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An overview of the Delta Region Areawide Aquatic Weed Project for improved control of invasive aquatic weeds in the Sacramento–San Joaquin Delta

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ABSTRACT

The 27,540-ha (68,000-acre) Sacramento–San Joaquin River Delta of northern California is the largest freshwater estuary on the western coast of the United States. The Delta provides irrigation water for over $30 billion in crops in the Delta and Central Valley and drinking water for 27 million people, supports $300 million in recreational boating, and includes the ports of West Sacramento and Stockton. The Delta's sloughs, wetlands and riparian habitats host 56 threatened or endangered species. Invasions by nonnative aquatic weeds constitute a major environmental challenge. The USDA–ARS Areawide Pest Management Program focuses on integrated, adaptive control of invasive pests, by supporting implementation of new, science-based control solutions. The Delta Region Areawide Aquatic Weed Project (DRAAWP) was funded from 2014 to 2018 to improve control of floating water hyacinth [*Eichhornia crassipes* (Mart.) Solms], submersed Brazilian waterweed (*Egeria densa* Planch.), and riparian arundo (*Arundo donax* L.) in the Delta. Outputs from the DRAAWP are now informing control of nine aquatic weeds and arundo using adaptive, integrated chemical, mechanical, and biological approaches. Project outputs include improved knowledge of aquatic weed growth and dispersal, models of watershed nutrients, weed control prioritization protocols based on remote sensing and economic cost modeling, and new tools. Outcomes include the implementation of use of new herbicides and biological control agents, improved control efficacy, lowered stakeholder costs, and the leveraging of expertise and funding focused on aquatic weed control for habitat restoration. Benefits include reduced floating aquatic weed coverage, conservation of water and wildlife natural resources, and protection of boating and other economic activities.

Key words: adaptive management, decision support tool, economic impact, integrated weed management, IWM, remote sensing, weed phenology.

INTRODUCTION

Invasive aquatic vegetation incurs billions of dollars in direct control costs and lost economic opportunity (Pimentel 2005, Getsinger et al. 2014, Hussner et al. 2017, Madsen and Wersal 2017) while causing significant environmental damage and adversely affecting water use. Examples includes floating aquatic vegetation (FAV) species such as water hyacinth (*Eichhornia crassipes* (Mart.) Solms) (Villamagna and Murphy 2010), submersed aquatic vegetation (SAV) species such as Brazilian waterweed (*Egeria densa* Planch) (Yarrow et al. 2009, Durand et al. 2016), and riparian weeds such as giant reed or arundo (*Arundo donax* L.) (Cal-IPC 2020). FAV and SAV alter water velocity, water dissolved oxygen, temperature and sedimentation, displace native plants, and reduce habitat for native fish and other animal species (Chamier et al. 2012, Getsinger et al. 2014). Major impacts on human activities include impairment of water conveyance and damage to infrastructure, loss of access to water for boating, commercial shipping and transportation, and increases in disease-vectoring organisms such as mosquitos (Villamagna and Murphy 2010, Getsinger et al. 2014, Yan et al. 2017). In complex estuary systems, the ecological and economic impacts of invasive weeds are compounded by human alterations of land composition (e.g., conversion of marsh to farmlands), water flow (e.g., channelization into canals) and water nutrient profiles, and invasions by nonnative species (Glibert et al 2011, Ustin et al. 2014, Lund 2016). Successful control of aquatic weeds in these ecosystems requires integration of financial and logistical support, in-depth knowledge of weed invasions and impacts, and a range of control tools (Getsinger et al. 2014, Madsen 2014, Ta et al. 2017) extending beyond the capacity of one agency or organization.

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Area-wide pest management (AWPM) emphasizes synchronization of established and new pest control strategies over large geographic areas where pests (typically insects or weeds) are causing environmental and economic damage (Smith 1998, Pimentel 2007, Schellhorn et al. 2015). Successful programs reduce pest populations and impacts while also reducing pesticide use through implementation of integrated adaptive management (Elliott et al. 2008, Smith and Sheley 2012), supported by applied research, assessment, and outreach. The U.S. Department of Agriculture, Agricultural Research Service (USDA–ARS) Areawide Pest Management (AWPM) Program has focused mostly on agricultural insect pests and human disease vectors (Meer et al. 2007, Vargas et al. 2007, Browne et al. 2013, USDA–ARS 2019). Successful areawide pest management requires the formation of collaborative networks as much as actual pest control. USDA and university scientists who have developed new and improved technologies communicate with natural resource management agencies and agricultural producers. Researchers and agencies work together to assess project implementation and control success, and to communicate results to scientific and resource agency communities and the general public. Four USDA–AWPM projects have focused on invasive weeds of noncrop areas: leafy spurge (*Euphorbia esula* L.) (Prosser et al. 2002), melaleuca (*Melaleuca quinquenervia* (Cav.) S.T. Blake) (Silvers et al. 2007), saltcedar (*Tamarix ramosissima* Ledeb.) (Carruthers et al. 2008), and grassland weeds in the arid Great Basin of the western United States. (Smith and Sheley 2012). In all four of these projects, end user (natural resource agency and landowner/producer) adoption of new integrated management tools and strategies was substantial, and weed populations were reduced, while also reducing herbicide use.

The Sacramento–San Joaquin River Delta of northern California (hereafter called "the Delta") is the largest freshwater estuary on the west coast of North America. The Delta is an unusual "inverted" inland river delta because its freshwater outflow westward is constrained by the Montezuma Hills to the north and Mt. Diablo to the south (Figure 1). It encompasses 340,200 ha (840,000 acres) land and water area, consisting of marshes and wetlands, sloughs and two rivers that have mostly been channelized with levees (Laćan and Resh 2016), and islands consisting of drained marshes converted to peat soil farmland (DSC 2019a). This paper provides an overview of the USDA–ARS Delta Region Areawide Aquatic Weed Project (DRAAWP) and introduces the collaborative implementation, assessment, and research team whose work is covered in this Special Issue of the Journal of Aquatic Plant Management. Funded from 2014 to 2018, the DRAAWP was the first USDA–ARS AWPM project to focus on invasive aquatic plants. The project's existence signifies the importance of the freshwater estuary of the San Francisco Bay–Delta as a critical water resource nexus (Laćan and Resh 2016, Wiens et al. 2017, DSC 2019a) supporting the most agriculturally productive state in the United States; the natural habitat that the estuary provides for hundreds of plant and animals, including listed (threatened or endangered) species (DSC 2019a); and the status of the estuary as one of the world's most-invaded ecosystems (Cohen and Carlton 1998).

