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RESEARCH

Invasive Aquatic Vegetation Management in the Sacramento–San Joaquin River Delta: Status and Recommendations

Jenny Ta*[,1], Lars W. J. Anderson[2], Mairgareth A. Christman[3], Shruti Khanna[4], David Kratville[5], John D. Madsen[6], Patrick J. Moran[6], and Joshua H. Viers[7]

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* Corresponding author: *jenta@ucdavis.edu*

1 School of Engineering, University of California, Merced
Merced, CA 95343 USA

2 Waterweed Solutions
Point Reyes Station, CA 94937 USA

3 Delta Science Program, Delta Stewardship Council
Sacramento, CA 95814 USA

4 University of California, Davis
Davis, CA 95616 USA

5 Integrated Pest Control Branch
California Department of Food and Agriculture
Sacramento, CA 95832 USA

6 Exotic and Invasive Weed Research Unit,
U.S. Department of Agriculture–Agricultural Research Service and
Department of Plant Sciences, University of California, Davis
Davis, CA 95616 USA

7 Department of Civil and Environmental Engineering,
University of California, Merced
Merced, CA 95343 USA

ABSTRACT

Widespread growth of invasive aquatic vegetation is a major stressor to the Sacramento–San Joaquin River Delta, a region of significant recreational, economic, and ecological importance. Total invaded area in the Delta is increasing, with the risk of new invasions a continual threat. However, invasive aquatic vegetation in the Delta remains an elusive ecosystem management challenge despite decades of directed scientific research and prioritized policy recognition. In this paper, we summarize the current state of knowledge of the history, status, and potential future directions for coordinated research, management actions, and policy, based on topics discussed at the symposium held on invasive aquatic vegetation on September 15, 2015. Remote sensing technology; mechanical, chemical, and biological control; as well as community science networks have all been shown to be effective management tools, but overall effectiveness has been hindered by complex regulatory structure, the lack of a consistent monitoring program, regulations that restrict treatments in space and time, and funding cuts. In addition, new management options depend on continued research and development of new active ingredients for chemical control as well as testing of biological control agents. The ongoing development and implementation of new strategies for adaptive, integrated management of aquatic weeds—using currently-available management tools, new knowledge derived from remote sensing and plant growth models, and an area-wide, ecosystem-based approach—is showing promise to achieve improved management outcomes and enhance protection of the Delta's water resources.

KEY WORDS

Aquatic vegetation, invasive species, invasive species management, ecosystem engineers, remote sensing, biological control, Sacramento–San Joaquin River Delta

INTRODUCTION

The confluence of the Sacramento and San Joaquin rivers in northern California serves as a vital crossing point for water conveyances and shipping channels, and as habitat for numerous aquatic species and waterfowl along the Pacific Flyway. From early construction of levied islands, to the export of water to central and southern parts of the state, to alterations in the natural flow of tributaries, more than a century of human alteration has dramatically changed the Delta (Whipple et al. 2012). Among the more recent critical changes is the proliferation of invasive aquatic vegetation. The San Francisco Estuary, including the Sacramento–San Joaquin River Delta, is known to be the primary gateway for biological invasion in the western United States, and has been described as one of the most invaded estuaries in the world (Cohen and Carlton 1998). If not successfully managed, invasive aquatic macrophytes are one of the potential dynamic drivers that could upend Delta recovery. Because of the ecological and economic significance of the Delta, it is imperative that we strive to understand the effects of invasive aquatic vegetation and take appropriate management action to mitigate these effects.

The Delta Interagency Invasive Species Coordination Team (DIISC), an interagency working group made up of representatives from agencies involved in detecting, preventing, and managing invasive species and invaded habitats in the Sacramento-San Joaquin Delta, is working to improve collaboration, coordination, and communication for invasive species management issues. Members of this collaborative process have identified the following key topics regarding invasive aquatic vegetation.

- Environmental drivers of infestations
- Understanding of spatial dynamics by mapping tools
- Regulatory and governance hurdles
- Risk assessment
- Options for control
- Lessons from other regions such as Florida

These topics were the focus of a day-long invasive aquatic weed symposium at the University of California, Davis was held on September 15, 2015, with the goal of summarizing current understanding of these issues identified by agency leaders and developing recommendations on next steps for aquatic weed management in the Delta (DSC 2015). The symposium focused primarily on four taxa: hydrilla (*Hydrilla verticillata*), Brazilian waterweed (*Egeria densa*), water hyacinth (*Eichhornia crassipes*), and water primrose (*Ludwigia* spp.). Participants of the symposium included representatives from the Delta Science Program, U.S. Department of Agriculture (USDA) Agricultural Research Service, California Department of Fish and Wildlife, California Department of Food and Agriculture, National Aeronautics and Space Administration, University of California–Davis, Smithsonian Environmental Research Center, Florida Fish and Wildlife Conservation Commission, Anaerobe Systems, and the U.S. Army Engineer Research and Development Center. Presentation videos have been made available online by the Delta Stewardship Council (Delta Stewardship Council 2015). This article summarizes the current status of the key topics symposium organizers identified.

AQUATIC MACROPHYTES OVERVIEW

Environmental Drivers

Aquatic vegetation or macrophytes, including emergent, floating, or submersed forms, grow in the littoral zone of water bodies. Generally, emergent macrophytes are found in shallow areas, with submersed plants in deeper water, and free-floating plants throughout the water surface. Floating and emergent plants have unlimited water, unimpeded access to light, and an atmospheric source of carbon dioxide. In contrast, submersed plants are subject to much lower levels of light and carbon dioxide. Water clarity and the maximum depth of light penetration typically drive submersed plant distribution and abundance.

In the Delta, both water depth and high turbidity have been correlated with distribution of submersed vegetation, particularly *Egeria densa* (Durand et al. 2016). Water velocity is also an important environmental factor. Floating aquatic macrophytes grow in slower- moving water compared to submersed aquatic macrophytes, which grow in slightly swifter water flows and tend to grow more rapidly in flowing water. The twice-daily tidal flows in the Delta thus provide ideal conditions for rapid growth of submersed aquatic plants. Rooted aquatic macrophytes obtain their nutrients mainly from sediment but can utilize nutrients in the open water as well. High levels of nutrients, particularly nitrogen and phosphorus, have been suggested as facilitating the recent expansion of aquatic vegetation in the Delta, but very little evidence exists to conclusively determine the role of nutrients in driving this growth (Boyer and Sutula 2015; Dahm et al. 2016).

