

# Factors Controlling Submersed and Floating Macrophytes in the Sacramento-San Joaquin Delta

Prepared for:

The Central Valley Regional Water Quality Control Board

And

The California Environmental Protection Agency

State Water Resources Control Board

(Agreement Number 12-135-250)

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**Draft Technical Report XXX**

**April 2015**

## Acknowledgements

The authors of this document wish to thank the members of the Submersed and Floating Macrophyte Technical Advisory Group. This report was produced under California State Water Board contract to the Southern California Coastal Water Research Project (Agreement Number 12-135-250).

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This report should be cited as:

Boyer K and Sutula M. 2015. Factors Controlling Submersed and Floating Macrophytes in the Sacramento-San Joaquin Delta. Southern California Coastal Water Research Project Technical Report No. XXX. April 2015.

## Executive Summary

The Central Valley Regional Water Quality Control Board (Water Board) is developing a plan to generate the science needed to support decisions on policies governing nutrient management in the Delta. Non-native, invasive floating and submersed aquatic vegetation (SAV) are one of three areas, identified by Water Board, that represent pathways of potential impairment that could be linked to nutrients. The Water Board commissioned a literature review of the factors that may be controlling the prevalence of floating and SAV. This literature review addresses four major questions:

- 1) How do submersed and floating aquatic vegetation support or adversely effect ecosystem services and related beneficial uses?
- 2) What is known about the spatial and temporal trends in submersed and floating aquatic vegetation in the Delta?
- 3) What is the relative importance of nutrients and organic matter accumulation versus other factors in promoting observed trends in submersed and floating aquatic vegetation in the Delta?

This review had five major findings:

**#1. Native SAV are a beneficial component of the Delta; however, non-native and invasive floating and SAV have the potential to adversely affect Delta ecosystem services and associated beneficial uses.** Adverse effects include: 1) organic matter accumulation in surface waters and sediments that can lead to diurnal swings in pH and DO and ultimately chronic hypoxia, 2) outcompetition of phytoplankton, native SAV and other benthic primary producers, 3) habitat alteration, 4) changes to the food web, 5) impence of navigation and obstruction of industrial intake pipes and 6) poor aesthetics.

**#2. Two invasive species, *Egeria densa* (Brazilian waterweed) and *Eichhornia crassipes* (water hyacinth) are now dominant throughout the Delta. *E. densa* is found in >2000 hectares (~10% of Delta waters and *E. crassipes* covers about 200 hectares (~1%) according to remote sensing estimates (Santos et al. 2009). Lack of a routine monitoring program hampers our ability to discern recent spatial and temporal trends.** However, a collection of research studies and California Department of Boating and Waterways aquatic weed control programs suggest that both of these species may be expanding despite control efforts.

**#3. Existing scientific literature has documented a host of environmental factors that have control over the growth of *E. densa* and *E. crassipes* worldwide.** These include: 1) nutrients, 2) light, 3) temperature, 4) salinity, 5) dissolved inorganic carbon (SAV), 6) flow, turbulence and residence time, and 7) interaction with other species.

**#4. Studies have documented the importance of a subset of these factors in the Delta, but insufficient evidence exists to determine the relative importance of nutrients versus other factors in promoting the expansion of these species.** Drawing on available information, we can conclude the following:

- Conditions in the Delta, including seasonal low flow (and lack of turbulent mixing), high light, warm temperatures, and freshwater (low salinity) regime appear to favor the establishment and growth of the *E. densa* and *E. crassipes*.
- Aquatic plants require macronutrients (nitrogen, N and phosphorus, P) for growth. N and P are available in relatively high concentrations in the Delta, suggesting that available nutrients are not limiting growth. However, it is not possible to discern the relative influence of nutrients versus other factors. In addition, it is not clear to what degree new versus remineralized N and P (regenerated from sediment organic matter) are subsidizing this growth, making it unclear the effect that nutrient management could have on growth and persistence of these invasive aquatic plants.

