■	▩	▩	░	░	░	░	░	░	░	░	□	■	G 1,18
G5	Phytoplankton Community: High&low resolution (space,time): composition, densities, biovolume	░	░	░	■	■	■	■	■	■	■	▩	▩	▩	▩	□	□	□	□	□	■	G 1,18
G6	Quantify phytoplankton primary production rates + nutrient requirements alongside other drivers	▩	▩	▩	■	■	■	■	■	■	■	░	░	░	░	□	□	□	□	□	■	G 1,18
G7	Quantify phytoplankton (and microbe) loss rates to grazers (planktonic, benthic)	░	░	░	■	■	■	■	■	░	░	░	■	■	■	□	□	□	□	□	■	G 4,5
G8	Quantify HA abundance/toxins relative to nutrient field/other drivers, incl. in-situ+molecular	□	□	□	▩	□	░	░	■	■	■	░	░	░	░	□	□	□	□	□	□	G 1,18
G9	Characterize microbial assemblage (space,time) relation to nutrients, transformation rates, other drivers	▩	▩	▩	░	░	░	░	░	░	░	■	■	▩	■	░	░	░	░	░	░	G1,2,18
G10	Quantify contribution of microbial community to the foodweb.	▩	▩	▩	□	□	□	□	□	□	□	■	■	■	■	□	□	□	□	□	▩	G 4-7,9
G11	Characterize interactions among primary producers (phyto, AVs, HABs, microbes)	░	░	░	■	□	■	■	■	■	■	■	■	■	■	▩	▩	▩	▩	▩	░	G 1-5,8-9,15,18
G12	Identify nutrient thresholds affecting AV growth by species (concentrations, form, timing)	░	░	□	░	□	░	░	□	░	□	□	□	□	□	■	■	■	■	■	□	G 1,3
G13	Quantify AV nutrient demand to determine effects on water column nutrient concentrations	▩	▩	▩	░	□	░	░	■	░	■	░	░	░	░	■	■	▩	▩	░	░	G1,2,3
G14	Monitor AV biomass and species composition over space/time	▩	▩	▩	░	░	░	░	░	░	░	░	░	░	░	■	■	■	■	■	■	
G15	Zooplankton sampling at relevant space/time freq, changes to carbon/energy delivery to food web	□	□	□	░	░	░	░	░	░	░	░	░	░	░	□	□	□	□	□	■	G1-7,18
G16	Characterize food source/quality consumed/assimilated by zooplankton and effects on abundance	□	□	□	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	░	░	░	░	░	■	
G17	Quantify wetland nutrient demand, transformation rates, net exchange with adjacent habitats	▩	▩	▩	▩	□	▩	▩	░	▩	░	░	░	░	░	▩	▩	▩	▩	▩	░	
G18	Integrated collection of physical data to support multiple investigations (temperature, salinity, light, velocity/flow)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	G 1-3,12-15,18
G19	Develop hydrodynamic/biogeochemical models: test hypotheses, exp'l design, synthesize results	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
G20	Maximize coordination: data + analysis across entities (monitoring, studies, modeling, synthesis	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
G21	Develop/Validate techniques to further enable cost-effective monitoring (discrete ↔*in situ*|HF↔RS)	■	■	■	■	■	■	■	■	■	■	░	░	░	░	■	■	■	■	■	░	G 1,3-5,14,18

*AV, Aquatic Vegetation; HAB, Harmful algal blooms; phyto, phytoplankton; FW, Food web; HF, high frequency, RS: remote sensiting

Table 3B Summary of data needs and knowledge gaps identified in Table 3A

Nutrients: G1-G3 were included as highly-relevant gaps related to response scenarios N1, N2, and N3. G1-G3 also rank among the highest priority gaps for Phytoplankton, HAB, Microbe, iAV, Microbe, and FW response scenarios, emphasizing the need to quantify or predict $\Delta[\mathrm{DIN}]_{\mathrm{direct}}$, $\Delta[\mathrm{NH4}]_{\mathrm{direct}}$, sed-orgN, and sed-N-flux for exploring all of the response scenarios. Several other gaps, identified primarily for other response scenarios, emerge as additional high or moderate priorities for nutrient response scenarios (i.e., other red boxes in columns below N1-N3). These priorities reflect the important influences, or feedbacks, of some T2 responses on N concentrations (G6, G13, G14, G10).

Phytoplankton: G4-G5 highlight the need for targeted phytoplankton biomass and community composition data, both discrete and high-frequency, co-collected with nutrient and physical data, to better enable testing nutrient-related phytoplankton response scenarios. With potential phytoplankton community response times on the order of days, biomass and composition data are needed at comparable or higher space/time resolution to capture those changes, and foster efforts to quantitatively explore influential mechanisms. Some of that work, especially for composition, will require testing and validating new techniques that provide the necessary precision/accuracy, taxonomic resolution, and temporal resolution, including field instrumentation (e.g., advanced in vivo fluorescence; radiometers), molecular techniques, and building capacity for remote sensing. Rate data are also needed (growth, grazing; G7-G8). In addition, a growing body of evidence shows that phytoplankton and other microbes often live in consortia, influencing each other's abundance and succession (e.g., contributing unique compounds needed by other organisms). Given that substantial changes to the microbial community are expected (Box 5), characterizing those changes alongside phytoplankton changes could prove extremely valuable.

HABs: HAB response scenarios, not surprisingly, share multiple priority data gaps with Phytoplankton. CyanoHAB data are not currently collected as part of routine Delta monitoring activities. Instead, much of the available cyanoHAB and toxin data are from event-driven observations (Lehman et al., 2008; Lehman et al., 2017; Otten et al., 2017). Routinely-collected cyanoHAB toxin measurements are therefore an important gap (G8). In addition, since methods commonly-used for phytoplankton sampling and enumeration often do not adequately quantify some cyanoHAB taxa, techniques currently being used should be evaluated and, if necessary, be modified before the upgrade, so that baseline pre- and post-upgrade observations are using robust techniques (G21).

iSAV, iFAV: G13, G14, and G15 specifically address iFAV and iSAV data and knowledge gaps (Table 3). Growth-rate limiting N concentrations in the water column and sediments are critical unknowns, as are the abilities of species to utilize nutrients from both compartments (G13). While iFAV and iSAV undoubtedly act as N sinks, little is known about their quantitative influence on ambient concentrations (G14), and nutrient transport and response scenarios downstream. Lastly, while several studies have rigorously investigated iFAV and iSAV spatial distributions, and documented some changes over time, no routine iFAV or iSAV monitoring program exists (G15), which will be essential for documenting baseline conditions and changes over time. Shared priority knowledge gaps include those relevant to nutrient cycling and ZOI determination (G1-G3); interactions with or implications for wetland restoration (G18) and potential microbial-AV interactions; development of remote sensing capacity as an option for or component of sustained monitoring; and other jointly-beneficial work (G19-G21).

Microbial community G9-G11 explore mechanisms related to microbial abundances/community composition and transformation rates, contribution of microbes to the food web, and mechanistic exploration of interactions between microbes and primary producers, respectively. Shared priority gaps include those relevant to nutrient cycling that are important for determining the $\mathrm{ZOI}_{\mathrm{DIN}}$ and $\mathrm{ZOI}_{\mathrm{NH4}}$ (G1-G3); other specific food quality (zoops) or grazing information (G16, G7); and collection along with monitoring or on-going phytoplankton biomass and community investigations (G4-G5). Since there is currently a paucity of microbial community data in the Delta, and these organisms may respond rapidly even to early upgrade steps, investigations need to be launched to establish baseline microbial community structure before the upgrade is on line.

Pelagic food web: G15-G16 were included to address data needs for changing food resources reaching target organisms). Additional FW1b priorities align closely with nutrient cycling and phytoplankton production. For pelagic fish response scenarios (FW1a, FW2, FW3, FW*slow*), the likelihood of detecting a nutrient-related response, and robustly testing its link to the upgrade through either enhanced monitoring or directed research, are low. There are simply too many possible interactions and covariates to consider. Monitoring and research related to the upgrade are likely better focused on T1 and T2 responses: nutrient processes, primary producers and lower level consumers, primarily clams and zooplankton. Results from such studies could then be integrated with ongoing and future work on pelagic fish monitoring conducted by IEP and others.

3.2 Response Scenarios: Tier 1, Tier 2, and Tier 3

Tier 1 – Ambient Nutrient Conditions (Box 1)

Large changes to water column DIN and NH4 concentrations ([DIN], [NH4]) are expected to occur in some regions of the nSFE immediately after the upgrade goes on line (once accounting for travel time), and those changes will be readily detectable and readily-linked to the upgrade (Table 2: rows N1, N2, N*slow*). The magnitude of changes to [DIN] and [NH4], though, are expected to vary strongly as a function of space and time (season, interannually). Sediment organic N (sed-orgN) levels are also expected to decrease, but the magnitude and time-scales of change are less certain. Accurate prediction or measurement of changes to [DIN], [NH4], and sed-orgN will be essential for well-designed studies of Tier 2 and Tier 3 responses (phytoplankton production and community; HABs; invasive aquatic vegetation; and microbial community).

N1, N2: Decrease in water column DIN and NH4 concentrations: In regions strongly influenced by the Sacramento River and thus SRWTP effluent (i.e., within the moderate to high Zone of Influence, ZOI; see Figure B1.5-B1.6), water column DIN and NH4 concentrations ([DIN], [NH4]) will change substantially between pre- and post-upgrade (▵[DIN], ▵[NH4]; Figure B1.4). The changes will be readily detectable and linkable to the upgrade (Table 2): for example, during low flow months, post-upgrade [DIN] is expected to be roughly half pre-upgrade [DIN], and [NH4] should decrease 10-fold from current concentrations of ~30 µM to near background (<1-2 µM) levels (Figure B1.4). In addition, the chemical form of DIN will shift to predominantly NO3. These changes will be evident almost immediately, lagging upgrade implementation by only water travel time from the outfall.

▵[DIN] and ▵[NH4] magnitudes will decrease with increasing travel times (τ) from the outfall (Figure B1.3). The spatial contours of ▵[DIN] and ▵[NH4] will vary seasonally (and interannually), with the sharpest gradients occurring during summer months during warm, low-flow periods (Jun-Sep), with the combination of slower transport and faster transformations tending to attenuate ▵[DIN] and ▵[NH4] (Figures B1.4, B1.6). With increasing travel times from the outfall (τ > several days), summertime ▵[DIN] and ▵[NH4] will approach zero, even in Sac-River dominated areas (Figure B1.4-B1.5). Seasonal variations in water withdrawals and flow routing (e.g., opening/closing the Delta Cross Channel) could result in important exceptions to this generalization.

▵[DIN] or ▵[NH4] predictions will be essential for investigating T2 and T3 responses (phytoplankton production and community; HABs; invasive aquatic vegetation; and microbial community). Currently, ▵[DIN] and ▵[NH4] contour predictions (space, time) would be highly uncertain. Those uncertainties result in part from the extremely sparse data on N transformation rates in the nSFE (e.g., nitrification; denitrification; uptake by phytoplankton, microbes and aquatic vegetation; mineralization of organic N; sediment←→water column). Those uncertainties could be mitigated through targeted field studies, collection of higher-resolution (space, time) water quality data, and through on-going development of numerical models (Table 3A, in particular G1-G3 , G19).

N*slow: Gradual decrease of labile sediment org-N (↓[sed-orgN], ↓sed-N-flux):* We hypothesize that bioavailable N stored in bed sediments ([sed-orgN]), and N efflux from sediments (sed-N-flux), play important roles shaping [DIN] and [NH4] in some nSFE regions, and will play a relatively larger role after the upgrade, in particular in regions at large τ from the SWTP outfall. Post-upgrade, [sed-orgN] and sed-N-flux are expected to gradually decrease. However, severe data gaps make it difficult to predict the rates of decrease for [sed-orgN] and sed-N-flux, and therefore difficult to predict post-upgrade [DIN] and [NH4] in large-τ regions. It is likely that the response time scales for [sed-orgN] and sed-N-flux will dictate when some T2 response scenarios may occur or become detectable: e.g., because sed-N-flux maintains [DIN] or [NH4] at sufficiently high levels to support phytoplankton and HAB responses; or because [sed-orgN] remains at levels sufficient to support invasive aquatic vegetation growth.

Tier 2 – Phytoplankton Production (Box 2)

Phytoplankton serve as a vital food resource at the base of nSFE food webs, and decreased phytoplankton productivity in the system over recent decades is considered to be among the important factors contributing to declining pelagic fish populations (Sommer et al. 2007; NRC 2012). Across all the response categories (Figure 4), phytoplankton production boasts the most diverse set of potential responses, including directly opposite outcomes (Box 2). The disparity stems from incomplete quantitative understanding of the interrelated factors that shape phytoplankton responses (or at least incomplete data to make confident quantitative predictions); and strongly diverging conceptual models for factors regulating phytoplankton dynamics in the nSFE (see Box 2, p. B2.3). Despite the uncertainty, the upgrade offers tractable opportunities to gain important insights into the factors regulating phytoplankton dynamics, and to test competing hypotheses (Table 2, rows P1a, P1b, P2a, P2b, P12s*low*). However, the likelihood with which responses will be detectable and linkable back to the upgrade are lower than for Tier 1, owing to the additional factors that can influence phytoplankton response (Box 2, and below).

P1a and P2a: ↓DIN, Decreased Phytoplankton Production, Community Composition Changes: To produce new biomass, the phytoplankton community as a whole needs N (Box 2), and N availability can influence phytoplankton production and community composition and succession (Figures B2.3, B2.4). Decreased phytoplankton production or altered community composition may, therefore, at first seem like obvious responses to anticipated Δ[DIN]. However, predicting the likelihoods of P1a or P2a occurring at ecologically-meaningful levels, or predicting the magnitude of change, is far from straightforward. Most observations in the nSFE indicate that other factors (e.g., light limitation, strong benthic grazing), besides nutrients, control phytoplankton biomass and growth. In order for lower post-upgrade [DIN] to influence phytoplankton production (P1a), other often-dominant constraints on production must relax sufficiently to allow nutrient availability to become the 'bottleneck' that slows phytoplankton growth and [DIN] concentrations must reach growth-limiting levels; Figure B2.4). A similar argument can be made for lower post-upgrade [DIN] causing changes in phytoplankton community composition.

Will P1a or P2a occur in some locations or times? Will changes reach ecologically-significant levels? It seems quite plausible that, post-upgrade, N-limited growth will occur and be detectable at some locations or times. The fact that, under current conditions, blooms occur (albeit sporadic and generally short-lived; e.g., Wilkerson et al. 2006; Dugdale et al. 2007, 2012) offers evidence that spatial-temporal windows favorable to phytoplankton growth can occur. If large enough Δ[DIN] co-occurs with those windows, community-wide growth rates could slow due to DIN limitation, and some taxa may outcompete others for N, leading to changes in community (Figure B2.3). It is much less clear, however, whether ecologically-significant (or measurable) changes to phytoplankton production or composition would occur. One reason for this uncertainty is that other factors, like low light levels or high grazing pressure could continue exerting predominant control over phytoplankton productivity. In addition, it is plausible that biological feedbacks could buffer increases in phytoplankton production. For example, an initial decrease in phytoplankton biomass could cause subsequent decreased benthic grazer populations and lower grazing rates that would offset growth rate changes.

While the above uncertainties could be interpreted as discouraging the pursuit of P1a and P2a, we actually reach the opposite conclusion. Phytoplankton play a critical role in supporting nSFE food webs role; and our understanding of nSFE phytoplankton dynamics remains far from complete (Ward and Pearl, 2017; Cooke et al. 2018), including how a large and sustained decrease in an essential substrate might alter those dynamics. This argues for using the upgrade to, as much as possible, advance our understanding of phytoplankton dynamics. However, carefully-designed holistic studies that measure N-related and non-nutrient controls will be needed to detect responses and to accurately attribute any responses to the correct causal mechanism. To explore phytoplankton community composition, studies will require robust analytical techniques to detect anticipated changes in assemblage (taxonomic resolution, accuracy, detection limits) and sufficiently resolved (time, space) measurement frequency to inform mechanistic interpretations.

When? Where? Based on phytoplankton's response rates, P1a and P2a could in theory be evident within days to weeks of observing Δ[DIN] (Figure B2.5). In practice, however, multiple years of observations will likely be required to reach confident answers about these response scenarios, considering natural variations (seasonal, interannual) in the physical and biological factors that influence phytoplankton production, biomass, and community composition. Relevant locations include those characterized as moderate ZOI_{DIN} - long-enough τ for nutrients to reach rate-limiting concentrations.