Major Aquatic Macrophytes in Sacramento–San Joaquin Delta

Table 1 lists the major aquatic macrophytes observed in the Delta. This section summarizes information on four taxa: hydrilla (*Hydrilla verticillata*), Brazilian waterweed (*Egeria densa*), water hyacinth (*Eichhornia crassipes*), and water primrose (*Ludwigia* spp.) (Figure 1), with a few additional key species such as giant reed (*Arundo donax*) and Eurasian watermilfoil (*Myriophyllum spicatum*). Of these species, all occur in California, but only hydrilla is not currently found in the Delta.

Hydrilla is a non-native submersed aquatic macrophyte that can fill the water column up to 20 feet in depth. It comes in monoecious and dioecious forms, and can be identified by five heavily

Figure 1 Four invasive aquatic macrophytes, clockwise from upper left: *Eichhornia crassipes* (Photo credit: Wouter Hagens, public domain); *Ludwigia peploides* (Gabriel Bell, public domain); *Egeria densa* (Photo credit: Lara Gudmundsdottir, CC BY-SA 4.0); *Hydrilla verticillata* (Photo credit: Andrew Benassi, public domain).

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Table 1 Common floating and submersed aquatic macrophytes found in the Delta (modified from Boyer and Sutula 2015)

Species (common name)	Invasive?	Type
Egeria densa (Brazilian waterweed)	invasive	submersed
Myriophyllum aquaticum (Parrot feather)	invasive	submersed/emergent
Myriophyllum spicatum (Eurasian watermilfoil)	invasive	submersed
Potamogeton crispus (curlyleaf pondweed)	invasive	submersed
Cabomba caroliniana (Carolina fanwort)	invasive	submersed
Stuckenia pectinata (sago pondweed)	native	submersed
Ceratophyllum demersum (coontail)	native	submersed
Potamogeton nodosus (American pondweed)	native	submersed
Elodea canadensis (common waterweed)	native	submersed
Eichhornia crassipes (water hyacinth)	invasive	floating
Limnobium laevigatum (South American sponge plant)	invasive	floating
Ludwigia hexapetala (Uraguayan water primrose)	invasive	floating
Ludwigia peploides (water primrose)	invasive	floating
Hydrocotyle umbellata (pennywort)	native	floating
Azolla (mosquito fern)	native	floating
Lemna spp (duckweed)	native	floating
Potamogeton foliosus (leafy pondweed)	native	submersed
Ludwigia palustris (water purslane)	native	floating
Ruppia maritima (widgeongrass)	native	submersed

serrated leaves in a whorl, with stipules (small spines) on the mid-vein. *Hydrilla* is adapted to climates with alternating rainy and dry seasons, and produces tubers 5- to 25-cm deep in the sediment, which allows them to survive dry seasons. These tubers can last for over 4 years and regrow with rain (Van and Steward 1990). *Hydrilla* can also disperse vegetatively through turions, or buds, that fall off and disperse in the water column. It also spreads through stem fragments (two to three nodes can start a new plant). *Hydrilla* has perennial root crowns that can over-winter and re-grow rapidly in the spring. *Hydrilla* was first discovered in Imperial County, in southern California, and in a Yuba City park lake. Models have shown that California is very suitable for growth of *Hydrilla* (Barnes et al. 2014), and lessons learned from other systems (e.g., Florida) indicate that *Hydrilla* is a significant threat to most if not all the freshwater California ecosystems, and would be particularly problematic if it were to successfully establish in the Delta.

A major challenge associated with *Hydrilla* control and eradication is the persistence of its abundant propagules: turions and tubers. To date, the most effective technique for targeting tubers is a modified gold dredge, capable of removing sediment, which is then screened for plant fragments. The combination of two types of chemical applications has proven effective in California. Contact herbicides (copper, endothall) are used to kill or suppress actively growing plants to stop propagule production and fragmentation. The systemic herbicide fluridone is utilized to wear down the tuber population by killing existing *Hydrilla* as well as the newly sprouted tubers. Seasonal applications must be continued for 5 to 7 years to ensure that no plants are able produce new propagules of any kind. Historically, fumigation of drawn down (de-watered) water bodies was very effective at killing tubers in the soil. However, currently no fumigants are registered for use in California aquatic systems. Cultural controls, such as pond liners and cement lining have been used to isolate the tubers from contact with the water body. Broad-spectrum biological controls have also been used in Imperial County, where triploid grass carp were released to consume all the submersed vegetation.

Brazilian waterweed is an invasive submersed aquatic macrophyte native to Brazil and Argentina that was introduced to the Delta in the 1960s, reaching problem levels in the 1990s (Cook and Urmi–Konig 1984; Foschi and Liu 2002, unreferenced, see "Notes"). Its presence increases sedimentation and reduces water velocity, which helps support its expansion (Yarrow et al. 2009). Mats of Brazilian waterweed grow up to 13 feet deep in clear channels, reducing oxygen levels during the night and hindering the movement of fish between subtidal open water and tidal wetlands. *Egeria*'s relatively low salinity tolerance hinders its competitive ability in the western Delta and Suisun Marsh relative to *Stuckenia pectinata*, a native submersed species that tolerates moderately saline (brackish) conditions (Borgnis and Boyer 2015).

Besides submersed aquatic macrophytes, the Delta also has abundant floating aquatic macrophytes. The most abundant invasive floating aquatic macrophyte is water hyacinth, which was first documented in the Sacramento River in 1904 (Finlayson 1983; Toft et al. 2003). Water hyacinth has one of the highest growth rates of any vascular macrophyte, and studies have found a doubling time that ranges from 10 to 60 days (Téllez et al. 2008). It is a freshwater plant that cannot tolerate more than about 3 ppt salinity (Haller et al. 1974). It has a highly plastic (variable) morphology with two to three phenotypic forms. Mats of water hyacinth depress oxygen levels (Penfound and Earle 1948; Villamagna and Murphy 2010) and have been shown to support different invertebrate communities compared to native species such as pennywort (*Hydrocotyle umbellata*) (Toft et al. 2003).