CRITICAL ATTRIBUTES OF THE SACRAMENTO–SAN JOAQUIN DELTA

The Delta's water surface of 27,540 ha (68,000 acres) forms the confluence of California's two largest rivers, the Sacramento, with a drainage basin of 72,132 km^2 (7.1 million ha), and the San Joaquin with a basin of 83,409 km^2 (4.1 million ha) (Laćan and Resh 2016) (Figure 1), and it drains 40% of the area of California. Among the many factors motivating the development of the DRAAWP are the following characteristics of the Delta related to natural resource and species protection, agriculture and other human use (all taken from the Delta Plan (DSC 2013a,b,c, DSC 2018, DSC 2019a, DSC 2020a) and other sources as noted):

- Water from the Delta, moving through sloughs and pumped south into canal systems (the federally operated Central Valley Project and the California State Water Project) irrigates over 190,000 ha of farmland in the Delta and 1.2 million ha in the Central Valley of California, producing tree nuts, grapes, citrus, vegetables, and other crops valued at over $30 billion per year.
- Water from the Delta also provides part or all of the drinking water for 27 million people.
- The mixing of highly variable freshwater inflows and contrasting saltwater from San Francisco Bay (Hutton et al. 2019) has allowed highly productive and diverse natural ecosystems to develop in the Delta. Although highly modified since the mid-1800s, the Delta continues to provide ecological services. It, along with neighboring Suisun Marsh, supports over 750 plant and animal species, of which about one-third are considered as rare or special status, including 56 listed (threatened or endangered) species.
- The Delta hosts 12 million person-visits per year for recreational boating, supporting a boating industry worth $300 million. Many others visit for hunting, agritourism, and other pursuits.
- Commercial shipping on the Delta through the deepwater ports of Stockton and West Sacramento moves over 4.5 tonnes (5 million tons) of agricultural goods, construction materials, metals, and other cargo per year, reducing truck traffic in the congested region.
- The Delta is home to 12 mostly small communities founded originally for river shipping and agriculture, and over 800,000 people when the largest cities on its edges, Sacramento and Stockton, are included. With the inclusion of the San Francisco Bay Area, the regional population exceeds 10 million.
- The Delta faces several major environmental crises caused by human alteration of habitat, continued intensive use of water and soil resources, and sea level rise related to climate change. These include: land subsidence (Deverel et al 2015, Bekaert et al. 2019, Hemes et al. 2019) and resulting risk of levee failure and flooding; reduced availability of water

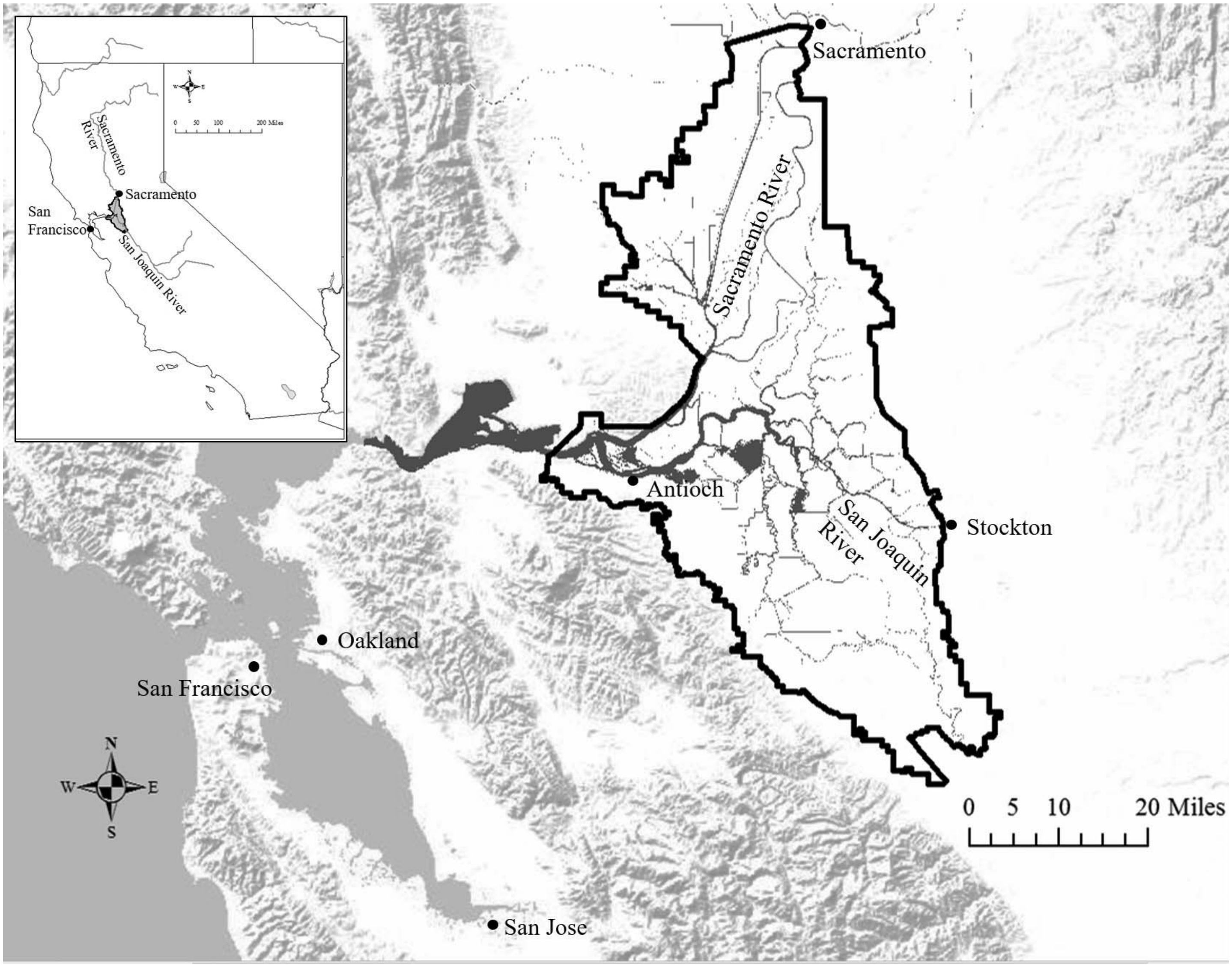

Figure 1. The Sacramento–San Joaquin Delta of northern California. Inset on left shows location in northern California. Larger map shows legal Delta boundary as dark line (DSC 2019a), the confluence of the Sacramento and San Joaquin Rivers, and the complex network of sloughs and canals, mostly built over the past 150 yr to drain land for farming. Map made by J. Miskella, USDA–ARS, Davis, CA using ArcGIS 10.6[1].

(Lund 2016); reduced water quality (e.g. Bachand et al. 2019); and species invasions by vertebrates (fish, snakes, and rodents), invertebrates (clams, crustaceans, and arthropods), and plants (both terrestrial and aquatic). At least 185 nonnative species are present.

