Delta Science Program

DELTA STEWARDSHIP COUNCIL

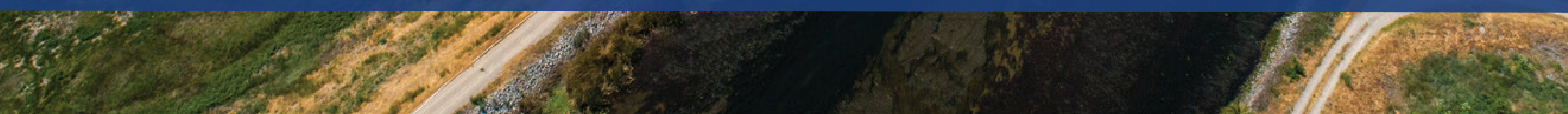
State of Bay-Delta Science 2022

Executive Summary

The State of Bay-Delta Science (SBDS) is one of the core strategic documents issued by the Delta Science Program, intended to summarize the "best-available science" for a broad range of topics relevant to decision making in the San Francisco Estuary. Historically released every 5-6 years, it is now planned for approximately biennial release, with each issue focusing on a timely theme. The 2022 edition focuses on primary producers—plants and algae—and how they impact human and nonhuman communities in the Delta in ways both beneficial and detrimental. The topic is timely, as evolving statewide strategies for adapting to climate change (e.g., carbon neutrality, promoting native species recovery) invoke the natural services provided by plants and algae (e.g., carbon sequestration, food web supply). Meanwhile, some of the most costly and concerning aspects of resource management in the Bay-Delta revolve around disservices of primary producers, including invasive species proliferation and toxic algae blooms.

The 2022 edition of SBDS contains seven peer-reviewed articles published in the online, open access journal San Francisco Estuary and Watershed Science. Here we summarize those articles and curate a set of key takeaways for managers.

— Dr. Laurel Larsen, *Delta Lead Scientist*



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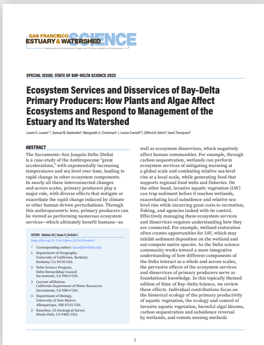
SAN FRANCISCO ESTUARY & WATERSHED SCIENCE

SPECIAL ISSUE: STATE OF BAY-DELTA SCIENCE 2022

Ecosystem Services and Disservices of Bay-Delta Primary Producers: How Plants and Algae Affect Ecosystems and Respond to Management of the Estuary and Its Watershed

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ARTICLE

https://doi.org/10.15447/sfews.2023v20iss4art1

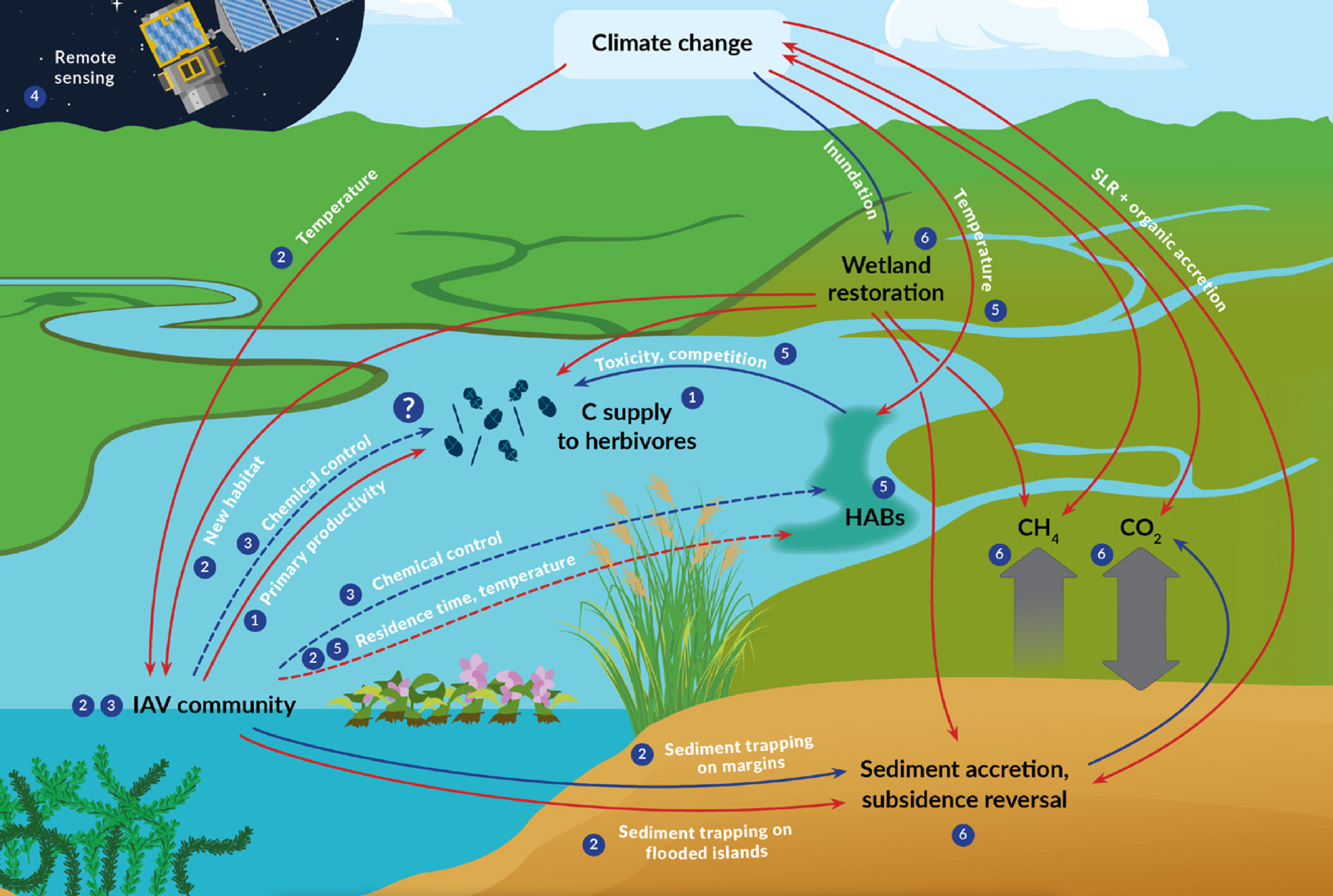
Chapter Focus

This themed edition of ***The State of Bay-Delta Science*** includes six topical chapters exploring the important contributions and impacts of plants and algae (i.e., primary producers) in the Bay-Delta system. Collectively, these articles address research priorities identified in the 2022–2026 Science Action Agenda[1] and allow Delta scientists and managers to address questions such as "What is the relative value in investing in invasive aquatic weeds control for fish relative to promoting wetland restoration?" or "How might alternative strategies for wetland restoration impact Delta sediment and carbon balances, invasive aquatic vegetation coverage, and economic and recreation impacts on human communities?"

Key Points

- Primary producers provide numerous ecosystem services—which ultimately benefit humans—as well as so-called "ecosystem disservices," which have negative effects on human communities.
- Individual articles focus on the historical ecology of aquatic vegetation, primary production, the ecology and control of invasive aquatic vegetation, harmful algal blooms, carbon sequestration and subsidence reversal by wetlands, and remote sensing methods for quantifying ecosystem services and disservices of Delta primary producers.

1. University of California, Berkeley
2. Delta Stewardship Council, Delta Science Program
3. State Water Resources Control Board
4. California Department of Water Resources
5. University of New Mexico
6. United States Geological Survey, Water Resources Mission Area (Emeritus)



CAPTION: Diagram connecting major scientific messages across all the chapters forming this edition of The State of Bay-Delta Science. The circled numbers indicate the chapter or chapters in which the depicted relationship, process, or primary producer community is discussed: **1)** Boyer et al.; **2)** Christman et al.; **3)** Conrad et al.; **4)** Hestir et al.; **5)** Kudela et al.; **6)** Windham-Myers et al.

Abbreviations: C, carbon; CH4, methane; CO2, carbon dioxide; HABs, harmful algal blooms; IAV, invasive aquatic vegetation; SLR, sea level rise.

FROM THE MAIN ARTICLE:

“Primary producers in the Delta infuse energy into the food web, regulate regional carbon and radiative balances, provide habitat, and influence human health, recreations, and livelihoods for better (services) or worse (disservices).”

Read more at https://doi.org/10.15447/sfews.2023v20iss4art1

Chapter Summary

Plants and algae form the basis of food webs by functioning as ‘primary producers,’ transferring light energy into food for ‘consumers’ of this energy (e.g., fish and other wildlife). Primary producers also play a major role in moderating other important components of the ecosystems in which they are found, including change due to climate or other human-driven factors. In the Sacramento-San Joaquin Delta, primary producers perform numerous ecosystem services—which ultimately benefit humans—as well as ecosystem disservices, which have negative effects on human communities. For example, primary producers generate energy for food webs, provide habitat to fish and wildlife, influence carbon and sediment cycles with local, regional, and global implications, and influence human health, recreation, and livelihoods. Depending on the socioecological context, these services may be perceived as positive benefits (e.g., services) or negative impacts (e.g., disservices), and these effects may be simultaneous.

For this edition of the State of Bay-Delta Science (SBDS), we highlight the many ways in which primary producers provide such ecosystem services and disservices and highlight key contributions to science needed for management, including:

- Defining key drivers for estimating or forecasting ecosystem services (e.g., carbon sequestration; Windham-Myers et al. – Chapter 6) or disservices (e.g., harmful algal blooms (HABs); Kudela et al. – Chapter 5) and highlighting emerging technology and analyses relevant to modeling these processes (Hestir and Dronova – Chapter 4).

- Assessing cumulative impacts of wetland restoration, invasive aquatic vegetation management, or alternative strategies for managing wetland and agricultural land on Delta-wide carbon balances and carbon inputs to food webs—a necessary step toward Delta-wide planning for carbon neutrality and species recovery (Windham-Myers et al. – Chapter 6; Boyer et al. – Chapter 1).

- Laying a conceptual foundation for estimating cumulative impacts of wetland restoration and invasive aquatic vegetation management on Delta sediment balances and sea-level rise resilience strategies (Christman et al. – Chapter 2).