Another more recent, invasive, rooted emergent aquatic macrophyte found in the Delta is water primrose. *Ludwigia peploides* was found in the Delta in 1949, and in California as early as 1916 (Light et al. 2005). It has been considered invasive during the past 5 years because of its rapid and dramatic increase in coverage in the Delta (Khanna et al. 2015, unreferenced, see "Notes"). Water primrose grows in slow-moving or still water and is also highly plastic in morphology, able to grow erect on water and in creeping form on land. New information suggests there are no native *Ludwigia* species in the Delta, but rather only three species, all of which originate from South America; *L. peploides*, *L. hexapetala*, and *L. grandiflora* (Grewell et al. 2016). Purported ecosystem effects of water primrose are similar to those of water hyacinth, including reduced oxygen levels, hindered fish movement, and mosquito breeding habitat. A study of *Ludwigia hexapetala* and *L. grandiflora* in California freshwater wetlands found that because of low seedling recruitment, management should focus on the clonal vegetative dispersal of these species (Okada et al. 2009).

DELTA TRENDS

Based on 2014 remote sensing data, the Delta was covered by 7,550 acres of submersed aquatic vegetation and 3,810 acres of floating aquatic vegetation (Khanna et al. 2015; SFEP 2015). Total wetted area of the Delta is on the order of 60,000 acres, which fluctuates with tides and seasons. From 2008 to 2014, the total invaded area of submersed and floating aquatic vegetation in the Delta increased by 60%, from 7,100 acres to 11,360 acres. Submersed aquatic vegetation composition showed little change and remains dominated by Brazilian waterweed. From 2004 to 2008, the co-dominant floating aquatic species were pennywort, water hyacinth, and water primrose. In 2014, the co-dominant species were water primrose and water hyacinth, with coverage of 1,050 and 3,000 acres, respectively. More recent 2014 and 2015 remote sensing data for the Delta include areas that are proposed for restoration, such as Prospect Island. Taken together, these data show increases in submersed aquatic vegetation from 11,876 acres in 2014 to 13,950 acres in 2015. Floating aquatic vegetation decreased from 4,156 acres in 2014 to 3,457 acres in 2015. Coverage of water hyacinth dropped from 3,151 acres in 2014 to 1,072 acres in 2015. In contrast, water primrose species increased from 1,005 acres in 2014 to 1,267 acres in 2015. The increasing rate of spread of water primrose in the northwest Delta is becoming a major concern, and the California Department of Parks and Recreation, Division of Boating and Waterways (CDBW) recently (2016) authorized chemical control for this species using the same tools as for water hyacinth.

The following section describes general trends in spatial distribution of floating aquatic macrophytes in the Delta. Water primrose dominates in the

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northwest, such as at Liberty and Prospect islands. It is also present in Sherman Island, an area that is near brackish water. Water primrose is not a true floating plant like water hyacinth, but is instead a creeping emergent with floating stems and highly variable leaf morphology, better adapted to high flow, tidal and wave action, and higher salinity than water hyacinth (Ustin et al. 2015b). Though water primrose is generally found everywhere in the Delta where water hyacinth exists, the central and southern Delta is dominated by water hyacinth. In the southeast and east Delta, water hyacinth and water primrose are co-dominant (Ustin et al. 2015b). Water primrose occurs at the emergent marsh edge along shorelines, while floating mats of water hyacinth tend to be found in deeper water. The northern part of the flooded Liberty Island in the Delta has experienced an increase in emergent vegetation every year. Based on available remote sensing data, water primrose coverage at the island has increased every year.

Factors Facilitating Increase in Invasive Aquatic Macrophytes in the Delta

Further research is needed to better understand the drivers of increasing invasive aquatic macrophytes in the Delta. Here, we highlight a few issues that may have contributed to the spread of aquatic invasive plants. Although state agencies play a critical role in management of invasive vegetation, the loss of funding in recent years has limited their ability to take management actions. For example, budget cuts in 2010 and 2011 eliminated nearly $3 million from the terrestrial and aquatic weed programs. In addition, between fiscal years 2010/2011 to 2012/2013 the California Department of Food and Agriculture (CDFA) Weed Biocontrol funding was cut from a little more than $1 million to zero. Furthermore, water primrose, a key species that has greatly expanded its coverage over the past 5 to 7 years, has only recently (2016) been authorized for treatment with herbicides.

Regulations restrict when and where mechanical control occurs, when and where herbicides can be used, and which herbicides can be used. The fish passage protocol restricts treatments to one-half to one-third of the water hyacinth mat at a time, which is problematic since the plant doubles in 7 to 10 days. Lawsuits prevented all control of invasives for two years in 2000 and 2001, which led to a huge increase in water hyacinth cover.

The continuing drought and resulting increase in shallow water habitat may also provide more suitable habitat for invasive weeds. Invasive weeds such as water hyacinth are vulnerable to frosty nights (Penfound and Earle 1948) but mild winters in the past few years, along with the lack of large storms and fast flows, have favored the persistence and spread of submersed and floating aquatic vegetation. High nutrient levels, while perhaps not driving growth, likely at least support the high growth rates (Dahm et al. 2016). Finally, invasive plants act as ecosystem engineers and, through positive feedbacks such as low velocity, sediment deposition, and lower turbidity, support their own spread (Shih and Rahi 1981; Petticrew and Kalff 1992; Green 2005).

Future Implications for the Delta

Recent (2015) increased funding for CDBW aquatic invasive plant control programs, recent (2015–2016) approvals of two additional species for treatment, and the implementation, since 2014, of the USDA–ARS (Agricultural Research Service)-funded Delta Region Area-wide Aquatic Weed Project (DRAAWP) should result in better implementation of integrated, adaptive management of invasive aquatic weeds in the Delta. It is important to consider, however, that the reduction of invasive plant coverage does not necessarily favor native species in open water. For example, Brazilian waterweed and water hyacinth are ecosystem engineers which modify their environment to benefit their growth. When Brazilian waterweed is removed, other non-native and native submersed aquatic vegetation patches may replace it. The removal of water hyacinth in the Delta can unexpectedly favor the spread of submersed aquatic plants like Brazilian waterweed (Khanna et al. 2011a). All these examples indicate that a return to a pre-invasion state of the system is unlikely, despite invasive plant removal, as evidenced in the state of Florida, where active management of an even broader range of non-native aquatic macrophytes has occurred for many more decades than in the Delta. Sea level rise may push more saline water into the Delta and reduce the cover of freshwater invasive species, but warmer temperatures may favor the growth of tropical invasive plants. Management of invasive aquatic macrophytes may need to take advantage of new climatic and environmental conditions.