THE DELTA AS A NEXUS OF NATURAL RESOURCE PLANNING, REGULATION, RESEARCH, AND RESTORATION

For several decades, the Delta has been at the center of intensive policy debates, legislation, and research, because of the importance of its water resources both as habitat for threatened and endangered fish, and as a source of agricultural and drinking water (DSC 2019a; DPC 2020). The U.S. federal–CA–state Bay–Delta Interagency Ecological Program (IEP) has provided a collaborative framework for project planning, funding, and execution with an emphasis on distribution, abundance, and ecology of state- and/or Federally-listed fish species, and monitoring of water quality and related ecological factors (Erickson et al 2014, Baxter et al. 2016, Culberson et al. 2019). The "coequal goals" contained in the California Water Code (Section 85054)—to provide a more reliable water supply for California, and to protect, enhance, and restore Delta ecosystems—have guided recent additional efforts (Alexander et al. 2018, Sloop et al. 2018, DSC 2019a). Success will be evaluated in the context of climate change and resulting stress on Delta water resources (Cloern et al. 2011, Knowles et al. 2018, Beller et al. 2019). There are dozens of federal, state, regional, county, and local government agencies/departments, and interagency groups with responsibility for management of water and/or land resources in part or all of the Delta (SFEP 2015, Robinson et al. 2017, Culberson et al 2019, DSC 2019a). In 2009, California enacted the Delta Reform Act, creating two new state agencies, the Delta Stewardship Council (DSC) (DSC 2019a), and the Sacramento–San Joaquin Delta Conservancy (SSJDC) (SSJDC 2019). The DSC produced the Delta Plan (DSC 2013a,b,c, DSC 2018, DSC 2019a,b, DSC 2020a,b) to implement coordinated adaptive management of Delta natural resources and ecosystems. Among its legally binding policies is a requirement for all projects in the Delta undertaken or funded by any public agency, including all techniques of aquatic weed control, to be certified for consistency with the Delta Plan. The SSJDC was responsible for facilitating regulatory review of a $50 billion Bay–Delta Conservation Plan, replaced in 2015 with two initiatives, Delta Eco Restore (EcoRestore 2019), and the California Water Fix. Delta Eco Restore, run by the California Natural Resources Agency (which oversees the Department of Water Resources [CDWR] and the Department of Fish and Wildlife [CDFW], among others) has completed over 3,000 ha in aquatic, wetland, and riparian restoration projects (EcoRestore 2018). The California Water Fix was withdrawn in May 2019 and CDWR is now working on a smaller-scale water diversion plan (CDWR 2020, DPC 2020). Various summaries and plans intended to coordinate and provide direction for resource protection, environmental restoration, and research activities have been issued, including the Delta Science Plan (DSC 2019b), the California Water Plan (CDWR 2018), State of the Estuary 2015 (SFEP 2015); Delta Landscapes Strategy (SFEI 2016, Robinson et al. 2017); the Delta Conservation Framework (Sloop et al. 2018); and restoration planning reviews (Laćan and Resh 2016, Milligan and Kraus-Polk 2017, Beller et al. 2019). In March 2019, the Sacramento–San Joaquin Delta National Heritage Area was established by the U.S. Congress to protect the Delta's unique historical, cultural and environmental attributes, and a management plan is in progress (DPC 2020).

NATURAL RESOURCES AND INVASIVE AQUATIC PLANTS IN THE DELTA

The USDA–ARS supported the DRAAWP because of its potential to improve and integrate FAV and SAV control to enhance protection of water resources, and to facilitate conservation of native species. Additional background information on these topics will thus place the DRAAWP in context.

Delta water is vital for Central Valley agriculture and for densely populated and growing urban centers in the Bay Area, Central Valley, and southern California, supplying around 25% of the water required (DSC 2018). Supply occurs through two pumping and conveyance systems, the Federal Central Valley Project (CVP) and the California State Water Project (SWP), both drawing water from Clifton Court Forebay in the southern Delta. The water allocation system is based on regulations requiring two to five times (more in wet years) the volume of supplied or "exported" water to be allowed to pass through the Delta end empty into San Francisco Bay, to prevent salinity intrusion and preserve wetland and aquatic habitat (DSC 2018, Hutton et al. 2019). The system is vulnerable to California's highly variable annual rainfall patterns, in particular prolonged droughts (Moyle et al. 2013, Lund 2016, Moyle 2016, DSC 2018, Beller et al. 2019). Conflicts among competing human and ecosystem uses for Delta water are most pressing in dry years (Alexander et al. 2018). When planning for the DRAAWP began in 2012 to 2014, the Delta was in the midst of one of the worst droughts in state history, lasting through 2016 (CDWR 2018). Emergency barriers were built to prevent saltwater intrusion, and supply to Central Valley irrigation districts were curtailed or ceased. Water availability has improved since 2016, but the current pattern of use of Delta water resources is still unsustainable in terms of the coequal goals (DSC 2018).

Native fishes, including but not limited to endangered Delta smelt (*Hypomesus transpacificus* McAllister) and endangered Sacramento River winter-run Chinook salmon [*Oncorhynchus tshawytsha* (Walbaum)] depend on a complex set of ecological parameters to survive, and they spawn and grow (Delta smelt) (Moyle et al. 2016) or pass through (salmonids) (NMFS 2016a) the Delta. Key survival factors include water flow and turbidity levels, prey availability (Hamilton and Murphy 2018, Johnston et al. 2018, Moyle et al. 2018), and the presence of nonnative fishes that either prey directly on the listed fishes or compete for shared prey (Merz et al. 2016, Mahardja et al. 2017, Michel et al. 2018, Young et al. 2018, Sabal et al. 2019, Weinersmith et al. 2019). As the DRAAWP project began, Delta smelt survey trawls indicated populations at near-extinction low levels (Moyle et al. 2016; CDFW 2018), and a sharp decline in Chinook salmon populations had occurred (NMFS 2016b).

There are at least 19 aquatic plant species in the Delta, and half are nonnative (Anderson 1990, Santos et al. 2009, Santos et al. 2012, Boyer and Sutula 2015). Until recently, the most widespread invasive FAV was water hyacinth, occupying at least 800 ha (2,000 acres) annually (Boyer and Sutula 2015). Over the past 10 to 15 yr, floating/rooted water primrose (*Ludwigia* spp. and hybrids) (Grewell et al. 2016, Reddy et al. 2021) populations have increased rapidly (Ta et al. 2017, Khanna et al. 2018) and are overtopping water hyacinth in some Delta sloughs. Other Delta FAV invaders include floating spongeplant [*Limnobium laevigatum* (Humb. & Bonpl. ex Willd.) Heine], and, just detected in the Delta in 2017, floating/rooted alligatorweed [*Alternanthera philoxeroides* (Mart.) Griseb.]. The most troublesome SAV in the Delta for many years has been Brazilian waterweed or egeria (*Egeria densa*), occupying at least 1,900 ha (7,600 acres) annually (Boyer and Sutula 2015). Other nonnative, invasive SAVs include curlyleaf pondweed (*Potamogeton crispus* L.), Eurasian watermilfoil (*Myriophyllum spicatum* L.), and Carolina fanwort (*Cabomba caroliniana* A. Gray). Increases in nonnative FAV coverage in the Delta have occurred since 2000 (Santos et al. 2009, Khanna et al. 2012, Khanna et al. 2018), and populations of Brazilian waterweed and other nonnative SAV in the Delta have also increased (Durand et al. 2016, Santos et al. 2016; Conrad et al. 2020). Intensive management of SAV in Franks Tract has led to an increase in native plant diversity and in abundance of native Richardson's pondweed [*Potamogeton richardsonii* (Benn.)