P1b and P2b: ↓NH4 leading to Increased Phytoplankton Production or Improved Food Quality

The degree to which elevated [NH4] may influence phytoplankton growth or community in the nSFE has received considerable investigation and debate over the past decade (Box 2, see p. B2.3; Dugdale et al. 2007; Parker et al. 2012; Glibert et al. 2016; Ward and Paerl 2017; Berg et al. 2017, 2019). Recognizing that disagreements remain about whether the form of DIN (NH4 vs. NO3) influences phytoplankton production or community composition in the nSFE, the likelihoods of response scenarios P1b and P2b occurring were assigned 'unknown'. As a result, P1b and P2b response scenarios were assigned 'unknown' likelihoods of occurring (Tables 2, B2.1). Nonetheless, the upgrade, by drastically reducing NH4 loads to the Sacramento River, does offer opportunities to study P1b and P2b. Similar to above, for P1b or P2b to occur to an ecologically-meaningful degree, the NH4-related mechanisms must be one of the most important factors regulating growth at the field scale. In addition, the 'well-buffered-system' argument also applies here: if production increases, grazer populations and grazing pressure may increase and effectively offset the increased production.

When-Where? Based on characteristic response times of phytoplankton growth rates and community composition turnover (days to week), P1b and P2b could conceivably be detected within days to weeks of the upgrade. However, as noted above, natural variations in other factors would likely make multiple years of observations necessary to confidently quantify changes. The field observations that led to the 'Ammonium Paradox' hypothesis, and monitoring data used to support the 'Ecological Stoichiometry' hypothesis were primarily from Sacramento River and Suisun Bay sites, including locations where changes to ▵[NH4] will be greatest (Figure B2.5), making site selection for some study types straightforward. Spatial variations in current [NH4] concentrations (Figure B1.2), and hypothesizd sharper ▵[NH4] than ▵[DIN] contour gradients (Figure B1.6), suggest qualitatively that the ZOI$_{NH4}$ may occupy a smaller area than the ZOI$_{DIN}$.

***P1,2slow: Changes in production or community due to* ↓sed-N-flux** In low-ZOI (Figure B1.6), we hypothesize that sed-N-flux will buffer post-upgrade [DIN] or [NH4] maintaining their levels above thresholds for phytoplankton response (P1a, P1b, P2a, P2b) for extended periods beyond the upgrade. To effectively investigate the above phytoplankton response scenarios, study designs and site selection will therefore also need to consider the importance of sed-N-flux, and the potential lag before sed-N-flux [DIN] or [NH4] concentrations decline sufficiently to cause a measurable response.

Tier 2 – Harmful Algae Blooms (Box 3)

The upgrade provides tractable opportunities to investigate HAB-nutrient linkages in the nSFE. Since their first documented appearance around 2000, HABs have become an increasingly concerning issue in the nSFE (Lehman et al. 2017; Box 3). HABs have multiple management relevant implications (Figure 4), including ecological health impacts due to direct and indirect toxicity (copepods, fish, other aquatic animals); and human health risks due to HAB events occurring in close proximity to critical water supply infrastructure, and impacts on recreational use. The HAB discussion (Box 3) focuses primarily on the most problematic harmful algae taxa in the nSFE, the cyanobacterium *Microcystis* spp., and the toxin it produces, microcystin (MCY).

P3 & P4 Decreasing HAB magnitude and toxicity due to ▵[DIN] A relatively straightforward, plausible mechanistic case can be made for decreased HAB event magnitude (frequency, duration, density, area) and toxicity resulting from the upgrade ▵[DIN]. Unlike some cyanobacteria, *Microcystis* is incapable of fixing N and requires bioavailable N to grow. In addition, microcystin (MCY) is a nitrogen-rich molecule, with available evidence indicating that MCY gene transcription is down-regulated in response to decreasing N availability (Harke and Gobler, 2015). Several key issues and dependencies, however, make it highly uncertain whether P3 or P4 will occur. First, ▵[DIN]$_{direct}$ must be large enough in high-risk HAB areas for DIN to reach levels that cause decreased HA growth rates or toxin production. In general, high-risk HAB areas fall in the interior Delta (Figure B3.1), still within the ZOI but at moderate to large $\boldsymbol{\tau}$, where ▵[DIN] may be relatively small (Figure B.3.4). Second, multiple other factors strongly influence HAB occurrence and toxicity, and, in many cases the specific mechanisms and interactions between biotic and abiotic factors remain poorly characterized (see Box 3). Studies exploring the upgrade-HAB linkage will therefore need to measure, or otherwise control or account for, those other factors, in order to isolate and test for the role that nutrients play in HAB dynamics. Given phytoplankton response times (days to week), HAB responses could be measured within days to weeks of post-upgrade SacRiver water reaching *Microcystis*-prone areas. In reality, multiple years of observations would likely be needed to observe conditions across a range of physical forcings to confidently detect changes.

P3slow Decreasing HAB magnitude and toxicity due to ↓[sed org-N] and ↓sed-N-flux Most of the nSFE's *Microcystis* impacted regions occur in areas with moderate to large $\boldsymbol{\tau}$ (>10-15 days; Figures B1.4 and B3.4). In these regions, △[DIN] could initially be fairly small, due to transformations along the flow path and continuation of sed-N-flux after the upgrade. To the extent that DIN availability plays an important role influencing HABs in the nSFE (frequency, magnitude, toxicity), it is plausible that sed-N-flux could satisfy HAB demand in these regions for some unknown lag period after the upgrade, and that HAB occurrences would decrease gradually, following the decrease in sed-N-flux (Figure B3.4).

Tier 2 – Invasive Floating and Submerged Aquatic Vegetation (Box 4)

Invasive floating and submerged aquatic vegetation (iFAV, iSAV) severely impact nSFE beneficial uses along multiple pathways (Figure 4, Box 4). Although eradication of invasive vegetation from the Delta would not be expected due to the upgrade, it is plausible that the upgrade could have detectable impacts on the areal extent or density of some iAV, that those effects could be linked back to the upgrade (Table 2 AV1, AV2, AV3, AV*slow*). However, the degree to which changes would occur, magnitude of effects, and response times of strongly hinge on a several important dependencies. The discussion below focuses on a subset of response scenarios (see Box 4 for others).

***AV1 Decreased iFAV biomass or spatial distribution due to* △[DIN]** On a mechanistic basis, it appears plausible that iFAV biomass and spatial distribution will decrease due to decreased water column DIN, △[DIN]. The dense water hyacinth mats, for example, that cover large swaths of the Delta must require substantial amounts of N to build and maintain that biomass, in particular since much of that biomass dies back and regrows annually. Eliminating a substantial portion of DIN influx to iFAV regions, therefore, has the potential to limit new growth.

Nonetheless, despite AV1 appearing plausible, multiple factors beyond water column N influence iFAV's ability to establish and spread, leading to AV1 being designated as likely to occur, but with low confidence (Tables 3 and B4.1). The upgrade offers tractable opportunities to hypothesis AV1, in particular because iFAV biomass can be readily detected. Similar to other T2 response scenarios, spatial overlap between ZOI_{DIN} and iFAV problem areas will be essential for meaningful-effects to occur and be measurable. In addition, post-upgrade [DIN] must drop below growth-rate limiting concentrations. If △[DIN] is a major influence on iFAV, responses could become evident within one to several years (Figure B5.4), influenced by how much of a summer's biomass survives into the subsequent spring/summer, and the relative rates of N recycling (including after settling to the sediments) versus N flushing from the system. Some iFAV (e.g., water hyacinth) can in some instances extend their roots into the benthos and directly access sediment-N, which, if important, would shift response times closer to those for AV*slow*. A key data gap or uncertainty is quantitative information about growth-rate limiting DIN concentrations for relevant iFAV species

AV3 Decreased iSAV biomass or spatial distribution due to △[DIN] iSAV acquire much if not all of their nutrients from bed sediments via roots. Some species, however, can also incorporate dissolved nutrients directly from the water column (e.g., *Egeria*). For AV2 to occur, iSAV must be sufficiently reliant on [DIN] that anticipated △[DIN] would curtail growth. While mechanistically plausible, in particular in terms of delivering a species some competitive advantage, we hypothesize that large changes to iSAV biomass or spatial coverage would be more likely to come through decreased sed-orgN (below) than △[DIN].

AVslow: Decreased iFAV or iSAV biomass/spatial distribution due to ∆[sed-orgN] If iSAV abundance does ultimately decrease, we posit that it would be most likely to occur after sufficient decreases in [sed-orgN]. Under this scenario, iSAV relevant response times would be on the order of years (Figure B5.4), dictated by sed-orgN response times (N3). With multiple factors influencing iSAV prevalence, considerable uncertainty remains about whether decreases will in fact occur. However, if substantial decreases do occur, there is reasonable likelihood that those changes would be detectable and the upgrade-link testable (Table 4, Table B4.1). For iFAV, AV*slow* and AV1 have comparable likelihoods of being the causal pathway. In both cases, [DIN] must decrease to growth-rate limiting levels. Several key unknowns, though, prevent us from landing more confidently on one over the other; these include quantitative information about growth-rate limiting DIN concentrations for relevant AV species; linkages between water column N concentrations and sediment N stores; and sed-N-flux and its rate of change over time. A major unknown is growth-rate limiting sed-orgN concentrations.

Tier 2 – Microbial Community (Box 5)

The microbial community structure appears poised to change substantially in response to the upgrade, in ways that should be readily detectable and linkable to the upgrade (Table 2 M1, M2, M3, M*slow*). Nitrifiers and denitrifiers fuel their growth and metabolic activity by directly utilizing NH4 and N03 in energy-yielding biochemical reactions. It therefore stands to reason that nitrifier (*M1*) and denitrifier (*M2*) biomass and community composition (or diversity) will be substantially altered in regions experiencing large ∆[NH4] and ∆[DIN], with some specific example hypotheses discussed in Box 5. To the extent that ∆[DIN] leads to decreases in both phytoplankton production and fresh labile organic matter delivery, then heterotrophic microbes (mineralizing communities) may also be affected (*M3*). Observing these changes, in both the surface sediments and water column, could yield critical insights into how microbial communities respond to dramatic shifts in nutrient availability. In addition, a growing body of evidence indicates that non-photosynthetic microbes co-vary with phytoplankton, sometimes working symbiotically (Bertrand et al. 2015; Amin et al. 2015), other times antagonistically, but in both cases strongly influencing the others growth. With some studies postulating that these types of relationships are "key to understanding the controls on marine primary productivity" (Bertrand et al. 2015), there is good reason to consider examining whether analogous relationships could have ecologically-meaningful influences on phytoplankton productivity in the nSFE.

Tier 3 – Pelagic Food Web (Box 5)

The health of the pelagic food web features prominently in nSFE ecosystem management decisions, because of the stark declines over the past few decades in native and other recreationally-important fish populations (e.g., Sommer et al. 2007; NRC 2012; Brown et al. 2016). However, relative to Tier 1 and Tier 2 responses, upgrade-related responses among pelagic fish populations (Tier 3) will be the most difficult to detect and confidently link back to the upgrade (Table 2), because of the multiple factors that can influence fish populations over the multi-year response times that would be needed to register population-level changes (Figure 4 and B6.1; Box 6). Among the Tier 3 response scenarios (Figure 4), a change to copepod abundance (FW1a) offers the greatest likelihood of being detected and linked to the upgrade, if such a change occurred. For the remaining responses, their likelihoods of being detected and linked to the upgrade are unknown or unlikely (Table 2 FW1a, FW1b, FW2, FW3, FW*slow*). Therefore, only FW1a is discussed below, with others discussed in Box 6.

FW1a Changes in copepods or other zooplankton in response to changes in phytoplankton production or phytoplankton food quality Changes to copepod-related indicators (e.g., abundance, reproduction rates, growth) could conceivably be detectable shortly after the upgrade, because these indicators can respond relatively quickly (weeks; Kimmerer et al. 2014) to changing conditions, including food availability (phytoplankton abundance, community). Detecting changes to copepod indicators would likely require intensive field studies, that simultaneously tracking changes to phytoplankton production and community, nutrient changes, and changes to physical forcings. In addition, those studies would need to target space-time windows when any changes to phytoplankton production (increase or decrease) were largely unattenuated by benthic grazers, allowing them to influence copepod food supply. See Box 6 for further discussion.

4. SUMMARY

Beginning in 2021, major upgrades to the Sacramento Regional Wastewater Treatment Plant (SRWTP) will substantially change nitrogen (N) loads to the northern San Francisco Estuary (nSFE), with SRWTP's dissolved inorganic N (DIN) loads decreasing by >65% and the predominant form of effluent N shifting from ammonium (NH4) to nitrate (NO3). This study developed and applied a framework for identifying and exploring potential ecosystem response scenarios to the forthcoming decreased N loads to identify opportunities and constraints for investigating those responses. Following this framework, a wide net was cast to identify a diverse starting set of response scenarios. Response scenarios were then systematically examined to assess the degree to which they could be feasibly or successfully investigated, and to identify study design priorities and key data gaps. Twenty five response scenarios were identified across three tiers (Tier 1: Ambient N Concentrations; Tier 2: Direct Biological Responses; Tier 3 Indirect Biological Responses). While the response scenarios can, in concept, all be linked to load reductions via mechanistic step(s) discussed in the scientific literature (some well-established, others hypothesized), the predictive-confidence and 'study-ability' vary widely among the response scenarios.

In regions that are strongly influenced by the Sacramento River and therefore SRWTP effluent (zone of influence, ZOI), large decreases in water column DIN and NH4 concentrations ([DIN], [NH4]) are expected to be detectable immediately post-upgrade (once accounting for travel time). The magnitude [DIN] and [NH4] changes, though, will vary strongly as a function of space and time (season, interannually). Sediment organic N (sed-orgN) levels are also expected to decrease, but the magnitude and time-scales of sed-orgN changes are less certain. Accurate predictions of the ZOI and changes to [DIN], [NH4], and sed-orgN will be essential for well-designed studies of Tier 2 responses (e.g., phytoplankton production and community; HABs; invasive aquatic vegetation; microbial community). While nontrivial data gaps need to be addressed in order to achieve that accuracy, the studies needed to address those gaps are feasible.

Tier 2 responses are more difficult to predict than Tier 1, and will also be more difficult to confidently detect and attribute to the upgrade. Despite the uncertainty, the upgrade does provide valuable opportunities to investigate several Tier 2 response scenarios that are highly relevant to nutrient management issues in the nSFE. Across all the response categories, the diversity of response sceanrios is arguably greatest for phytoplankton production, including some that predict very different if not opposite system responses (production will increase vs. decrease vs. not change at all). This disparity is due in part to strongly diverging conceptual models for factors regulating phytoplankton dynamics in the nSFE, and also substantial data or knowledge gaps related non-nutrient drivers of phytoplankton production. The upgrade nonetheless offers unique opportunities to gain important insights into the factors regulating phytoplankton dynamics, including testing competing hypotheses related to whether the form of N (NH4 vs. NO3) has a major influence on phytoplankton. In addition, the upgrade appears to provides tractable opportunities to investigate if SRWTP's nutrient loads have contributed to HAB occurrences in the nSFE, or encouraged the spread of some invasive aquatic vegation (iAV) species, and whether the load reductions will help mitigate some HAB and iAV impacts. The upgrade would also create a window through which to gain valuable ecosystem-scale insights into nutrient-microbial community dynamics, and shifting balances in response to a major change in [DIN] and [NH4]. Given the food-limited state of the nSFE's pelagic food web, and considering growing evidence from other systems of strong growth-influencing interactions between microbes and phytoplankton, nutrient-microbial-phytplankton interactions, and potential post-upgrade shifts, seem worthy of exploration.

Lastly, it will be difficult to confidently demonstrate higher-trophic level pelagic food web responses (Tier 3) to the upgrade, through either enhanced monitoring or directed research, in particular in pelagic fish populations. There are simply too many possible interactions and covariates to consider. One exception is the possibility that lower trophic level (e.g., copepods) effects may be observed in targeted studies. Beyond this, monitoring and research related to the upgrade are likely best focused on Tier 1 and Tier 2 responses, and integrating results at a later date with findings from ongoing and future fish studies in the nSFE.

Box 1 Ambient Nutrient Responses (Tier 1)

- The nSFE receives elevated inputs of N and P from anthropogenic sources, including wastewater treatment plant (WWTP) effluent, agricultural runoff and urban runoff. N and P occur in a variety of chemical forms (Table B1.1), distributed between the water column, sediments, and living organisms. Long-term nSFE monitoring data show that DIN concentrations vary by ~100-fold over space and time (Figure B1.1).
- Regional San's upgrade will constitute a large shift in both the amount and form of N entering the nSFE (Figure 2A).
- Investigating upgrade-related biological responses (T2, T3) will require selecting study sites based on anticipated changes in N availability. While some T1 changes can be easily predicted, accurately predicting others -- the *where*, *when*, *what*, and *how much* - will require addressing important knowledge/data gaps.