- Compiling specific science-based management recommendations, including:

  » the establishment of quantitative targets for invasive aquatic vegetation controls (Conrad et al. – Chapter 3) and HAB toxins (Kudela et al. – Chapter 5),

  » development of more effective monitoring strategies for HABs (Kudela et al. this issue) and invasive aquatic vegetation (Conrad et al. – Chapter 3), and

  » expanded use of specific techniques to limit carbon emissions (e.g., flooding agricultural fields, intermittently draining rice fields, developing new impounded wetlands for subsidence reversal, tidal restoration to impounded wetlands, expanding riparian forest (Windham-Myers et al. – Chapter 6).

Looking Across Chapters

In addition to contributing synthetic takeaways, each chapter identifies research gaps that span specific ecosystem services and disservices up to system-level impacts or management needs. Looking across chapters also provides additional opportunities to synthesize takeaways, including:

- Changing climate locally creates new opportunities for aquatic weeds to invade (Christman et al. – Chapter 2) and HABs to proliferate (Kudela et al. – Chapter 5), and it may threaten planned wetland restoration with inundation. However, in a global-scale feedback, climate is not purely a driver but could also respond to human-ecological actions in the Delta, as planned wetland restoration sequesters carbon from the atmosphere (Windham-Myers et al. – Chapter 6).

- Proliferation of invasive aquatic weeds has pervasive and diverse impacts on the Delta that underscore the theme that agents of ecosystem disservices may also provide ecosystem services, and vice-versa.

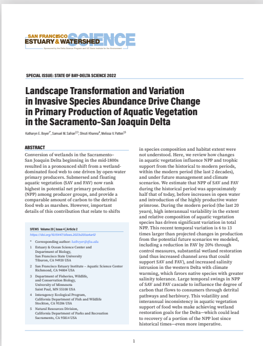
- Of all the connections explored through this edition, the best quantified are the connections between wetland restoration and carbon supply to herbivores at the base of the food web and that between invasive aquatic weeds and carbon supply.

- Interactions with humans pervade the system. In addition to experiencing impacts, humans can exert strong control over the ecosystem services and disservices considered here.

1. Delta Stewardship Council, Delta Science Program. 2022. 2022–2026 Science Action Agenda.

Chapter 1

Landscape Transformation and Variation in Invasive Species Abundance Drive Change in Primary Production of Aquatic Vegetation in the Sacramento–San Joaquin Delta


SAN FRANCISCO ESTUARY & WATERSHED SCIENCE

Sponsored by the Delta Science Program and UC Davis Institute for the Environment

SPECIAL ISSUE: STATE OF BAY-DELTA SCIENCE 2022

Landscape Transformation and Variation in Invasive Species Abundance Drive Change in Primary Production of Aquatic Vegetation in the Sacramento–San Joaquin Delta

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ABSTRACT

Conversion of wetlands in the Sacramento–San Joaquin Delta beginning in the mid-1800s resulted in a pronounced shift from a wetland-dominated food web to one driven by open-water primary producers. Submersed and floating aquatic vegetation (SAV and FAV) now rank highest in potential net primary production (NPP) among producer groups, and provide a comparable amount of carbon to the detrital food web as marshes. However, important details of this contribution that relate to shifts in species composition and habitat extent were not understood. Here, we review how changes in aquatic vegetation influence NPP and trophic support from the historical to modern periods, within the modern period (the last 2 decades), and under future management and climate scenarios. We estimate that NPP of SAV and FAV during the historical period was approximately half that of today, before increases in open water and introduction of the highly productive water primrose. During the modern period (the last 20 years), high interannual variability in the extent and relative composition of aquatic vegetation species has driven significant variation in total NPP. This recent temporal variation is 6 to 13 times larger than projected changes in production from the potential future scenarios we modeled, including a reduction in FAV by 20% through control measures, substantial wetland restoration (and thus increased channel area that could support SAV and FAV), and increased salinity intrusion in the western Delta with climate warming, which favors native species with greater salinity tolerance. Large temporal swings in NPP of SAV and FAV cascade to influence the degree of carbon that flows to consumers through detrital pathways and herbivory. This volatility and interannual inconsistency in aquatic vegetation support of food webs make achieving wetland restoration goals for the Delta—which could lead to recovery of a portion of the NPP lost since historical times—even more imperative.

SFEWS Volume 20 | Issue 4 | Article 2

https://doi.org/10.15447/sfews.2023v20iss4art2

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ARTICLE

https://doi.org/10.15447/sfews.2023v20iss4art2

Chapter Focus

Aquatic vegetation plays an important role in the flow of energy through ecosystems. Carbon that is assimilated through photosynthesis is released to food webs through herbivory and decomposition processes, and the net carbon provided by vegetation to ecosystems is quantified in a measurement of 'net primary production.' This chapter explores how changes in aquatic vegetation species, including new introductions of species and changes in the amount of invasive aquatic vegetation in the Delta, has affected net primary production and thus impacted food webs supporting native species.

Key Points

- Increases in open water and proliferation of invasive aquatic vegetation in the last 20 years led to a doubling of the net primary production of floating and submerged aquatic vegetation relative to the historical period (circa 1850).
- Projected future changes will alter net primary production by floating and submerged aquatic vegetation and thus food web support, but effects will be minimal compared to recent interannual variability in their net primary production.

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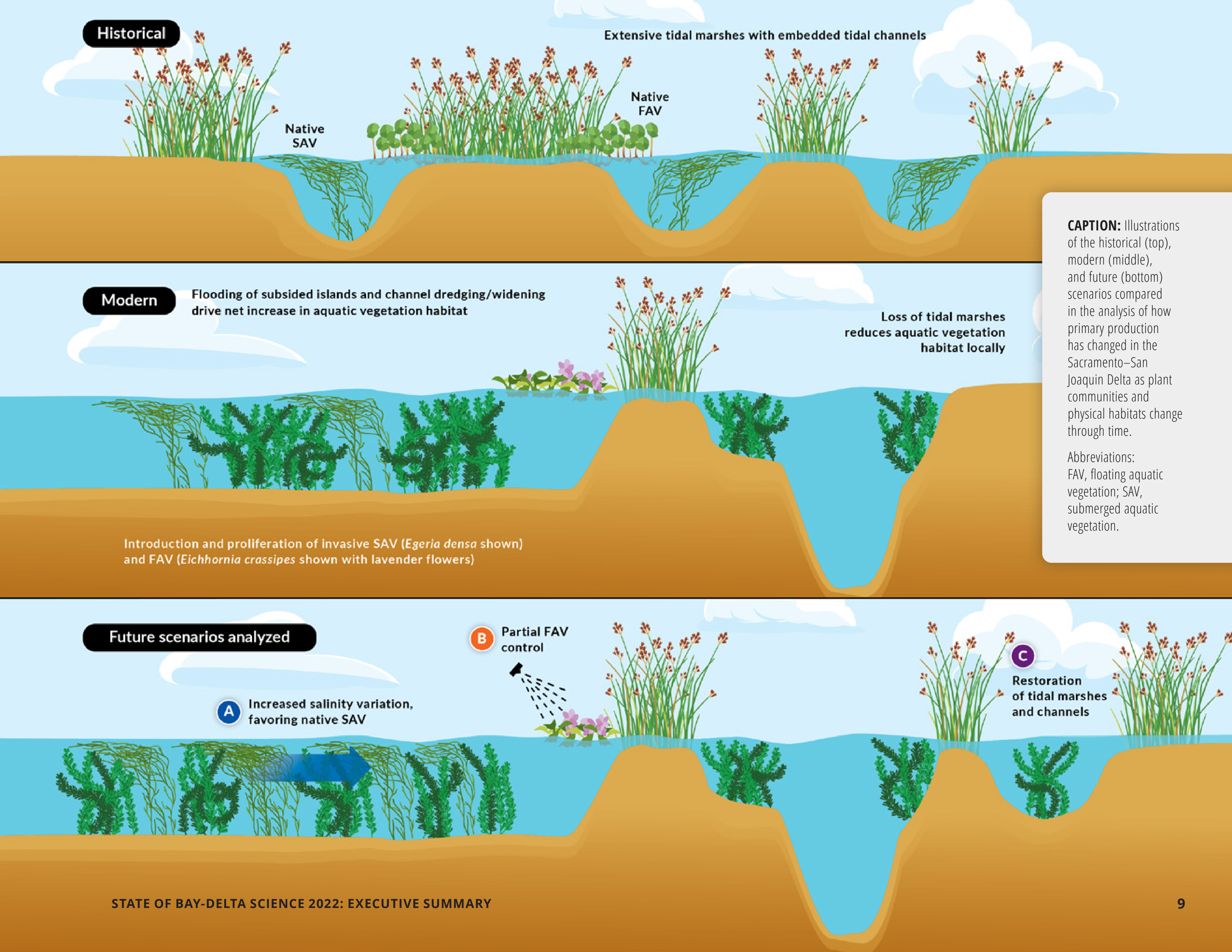


CAPTION: Illustrations of the historical (top), modern (middle), and future (bottom) scenarios compared in the analysis of how primary production has changed in the Sacramento–San Joaquin Delta as plant communities and physical habitats change through time.

Abbreviations: FAV, floating aquatic vegetation; SAV, submerged aquatic vegetation.