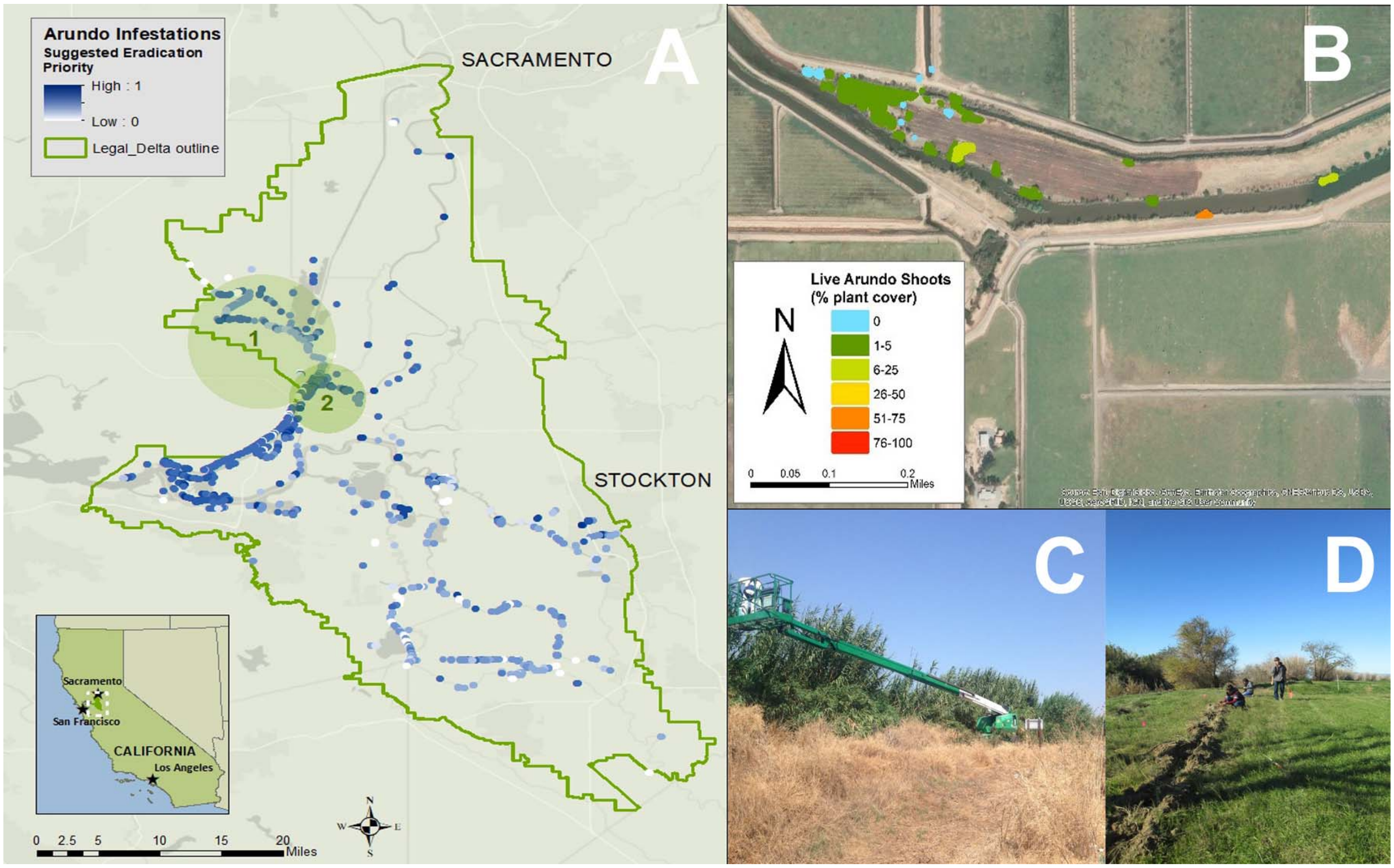

Figure 2. Arundo infestations and control in the Sacramento–San Joaquin Delta**.** (A) Infestation and control prioritization map made by the Sacramento San Joaquin Delta Conservancy (SSJDC) based on aerial imagery to detect arundo populations, which were then prioritized for control and restoration. Delta legal boundary as defined in DSC (2019a). Circle #1 denotes the Cache Slough Complex in the northwestern Delta where herbicides were applied in 2016. Circle #2 denotes the Brannan Island area of the western Delta where similar herbicide control was integrated with biological control in unsprayed plots in 2017. (B) Remote sensing map of part of the Cache Slough are shows reduction of arundo to 10% or less cover in 2018. (C) Herbicide application with a boom lift to facilitate access in Circle #2 area, September 2017. (D) Restoration replanting activities in the Cache Slough area, with dead arundo in background. All images provided by SSJDC.

Rydb.] (Caudill et al. 2019). However, Delta-wide FAV and SAV invasions were causing major crises—ongoing or expected—for water conveyance, recreational boating, ecosystem protection, and public health in the Delta when the DRAAWP was initiated in 2014 (DSC 2013a,b,c, Ta et al. 2017, DSC 2018, DSC 2019a, SSJDC 2019; DSC 2020a). For example, SAV can provide habitat for nonnative predatory fish such as largemouth bass (*Micropterus salmoides* Lacépède) (Conrad et al. 2016), and reduce water column turbidity (Hestir et al. 2016). Delta smelt prefer unstructured, turbid, pelagic habitat (Rasmussen et al. 2020); thus excessive SAV can create unsuitable habitat and increase predation. Additional information on Delta FAV and SAV populations is provided in this issue by Bubenheim et al. (2021) and Caudill et al. (2021).

Emergent weeds are also a major concern in the Delta (e.g., Portier et al. 2019), although mainly outside the scope of the DRAAWP. However, arundo or giant reed, which grows on the edges of Delta sloughs and coves, was included in the project because of its known negative effects on water quantity and availability, fire and flood control, and native species in California (Cal-IPC 2020) and elsewhere (Watts and Moore 2011, Jain et al. 2015). The SSJDC, a DRAAWP partner, mapped Delta arundo populations using aerial imagery (Figure 2). Infestations were prioritized by SSJDC for integrated management followed by restoration.

