1. Contact Information: "Area-Wide Management of Aquatic Weeds in the Sacramento-San Joaquin Delta for Protection of Critical Water Resources in Farming Area, Wildlife Habitats, Recreational and Commercial Navigation Areas, and Water Conveyance Systems Important for California Agriculture and Human Health". Lead PI: Dr. Patrick J. Moran, Research Entomologist, USDA-ARS ISPHRU, 800 Buchanan St., Albany, CA 94710. Patrick.Moran@usda.gov

2. Final Progress: The Delta Region Areawide Aquatic Weed Project (DRAAWP) has concluded (no funding since FY18). Three cooperative agreements continued in FY20, including with the Sacramento-San Joaquin Delta Conservancy (SSJDC), UC-Davis Department of Plant Sciences (UC-PS) and UC-Berkeley-ESPM. Past cooperative agreements included the operational partner, the Division of Boating and Waterways-California Department of Parks and Recreation (DBW); University of California-Davis (Department of Entomology and Nematology (UC-Ent); Agricultural Issues Center (UC-AIC); and Department of Land, Air and Water Resources (UC-LAWR)). Other expired agreements included the Contra Costa Mosquito Vector Control District (CCMVCD), San Joaquin County MVCD (SJMVCD) and NASA-Ames Research Center (NASA). Progress in FY20 focused on completion of implementation and tech transfer.

Operational Outputs: In 2020, DBW has treated 653 acres of floating aquatic vegetation (FAV) including water hyacinth (WH), water primrose (WP), spongeplant (SP) and alligatorweed (Obj. 4), due to Covid. In 2019, 2,256 acres were treated, of which 34% involved imazamox, developed under DRAAWP (Obj. 3). As predicted in the FY15 proposal, total FAV acreage treated declined (by 49%) between 2015 and 2019 (Fig. 1) with no loss of efficacy, and evidence of decreased peak annual acreage (Fig. 2). DBW did not conduct mechanical control in 2020, compared to 6.5 acres in 2019. In 2020, DBW has treated 2,098 acres of submersed aquatic vegetation (SAV), including Brazilian waterweed (BW), curlyleaf pondweed (CLP), Eurasian watermilfoil, Carolina fanwort, and coontail (Obj. 4) (Fig. 1). In 2019, DBW treated 2,439 acres. A new, cheaper chemical tool, endothall (7% of 2019 operational acres) was first tested under DRAAWP (Obj. 3). Diquat was used (7% of acres in 2020) to control SAV, based on dialogue with regulatory agencies, that led to increased authorization for use. Biocontrol of WH in 2020 focused on seven sites (Obj. 4) (Fig. 3), and 306,450 planthoppers were released. 2020 surveys indicated establishment of dispersing populations of the arundo biocontrol wasp at two upstream watershed sites sites, with low populations at three Delta sites (Fig. 4). Reproductive females of the arundo armored scales were found at seven sites in 2019-2020, including two in the Delta. The wasp and scale were released at two new sites in the south Delta. The SSJDC completed integrated chemical and biocontrol of arundo at two Delta sites (2017, 2020) (Obj. 4) (Fig. 4). UC-AIC finished a bioeconomic model of FAV management (Obj. 1, 3). NASA and ARS provided a plant growth component. UC-AIC incorporated information on cost of herbicides, fuel, and labor. The model indicated that treating FAV early in the season (March or April) reduces costs by 50% (Obj 1, 4) compared to a June start. SWAT-based modeling of pesticide and nitrogen inputs (Obj. 1) (UCD-LAWR) suggested possible limitations on biocontrol and plant growth. Restoration (Obj. 4) of native vegetation in Frank's Tract was documented.

Assessment Outputs: In 2019-2020, NASA-Ames completed a transition in remote sensing technology transferred to DBW from Landsat to Sentinel (Obj. 2) (Fig. 2). Retrospective analysis using the Sentinel-2 Acolite algorithm suggested a 20% decline in FAV acreage generally from 2016 to 2017 (Fig. 2). The 32% decline in peak annual acreage reported in prior FYs was based on Landsat analysis (Fig. 2). With Acolite, Sentinel removes the 'noise associated with confusion of emergent vegetation with FAV (Fig 2). A control cost survey by UC-AIC, concluded in 2018 and summarized in 2019, found that costs for mechanical control and hand removal for non-DBW stakeholders decreased by 84 to 100% between 2015 and 2018 (Table 1).