FROM THE MAIN ARTICLE:

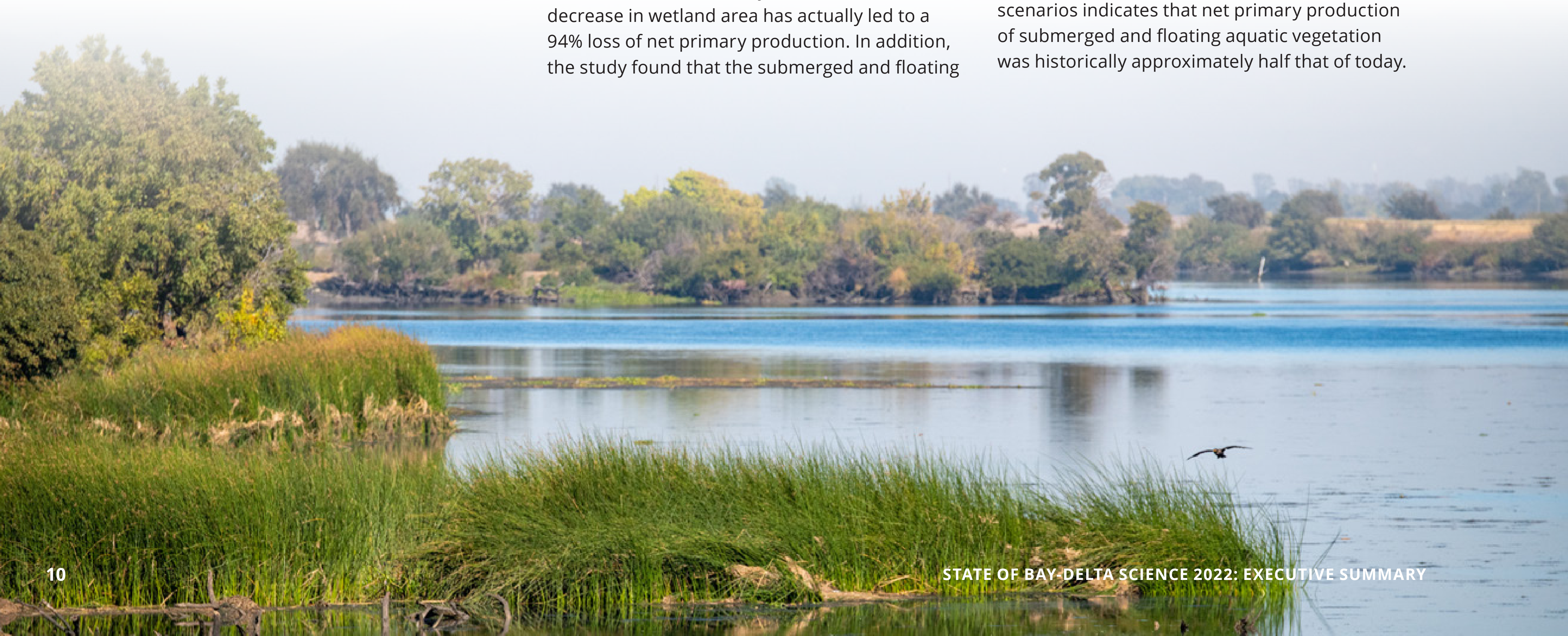
"The massive loss of Delta food web support since historical times may be partially recoverable through management activities that change the landscape configuration."

Read more at https://doi.org/10.15447/sfews.2023v20iss4art2

Chapter Summary

The Sacramento–San Joaquin River Delta (the Delta) has undergone extensive conversions of wetlands to human uses, which has led to significant changes to the ecosystems and species supported throughout the system. Chief among these changes is the drastic decrease in net primary production, a measure of the energy provided by plants through herbivory (food webs) and decomposition processes. Along with wetland losses, aquatic vegetation has dramatically shifted from native species to predominantly non-native, invasive species like Brazilian waterweed (*Egeria densa*), water primrose (*Ludwigia* spp.), and water hyacinth (*Eichhornia crassipes*), which has likely altered the contribution of aquatic vegetation to net primary production relative to historical conditions. A recent study[1] estimated that a 77% decrease in wetland area has actually led to a 94% loss of net primary production. In addition, the study found that the submerged and floating aquatic vegetation communities now contribute more to ecosystem net primary production than any other major group in the Delta, including marsh and riparian vegetation, phytoplankton, and microalgae. Historically, aquatic vegetation was likely a much lower—possibly even negligible contributor—to ecosystem primary production.

Building on this recent work, this article explores several historical, modern, and future scenarios to investigate how specific changes in aquatic vegetation species through time have affected net primary production. Models were used to predict how future scenarios involving specific management actions, such as wetland restoration and aquatic vegetation control efforts, and how future environmental conditions, such as increased salinity intrusion, might further affect net primary production. Modeling these various scenarios indicates that net primary production of submerged and floating aquatic vegetation was historically approximately half that of today.



Furthermore, the relatively early introduction of water primrose (specifically *Ludwigia peploides*) may have dramatically increased total production from aquatic vegetation early on, just as water primrose appears to strongly affect production patterns in the modern Delta. Projected changes in net primary production in the potential future scenarios modeled in this study show much lower changes in production than have already occurred in recent years due to variability in the extent of various species, particularly water primrose, observed in the last few decades. The study concludes with an acknowledgement that while recovering a portion of lost net primary production is possible through wetland restoration in the Delta, variation across years in extent for specific aquatic plant species will likely have a large effect on how aquatic vegetations support food webs.

Next Steps

This study provides several recommendations aimed at further building on our understanding of how aquatic vegetation communities affect production and thus Delta food webs.

- Measure productivity rates of floating and submerged aquatic vegetation species as individual species as well as in mixed communities, and under current and predicted future conditions.
- Incorporate additional climate-related changes into predictions of net primary production, including predicted changes in average conditions as well as changes in frequency and magnitude of extreme conditions.
- Consider other scenarios of increased open water besides tidal marsh restoration, such as incremental (e.g., a single levee breach that could result from a flood event) and catastrophic (e.g., multiple levee failures at once from an earthquake) changes in aquatic acreage.
- Anticipate effects of recent invaders on primary production. Very recent introductions (last 5-7 years) of the rapidly spreading aquatic species ribbon weed (*Vallisneria australis*) and alligator weed (*Alternanthera philoxeroides*) illustrate the continuing potential for invasion of the Delta.
- Conduct annual, Delta-wide monitoring of submerged and floating aquatic vegetation. Annual monitoring, including remote sensing and point sampling of species composition, is needed to track localized and Delta-wide changes in distribution and relative abundance of aquatic plants, including new invaders.
- Refine our understanding of food web contributions of submerged and floating aquatic plant species, including how large swings in aquatic vegetation coverage through time impact food webs.
- Consider other functional differences between aquatic vegetation species. Submerged plant species were found to have a small range in productivity rates and thus similar potential to supply carbon to fuel food webs while floating aquatic vegetation species were found to differ greatly in net primary production, which means lumping species together into groups for the purposes of management will undercut our understanding of how these species contribution to net primary production.
- Use tidal marsh restoration as a tool to even out extreme swings in Delta-wide net primary production. Recovering even a small percentage of lost tidal marshes through restoration actions could even out the annual variation in primary production and food web contributions of aquatic vegetation in the Delta.

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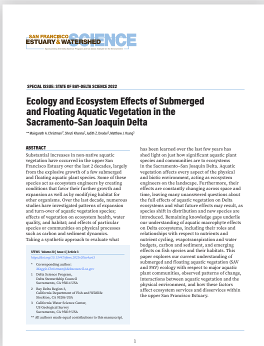
1. Cloern JE, Safran S, Vaughn LS, Robinson A, Whipple AA, Boyer KE, Drexler JZ, Naiman RJ, Pinckney JL, Howe ER, Canuel EA, Grenier JL. 2021. On the human appropriation of wetland primary production. Science of the Total Environment 785. https://doi.org/10.1016/j.scitotenv.2021.147097

Chapter 2

Ecology and Ecosystem Effects of Submerged and Floating Aquatic Vegetation in the Sacramento-San Joaquin Delta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SPECIAL ISSUE: STATE OF BAY-DELTA SCIENCE 2022

Ecology and Ecosystem Effects of Submerged and Floating Aquatic Vegetation in the Sacramento-San Joaquin Delta

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ARTICLE

https://doi.org/10.15447/sfews.2023v20iss4art3

Chapter Focus

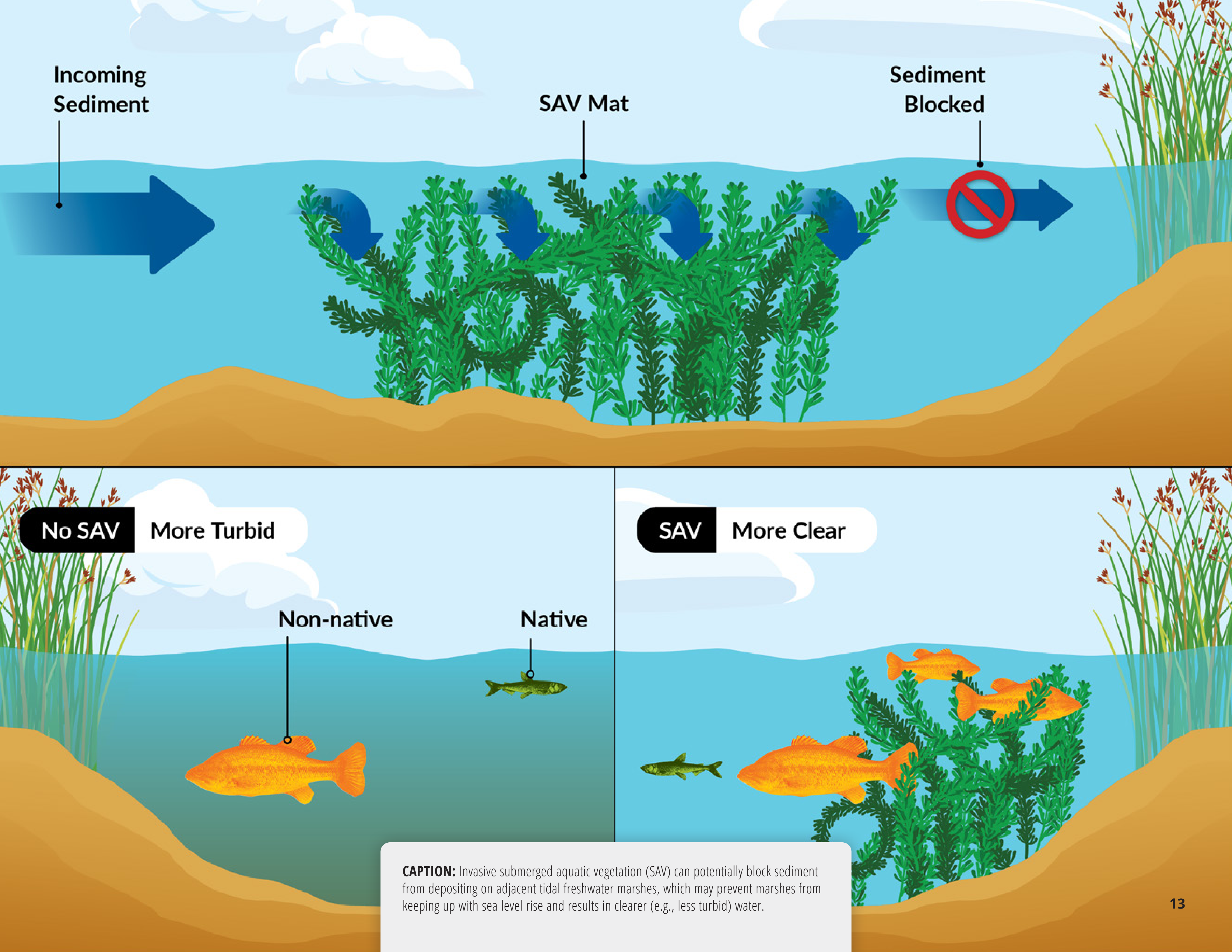
In the upper San Francisco Estuary, aquatic vegetation affects every aspect of the physical and biotic environment including ecosystem properties and processes. Impacts are constantly changing across space and time as species change in distribution, respond to environmental conditions, and new species are introduced. This chapter reviews the ecology of plant species found as submerged and floating aquatic vegetation communities in the modern Delta, including how environmental conditions drive changes in plant species and communities and how those species and communities in turn affect the physical and biotic environments in which they are found.

