Environmental Drivers of Water Hyacinth and Other Floating Aquatic Macrophytes, and Their Impact on Water Quality and Habitat

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Each summer and fall for the past few decades, floating invasive aquatic plants have interrupted the movement of commercial and recreational boats, obstructed access to docks and marinas, and hindered water conveyance for Delta regional agricultural and domestic water use, as well as the state and federal water projects to the Central Valley. Equally significant, but less documented, are the ecological impacts of these floating plants. Before an integrated management plan can be implemented, the first step is to understand the environmental drivers and ecological effects of floating aquatic plant growth. While some native plants are present, most of the nuisance growth is caused by water hyacinth (*Eichhornia crassipes* (Mart.) Solms). Water hyacinth is well adapted to grow in a freshwater estuary such as the Delta, whether freely moving with winds and tides, or loosely rooted in shallow water. In addition to abundant light energy in the dry summer, water hyacinth growth is accelerated by Delta-wide warm air and locally warm water temperatures, possibly excess nutrients available in the water and sediment, and the presence of flooded islands and other backwater areas protected from wind and waves. Under optimal conditions, water hyacinth may double its area coverage or biomass in 8 days. A lack of stormflow and freezing temperatures in the past few years have allowed large quantities of water hyacinth to overwinter, acting as 'nurseries' to increase summer populations. Dense water hyacinth mats restrict reoxygenation of the water, increase sedimentation, and add organic matter to the sediment. Water hyacinth displaces native vegetation, and may impact habitat quality for rare, threatened, endangered, and sensitive fish and other species. The USDA-ARS funded Delta Region Areawide Aquatic Weed Project (DRAAWP) is supporting, among other foci, detailed studies of water hyacinth population growth, phenology, and dispersal, in relation to management techniques.

Keywords: invasive plant, integrated plant management, *Eichhornia crassipes*
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Environmental Drivers and Effects of Invasive and Native Submerged Aquatic Macrophytes in Suisun Bay and the Delta

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Understanding the factors that influence the distribution and abundance of native and invasive submerged aquatic vegetation (SAV) in San Francisco Estuary is important to the management of these species. We evaluated the distribution and characteristics of native *Stuckenia pectinata*-dominated beds in Suisun Bay and invasive *Egeria densa*-dominated beds in the west Delta through field surveys, and conducted experiments testing the effects of salinity, turbidity, and herbivory on, and competition between, *Stuckenia* and *Egeria*. Our results suggest *Egeria* is limited to the Estuary's fresh waters because it cannot endure higher salinities, with signs of severe stress at a salinity of 5 and complete mortality at 10 or 15. In contrast, *Stuckenia* biomass increased 4-fold over 3 months at salinities of 0 and 5, doubled at 10, and maintained biomass at 15. Competition may also be important in determining distributions at low salinities, as *Egeria* presence led to a 70% decrease in *Stuckenia* biomass in fresh water, while at a salinity of 5, a decline in *Egeria* performance coincided with a doubling of *Stuckenia* shoot density. An experiment testing increased light availability, as is expected with depletion of the erodible sediment pool, showed enhanced growth and flowering for both species with greater light, but that only *Stuckenia* had negative effects of salinity ameliorated through increased light. Common invertebrates (two amphipods, an isopod, and a snail) consumed little live biomass of either species regardless of salinity, with *Egeria* a highly undesirable food choice. In addition to aiding our understanding of current patterns in native and invasive SAV within the low salinity zone, these results can help to predict future patterns under a variety of scenarios of management and climate change. Other submerged plants in the region have not been evaluated for these kinds of biotic and abiotic interactions.

Keywords: Stuckenia, Egeria, pondweed, salinity, turbidity, herbivory, competition
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A Delta-wide Programmatic Approach: Evaluating the Effects of Aquatic Invasive Macrophyte Control on ESA-listed Salmonids and their Habitat