CALIFORNIA MANAGEMENT PROGRAMS

Management of invasive aquatic macrophytes in the state of California is conducted through a number of different federal and state agency programs in coordination with non-profit organizations and research universities. The lead department for the control of noxious weeds state-wide is the CDFA (CDFA [date unknown]). The CDBW is currently the lead agency for cooperating and administering aquatic plant management programs in the Sacramento–San Joaquin Delta, its tributaries, and the Suisun Marsh. Legislation (AB 763 [2013], which added Section 64.5 to the Harbors and Navigation Code), requires the CDBW to consult other agencies to add aquatic weed species to the management program and determine management priorities through an interagency process.

As the lead agency in the state for noxious weed control, the CDFA cooperates with federal, state, county, and local agencies; county agricultural commissioners; and private entities to prevent the spread of invasive aquatic weeds (CDFA [date unknown]). The main focus of the CDFA's Hydrilla Eradication Program is to protect state water resources from invasive aquatic weed infestations, primarily *Hydrilla*. The program surveys waterways and implements a zero-tolerance policy, with the explicit goal of eradicating *Hydrilla* once detected. *Hydrilla* is the only aquatic macrophyte mandated by state law to be eradicated. As of September 2015, *Hydrilla* has not been found in the Delta, unlike Brazilian waterweed, which is found in high abundance throughout the Delta. The Hydrilla Eradication Program plays a critical role in early detection and rapid response, and is important for preventing the introduction and establishment of *Hydrilla* in the Delta. However, this program in recent years has faced funding cuts that limit detection surveys, thereby increasing the risk of *Hydrilla* establishment. Active projects to eradicate *Hydrilla* are in Clear Lake, Yuba County, Nevada County, and at the Sacramento River near Redding. Because of the long-lived tuber "bank," herbicide applications need to be maintained for many years before eradication is approached. Research needs for the eradication of *Hydrilla* are: a replacement for fumigation, DNA tracing of populations and introductions, management strategies that prevent development of herbicide resistance, and studies on how to maintain herbicide contact time with water flow and tidal influence. To maintain the continued success of *Hydrilla* eradication, management alternatives for fumigation need to be developed.

The California Department of Fish and Wildlife (CDFW) has adopted the U.S. Aquatic Weed Risk Assessment (WRA) model to estimate the "risk of invasion" posed by introduced aquatic species (Gordon et al. 2012) and to approve their treatment. The review process consists of 36 questions related to the ecology, competitive ability, dispersal modes, reproductive capacity, potential effects, management resistance, and invasion history of a species. The model produces a cumulative numerical score; a score under 31 indicates non-invasiveness, and scores above 39 indicate major invasiveness. The CDBW has requested that five species be assessed (as of September 2015):

1. curlyleaf pondweed (*Potamogeton crispus*) with a U.S. Aquatic WRA score of 66, authorized for treatment in 2015 using the same tools as for Brazilian waterweed;
2. Eurasian watermilfoil, with a tentative score of 76;
3. water primrose, authorized for treatment in 2016 using the same tools as for water hyacinth;
4. coontail (*Ceratophyllum demersum*); and
5. Carolina fanwort (*Cabomba caroliniana*), in queue for assessment.

Interagency Coordination

Management of other invasive aquatic macrophytes in California is conducted by several different agencies, leading to complexity in coordinating management actions. The current state of how invasive aquatic macrophytes are managed needs to be more clearly understood, as do the authorities, roles, and goals of the various agencies (e.g., CDFA, CDBW, CDFW, etc.). In contrast to California's multi-

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agency approach, the state of Florida has a single agency, the Florida Fish and Wildlife Conservation Commission Aquatic Plant Management Section, which funds, designs, coordinates, and contracts invasive non-native aquatic plant control efforts in the state's 1.25 million acres of public waters (FDFWCC 2012).

In response to the large number of agencies and organizations involved in invasive plant management in California, inter-agency partnerships such as the Delta Interagency Invasive Species Coordination Team have emerged to promote greater coordination and information sharing. In 2016, the Interagency Ecological Program (IEP) formed the Aquatic Vegetation Project Work Team (PWT). The team is planning to develop conceptual models that describe aquatic plant species in the Delta, along with special studies and monitoring strategies to determine the effects of management activities on the aquatic ecosystem. In addition, there is a new IEP Management, Analysis, and Synthesis Team (IEP–MAST) project focused on developing effective control strategies in the Delta to promote Delta Smelt resilience, and to test the water quality effects of herbicides and invasive-weed removal.

Delta Region Area-wide Aquatic Weed Project

Currently in its third year, the DRAAWP aims to conduct area-wide adaptive, integrated management of water hyacinth, Brazilian waterweed, and giant reed in the Delta through science-based control strategies. This approach includes prioritization and optimization of management actions. The strategies and technology developed through DRAAWP will have applications for control of other aquatic invasive weeds. Expected outcomes are decreased control costs, increased water conveyance efficiency, decreased economic damage to navigation, improved suppression of mosquito populations near aquatic weed infestations, and increased wetland restoration opportunities. The project aims to improve long-term sustainable management of aquatic weeds by providing agencies with the information necessary to optimize control methods for the seasonal and spatial targeting of aquatic weed populations. The project has enabled federal, state, regional, and local agencies and stakeholders to work together to improve control outcomes and reduce damage. The project funds implementation of improved integrated, adaptive management of water hyacinth, Brazilian waterweed, and giant reed by supporting the CDBW's environmental monitoring while they conduct chemical and mechanical control of water hyacinth and Brazilian waterweed, and by supporting the Sacramento–San Joaquin Delta Conservancy's efforts to control giant reed using mostly chemical herbicide application methods. The project also augments the USDA–ARS and cooperators' implementation of biological control of water hyacinth and giant reed, using insects recently permitted for field release. The DRAAWP supports assessment of aquatic weed populations and of control success using remote sensing tools developed by NASA–Ames Research Center and on-water assessment of both aquatic weed populations and key environmental variables such as dissolved oxygen. The DRAAWP supports research by the USDA–ARS and UC Davis scientists to test new herbicides and integrated control methods, and to determine seasonal aquatic weed growth cycles in relation to control. Other research goals supported by the project include the following:

1. Development, by NASA and UC Davis scientists, of a USDA–ARS Soil–Water Assessment Tool (SWAT) and GIS-based model to determine the effects of land use on water quality with relevance to aquatic weed growth;
2. Determination by UC Davis scientists and local mosquito vector control districts of associations between aquatic weeds and populations of mosquito larvae; and
3. Development, by UC Davis, of a "bioeconomic" model of costs and damage associated with aquatic weed invasions in the Delta, and an estimation of project benefits.

DETECTION AND MONITORING

Remote Sensing Technology

The standard approach to invasive aquatic macrophyte management has generally been guided by the doctrine of early detection and rapid response, for which remote sensing is the tool of choice (Hestir et al. 2008), though it is limited by the frequency of data acquisition. In the Delta, this approach has provided the majority of the data available for species distribution and coverage over the last 10 to 15 years. It is important to keep in mind that remote sensing is best complemented with ground-based surveys, in particular to identify species of submersed plants. Hyperspectral remote sensing, an imaging spectroscopy technique that produces data sets with hundreds of spectral bands of narrow bandwidth (5–15 nm), has been used to map invasive aquatic macrophytes in the Delta (Hestir et al. 2008; Khanna et al. 2011b; Ustin et al. 2015b).

Consistent hyperspectral remote sensing data are needed to map and monitor the spread of invasive species. Hyperspectral data is particularly useful because of the large number of bands available. For example, HyMap data consists of 126 bands (400–2400 nm), and AVIRIS–NG Airborne Visible and InfraRed Imaging Spectrometer – Next Generation, NASA JPL's high-resolution platform data consists of 432 bands (350–2500 nm). Hyperspectral data enable the measurement of biophysiological characteristics of different aquatic macrophyte species, which cannot be measured using the few broad bands available in current satellite sensors. Five consecutive years (2004–2008) of 3-m pixel resolution hyperspectral HyMap data of the Delta was acquired in late June of each year and used to map and monitor the spread of invasive species (Hestir et al. 2008; Khanna et al. 2011b, 2015). AVIRIS-NG data acquisition was funded through the California Department of Fish and Wildlife (CDFW) to determine how drought affected invasive species. It was flown in November 2014 and again in September 2015 (Ustin et al. 2015b).

Up to 20 years of Landsat satellite data is available with flyovers of California every 16 days. This frequency of data acquisition, which is essential for adaptive management, is a key advantage of this relatively inexpensive remote sensing platform. CDBW in cooperation with NASA Ames scientists have field-validated that mapping the Delta has been reliable. Landsat data has been used to study spatial and temporal aspects of mechanical harvesting and biocontrol. These data have also been applied to studies of Delta management actions such as the Emergency Drought Barrier in 2015, as well as to mapping risk zones and providing insight on factors that drive population spread. Landsat is currently the only reliable platform able to track on a biweekly basis the intra-annual (within-season) variation in floating aquatic vegetation surface coverage, climate effects, and the effects of integrated aquatic weed management. Both Landsat and AVIRIS data, contribute to analysis of inter-annual trends in floating aquatic weed abundance and coverage. For example, algorithms applied to Landsat data can geographically isolate and pinpoint locations of interest, such as persistent overwintering nursery populations, for targeted early-season treatments. These data can also track movement of water hyacinth populations in the central and southern Delta late in the field season. Knowledge of this movement can direct control efforts and prevent aquatic weeds in the south Delta from blocking fish screens and pumps in the fall and winter, which is critical to water conveyance in the state.

The floating aquatic vegetation community (FAV) and the submerged community (SAV) can both be mapped by a good multi-spectral sensor with at least a few bands in the NearInfraRed (NIR) to ShortWave InfraRed (SWIR) range of the electromagnetic spectrum and at least 5-×-5 meter spatial resolution or better (Marshall and Lee 1994; Vis et al. 2003; Phinn et al. 2008; Dogan et al. 2009; Heblinski et al. 2011; Bresciani et al. 2012; Villa et al. 2015). Sensors such as WorldView 2/3, IKONOS, RapidEye, QuickBird, SPOT 5 through 7, etc. all satisfy these criteria to some extent (Jensen 2000). Landsat data with 30-×-30 meter pixels, though free, is too coarse. Hyperspectral imagery, such as used in this study, enables discrimination of FAV genera as water hyacinth, water primrose, or the native pennywort (Khanna et al. 2011b; Ustin et al. 2015a, 2015c). Thus, it allows us to follow the progress of each invasive plant individually, while also keeping track of the native FAV community. Efforts are currently underway to evaluate the possibility of monitoring the Delta consistently through remote sensing imagery. A group of multi-agency scientists will develop a plan and evaluate the ability of various sensors to map SAV and FAV, the cost of acquisition, temporal repeatability, and other requirements of a good monitoring program.

Continued monitoring of invasive aquatic macrophytes in the Delta relies on the availability of remote sensing data, either hyperspectral or hyperspatial. In the past, the CDBW funded HyMap image data collection from 2004 to 2008 and the

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CDFW funded AVIRIS–NG image data collection from 2014 to 2015. Although efforts to fund future short-term data acquisition exist, the lack of a consistent monitoring program severely limits invasive aquatic macrophyte management.