Table B1.1 Major N and P Chemical Forms

NO_3^-	Nitrate
NH_4^+	Ammonium, primary form of ammonia at pH<8
DIN	Dissolved inorganic N (essentially NO_3^- + NH_4^+).
N_2	(di)Nitrogen gas
DON, PON	Dissolved and Particulate organic N
TN	DIN + DON + PON. In nSFE, 25-50% *TN = DIN
o-PO_4	orthophosphate (inorganic)
DOP, POP	Dissolved and Particulate organic P
✣-PO_4	Inorganic P bound to particles

Other common N forms in water: NO_2^- *(nitrite),* N_2O *(nitrous oxide)*

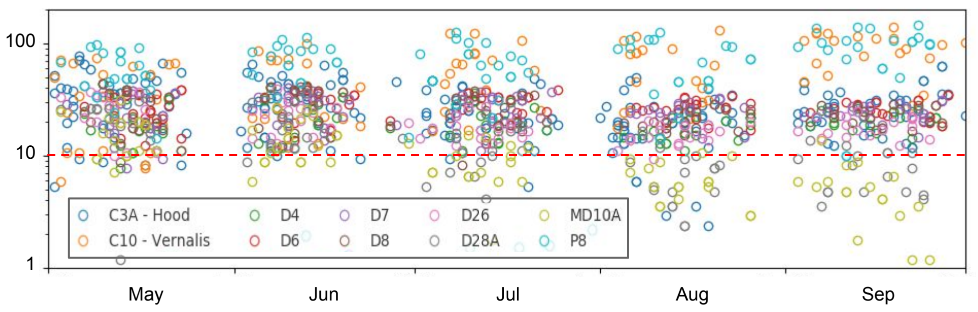


Figure B1.1 DIN concentrations (µM) vs. day-of-year (May-Oct) 2000-2015, at stations across the nSFE. Red line depicts 10*K_s (K_s, half-saturation constant, ~1 µM represents a central tendency value for diatoms, Kudela et al, 2010; see also Box 2). When DIN > ~10 µM, DIN is unlikely to limit phytoplankton growth rates See station locations in Figure B1.4A; D6, D7, and D8 are in Suisun Bay. Data: DWR-EMP

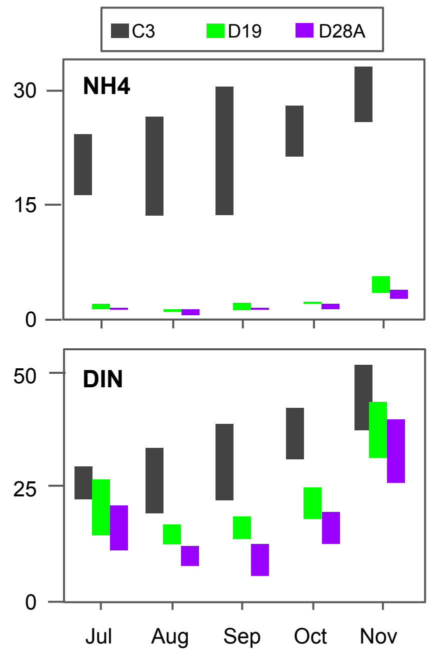


Figure B1.2 Interquartile range for NH4 (µM) and DIN (µM) during low flow months at three SacRiver dominated locations (1998-2011). See Figure B1.4 for locations. Data: DWR-EMP

How do N concentrations vary spatially in nSFE? SRWTP currently discharges N primarily as NH4 (~90% of TN), and, post-upgrade, will discharge N primarily as NO3. Upon entering the Delta, both NH4 and NO3 undergo reactions that alter their chemical form. Long-term monitoring data offer evidence of these transformations, and a sense of their quantitative importance along the SacRiver's flow path (Figure B1.2). [NH4] and [DIN] were >10-fold and 2-4 fold lower, respectively, at downstream stations (D19, D28A) than near SRWTP's outfall (C3). All three stations are dominated by SacRiver water during low flow months; but travel times (τ) to D19 and D28A could be weeks longer than to C3, allowing substantial transformations to occur en route (Novick et al. 2015).

These observations suggest that biogeochemical transformations along some nSFE flowpaths can be large enough to substantially attenuate the effluent nutrient signal under current loads. As a result, predicting upgraded related changes to [NH4] and [DIN] will require: *1.* Accurate predictions of physical transport (water, chemicals) through the system; and *2.* Estimates of transformation rates, and how they vary temporally and spatially (i.e., along flow paths).

Conceptual Model: Nutrient Cycling and Transport in the nSFE

The conceptual diagram in Figure B1.3 depicts a comprehensive set of N-transformation processes relevant to aquatic ecosystems, and the compartments where they occur (water column, sediments).

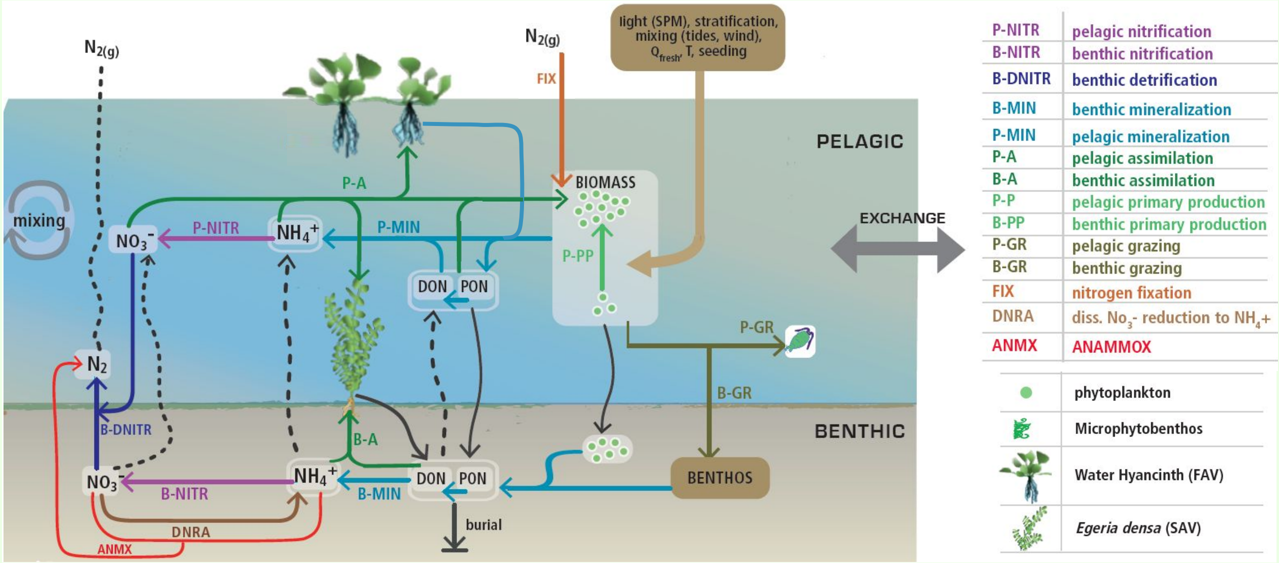


Figure B1.3 Major forms of N and biogeochemical processes influencing N cycling in aquatic ecosystems.

Space-Time variations in [DIN] and [NH4] [DIN] and [NH4] are highly variable in both space and time within the nSFE, due to biogeochemical transformation (Figure B1.3) and physical intricacies of the system - multiple nutrient sources; network of interconnected channels; flow management infrastructure; and tides. As a starting place, it is therefore useful to consider a plug, or parcel, of water traveling along an idealized one-dimensional (1-D) river channel that receives a constant flow of nitrogen-rich WWTP effluent, and focus on a subset of processes that are expected to have the largest influence on water column N concentrations (Figure B1.4). Prior to reaching the WWTP outfall, the water parcel already contains some NO3 and NH4 from upstream sources; as the parcel passes the WWTP outfall, N-containing effluent quickly mixes uniformly over the river's cross-section to yield a final well-mixed concentration. The curves qualitatively depict how [NH4], [NO3], and [DIN] in the parcel are expected to change vs. travel time, or age (τ), as the parcel moves along the idealized 1-D flow path, in response to transformations. Although Figure B1.4 depicts water column N concentrations, those concentrations can be strongly influenced by interactions between the water column and the underlying sediments. N accumulates in the sediment compartment through settling of particulate organic N; submerged aquatic vegetation (SAV) root mass accumulation; and settling detritus from floating aquatic vegetation (Figure B1.3). However, sediments are a leaky N repository: microbes mineralize sediment org-N, creating NH_4^+ that gradually fluxes back to the water column. In addition, DIN loss from the water column occurs through NO3 diffusing into the sediments where it undergoes denitrification. Water columan and sediment N transformation rates vary temporally and spatially. For example, greater solar insolation and higher temperatures during summer months lead to higher transformation rates; these higher rates, along with lower summer flow velocities, will generally translate into sharper spatial gradients in [NH4] and [DIN] during summer compared to winter.

Predicting upgrade-related changes to [NH4] and [NO3] Pre-upgrade and post-upgrade water column [NH4] and [NO3] are represented by the blue and red curves, respectively, in Figure B1.3. Vertical differences between blue and red curves ($\triangle$[NH4], $\triangle$[DIN]) represent the expected relative changes to [NH4] and [DIN] due to the upgrade. With increasing τ, $\triangle$[NH4] and $\triangle$[DIN] are expected to decrease due to transformations and N recycling along the flow path. At large τ little or no change will occur. Figure B1.4 translates $\triangle$[DIN] vs. τ into a 2-D spatial 'Zone of Influence' for DIN (ZOI_{DIN}). The gradations in ZOI_{DIN} correspond to the range of $\triangle$[DIN], with ZOI_{DIN} decreasing with τ and distance from the WWTP increase. Although, in general, the water in the interior Delta during mid- to late-summer is predominantly from the Sacramento River (Figure B1.4A), both ZOI_{DIN} and ZOI_{NH4} are expected to decrease sharply along flow paths into the interior Delta due to increasing sharply increasing τ (Figure B1.4B), meaning less change in N levels.

In moderate and high ZOI_{DIN} and ZOI_{NH4} regions, substantial △[DIN] and △[NH4] will be measurable shortly after the upgrade (days to weeks; Figure B1.6). The amount of N stored in the underlying sediment compartments (sed-orgN), however, will decrease more slowly (Figure B1.6) as microorganisms gradually convert sed-orgN into NH4. A portion of that 'recycled' NH4 will flux from the sediments to the water column (sed-N-flux), causing sediments to act as an on-going N source the water column, and effectively buffering water column [DIN] and [NH4]. It is reasonable to hypothesize that the magnitude of this buffering effect will be proportionally greater in low-ZOI regions, because of the relatively-small direct effects on △[NH4] and △[DIN] with increasing **τ** (Figure B1.3). However, the magnitudes and importances of sed-orgN, sed-N-flux, and their rate of decrease are poorly known in the nSFE because of limited study (e.g., Cornwell et al. 2014), and represent an important data gap.

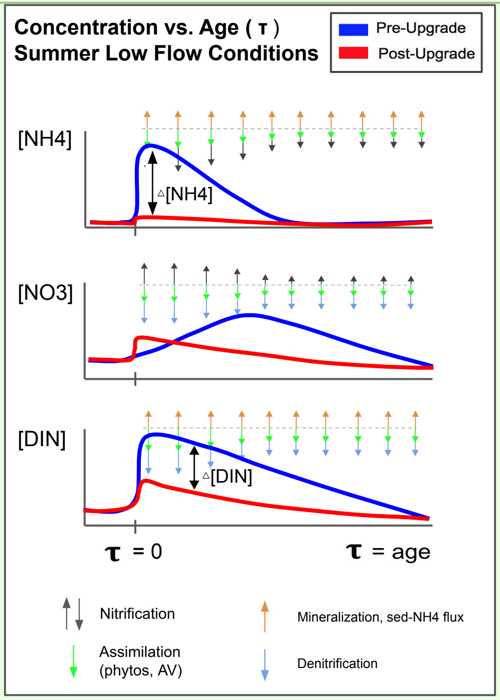
Figure B1.4 NH4, NO3, and DIN concentration variations (conceptual) within a water parcel traveling along an idealized 1-D channel, subjected to transformations and losses (vertical arrows). The x-axis, tau (τ), represents water parcel age, or elapsed time since effluent addition. At $\tau = 0$, the water parcel passes the WWTP outfall pipe, and effluent mixes into the water parcel. Immediately downstream, nutrient concentrations are determined by effluent nutrient speciation and dilution in the river water, as well as upstream nutrient concentrations. As the parcel travels downstream, NH4, NO3, and DIN undergo transformations (arrows), which result in net changes in concentrations with increasing τ. Blue curves qualitatively depict pre-upgrade conditions. Red curves depict post-upgrade concentrations, shortly after the upgrade (before changes to sediment fluxes are evident). The differences between post-upgrade and pre-upgrade concentrations, △[NH4] and △[DIN], will be large under some conditions, but are expected to decrease with increasing τ.

Nitrification: NH4→NO3 (source for NO3; sink for NH4), occurs in oxic water column or at sediment-water interface

Denitrification: NO3→N_2, occurs within sediments, at sed:-water interface

Assimilation: NH4 or NO3 uptake by phytoplankton or aquatic vegetation

Mineralization, **sed-NH4-flux:** org-N→ NH4, NH4 flux seds→water column



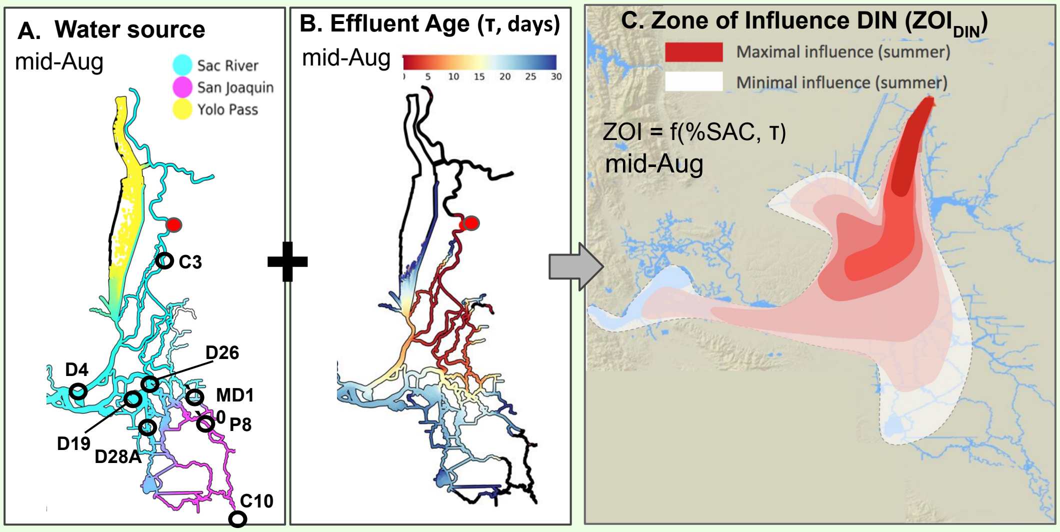


Figure B1.5 A. Mid-summer water source distribution, based on conservative tracers in a numerical simulation **B.** Water parcel age (τ) based on numerical age-tracer added at the location at the SRWTP outfall (outfall = red circle). **C.** The WWTP upgrade's Zone of Influence for DIN (ZOI_{DIN}) during summer/low-flow periods. Maximal and Minimal influence refer to largest and smallest changes to water column DIN concentrations (△[DIN]; Figure B1.3), respectively. The ZOI_{DIN} will vary strongly in space and time, influenced by the proportion of SacRiver water (**A**) and τ (**B**). ZOI_{DIN} gradations are approximated based on biogeochemical model output, comparing simulations with pre- vs. post-upgrade N loads. Conditions depicted are for mid-August 2011. Source for modeling output: Zhang et al. 2018

OVERVIEW - Nutrients

Det?	Link?	Occ?	Table B1.2 Nutrient Response Scenarios	Dependencies*
			$N.H_0$ No change in N concentrations.	
🟦	🟦	🟦	**N1** Decrease in water column DIN concentrations	***dn1,dn2,dn3***
🟦	🟦	🟦	**N2** Decrease in water column NH4 concentrations	***dn1,dn2,dn3***
🟦	🟦	🟦	**N*slow*** Gradual decrease of labile sediment org-N (↓[sed-orgN], ↓sedN-flux)	***dn1,dn2,dn3***

*See Table A.1 for descriptions of dependencies

B3.1 Summary: Nutrient Response Scenarios

- **Occur?** High Confidence that water column DIN and NH4 concentrations will decrease substantially (N1, N2), Also High Confidence that sediment org-N levels will decrease (N*slow*), but the magnitude and response times of those changes are highly uncertain.
- **Detect? Link?** *N1, N2* Readily detectable and linkable in the near-field of the outfall and in SacRiver dominated areas; more difficult/uncertain with increasing distance or travel time from the outfall or where/when other water or nutrient sources contribute. N*slow* will be less straightforward, but still feasible to detect.
- **Response times** (Figure B1.6): N1, N2: Near field (small τ): An almost immediate response (hours to days) would be expected (leftmost curve). Moderate to long τ: [DIN] and [NH4] may show early partial responses (dashed curve), but remaining changes could occur gradually (anywhere in shaded grey area). N*slow*: Sediment orgN (sed-orgN), and sediment fluxes are expected to respond slowly (years to decades, right-most curve).
- **N1, N2:** *Key dependencies:* Changes will be most evident at locations/times within maximal or intermediate ZOI contours (Figure B1.4) The magnitude of [DIN] and [NH4] changes will vary greatly as a function of space and time, including among areas dominated by Sacramento River water, due to nutrient transformations along flow paths, and the age, or travel time (τ), of effluent-containing water will be a more relevant predictor than distance. In addition, other physical and biological characteristics of habitats (depth, vegetation, phytoplankton growth, etc.) will influence the detectability of concentration changes. Accurate assessments, or predictions, of [DIN] and [NH4] changes will require: sufficient pre- and post-upgrade data to account for temporal variability at multiple time-scales (interannual, seasonal, tidal); and data on transformation rates, which are currently poorly constrained.
- **N*slow*:** *Key dependencies:* Similar to N1, N2. In addition, the ZOI for sed-orgN may extend further than ZOI-DIN because continual recycling and benthic fluxes would allow for a larger effluent-related footprint. In areas where the source water fingerprint changes substantially by season (e.g., interior Delta, with San Joaquin River dominance during winter/spring), the influence of other source waters could obscure the signal. Predictions of how much (and how fast) sed-orgN will change are difficult to make because of the paucity of relevant data about sediments, including: magnitude of the current sediment N pool; the proportions of sed-orgN that are relatively bioavailable vs refractory; and the major sources of orgN to the sediments (e.g., transport of particulate orgN by tributaries, internal production by phytoplankton; internal production by macrophytes).