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Aquatic invasive macrophytes are capable of causing extinction of native aquatic plants, reducing biodiversity, competing with native organisms for limited resources, and altering ecosystem processes. Recent initiatives to better understand and address aquatic invasive macrophyte impacts to Endangered Species Act (ESA)-listed fish and their habitat in the Delta have highlighted the complexity of the programs and the regulatory environment in which they operate. As a result, NOAA's National Marine Fisheries Service (NOAA Fisheries) and stakeholders (*e.g.,* California Department of Boating and Waterways, United States Department Agriculture, and United States Fish and Wildlife Service), propose to develop a more holistic and comprehensive approach to aquatic invasive macrophyte control in the Delta that links data and decisions. We propose a new process for planning and regulatory compliance that could streamline the existing process and manage the on-going, expanding, and challenging issues facing invasive macrophyte control. The current control programs are based on a species-by-species approach. The new approach proposes one comprehensive ESA Section 7 Programmatic that incorporates all current and potential future control activities. This shifts the focus from a particular plant species to treatment methods used to control multiple invasive species (*e.g,* chemical, mechanical, physical, and biological). This type of program-level consultation process: (1) provides a new adaptive frame-work for prescribed management actions, (2) has the potential to streamline the existing regulatory process, and (3) decreases the time to implementation. A Delta-wide programmatic approach to aquatic invasive macrophyte control is a prudent step forward to help better inform management actions, minimize future risk to listed species and their habitat to help meet ESA-listed species recovery goals and objectives.

Keywords: aquatic invasive species, macrophytes, Endangered Species Act, Section 7, NOAA
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Watershed-Scale Modeling of Land-Use and Altered Environment Impacts on Aquatic Weed Growth in the Delta

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The California Delta is the hub for California's water supply. Changes in climate, long-term drought, and water quality have all been suspected as playing role in the dramatic expansion of invasive aquatic plants and their impact on ecosystems of the Bay / Delta complex. NASA, USDA, Cal-DBW, and UC Davis have partnered to develop science-based, adaptive-management strategies for invasive aquatic plants in the Delta. Effective management strategies to require understanding of how the magnitude of fluctuations in land-use and climate / drought induced altered environments affect plant growth. We utilize the Soil Water Assessment Tool (SWAT), a watershed-scale model, as the backbone for a customized Delta model – Delta-SWAT. The model uses land-use, soils, elevation, and hydrologic routing to characterize pesticide and nutrient transport from the Sacramento and San Joaquin watersheds and loading into the Delta. Land-use within the Delta, as well as water extraction to supply those functions, and the resulting return of water to Delta waterways are included in Delta-SWAT. Delta-SWAT water quality trend estimates are compared with water quality monitoring conducted throughout the Delta. Aquatic plant response to water quality and other environmental factors is carried out using a customized model component. Plant response to the range of water quality factors, response times, and altered temperature and light regimes of the Delta have required gap-filling studies to provide model parameters. Delta-SWAT provides a tool for evaluating temporal and spatial effects of land-use and altered environments in the Delta and contributing watersheds on aquatic weed growth. Using Delta-SWAT for simulation modeling allows evaluation of historic and current conditions as well as consideration potential climate change and management practice outcomes. Delta-SWAT adds to the scientific understanding of dynamics in the Delta and enhances development of science-informed, management strategies and practices.

Keywords: modeling, invasive aquatic plants, climate change, drought
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High-Resolution Mapping for Determining Long-Term Trends in the Distribution of Floating and Submerged Aquatic Macrophytes in the Delta

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The Sacramento-San Joaquin Delta is one of the most modified estuaries in the world with a network of levees, dams, and canals, which has made it vulnerable to biological invasions. There are two dominant invasive floating aquatic vegetation (FAV) genera, water hyacinth (*Eichhornia crassipes*) and water primrose (*Ludwigia* spp.), and several non-native submerged aquatic vegetation (SAV) species that have invaded the Delta. We acquired imaging spectroscopy data in June 2004 through 2008, November 2014, and September 2015 at a pixel resolutions of 2.5 to 3 m for the entire Delta (~2500 km^2). The two main objectives of our current study are: 1) classify SAV, emergent, and FAV communities in the Delta, and quantify change in abundance and distribution; and 2) determine the interactions between these communities and their response to the California drought. We used the machine learning algorithm Random Forest to classify the communities and species, and multiple change detection algorithms to determine species interactions. Our results show the total invaded area increased from 6,700 acres in 2008, to 11,400 acres in 2014, with the largest increase in spatial spread of FAV species. Both water hyacinth and water primrose have replaced native pennywort (*Hydrocotyle umbellata*) cover becoming the two main co-dominant FAV plants. Invasive SAV cover remains relatively constant and is still dominated by invasive *Egeria densa*. Furthermore, our results show that invasive FAV invade areas already colonized by SAV and when they are treated and removed, SAV re-colonize the same areas. SAV species reduce water velocity by increasing roughness causing sediment to fall out of the water column and turbidity to decrease. These results have major implications for the restoration and management of invasive species in the Delta, potentially guiding control efforts in major nurseries of both FAV and SAV invasive species.

