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RESEARCH

Restoring the Heart of a Healthy Estuary: A Review of Restoration in the Sacramento–San Joaquin Delta and Suisun Marsh

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ABSTRACT

The restoration of native species-dominated ecosystems is critical for improving ecosystem health and meeting policy goals in the Sacramento–San Joaquin Delta and Suisun Marsh (upper San Francisco Estuary, collectively), one of the largest estuarine systems in North America. To accomplish large-scale restoration in this heavily altered system, a variety of projects, programs, and motivations inform restoration planning and implementation. Chapter 4 of the *Delta Plan* synthesizes restoration goals across these efforts to produce comprehensive ecosystem restoration targets of between 60,000 and 80,000 acres across seven ecosystem types by 2050, but a comprehensive review of restoration progress and planning to date is needed. To fill this gap, this paper analyzes the current state of ecosystem restoration in the upper San Francisco Estuary in the context of the *Delta Plan* targets. We review current scientific and management literature and implementation approaches, and synthesize acreage totals across completed, in-progress, and planned projects for four ecosystem types where substantial development of restoration in the system has occurred: tidal wetland, non-tidal wetland, riparian, and floodplain. We find that tidal wetland restoration has progressed more rapidly than other ecosystem types, motivated by mitigation requirements related to the federal Endangered Species Act. Across all ecosystem types, we identify both promising progress and clear needs for accelerated planning and implementation of restoration projects to meet *Delta Plan* 2050 targets, and discuss ongoing needs related to science, funding, and implementation.

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INTRODUCTION

Across the globe, degraded estuarine systems require extensive ecological restoration to recover vital ecological functions, support ecosystem services (such as carbon sequestration and flood control), and reconnect human communities to natural landscapes (USEPA 2012; Alexander et al. 2016; Waltham et al. 2020). (Ecological restoration is defined broadly as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed;" Clewell et al. 2004.) To support restoration planning, implementation, and adaptive management, it is crucial to understand the scope of related restoration projects across space and time (Moreno–Mateos et al. 2012; Gittman et al. 2019). This is the case in California's Sacramento–San Joaquin Delta (Delta) and the Suisun Marsh, which comprise the upper portion of the San Francisco Estuary (hereafter the "upper estuary"), where large-scale restoration is underway to address historic ecosystem degradation. The San Francisco Estuary, comprising several connected bays and the Delta, is one of the largest estuaries on the west coast of North America, with a watershed that drains approximately 40% of California's land before mixing with ocean tides. Freshwater availability varies widely from year to year, depending on precipitation and water management (Hutton et al. 2016; Andrews et al. 2017). The Delta is home to approximately 500,000 residents, 415,000 acres of farmland, a robust recreational boating and fishing industry, and hundreds of resident and migratory fish and wildlife species (Robinson et al. 2016; DPC 2020). Suisun Marsh is situated west of the Delta and contains the largest contiguous brackish wetland on the West Coast (Figure 1).

While the upper estuary still provides important habitat for over 700 species, it has experienced extensive habitat loss, including over 97% of its historic freshwater wetlands. Natural habitats have largely been converted to agriculture in the Delta region, and managed wetlands for duck hunting in Suisun Marsh (Robinson et al. 2016; SFEI–ASC 2022). Beginning in the mid-19th century, colonization promoted genocidal practices to remove indigenous people from their ancestral lands, and established land-use practices that excluded indigenous management, greatly reducing ecocultural value and ecological function by modifying the landscape and its hydrology (SFEI–ASC 2016; Hankins 2018; Zedler and Stevens 2018). Today, freshwater is exported from from pumps in the southern part of the upper estuary through the Federal Central Valley Project (CVP), which provides water primarily for irrigating agricultural areas in the San Joaquin Valley, and the State Water Project (SWP) which provides water primarily for municipal use in Southern California. The State Water Project (SWP) exports freshwater from the San Francisco Bay (hereafter, SF Bay or lower estuary) to Los Angeles primarily, for municipal use in urban areas. The US Bureau of Reclamation (Reclamation) operates the CVP; the California Department of Water Resources (CDWR) operates the SWP. These projects (hereafter, water projects) provide water for approximately two-thirds of California's population, and irrigation for over 4 million acres of farmland (Gartrell et al. 2017). Taken together, these changes to the landscape, watershed, and natural hydrograph have led to a number of effects, including but not limited to reduced primary productivity, the introduction of numerous contaminants, increased nutrient loading, and non-native species invasion, leading to population declines of native species (Robinson et al. 2014, 2016; Sommer 2020; DSC 2021).

Addressing these constraints on ecosystem function to support the recovery of native species and habitats requires re-establishing land–water connectivity (e.g., for riparian, floodplain, and tidal wetland restoration), restoring native vegetation communities at large scales, managing hydrology for native species needs, improving water quality, and supporting a wide range of related activities (Seavy et al. 2009; Robinson et al. 2016; DSC 2022). This paper focuses on ecological restoration activities that are critical for a number of reasons, including supporting the persistence and recovery of endangered fish and wildlife (Sherman et al. 2017; Dybala et al. 2020), expanding native plant populations (Boyer and Thornton 2012; Kerr et al. 2016), improving the aquatic food web (Robinson et al. 2016), increasing

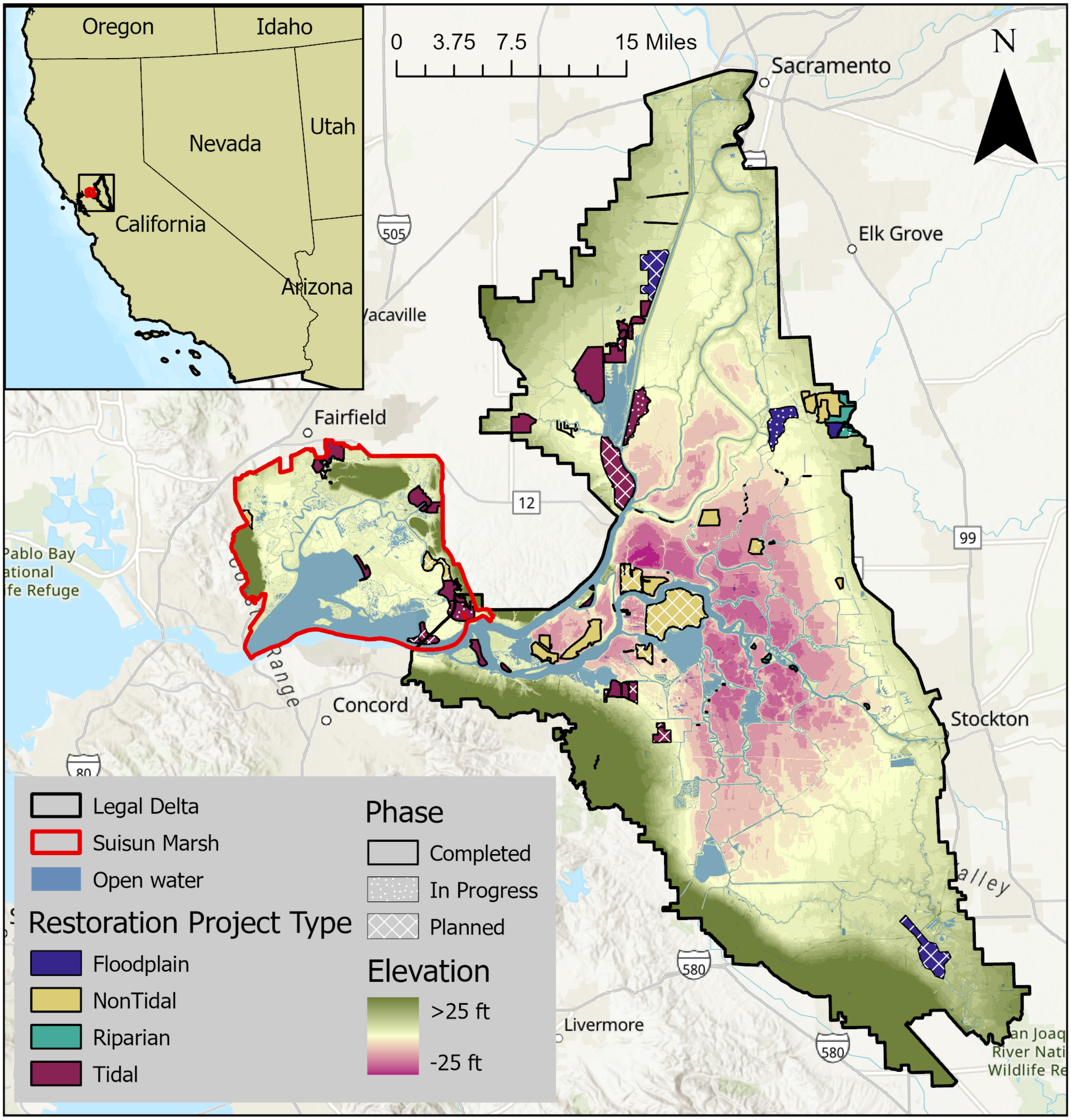

Figure 1 Study area map: Legal boundaries of the Sacramento–San Joaquin River Delta and Suisun Marsh as specified in the Delta Plan, elevation derived from digital elevation model, and location of restoration projects. Elevation is represented by a *color gradient* that ranges from heavily subsided islands in *maroon* (maximum depth of -25 feet [7.6 m] below sea level) to areas with elevation of 25 feet (7.6 m) or more above sea level in *dark green* (Source: CDWR 2020 Delta LiDAR Digital Elevation Model, 0.5-m-resolution, bare-earth digital elevation model. Vertical units in feet relative to mean sea level, referenced to NAVD88 datum). Restoration project layer includes locations, primary type (tidal, non-tidal, riparian, floodplain), and completion phase (completed, in progress, planned). See Figure 2 and Table 2 for restoration project details. Study area extent shown in reference to California. (Esri, TomTom, Garmon, FAO, NOAA, USGS, USEPA, USFWS, Source: US National Park Service, Esri, CIGAR)