Role of Citizen Science

Citizen science can be an effective tool for the early detection, survey, and removal of invasive species, though there has been little organized citizen science activity in the Delta targeted at freshwater invasive aquatic vegetation. Successful citizen science models, such as the Invaders of Texas Program and the Invasive Plant Atlas of New England, have demonstrated that properly trained citizen scientists are able to detect and report invasive plants in their local areas and provide useful data to professional scientists (Gallo and Waitt 2011). Actual removal campaigns are likely to be only locally and temporarily effective for widespread Delta invaders like water hyacinth, Brazilian waterweed, and water primrose, but may reduce or prevent the spread of other relatively recent aquatic invasive species such as South American spongeplant, or the introduction of *Hydrilla*. The Smithsonian Environmental Research Center (SERC) uses citizen scientists to help detect invasive species such as invasive kelp (e.g., *Undaria pinnatifida*) in their Kelp Watch program, which targets the boating public and provides a website for sighting reports. Several programs have been developed that enable users to report locations and take photographs of individual plants or populations using smartphones, including iNaturalist and EDDMapSWest. CalFlora's Weed Manager includes a suite of tools developed for organizations involved in land management to track the locations of invasive plants and treatments through time. These programs are easy to use, do not require knowledge of GIS, and allow for rapid reporting of invasive plant species. These kinds of citizen science initiatives could be adapted to detection and monitoring of freshwater invasive aquatic vegetation in the Delta.

CONTROL METHODS

Mechanical Control

Mechanical control methods physically harvest vegetation typically using large, power-driven machinery. Although favored by some groups because no herbicides are discharged into water, several important drawbacks limit their use. Fragmentation of many aquatic plants can create propagules, which can float downstream and lead to colonization of additional areas. Mechanically shredding water hyacinth was found to increase the overall abundance of carbon, nitrogen, and phosphorus in the Delta water column, though estuary-wide effects were limited (Greenfield et al. 2007). The Greenfield study provides an example of a regional-scale assessment of how community-level management actions can affect ecosystem processes. More ecosystem-scale experiments and system integration efforts in aquatic plant management are needed.

In the Delta, limitations on using mechanical control methods result primarily from concerns about fish being killed during harvesting operations, accessing sites with large machinery and/or gaining permits and access to privately-owned but publically-regulated levees to access the water with heavy equipment, and the very high cost relative to chemical control. Until 2016, mechanical control could only be done in the winter (November to March), and only on floating plants. Removal, transport, and disposal of wet biomass is costly. Despite this, the CDBW does now utilize mechanical control methods both during the winter and in critical locations during the chemical control season. Because of concerns for listed fish species, mechanical control is not permitted in certain areas, or Delta-wide in the month of May.

To offset the cost and additionally provide a beneficial reuse for harvested biomass, novel uses of the plant material to produce bioenergy—including production of hydrogen or methane biofuels via anaerobic digestion—have been proposed (Wilkie and Evans 2010). Pilot-scale projects are needed to determine at what scale bioenergy production is feasible using invasive aquatic plants harvested from the Delta. A major concern associated with programs such as these is that they could indirectly lead to conflicts for management priorities if energy generation became dependent on the availability of biomass from nuisance species.

Chemical Control

The chemical control of invasive aquatic plants depends on the adaptive, strategic use of existing permitted compounds, and, when available, their integration with or replacement by newly-permitted compounds. Issues that have arisen regarding herbicide use, as observed in the state of Florida, are herbicide resistance and non-target toxicity.

The following is a description of chemicals used for aquatic vegetation control in the Delta. Diquat is an example of a chemical that has been successfully used to rapidly control *Egeria*. However, its toxicity profile indicates some elevated risk to zooplankton food chains. Fluridone, which is extensively used in the Delta as well as in Florida, can be applied in liquid, granular, and pellet forms. Pellets can maintain a fluridone concentration of 3 ppb in the water column for 12 weeks. The concentration must be high enough to kill the target species but low enough to be safe for non-target species. Penoxsulam is a relatively new herbicide that Florida is utilizing for floating plant management, but it is not currently permitted for aquatic use in California. In the Delta, 2,4-D and glyphosate are two herbicides than have been used to control water hyacinth. The DBW has authorization to use a newer chemical, imazamox, which may control water hyacinth (and water primrose) more efficiently with reduced dosages than the two older herbicides, which reduces control costs. USDA–ARS is cooperating with the DBW to examine the efficacy of imazamox, and possibly other new herbicides, on water hyacinth and Brazilian waterweed in comparison to 2,4-D and glyphosate.

The potential herbicide risks to aquatic species such as a species of calanoid copepod (*Eurytemora affinis*) and Delta Smelt (*Hypomesus transpacificus*) have been investigated by Swee Teh's research group at UC Davis (DSC 2015). Teh's research, funded by the CDBW, examined the toxicity of fluridone, 2,4-D, glyphosate, penoxsulam, and imazamox on *E. affinis* and embryo and early larval stages of Delta Smelt. Observed effects of herbicide toxicity on the test species were found only at concentrations much higher than those typically found in the water near treated plants. The research group also found that Delta Smelt are more sensitive to imazamox than are *E. affinis*, although *E. affinis* was found to be more sensitive to penoxsulam and the lipophillic herbicide adjuvant, Agridex. Mixtures of penoxsulam and Agridex were found to have additive effects on *E. affinis*. Overall, based on these laboratory studies, the effects of these herbicides at concentrations relevant to their label-mandated use rates were non-detectable to negligible on food webs and Delta Smelt. Additional studies on Delta-specific food webs and listed species are the focus of studies to be conducted by the newly formed Aquatic Vegetation PWT and are called for by the recently released Delta Smelt Resiliency Strategy (CNRA 2016).

Biological Control

Biological control is a useful management tool for invasive aquatic plants that are already widespread. Biocontrol is defined as "the planned use of undomesticated organisms (usually insects or plant pathogens) to reduce the vigor, reproductive capacity, or density of weeds." (Cuda et al. 2008). Invasive weeds, without the presence of their natural enemies, are free to proliferate. Biocontrol introduces a natural enemy, known as a biocontrol "agent," to lower the density of invasive species. The intentional release of grass carp to control hydrilla, most typically in canals and man-made lakes (Stocker and Hagstrom 1986), is not germane to the Delta, because *Hydrilla* is not present, and, in any event, grass carp are not host-specific, precluding their use in Delta ecosystems. Most typically, biological weed control involves host-specific, non-native insects or mites from the weed's native range as natural enemies; native or non-native pathogens have also occasionally been considered. The process of implementing a biocontrol management project involves the following:

1. Finding natural enemies through lab tests to verify narrow (genus- or species-specific) host specificity, determine the organism's biological life cycle, and demonstrate its efficacy (Briese 2005; Stastny et al. 2005; Suckling and Sforza 2014);

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2. Providing extensive information for peer-review and regulatory review processes at the federal, state, and tribal level;
3. Receiving a permit for field release;
4. Completing additional permit processes to gain site access at regional, state, and local levels;
5. Releasing the agent; and
6. Evaluating its establishment, dispersal, and effect.