Research Outputs: Experimental testing of eight new herbicides as well as tank mixes for FAV and SAV control (Obj. 3) (ARS, UC-PS); operational testing of three new herbicides (Obj. 4) (DBW, ARS, UC-PS); determination of field phenology of WH, ED, and CLP (Obj. 1) (ARS); determination that healthy FAV reduces dissolved oxygen more than the transient effect of decaying, treated FAV, increasing the imperative for treatment (Obj. 3) (ARS); determination, with GPS drogues, that WH plants move in response to tidal forces (Obj. 3) (ARS); development of new (species or accessions) biocontrol agents targeting WH, WP, and alligatorweed (Obj. 4) (ARS); determination of water and air temperature and nutrient factors that determine growth of WH, SP, WP and ED (Obj 1, 3) (ARS, NASA); and determination of effects of WH and ED on mosquitos (Obj 4) (ARS, UC-Ent, SJMVCD, CCMVCD). 26 journal papers were produced (Appendix 1), including a Special Issue of the J. Aquatic Plant Manage., with 14 papers, edited by J. Madsen (ARS), to be published in early 2021.

Tech Transfer and Education Component Outputs: The DRAAWP won two awards in 2020. The national Aquatic Plant Management Society awarded its 2020 Outstanding Technical Contributor Award to the DRAAWP Executive Committee (Moran, Madsen, Pratt-ARS; Hard-DBW; Bubenheim-NASA). The Federal Laboratory Consortium (FLC), Far West Division, bestowed its 2020 Outstanding Agency Partnership Award on the four Federal Co-PIs. The DRAAWP produced its third Ph.D. graduate (UC-Ent) in 2020, and provided research systems for two postdocs and several other graduate students throughout. The DRAAWP organized 4 stakeholder update meetings, with media coverage in some cases. DRAAWP developed a webpage (https://ucanr.edu/sites/DRAAWP/) and blog. DRAAWP organized five symposia at regional and national conferences, including the first-ever (2015-2018, three total) focused specifically on aquatic weeds in the Delta. There were 51 presentations at DRAAWP-organized events and 44 other scientific presentations. DRAAWP presented technical information to natural resource agencies and policymakers on 55 occasions. Tech transfer led to expansion of approaches from the original two aquatic weeds (and arundo) in the FY15 proposal to a total of ten weeds (4 FAVs, 5 SAVs, and arundo). A new realization among 15 state and Federal natural resource agencies of connections between aquatic weeds and habitat quality led to the creation of new interagency groups: Delta Interagency Ecology Program, Invasive Aquatic Vegetation-Project Work Team (IEP IAV-PWT); and the Delta Interagency Invasive Species Committee (DIISC).

Key Partnerships: CA Dept. of Water Resources (CDWR); CA Dept. of Fish and Wildlife (CDFW); IEP-IAV-PWT;

Areas for Improvement: Not applicable. **Corrections:** Not applicable.

3. Anticipated Benefits: **Operational:** Two new herbicide tools were operationalized. FAV annual herbicide acres were reduced by 49% with no loss in efficacy. FAV and SAV were targeted strategically and adaptively with appropriate remote sensing, photomonitoring and bioacoustic assessment techniques. Three biocontrol agents released. **Ecological**. Restoration of native submersed and wetland plant communities, and a new initiative to control FAV and SAV to restore fish habitat. **Economic**: Reduced control costs and improved economic opportunities.

4. Additional Funds Leveraged: DBW received \$3.9M in new appropriated CA state funding in 2015, and \$2.8M annually from 2016. CDWR granted \$32M and CDFW \$1.8M to DBW for FAV and SAV control. The non-Federal funded agencies on the DRAAWP contributed \$1,036,589 in matching funds. Total leveraging: \$49.9M. The USDA-ARS Areawide investment was \$4.45M.