climate change resilience (Dettinger et al. 2016), provisioning of ecosystem services (Deverel et al. 2020), and increasing recreation opportunities in the region (Sloop et al. 2018). To address the broad range of target benefits across ecosystem types, restoration projects in the upper estuary and elsewhere have varied objectives and are designed to develop physical attributes that reflect the motivations of project proponents (Suding et al. 2015; Gittman et al. 2019). Understanding the motivations for different types of restoration projects and their relative contributions to landscape-scale changes will help inform policy and future restoration investments. In recent decades, relatively few restoration projects have been completed in the upper estuary, compared to the SF Bay (Williams and Faber 2001; Williams and Orr 2002; Boyer and Thornton 2012; Goals Project 2015). Because of this relatively short history of large-scale restoration implementation in the upper estuary, and the decadal time-scales often needed for restoration objectives to be realized (Moreno–Mateos et al. 2012), considerable uncertainty persists about whether restoration will affect recovering species populations and ecological functions (Sherman et al. 2017). There is, however, a rapidly developing body of related scientific literature on the subject (see Hartman et al. 2024).

In 2022, the *Delta Plan*—a comprehensive planning document that outlines goals and policies pertaining to the management of the Delta and Suisun Marsh—was updated with new ecosystem-restoration targets based on 14 state, federal, and local recovery plans and similar documents that identify goals of between 60,000 and 80,000 additional acres of restored ecosystems over a 2007 historical baseline (DSC 2013a, 2022). Tracking progress since the 2007 baseline is critical for informing future efforts, but a comprehensive review of restoration activities in the upper estuary does not exist. This information gap precludes a landscape-scale understanding of where, when, why, and how restoration projects have been implemented, as highlighted by the Delta Independent Science Board in their 2013 review of restoration in the system (DISB 2013).

To address this gap and inform public agencies, policy-makers, scientists, and other interest groups, this paper analyzes progress on planning and implementation of ecosystem restoration, synthesizes current understanding of the science and management that guides restoration processes, and highlights select lessons learned from projects implemented in the upper estuary. The scope of this effort is limited to spatially explicit, on-the-ground restoration actions which aim to re-establish the physical and biological processes needed to achieve specified ecosystem functions in degraded areas. While freshwater flow-management interventions are also critically important actions that interact with restoration to support fish and wildlife species in the upper estuary, they are beyond the scope of this paper (see Sommer 2020 for an overview of flow interventions).

Research Questions

To accomplish the large-scale restoration goals identified in the *Delta Plan*, science-based adaptive management at both project and landscape scales will be important to ensure ecosystem benefits are realized (DSC 2013b). To inform progress to date toward these restoration targets, we provide an overview of restoration history and types in the system, and answer the following guiding questions:

1. Where and when have projects been implemented?

2. What has motivated their funding?

3. What key lessons learned can inform the management, design, and acquisition of restoration projects?

Addressing these questions provides a basis for future scientific and policy analyses of restoration as sites develop over the coming decades.

HISTORY AND CURRENT STATUS OF RESTORATION IN THE UPPER ESTUARY

Landscape Change: Past, Present, and Future

Restoration in the upper estuary occurs in the context of extensive land-use and hydrological changes from its pre-colonization state. Before 1850, the upper estuary was a vast network of emergent tidal wetlands intersected by many hundreds of miles of tidal slough, two major—and multiple minor—river corridors and their associated riparian banks, in-channel islands, seasonal floodplains, seasonal wetlands, and grasslands (Robinson et al. 2014). The land was and continues to be inhabited and stewarded by more than 11 Tribal groups including but not limited to the Bay Miwok, Coast Miwok, Plains Miwok, Maidu, Nisenan, Ohlone, Patwin, Pomo, Wappo, Wintun, and Yokuts. However, traditional management practices that fostered ecological and cultural resiliency were nearly entirely excluded from the landscape after European colonization (Hankins 2018). Over 98% of the historical habitat extent in the Delta was rapidly converted to agriculture and other land-use types across the 19th and 20th centuries (Robinson et al. 2014), using predominantly Chinese labor to create drained, leveed islands for farming (Chu 1970; Arreola 1975). Over time, levees and other water-management structures were created to “reclaim” land for agriculture, move water rapidly through the system, and cut off Delta islands from daily and seasonal inundation, limiting lateral connectivity for species, and reducing both primary productivity and species diversity (Robinson et al. 2016; Cloern 2021; Keeley et al. 2022). This loss of land–water connection also exposed wetland peat soils to oxygen, leading to microbial oxidation and subsequent sinking of the land surface, which is known as subsidence. This has led to land surface elevations as much as 25 feet (7.6 m) below sea level, necessitating constant pumping, increasing flood risk (from increased hydrostatic pressure on levees), and reducing options for ecological restoration (Figure 1; Durand 2017; Deverel et al. 2020).

Parallel processes in the Suisun Marsh converted brackish tidal wetland to managed wetland areas for hunting waterfowl, which are operated by more than 100 separate private land-owners and the California Department of Fish and Wildlife (CDFW; Moyle et al. 2014; SFEI–ASC 2022). These areas produce considerable primary productivity when they are flooded and can benefit native species under certain operational scenarios (Aha et al. 2021) but are controlled by levees and water-management structures and not consistently connected to the broader hydrologic system (Moyle et al. 2014). As a result of management practices that keep water on the landscape and less organic matter in the region's soils, subsidence is less acute in Suisun Marsh, but levees are vulnerable to overtopping under current conditions and projected sea-level-rise scenarios (DSC 2021).

Upstream, dams were constructed to store and release freshwater that is transported to the state and federal water-project pumps in the South Delta, limiting the natural hydrologic variability that native species had evolved to tolerate (Sommer 2020). The loss of connectivity between river channels and their floodplains—and the loss of connectivity upstream from river impoundment in the upper watershed—left physical processes such as sediment flux and deposition impaired, trophic systems interrupted, and species unable to access habitats (Robinson et al. 2014; DSC 2021). This and other changes have also facilitated non-native species invasions, which have altered the food web at every trophic level and affected native species habitat and food supply (Alpine and Cloern 1992; Jassby 2008; Greene et al. 2011; Kratina et al. 2014; Lucas et al. 2016; Kayfetz and Kimmerer 2017; Nobriga and Smith 2020). These altered conditions in the upper estuary have also made the system particularly sensitive to the effects of climate change, including sea level rise (Schile et al. 2014; Swanson et al. 2014; Buffington et al. 2021), flooding from intensified storms (Mount and Twiss 2005; Dettinger et al. 2016), and their combined effect on leveed subsided islands (Suddeth et al. 2010; DSC 2021).

The sum of these and other changes to the system have led to substantial declines in native species populations in the upper estuary, most notably in

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native fishes. In the early 2000s, the populations of native Delta Smelt (*Hypomesus transpacificus*) and Longfin Smelt (*Spirinchus thaleichthys*), non-native Striped Bass (*Morone saxatilis*), and Threadfin Shad (*Dorosoma petenense*) all declined rapidly, a phenomenon referred to as the Pelagic Organism Decline (POD) (Thomson et al. 2010). No single factor is responsible; rather, a combination of interactive factors has contributed, including invasions of aquatic plants (Rasmussen et al. 2022) and clams, decreases in turbidity, decreases in flow, drought (Mahardja et al. 2021), habitat loss, reduced primary productivity (Brown 2003; Hartman et al. 2024; Cloern 2021) and diminished food resources (Sommer et al. 2007). Recovery of native fish species is a major motivation for tidal wetland restoration activities (see "Restoration Types in the Upper Estuary"). Also motivating restoration are requirements related to endangered terrestrial species, including the giant garter snake (*Thamnophis gigas*), Swainson's hawk (*Buteo swainsoni*), valley elderberry longhorn beetle (*Desmocerus californicus dimorphus*), riparian brush rabbit (*Sylvilagus bachmani riparius*), and salt marsh harvest mouse (*Reithrodontomys raviventris*) (Sloop et al. 2018).