Benefit-to-cost ratios range from 8:1 to 300:1 (Culliney 2005; Van Driesche et al. 2010; van Wilgen et al. 2013). Research on and development of new biological control agents, and performing initial releases and impact evaluations, require up-front costs ($3 to $8 million) and a substantial time commitment (5 to 10 years). The release of agents, once established, is irreversible. Biological control typically takes 5 or more years for full effect and does not eradicate the weed. However, effective biological control agents will control invasive aquatic plants in a very targeted manner, and control their spread in the long-term through self-replenishment and dispersal.

The status of biological agents for six major aquatic weeds is summarized in Table 2. Two biocontrol agents that target *Arundo donax* and three that target water hyacinth have been released in the Delta; both of these weeds are good targets because they don't have any close native relatives in California. To date, only one of these five has been documented as established in the Delta, the leaf-chewing and stem-mining water hyacinth weevil, *Neochetina bruchi*; its populations can be dense but its impact is not sufficient to obviate other control methods (Akers et al. 2017; Hopper et al. 2017). Some researchers are actively seeking to obtain permission to re-release another weevil, *Neochetina eichhorniae*, and to release a planthopper, *Megamelus scutellaris*, that feeds on vascular tissues, and that is established outside of the Delta (Moran et al. 2016). The thermal tolerance of the weevil is being studied by the USDA–ARS in Albany (P. Moran, 2016a email to J. Ta, unreferenced, see "Notes"), and the toxicity (or lack thereof) of possible ingestion of the planthopper and weevil by listed fish species is being investigated by fish biologists at the University of California-Davis in cooperation with USDA–ARS and the CDBW. One candidate agent, a leaf-mining fly, that targets Brazilian waterweed (*Egeria densa)* was rejected because of non-target feeding in lab tests (P. Moran, 2016b email to J. Ta, unreferenced, see "Notes"). The *Ludwigia* genus, which also has a native species, *Ludwigia palustris*, is still in the genetic evaluation process so biocontrol cannot yet be considered. The USDA–ARS offices located in Albany and Davis, California, have collaborative agreements with the *Fundación para el Estudio de Especies Invasivas* (FUEDEI) lab in Argentina, the native region for invasive *Ludwigia* spp. and South American spongeplant, so biocontrol agents may become available in the future. Unlike the other invasive aquatic weeds in the Delta, *P. crispus* has numerous native relatives (same genus) in California, and it might, therefore, be difficult to identify biocontrol agents that are sufficiently host-specific.

Economic Incentives

The use of economic incentives to manage invasive aquatic macrophytes has been a recent area of development. For example, the expansion of fuel-cell technology and its commercial applications, such as hydrogen fuel cell-based fork lifts, may advance expansion of commercial harvesting of invasive aquatic plants for biofuel and fertilizer production. Recent efforts have focused on harvesting water hyacinth and possibly *Arundo donax*, which could dramatically reduce plant cover. However, significant economic hurdles have to be overcome, including the cost to transport aquatic weed biomass from field sites to processing sites, and the economies of scale associated with constructing and operating these facilities. The other limitation is the relatively short season in the temperate environment of the Delta.

RECOMMENDATIONS

Though these are not intended to represent all relevant recommendations on this topic, we recommend the following, based on presentations at the 2015 symposium, as well as our own expert opinions as co-authors of this paper.

- A consistent monitoring program for invasive aquatic vegetation at several levels of accuracy and precision is needed. The most widespread

Table 2 Status of biological control of six major aquatic weeds in the Delta

Species	Introduced agents	Effects and status	Supporting studies
Water hyacinth (*Eichhornia crassipes*)	Two weevils: • *Neochetina bruchi* • *Neochetina eichhorniae* Introduced to the Delta along with one moth (*Niphograpta albiguttalis*) by USACE in early 1980s.	• Only *N. bruchi* established in Delta (1985), and was later detected (early 2000s to present). Currently widespread and locally abundant both in and outside of the Delta, but populations insufficient to reduce need for chemical and mechanical control.	Stewart and Cofrancesco (1988)
	A South American delphacid planthopper: • *Megamelus scutellaris* Released in limited numbers in 2011 by CDFA.	• Only confirmed establishment outside Delta, near Folsom, California. Small initial release size, climate factors, or pesticide drift may have affected Delta releases. • Regulatory review (by USFWS and NOAA NMFS for CDBW-Parks integrated adaptive management plan) needed for widespread Delta releases.	Tipping et al. (2011) Moran et al. (2016)
Giant reed (*Arundo donax*)	An *Arundo* stem-galling wasp: • *Tetramesa romana* Currently being released in Delta by USDA ARS.	• Released in Texas, Arizona, and California. • *T. romana* only develops on genus Arundo with 90% of egg-laying and feeding occurring at shoot tips, causing galls that stunt plant growth. • Observed in Texas to reduce *Arundo* stand biomass by 30% to 40% after 7 years, fostering colonization by native plants • Adventive in southern California (Ventura and Santa Ana rivers)	Goolsby et al. (2009) Moran and Goolsby (2009) Goolsby et al. (2014) Moran et al. (2016) Goolsby et al. (2016) Moran et al. (2017)
	An *Arundo* armored scale: • *Rhizaspidiotus donacis* Released in Delta within last two years.	• Due to recent release, no available data on impact of either agent in the Delta region or elsewhere in California. • *R. donacis* observed in Texas to cause distortion and death of lateral shoots and accumulations of scales on rhizomes.	Moran and Goolsby (2010) Cortes et al. (2011a) Cortes et al. (2011b) Goolsby et al. (2011)
Brazilian waterweed (*Egeria densa*)	No agent introduced.	• USDA ARS initiated biological control studies in 2009. • A fly species, *Hydrellia egeriae*, was found to feed and reproduce on native *Elodea canadensis* during quarantine tests and rejected. • No other potential agents are in quarantine.	
Water yellow-primrose (*Ludwigia hexapetala* or *L. peploides* ssp. *montevidensis*)	No agent introduced.	• Preliminary biocontrol studies began in 2010 in the native range in South America. • Critical questions being addressed by USDA ARS are genetic identity of invasive California populations and polyploidy as well as environmental factors that promote or limit growth. • No agents are currently in quarantine.	Grewell et al. (2016)
South American sponge plant (*Limnobium laevigatum*)	No agent introduced.	• No biological control project or pre-release risk assessment has been initiated. • CDFA successfully eradicated plant in Sonoma County and reduced populations in Delta region as well as Shasta and Merced counties. Management has transitioned to control program under CDBW.	
Curlyleaf pondweed (*Potamogeton crispus*)	No agent introduced.	• No biological control project or pre-release risk assessment has been initiated.	