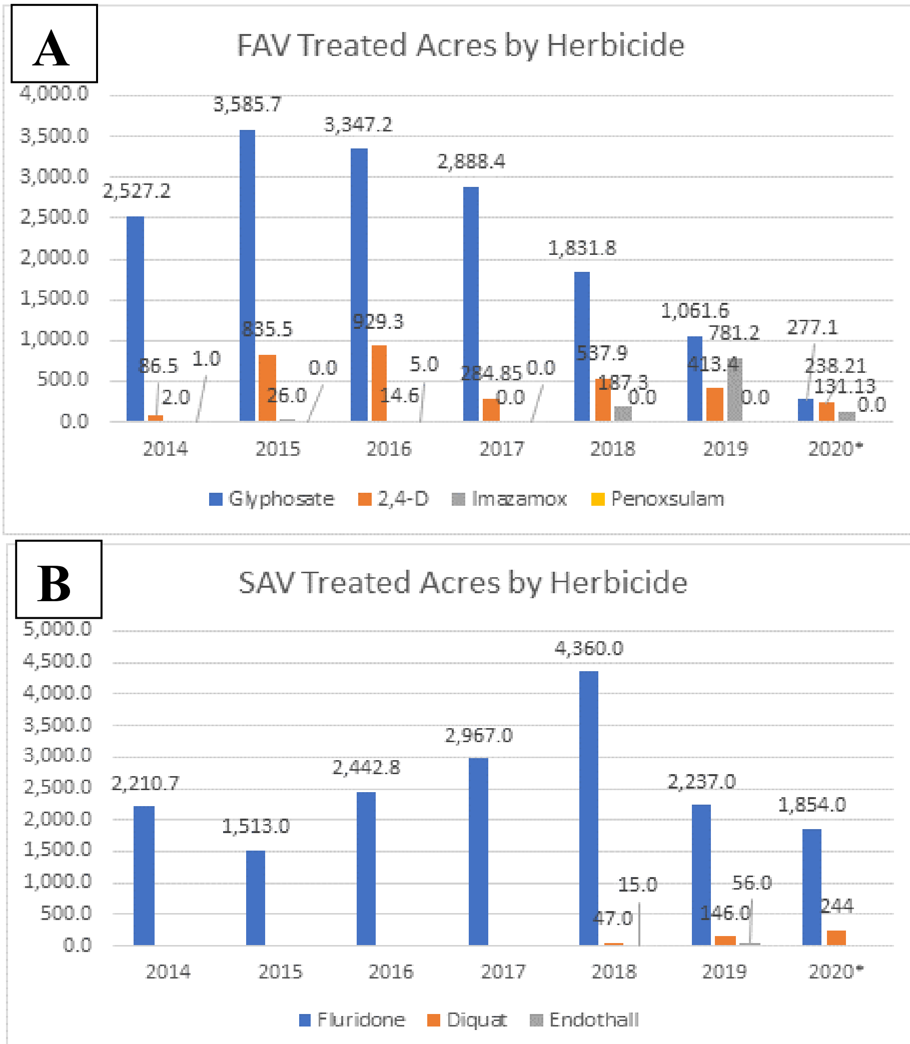

Figure 1. A, Acres of floating aquatic vegetation (FAV) and, **B,** submersed aquatic vegetation (SAV) treated by DBW during the years of the DRAAWP (2014-2019) and 2020. As predicted in the FY15 proposal, total FAV acres treated declined (by 49% in 2019 compared to 2015; 2020 values reflect Covid-related logistical constraints) with no loss of efficacy, as evidenced by steady or decreased annual FAV acreage (see Fig. 2). A herbicide new to the Delta, imazamox, tested by ARS and UCD-PS, was implemented and represented 34% of operational applications against FAV in 2019. Testing of diquat led to a 3.3-fold increase in regulatory maximum acres permitted, and endothall was operationally tested against SAV.