Keywords: invasive floating macrophytes, submerged macrophytes, remote sensing, delta
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Testing New Herbicides for Control of Invasive Aquatic Plants in the Delta

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A limited selection of herbicides is available for controlling aquatic plants. In particular, the chemicals most commonly used for controlling emergent species include glyphosate and 2,4-D, both of which have come under increasing scrutiny. We have addressed this issue by conducting screening trials for new and under-used herbicides on two of the Delta's most problematic invasive aquatic plants, water hyacinth and egeria. The new herbicides selected are classified as reduced-risk pesticides by US EPA. Water hyacinth studies were conducted during summer 2016, in 1-m^2 floating quadrats anchored to the sediment within a submerged island in the Sacramento/San Joaquin River Delta. Ramets were placed in the quadrats, allowed to propagate for four weeks, then treated with foliar herbicides at several rates, in four replications per treatment. Among other treatments, the newly registered chemicals penoxsulam and imazamox were compared with the established herbicides glyphosate and 2,4-D. Evaluations were conducted four weeks after application. This study was repeated during the season, with some changes in the rates of herbicides tested. In a second study, we evaluated the effect of available labeled aquatic herbicides on egeria. This trial was conducted on established colonies of egeria in 40-gallon mesocosms at the USDA-ARS Aquatic Weed Lab, Davis, California. Ten registered herbicides, in four replications, were applied in standard concentrations. Treatments were evaluated ~12 weeks after application. This set of studies will allow us to make best-use recommendations for herbicide control of water hyacinth and egeria, with the ideal outcome of reducing populations of invasive aquatic plants in the Delta while minimizing environmental risks.

Keywords: invasive, weeds, aquatic, herbicides, egeria, hyacinth
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The Present and Future Contribution of Biological Control to Integrated Adaptive Management of Water Hyacinth and other Invasive Aquatic Macrophytes in the Delta

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Non-native, invasive aquatic plants in the Delta block water conveyance for irrigation and urban use, impede navigation, and negatively influence critical aquatic habitat quality parameters. Chemical and mechanical control of floating water hyacinth (*Eichhornia crassipes*) and submersed Brazilian waterweed (*Egeria densa*) are hindered by lack of access to some invasive plant populations. The use of biological control, specifically insects from the native range that can survive only on the weed and that disperse to all weed populations, needs to be increased. Three insects were previously released for biocontrol of water hyacinth. In the present study, water hyacinth was surveyed monthly at 16 locations in the Delta and nearby. Only one weevil species, *Neochetina bruchi*, was present, averaging five adults and 14 larvae per plant in early summer and fall population peaks. Weevil densities were not associated with water nitrogen content. Efforts are underway to test accessions of the weevil *N. eichhorniae* that are better-adapted to Delta climatic conditions than the one previously released. The planthopper *Megamelus scutellaris* was released in 2011 and has established a population on water hyacinth upstream of the Delta, increasing its density 10-fold between 2012 and 2015. A potential agent of Brazilian waterweed, a leaf- and stem-mining fly, was not released due to nontarget feeding in laboratory tests. In recent years, other floating invasive macrophytes have emerged as significant threats, including water-yellow primrose (*Ludwigia* spp.) and South American spongeplant (*Limnobium laevigatum*). Insects are being searched for and tested by foreign collaborators as potential biocontrol agents of these weeds. The development of well-established, efficacious biocontrol agents targeting invasive aquatic macrophytes in the Delta is expected to contribute to an adaptive, integrated management framework being implemented under a USDA-ARS-funded Delta Region Areawide Aquatic Weed Project. Improved control is expected to protect water resources and enhance habitat quality.

Keywords: Biological control, Invasive aquatic weeds, herbivory, integrated weed management
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Early Results of Improved Delta-Wide Integrated Adaptive Management of Water Hyacinth, Brazilian Waterweed and Curly-Leaf Pondweed