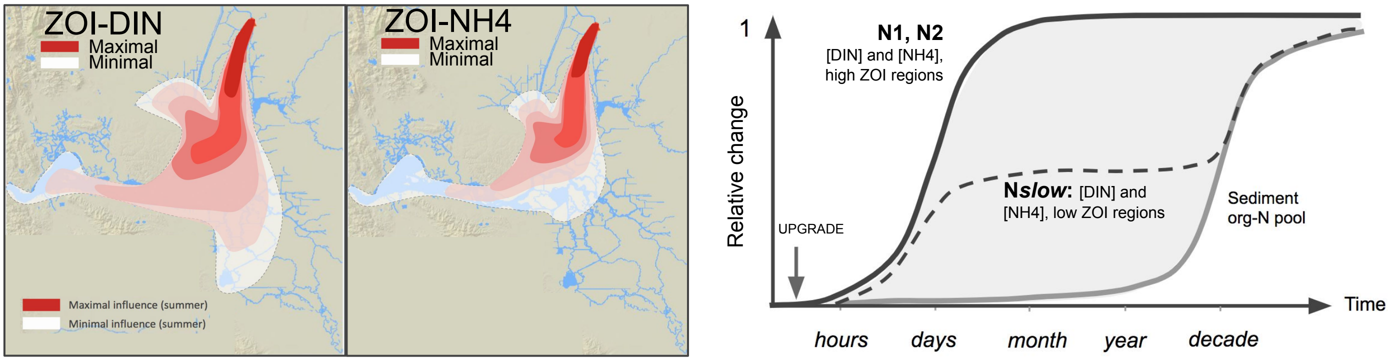


Figure B1.6 *left*: Conceptualization of spatial extents of ZOI_{DIN} and ZOI_{NH4}, for late-summer conditions (August). Contours based qualitatively on numerical simulations (Zhang et al. 2018) . *right:* Characteristic response times for Tier 1 nutrient responses.

Box 2 Phytoplankton Production (Tier 2)

- Phytoplankton serve as a vital food resource at the base of nSFE food webs. Phytoplankton value as a food resource derives from both its quantity (biomass, Müller-Solger et al. 2002) and the nutritional quality of the overall community composition (Cloern et al. 2015; Winder et al. 2017). The pre-1980s nSFE, despite its elevated nutrient levels, had relatively low phytoplankton production and biomass (Figure B2.1).
- Phytoplankton production and biomass (Figure B2.1) decreased dramatically throughout much of the nSFE in the 1980s (Jassby et al. 2002; Jassby 2008), and remains low today. The loss of this critical food resource is considered to be among the factors contributing to declining fish populations (Sommer et al. 2007; NRC 2012). Modest phytoplankton blooms still occur occasionally in the nSFE, and, even when biomass is low, the community often consists of compositions that have high nutritional value overall (Figure B2.2).
- Although N is an essential ingredient for primary production, there is considerable uncertainty, and disagreement, within the nSFE scientific community about how the upgrade will affect phytoplankton biomass, growth rates, and community. The uncertainty, and diverging hypotheses, are driven by two considerations:
  - Two other factors strongly limit nSFE phytoplankton production and biomass (high turbidity, grazing by invasive clams), leading to uncertainty about whether lower DIN will have a meaningful additional influence on phytoplankton response at the ecosystem scale.
  - Divergent conceptual models about factors influencing phytoplankton production and community, in particular related to the role of NH4.

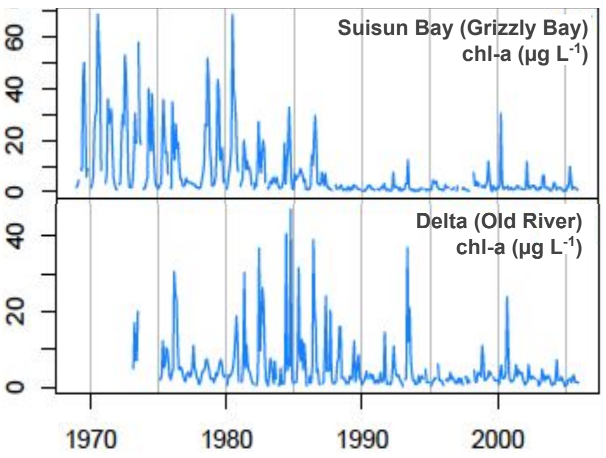


Figure B2.1 Phytoplankton biomass, based on chl-a concentration, from the 1970s-2005. Graphic: Modified from Jassby 2008

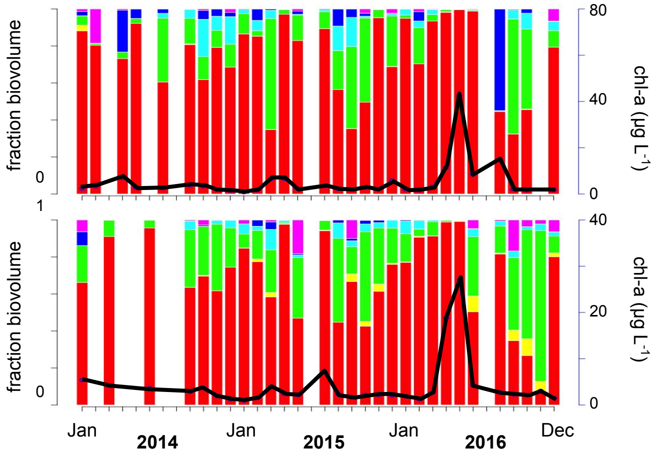


Figure B2.2 Monthly Chl-a (black) and phytoplankton community composition (fraction biovolume; stacked bars) in the Lower Sacramento River (top) and Suisun Bay (bottom). Source: SFEI 2017

Relative food quality: Dinos>Cryptos>Diatoms>>Greens>Cyanos (Winder et al. 2017)

Phytoplankton Conceptual Model(s)

Multiple factors influence phytoplankton Growth, Biomass, and Community Composition (Figure B2.3). Among these, there is broad agreement that two factors strongly regulate nSFE phytoplankton production:

i) High suspended sediment concentrations (SPM) cause low light levels in the water column, resulting in phytoplankton growth being light-limited (Kimmerer and Thompson, 2014).

ii) High grazing rates from two invasive clam species maintain phytoplankton biomass at low levels (Kimmerer and Thompson, 2014).

Under what conditions would changes in nitrogen concentrations have ecologically meaningful (and measurable) affects on phytoplankton production, biomass, or composition?

A conceptual model based on observations in the nSFE and estuaries worldwide would argue that two basic criteria must be satisfied:

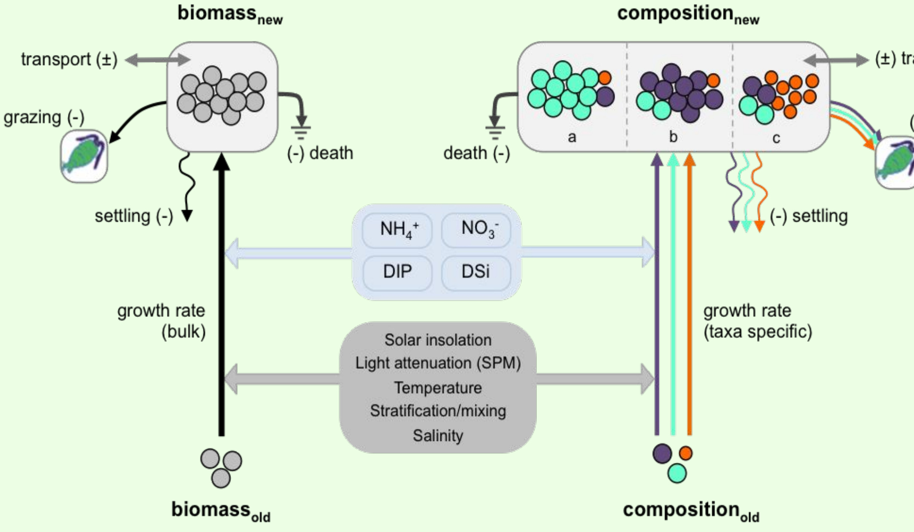


Figure B2.3 Factors influencing phytoplankton growth, biomass, and community composition. Many of the the same factors that influence bulk community growth and biomass also influence community composition, with different compositions emerging (a, b, c) because of inter-taxa variations in growth optima or loss rates.

Influential factors:

- **Growth rate**: Temperature (+), light (+), stratification (+), nutrients (+), toxins (- ; xenobiotics, heavy metals)
- **Biomass**: Growth rate (+), grazing (-), settling (-), transport (±) , death (-), flushing rate (-)
- **Community composition**: inter-taxa differences in growth optima (light, nutrients, T); inter-taxa differences in physiology/behavior (e.g., motility; buoyancy regulation; settling velocities); selective grazing by consumers;

Criterion 1: N concentrations must drop below levels that substantially limit growth rates (Figure B2.4): reductions in DIN will only substantially influence phytoplankton growth if DIN drops below growth-rate limiting concentrations, [DIN] < ***B***. Currently, DIN seldom reaches growth-rate-limiting concentrations in routinely monitored areas (Figure B1.1). Given the large DIN load decrease, it is reasonable to expect that post-upgrade DIN will more frequently reach growth-rate-limiting concentrations. Predicting where and when post-upgrade concentrations drop below growth-limiting levels will therefore be essential for successful phytoplankton studies.

Criterion 2: N-growth-limiting effects (Criterion 1) must be substantial and sustained, over time and space, relative to other factors that influence phytoplankton dynamics (light attenuation by suspended sediment; grazing by invasive benthos). It is highly uncertain how frequently this criterion will be satisfied, due to *a)* the strength of those other controls; and *b)* the inter-relationships between transport, light availability, phytoplankton production, and grazing rates. For example, populations of both clam species appear to be food limited, meaning that phytoplankton biomass in the system may be "well-buffered': i.e., if phytoplankton growth rates decrease, clam grazing pressure could decrease accordingly (over months to years). Conversely, if production increases (i.e., relevant to the NH4 paradox; see next page), clam abundance and grazing could increase in response to greater food availability, consuming any increase in phytoplankton biomass.

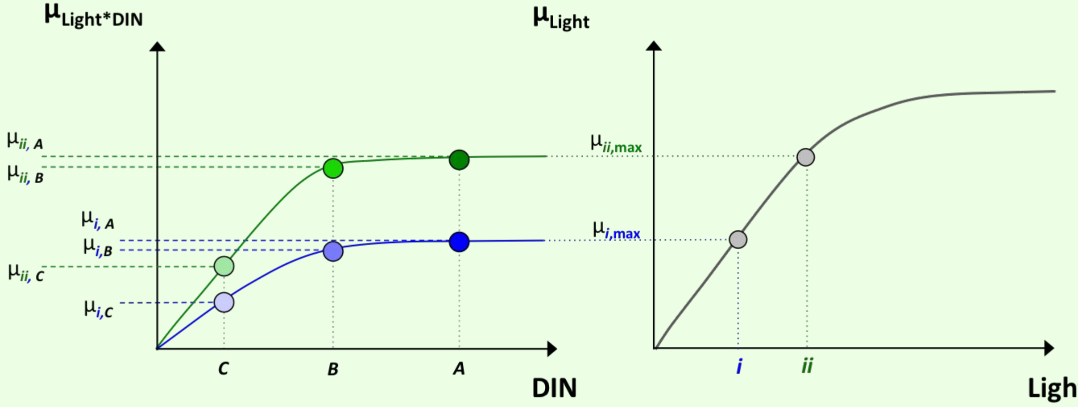


Figure B2.4 (right) Idealized phytoplankton growth rates (μ_{Light}) as a function of light availability (when nutrients are present in excess). **(left)** Growth rate as a function of DIN and light ($\mu_{Light*DIN}$), at two light levels (**i** and **ii**). At high enough DIN levels, more DIN does not change the growth rates. If DIN concentrations change from ***A*** to ***B***, growth rates will remain nearly the same. DIN must decrease further (e.g., to ***C***) for growth rates to drop substantially.

Differing Conceptual models for nSFE's low phytoplankton production: Across all the response scenario categories (Figure 4), phytoplankton production boasts the most diverse set of potential responses, including ones in direct opposition (e.g., P1a and P1b). That diversity results in large part from strongly divergent conceptual models (CMs) for the underlying causes of low phytoplankton productivity in the system. The different conceptual models are summarized below, and the related response scenarios are included in Table B2.1

***CM.A. Light Limitation and Clams*:** Monitoring data (since the 1960s) indicate that the nSFE has long experienced relatively low phytoplankton productivity. The nSFE's highly turbid waters (from suspended sediments) severely restrict light penetration into the water column, and cause light availability to be a major factor limiting growth (Cloern 1987; Jassby et al. 2003; Kimmerer and Thompson 2014). Even with the highly-turbid waters, nSFE phytoplankton production prior to the mid-1980s was much greater than today. For CM.A, the hypothesized cause of dramatically lower post-1980s phytoplankton biomass levels in Suisun Bay and the western Delta is the introduction (ca. 1987) of a voracious filter-feeding clam, *Potamocorbula amurensis,* that now dominates nSFE salty and brackish benthic habitats (Kimmerer and Thompson 2014; Nichols et al. 1990; NRC 2012; Jassby et al. 2003). A freshwater invasive clam (*Corbicula fluminea*, established *ca*. 1950s) is hypothesized to be a major factor impacting biomass in the Delta. *Corbicula,* however, cannot alone explain the post-1980s sharp decline phytoplankton biomass, because it was introduced much earlier. Based on monitoring data (Figure B1.2), nutrient levels are hypothesized to substantially exceed growth-limiting thresholds (e.g., Jassby 2008), and therefore seldom restrict overall growth rates, or favor the growth of one taxa over another.

CM.B. Nutrient-Centric: Two conceptual models emerged over the past decade whose central hypotheses attribute declines in nSFE productivity to elevated NH4 levels. While these hypotheses have received considerable attention in nSFE adaptive management discussions, there is substantial disagreement within the scientific community about their validity and/or quantitative importance.

Ammonium Paradox (Dugdale et al. 2007; Parker et al.2012): i) Phytoplankton utilize only NH4 (and not NO3) when NH4 levels exceed a threshold value (e.g., ~4 μM); ii) At the community level, phytoplankton grow slower when utilizing NH4 than NO3; iii) Elevated NH4 concentrations in the nSFE, primarily from WWTP loads, are therefore an important contributing factor to decreased primary productivity, and consequently decreased production, at higher trophic levels.

Ecological Stoichiometry (Glibert 2010; Glibert et al. 2011): i) Elevated NH4 levels (or elevated N:P) select for phytoplankton taxa that have relatively low food quality; ii) Poor food quality at the base of the food web propagates to and negatively impacts higher trophic level organisms; iii) Elevated NH4 from WWTP discharges has caused a shift in phytoplankton food quality, and this bottom-up perturbation is a primary driver of declining fish populations.