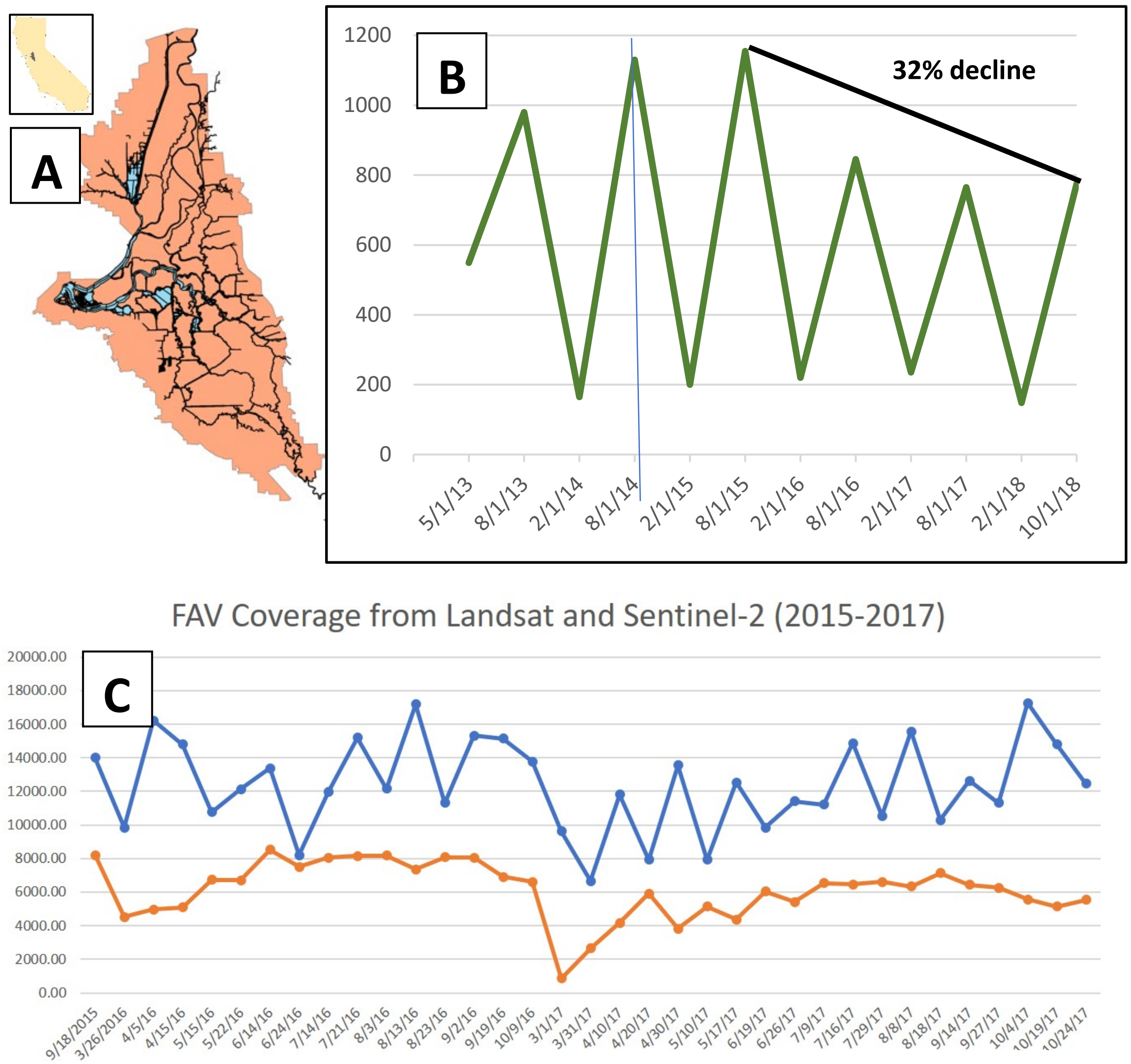

Figure 2. **A**, Map of Delta. **B**, Prior analysis of peak annual acreage using the Water Hyacinth Mapper Tool developed by NASA suggested a 32% decrease in peak annual acreage. **C**, In 2019-2020, NASA switched from Landsat to the Sentinel satellite tool, which has 3-fold greater resolution, more color bands, and provides images every 5 days instead of 14 days. Using the 'Acolite' (Sentinel-2) algorithm in 2020, NASA was able to overcome a problem of Sentinel encountered in 2019- overestimation of FAV cover due to intermixing of emergent reeds and FAV (**D**), and Acolite (orange line) provided lower acreage estimates compared to Landsat (blue line) (**C**). Based on Sentinel-2 images and Acolite processing, but not the Landsat-based WH Mapper Tool, FAV Delta wide estimates tended to be about 20% lower in 2017 than 2016 (**C**).