Restoration Types in the Upper Estuary

To address the issues discussed in the previous section, restoration progress in the upper estuary has largely focused on the following ecosystem types (using the *Delta Plan*; DSC 2022): tidal wetland, non-tidal wetland, riparian, and floodplain. See Appendix B (see "Data Availability") for detailed discussion of these ecosystems, restoration processes, and ecological functions.

Tidal wetlands are composed of multiple features including channels, ponds, and other tidal aquatic habitats, but are most characterized by (1) emergent vegetation generally found at elevations between mean lower low water and mean high water (with some exceptions) and (2) extensive channel networks. They historically covered much of the upper estuary and provide critical habitat and food resources for native species (Robinson et al. 2014; Table 1). Restoring tidal wetlands typically involves some combination of breaching levees to allow for tidal exchange, planting native species, manipulating topography and hydrology, and creating channel networks (Williams and Faber 2001; Williams and Orr 2002). In the San Francisco Estuary, the elevation range for the composition of the tidal wetland plant community is determined by a wetland's position along the salinity gradient, with freshwater emergent wetlands in the Delta, brackish wetlands in Suisun Marsh, and saline wetlands in the San Francisco Bay (Callaway et al. 2007).

Non-tidal wetlands in the upper estuary include seasonal wetlands, wet meadows, non-tidal wetlands, and alkali seasonal wetlands (CDFW 2007; DSC 2021). The most common type of non-tidal wetland restoration in the Delta is large-scale freshwater wetlands, designed to reverse subsidence and sequester carbon on heavily subsided islands in the central Delta. These subsidence-reversal projects convert land use from agriculture or pasture to wetlands (Deverel et al. 2020). Typically, these wetlands are managed by building internal berms to separate sections of the land that will be wetted and then pumping water onto the island surface while maintaining a target water depth that promotes the growth of peat-producing freshwater wetland plants, primarily tule and cattail species (Hemes et al. 2018). These freshwater non-tidal wetlands are distinct from brackish managed wetlands in Suisun Marsh maintained for waterfowl hunting, with seasonal flooding and plant species maintenance (Moyle et al. 2014), which are not included in the *Delta Plan* targets.

Upper estuary riparian forests and scrub are typically defined as vegetation communities that grow along rivers and streams, characterized by willow thickets, willow riparian scrub or shrub, and valley foothill riparian forest (CDFW 2007; Table 1). Because the system has been extensively modified, many of these ecosystems are no longer directly connected to rivers and streams and are instead fed by groundwater and runoff (DSC 2021). Restoration of these areas typically involves planting native species and/or manipulating land surfaces to allow for increased inundation at the land–water interface (Davenport et al. 2016)

Table 1 Delta Plan Acres Restored Goals. Net increase of target acres of natural communities by 2050 and historic acreages for ecosystem types considered in this paper.

Ecosystem type (Sub-types)	Historic (1800s)[a]	Baseline acres (2007)[b]	Restoration target acres (above baseline)[c]	Projected total 2050 area (baseline acres plus restoration)
Non-tidal Wetlands (Seasonal Wetland, Wet Meadow, Non-tidal Wetland, Alkali Seasonal Wetland)	116,524	5,800	19,230	24,330
Riparian and Floodplain (Willow Riparian Scrub/Shrub, Valley Foothill Riparian, Willow Thicket)	51,427	14,200	16,300	30,500
Tidal Wetland (Brackish [Suisun], Freshwater [Delta])	530,541	19,900	32,500	52,400

a. Historic acreages combined across the Delta from SFEI–ASC (2016, 2022).
b. Baseline Acres are acres of natural communities from the 2007 Vegetation Classification and Mapping Program (VegCamp) dataset (CDFW 2007).
c. See page 416 in Appendix A of DSC (2022b) for a list of the 14 documents used to create Delta Plan restoration targets.

Floodplains are closely related to riparian areas, and do not have a separate acreage-based target in the *Delta Plan*. In the upper estuary, most of the floodplain habitat is in the Consumnes River floodplain and the Yolo Bypass (a major piece of flood-control infrastructure for the city of Sacramento and surrounding areas), which is largely situated outside of the legal boundaries of the Delta. Land cover of these managed floodplains, when not flooded, consists mainly of agricultural fields, including rice fields, managed wetlands, and riparian vegetation (Sommer et al. 2001). Historically, seasonal floodwaters associated with large precipitation events and spring snowmelt filled substantial portions of the Central Valley in wet years, inundating emergent wetlands, perennial and seasonal ponds, willow thickets, and seasonal wetlands (Robinson et al. 2014); thus, restoration efforts focus on manipulating levee systems and land surfaces to increase the frequency, duration, and extent of inundation (Sommer 2020).

Restoration Governance in the Upper Estuary

Over the previous 3 decades, a series of different governance approaches have been undertaken to facilitate restoration in the upper estuary, the first of which was the CALFED Ecosystem Restoration Program (ERP), a state and federal partnership in place from 1993 through 2008 (see LAO 2006, Kallis et al. 2009, and Lubell et al. 2013 for in-depth discussions of CALFED). After CALFED was disbanded, the 2009 Sacramento–San Joaquin Delta Reform Act established the Delta Stewardship Council (DSC)—a state agency designed as a partial successor to CALFED and charged to create and implement the *Delta Plan*. The *Delta Plan* aims to achieve the state's coequal goals of providing a more reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem "in a manner that protects and enhances the unique cultural, recreational, natural resource, and agricultural values of the Delta as an evolving place" (DSC 2013a). The *Delta Plan* exists in the context of numerous other plans and regulations, including the Bay Plan, which also applies to Suisun Marsh and is implemented by the Bay Conservation and Development Commission (BCDC); the Bay Plan highlights the critical connections between the upper and lower estuary. The Delta Reform Act also established the Sacramento–San Joaquin Delta Conservancy and clarified the role of the Delta Protection Commission (intially established in 1992), to pursue the co-equal goals of environmental and economic protection of the Delta. The Delta Conservancy utilizes both internal programs and grant funding to facilitate implementation of restoration projects.

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Parallel to the establishment of these agencies, the Governor Brown administration proposed the Bay–Delta Conservation Plan (BDCP), which was separated into two initiatives: Water Fix focused on water conveyance and EcoRestore focused on ecosystem restoration (Gray et al. 2014; CNRA c2018). The BDCP was initially scoped to include restoration targets that would be included in the *Delta Plan*, but these targets were not developed after the creation of these separate programs. After this shift, the DSC amended Chapter 4, "*Protect, Restore, and Enhance the Delta Ecosystem*," of the *Delta Plan* to establish comprehensive, long-term ecosystem goals for the upper estuary, which were originally envisioned as part of the BDCP. The DSC adopted the amended chapter in June 2022. It includes a suite of ecosystem restoration targets that total between 60,000 and 80,000 acres (above a 2007 baseline) by 2050 (DSC 2022). These targets were developed to help recover listed species and restore ecosystem functions by synthesizing complementary restoration goals across 14 recovery plans, conservation strategies, and species-specific resiliency plans that set acreage-specific goals for restoration (DSC 2022). For example, the targets include the 5,000 to 7,000 acres of tidal wetland restoration identified in the Suisun Marsh Habitat Management, Preservation, and Restoration Plan (USBR et al. 2011), the guiding document for management in the Suisun Marsh. The targets were intended to be feasible and achievable, considering climate change, existing land cover, elevation, expected water surface elevation, and historical ecology. The *Delta Plan* now includes a series of tiers (used for reporting but not required for compliance) for restoration efforts based around the following priority attributes: (1) restoring hydrological, geomorphic, and biological processes; (2) being large-scale; (3) improving connectivity; (4) increasing native vegetation; and (5) contributing to the recovery of special-status species. Directors of state and federal agencies are coordinating around the implementation of the new targets through the *Delta Plan* Interagency Implementation Committee, whose member agencies are collectively responsible for implementing most of the restoration in the system.

Restoration Motivations in the Upper Estuary

Broadly, ecological restoration may be undertaken voluntarily, to re-establish processes that provision goods and services to human society, or as mitigation required by laws and regulations. Voluntary restoration is restoration for the benefit of natural communities and/or to achieve goals not mandated by a regulatory action, enforcement action, court settlement, or court order [Gittman et al. 2019; California Fish and Game Code §2081.2(a)(6)]. Human-centric motivations for restoration can include the use of ecological processes to benefit society (ecosystem services, e.g., carbon sequestration) and improve outcomes in engineered systems that use a mix of hard infrastructure and purpose built natural areas that provide specific functions (green infrastructure, e.g., floodplains constructed for flood control). In the upper estuary, voluntary restoration, ecosystem services, and green infrastructure projects each play some role in motivating projects across ecosystem types.