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monitoring, using hyperspectral remote sensing techniques and coordinated field campaigns, has so far been funded through short-term grants, limiting its potential longevity.

- Robust funding is needed for effective early detection and rapid response. The CDFA's Hydrilla Eradication Program exemplifies a very successful early-detection and rapid-response strategy that has prevented the introduction and establishment of *Hydrilla* in the Delta and in hundreds of water bodies in California. However, funding cuts in recent years have weakened the effectiveness of the program and may increase the possibility of small, undetected populations of *Hydrilla* being established in the Delta.
- To prevent accumulation of large biomass, policies need to enable early management of invasive aquatic vegetation before their growth accelerates. In the Delta, management actions are often delayed until after exponential growth occurs, making control much more challenging. For example, herbicide treatments are not allowed until March in the south Delta, and until mid-summer in the north Delta.
- Improved coordination among agencies is necessary to achieve effective management. To address this need, the USDA–ARS-funded DRAAWP; the new Aquatic Vegetation PWT; the DIISC are all bringing federal, state, regional, and local agencies together, so expertise and new funding opportunities can be leveraged. Efforts like these should be sustained and expanded.
- Research is needed to successfully develop fully integrated control methods (chemical, mechanical, and biological) and to manage the suite of invasive aquatic plants—as opposed to single species—at the population and community level. Better coordination among agencies as mentioned earlier would support this effort.
- New options in chemical control depend on continued research and development of new active ingredients that may be used to decrease the reliance on only one or two active ingredients. Regulations restrict herbicide treatments both spatially and temporally, and only a few herbicides are currently approved. Herbicides with new modes of action need to be approved so that management agencies can rotate modes of action to avoid resistance.
- Biological control is a useful management tool for controlling widespread invasive aquatic plants that are beyond the point of eradication. Support of and funding for the development of new biocontrol agents should continue. In addition, further studies are needed on how environmental parameters such as water quality and plant nutrient states influence biological control agents and their establishment.
- Synthesis of existing data and, possibly, new studies are needed to evaluate the effects of invasive aquatic vegetation and their control of the habitat quality of listed fish species such as Delta Smelt and salmonids. Many key regulations that govern aquatic weed control in the Delta result from statutes that require protection of these species. In particular, the presumed risk of early herbicide use on Endangered Species Act (ESA)-listed fish populations needs to be substantiated by toxicology studies, because seasonally delayed management actions to protect these fish result in massive invasive vegetation biomass, exacerbating the management challenge.
- A truly preventative program should be developed and implemented. It should include inspections, education, and training of marine managers, boaters, anglers, and other key users of Delta water bodies not only for early detection and rapid response, but also as insurance to protect management actions.
- There are currently no major, organized citizen science initiatives for detection, survey, and removal of invasive aquatic vegetation in the Delta, but other successful approaches could be adapted for these purposes.

CONCLUSIONS

The September 15, 2015, symposium on invasive aquatic vegetation at UC Davis, brought together researchers and natural resource managers to discuss the current knowledge and management of invasive macrophytes in the Delta. Although there has been ongoing foundational research on the environmental drivers of aquatic plant growth, much remains to be understood about the role invasive aquatic vegetation play as ecosystem engineers in altering water quality, nutrient levels, sedimentation, and ecological communities, including effects on habitat for listed fish species. With increased awareness of macrophytes as ecosystem engineers, there is a growing call to address management of aquatic systems and community interactions at the ecosystem level, not just to control individual plant species.

Although several options in mechanical, chemical, and biological controls are available for management of invasive macrophytes, notable challenges have emerged that call for innovative solutions. In particular, documented cases of herbicide resistance, which have been observed in other states such as Florida, call for management practices that aim to minimize the development of herbicide resistance and rotate herbicide modes of action.

Funding management actions via soft money allows for prompt responses, but the lack of permanent funding remains a barrier toward creation of stable long-term monitoring and control programs (CDFG [now CDFW] 2008). For example, the hyperspectral remote sensing data used to monitor the presence and distribution of invasive aquatic vegetation described in this article was funded for 2004–2008 and 2014–2015, and recently funded for 2016, but future sustained funding remains uncertain. In addition, programs critical for rapid response and eradication such as the Hydrilla Eradication Program have faced budget cuts in recent years.

Successful management of invasive aquatic vegetation requires a clear identification of the desired outcome, which may differ depending on stakeholder values. In addition, the timing of management action is important, and the recommended management of high-priority introduced species is through prevention, early detection, rapid response, and eradication or control (Anderson 2005; Williams and Grosholz 2008). Approaching management at the population and community level will help reduce the "squeaky wheel" syndrome that often results in limited, transient success which itself is thwarted by the emergence of a formerly "minor" problem species. Bioeconomic modeling also indicates that money is better spent toward prevention of invasive species establishment (Leung et al. 2002). Because of the complexity of invasive macrophyte management, integrated management efforts by disparate organizations and agencies are critical. Although successful ecosystem management of invasive aquatic vegetation in the Delta remains an elusive goal, ongoing development and implementation of new strategies for adaptive, integrated management of aquatic weeds is showing promise to achieve improved management outcomes and enhance protection of the Delta's water resources.

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