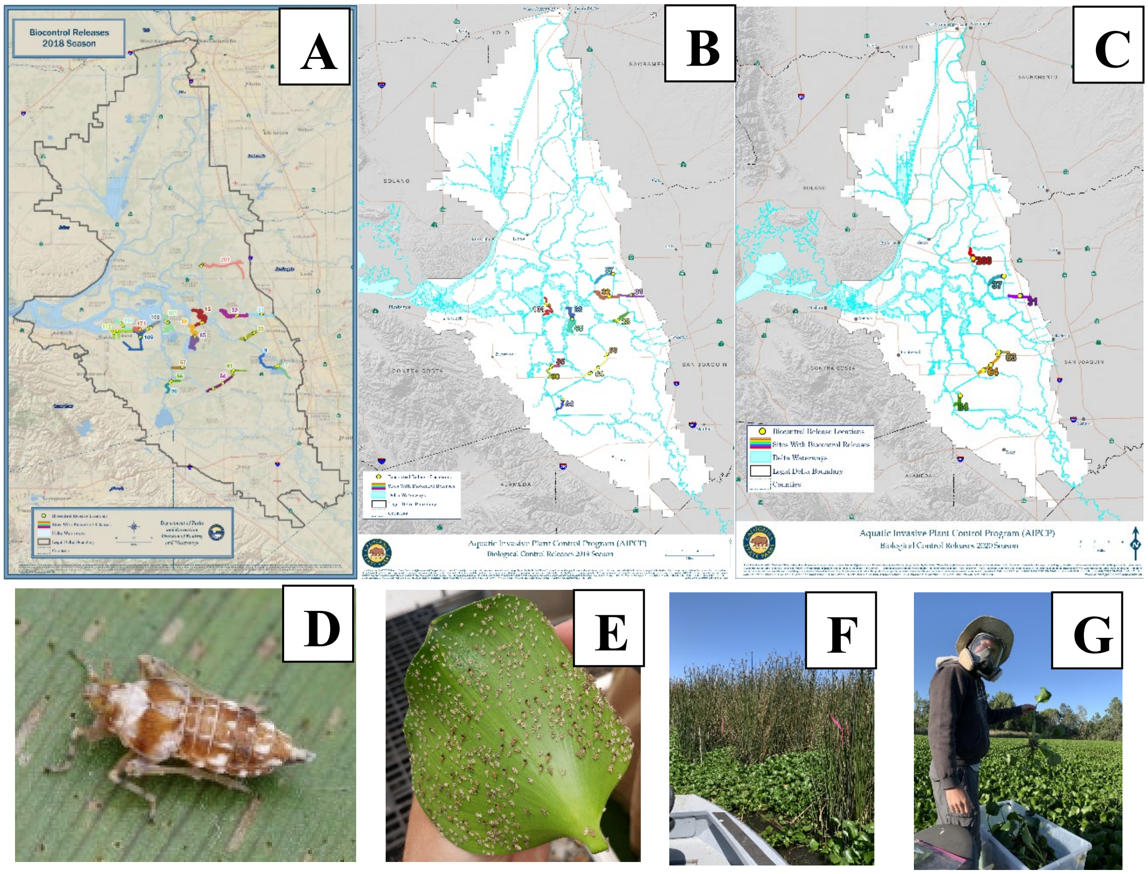

Figure 3. Biological control releases on water hyacinth by ARS and DBW. Maps of the Delta showing the 18 release sites in 2018 (**A**), 11 release sites in 2019 (**B**) and 7 release sites in 2020 (**C**). In 2018, 65000 adults and nymphs of the planthopper *Megamelus scutellaris* (**D**), which forms dense colonies in greenhouse cultures (**E**) were released at sites in the navigable Delta (**F**). 121,000 planthoppers were released in 2019, and 306,000 in 2020 (**G**). From 2018 to 2019, overwintering was observed at only two of 18 sites, and from 2019 to 2020, at only three of 11 sites. The objective in 2020 was to 'inundate' the seven sites, containing stable water hyacinth populations in backwater 'nursery' areas, by doing multiple planthopper releases in July-August. Planthoppers were present at 6 of the 7 sites in October 2020. A late fall survey and and overwintering studies in 2021 will determine establishment.