Mitigation is a major driver of restoration in the upper estuary, as a result of several environmental protection laws that require restoration as compensation for unavoidably affecting habitats, natural processes, and species. Federal and state regulations for threatened and endangered species ("listed species") are the primary environmental protection regulations that motivate restoration, and can be implemented through a variety of approaches, including Habitat Conservation Plans (Yolo Habitat Conservancy 2019). Water-project operation requires "take" authorizations under the federal Endangered Species Act (Biological Opinions, BiOps) and California Endangered Species Act (Incidental Take Permits, ITPs), which require restoration of 8,792.6 acres of tidal wetland (8,396.3 acres for Delta Smelt and 396.3 acres for Longfin Smelt, and enhancement and restoration of 20,000 acres of seasonal floodplain for Chinook Salmon, Central Valley Steelhead, Green Sturgeon, and other species (USFWS 2008 [BiOp]; NOAA 2009 [BiOp]; CDFW 2024 [ITP]; NOAA 2024 [BiOp]; USFWS 2024 [BiOp]). These mitigation requirements are being coordinated through the Fish Restoration Program (FRP)

Agreement between the CDWR and the CDFW (CDWR and CDFW 2010*),* with the CDWR responsible for implementing the required restoration projects and the CDFW responsible for monitoring. In Suisun Marsh, these efforts count toward the achievement of the restoration targets identified in the Suisun Marsh Habitat Management, Preservation and Restoration Plan (USBR et al. 2011), adopted in 2013. Restoration and other activities in Suisun Marsh are also under the BCDC's jurisdiction.

Maintenance and repair of the upper estuary's complex levee system also require compensatory restoration for listed species mitigation and general ecological uplift. In addition to other responsibilities related to levee maintenance, the CDWR's Delta Levees Program (DLP, now under the CDWR's Division of Multi-Benefit Initiatives) implements restoration projects under state Assembly Bill 360 (Davenport et al. 2016), which mandates no net loss of habitat and general enhancement of Delta ecosystems, and to satisfy mitigation requirements under the state and federal endangered species acts. The DLP has spent approximately $55 million dollars as of fall 2020 on restoration projects to meet these goals. As of 2022, the EcoRestore initiative had tracked expenditures of approximately $500 million dollars across 32 restoration and enhancement projects (including the DLP expenditures above) and expects to see expenditures of between $750 million and $950 million from various funding sources to complete these efforts (California EcoRestore 2020; 2022 in-person conversation between C. Biggs and DC, unreferenced, see "Notes").

Although mitigation obligations for listed fish species are the primary motivation for ecosystem restoration in the upper estuary, restoration is also required as mitigation for effects on other listed species. These species include the giant garter snake, Swainson's hawk, valley elderberry longhorn beetle, riparian brush rabbit, and salt marsh harvest mouse. For many of these species, mitigation is accomplished through private mitigation banks, which often provide guarantees for conserving and managing existing habitats in perpetuity (DIA c2025).

Once funded, all restoration projects go through an extensive review and permitting process. For example, the McCormack-Williamson Tract restoration project required permits, consultations, and determinations of consistency with the policies of at least 14 regulatory agencies (for a detailed discussion of restoration permitting, see Grenier et al. 2021). To increase the efficiency of regulatory processes and reduce the time, cost, and effort it takes to implement restoration projects, the California Natural Resources Agency has spearheaded the "Cutting the Green Tape" initiative (CDFW c2025). Given the critical role that permitting plays in restoration implementation, this program and others hold promise to accelerate restoration in the upper estuary and state-wide, but these processes are not a focus of our paper.

METHODS

Restoration Typology Development

Chapter 4 of the Delta Plan identifies overall restoration targets of 60,000 to 80,000 acres, to be met by 2050 (DSC 2022; Table 1). Under these broad restoration targets, the Delta Plan identifies specific restoration acreage targets for eight types of natural communities (Table 1). Of these eight types, this paper addresses the following four: riparian areas, floodplains, non-tidal wetlands, and tidal wetlands. We do not include analysis of ecosystem types where restoration has not progressed measurably (DSC 2022), or a full list of restoration targets, or where restoration targets are not specified by the *Delta Plan* (e.g., managed wetlands in Suisun Marsh). See Appendix B (under "Data Availability") for a detailed discussion of restoration types, including restoration processes and ecological functions. Notably, these targets do not include an acreage-specific total for floodplains, because the *Delta Plan* assesses floodplains through restoration goals that target increased frequency and duration of inundation rather than acreage-specific goals. The specific goal for floodplains is the inundation of 20,000 additional acres on a 2-year recurrence interval, with 16,000 acres of riparian habitat within and adjacent to these floodplain areas (DSC 2022). Thus, we count floodplain projects toward the riparian acreage goal.

Acreage Calculations

We quantified the project area covered by riparian, floodplain, non-tidal wetlands, and tidal wetlands (vegetated tidal emergent wetlands) projects within the legal boundaries of the Delta and Suisun Marsh. We selected this geographic boundary to match the jurisdiction of the *Delta Plan*, but it is important to acknowledge that restoration projects outside of these boundaries also influence ecosystem dynamics (for example, the Lower Elkhorn Basin Setback Levee floodplain restoration project in the upper Yolo Bypass). We first reviewed projects from the EcoAtlas Project Tracker (SFEI c2025), where information on restoration projects is uploaded by project proponents and other entities. We began with the full dataset of projects (n = 178) extracted directly from the EcoAtlas Project Tracker and clipped this data to the geospatial boundaries of the Delta and Suisun Marsh using ArcGIS Pro. To focus our analysis on projects where outcomes of direct interventions could be assessed quantitatively by future efforts, we reviewed planning documents and other available information to create a subset of the larger dataset, which included only restoration projects where hydrology, geomorphology, or biological communities were actively manipulated with the goal to improve either ecological function or species habitat quality; we excluded land preservation and other projects where no on-the-ground interventions were performed or planned. In general, recent large-scale projects employ process-based restoration, which aims to re-establish rates and magnitudes of physical, chemical, and biological processes needed to re-establish and maintain ecosystems in degraded areas and allows projects to respond to changing conditions while maintaining ecological function (Beechie 2010; Robinson et al. 2016).

Uploading information to EcoAtlas is not a requirement for all projects, and project information may be out-of-date or missing altogether. To include the most up-to-date project information, we performed web searches for each project to identify where project information may be out of date or missing entirely, drew on agency documents and court settlements, consulted local restoration practitioners, and used the DSC's database of the *Delta Plan*'s "Covered Actions" regulatory certification documents (DSC 2023). To identify supplemental projects not included in EcoAtlas, we consulted collaborative groups working on restoration in the system (the Interagency Adaptive Management Integration Team, FRP Monitoring Team, Interagency Ecological Program (IEP) Tidal Wetland Monitoring Project Work Team, IEP Synthesis Project Work Team, Estuarine Ecology Team), which resulted in the final list of 84 projects presented here.

We used ecosystem-specific acreages based on the most recent available project documents as of October 2024. Projects where specific acreages were not available by this date are not included in our analysis. Because funding information was not always available or up-to-date, and projects in the planning process may not have all their funding identified, we do not list specific costs for each project. We identified the CEQA lead agency for each project and listed funding sources where information was available (Appendix A). To further categorize projects, we assigned the following groupings related to project motivation (for details on motivations see "Restoration Motivations in the Upper Estuary"): general mitigation, DLP mitigation, water project mitigation, AB 360 projects, voluntary projects, and green infrastructure and ecosystem services (Suding et al. 2015; Gittman et al. 2019).

We acknowledge that there is often considerable overlap between these project motivations; thus, these categories reflect the primary factors that motivate project implementation, not the full extent of future project benefits.

To reflect project status, we assigned one of the following categories: completed, in-progress, or planned. Completed projects have finished the main construction activities (including physical site work and native species planting) described in environmental compliance documents. In-progress projects have completed their environmental permitting processes, and construction activities have begun but are not finished (some projects are constructed in phases that span multiple years). Planned projects have some degree of documentation that include specific acreages, funding information, programmatic affiliation (like EcoRestore), and a reasonable chance of being implemented but have not started any construction activities. Acreages for planned projects are subject to change.

To look at spatial trends in restoration projects, we categorized projects by region (Suisun, Central Delta, North Delta, Cache Slough/Yolo Bypass, and South Delta) using geospatial layers developed for the Delta Adapts Ecosystem Chapter (Figure 2; DSC 2021). To assess progress made toward the *Delta Plan* ecosystem targets, we grouped projects implemented before and after the 2007 baseline.