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Invasive plants cost the state of California at least $82 million each year for control, monitoring, and outreach while negatively impacting property values, agricultural productivity, outdoor recreation and ecosystem health. The California State Parks Division of Boating and Waterways (Parks-DBW) is designated as the lead State agency for cooperating with Federal, state, and regional public agencies to control invasive aquatic plants in the Sacramento-San Joaquin Delta, its tributaries, and the Suisun Marsh. The Delta provides water for more than 25 million Californians, millions of farmland acres, fish and wildlife habitat and recreational opportunities. Parks-DBW currently implements chemical and mechanical control measures through an integrated management approach for water hyacinth (*Eichhornia crassipes*), Brazilian waterweed (*Egeria densa*), South American spongeplant (*Limnobium laevigatum*), and curly leaf pondweed (CLP) (*Potamogeton crispus*). Mechanical control has been utilized for water hyacinth since 2013 in the Delta. Annual acres of water hyacinth and *Egeria* treated with herbicides have averaged 1,600 and 1,643 since 1990 and 2004, respectively, but increased to 4,447 acres in the case of water hyacinth in 2015. Plans for 2016 target similar acreage for water hyacinth and spongeplant, and over 2,200 acres of *Egeria* and CLP. A new adaptive management program is being developed with research partners based on knowledge derived from remote sensing, weed population growth modeling, the testing and use of new herbicides, efficacy tracking, surveys of aquatic plants, and analysis of water quality in relation to weeds control. While chemical treatments remain the most effective control option available, other methods including targeted mechanical control and possible biological control pending federal approvals are being implemented as part of Parks-DBW's integrated management approach to maximize efficacy and minimize program impacts. Ongoing research and conceptual models provide valuable insight into determining the sustainable balance between the various control measures and ecosystem health.

Keywords: Invasive species, nonnative, integrated pest management, water hyacinth, Egeria densa
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Analysis of Satellite and Airborne Imagery for Detection of Water Hyacinth and other Invasive Floating Macrophytes in the Delta

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Waterways of the Sacramento San Joaquin Delta have recently become infested with invasive aquatic weeds such as floating water hyacinth (*Eichhoria crassipes*) and water primrose (*Ludwigia peploides*). These invasive plants cause many negative impacts, including, but not limited to: the blocking of waterways for commercial shipping and boating; clogging of irrigation screens, pumps and canals; and degradation of biological habitat through shading. Zhang et al. (1997, Ecological Applications, 7(3), 1039–1053) used NASA Landsat satellite imagery together with field calibration measurements to map physical and biological processes within marshlands of the San Francisco Bay. Live green biomass (LGB) and related variables were correlated with a simple vegetation index ratio of red and near infra-red bands from Landsat images. More recently, the percent (water area) cover of water hyacinth plotted against estimated LGB of emergent aquatic vegetation in the Delta from September 2014 Landsat imagery showed a 80% overall accuracy. For the past two years, we have partnered with the U. S. Department of Agriculture (USDA) and the Department of Plant Sciences, University of California at Davis to conduct new validation surveys of water hyacinth and water primrose coverage and LGB in Delta waterways. A plan is underway to transfer decision support tools developed at NASA's Ames Research Center based on Landsat satellite images to improve Delta-wide integrated management of floating aquatic weeds, while reducing chemical control costs. The main end-user for this application project will be the Division of Boating and Waterways (DBW) of the California Department of Parks and Recreation, who has the responsibility for chemical control of water hyacinth in the Delta.

Keywords: Sacramento San Joaquin Delta, water hyacinth, Landsat remote sensing
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Bio-Economic Modeling of Invasive Aquatic Weed Management

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Problem statement: Effective management of invasive weeds requires knowledge of current management costs, and the cost of alternative management options.

Approach: A summary of costs by different agencies that are affected by aquatic weeds in the Delta will be presented. A bio-economic management model will then be presented demonstrating cost trade-offs in weed management. This model takes into account weed spread and whether an area is primarily a site from which weeds spread (i.e. a nursery site) or a site where weeds accumulate (i.e. a slough). Different weed management options are then simulated, and the cost estimated for each option. The options are then compared to determine the least cost solution.

Results: The result of the surveys show that the costs incurred by agencies, such as the Port of Stockton, and marinas that manage aquatic weeds in the Bay-Delta have been increasing. In addition, many agencies and marinas are looking into investing in more long-term solutions to local weed management such as purchasing harvesters or conveyors to remove weeds.

The results of the bio-economic model show that the least cost solution when all agencies are grouped together is the one that treats infestations when they are as small as possible. However, when costs are separated into costs incurred by agencies that provide areawide control, and those agencies that manage local infestations, the least cost solution may change. It also shows that the size of the infestation to manage may not be the determining factor. For effective cost management of invasive weeds the determining factor may be how many times an area will be treated.

Relevance: The bioeconomic model uses both weed growth models and economic models to determine optimal management under different scenarios. The model can also be adapted to incorporate additional weed management scenario as new information becomes available.

Keywords: Management costs, bio-economic modeling, simulation models
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