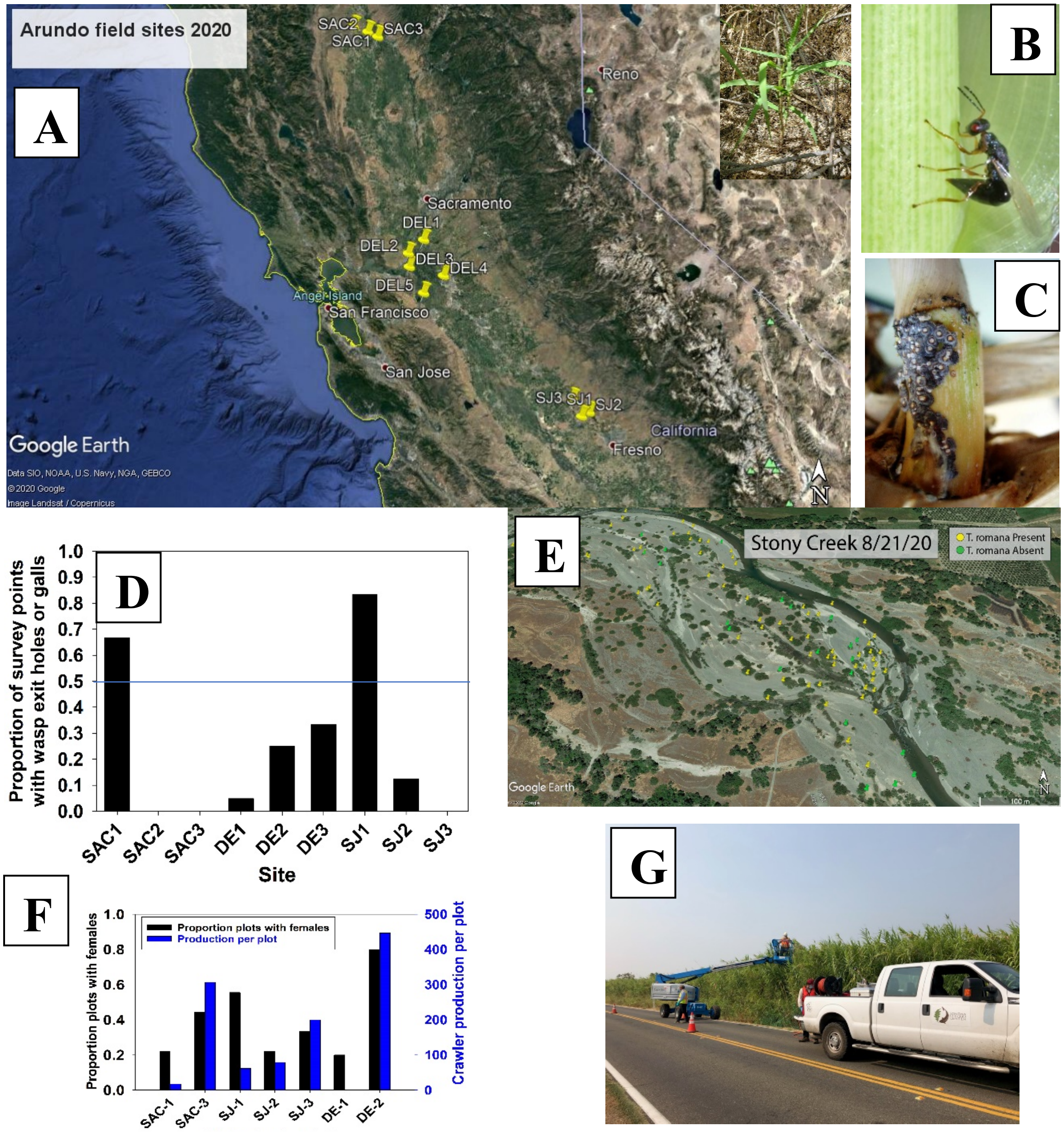

Figure 4. Biological control of arundo by ARS with integrated control by SSJDC in the Delta. Map in **A** shows five Delta and 11 total sites. The arundo wasp *Tetramesa romana* (**B**) was released at three Delta and nine total sites in 2017. Inset in A shows galled stem. Surveys in 2019 indicated establishment (> 50% of survey points with wasp galls) at 2 non-Delta sites and low populations in the Delta (**D**). At one site in the Sacramento River watershed, 75% of 99 survey points had galls (yellow points) in 2020 (**E**), and at the other site, in the San Joaquin Valley, 89%. The arundo armored scale (**C**) was released at seven sites. Surveys in 2019 indicated adult females at all sites (**F**). In 2019-2020, both biocontrol agents were released at two new sites in the southern Delta (DEL 4, 5 in **A**). The SSJDC conducted herbicide (glyphosate and imazapyr) application outside of biocontrol plots at the DEL 1 site in August 2020 (**G**).