FORMATION OF THE USDA–ARS DELTA REGION AREAWIDE AQUATIC WEED PROJECT

Prior to the DRAAWP, the USDA–ARS was performing research on growth (Spencer 2005) and integrated management (Anderson 2003) of FAV and SAV in the Delta, and also ecology and control of arundo (Spencer et al. 2013). Beginning in the early 2000s, the USDA–ARS, supported by scientists in the Invasive Species and Pollinator Health Research Unit, assumed the "Federal Nexus" role for the Biological Assessments (BAs) required from the (then) California Department of Boating and Waterways. The BAs were submitted to the U.S. Fish and Wildlife Service (USFWS) and the National Oceanic and Atmospheric Administration (NOAA)–National Marine Fisheries Service (NMFS), for regulatory review in compliance with the Endangered Species Act. FAV and SAV management in the Delta was regulated and carried out largely in isolation from the complex resource protection processes described earlier. Authorizations (Letters of Concurrence or Biological Opinions) from USFWS and NMFS were granted annually and separately for each aquatic weed species. Regulatory backlog led to delays in spring/summer treatment start dates, allowing FAV and SAV populations to build. Treatment plans were annual and reactive to crisis conditions. Both then and today, only one agency, the (now) Division of Boating and Waterways within the California Department of Parks and Recreation (CDBW), has the required authorizations, permits, funding, and expertise to treat invasive FAV and SAV in the Delta with herbicides and large-scale mechanical control.

Local, state, and federal policymakers as well as state natural resource agencies were inundated with complaints in 2011 to 2012. In addition to issues around water quantity and quality, native fish species, and habitat suitability, stakeholders expressed concerns for the Delta's recreational boating industry and the loss of local cultural attributes and commerce. Blockage of commercial shipping channels in Stockton and West Sacramento was an additional concern. Finally, mosquito control is important in the Delta, in particular those species that vector West Nile Virus (Foss et al. 2015). Laboratory studies have shown that FAV can alter habitat suitability (Turnipseed et al. 2018, Portilla et al. 2021), and local mosquito vector control districts had spent substantial time and money physically removing FAV from mosquito-infested backwaters.

The USDA–ARS was asked to provide critical input on the knowledge components needed to develop a more effective aquatic weed management program. One of us (Carruthers) was asked to gather scientific expertise for policymakers, which led to several meetings, followed by a proposal to and funding from the USDA–ARS AWPM in 2014. Resources were allocated to the National Aeronautics and Space Administration (NASA)–Ames Research Center; three Departments at the University of California–Davis (Plant Sciences; Entomology, and Nematology; Agricultural and Natural Resource Economic–Agricultural Issues Center); CDBW; and two mosquito control districts (in Contra Costa and San Joaquin County in the western, central, and southern Delta). Funding was retained by ARS to help build a collaborative framework and increase ARS research on new control tools. The project was funded annually on the basis of progress from 2015 through 2018 (total of $4.45M in funding across 5 yr). Two cooperators were added to the project in 2015: the SSJDC, and one additional department at UC–Davis (Land, Air and Water Resources). In 2016, the project website (UCANR 2019) was first released, and the project acquired its official name: USDA–ARS Delta Region Areawide Aquatic Weed Project, or DRAAWP.

ORGANIZATION OF THE DRAAWP

The USDA–ARS DRAAWP effort was organized into five objectives: 1) develop models of Delta weed growth based on water nutrients (including runoff from watersheds), temperature, and field phenology, and use to inform spatial and phenological targeting and prioritization of weed populations for control; 2) collect remote sensing data and integrate with aquatic weed growth models to provide decision support for control; 3) conduct assessments of the efficacy of control using new and improved techniques, and assess effects on nontarget organisms such as aquatic invertebrates and mosquitos; 4) carry out integrated adaptive management of aquatic weeds using models and new tools developed in objectives 1, 2 and 3, including chemical, physical, and biological control methods, with a long-term goal to reduce herbicide use; and 5) compare project outcomes with biological and economic indicators of success, and report progress and success. These objectives were carried out in the context of four Project Components required of all USDA–ARS-funded AWPMs: Implementation, Assessment, Research, and Technology Transfer and Education. Table 1 shows a breakdown of DRAAWP activities covered in this Special Issue by objective and AWPM component.

The Implementation Component was the largest in the DRAAWP, because it refers to actual control of the invasive FAVs, SAVs, and arundo. However, implementation also included measurement and modeling of factors critical for aquatic weed growth, including nitrogen runoff from watersheds (Chen et al. 2017, Wang et al. 2019, Wang et al. 2021); air and water temperature in mesocosms (Bubenheim et al. 2019, Madsen and Morgan 2021); and weed phenological information from Delta field studies (Madsen et al. 2021b) to help build weed growth models. A bioeconomic model focused on water hyacinth was developed to take into account the cost and effectiveness of various control tools in relation to the growth model (Jetter et al. 2021). Satellite-based remote sensing algorithms to detect FAV and bioacoustic protocols to detect SAV were essential for planning and implementation of adaptive control by CDBW (Bubenheim et al. 2021, Caudill et al. 2021). Implementation included operational use of herbicides new to the Delta (Caudill et al. 2021, Madsen and Kyser 2020). Mechanical control with land- and water-based equipment was used strategically (with spatial and temporal targeting) instead of reactively (Caudill et al. 2021). Biological control tools for water hyacinth and arundo were integrated into control operations (Pratt et al. 2021). The two largest Delta mosquito vector control districts (in Contra Costa and San Joaquin Counties) used information about FAV population sizes and CDBW control schedules to inform their operations. Implementation also included restoration. The DRAAWP led to retrospective analysis of the benefits of long-term weed treatment (Caudill et al. 2019), supporting decision making, and enhancing overall understanding of aquatic weed dynamics.

Arundo occupying patches across 1.5 ha on slough banks in the Cache Slough Complex in the northwestern Delta (Figure 2) was treated as spot treatments in 2016 with a mix of 3% glyphosate isopropylamine salt[2] (1.6% ai in spray mixture) and 1% imazapyr[3] (0.3% ai in spray mixture) with 1% nonionic surfactant[4] to 90% leaf coverage using a boom-mounted or backpack sprayer, followed by spot retreatment and planting of native plants in 2017 and 2018. A second project began at sites on Brannan and Andrus Islands in the western Delta along the Sacramento

Table 1. Activities associated with the Delta Region Areawide Aquatic Weed Project (DRAAWP) categorized by areawide project objectives and components, and associated papers in this Special Issue.