***Counter Arguments*:**

- The broader phytoplankton ecology literature contains a large body of evidence demonstrating that, overall, phytoplankton taxa exhibit a diversity of relative growth rates on NH4 vs. NO3 (e.g., Ward and Paerl, 2017; Berg et al. 2017, 2019).
- A field-scale experiment conducted along the Sacramento River during a temporary hold of WWTP inputs found no clear evidence supporting the ammonium paradox (Kraus et al. 2017c).
- Reanalysis of the data supporting the ecological stoichiometry studies indicates that the proposed 'community shifts' were actually artifacts introduced by problematic statistical methods (Cloern et al. 2012) and poor data quality (Senn et al. 2016).
- While phytoplankton productivity and biomass in the nSFE have decreased, phytoplankton communities are still typically comprised of high-food-quality organisms on a biomass basis (e.g., Figure B2.2), suggesting that food limitation is an issue of quantity, not quality (Cloern et al. 2015).

OVERVIEW - Phytoplankton Production and Community Composition

Det?	Link?	Occ?	**Table B2.1 Phytoplankton Production and Community Response Scenarios**	**Dependencies***
			P1,2.H_0 No change in production rates, biomass, or assemblage	
🟦	🟦	🟦	**P1a:** ↓Phytoplankton primary production (and ↓biomass) due to ↓ **[DIN]**	***dp1,2,3***
🟦	🟦	░	**P1b:** ↑Phytoplankton primary production (and ↑biomass) due to ↓**[NH4]** (*NH4 Paradox*)	***dp4,5,2-3***
░	░	🟦	**P2a:** Phytoplankton assemblage: changes due to ↓ **[DIN]**	***dp6,2,3***
░	░	░	**P2b:** Phytoplankton assemblage: ↑food quality due to ↓**[NH4]** (*Ecological Stoichiometry*)	***dp5,7,2,3***
■	░	🟦	**P1,2.*slow*** One of the above, but after years or decades, due to ↓ **[sed org-N]** and ↓ **sed-N-flux**	***dp8,9*** *+ above*

*See Table A.1 for descriptions of dependencies

The phytoplankton response scenarios (Table B2.1) point to starkly different potential outcomes -- including direct opposites (P1a vs. P1b) -- and highlight important issues central to ongoing nSFE adaptive management discussions: how to increase lower food web productivity, and what effect (if any) will nutrient management actions have.

- **Occur?** Uncertain. Although DIN and NH4 load reductions will be substantial, the numerous and complex factors controlling phytoplankton production prevent confident predictions about ecosystem-scale/ecologically-meaningful responses at this point.
- **Detect? Link?** The upgrade presents the opportunity to investigate or test conceptual models or hypotheses.
- **Response times** (Figure B2.5): Response times for phytoplankton productivity and assemblage to △[DIN] or △[NH4] would be days to weeks. In habitats where sediment fluxes substantially influence [DIN] or [NH4], phytoplankton response times would follow those for sed-orgN or sed-N-flux (months to years).
- **P1a, P2a:** *Key dependencies*: Other dominant factors do not limit growth (e.g., low turbidity); and [DIN] decrease to growth limiting levels, for overall community (P1a) or individual taxa (P2a). *Locations:* Habitats within the pre-upgrade ZOI, but with sufficiently large τ that post-upgrade [DIN] drops below growth-limiting levels ([DIN] along Sacramento River will likely exceed thresholds). Detecting P1a may be more straightforward than P2a because of the additional analytical challenges of quantitatively characterizing and interpreting community changes.
- **P1b, P2b**: *Key dependencies*: Hypothesized mechanisms need to be quantitatively important at ecosystem scales. *Locations*: Hypotheses emerged from Suisun Bay and the Sacramento River observations, placing those areas on the list of where to observe any changes. Assessing the hypothesized impacts on system-wide productivity requires studying this over broader areas, still within the ZOI, but at larger τ. Detecting P1b may be more feasible than P2b (similar to P1a vs. P2a, above).
- **P1,2*slow*** It is highly plausible that any of the above responses could be delayed in areas where N sediment fluxes are large enough to maintain sufficiently high [DIN] or [NH4].

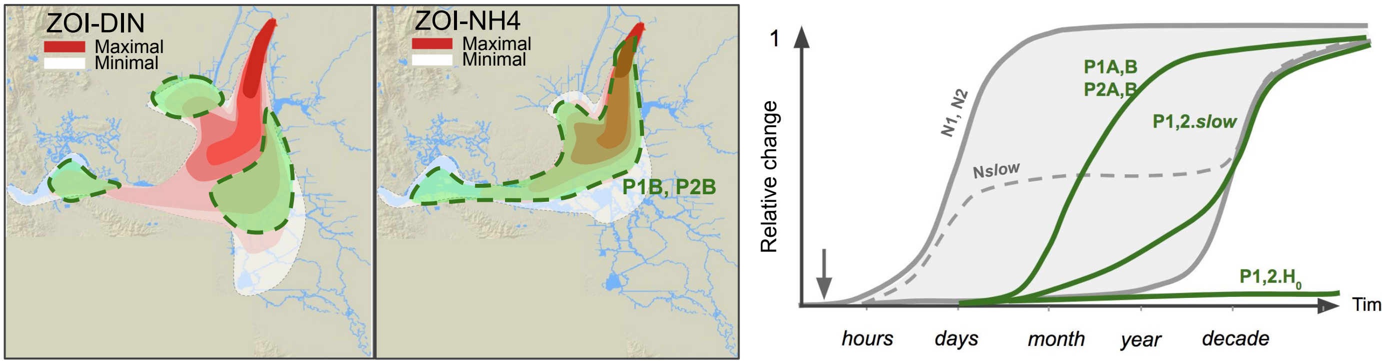


Figure B2.5 (Left) Relevant zones for phytoplankton response scenarios (green), and their overlap with ZOI (red), indicate potential areas where upgrade-related changes may occur. **(Right)** Anticipated response times for phytoplankton response scenarios. Grey curves and grey shaded area, are same as Figure B1.6, and denote ranges of response times for N1, N2, N*slow*, for comparison with phytoplankton response scenarios.

Box 3 Harmful Algal Blooms (Tier 2)

- Harmful Algal Blooms (HABs) in the nSFE have become a growing problem since the early 2000s, with the potential of having diverse and severe negative impacts (Figure 4 and Figure B3.1) including; toxins entering water supplies (CW2); toxicity to sensitive biota via the food web and direct exposure (H3, H2); and recreational and aesthetic impacts from dermal exposure to toxins and nuisance/noxious blooms (Dahm et al. 2016; Lehman et al. 2015).
- HAB events in the Delta are primarily related to cyanobacteria (cyanoHABs), and specifically *Microcystis* spp. and the toxin it produces, Microcystin (MCY). *Microcystis* were first documented in the Delta in 1999 (Lehman et al. 2005). Since then, HAB events have become fairly common (Lehman et al. 2008; Lehman et al. 2017). Delta *Microcystis* blooms tend to occur during summer and early fall, and can be widespread; during HAB events, MCY concentrations commonly exceed World Health Organization guidelines for humans and wildlife (e.g., Lehman et al. 2005; Lehman et al. 2008).
- *Microcystis* blooms and MCY have the potential to negatively impact vital food web constituents (e.g., copepods and sensitive fish species (Ger et al. 2009; 2010)); limit recreational water uses (rashes from dermal exposure, Backer et al. 2008); and threaten a critical drinking water supply for 25 million people.
- While other potentially-harmful cyanobacteria have been observed in the Delta, thus far, *Microcystis* is the only confirmed toxin-producer (Otten et al. 2017; Lehman et al. 2017), and thus this section focuses primarily on *Microcystis* events.

- There is currently no sustained cyano-HAB monitoring program in the Delta. Instead, most available data on cyanoHABs have emerged from event-driven observations, which indicate that the the severe *Microcystis* events occur most frequently in the central/interior Delta (Figure B4.2), including proximal to Delta water withdrawals, and along San Joaquin River as it approaches the confluence with the Sacramento River.

- While elevated *Microcystis* abundances often co-occur with elevated MCY, that is not always the case, likely because: i. Not all *Microcystis* strains found in the Delta produce MCY (Otten et al. 2017; Lehman et al. 2017); ii. When toxigenic strains are present, their MCY production rates vary depending on environmental factors (Figure B3.4).
- Detections of MCY in Suisun Bay filter-feeding clams indicate that MCY produced within the Delta are transported to down-estuary habitats (SFEI 2017). Particulate and dissolved MCY have been consistently detected in Suisun Bay (SFEI 2017; Peacock et al. 2018).
- *Aphanizomenon flos-aquae* (diazotrophic organisms that are able to fix atmospheric nitrogen, N2) are the nSFE's most abundant cyanobacteria. At times *Dolichospermum* and *Nodularia*—also diazotrophs—also become abundant (Otten et al. 2017). While these genera do produce toxins in others systems, their toxin-producing ability has not yet been documented in the nSFE.

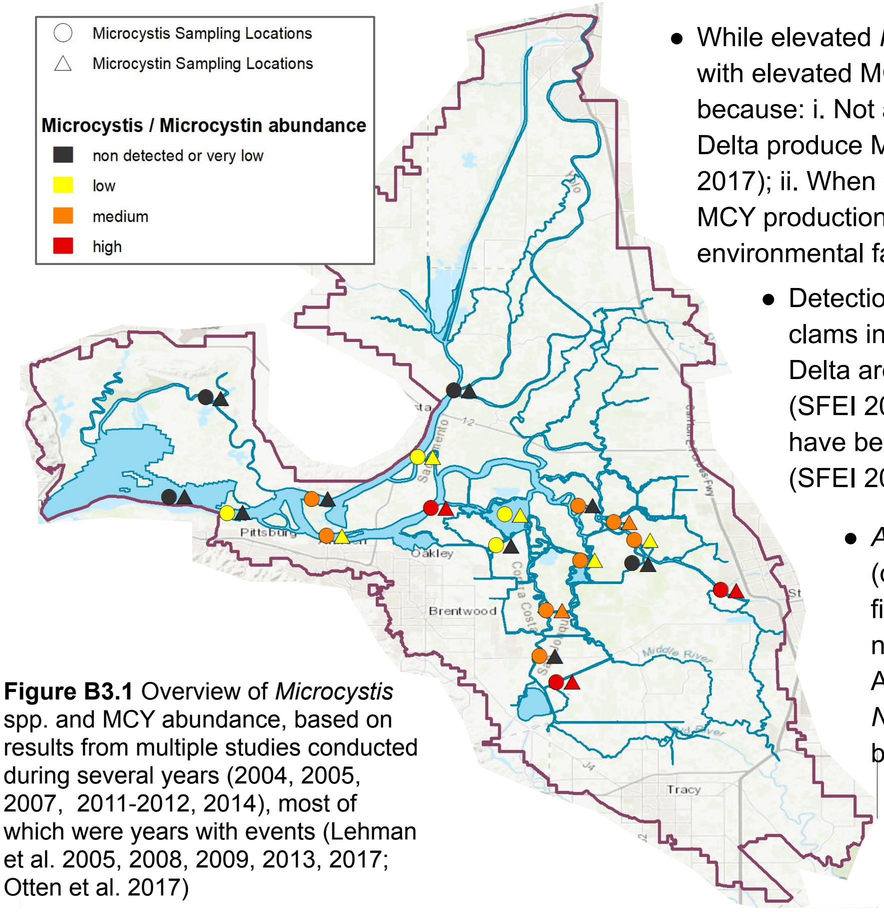


Figure B3.1 Overview of *Microcystis* spp. and MCY abundance, based on results from multiple studies conducted during several years (2004, 2005, 2007, 2011-2012, 2014), most of which were years with events (Lehman et al. 2005, 2008, 2009, 2013, 2017; Otten et al. 2017)

HAB Conceptual Model

Multiple factors influence *Microcystis* blooms (Figure B3.2; Paerl and Otten, 2016; Lehman et al. 2017):

↑ *Microcystis*, ↑MCY ← ↑ Temperature , ↑ Light, ↑ Residence time, ↓ Mixing/turbulence

In the nSFE, three factors (Temperature, light, residence time) reach *Microcystis*-favoring levels in July-Sept, coinciding with time periods when blooms tend to be most severe (Lehman et al. 2017; Otten et al. 2017).

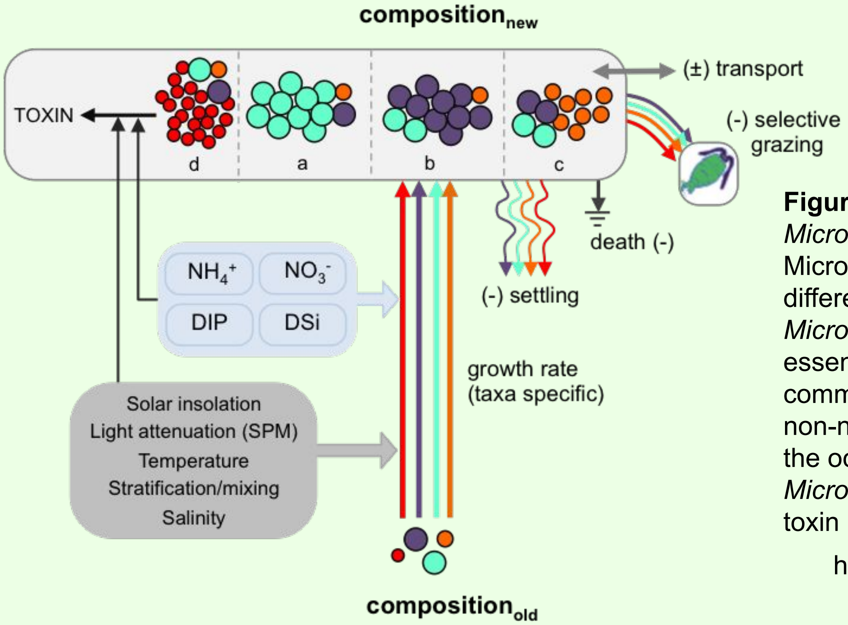


Figure B3.2 Factors influencing *Microcystis* growth, and production of Microcystins (MCY). Colored circles = different phytoplankton taxa; red circles = *Microcystis;* other c A HAB event is essentially a special case of phytoplankton community succession. In addition to non-nutrient and nutrient factors influencing the occurrence and magnitude of a *Microcystis* event, they may also influence toxin production: e.g.,

higher light levels → higher toxin
lower N → lower toxin

Influence of DIN loads: While nutrient over-enrichment is expected to promote *Microcystis* blooms (Paerl and Otten 2013), N and P concentrations alone tend to be poor predictors of *Microcystis* bloom dominance and succession in environmental systems (Paerl and Otten, 2016; Otten et al. 2017). However, when other environmental factors (e.g., light, temperature, hydrodynamics, salinity; Figure B3.2) align to favor *Microcystis* growth, N and P availability can regulate the biomass or areal extent of a *Microcystis* event. Therefore, decreasing DIN fluxes to the nSFE's *Microcystis*-bloom-prone areas has the potential to decrease the magnitude of HAB events. DIN availability can also influence bloom toxicity: toxin-producing *Microcystis* strains tend to dominate under replete N and P conditions compared to N- and P-limiting conditions (Vézie et al. 2002; Otten et al. 2012); cell toxin quotas (toxin per cell) are reduced (Horst et al. 2014); and MCY biosynthesis genes are downregulated under N-limiting conditions (Harke and Gobler, 2013). To the extent these observations point to mechanistic relationship(s) that would hold in the Delta, it is plausible that the toxicity of *Microcystis* events could also decrease following reduced N availability. In the cases of both bloom magnitude and toxicity, for a substantial change to occur, a sufficiently large △[DIN] will be required. Since cyano-HAB events have occurred most frequently in low-ZOI$_{DIN}$ regions (Figures B3.1 and B3.4), the magnitude of sed-N-flux may play an important role in whether, and when, cyano-HAB occurrence responds to the upgrade.

Influence of NH4 vs. NO3: Although there is some evidence to suggest that *Microcystis* growth rates or N-uptake rates can vary depending on the form of N utilized (Chaffin et al. 2018), *Microcystis* overall grows fairly well utilizing either NH4 or NO3 (Lee et al. 2015). Perhaps more importantly, during summer months, the travel times, τ, from the WWTP outfall to *Microcystis* problem areas (Figure B3.1) are long (weeks). Under current conditions, NH4 concentrations in those areas are already low during the summer, due to transformations and recycling of N during transport along flow paths (Figure B1.2). As a result, changes to NH4 concentration (△[NH4]) in these regions will be fairly small. Taken together, the effects from changes in the DIN concentration rather than DIN chemical form (NH4 vs. NO3) seem more likely to have effects on *Microcystis* blooms in the nSFE that could be meaningful at the ecosystem scale, and could be detected and traced back to the upgrade. While this line of reasoning does not rule out effects related to NH4 changes, the HAB response scenarios (Table B3.1) focus on DIN responses.