Table 1. Control cost survey conducted by Dr. Karen Jetter at UC-AIC beginning before the DRAAWP project in 2013, and continuing through 2018. Control costs (hand removal and mechanical control) decreased to $0 (100% decrease) for several key local stakeholders, including the Port of Stockton and county weed control districts. Control costs for the U.S. Bureau of Reclamation, which controls one of the two massive pumping station in the south Delta that convey water to the Central Valley, decreased by 92% from a 2015 peak by 2018. Control costs for local marinas decreased by 84% during this period. Control costs for the California Department of Water Resources, which operates the other south Delta pumping facility, increased from 0 to $1.8M late in the DRAAWP project as a result of a Delta Smelt Resiliency Strategy initiative to control FAV and SAV and restore habitat for this endangered fish in the northern Delta. The main operational partner, DBW, received a fund increase of $3.9M in 2015 from its state appropriations that was leveraged in part by the DRAAWP. This decreased to $2.8M in subsequent years. The additional funds were used to buy new boats and hire more personnel to implement operational adaptive integrated management of FAV and SAV.

Agency	2013	2014	2015	2016	2017	2018
Public Agencies						
CA. Div of Boating and Waterways (DBW)	7,124	6,804	13,718	12,545	12,545	12,545
U.S. Bureau of Reclamation	343	833	921	658	215	71
CA Dept. of Water Resources	0	821	0	0	484[1]	1,795[1]
San Joaquin Weed Control Dist.	223	73	37	155	11	19
Contra Costa Weed Control Dist.	74	0	0	0	0	0
Port of Stockton	51	306	168	0	0	0
Private Entities						
Local marinas	169	576	943	310	21	150
TOTAL-other than DBW	**691**	**2,033**	**2,069**	**1,123**	**731**	**2,035**
TOTAL-including DBW	**7,815**	**8,837**	**15,787**	**13,668**	**13,276**	**14,580**

[1]Targeted funding initiative-Delta Smelt Resiliency Strategy in the northern Delta

Appendix 1. Publications arising from cooperative research, assessment and implementation under the DRAAWP.

Chen H, Luo Y, Potter C, Moran PJ, Grieneisen ML, Zhang M**.** 2017. Modeling pesticide diuron loading from the San Joaquin watershed into the Sacramento-San Joaquin Delta using SWAT. Water Res. 121:374-385.

Hopper JV, Pratt PD, McCue KF, Pitcairn MJ, Moran PJ, Madsen JD. 2017. Spatial and temporal variation of biological control agents associated with *Eichhornia crassipes* in the Sacramento-San Joaquin River Delta, California. Biol. Cont. 111:13-22.

Ta J, Anderson LWJ, Christman MA, Khanna S, Kratville D, Madsen JD, Moran PJ, Viers JH. 2017. Invasive aquatic vegetation management in the Sacramento-San Joaquin River Delta: status and recommendations. San Francisco Estuary and Wat. Sci 15:4, Art. 5: 1-19. doi: 10.15447/sfews.2017v15iss4art5

Jetter J, Nes, K. 2018. The cost to manage invasive aquatic weeds in the California Bay-Delta. University of California Giannini Foundation of Agricultural Economics 21(3): 9-11. https://s.giannini.ucop.edu/uploads/giannini_public/6a/a3/6aa3af10-27ab-4898-9a6d-335c39d7e8d9/v21n3.pdf

SF Estuary Partnership 2018. A stream of science take-aways: The September 11-13 2018 Bay-Delta Science Conference. Pearls online newsletter, San Francisco Estuary Partnership. https://www.sfestuary.org/estuary-news-pearls-bay-delta-science-2018/ (includes coverage of remote sensing and biocontrol)

Reddy AM, Pratt PD, Hopper JV, Cibils-Stewart X, Cabrera Walsh G, McKay F. 2018. Variation in cool temperature performance between populations of *Neochetina eichhorniae* (Coleoptera: Curculionidae) and implications for the biological control of water hyacinth, *Eichhornia crassipes*, in a temperate climate. Biological Control 128: 85-93.

Turnipseed RK, Moran PJ, Allan SA. 2018. Behavioral response of gravid *Culex quinquefasciatus*, *Aedes aegypti*, and *Anopheles quadrimaculatus* (Diptera: Culicidae) to aquatic macrophyte volatiles. J. Vector Ecology 43(2): 252-261.

Caudill J, Jones AR, Anderson L, Madsen JD, Gilbert P. Shuler S, and Heilman, MA. 2019. Aquatic plant community restoration following the long-term management of invasive *Egeria densa* with fluridone treatments. Mange. of Biol. Inv 10: 473-485.

Miskella J, Madsen JD. 2019. The effect of temperature on waterhyacinth stem base regrowth. Journal of Aquatic Plant Management 57:99-100.