Key Points

- Over the last decade, invasive aquatic vegetation has been the subject of numerous studies that have investigated patterns of expansion and turnover of species; impacts of vegetation to ecosystem health, water quality, and habitat; and effects of particular species or communities on physical processes like carbon and sediment dynamics.

- While invasive submerged aquatic vegetation can provide beneficial ecosystem services such as storage of carbon at the landscape scale, the presence of dense beds of these species can block sediment from depositing in marshes and increase water clarity (i.e., decrease turbidity). This impacts their resilience to sea-level rise by preventing marsh land elevations from keeping pace with rising water levels. Increased water clarity is also observed near submerged

1. Delta Stewardship Council, Delta Science Program
2. California Department of Fish and Wildlife
3. United States Geological Survey, California Water Science Center



CAPTION: Invasive submerged aquatic vegetation (SAV) can potentially block sediment from depositing on adjacent tidal freshwater marshes, which may prevent marshes from keeping up with sea level rise and results in clearer (e.g., less turbid) water.

Key Points (continued)

aquatic vegetation beds, which can lead to enhanced predation of native fish by non-native fish species.

- Key remaining knowledge gaps in understanding invasive aquatic vegetation's impacts to Delta ecosystems include their roles in nutrient cycling, evapotranspiration, carbon and sediment dynamics, and fish populations and distributions.

FROM THE MAIN ARTICLE:

"While it is evident that aquatic plants affect every aspect of the physical and biotic environment, trying to gain a more complete understanding of these issues is a constantly moving target as new species are introduced and existing species change in abundance and distribution in response to any number of natural or anthropogenic disturbances."

Read more at https://doi.org/10.15447/sfews.2023v20iss4art3

Chapter Summary

Over the last several decades, significant changes in the distribution and abundance of several species of aquatic plants has had profound impacts on the Delta's ecosystems. Globally, aquatic vegetation provides important ecosystem services, such as supporting the foundation of food webs, impacting distributions and interactions of fish and wildlife, and contributing to physical processes like carbon and sediment cycling. Certain species are said to act as "ecosystem engineers," meaning that they transform their environments in significant ways that promote their own growth and survival. Such aquatic vegetation species have been found to impact key physical and biotic properties and processes such as water quality, flow, and sediment dynamics.

Several recent studies highlighted in the chapter have made substantial contributions to our understand of the ecosystem services and disservices of the Delta's aquatic vegetation communities. These efforts have specifically highlighted that composition and architecture of these plant communities strongly affect physical aspects of the Delta and that those effects in turn alter ecological processes and ecosystem functions at the landscape scale. For example, a suite of recent studies found that while invasive submerged aquatic vegetation can provide beneficial ecosystem services such as storage of carbon at the landscape scale, the presence of dense beds of these species blocks sediment from accreting in marshes, reducing resilience to sea-level rise.

While it is evident that aquatic plants affect every aspect of the physical and biotic environment, trying to gain a more complete understanding of these issues is a constantly moving target as new species are introduced and existing species change in abundance and distribution in response to any number of natural or anthropogenic disturbances. Studies aiming to characterize specific aspects of aquatic vegetation in the Delta may not elucidate the full range or magnitude of ecosystem impacts. Future studies taking a holistic approach to assess synergistic effects could be instrumental in determining the full extent to which aquatic vegetation provides ecosystem services and disservices in the Delta.

Next Steps

The following areas are highlighted as key knowledge gaps which have been historically understudied. Research in these areas could improve understanding of the ecological roles and functions of submerged and floating aquatic vegetation in the estuary and inform ecosystem management and wetland restoration across the Delta region.

- Greater capacity for rapid detection and response to new species invasions could prevent major disruptions to ecosystem health.
- Adaptive management of non-native aquatic vegetation requires identification of impacts to ecosystem services and processes in addition to determining changes to ecosystem properties.
- A better understanding of the extent to which SAV has directly contributed to native fish species declines could ultimately improve populations of these sensitive species.
- Synthesis of currently available data could support model development to predict which environmental conditions increase the spread of aquatic vegetation and lead to ecosystem disservices.

Chapter 3

Invasive Aquatic Vegetation in the Sacramento-San Joaquin Delta and Suisun Marsh: The History and Science of Control Efforts and Recommendations for the Path Forward


Invasive Aquatic Vegetation in the Sacramento-San Joaquin Delta and Suisun Marsh: The History and Science of Control Efforts and Recommendations for the Path Forward

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https://doi.org/10.15447/sfews.2023v20iss4art4

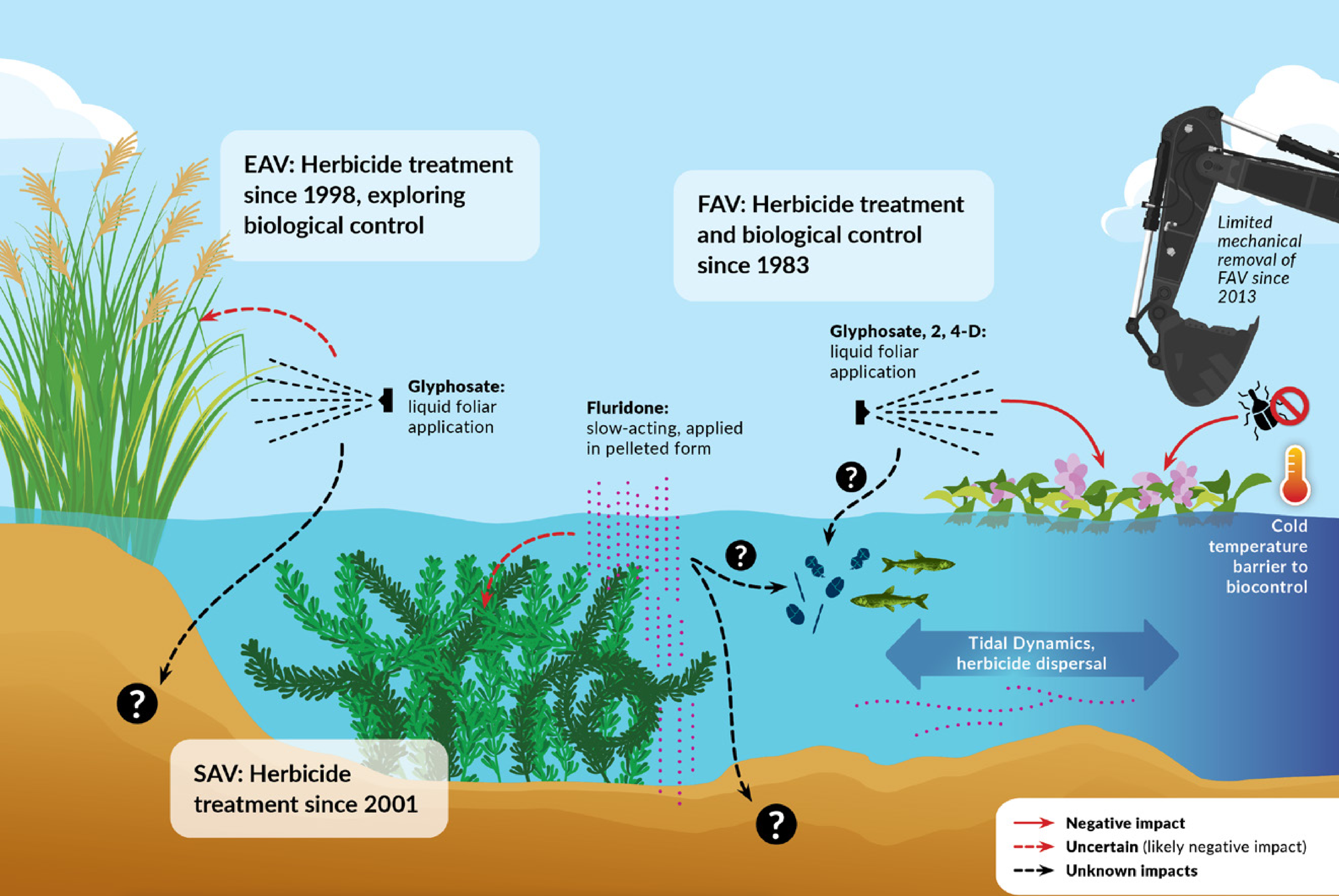
Chapter Focus

Invasive aquatic vegetation is a major management challenge in the Sacramento-San Joaquin Delta and the Suisun Marsh due to its impacts on recreational and commercial boating, operation of critical water infrastructure, and numerous ecosystem impacts. Control efforts, including chemical, biological, mechanical, and physical approaches, have been a major resource investment for four decades, but the science of control efforts only started in earnest in the early 2000s, with increased attention in just the last ten years. This chapter explores the history and supporting science of invasive aquatic vegetation control efforts in the Delta and Suisun Marsh in the context of control efforts used in other similar (e.g., flowing water) systems. The chapter concludes with a series of recommendations for continued advancement of science in support of adaptive management of invasive aquatic vegetation.

Key Points

- Control efforts for submerged and floating aquatic vegetation have been ongoing in the Delta since 1983 and rely primarily on herbicides, centralized and conducted within the California Department of Parks and Recreation, Division of Boating and Waterways. However, results have been mixed due to the tidal dynamics of the Delta. Parallel investment in biological control agents over the same timeframe has yielded no appreciable control benefit.
- Control efforts for emergent aquatic vegetation invaders such as the common reed have been uncoordinated, with no centralizing body, limited experimental research, and sporadic monitoring.