Activity	DRAAWP Objective(s)[1]	DRAAWP Component[2] Implementation	Assessment	Research	Technology Transfer	Reference in This Special Issue
Measure field phenology	1			X		Madsen et al. (b)
Measure response to nutrients and temperature	1			X		see also Bubenheim et al. 2019, Madsen and Morgan,
Model inputs of nutrients from watersheds	1			X		Wang et al.
Track movement of water hyacinth	1			X		Miskella and Madsen
Develop bioeconomic model of weed growth	1, 5	X	X	X	X	Jetter et al.
Detect floating aquatic weeds remotely	2, 3, 4	X	X	X	X.	Bubenheim et al., Caudill et al.
Determine effect of control on dissolved oxygen	3	X	X	X	X	Miskella et al.
Determine effect of weeds on mosquitos and aquatic invertebrates	3	X	X	X	X	Portilla et al., see also Turnipseed et al. 2018, Donley et al. 2019
Detect submersed aquatic weeds bioacoustically	3, 4	X	X		X	Caudill et al.
Test new chemical control tools in field and mesocosms	3	X	X	X	X	Kyser et al., Madsen et al. (a), see also Madsen and Kyser 2020
Evaluate biocontrol baseline and test new agents	3	X	X	X	X	Pratt et al, Reddy et al., see also Hopper et al. 2017, Reddy et al. 2019
Conduct chemical and mechanical control of floating aquatic weeds	4	X				Caudill et al.
Conduct chemical control of submersed aquatic weeds	4	X				Caudill et al.
Conduct biological control of water hyacinth and arundo	4	X				This paper, Pratt et al.
Communicate with stakeholders	5	X		X	X	This paper
Stakeholder control cost survey	5		X		X	Jetter et al.

[1]Brief Objectives of the DRAAWP are as follows: 1) Develop models of weed growth based on water nutrients (including runoff from watersheds), temperature, and field phenology, and use to inform spatial and phenological targeting and prioritization of weed populations for control. 2) Collect remote sensing data and integrate with aquatic weed growth models to provide decision support for control. 3) Assess efficacy of aquatic weed control with existing and new tools, and effects on mosquitos and other nontarget organisms. 4) Carry out integrated adaptive management of aquatic weeds informed by models and tools developed in Objectives 1, 2, and 3. 5) Compare project outcomes with biological and economic indicators of success.

[2]The DRAAWP is divided into four Components. **Implementation:** Aquatic weed control using any method (chemical, mechanical, physical, biological) carried out in an informed, integrated weed management framework, with appropriate use of new tools developed by the project or elsewhere, supported by modeling and remote sensing, and contributing to restoration. **Assessment:** Evaluation of the efficacy of aquatic weed control using water-based and remote sensing tools, impacts on other species and their habitat parameters, and determination of economic and ecological impacts/benefits**. Research:** Development and testing of new models, aquatic weed detection methods, and control tools. **Technology Transfer:** Activities to communicate new control technologies and assessments of their efficacy to end users for implementation, collaborate with natural resource agencies and stakeholders to develop new projects, and inform policymakers and the public.

River in 2017, involving similar spot herbicide application on 0.5 ha of arundo integrated with biocontrol in 2 m by 2 m plots (Pratt et al. 2021).

The Assessment Component examined the ability of the DRAAWP to improve FAV and SAV control, through several efficacy evaluation methods. Remote sensing measured intra- and interannual changes in FAV surface coverage (Bubenheim et al. 2021). Photomonitoring was used to illustrate efficacy of FAV control, and efficacy against SAV was measured with bioacoustic mapping (Caudill et al. 2021). Biological control agents were assessed for successful establishment (Pratt et al. 2021). Assessment went beyond counting dead or damaged aquatic weeds and estimating their acreage. This component included critical evaluations of the impact of control operations on habitat quality, including dissolved oxygen (Miskella et al. 2021) and invertebrate prey communities (Donley et al. 2019). A cost assessment (Jetter et al. 2021) was conducted to track control costs over 6 yr incurred by non-CDBW stakeholders who carried out hand-removal or mechanical control in limited areas such as marinas, ports, and water conveyance intakes.

USDA–ARS AWPMs such as the DRAAWP are not research grants, but the project included a Research Component to support implementation. Studies of FAV (Bubenheim et al. 2019, Madsen and Morgan 2021) and SAV growth response to air and water temperature in mesocosms informed the determination of vulnerable points in weed growth cycles under Delta conditions. Studies of field phenology (Madsen et al. 2021b) provided additional insight. Studies on the importance of water and wind and effect of patch size on movement of GPS-tagged water hyacinth patches revealed the complexity of movement in the Delta (Miskella and Madsen 2021). The efficacy of new chemical control tools was tested in mesocosms and field plots (Kyser et al. 2021, Madsen and Kyser 2020, Madsen et al. 2021a). Studies on field limitations of current water hyacinth biocontrol agents (Hopper et al. 2017) were followed by discovery of a new agent biotype potentially more suitable for temperate Delta conditions (Reddy et al. 2019). Studies were initiated to develop new biocontrol agents for other FAVs (Pratt et al. 2021, Reddy et al. 2021). Research also included studies of the effects of new (to the Delta) herbicides and tank mixes on Delta smelt and their prey (Jin et al. 2018). The effect of healthy aquatic weeds in mesocosms on mosquito populations was also studied (Turnipseed et al. 2018, Portilla et al. 2021).

TABLE 2. EXAMPLES OF LINKAGES BETWEEN ACTIVITIES OF THE USDA–ARS DELTA REGION AREAWIDE AQUATIC WEED PROJECT (DRAAWP). RECOMMENDATIONS IN THE DELTA PLAN OR OTHER KEY DELTA WATER RESOURCE PLANNING INITIATIVES AND THE REALIZED OR EXPECTED PRODUCTS OR OUTCOMES OF THE DRAAWP.

DRAAWP Activities[1]	Delta Plan Recommendation or Other Project Goal[2]	DRAAWP Realized or Expected Products or Outcomes
Integrated control; communicate with stakeholders	DP R11: Provide new and protect existing recreation opportunities	Improved availability of water for recreation
Integrated control; detect weeds remotely; assess effects on other species	ER R2: Prioritize and implement projects that restore Delta habitat	Habitat available for restoration and monitoring
Develop new control tools; integrated control	ER R7: Prioritize and implement actions to control nonnative invasive species	Improved operational control
Integrated control	WQ R1: Protect beneficial uses	Protection of conveyance through pumping stations at lower cost
Determine effect of control on dissolved oxygen	WQ R8: Completion of regulatory processes, research, and monitoring for water quality improvements	Knowledge of effect of FAV on dissolved oxygen
Integrated control; assess effects on other species	Delta Conservation Framework Goal D, Strategy D5: Early detection, rapid response, and control of invasive species	Habitat made available for restoration and monitoring
Integrated control; assess effects on other species	Delta EcoRestore Fish Restoration Program Projects	Improved habitat for listed fish species
Integrated control; assess effects on other species	Delta Smelt Resiliency Strategy Actions: Control aquatic weeds	Improved habitat for listed fish species

[1]Activities summarized from Table 1.
[2]Recommendations (R) from the Delta Plan (DP). DP R11 from Chapter 5 (DSC 2013b). Environmental restoration (ER) recommendations from Chapter 4 (DSC 2013a). Water quality (WQ) recommendations from Chapter 6 (DSC 2013c). Delta Conservation Framework goals from Sloop et al. (2018). Delta EcoRestore projects from Eco Restore (2019). Delta Smelt Resiliency Strategy actions from Rasmussen et al. (2020).