RESULTS

Across the upper estuary, we identified 84 completed, in-progress, or planned restoration projects across the typology categories totaling 30,037 acres (Figure 2; Table 3; Appendix A). Some projects span more than one restoration type and are thus reflected in multiple typology categories; however, project acreages are not double counted in total restored acres.

Across all habitat types as of October 2024, we identified 14,269 acres of completed restoration across 55 projects (with 12,493 total acres completed across 31 projects after the 2007 historical baseline). An additional 5,071 acres across 11 projects are in-progress, and 10,697 acres across 18 projects are planned for restoration (Table 3). Across all project phases, 42 of these projects (50%) are less than 100 acres, 23 (27%) are between 100 and 500 acres, 9 (11%) are between 500 and 1,000, and 10 (12%) are more than 1,000 acres. Across regions, restoration progress from greatest to least acreage is as follows: Central Delta, Cache Slough/Yolo Bypass, Suisun Marsh, North Delta, South Delta (Table 4)

Restoration Progress

Riparian and floodplain restoration accounted for 8% of total acreage above the 2007 baseline. We identified 35 projects that include restored riparian or floodplain habitats, totaling 4,290 acres across completed, in-progress and planned projects (Table 3). The *Delta Plan* restoration target for riparian and floodplain wetlands above the 2007 baseline is 16,300 acres by 2050 (Table 1). Completed restoration meets just over 6% of this goal, leaving 14,649 acres to be restored once in-progress projects are completed, and 12,010 acres to be restored if all planned projects are implemented. Pre-2008, 1,039 acres of riparian habitat were restored; however, no floodplain habitat was intentionally restored. As described in "Restoration Typology Development," the *Delta Plan* restoration target for riparian ecosystems is 16,300 acres, but does not include a separate, acreage-based category for floodplains, so we combine them here (Table 1).

Non-tidal wetland restoration accounted for 22% of total completed acreage above the 2007 baseline. We identified 19 projects that include restored non-tidal wetland habitat, totaling 9,252 acres across completed, in-progress and planned projects (Table 3). The *Delta Plan* restoration target for non-tidal wetlands above the 2007 baseline is 19,230 acres by 2050 (Table 1). Completed restoration meets 14% of this goal, leaving 15,692 acres to be restored once in-progress projects are completed, and 9,978 acres to be restored if all planned projects are implemented. Pre-2008, 551 acres of non-tidal wetland habitat was restored, indicating an increased pace in restoration efforts (Figure 3).

Tidal wetland restoration accounts for nearly 70% of total acreage completed above the 2007 baseline. We identified 31 projects that include restored tidal wetland habitat, totaling 14,719 acres across completed, in-progress and planned projects (Table 3). The *Delta Plan* restoration target for tidal wetlands above the 2007 baseline is 32,500 acres by 2050 (Table 1). Completed restoration achieves just above one-quarter of this goal, leaving 20,125 acres to be restored once all in-progress projects are completed, and 17,781 acres to be restored

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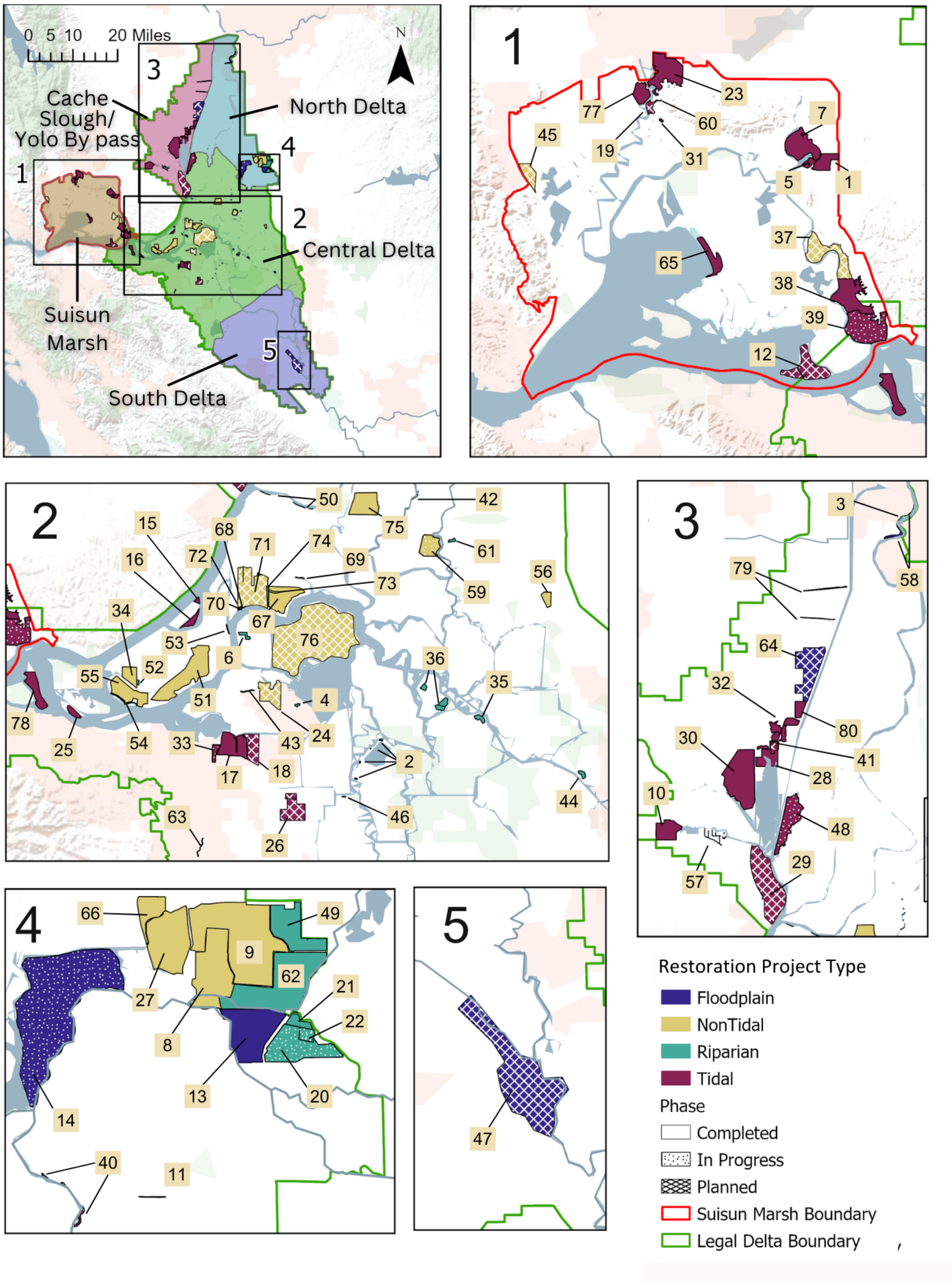

Figure 2 Ecosystem restoration projects in the legal Delta and Suisun Marsh by main ecosystem type, project phase, and Delta Region (1) Suisun Marsh, (2) Central Delta, (3) Cache Slough/Yolo Bypass, (4) North Delta, and (5) South Delta. See Appendix A for full project names and details.