OVERVIEW - HABs

Det?	Link?	Occ?	**Table B3.1 HAB Response Scenarios**	**Dependencies***
			P3.H$_0$ No change in HA occurrences: magnitude, severity, spatial extent, toxin concentrations	
🟦	▦	⬜	**P3A:** ↓HAB severity (biomass, area), due to ↓[DIN]	***dp11,12***
▦	▦	⬜	**P3B:** ↓HA toxin production, due to ↓[DIN]	***dp13,11,12***
🟦	▦	⬜	**P3.*slow*** One of the above, but after years or decades, due to ↓[sed org-N] and ↓sed N flux	***dp14,15,11,12,13***

*See Table A.1 for descriptions of dependencies

- **Occur?** Plausible, but uncertain. cyanoHABs clearly utilize and require N. However, multiple other factors strongly influence when and where cyanoHAB events occur, and their magnitude or severity.
- **Detect? Link?** The upgrade presents tractable opportunities to investigate HAB-related hypotheses, in part because it is such a large change in N inputs. Since cyanoHAB's occurrence and toxin production are influenced by numerous factors, studies will need to control or account for the role of those factors in order to test the hypothesis that upgrade-related nutrient changes caused a change: e.g., sufficient ancillary data collection, study over multiple years to capture interannual variations in those other forcings.
- **Response times** (Figure B3.4): If the initial △[DIN] that occurs post-upgrade (before any decreases in sed-N-flux), HAB response could, in theory, be rapid (weeks to months). In practice, though, the long transit times (large τ) during the narrow seasonal cyanoHAB window (Jul-Sep) would make it more likely to see a change from one year to the next. Although the effect could occur within 1 yr, considering interannual variability in cyanoHAB events, several years (up to a decade) may be needed to confidently detect a change. If sed-orgN or sediment N fluxes are important, responses would only begin becoming evident after years to decades.
- **P3A & P3B:** *Key dependencies*: i) Spatial overlap between cyanoHAB zones and zones with substantial △[DIN]. ii) N availability must be among the most important factors triggering HAB events and/or regulating their severity; iii) The change in ambient [DIN] caused by △[DIN] must be large relative to other DIN sources (i.e., on-going sed-N-flux, San Joaquin River). iv) Post-upgrade [DIN] must fall below thresholds that limit cyanoHAB growth, or limit the severity of events. v) (for P3B) [DIN] must fall below thresholds that would limit cyanotoxin production. *Locations:* While there is some overlap in cyanoHAB hotspot areas and ZOI$_{DIN}$, much of that overlap occurs at the ZOI's outer edges, where △[DIN] will be smaller due to relatively longer τ (Figure B3.4). To test cyanoHAB hypotheses, there will need to be reliable information about △[DIN]; best opportunities will be areas with smaller τ .
- **P3.*slow***: *Key dependencies*: i) Spatial overlap between cyanoHAB zones and zones where sedNflux is substantial source of DIN. ii) N availability must be among the most important factors triggering HAB event and/or regulating its severity; ii) DIN available to cyanoHABs from sedNflux must drop below thresholds that influence growth rate, magnitude of biomass, and/or cyanotoxin production. *Locations:* Areas still within the ZOI$_{DIN}$ but at large τ .

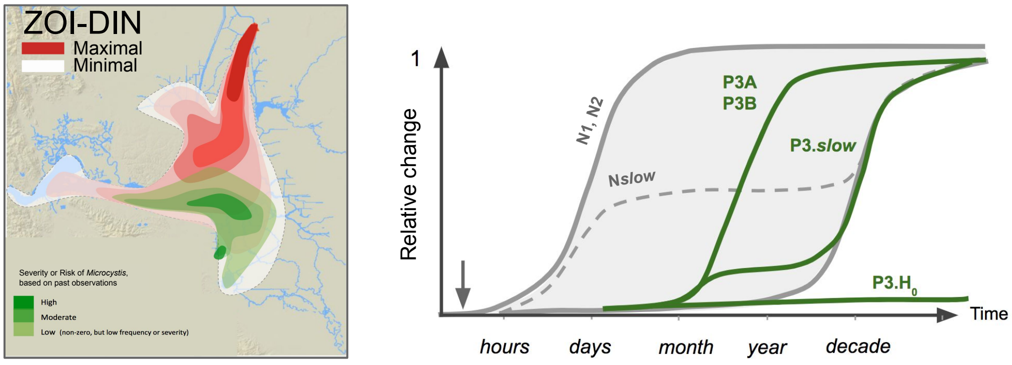


Figure B3.4 (Left) Spatial extent of (green) regions in the Delta where *Microcystis* events occur most frequently or have been most severe; and (red) Zone of Influence (ZOI) for changes in dissolved inorganic nitrogen related to the SRWTP upgrade. **(Right)** Anticipated response times for HAB response scenarios. Grey curves and grey shaded area, are same as Figure B1.6, and denote ranges of response times for N1, N2, N*slow*, for comparison with HAB responses.

Box 4 Invasive Aquatic Vegetation (Tier 2)

- The spread of invasive submerged and floating aquatic vegetation (iSAV, iFAV) acts along multiple pathways to severely impact nSFE ecosystem health (Figures 4 and B5.1, Table 2)
- Invasions are a widespread and growing problem, with numerous species, broadly distributed throughout the Delta (Table B5.1). There have been large increases in density and areal coverage, crowding out beneficial native emergent aquatic vegetation (Figure B5.2), with implications for protecting current high-value habitats, and for planned wetland restoration.
- To date, iSAV and iFAV research studies in the nSFE have focused primarily on changes in coverage and distribution, and found large interannual variation for some taxa (Figure B5.2; e.g., Santos et al. 2016, Khanna et al. 2012, Ustin 2017).

Table B5.1 Important Invasive iSAV and iFAV Species

invasive Submered Aquatic Vegation (iSAV)	
Carolina fanwort	*Cabomba caroliniana*
Brazilian waterweed	*Egeria densa*
Eurasian watermilfoil	*Myriophyllum spicatum*
Crisped or curly-leaf pondweed	*Potamogeton crispus*
invasive Floating Aquatic Vegation (iFAV)	
Water hyacinth	*Eichhornia crassipes*
South American sponge plant	*Limnobium laevigatum*
Uruguay water primrose	*Ludwigia hexapetala*
Water Primrose	*Ludwigia peploides*
Parrot's feather	*Myriophyllum aquaticum*

Meyerson et al. 2010; Khanna et al. 2012; Santos et al. 2016; Ustin 2017; Ta et al. 2017; Boyer and Sutula, 2015.

iSAV and iFAV have spread throughout the nSFE over the past ~20 years (Figure B5.2; Meyerson et al. 2010; Khanna et al. 2012; Santos et al. 2016; Ustin 2017; Ta et al. 2017). Impacts include:

Altered ecosystem function and habitat quality: physical and biogeochemical changes such as decreased water flow, temperature modifications, sediment retention, and reduced oxygen levels; modified lower food web structure, through crowding out native aquatic vegetation, reducing phytoplankton and benthic primary production; providing refuge to invasive predator fish.

Water resources management: increased operation and maintenance costs for drinking water exports; impeded recreational and commercial navigation; promotion of mosquito habitat; and degraded aesthetics (Brown et al. 2007; Yarrow et al. 2009; Hestir et al. 2016; Boyer and Sutula, 2015; Conrad et al. 2016; Ta et al. 2017).

Conversely, in the remaining nSFE areas where *native* aquatic vegetation still dominate, those communities deliver vital ecosystem services, such as stabilizing shorelines, attenuating flooding, and providing habitat to native animals (Vitousek et al. 1997, Johnston 1991, McGonigal and Neubauer 2009, Smyth et al. 2013). To the extent that the nSFE's elevated N levels have contributed to the establishment or spread of iSAV and iFAV, it is conceivable that the SRWTP upgrade could lead to decreased iSAV or iFAV coverage.

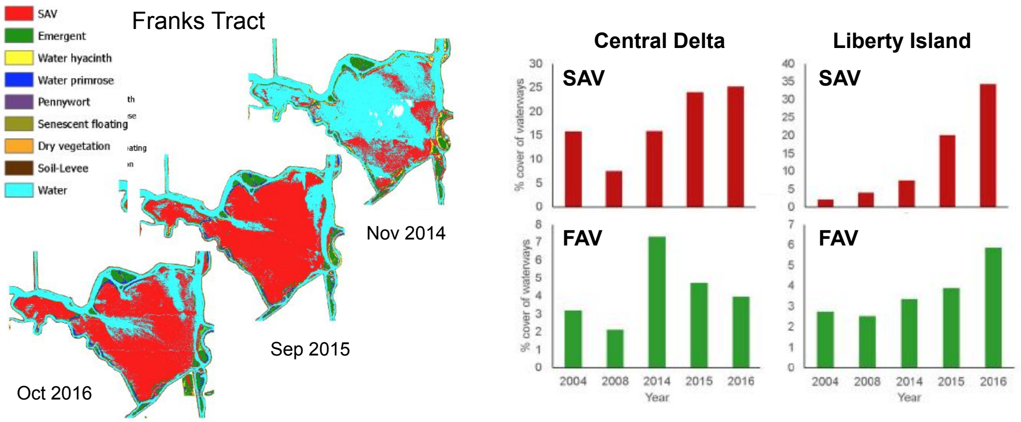


Figure B5.1 Changes over time in SAV and FAV spatial coverage. In both the Franks Tract spatial images and summary bar plots, the primary contributors to SAV and FAV were *Egeria* and water hyacinth, respectively. Graphics modified from Ustin et al. 2017 .

Invasive Aquatic Vegetation Conceptual Model

Key Factors regulating iSAV and iFAV (For details, see Boyer and Sutula 2015, Anderson 1990, 2003)

Abiotic and Biotic Factors: Light, temperature, salinity, channel depth, hydrodynamics (water velocity, residence time, mixing energy), sediment substrate (quality, stability), dissolved oxygen, pH, nutrients.

Ecosystem Engineers: Growth alters surroundings to favor further growth, e.g., trap sediments, ↓ velocities.

Influence of Nutrients: iSAV and iFAV clearly need nutrients to grow. However, important mechanisms and nutrient-concentration thresholds relevant for growth are poorly understood and poorly quantified.

No nutrient-focused iFAV or iSAV studies have been conducted for the Delta. While aspects of the physiology or behavior of Delta-relevant iSAV and iFAV species have been studied in other systems, there is limited information on growth-limiting nutrient concentrations at ambient concentrations comparable to those observed in the Delta (Boyer and Sutula 2015). The concept of growth-limiting concentrations for AV is analogous to that for phytoplankton, whereby iAV would change little despite the upgrade, as long as nutrients remain in excess (see Figure B2.4A).

Water column DIN vs. sediment N: While iFAV and iSAV are generally assumed to access different nutrient pools (water column and sediment, respectively), some FAV and SAV can utilize both. For example, water hyacinth can extend their roots into the sediment layer, allowing them to utilize sediment derived DIN in addition to water column DIN sources. *Egeria*, a rooted SAV, can acquire N from sediments or the water column, depending on relative nutrient abundance (Mony et al. 2007). Some studies have observed that *Egeria* utilizes NH4 before NO3 when both are present in the water column (Reddy et al. 1987); however, there is no information about whether that influences growth rates. In addition, much of the current understanding of N utilization by SAV and FAV is based on results from experiments using much higher water column N concentrations.

Some species can tolerate periods of low nutrient availability, making it challenging to study nutrient:iAV relationships at the field scale, in particular given the large seasonal and interannual changes in Delta water column nutrient concentrations (Novick et al. 2015; Downing et al. 2017; Kraus et al. 2017a, 2017b).

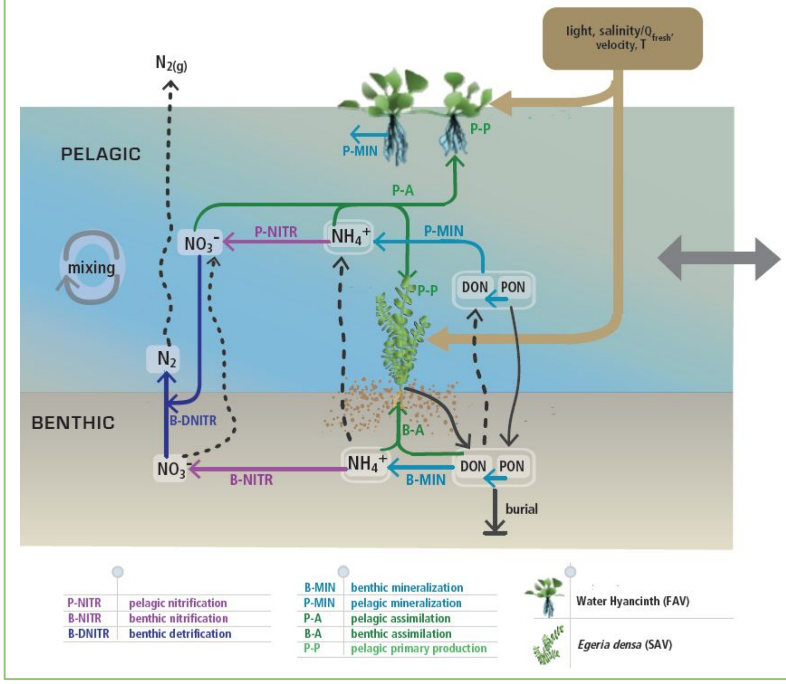


Figure B5.2 Conceptual diagram of factors influencing FAV and SAV growth. Important non-nutrient factors influencing growth include: temperature; hydrodynamics (eg., water depth, velocity, inundation, turbulence, residence time); salinity; channel morphology; delivery of suspended particulate matter (SPM); sediment properties (physical and chemical, e.g., bulk density, Porosity, redox potential, stability); management actions (control measures).

OVERVIEW - Invasive Aquatic Vegetation

Det?	Link?	Occ?	**Table B4 Invasive Aquatic Vegetation Response Scenarios**	**Dependencies***
			iAV-H_0 No change in FAV or SAV density, spatial distribution, or assemblage	
■	▣	▨	**iAV1** ↓FAV biomass or altered spatial distribution, ↓[DIN]	***dAV1,2***
▣	▨	□	**iAV2** Changes to FAV community, ↓[DIN]	***dAV1,2***
■	▨	□	**iAV3** ↓SAV biomass or altered spatial distribution, ↓[DIN]	***dAV1,2***
▣	▨	□	**iAV4** Changes to SAV community, ↓[DIN]	***dAV1,2***
▣	▨	▨	**iAV.*slow*** One or more of the above becomes evident after years or decades, as ↓[sed-orgN]	***dAV3,4,1,2***

*See Table A.1 for descriptions of dependencies

- **Occur?** Highly plausible, but also highly uncertain whether iFAV and iSAV abundance could eventually decrease in response to the upgrade (iAV1, iAV3, iAV.*slow*). It is reasonable to argue, at a basic level, that: i. System-wide, given their large (and expanding) biomass, iSAV+iFAV have substantial N demands; and therefore ii) Substantially decreasing N availability should curtail their production and biomass. However, the magnitudes and response times of iAV1, iAV3, and AV.slow strongly hinge on a few key dependencies (below). While iFAV and iSAV decreases seem plausible, it is highly unlikely that they would ever be eradicated. Changes to iAV community composition are highly uncertain (iAV2, iAV4), and not discussed below.
- **Detect? Link?** Yes: The upgrade presents opportunities to investigate.
- **Response times** (Figure 5.4): If iFAV or iSAV species rely heavily on water column [DIN], timescales of year-years could be expected, as vegetation gradually dies off without new growth keeping apace. If sed-orgN (especially for SAV) or sedN-fluxes are important N sources, responses would only become evident after several years to decades when sediment N availability declines (Figure B1.6).
- **AV1:** *Key dependencies*: i) Spatial overlap of high-FAV and substantial △[DIN]. ii) Post-upgrade [DIN] must fall below growth-limiting thresholds, which are poorly known. *Locations:* Some high-FAV areas overlap with areas where large [DIN] decreases (small τ) could be expected. Most high-iFAV areas lie at the ZOI's edges (Figure B5.4).
- **AV3**: *Key dependencies*: i) Spatial overlap of SAV and substantial △[DIN]. ii) Strong dependence of iFAV species on water column [DIN], as opposed to sed-orgN. While there is evidence that some iSAV species do utilize water column N (e.g., *Egeria*), its importance relative to sediment N pools is poorly understood from a quantitative standpoint.
- **AV*slow***: *Key dependencies*: i) sed-orgN or sedN-fluxes (and resulting [DIN]) decreasing enough over time to limit growth. iAV*slow* emerges as the most likely of the iAV response scenarios for several reasons: a) Although some iSAV can take up water column DIN, iSAV would continue utilizing sed-orgN, which will likely decrease slowly. b) Most of the high-iFAV area lies at the outer edges of the ZOI: [DIN] changes from the upgrade will be smallest there; sedN-flux will continue supplying DIN to the water column, which may remain sufficient to support FAV growth. c) Some iFAV (e.g., water hyacinth) can directly access sed-orgN via shoots. d) The current standing stock of iFAV and iSAV represents a large reservoir of N. As those plants die and accumulate in sediments, and slowly degraded, the liberated N will serve as a continued source to other plants.