1. California Department of Water Resources
2. Agricultural Issues Center, University of California, Davis
3. University of California, Davis
4. Agricultural Research Service, US Department of Agriculture
5. Suisun Resource Conservation District
6. California Department of Fish and Wildlife



CAPTION: Conceptual model of common invasive aquatic vegetation control methodologies in the Delta and Suisun Marsh, with relative knowledge of their target and non-target impacts.

Abbreviations: EAV, emergent aquatic vegetation; FAV, floating aquatic vegetation; SAV, submerged aquatic vegetation.

Key Points (continued)

- The science assessing target and non-target impacts of control efforts in the Delta is nascent, and further advancement requires continued collaboration between regulating entities and those leading and innovating control measures.
- Setting quantitative targets for invasive aquatic vegetation control informed by social and ecological assessments of acceptable levels of invasive aquatic vegetation coverage is critical for strategic planning and must be accompanied by a robust monitoring program.

Chapter Summary

Management efforts to control submerged and floating invasive aquatic vegetation, like Brazilian waterweed (*Egeria densa*) and water hyacinth (*Eichhornia crassipes*), have been centralized within the California State Parks Division of Boating and Waterways since 1983. The current annual budget is $12.5 million. However, results of control efforts have been mixed due to the challenge of effective herbicide application in a tidal system. In particular, submerged aquatic vegetation is particularly difficult to effectively treat because tidal action in the Delta dilutes herbicides that must maintain certain concentrations for extended periods of time to be effective. In addition, regulatory complexity has increased over recent decades, hampering efforts to innovate alternative methods or respond quickly to new invaders due to concerns of potential harm to non-target species (e.g., possible toxicity to other wildlife).

Herbicides are the primary weed control treatment mechanism used in the Delta, but their use is restricted to certain times of the year to minimize potential harm to fish species of concern. Biological control agents for water hyacinth and giant reed (*Arundo donax*) have been released but have not provided an appreciable control benefit, likely because they are not suited for the temperate Delta climate. Efforts are underway to identify climate-appropriate agents for water hyacinth, water primrose (*Ludwigia* spp.), alligatorweed (*A. philoxeroides*) and giant reed.

Over the last decade, the effectiveness of control treatments has been the subject of several studies. Many tradeoffs for effectiveness and feasibility of various chemical, biological, physical, and mechanical approaches to controlling aquatic vegetation exist and must be considered in each circumstance. As invasive aquatic vegetation continues to expand across the system despite our efforts at managing these species, developing an informed, adaptive, and systematic approach to control will require additional focus on research and monitoring and adequate capacity for innovation and coordination among managers, permitting entities, and scientists.

Next Steps

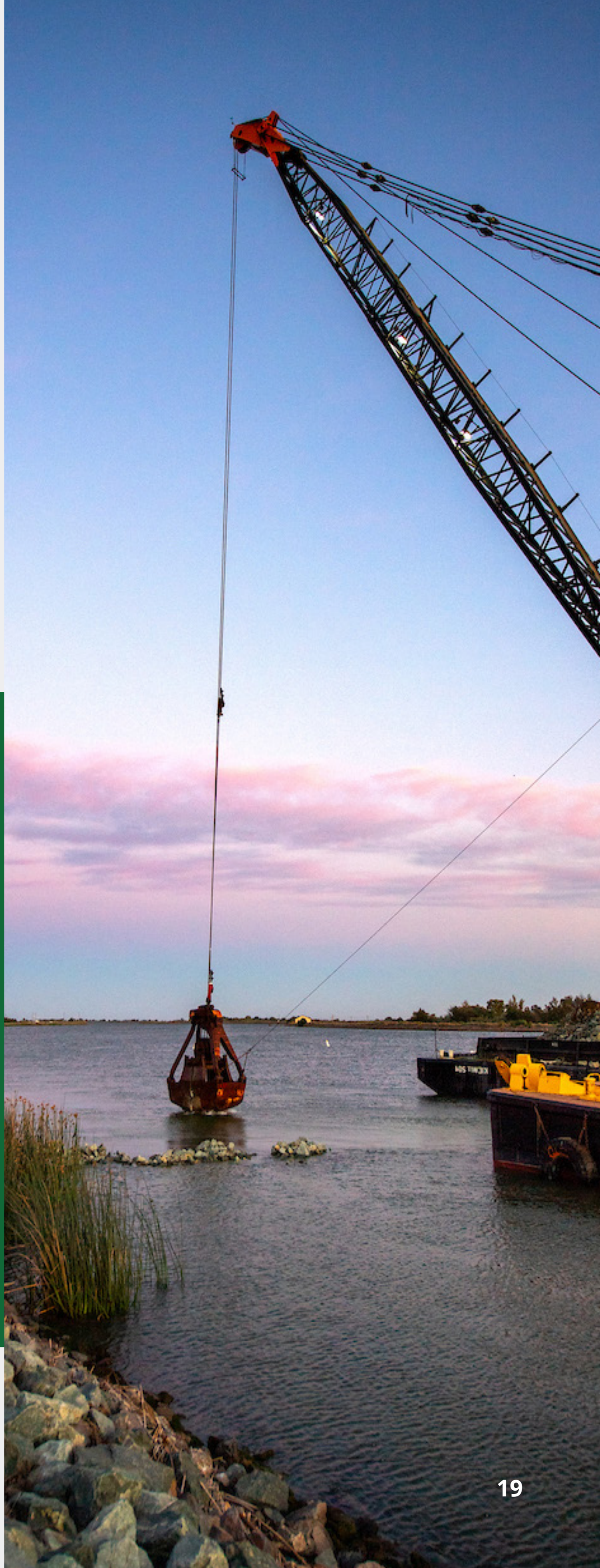
Based on the history of aquatic vegetation control efforts in the Delta, recommendations for advancing invasive aquatic vegetation control and its supporting science in the Delta and Suisun Marsh include priorities for leadership to support adaptive management and critical science actions to enable rapid response to changes. Specifically, these recommendations include:

- Set informed management targets for invasive aquatic vegetation control programs.
- Maintain a regulatory framework that enables research for effective control methodologies for all invasive aquatic vegetation growth forms.
- Enhance investments in researching physical and biological control approaches and expanding herbicidal tools to develop effective integration of control methods.
- Establish a consistent monitoring program for all invasive aquatic vegetation growth forms.
- Develop modeling tools to enable prediction and preparation for a changing climate and invasive aquatic vegetation community.
- Develop bioeconomic models to enable evaluation of the socio-ecological tradeoffs across management alternatives.

FROM THE MAIN ARTICLE:

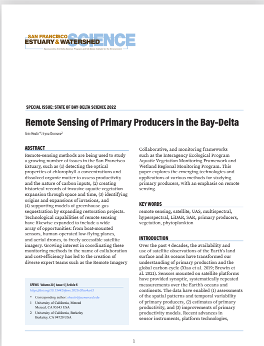
"Invasive aquatic vegetation (IAV) is a management challenge in the Sacramento-San Joaquin Delta and the Suisun Marsh that has commanded major resource investment for four decades."

Read more at https://doi.org/10.15447/sfews.2023v20iss4art4



Chapter 4

Remote Sensing of Primary Producers in the Bay-Delta


Remote Sensing of Primary Producers in the Bay-Delta

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https://doi.org/10.15447/sfews.2023v20iss4art5

Chapter Focus

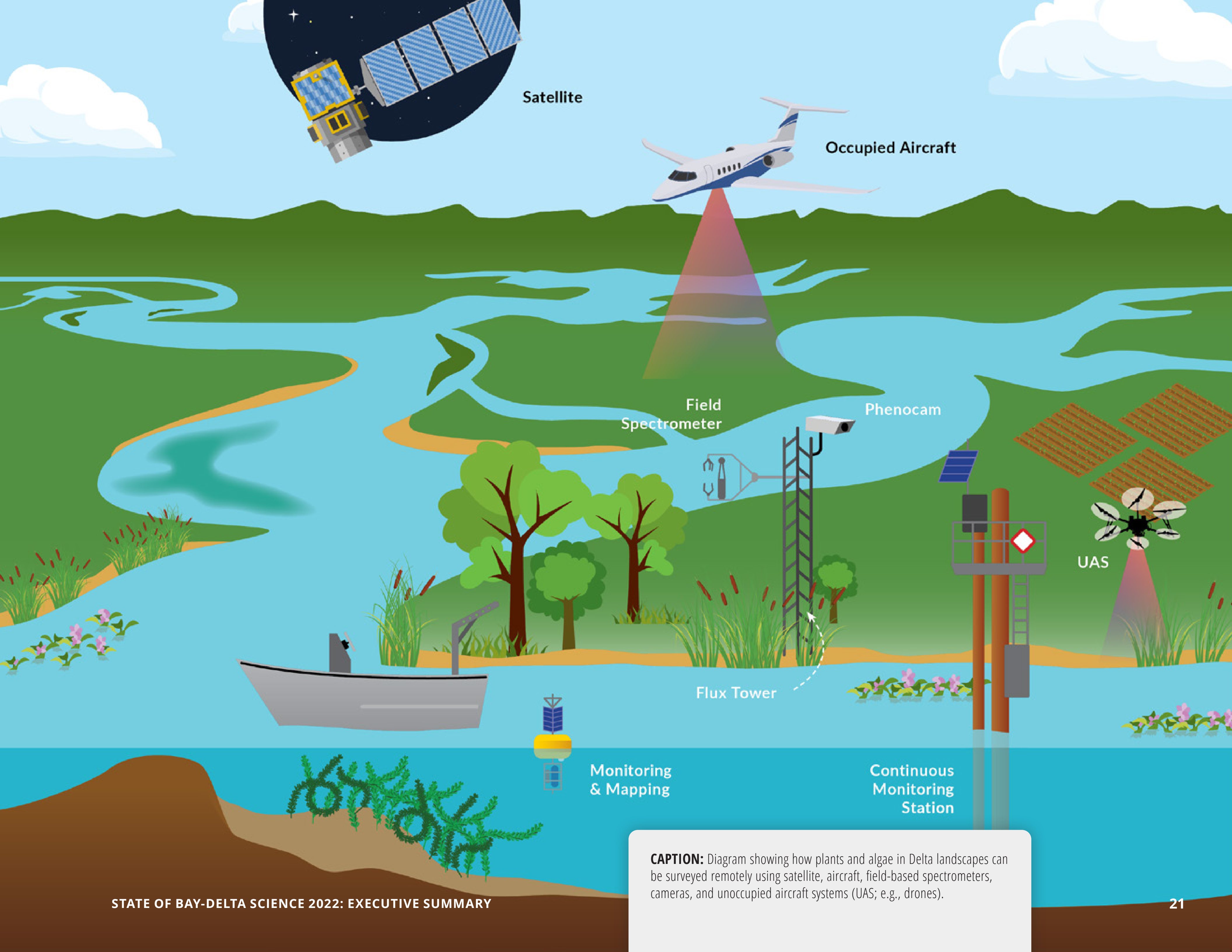
Remote sensing methods include a variety of techniques of capturing information about organisms or the physical environment from a distance, such as imagery captured from aircrafts, satellites, or drones. Collectively these methods are an effective tool to support monitoring of plants and algae in the Delta across the full environmental gradient from water channels to wetlands and terrestrial environments. This chapter reviews the breadth of applications, considerations, and resolutions for remote sensing to address major questions regarding primary producers (e.g., plants and algae) in the Delta with an emphasis on how remote sensing technologies have evolved in recent years and the resulting advancements in knowledge that have resulted from their application.