The Technology Transfer and Education Component of the DRAAWP was essential for project success. The DRAAWP was unusual among USDA–ARS AWPM projects in that there was no large group of stakeholders (e.g., marinas, local irrigation districts) both permitted and equipped to control the targeted pests (weeds) across the Delta. However, tech transfer did extend well beyond the one permitted agency, CDBW. Every 2 to 4 mo, the funded cooperators held technical update meetings to keep each other informed. DRAAWP organized annual "Stakeholder Update" meetings attended by local, regional, state, and federal natural resource agencies, marina owners, boating organizations, and homeowners. DRAAWP scientists presented at meetings and hearings called by legislators and agencies. In response to feedback from these meetings, since March 2015, CDBW has been providing lists of FAV and SAV sites to be treated through weekly public email distributions during the herbicide treatment season (March 1 to November 30), along with a list of herbicide tools. More detailed information is provided in Annual Treatment Notices published at the start of each year (e.g. for FAV, see CDBW 2020), including maps of the treatment area along with a color scheme showing the site treatment prioritization system developed in part through the DRAAWP (Caudill et al. 2021). The DRAAWP website (UCANR 2019) provides detailed information on the work of each cooperating agency, and the associated DRAAWP blog features the latest developments. DRAAWP researchers coordinated five scientific symposia at regional and national conferences and gave presentations at many other meetings.

Outreach originating from the DRAAWP led to many additional opportunities for collaboration. Elected officials and policymakers from the U.S. House of Representatives, California State Assembly, California State Senate, Contra Costa Board of Supervisors, the DSC–Delta Plan Interagency Implementation Committee (DPIIC), the SSJDC Interagency Invasive Species Committee, the Metropolitan Water District, which supplies drinking water to 19 million people in southern California, and a local homeowner group called over 20 "oversight hearings" or update meetings involving participation from USDA–ARS, CDBW, NASA, and other agencies to describe the adaptive integrated management plan and the results/impacts. One outcome of these meetings was the formation of an Aquatic Vegetation–Project Work Team (AV–PWT) within the IEP (Conrad et al. 2020). DRAAWP activities led to a new awareness of the connection between invasive FAV and SAV and habitat degradation, contributing to new FAV/SAV mapping, control, and habitat restoration projects (Eco Restore 2018, Khanna et al. 2019; Conrad et al. 2020, Rasmussen et al. 2020). DRAAWP scientists have served on advisory and review panels—for example on a report on links between FAV and SAV and Delta water nutrients commissioned by the Central Valley Regional Water Quality Control Board (Boyer and Sutula 2015) and as part of the AV-PWT (Conrad et al. 2020). Another key outcome of DRAAWP outreach can be found in the Delta Plan Performance Measures (DSC 2020b), which include metrics for aquatic invasive weed control, including a baseline of 2013, a 50% reduction in peak annual weed coverage by 2030, and a target annual treatment area of 2,025 ha of FAV and 1,013 ha of SAV by that time. DRAAWP scientists provided critical input for these measures.

DRAAWP PROJECT IMPACTS

Impacts of the DRAAWP can be categorized as operational, environmental/ecological, economic, and collaborative. Table 2 shows examples of realized or expected project products and outcomes in relation to relevant Delta Plan recommendations and goals from other initiatives (DSC 2013a,b,c, DSC 2018, Sloop et al.

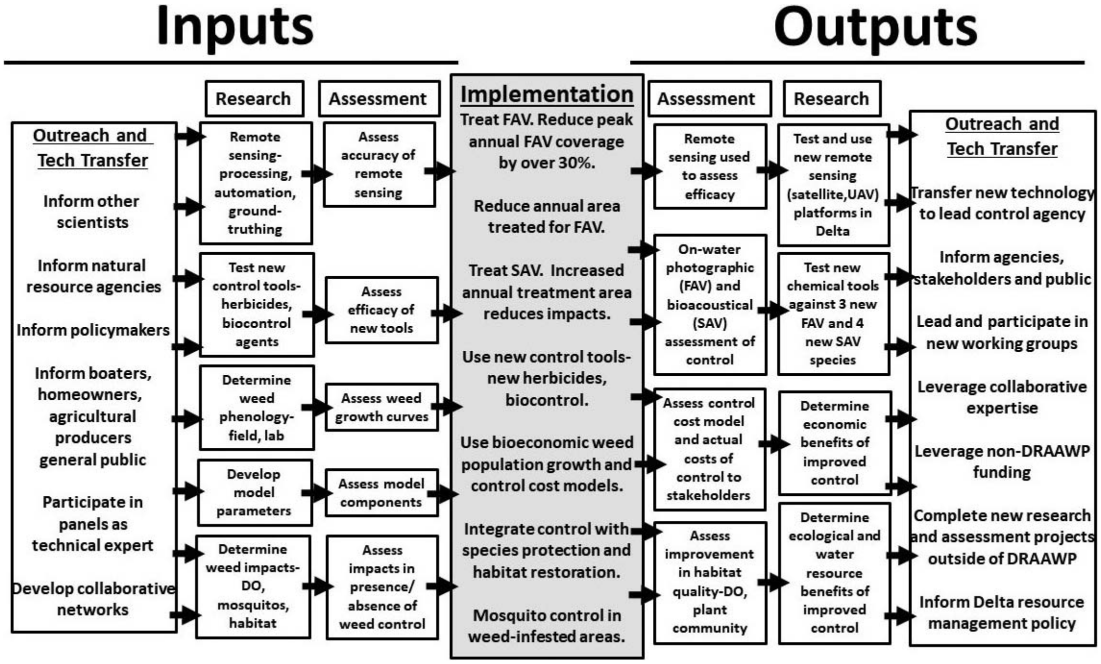

Figure 3. Flowchart illustrating relationships between the four Components of the Delta Region Areawide Aquatic Weed Project (DRAAWP). Combined activities under the Outreach and Technology Transfer Component informed priorities under the Research Component. Each research activity provided data for an activity under the Assessment Component. Assessment activities as a group guided the largest project Component, Implementation, focused on operational Delta-wide aquatic weed control activities. Both successes and problems in project implementation drove new activities under the Research Component, and project outputs were examined under the Assessment Component, leading to new opportunities for Outreach and Technology Transfer, including the development and execution of major new projects. DO, dissolved oxygen; FAV, floating aquatic vegetation; SAV, submersed aquatic vegetation.