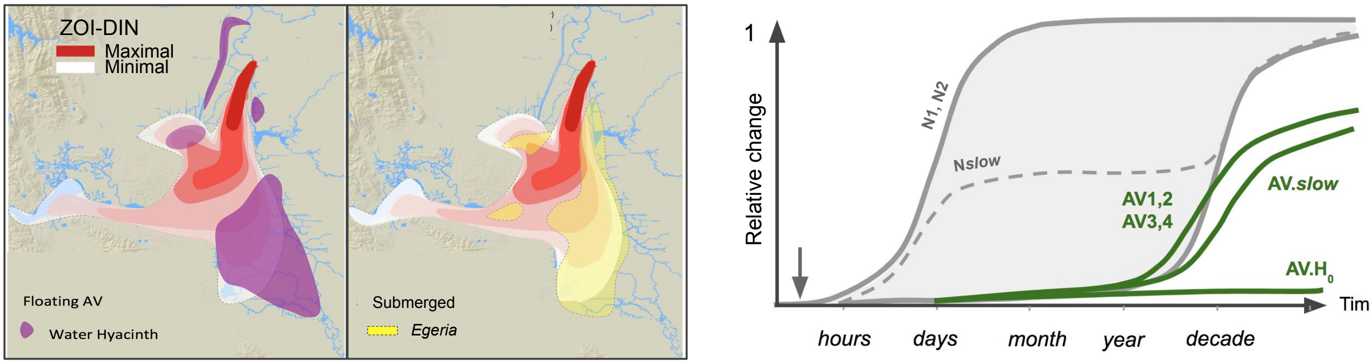


Figure B5.4 (Left) Zones where two of the most problematic iFAV (water hyacinth) and iSAV (*Egeria*) invasive vegetation species commonly occur. Areas of overlap with ZOI (red) indicate potential areas where upgraded-related changes may occur. Note: iAV do no occur throughout these entire areas, but rather in specific habitat-types within these areas. **(Right)** Anticipated response times for iAV response scenarios. Grey curves and grey shaded area, are same as Figure B1.6, and denote ranges of response times for N1, N2, N*slow*, for comparison with iAV responses.

Box 5 Microbial Community (Tier 2)

- The non-phototrophic microbial community (chemoautotrophs, heterotrophs) are key players in the nitrogen cycle, with nearly all of the most important (non-photosynthesis-related) transformations being biologically-mediated by microbes (e.g., Figure B1.5; nitrification, denitrification, mineralization, etc.; see Damashek and Francis, 2018).
- The nSFE microbial community will likely experience major changes in response to the upgrade due to the large decreases in NH4 and NO3 concentrations, essential substrates fueling the chemical reactions that N-transformation specialists mediate to generate energy, build biomass, and produce compounds that other microbes and primary producers rely on for carrying out their own metabolic processes.
- The microbial community likely also has other important, but poorly characterized and poorly understood roles in the nSFE, from their role as a food resource to working synergistically (or antagonistically) with other microbes, phytoplankton, and other primary producers.

Microbial Community Conceptual Model

Microbes degrade both particulate and dissolved organic nitrogen, transforming it into more bioavailable DIN forms (mineralization); they also convert N between DIN species (nitrification, dissimilatory nitrate reduction to ammonium); and they convert dissolved N to the gas phase (denitrification) thereby providing a pathway for aquatic N removal. Together these process mediate net fluxes between the water column and the benthos, and N loss from the system as N_2 gas.

Microbes are believed play important roles in some nSFE food webs: e.g., breaking down organic matter and regenerating N, making organicN available for other organisms to utilize; and through their biomass serving as carbon and energy sources to primary consumers. Although important roles for microbes in the nSFE food web have been previously hypothesized, those roles and their quantitative importance relative to other food resources are poorly understood (Durand et al. 2015; Dahm et al. 2016). Recent studies in other systems have found that phytoplankton and non-photosynthetic microbes not only coexist and co-vary, but do so while working in consortia, each carrying out essential biosynthetic reactions that another cannot (e.g., vitamin B_{12} production; Bertrand et al. 2015). While evidence continues to accumulate for covarations and consortia-like dynamics in freshwater and marine systems (Yang et al. 2017; Amin et al. 2012; Heal et al. 2018), much less information is available about such interactions within estuarine systems.

Considering that NO3 or NH4 act as critical substrate in energy yielding reactions mediated by nitrifiers and denitrifiers, it stands to reason that the abundance (or biomass) and community composition/diversity of N-cycling microbes will be substantially altered in regions experiencing large $\triangle[NH4]_{direct}$ and $\triangle[DIN]_{direct}$. Nearfield to the outfall, [NH4] will in general decrease by >90%, which in turn has the potential to fundamentally reshape the ammonia-oxidizing (nitrifying) community (M1, Table B5): since ammonia-oxidizing archaea (AOA) have much greater ability to assimilate low-level NH4(i.e., low Km) than ammonia-oxidizing bacteria (AOB; Martens-Habbena et al. 2009), one might predict that the first step of nitrification would be driven primarily by an AOA-dominated community, and a shift in relative abundance from what may now be an AOB dominated community high [NH4] to a post-upgrade AOA dominated community. Since NO3 flux from the water to the sediments fuels denitrification within bed sediment anoxic layers (or NO3 from nitrification, at the sediment-water interface), the denitrifier community/activity may be impacted in ways analogous to the AOB to AOA description above (M2). To the extent that $\triangle[DIN]_{direct}$ leads to decreased phytoplankton primary production and decreased delivery of fresh labile organic matter, then heterotrophs (mineralizing communities) may also be affected (M3). Observing these changes, in both the surface sediments and water column, has the potential to provide critical insights into how microbial communities respond to dramatic shifts in nutrient availability. Because studies of this kind usually focus on microbial responses to increased nutrients, this represents a truly unique and valuable research opportunity. These types of changes (above) would begin happening immediately upon the upgrade coming on-line, necessitating pre-upgrade sampling to establish baseline information about community structure prior to load changes.

OVERVIEW - Microbial Community

Det?	Link?	Occ?	Table B5 Microbial Community Response Scenarios	Dependencies*
			M-H$_0$ No change in microbial assemblage	
■	■	■	**M1** ↓ nitrifier activity or abundance (or assemblage change) due to ↓[NH4] and ↓[DIN]	***dm1***
▨	░	▨	**M2** ↓ denitrifier abundance or change in assemblage due to ↓[NO3]	***dm2***
▨	▨	▨	**M3** Other changes to biological communities (e.g., synergisms), via microbes, due to ↓[DIN]	***dm1,dm2,dm3***
░	░	▨	**M.*slow*** As sediment N pool changes, longer-burn, slow changes in assemblage may be expected.	***dm4***

*See Table A.1 for descriptions of dependencies

- **Occur?** In regions that experience large $\triangle[NH4]_{direct}$ and large $\triangle[DIN]_{direct}$, the likelihoods of M1 and M*slow* occurring are high. In regions with moderate to high $\triangle[DIN]_{direct}$, M2 and M3 are highly plausible, but characterizing the specific types of change is less straightforward than M1.

- **Detect? Link?** M1: If $\triangle[NH4]_{direct}$ is large, high likelihoods for both detecting and linking back to upgrade. M2,M3,M*slow*: with sufficient baseline data, detections/successful-linking also appear moderately likely.

- **Response times** (Figure B5.3): In regions that experience large $\triangle[NH4]_{direct}$ or $\triangle[DIN]_{direct}$, microbial community changes, in the water column or in near-surface sediments, could be evident on time scales of days to weeks. For microbial communities deeper in sediments, response times will more closely align with sediment-N response times (years).

- **M1,M2,M*slow***: *Key dependencies:* Short τ to ensure large $\triangle[NH4]_{direct}$ or large $\triangle[DIN]_{direct}$. For M1, this will increase the likelihood of major changes in nitrifier community by changing NH4 availability, a key ingredient for their energy production. Recent observations in the nSFE (Damasheck et al. 2015, 2016) demonstrated that the nitrifier community varies seasonally and spatially due to factors other than NH4 concentration (e.g., temperature, salinity). Therefore, sufficient pre- and post-upgrade data will be needed to unambiguously distinguish upgrade-related changes from other factors. For M2, while $\triangle[DIN]_{direct}$ could influence the denitrifier community by decreasing its oxidant source (NO3), that community may also respond to other changes in conditions that foster denitrification: e.g., changes in phytoplankton primary production and subsequent settling of fresh organic matter to the sediments (substrate for denitrification); and thickness of sediment aerobic surface layer (since denitrification only occurs under anaerobic conditions), which are themselves related. Thus, changes to DIN could also indirectly influence the microbial community by altering phytoplankton production rates. M*slow*: Similar dependencies as for M1 and M2. In addition, to the extent that in some regions sedN or sedN-flux remain great enough immediately post-upgrade to satisfy microbial N demand (in water column or sediments), sedN or sedN-flux will need to decrease sufficiently in order for changes in nitrifier or denitrifier communities to become evident.

- **M3** *Key dependencies:* Similar dependencies as M1 and M2. While interactions between microorganisms, or between the microbial community and and other biota (microbe←→microbe; microbe←→phytoplankton; microbe←→AV; microbe←→animal), are poorly understood, recent field studies have begun documenting such interactions, including synergistic or antagonistic interactions. Therefore, while we cannot predict the nature of those interactions or changes or their ecosystem-scale importance, it is reasonable to argue that: i) it is quite plausible that they could occur; ii) the potential for such interactions to be ecologically-meaningful can not be ruled out.

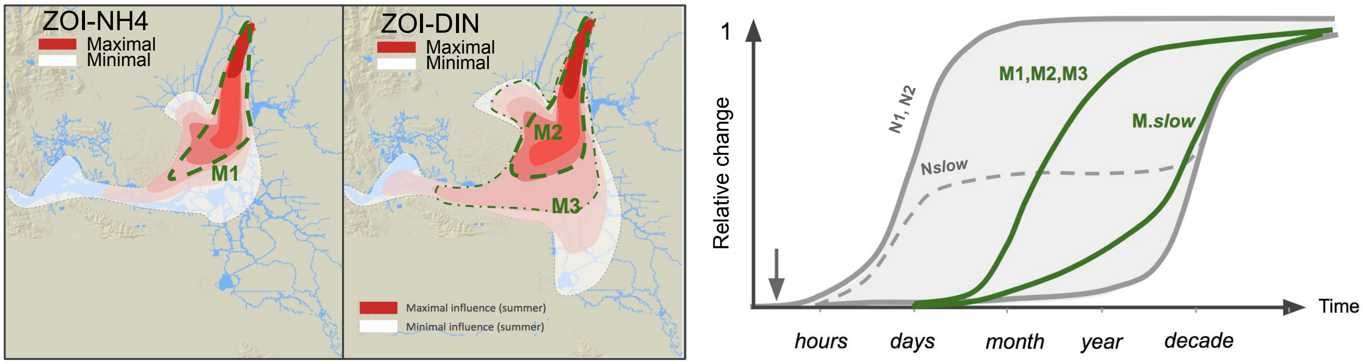


Figure B5.3 (Left) Zones where microbial response scenarios may be most readily studied or observed. **(Right)** Anticipated response times for microbial response scenarios. Grey curves and grey shaded area, are same as Figure B1.6, and denote ranges of response times for N1, N2, N*slow*, for comparison with microbial responses.

Box 6 Higher Trophic Level Food Web Responses (Tier 3)

- Pelagic fish occupy a prominent role with regard to nSFE ecosystem management decisions, because of major declines in the abundances of several native and introduced (but recreationally important) fishes (Sommer et al. 2007; NRC 2012; Brown et al. 2016, Moyle et al. 2016). Numerous natural and anthropogenic factors can influence fish populations. A subset of those factors operate within or through the food web, including phytoplankton production and other pathways having potential mechanistic links/interactions with nutrients (Figure B6.1; Figure 4). Most prominent among plausible food web pathways is low phytoplankton productivity and resultant food limitation that may represent additional stressors to already struggling pelagic fish populations. As a result, productivity and overall health of the pelagic food web have also become a focus of nSFE management considerations.
- In this context, the SRWTP upgrade is important because it will change N delivery to the nSFE ecosystem, with the potential for subsequent direct and indirect food web effects (see Boxes 1-5). The discussion below focuses on higher trophic level food web response scenarios, with a particular emphasis on the pelagic food web. The roles played by other influential factors are also covered through their potential influence on whether of nutrient-related response scenarios may occur or reach detectable levels.

Food Web Conceptual Model

Food webs describe the sources and flow of energy and biomass, from primary producers to consumer organisms, and ultimately to species of interest to humans (Figure B6.1). Since the 1980s, phytoplankton production throughout much of the nSFE has dropped substantially, decreasing phytoplankton biomass available for primary consumers, including copepods that are important food resources within the pelagic food web. A growing body of evidence suggests that Delta Smelt declines are due in part to declining availability of their zooplankton prey (Brown et al. 2016, Moyle et al. 2016), in particular nutritious copepods thought to derive much of their nutrition from phytoplankton produced within the system. Other proposed food-web-related pathways that may be affecting pelagic fish include: direct and indirect effects of toxins produced during HAB events (Box 3); and invasive SAV or FAV (Box 4). For simplicity, most of the subsequent discussion focuses on Delta Smelt and other pelagic fishes as the upper trophic level species of interest.

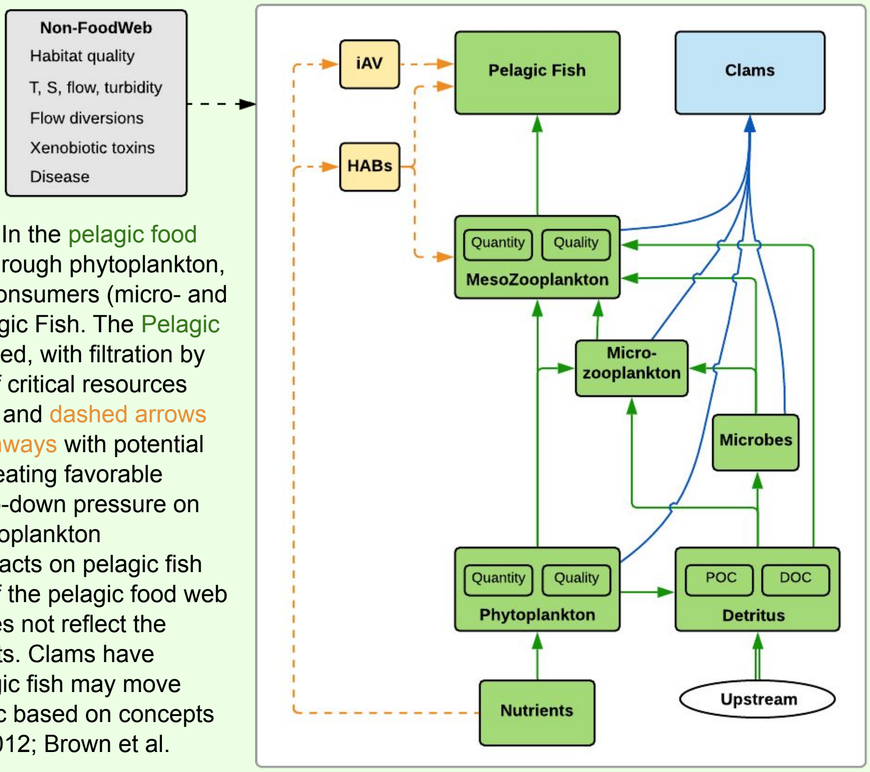


Figure B6.1 A simplified depiction of nSFE food webs. Pelagic fish abundances are influenced by multiple factors, including Non-Food Web factors (grey box) and food-web related factors (inside red box). Solid arrows depict the flow of energy and nutrients through resource pools (boxes). In the pelagic food web (green), energy and nutrients pass through phytoplankton, detritus, and microbial pools, to primary consumers (micro- and meso-zooplankton) and ultimately to Pelagic Fish. The Pelagic and Benthic (blue) food webs are connected, with filtration by two introduced clam species siphoning off critical resources from the pelagic food web. Orange boxes and dashed arrows represent two other food web-related pathways with potential nutrient connections: SAV/FAV (Box 3) creating favorable habitat for invasive predators, causing top-down pressure on pelagic fish; and HAB toxins impacting zooplankton abundances or exerting direct toxicity impacts on pelagic fish (Box 4). Note that while all components of the pelagic food web are subject to transport, this depiction does not reflect the degree of connectedness between habitats. Clams have essentially fixed locations; however, pelagic fish may move between multiple distinct habitats. Graphic based on concepts discussed in Jassby et al. (2002); NRC 2012; Brown et al. 2016; and Moyle et al. 2016.