Table 2 Project name and map ID number that correspond with Figure 2

ID No.	Project	ID No.	Project
1	Arnold Slough	41	North Delta Liberty Island Conservation Bank
2	Bacon Island Levee Rehabilitation Project	42	North Mokelumne River Multi-Benefit Project
3	Bees Lake	43	Northwest Levee Improvements and Stone Road Seepage Reduction Project
4	Bethel Island Parcel (includes 3 projects)a	44	Pace Preserve (Wright–Elmwood)
5	Blacklock Tidal Marsh Restoration	45	Pacific Flyway Center Project
6	Bradford (50-ac mitigation)	46	Palm–Orwood Tract
7	Bradmoor Island	47	Paradise Cut
8	BLM Property C (Crump)	48	Prospect Island Tidal Habitat Restoration
9	BLM Property F (Fitzgerald)	49	Sacramento County FD
10	Calhoun Cut Ecological Reserve /Lindsey Slough Tidal Habitat	50	Sacramento River Erosion Control and Habitat Enhancement Project
11	Canal Ranch Attached Berm (Beaver Slough Waterside Vegetation Berm)	51	Sherman Island: Belly Wetland
12	Chipps Island Tidal Marsh Restoration	52	Sherman Island: Parcel 11 mitigation
13	Cosumnes Floodplain Mitigation Bank	53	Sherman Island: San Joaquin River 2016 DLP Multi-Benefit Project
14	McCormack-Williamson Tract	54	Sherman Island: Setback Levee Habitat Enhancement Project (Mayberry Slough)
15	Decker Island Habitat Development	55	Sherman Island: Whale's Mouth Wetland Restoration Project
16	Decker Island Tidal Habitat Restoration	56	Shin Kee
17	Dutch Slough Tidal Marsh Restoration Project Phase 1	57	Solano County Delta Habitat Restoration Partnership (includes Petersen Ranch)a
18	Dutch Slough Tidal Marsh Restoration Project Phase 2: Burroughs Parcel	58	Southport Setback Levee Project
19	Goat Island Marsh	59	Staten Island: Wetland Restoration Project
20	Grizzly Slough Floodplain Restoration	60	Suisun Hill Hollow
21	Grizzly Slough Phase I mitigation (35ac)	61	Terminous
22	Grizzly Slough Phase II mitigation (35ac)	62	The Nature Conservancy A (Nicolaus Ranch)
23	Hill Slough Tidal Restoration Project	63	Three Creeks Parkway Restoration Project
24	Hoover Ranch	64	Tides End Multi-Benefit Restoration Project
25	Kimball Island Mitigation Bank	65	Tule Red
26	Knightsen Restoration Project	66	Twin Cities Unit (Wong)
27	Kraus (Ducks Unlimited Grant)	67	Twitchell Island: East End Wetland Restoration (includes 3 projects)a
28	Liberty Island Conservation Bank	68	Twitchell Island: East Pocket ("4-acre")
29	Little Egbert Tract	69	Twitchell Island: 1997 On Site Restoration
30	Lookout Slough Tidal Habitat Restoration	70	Twitchell Island: Setback Levee (original)
31	Lower Spring Branch Creek	71	Twitchell Island: West End Wetland
32	Lower Yolo Ranch Restoration Project	72	Twitchell Island: West Pocket ("2-acre")
33	Marsh Creek Enhancement Area	73	Twitchell Island: West Pond
34	Mayberry Farms Subsidence Reversal/Carbon Sequestration Project	74	Twitchell Island: Willow Canal ("8-acre")
35	McDonald Island Mitigation	75	Tyler Island Restoration
36	Medford (136-acre mitigation—all fields)	76	Webb Tract: Wetland Mosaic Landscape
37	Meins Landing	77	Wings Landing Tidal Habitat Restoration
38	Montezuma Wetlands: Phase 1	78	Winter Island: Tidal Habitat Restoration
39	Montezuma Wetlands: Phase 2	79	Yolo Bypass Wildlife Area: Wildlife Corridors for Flood Escape
40	New Hope 2016 DLP Multi-Benefit Project NI-17-1.0	80	Yolo Flyway Farms Tidal Habitat Restoration Project

a. Projects with multiple sub-projects included in the map area.

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Table 3 Restoration acres by project completion phase. Total number of projects and acreages listed by habitat type and year. Total acres include projects in all phases (completed, in-progress, and planned). Darker shading indicates where more progress has occurred.

	Tidal	Non-Tidal	Riparian	Floodplain	Total (acres)
Total acres (# projects)	14,905 (35)	9,802 (31)	2,153 (44)	3,176 (9)	30,037
Acres completed 1985–2007 (# projects)	186 (4)	551 (11)	1,039 (18)	0 (0)	1,775
Acres completed 2008–2024 (# projects)	8,708 (16)	2,775 (8)	281 (11)	730 (4)	12,493
Acres in progress (# projects)	3,667 (7)	764 (3)	456 (8)	184 (3)	5,071
Acres planned (# projects)	2,344 (8)	5,714 (8)	377 (7)	2,262 (2)	10,697

Table 4 Restoration acres by Delta region. Includes projects in all phases (completed, in-progress, and planned) from 1985 to 2024.

	Tidal	Non-tidal	Riparian	Floodplain	Total (acres)
Suisun Marsh (# projects)	4,439 (11)	693 (3)	0 (0)	0 (0)	5,132
Central Delta (# projects)	1,638 (13)	8,756 (22)	930 (32)	2 (1)	11,326
North Delta (# projects)	2,281 (3)	354 (5)	1,182 (11)	763 (5)	4,580
South Delta (# projects)	0 (0)	0 (0)	0 (0)	500 (1)	500
Cache Slough/Yolo Bypass (# projects)	6,547 (8)	0 (0)	41 (1)	1,911 (2)	8,499

if all planned projects are implemented. Pre-2008, 186 acres of tidal wetland were restored, indicating an increased pace in tidal wetland habitat restoration in the Delta in recent years (Figure 3). Notably, this pre-2008 total does not include unintentional breaches (e.g., Liberty Island), which have added tidally connected acreage, but were not intentionally planned.

Restoration Leadership and Motivation

For all projects identified, the CDWR is responsible for the largest proportion of projects, leading 55 (65%) projects that span 19,669 acres (65% of total acres). The remaining 29 projects are led by a range of local governments (including counties and related entities), non-profits, private companies, reclamation districts, and other state and federal agencies (Appendix A). Of these groups, the Metropolitan Water District accounts for 10% of total acreage (at the planned Webb Tract Wetland Mosaic Landscape project, which accounts for 30% of all non-tidal wetland acreage); Montezuma Wetlands LLC accounts for 6% of total acreage (across the completed and planned phases of the Montezuma Wetlands Restoration project); and all other project leads account for 3% of total acreage or less (Appendix A).

For total project acreage across completed, in-progress, and planned projects in the upper estuary, 29% is mitigation for water projects implemented by the CDWR FRP. Ecosystem services and green infrastructure projects comprise 25% of the total and consist largely of subsidence reversal wetlands on the planned Webb Tract project, beneficial reuse of dredge materials in the Montezuma Wetlands project, and flood control in the South Delta at the planned Paradise Cut project. Notably, half of these projects are currently in the planning stage. Projects led by the CDWR that fulfill the requirement for general ecological uplift under

AB 360 account for 15%, and mitigation for CDWR levee maintenance accounts for 1%. Mitigation for other activities accounts for 8%, voluntary restoration accounts for 9%, and 10% have yet to be assigned a motivation (Figure 4).

DISCUSSION

Restoration Progress and Funding

This paper provides the first comprehensive assessment of restoration progress across major ecosystem types and their motivations in the upper estuary. Much of the progress has been made in recent years, with 55% of total tidal wetland restoration acres in the system completed since 2018, largely motivated by mitigation requirements related to endangered fish species. Still, the pace of restoration will need to increase substantially across restoration types to meet the 2050 *Delta Plan* restoration targets, particularly for riparian and floodplain ecosystem types. Notably, extensive restoration is currently occurring just outside our study boundaries in the Yolo Bypass and elsewhere, which will directly affect the health of the Delta ecosystem, indicating that future assessment of *Delta Plan* ecosystem types