2018, DSC 2019a, EcoRestore 2019, DSC 2020a, Rasmussen et al. 2020). Figure 3 illustrates the successful integration of DRAAWP Components to support key outcomes arising from project implementation, and examples of follow-on research and assessment activities. Key impacts to date include the following:

Operational impacts

DRAAWP operational benefits support the coequal goal of the Delta Plan to provide a reliable water supply for California (DSC 2019a) (Table 2). Analyses by NASA using Landsat-based remote sensing (Bubenheim et al. 2021) determined that peak annual FAV coverage in the Delta decreased over 30% between 2014 to 2018, while the number of FAV acres treated by DBW per year declined over 50% between 2015 and 2018 (Caudill et al. 2021), contributing to the aims of the DRAAWP AWPM to reduce both FAV populations and herbicide use. In 2016, the timing of the annual peak shifted from September and October to July. Lower amounts of FAV were thus floating toward key channels and pumps during the most critical season (fall and early winter) for water conveyance to the Central Valley south of the Delta. The U.S. Bureau of Reclamation, the Port of Stockton, and private marinas reported major decreases in mechanical or hand-removal control costs between 2015 and 2018 (Jetter et al. 2021). Two wet winters in 2017 and 2018, and subsequent increased flows, likely contributed to reductions in FAV. However, the impact of the new adaptive integrated management program was evident before the drought ended in 2017, and continues to play a major role. SAV area treated per year with herbicides has increased almost two-fold since 2016 (Caudill et al. 2021), and increases in SAV coverage remain major threats to Delta habitats (Conrad et al. 2020). The DRAAWP has tested new control tools against FAVs (Kyser et al. 2021, Madsen and Kyser 2020, Madsen et al. 2021a), and some are now in operational use. At least one new herbicide tested for control of Brazilian waterweed (Madsen et al. 2021a) shows promise for possible future use against SAVs as part of habitat restoration projects (Conrad et al. 2020).

In 2018 and 2019, DBW obtained new 5-yr Biological Opinions from USFWS and NMFS for integrated FAV and SAV control. These authorizations cover eight herbicides (previously four) for FAV control; six herbicides (previously two) for SAV control; and (for the first time), tank mixes. New chemical tools can be used in lower amounts with equal or greater efficacy than the older tools. For the first time, biological control, currently available only against water hyacinth among Delta aquatic weeds (Pratt et al. 2021), is included. Also, as a result of DRAAWP research and expertise, the current authorizations cover four species of invasive FAV (water hyacinth, spongeplant, water primrose, and alligatorweed) and five species of SAV [nonnative Brazilian waterweed, curlyleaf pondweed, Eurasian watermilfoil, Carolina fanwort, and native coontail (*Ceratophyllum demersum* L.)] (Caudill et al. 2021), well beyond the original project scope of water hyacinth, egeria, and arundo.

Environmental and ecological impacts

Improved water availability and quality resulting from improved FAV and SAV control is expected to increase habitat suitability. The DRAAWP thus supports the coequal goal of protecting and enhancing Delta habitats (DSC 2019a) (Table 2). For example, water dissolved oxygen (DO) is higher under open water than under dense mats of water hyacinth, and is not substantially reduced after herbicide application (Miskella et al. 2021). Treatment of FAV thus helps meet minimum DO standards for Delta smelt survival (DSC 2013a,c). New modeling of pesticide and nutrient loading into the Delta from soils in its watersheds informs water quality assessments (Wang et al. 2021), and new knowledge of FAV and SAV temperature growth responses (Madsen and Morgan 2021) and field phenology (Madsen et al. 2021b) is pinpointing when both the weeds and invaded habitats are most vulnerable. Reduced herbicide loading for control of FAV is reducing the risk of nontarget effects. Sustained control of aquatic weeds is increasing native aquatic plant diversity (Caudill et al. 2019), and successful control of arundo is facilitating restoration (Figure 2). Improved FAV control, and better knowledge of interactions between mosquitos and aquatic weeds (healthy and postherbicide) (Portilla et al. 2021) is improving targeting of insecticide applications for vector control.

Economic impacts

Annual costs to stakeholders other than DBW for local mechanical or physical weed control in marinas, water intakes, and ports have decreased since 2016 (Jetter et al. 2021). Major recreational boating events, sometimes cancelled prior to the DRAAWP, have been held since 2016, with hundreds of thousands of $US revenue generated for local businesses and communities. DRAAWP funds have been leveraged over 10-fold with non-Federal funds due to recent (since 2015) commitments by state agencies for increased FAV and SAV control for aquatic and wetland habitat restoration in the Delta (Conrad et al. 2020, Rasmussen et al. 2020).

Collaborative impacts

The three USDA–ARS DRAAWP investigators (Moran, Madsen, Pratt) coordinated or co-coordinated five symposia at scientific meetings, including the DSC-sponsored Science Symposium on Invasive Aquatic Vegetation in Davis, CA in 2015, and the 2016 and 2018 Bay-Delta Science Conferences, Sacramento, CA. To our knowledge, these were the first three symposia focused entirely on aquatic weed biology, ecology, and control in the Delta, and all were well-attended by Delta natural resource management agencies. Additional symposia were held at the 2018 Western Aquatic Plant Management Society in Reno, NV, and the 2019 APMS meeting in San Diego, CA. Over 95 total technical presentations were made at these five and many other technical conferences. Over 25 peer-reviewed publications have been produced (including 14 in this Special Issue) with more forthcoming, and the research of three Ph.D. students was funded partially by the DRAAWP.

In addition to the symposia, the weekly email updates from DBW informed stakeholders, including many natural resource agency professionals, of FAV and SAV control operations and led to new dialogue. Four DRAAWP-organized Stakeholder Update meetings drew attendance of over 200 people from 18 Federal, state, regional, and local natural resource agencies and interest groups. DRAAWP-supported scientists and resource managers participated in 48 other meetings called by agencies, legislators, or local interest groups, with total attendance of over 1,300 people. The formation of the AV–PWT is a key indicator of the success of the DRAAWP to leverage expertise leading to leveraged funding and new weed control and restoration initiatives (Eco Restore 2019, Conrad et al. 2020, Rasmussen et al. 2020). The AV PWT has about 30 members, representing five DRAAWP-funded agencies and university researchers, as well as members from 10 other government agencies, and researchers from three other universities.

CONCLUSIONS

The 14 articles that follow in this Special Issue illustrate the breadth and depth of the expertise, accomplishments, and products of the DRAAWP. Through its collaborative network, the DRAAWP has reduced FAV coverage in the Delta and provided new tools for control of FAV and SAV. The key Delta-wide water resource benefits are increased water availability for agriculture, domestic use, recreational activities, and ecosystem protection. The key ecological benefit is improved habitat and species protection. Economic benefits include reduced control costs for water resource agencies and marinas, and protected recreational boating and shipping economies. The collaborative framework is continuing beyond the life of the project. Aquatic weed monitoring and control remains challenging in the complex Delta environment (Culberson et al. 2019, Conrad et al 2020, Rasmussen et al. 2020). New and innovative ideas and projects will be needed to continue to build the knowledge base to manage aquatic weed invasions to protect resources, ecosystems, and public health and well-being.

SOURCES OF MATERIALS

[1]Arc-GIS 10.6, Environmental Systems Research Institute, 380 New York Street, Redlands, CA 92373 USA

[2]Roundup Custom, Bayer Crop Sciences, 800 Lindbergh Blvd, St. Louis, MO 63167 USA

[3]Habitat, SePRO,11550 N Meridian St., Suite 600, Carmel, IN 46032 USA

[4]Competitor, Wilbur-Ellis, 345 California St., 27th Floor, San Francisco, CA 94104 USA

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