Key Points

- The effectiveness of remote sensing applications depends on the management need and must be considered in the context of tradeoffs in spatial, temporal, spectral, and radiometric scales of both the image data and the ecological targets and processes of interest.

- Maximizing the benefits offered by a growing number of open and accessible new sensor data to meet regional needs requires greater capacity building for people and institutions, greater cooperation between research groups, and standardization of large file data management and sharing that meets user needs and legislated requirements (e.g., AB 1755: the Open and Transparent Water Data Act).

1. University of California, Merced
2. University of California, Berkeley



CAPTION: Diagram showing how plants and algae in Delta landscapes can be surveyed remotely using satellite, aircraft, field-based spectrometers, cameras, and unoccupied aircraft systems (UAS; e.g., drones).

FROM THE MAIN ARTICLE:

"Over the past four decades, the availability and use of satellite observations of the Earth's land surface and its oceans have been transformative in our understanding of primary production and the global carbon cycle."

"In the Estuary, remote sensing is a powerful and cost-effective tool to enrich ongoing research efforts on primary producers in a geospatially explicit context, often with regular, repeated sampling enabling measurements of seasonal and longer-term variability"

Read more at https://doi.org/10.15447/sfews.2023v20iss4art5

Chapter Summary

Among the many methods and techniques for studying primary producers, remote sensing applications provide unique opportunities for addressing key management questions about primary producers (e.g., plants and algae) in the Delta. Examples of these applications include assessing changes in aquatic vegetation distribution and abundance through space and time, assessing the physiological status of plants (e.g., measuring drought stress), estimating energy flows and carbon cycling dynamics, and modeling greenhouse gas fluxes resulting from restoration efforts. Multiple state, national, and even international initiatives call for coordinated assessments of primary producers, and there is growing interest in the Delta to coordinate these monitoring methods in the name of collaboration and cost-efficiency.

A wide variety of remote sensing methods, from boat-mounted sensors, human-operated low-flying planes, aerial drones, to freely accessible satellite imagery, are used in the Delta today. Remote sensing methods have been widely used in the Delta to map wetlands and marshes. In particular, mapping efforts have proven invaluable in tracking invasive aquatic plant species through space and time as well as in assessing vegetation change as a result of restoration activities. Although only a few Delta studies have used remote sensing to study how primary producers contribute to food webs (such as by collecting information about chlorophyll-a or phytoplankton), continual advancements in sensors as well as data analysis methods may lead to this application in the future. The ability for remote sensing methods to make repeated, systematic measurements across time makes it very desirable for studying primary producers, but funding constraints and the lack of coordinated monitoring programs present critical limitations to their use.

Several recent initiatives, including recently launched satellite-based instruments, provide promising opportunities for using remote sensing technologies to study primary producers as well as other applications highly relevant to management of the Delta. These applications include studies of wetland flooding patterns, soil moisture levels, and atmospheric gas fluxes. Realizing the potential benefits presented by this growing field will require additional funding and resources to support researchers and institutions, coordination and cooperation between research groups, and commitments toward standardizing data sharing and management.

Next Steps

This chapter identifies several recommendations for preparing for the future of remote sensing applications in the Delta, including:

- **Identifying Research Priorities:** The unprecedented monitoring capacity offered by modern remote sensing platforms should be explored as a critical step towards resolving uncertainties in our understanding of primary production.

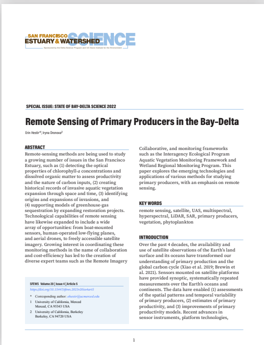
- **Closing the Loop Between Data and Management Decisions:** Remote sensing products need to be generated and delivered in a way that can be used across a broader segment of managers and stakeholders in the Delta, and feedback mechanisms need to be developed that can feed local knowledge into improving the accuracy of remote sensing products to meet local needs.

- **Collaboration Across Management Goals:** Evidence from diverse remote sensing applications in the region underscores the critical need for collaborations across different management goals.

- **Capacity Building:** Workforce development is critical to preparing the current and next generation of researchers and managers to exploit the oncoming data deluge. Capacity building also includes strengthening and integrating new and different areas of science and securing the necessary infrastructure to support current and future needs for these technologies.

Chapter 5

Status, Trends, and Drivers of Harmful Algal Blooms Along the Freshwater-to-Marine Gradient in the San Francisco Bay-Delta System


SAN FRANCISCO ESTUARY & WATERSHED SCIENCE

SPECIAL ISSUE: STATE OF BAY-DELTA SCIENCE 2022

Remote Sensing of Primary Producers in the Bay-Delta

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ARTICLE

https://doi.org/10.15447/sfews.2023v20iss4art6

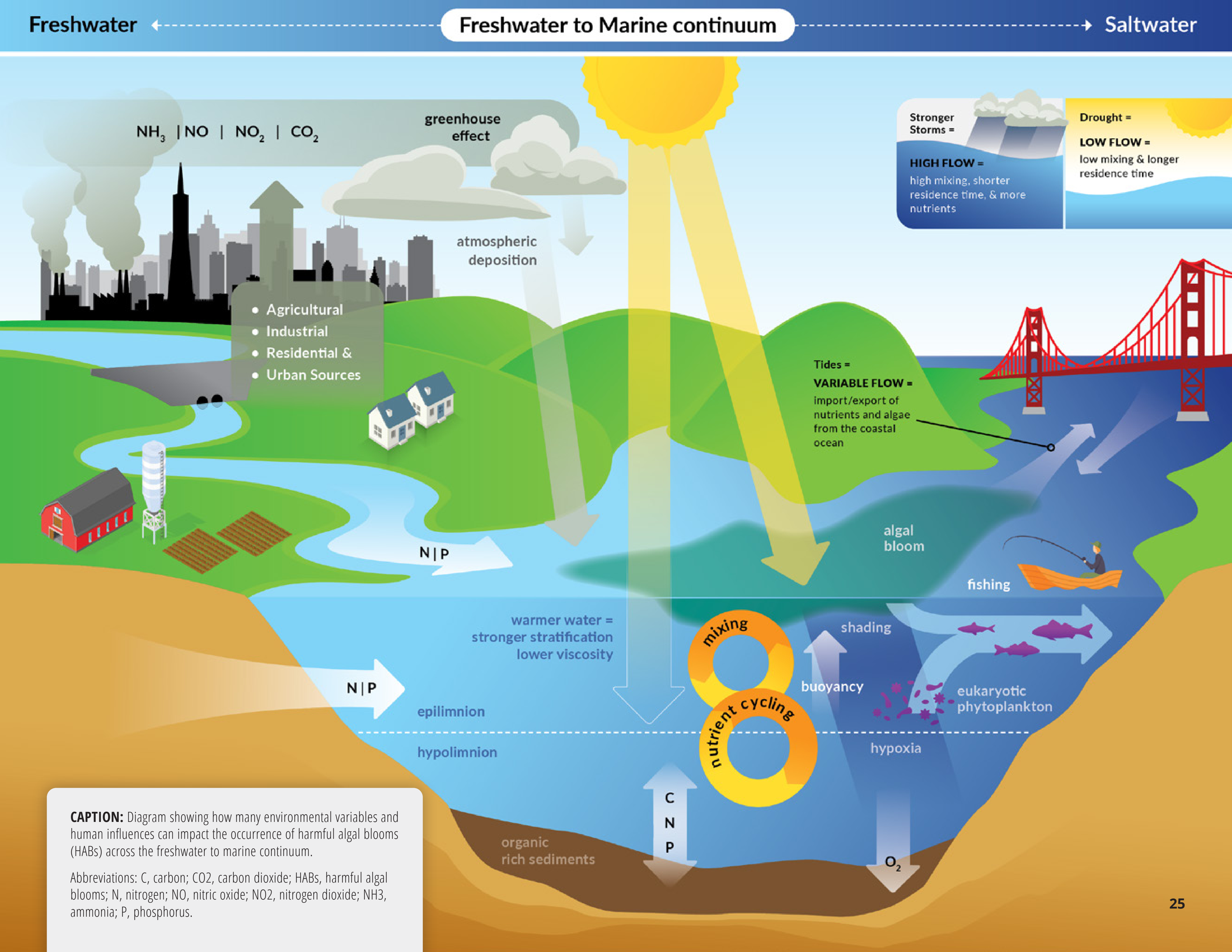
Chapter Focus

Harmful algal blooms, commonly referred to as HABs, are phenomena in which algae and other phytoplankton (e.g., microscopic plant-like organisms) grow explosively in certain conditions and create negative impacts to people and the environment. Examples of these impacts include production of toxins, reduction of oxygen levels in waterways, disruptions of food webs or nutrient cycles, and generally poor conditions. This chapter reviews the species and toxins that are involved with HABs in the San Francisco Estuary, environmental conditions which drive blooms, and the resulting impacts of these blooms and toxins to humans and the environment.