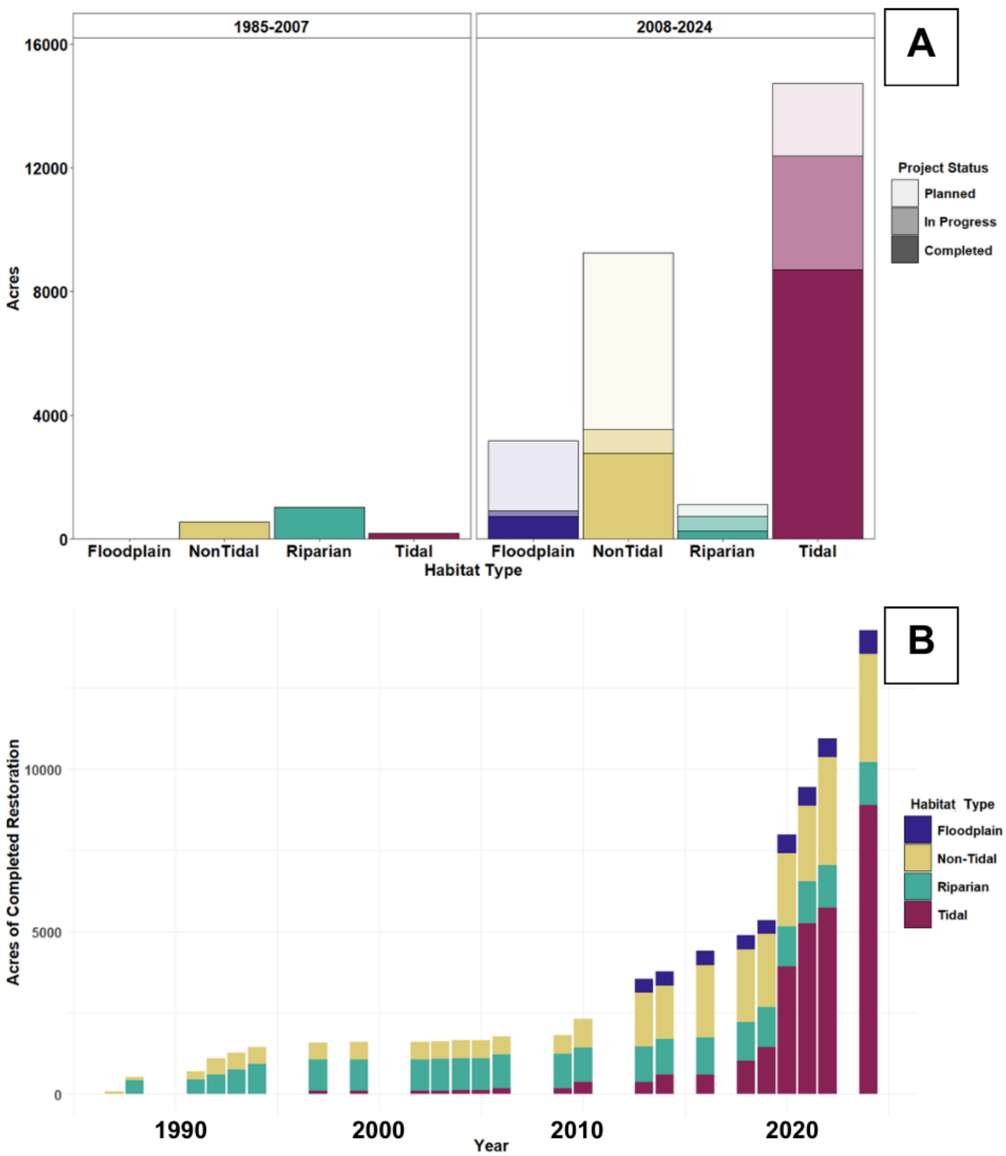

Figure 3 Habitat restoration trends in the Delta and Suisun March as of 2024. (**A**) Completed, in-progress, and planned restoration by habitat type before and after 2007. Delta restoration targets by 2050 are 32,500 acres of tidal habitat, 19,500 acres of non-tidal, and 16,300 acres of floodplain and riparian habitat. (**B**) Cumulative acres of total restored areas by habitat type over study period.

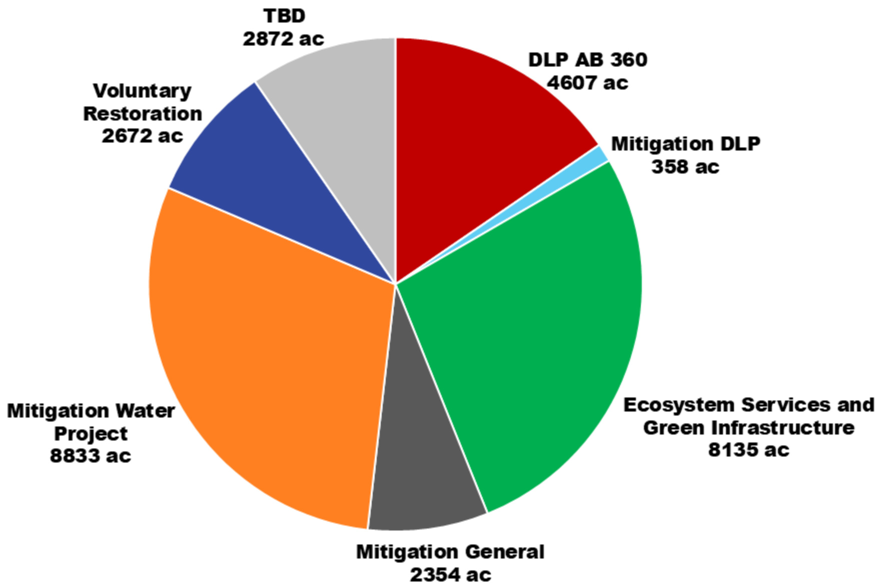

Figure 4 Project motivations by total acreage (ac) across completed, in-progress, and planned projects

could consider an expanded spatial footprint with regards to assessing progress.

In the lower estuary (San Francisco Bay), 11,200 acres of tidal wetlands were restored between 2009 and 2024, compared to 8,708 acres in the upper estuary (SFEP 2015, 2019; 2025 email communication between A. Robinson and DC unreferenced, see "Notes"). Ongoing coordination between restoration programs in the upper and lower estuary will be critical for sharing lessons learned. However, many of the projects completed in the upper estuary during this period had been in the planning process for many years—even decades—while funding was secured, restoration plans were designed, permits were obtained, and other logistical details were addressed. For example, the Dutch Slough Restoration project was initially identified in 1999 and planning began in the early 2000s, but Phase 1 of the project was not completed until 2021 (ESA c2023). Thus, to ensure that these targets are met, collaborative restoration efforts must continue to be prioritized and funded to address logistical complexities, permitting efficiencies, and new approaches for incorporating public input on projects (Sloop et al. 2018).

A mix of future mitigation requirements for operation of existing water project facilities, voluntary agreements under the proposed Healthy Rivers and Landscapes Program, potential construction of new water-conveyance infrastructure through the Delta, and updates to the SWRCB's Bay–Delta Water Quality Control Plan will likely drive a substantial portion of future restoration projects (SWRCB 2023). Conventional mitigation projects account for 8% of restoration acreage, but are unlikely to be a primary driver of large-scale restoration projects needed to meet the *Delta Plan* restoration targets. Projects under the CDWR DLP related to the AB 360 mandates account for 15% of restoration acreage, and the general requirement for "ecological uplift" is broad enough to be a potential vehicle for future large-scale projects. Dutch Slough is an example of an AB 360 project successfully funded by a wide range of bond funding sources and supporting agencies, including the CDWR, the California State Coastal Conservancy, the CDFW, the USEPA, the USFWS, and the Delta Conservancy (2022 in-person conversation between K. Bandy and DC, unreferenced, see "Notes"). However, this range of funding also highlights the opportunity to streamline and centralize funding to reduce the number of revenue streams required for restoration.

Ecosystem service and green infrastructure projects currently account for another 25% of restoration acreage. Promising directions for funding future restoration may include supporting subsidence reversal wetlands using public and private greenhouse gas-related funds, and multi-benefit riparian floodplain that leverage infrastructure-related funds. The recent funding of the Wetland Mosaic on Webb Tract project, using $20.9 million in grant funding from the Budget Act of 2022 (Delta Conservancy 2023) demonstrates the potential for bond funding to support large scale restoration projects. Lastly, voluntary restoration projects account for 9% of restoration acreage. While voluntary restoration is generally less common nationwide for wetland restoration, California supports a high proportion of the total voluntary restoration acreage in the US, driven by large-scale projects such as the South Bay Salt Pond Restoration Project in the lower estuary (Gittman et al. 2019). Increasing voluntary projects in the Delta could be another strategy for achieving *Delta Plan* restoration targets.

Funding pipelines for future restoration projects beyond currently mandated requirements are mostly unidentified. Many non-mitigation projects have been funded all or in part by bonds through Proposition 1 (Water Quality, Supply, and Infrastructure Improvement Act of 2014) and Proposition 68 (California Drought, Water, Parks, Climate, Coastal Protection, and Outdoor Access For All Act of 2018), but the terms of these funds have limited ability to support projects on private land. This is significant in the upper estuary, where much of the land adjacent to waterways is privately owned. Further, these funds are already mostly allocated. Proposition 4, approved by voters in 2024, will support $10 billion dollars of climate, water, and natural resource projects, but thus far only $29 million dollars has been allocated for restoration and related activities in the Delta (DSC 2025).

Providing steady funding for restoration implementation and maintenance from the state's General Fund is another promising avenue, given the state-wide importance of the Delta. For example, the CDWR is currently developing and implementing a general-fund-supported, land-stewardship program, which allows for critical continuity of restoration project maintenance and science post-completion (CDWR 2025a; 2022 in-person conversation between K. Bandy and DC, unreferenced, see "Notes"). For non-tidal wetlands, developing science on carbon sequestration has led to carbon market credits being developed for the private market through the American Carbon Registry, and future funding for restoration and maintenance may be possible through the more substantial California Air Resources Board regulatory carbon market credits (Windham–Myers et al. 2023). Delta restoration would also benefit from expanded federal funding similar to the Florida Everglades, where over $1 billion for restoration, management, and monitoring was included in the federal Infrastructure Investment and Jobs Act of 2021 (South Florida Ecosystem Restoration Task Force 2024). Another model is the SF Bay Restoration Authority, enacted by ballot initiative Measure AA, which allocates approximately $25 million per year from a SF Bay area parcel tax (California State Coastal Conservancy and San Francisco Estuary Partnership c2024). Lastly, private capital can also be leveraged, as is the case for the Montezuma Wetlands Restoration project, which uses dredge materials from the Port of Oakland to create habitat, funded by dredge disposal fees (Vollmar Natural Lands Consulting c2025). Pursuing a broad portfolio of funding approaches will help expand the scale of restoration in the system.