Potential Pelagic Food Web Outcomes: Delta Smelt are primarily dependent on the pelagic food web, feeding mostly on calanoid copepods (Sommer et al. 2007, Moyle et al. 2016), which rely on phytoplankton as an important part of their diet (Figure B6.1). When Delta management discussions turn to enhancing the pelagic food web's production, it is commonly assumed that increased primary production will enhance production of copepods and other zooplankton. While Delta Smelt and many other pelagic fishes are primarily dependent on the pelagic food web, the pelagic food web is not the only food web that needs to be considered when exploring tractable ways to augment pelagic fish food supply. Of particular importance is the interaction between the benthic and pelagic food webs through grazing effects of invasive bivalves on phytoplankton. Specifically, two species of introduced bivalve exert intense grazing pressure on small planktonic organisms (Figure B6.1). *Corbicula fluminea*, introduced in the 1940s, dominates the benthos in freshwater regions, and *Potamocorbula amurensis,* introduced in the mid-1980s, dominates brackish water regions (Cohen et al. 1984, Lucas et al. 2002, Lopez et al. 2006; Cloern 2001, Kimmerer and Thompson 2014). The invasion of *P. amurensis* coincided with the decline in phytoplankton biomass and other pelagic food web changes in the nSFE's low salinity zone (Cloern 2001, Kimmerer and Thompson 2014). *P. amurensis* has also been shown to feed on microzooplankton, including the early life stages of larger zooplankton that are eaten by Delta Smelt (Kimmerer et al. 1994, Kimmerer and Lougee 2015); thus, it has both direct and indirect effects on zooplankton eaten by Delta Smelt.

Even if the upgrade results in changes to phytoplankton production or food quality (P1a, P1b, P2a, P2b; Figure 4), it is still plausible that little or no changes in phytoplankton biomass or copepod abundances would be detected. This outcome could occur if the light-limitation, phytoplankton-production, and grazing strongly buffer, or self-regulate phytoplankton biomass. Both C*. fluminea* (Foe and Knight 1985) and *P. amurensis* are believed to be food limited in the Delta; therefore, their populations could respond relatively rapidly to changes in phytoplankton production through increases or decreases in biomass (and grazing rates), or by shifts in spatial distributions away from lower productivity zones and toward higher productivity zones. In other words, shifts in clam biomass (higher, lower) could occur instead of changes to zooplankton biomass, that supports pelagic fishes. Another often-overlooked factor in discussions of Delta Smelt food web support is the degree of spatial overlap between i) physical habitat most suitable for Delta Smelt (e.g., salinity, turbidity, and water temperature); ii) areas where zooplankton abundances might change; and iii) regions where phytoplankton productivity may change. Phytoplankton populations can respond to changing conditions on time scales of days, while the slower reproductive responses of zooplankton populations and pelagic fish populations will be on the order of weeks (Kimmerer et al. 2014) and months to years, respectively. The potential for spatial mismatches, combined with potential temporal mismatches, further detract from the feasibility of detecting changes in fish or copepod abundances that link back to the upgrade.

Lastly, numerous covariates could confound understanding of food web related outcomes from the upgrade. For example, Delta Smelt biology is influenced by numerous other potentially-dominant factors, most of them unrelated to food supply (see Baxter et al. 2015, Moyle et al. 2016), e.g., entrainment, inflow and diversions, position of the low salinity zone, and effects of SAV on turbidity.

All that said, it is reasonable to expect that windows will occur in space or time when phytoplankton dynamics and zooplankton dynamics align such that the influence of SRWTP upgrade-related changes to phytoplankton production (increase, decrease) and their influence on zooplankton production can be studied. Moreover, some sustained changes may occur, for example, if the frequency or intensity of short duration spring blooms increased in the low-salinity zone before spring recruits of *P. amurensis* become established in shallow waters where bird predation decreases their abundance in late fall and winter. It is less clear, however, whether ecologically-meaningful changes will occur, or, if they do, whether they will be detectable and traceable back to the upgrade, considering the numerous challenges outlined above. In addition to appropriate alignment of phytoplankton and zooplankton dynamics, multiple other dependencies must be satisfied (see Table B6, and inherited dependencies from T1 and T2 responses). In summary, it will be difficult to confidently demonstrate direct higher-trophic level pelagic food web responses to the upgrade, through either enhanced monitoring or directed research. There are simply too many possible interactions and covariates to consider. Monitoring and research related to the upgrade are likely best focused on T1 and T2 responses: nutrient processes, primary producers and lower level consumers, primarily clams and zooplankton. Results from such studies could then be integrated with ongoing and future work on fishes, including Delta Smelt, conducted by IEP and others.

OVERVIEW - Food Web

Det?	Link?	Occ?	Table B6 Food Web Response Scenarios	Dependencies*
			FW-H$_0$ No evidence of improved food web condition that can be traced back to N1-N*slow*.	
⬜	🟧	⬜	**FW1a:** Changes in pelagic target organisms' abundances due to changes in food resources	***dFW.1,2,3,4,5,6,7*** *+ inherited*
🟦	🟦	⬜	**FW1b** Changes in food resources reaching target organisms (e.g., change in copepod abundance)	***dFW.1,2,3,4,5,6,7*** *+ inherited*
⬜	🟧	⬜	**FW2:** Change in pelagic target organisms' abundances due to ↓ HA toxin exposure	***dFW.8,9,7 +*** *inherited*
🟧	🟧	⬜	**FW3** Decreased invasive predator habitat, indirect effects on target organisms (via the food web)	***dFW.10,11 +*** *inherited*
⬜	🟧	⬜	**FW.*slow*** One of the above, but after years or decades, due to ↓[sed org-N]	*see above*

*See Table A.1 for descriptions of dependencies

- **Occur?** Possible, but all are highly uncertain. There are numerous dependencies, in particular the numerous other factors that influence wildlife responses. Even if a nutrient-related factor changes, other dominant controls may prevent a meaningful food web response from occurring.
- **Detect? Link?** Among these scenarios, FW1b is the only one for which targed studies to detect a change and link to the upgrade could potentially be successful, given the potential of copepods and other zooplankton to respond rapidly to changes in food availability. Nonetheless, study design would need to overcome considerable uncertainty. For the remaining responses, ongoing long-term fish monitoring in the nSFE has the potential to detect the effects on populations over time. However, the likelihood of linking changes back to the upgrade is low, because of the relatively long response times and the other strongly-influential factors that will vary temporally.
- **Response times** (Figure B6.4): FW1b Changes in copepod abundances or other indicators (e.g., reproduction rates) could become evident shortly after the upgrade (weeks to months), within the context of, for example, a targeted mechanistic field study. Detecting changes over larger spatial scales (e.g., regional scale abundances) would likely require years for changes to be evident relative to interannual variability. Fish abundances (FW1a, FW2, FW3) at the population level would respond with time scales of years, and longer for those changes to be detectable above interannual variability. Any responses originating with [sed-orgN] will respond relative to that lag.
- **FW1a, FW1b**: Key dependencies: Inherit all relevant phytoplankton production dependencies (Box 2); and food quantity/quality would need to be among the most important factors currently impacting target organism(s); Changes in food pathways would need to sufficiently bypass the benthic food web to reach and benefit the pelagic food web; There would need to be temporal overlap (life-stages) and spatial overlap between zones with changed food production (or quality) and copepod populations or fish populations.
- **FW2:** Key dependencies: Inherit all relevant HAB dependencies (Box 3); toxin exposure must be among the most important factors impacting target organism(s); substantial changes in toxin production and exposure must occur.
- **FW3:** Key dependencies: Inherit all relevant iAV dependencies (Box 4); habitat for invasive predators (iAV) needs to be among the most important factors currently impacting target organism(s), and cause sufficient change to predation rate.

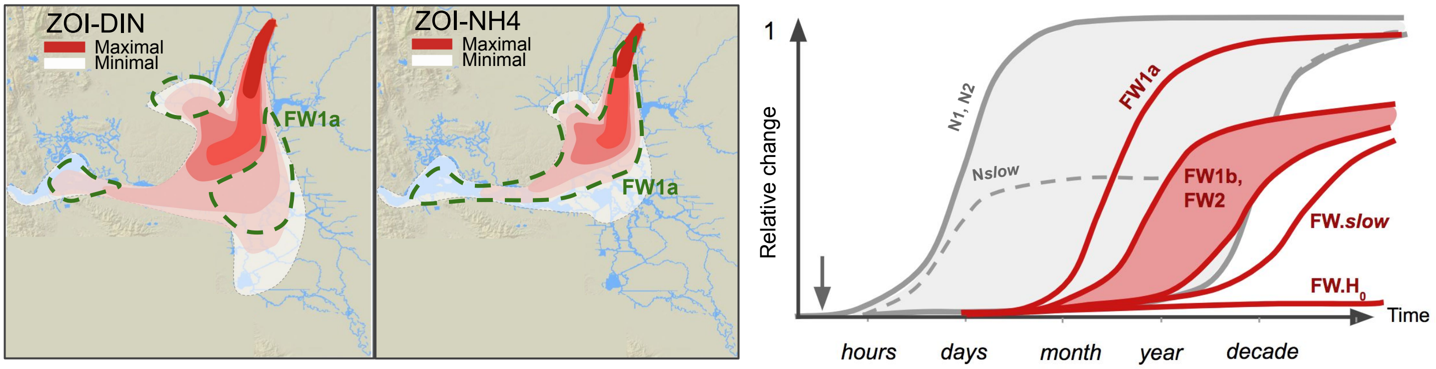


Figure B6.4 (Left) Relevant Food Web response zones overlain with ZOI$_{DIN}$ and ZOI$_{NH4}$. Note: **(Right)** Anticipated response times for Food Web response scenarios. The range of potential response times for FW1a and FW2 are represented by the red shaded area. Grey curves and grey shaded area are same as Figure B1.6, and denote ranges of response times for N1, N2, N*slow*, for comparison.

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Table A.1 Dependencies influencing the likelihood or ecological-significance of response scenarios.

dn1	Locations are within areas that are strongly influenced by effluent (maximal or intermediate ZOI, DIN or NH4)
dn2	Within the broadly defnied ZOIs, specific habitat or location has small or moderate τ.
dn3	Sufficient resolution of nutrient data to (space, time) to detect changes above interannual and seasonal variations
dp1	[DIN] fall below a threshold(s) at which overall community growth rates decline substantially.
dp2	N-related effects (DIN or NH4) are quantitatively important relative to non-nutrient factors
dp3	Spatial or temporal windows in which benthos minimally influence phytoplankton biomass.
dp4	NH4-inhibition mechanism occurs and is quantitatively important at the field scale.
dp5	[NH4] fall below a relevant threshold (NH4-inhibition hypothesis, ecological stoichiometry hypotheses)
dp6	[DIN] falls below growth-limiting thresholds, leading to competition and nutrient-driven community succession.
dp7	Ecological stoichiometry mechanism(s) occur and are quantitatively important at the field scale.
dp8	N fluxes from the sediments sustain DIN or NH4 above relevant thresholds after the upgrade (t~months to years)
dp9	N fluxes from sediments decrease over time, and [DIN] or [NH4] fall below relevant thresholds.
dp11	[DIN] or [NH4] concentrations are important factors contributing to the occurrence and severity of HA events
dp12	[DIN] or [NH4] decrease below relevant thresholds for HA growth or toxin production.
dp13	Microcystin production is strongly regulated by N availability.
dp14	N fluxes from the sediments sustain DIN or NH4 above relevant thresholds for HA growth or toxin production
dp15	N fluxes from sediments decrease over time, [DIN] or [NH4] fall below thresholds for HA growth or toxin production
dav1	[DIN] is a quantitatively important factor (ecosystem scale) contributing to FAVs or SAVs spread, density, distribution
dav2	[DIN] decreases below growth-limiting thresholds for FAV or SAV
dav3	N fluxes from the sediments sustain [DIN] above relevant thresholds for FAV or SAV growth
dav4	Bioavailable forms of N in the sediments decrease to levels that restrict SAV growth; or N fluxes from sediments decrease such that [DIN] eventually drops below growth-limiting thresholds for FAV
dm1	[NH4] decrease sufficient to cause changes within the nitrifier community.
dm2	[NO3] decrease sufficient to cause changes within the denitrifier community
dm3	Large enough changes in availability of oxidant (NO3) or organic matter to drive a change among heterotrophs
dm4	Sufficient changes in labile sediment organic matter stores to drive a change in the benthic microbial assemblage.
dfw1	Food quality is among the important factors that are currently influencing zooplankton and fish populations.
dfw2	The changes in food quantity/quality are not substantially affected by the benthic food web.
dfw3	Densities or spatial coverage of invasive clams do not increase in response to new food resources.
dfw4	Ecologically-meaningful change in food quality/quantity production rates, sufficient to affect target pelagic organisms
dfw5	Spatial overlap/connectedness between target pelagic organisms' habitat and regions having improved food quantity/quality
dfw6	Temporal overlap (seasonal) between food quantity/quality changes and organisms' food requirements (life cycle)
dfw7	Other factors influencing target micro- and macrofauna populations remain relatively constant (or can be controlled for statistically), i.e., lower 'noise' allowing better chance of identifying any nutrient-related signals
dfw8	HA toxin exposure is among the important factors that are currently influencing zooplankton and fish populations.
dfw9	Decreased toxin exposure: sufficient magnitude of change to influence population level success of target organisms
dfw10	Physical habitat is among the quantitatively important factors influencing zooplankton and fish populations.
dfw11	The magnitude and locations of changes to physical habitat are sufficient to have a measurable affect.

Appendix A Other Response Categories: Wetlands and Drinking Water

A.1 Wetlands

Tidal wetlands influence, and are influenced by, nutrient concentrations, and are sometimes considered “hot spots” of nutrient cycling based on evidence suggesting that nutrient transformation rates, removal, storage, and release are augmented by increased plant and microbial densities (McGonigal and Neubauer 2009). Under ‘goldilocks’ physical-exchange regimes, wetlands can experience high nutrient demand and turnover (Ensign et al. 2008; Loomis and Craft 2010; Gribsholt et al. 2005; Bowden 1987; Bowden et al. 1991) and receive sufficient nutrient inputs from adjacent water bodies via advective or tidal exchange. Changes in plant productivity along with changes in microbial activity resulting from altered nutrient regimes can influence the balance of soil organic matter production and decomposition rates, with possible consequences for soil stability and accretion rates, and therefore marsh integrity and resilience (Morris et al. 2016). Lastly, effects of nutrient concentrations on vascular plant and algae production in tidal wetlands could also affect local food webs (see food web section).

Nutrient dynamics in tidal freshwater wetlands in general, and Delta wetlands in particular, are not as well studied as in salt marshes. The SRWTP upgrade appears to provide opportunities to advance our understanding of these interactions, which is particularly relevant considering that large-scale Delta wetland restoration efforts are now underway (California Natural Resources Agency, 2017). The effects of nutrient changes on tidal wetlands may best be studied in existing wetlands and planned restoration projects closest to the outfall, including Delta Meadows, McCormack Williamson Tract, Cache Slough, Liberty Island, and Prospect Island. Interactions between the pelagic food web and the tidal wetland and SAV food webs are poorly characterized. The interaction with the tidal wetland food web is of interest because one of the proposed benefits of tidal wetland restoration is to create new habitat where pelagic species can feed and where excess production of phytoplankton, zooplankton, and other organic material can subsidize the pelagic food web (Herbold et al. 2014). To date, there is no evidence that tidal wetlands actually export zooplankton, but few studies have examined this question. Delta Smelt do consume prey other than zooplankton, including amphipods and insects (Whitley and Bollens 2014, Baxter et al. 2015), indicating they are not wholly dependent on the pelagic food web. Whitely and Bollens (2014) documented small numbers of Delta Smelt feeding in tidal wetland habitat.

A.2 Drinking Water

The Delta supplies drinking water to over 25 million Californians. Although nutrient concentrations in Delta waters are well below levels considered toxic to humans, nutrients indirectly affect drinking water quality via the production of cyanotoxins, taste and odor compounds, and organic carbon. In addition, nutrients can fuel the production of aquatic macrophytes and phytoplankton which clog infrastructure, leading to additional costs associated with water conveyance, storage, and drinking water treatment (Delta Drinking Water Work Group, 2017). These issues occur not only in the Delta proper, but also during water conveyance and storage via aqueducts and reservoirs which results in long detention times (weeks to years), providing additional opportunity for organisms to grow. As with many of the other nutrient-related responses discussed in this paper, links between nutrients and drinking water issues are complicated by a number of other abiotic (e.g., temperature, irradiance, flow) and biotic factors (e.g., phytoplankton abundance, community structure, physiological status) factors that affect how organisms grow and the compounds that they produce (Figure 1). Currently, the location, timing, and duration of cyanotoxins, taste and odor issues, and nuisance levels of phytoplankton and macrophytes in the Delta and in downstream conveyance and storage facilities occurs unpredictably, making it challenging to identify drivers of event initiation, duration, and attenuation, as well as predicting the fate of compounds of concern (Delta Drinking Water Work Group, 2017). As recommended by the Delta Drinking Water Work Group (2017), assessing whether nutrient reductions alone or in concert with other management actions will alleviate these occurrences will require continued monitoring, and would greatly benefit from modeling efforts.