Wang R, Chen H, Luo Y, Moran PJ, Grieneisen M, Zhang M. 2019. Nitrate runoff contributing from the agriculturally- intensive San Joaquin River watershed to Bay-Delta in California. Sustainability 11, art. 2845. doi: 10.3390/su11102845.

Wang R., Chen H, Luo Y, Yen H, Arnold JG, Bubenheim D, Moran P Zhang M. 2019. Modeling pesticide fate and transport at watershed scale using the Soil & Water Assessment Tool: General applications and mitigation. In: Goh KS, Gan J, Young DF, LuoY, Eds., Pesticides in Surface Water: Monitoring, Modeling, Risk Assessment, and Management. ACS Symposium Series Vol. 1308, Chapter 20, pp. 391-419. American Chemical Society, Washington, DC.

Madsen JD, Kyser GB. 2020. Herbicides for management of waterhyacinth in the Sacramento–San Joaquin River Delta, California. J. Aquat. Plant Manage. 58:98-104.

Portilla, MA, Lawler, SP. 2020. Herbicide treatment alters the effects of water hyacinth on larval mosquito abundance. J. Vector Ecol. 45:69-81.

Bubenheim DL, Genovese V, Madsen JD, Hard E. 2021. Remote sensing and mapping of floating aquatic vegetation in the Sacramento-San Joaquin River Delta. In press, J. Aquat. Plant Manage.

Caudill J, Madsen JD, Pratt W. 2021. Operational aquatic weed management in the California Sacramento–San Joaquin River Delta. In press, J. Aquat. Plant Manage.

Jetter KM, Madsen JD, Bubenheim DL, Dung, J. 2021. Bioeconomic modeling of floating aquatic weeds in the Sacramento – San Joaquin River Delta. In press, J. Aquat. Plant Manage.

Kyser G, Madsen JD, Miskella J, O'Brien J. 2021. New herbicides and tank mixes for control of waterhyacinth in the Sacramento/San Joaquin Delta. J. Aquat. Plant Manage.

Madsen JD, Morgan CM. 2021. Water temperature controls the growth of waterhyacinth and South American spongeplant. In press, J. Aquat. Plant Manage.

Madsen JD, Morgan CM, Miskella J. 2021. Seasonal growth and phenology of waterhyacinth, curlyleaf pondweed and Brazilian egeria in the Sacramento – San Joaquin River Delta. In press, J. Aquat. Plant Manage.

Madsen JD, Morgan C, Miskella JJ, Kyser GB, Gilbert P, O'Brien J, Getsinger KD. 2021. Brazilian egeria herbicide mesocosm and field trials for managing the Sacramento - San Joaquin River Delta. In press, J. Aquat. Plant Manage.

Miskella JJ, Madsen JD. 2021. Mapping waterhyacinth drift and dispersal in the Sacramento-San Joaquin Delta using GPS trackers. In press, J. Aquat. Plant Manage.

Miskella JJ, Madsen JD, Llaban A, Hard, E. 2021. Dissolved oxygen under water hyacinth following herbicide application. In press, J. Aquat. Plant Manage.

Moran PJ, Madsen JD, Pratt PD, Bubenheim DL, Hard E, Jabusch T, Carruthers RI. 2021. An overview of the Delta Region Areawide Aquatic Weed Project for improved control of invasive aquatic weeds in the Sacramento-San Joaquin Delta. In press, J. Aquatic Plant Manage.

Portilla MA, Moran PJ, Lawler, SP. 2021. Invasive aquatic weeds influence larval mosquito abundance. In press, J. Aquatic Plant Manage.

Pratt PD, Moran PJ, Pitcairn MJ, Reddy A, O'Brien J. 2021. Biological control of invasive plants in California's Delta: Past, present, and future. In press, J. Aquatic Plant Manage.

Reddy AM, Pratt PD, Grewell BJ, Harms NE, Cabrera Walsh G, Hernandez C, Falthauser A, Cibils-Stewart, X. 2021. Biological control of invasive water primroses, *Ludwigia* spp., in the United States: a feasibility assessment. In press, J. Aquat. Plant Manage.

Wang R, Chen H, Bubenheim DL, Moran PJ, Zhang M. 2021. Modeling nitrogen runoff from Sacramento and San Joaquin River Basins to Bay Delta Estuary: Current status and ecological implications. J. Aquatic Plant Manage. In press, J. Aquatic Plant Manage.

Portilla, MA, Lawler, SP. Non-anopheline mosquitoes and invasive plants: a review. In review, J Amer. Mosq. Cont. Assoc.