Restoration Locations and other Ecosystem Types

Across the upper estuary, restoration activities have been most concentrated in the Cache Slough/Yolo Bypass area, the confluence of the Sacramento and San Joaquin rivers in the Central Delta, and the Suisun Marsh, motivated by the importance of these regions for native fish and wildlife species and the availability of parcels at the correct elevations for intertidal restoration (Hanak et al. 2012). We were only able to identify a single planned project in the South Delta, the 500-acre Paradise Cut Floodplain Restoration; however, the Van Buskirk Multi-

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Benefit Ecosystem and Restoration Planning Project, which is just outside of the legal Delta Boundaries, has received planning funding from the Delta Conservancy (Delta Conservancy 2022b). Tidal wetland restoration has not been pursued in the South Delta because lands there are heavily subsided, and conditions are not favorable for native fish species or water project operations. If these considerations can be adequately addressed, though, this region may hold promise for future restoration of floodplain, riparian, and non-tidal wetland habitat types integrated with public access, specifically in the Mormon Slough area.

Critically, this paper only considers ecosystem types where significant restoration has been documented. While our review may have missed some smaller projects, we were unable to identify any projects that contribute toward the 13,000-acre goal for oak woodlands. We also did not identify substantial acreages of restored vernal pools or stabilized interior dune vegetation for our analysis. Some targets could be met by activities adjacent to but outside of the legal boundaries of the Delta, such as the Lower Elkhorn Basin Setback Levee and Big Notch projects in the Yolo Bypass. Thus, tracking of performance measures could account for changes to the system not reflected within the strict boundaries of the upper estuary.

Future Directions

This effort only considers reported acreages in a specific temporal snapshot, not ecological outcomes; thus, synthesizing outcomes from projects will be critical for refining the conceptual models that underpin restoration actions and drive the adaptive management process as new projects are completed and more information is available. Restoration projects can take many decades to develop (Moreno–Mateos et al. 2012; Chapple et al. 2017), and climate change, the cumulative effects of restoration projects on species and hydrodynamics, changes to the watershed, and other regional activities will all affect system dynamics over time, requiring ongoing science and monitoring to understand in detail. To account for these changes, adaptive management of individual projects and system-scale decisions about restoration scenarios will need to be responsive to current project outcomes, incorporating lessons learned into management of existing projects and implementation of future projects.

To identify future sites, approaches, and collaborative management opportunities for restoration, Tribes (Hankins 2018; Zedler and Stevens 2018), farmers, and various community and environmental justice groups (Sloop et al. 2018; DSC 2024) should be brought in to planning processes as early as possible to contribute ideas for novel restoration approaches that incorporate indigenous and local knowledge. Ecocultural knowledge and land-management practices that include extensive consideration of adaptive approaches to stewardship based on centuries of experience, and ecocultural restoration sites where indigenous use and management is permitted would aid in achieving both ecological (Hankins 2018; Zedler and Stevens 2018) and equity goals consistent with the 2022 CNRA Natural and Working Lands Strategy and the DSC tribal and environmental justice issue paper (CNRA 2022; see Rothrock 2023 for an example from Dos Rios State Park in the San Joaquin Valley; DSC 2024).

In environmental justice and other communities, social benefits should be considered alongside ecological benefits when locating and designing restoration. For example, the city of Stockton, a major population center in the South Delta, is home to the highest concentration of environmental justice communities in the Delta region (DSC 2024), and community perspectives and partnerships are being incorporated into planning for the Van Buskirk Multi-Benefit Restoration Project and related efforts on Mormon Slough (Delta Conservancy 2022b). In addition to Tribes and environmental justice communities, proactive considerations of effects on land-owners, including farmers (Luoma et al. 2015; Sloop et al. 2018), and community input on water-based recreational activities—such as boating, duck hunting, and fishing (Mickel et al. 2019)— should be considered when ecosystem restoration is planned. Existing tools, such as good-neighbor checklists (DSC 2022), and proposition funding programs such as those administered by the Delta Conservancy, can be leveraged to address conflicts, and provide support for farmers and others to engage in practices that promote subsidence reversal. Planning processes for the CDFW Franks Tract Futures and Metropolitan Water District Delta Island Adaptations are examples of projects that utilized a structured decision-making approach to engage Tribes, public agencies, and local interests to collaboratively develop restoration plans that consider ecological, ecocultural, water quality, community, and recreational benefits early in the planning process (CDFW 2020).

Future decision-making that considers where, when, and how to restore will also need to be adaptively managed, based on dynamic communication of best available science. For example, tidal wetland restoration projects are likely to have cumulatively affect salinity and tidal dynamics in the system (RMA 2021), underscoring the need for monitoring, modeling, and adaptive decision-making. To date, most projects have prepared project-specific adaptive management plans as required by the *Delta Plan* regulatory process; existing examples of venues for coordination and collaboration are the Collaborative Adaptive Management Team, the Delta Plan Interagency Implementation Committee, the Delta Interagency Adaptive Management Integration Team, and the Suisun Adaptive Management Advisory Team (Hartman et al. 2024). Synthesis efforts such as IEP reports, the Delta Independent Science Board Monitoring Enterprise Review (DISB 2022) and the Delta Science Program's Delta Science Tracker (DSC c2025) should be leveraged to identify further opportunities to integrate science and adaptive management into restoration planning. Further, targeted venues for communicating restoration science such as the 2023 Tidal Wetland Science Symposium are critical for informing adaptive management processes (Hartman et al. 2024).

These venues and others help communicate quantitative assessments of whether restoration projects provide the benefits they were designed to confer, particularly for endangered species recovery requirements. For many ecological functions, long-term data are needed to assess whether and how target conditions are being met. For example, initial observations of the Liberty Island Conservation Bank indicated that stunted vegetation could compromise ecological function (Orlando and Drexler 2017), but subsequent monitoring indicates that the site functions well as habitat for native fish species (2022 email between M. Young and DC, unreferenced, see "Notes"). For subsidence reversal wetlands in the Central Delta, monitoring during early years of site development showed high methane emissions (Hemes et al. 2018), but subsequent years of data show a rapid decline of methane as the sites evolve (2022 in-person conversation between D. Baldocchi and DC, unreferenced, see "Notes"). Learning from past projects will be key to adaptively managing ongoing activities at current sites, and planning future projects as required by the *Delta Plan* (DSC 2013a). However, detailed monitoring will often be out of scope for smaller projects with limited funding. Given this, both peer-reviewed and peer-to-peer communication of outcomes across projects are important for comprehensive social learning processes.

Despite widespread ecological degradation in the system, the ecosystems of the upper estuary still support significant components of biodiversity, and, relative to surrounding areas, may be resilient to climate change (Dybala et al. 2020). Addressing the loss of ecosystem extent and connectivity will increase the region's resilience to sea level rise and other climate-change effects (Seavy et al. 2009; DSC 2022). With restoration, the upper estuary has significant potential to serve as a climate refugia and buffer species populations within the region from climate change (Enright et al. 2013; Dybala et al. 2020; Hemes et al. 2021). Models project that the upper estuary's proximity to the coast and tidal connection will result in less pronounced increases in temperature compared to adjacent areas in the Central Valley, which are predicted to be 1.1 °C (2 °F) higher on average, relative to the Delta (Dettinger et al. 1995; Morelli et al. 2016; DSC 2021). Both tidal and non-tidal wetlands have the potential to sequester carbon. They both reduce greenhouse

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gas emissions from subsided lands (Deverel et al. 2016; Windham–Myers et al. 2023) and moderate surface temperatures (Hemes et al 2018), thus improving conditions for native species. These examples illustrate that, while climate change poses significant risks to ecosystems in the upper estuary, restoration can be a key tool for climate adaptation.

CONCLUSION

This paper demonstrates that the scale and scope of current restoration efforts in the upper San Francisco Estuary is progressing at an accelerated pace in recent years. Future restoration projects will be constrained by land acquisition cost (the state of California is legally mandated to pay appraised value), land-use conflicts, and finding parcels with appropriate elevations for specific restoration activities (DSC 2022). Given these and other challenges, tracking the progress of restoration projects identified in this effort will be critical for planning new, cost-effective projects that benefit ecosystems, species, and humans. This effort also serves as a case study for how different project motivations operate together to drive regional restoration (Gittman et al. 2019). That mitigation is the largest motivator of restoration in the upper estuary illustrates that global efforts such as the current United Nations Decade on Restoration may require alternative policy requirements and strong funding mandates for voluntary restoration in areas where mitigation is not a driver. Future efforts should build on this work to elucidate whether target ecological functions are realized, structure adaptive management interventions where they are not, and continue expanding new approaches for integrating tribal and community needs into restoration planning by providing support for these groups to participate in planning and implementation processes (Sloop et al. 2018; see DSC 2024 for specific recommendations).

DATA AVAILABILITY

All restoration project data in the current study are available in Appendix A of this paper. Additional material on restoration project types are available in Appendix B, which can be accessed online at this link: *https://figshare.com/s/4f7f397647ffa2c51991*.

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