Key Points

- Although potentially harmful organisms have long been present, harmful algal blooms (HABs) and associated toxins have emerged as a concern relatively recently in the Bay-Delta, and toxins from marine and freshwater species are often co-occurring.
- Organisms exposed to these toxins may accumulate them, and there is evidence that toxins may transfer to other organisms, including humans, through the food chain.
- Monitoring and mitigation in a changing climate requires better coordination among researchers and agencies and a focus on restoring/maintaining ecosystem resilience.

1. University of California, Santa Cruz
2. Central Valley Regional Water Quality Control Board
3. Stanford University
4. University of North Carolina, Chapel Hill



CAPTION: Diagram showing how many environmental variables and human influences can impact the occurrence of harmful algal blooms (HABs) across the freshwater to marine continuum.

Abbreviations: C, carbon; CO2, carbon dioxide; HABs, harmful algal blooms; N, nitrogen; NO, nitric oxide; NO2, nitrogen dioxide; NH3, ammonia; P, phosphorus.

FROM THE MAIN ARTICLE:

“There is clear evidence for global expansion of HABs in freshwater, estuarine, and marine waters with corresponding impacts and consequences for ecosystem health, food and water security, human health, and recreational and aesthetic value of these waters.”

Read more at https://doi.org/10.15447/sfews.2023v20iss4art6

Chapter Summary

While the occurrence of HABs and toxins has gained recognition globally over the last few decades, regulatory guidance regarding harmful levels of organism abundance or toxins is generally lacking with the exception of a few very specific cases. Until recently, the occurrence and impacts of these events were considered to be very low or unknown in the San Francisco Estuary.

Monitoring of HABs and their associated toxins in the estuary has primarily focused on detecting the presence of *Microcystis* (and microcystins, the toxins these organisms produce). While there has never been a consistent, widespread monitoring program for HABs (and prior to 2014, sampling was largely done on a project-by-project basis), existing data indicate that HAB species and toxins are almost always present in the Bay-Delta’s waters at low to moderate levels. The primary environmental factors that drive significant HAB events include temperature, salinity, light, nutrients, and water residence time—as well as the combined effect of these factors (e.g., increased temperature and salinity together) and influences of climate change. In particular, tidal flushing (or longer residence times) are likely to be strong regulators affecting the promotion or minimization of HABs in the estuary.

The most concerning impact of HABs is the direct exposure of humans to their toxins. However, this phenomenon has been very poorly documented in the estuary. Direct exposure through contaminated drinking water is of highest concern for humans as well as pets, livestock, and wildlife, but other mechanisms such as respiratory inhalation of toxins may be significant. In addition, effects of toxins on wildlife likely affect the entire food web and span multiple trophic levels. Development of a comprehensive monitoring, prediction, and mitigation strategy across the freshwater to marine continuum is critical to both obtain a better picture of the impacts of these driving factors as well as management actions for reducing or managing HABs.

Next Steps

Critical recommendations for the management of HABs in the San Francisco Estuary include:

- **A comprehensive HAB monitoring and management strategy for the ecosystem should be developed.** This strategy should include shared science and management goals and be based on the relevant strategies and recommendations provided from other sources.
- **Both short and long-term management and mitigation approaches should be developed.** Shorter-term mitigation approaches and technologies should be developed and appropriate long-term approaches, such as nutrient management. Implementation of a coordinated monitoring program can provide a comprehensive dataset across the freshwater to marine continuum to inform management actions.
- **Water quality objectives and health standards should be developed for toxins that are not well regulated, and for exposure to multiple toxins.** While some federal water quality criteria and guidance exists, there is a lack of regulatory standards and objectives for multiple routes of exposure of cyanotoxins.

In addition, management actions would be supported by additional research into the following recognized knowledge gaps:

- The system lacks a consistent monitoring program for both phytoplankton and toxins.
- The fate and transfer of toxins within the airshed, watershed, and foodweb are largely unknown, leading to large gaps in our understanding of potential exposure routes and impacts for both the ecosystem and humans.
- There is conflicting evidence on how the food web (particularly the microbial web and grazers) will respond on short versus long (evolutionary) timescales to the presence of toxic algae.
- Long-term mitigation strategies include hydrological modification and reduction in nutrients, but it is not clear that our ability to predict environmental responses is acceptable.
- For the most part, HAB abundance models spanning the freshwater to marine continuum are lacking, as are watershed-scale models focusing on HABs.
- To improve predictability on short and long timescales, both observational data and additional lab and field experimentation are required.
- Research studies and models should holistically evaluate and quantify the magnitude of nutrient reduction required to limit HAB occurrence and severity in the San Francisco Estuary.


SAN FRANCISCO ESTUARY & WATERSHED SCIENCE

SPECIAL ISSUE: STATE OF BAY-DELTA SCIENCE 2022

Landscape Transformation and Variation in Invasive Species Abundance Drive Change in Primary Production of Aquatic Vegetation in the Sacramento–San Joaquin Delta

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https://doi.org/10.15447/sfews.2023v20iss4art7

Chapter 6

Carbon Sequestration and Subsidence Reversal in the Sacramento-San Joaquin Delta and Suisun Bay: Management Opportunities for Climate Mitigation and Adaptation

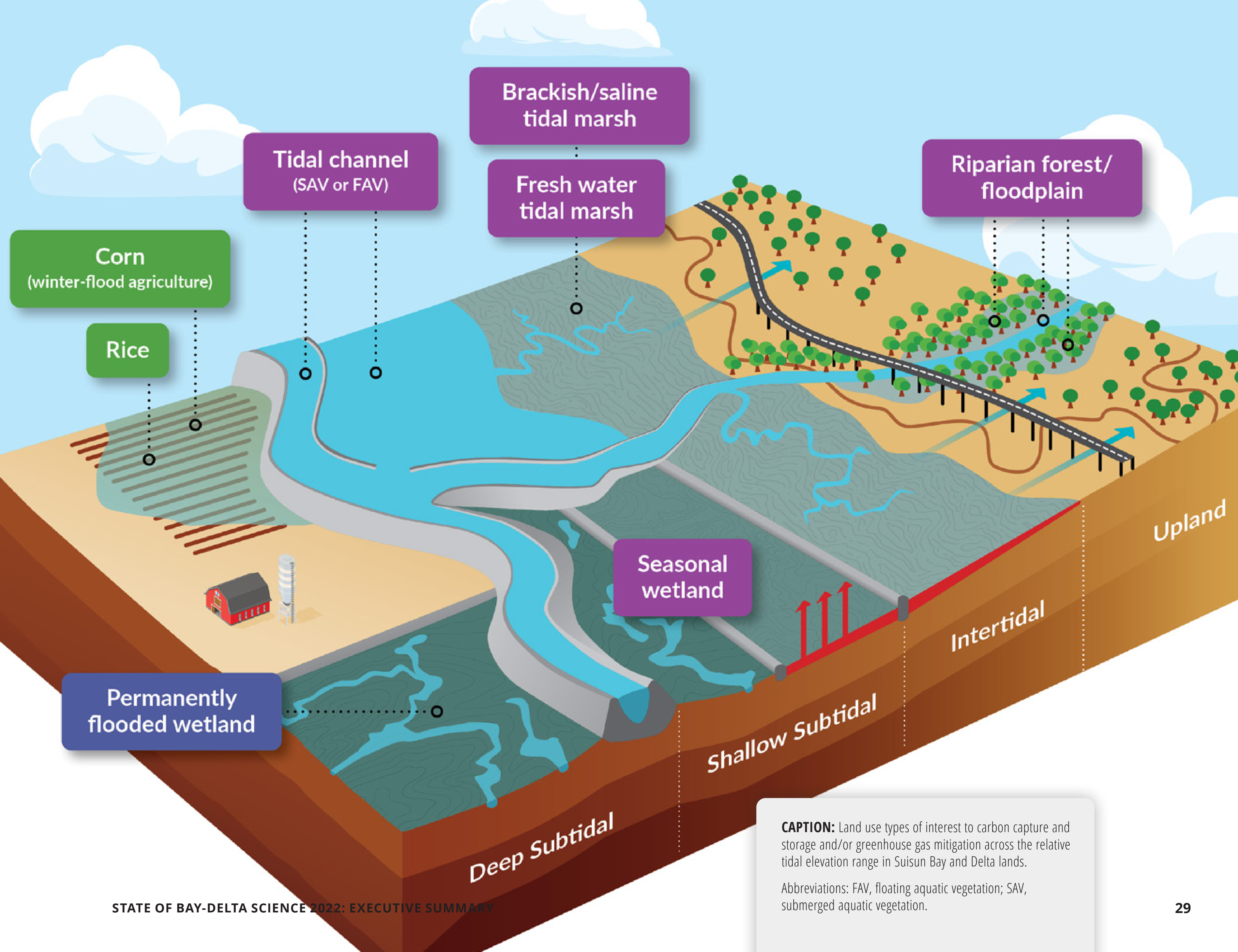
Chapter Focus

Over the last few centuries, changing landscapes and land uses in the Delta have resulted in loss of land elevation (subsidence), emission of greenhouse gases, and depletion of carbon from Delta soils. This chapter reviews the state of the science underlying the processes of carbon sequestration (i.e., capturing and storing carbon on the landscape) and subsidence reversal (i.e., reversing loss of land elevation) in the Delta and specifically explores how management interventions involving manipulating flows, vegetation, and nutrients, could slow or reverse carbon loss from Delta soils.

Key Points

- Water management strategies, such as through agricultural practices, flooding of peatlands, and tidal marsh restoration, are the dominant pathways to increase the capture and storage (i.e., sequestration) of carbon and reduce methane emissions in the Delta.
- Restoration of aquatic habitats can reduce current greenhouse gas emissions while providing additional ecosystem benefits to wildlife and water management.
- The largest uncertainties in estimating the contributions of restored wetlands to market-based climate mitigation estimates lie in projections of aquatic habitat type, as impacted by climate and operations-driven changes in water flows.

1. U.S. Geological Survey, Water Resources Mission Area
2. California State University, East Bay
3. Hydrofocus, Inc.
4. Delta Stewardship Council, Delta Science Program
5. U.S. Geological Survey, California Water Science Center



CAPTION: Land use types of interest to carbon capture and storage and/or greenhouse gas mitigation across the relative tidal elevation range in Suisun Bay and Delta lands.

Abbreviations: FAV, floating aquatic vegetation; SAV, submerged aquatic vegetation.

FROM THE MAIN ARTICLE:

"Optimizing ecosystem hydrology in the Delta and Suisun Bay could both reduce and reverse subsidence while also providing significant opportunities for climate mitigation and adaptation."

Read more at https://doi.org/10.15447/sfews.2023v20iss4art7

Chapter Summary

Transformations of landscapes and land uses in the Sacramento-San Joaquin Delta over the last few centuries have depleted the levels of carbon stored in Delta soils, resulted in emission of greenhouse gases (i.e., release of carbon dioxide and methane), and led to significant loss of land elevations (i.e., subsidence). Decades of research on the capture and storage of carbon (i.e., sequestration) and subsidence reversal suggest that optimizing hydrology could both reduce and reverse subsidence in the Delta as well as offset greenhouse gas emissions. On a larger scale, these strategies to store carbon on the landscape would also provide opportunities for mitigating and adapting to a changing climate.

The Delta's carbon-rich soils (e.g., peatlands) developed over millennia, but drainage of these lands since the mid-1800's has reduced the amount of carbon stored in these soils by half. Microbes in the soil are the primary source of greenhouse gas emissions as they convert carbon in soil to carbon dioxide and other greenhouse gases. Among land uses, agricultural practices are currently the single largest producer of carbon fluxes and thus greenhouse gas emissions in the Delta.

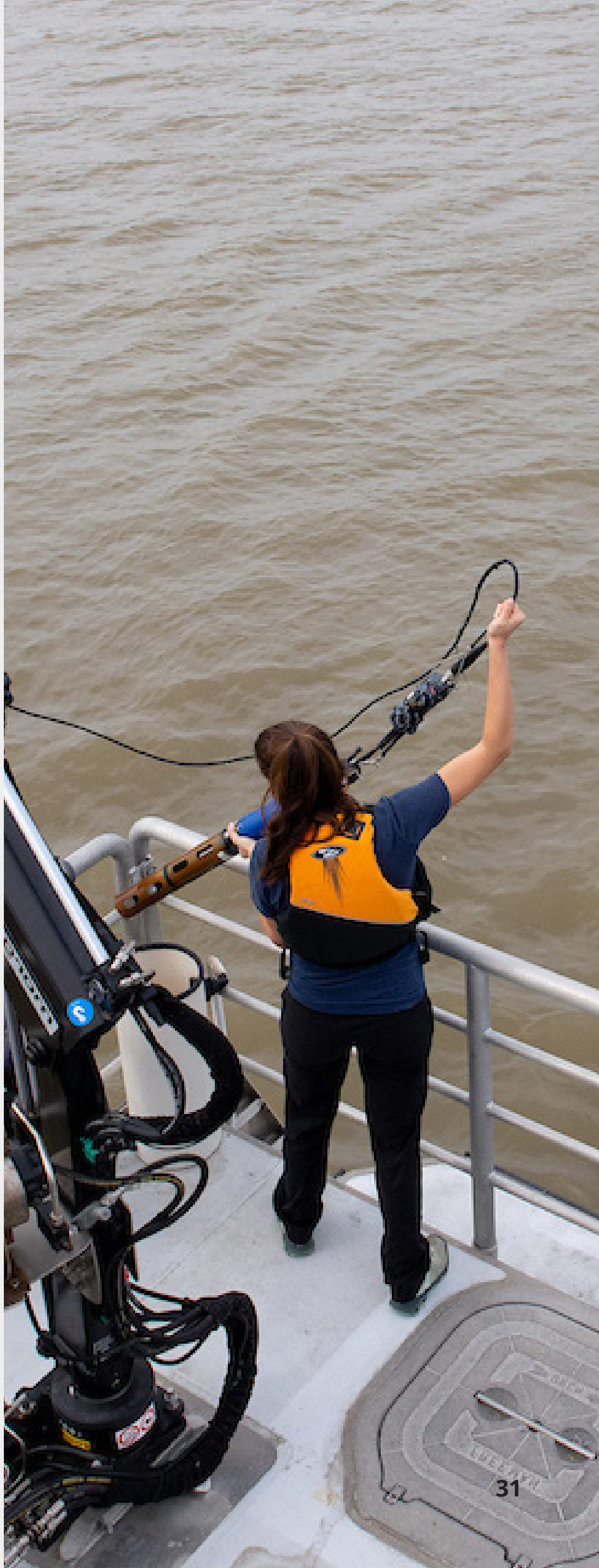
Strategies for managing and mitigating these processes exist. This chapter presents three main actions to address these challenges, including 1.) impounding (i.e., flooding) peatlands to allow peat re-establishment and accumulation to reverse subsidence, 2.) rewetting agricultural soils (e.g., as in rice cultivation) and reducing pulsed dry-down periods, and 3.) reintroducing and/or maintaining tidal connectivity in intertidal and subtidal habitats. Together, these three strategies could preserve carbon levels already present in Delta soils and restore net carbon flows into soils to result in net negative emissions in the Delta and Suisun Bay.

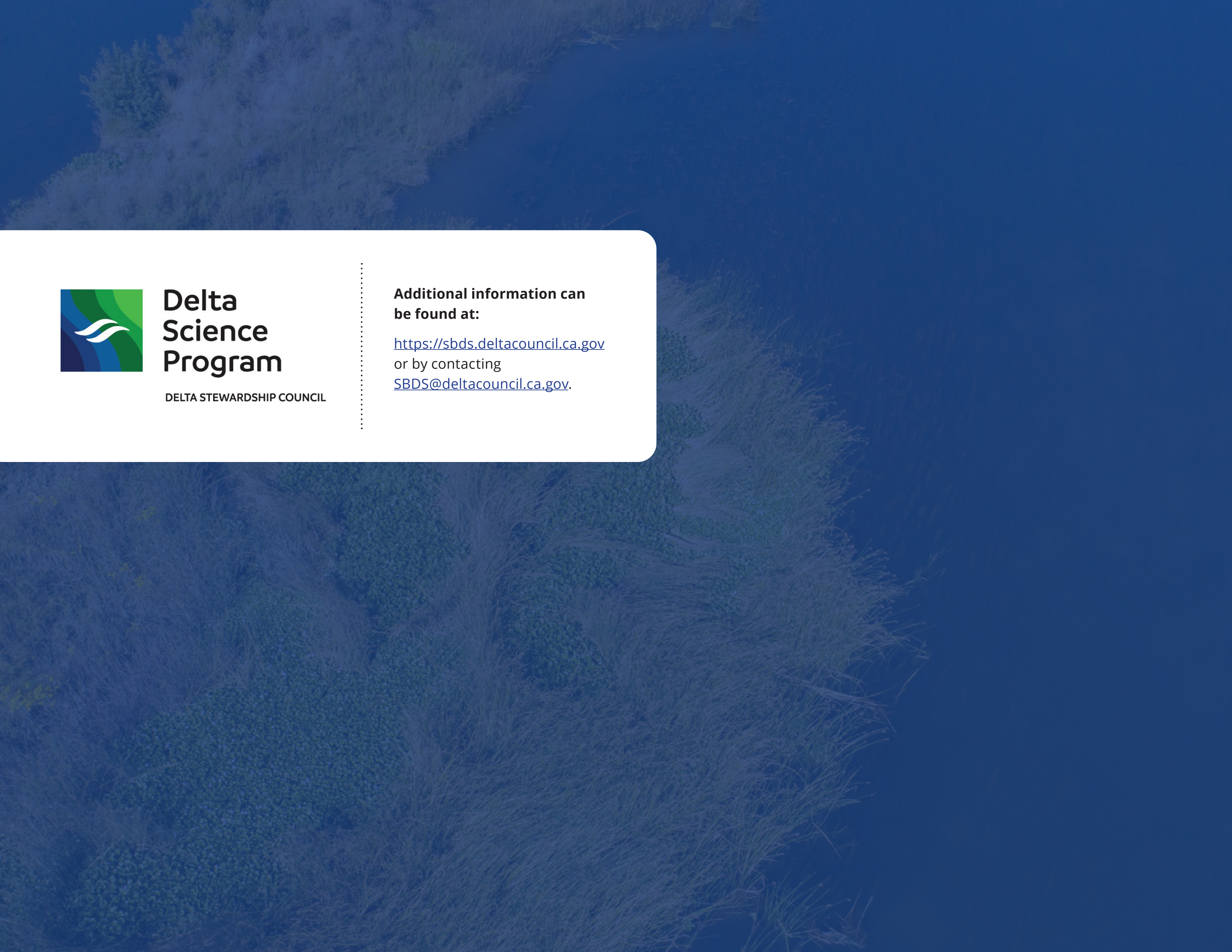
Current rates of subsidence due to climate, land-use, and modified hydrology are unsustainable, and little progress has been made in reversing it despite the risks it poses for the state's economy and water supply. Modeling indicates that accretion in impounded wetlands could restore elevations to projected sea levels within 50-100 years. Thus, hydrologic management has great potential for climate mitigation and adaptation, but projections are uncertain given many factors which influence land use and landcover in the Delta and Suisun Marsh.

Next Steps

How sustainable any climate mitigating intervention discussed in this chapter will be will largely depend on a combination of human and non-human drivers. In addition, this chapter highlights the following needs for future Delta research and management:

- Models can help anticipate the impact of management actions, providing insight into net carbon exchanges and methane emissions as elevations change and vegetation communities are altered by active and passive responses.
- Additional monitoring activities are necessary to obtain data required to validate models and to develop new estimates for the Delta's freshwater tidal wetlands.
- Large uncertainties exist in gas fluxes, particularly for methane and nitrous oxide.
- Some outstanding uncertainties and data gaps are evident in freshwater tidal and submerged and floating aquatic vegetation habitats, which are likely to expand dramatically through EcoRestore program objectives.
- Extreme events could alter the future scenarios estimated here, but transformation from a highly channelized and engineered landscape to a more open tidal system (marsh, floodplain) is predicted to protect historical soil carbon storage, increase soil carbon sequestration, and reduce methane emissions.
- In particular, actions focused on current agriculture, including restoration of historical peatlands through impounded wetlands and agricultural flooding, can reduce soil oxidation and provide a means for reaching open tidal elevations.





Delta Science Program

DELTA STEWARDSHIP COUNCIL

Additional information can be found at:

https://sbds.deltacouncil.ca.gov
or by contacting
SBDS@deltacouncil.ca.gov.