**#5. Climate change and anthropogenic activity associated with land use changes have the potential to further increase the prevalence of *E. densa* and *E. crassipes*.** Climate change will likely result in warmer temperatures and increased drought, the latter of which could result in reduced flows, increased residence time and water column stability in the Delta. These factors would provide a favorable environment for increased prevalence of *E. densa* and *E. crassipes*. However, increased salinity intrusion into the west Delta would favor native species of aquatic vegetation, in particular the pondweeds (*Stuckenia* spp.).

Given these findings, three major science recommendations are proposed:

**R1: Implement Routine Monitoring of Invasive Floating and Submersed Aquatic Vegetation.** Routine monitoring of floating and submersed aquatic vegetation should be undertaken to assess trends over time and to support ecosystem modeling of the Delta. Monitoring should be comprised of a combination of remotely-sensed areal coverage and field-based transects to estimate biomass. Estimates of biomass and areal cover should be conducted in combination with measures of the major factors that control growth of these primary producers. Early actions should include: 1) the development of a workplan to lay out the key indicators and cost estimates required for monitoring and 2) existing remote sensing data should be used in an attempt to thoroughly estimate areal coverage spatially and over time.

**R2: Develop a Biogeochemical Model of the Delta, focused on Nutrient and Organic Carbon Fate and Transport.** Understanding of factors controlling floating and SAV is critically hampered by the lack of information on nutrient and carbon budgets for the Delta and its subregions. In particular, it's important to quantify the storage in the compartments of the ecosystem (i.e. water, sediment, plant biomass, etc.) and fluxes or exchanges between compartments at varying seasonal and spatial scales. This information will provide an understanding of whether management of "new" nutrients can be effective in controlling floating and SAV relative to the contribution of nutrients recycled from sediment organic matter. To step into model development, three actions should be taken: 1) examine existing models already available to determine suitability for this task, 2) develop a work plan that lays out the modeling strategy, model data requirements, and implementation strategy, and 3) conduct special studies and other monitoring needed to support model development. This includes special studies that quantify N, P, and organic carbon associated with ecosystem compartments as well as uptake, release and flux rates. These

analyses should inform hypotheses that can be tested through model development as well as potential future scenarios.

**R3. Investigate control strategies for both *E. densa* and *E. crassipes* that include, among other strategies, mechanical removal.** Depending on the outcome of R2, nutrient management may be ineffective in controlling invasive floating and SAV. While monitoring, modeling and special studies are underway, research to determine more effective removal strategies should be conducted. This work should begin by: 1) conducting a literature review of control strategies to identify potential measures that may be useful in the Delta, and 2) funding research projects that pilot these strategies.

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# 1. Introduction, Purpose and Organization of the Review

## 1.1 Background and Context

The Sacramento–San Joaquin River Delta (hereto referred as “the Delta”), is an inland river delta and estuary approximately 1300 square miles in size, found in Northern California (Fig. 1.1). Formed at the western edge of the Central Valley by the confluence of the Sacramento and San Joaquin Rivers, the Delta is a key component of the State’s water resource infrastructure and a region that is rapidly urbanizing, yet serves as critical habitat for fish, birds and wildlife. Water from the 45,000 square mile Delta watershed fuels both local and statewide economies, including important agricultural commodities. The Delta is widely recognized as in “crisis” because competing demands for the Delta’s resources (Delta Plan 2013). The consequences of these competing demands include point and non-point discharges, habitat fragmentation and loss, modified flow regimes, introduction of non-native species, all of which combine to threaten ecosystem health, including the continued decline of threatened and endangered species (Delta Plan 2013).

In 2009 the California legislature passed the Delta Reform Act creating the Delta Stewardship Council. The mission of the Council is to implement the coequal goals of the Reform Act and provide a more reliable water supply for California while protecting, restoring, and enhancing the Delta ecosystem. The Council wrote and adopted a Delta Plan in 2013 to implement these goals. Chapter 6 of the Delta Plan deals with water quality and contains recommendations to implement the coequal goals of the Delta Reform Act. Recommendation # 8 states, in part, “...the State Water Resources Control Board and the San Francisco Bay and Central Valley Regional Water Quality Control Boards (Water Board) should prepare and begin implementation of a study plan for the development of objectives for nutrients in the Delta ... by January 1, 2014. Studies needed for development of Delta... nutrient objectives should be completed by January 1, 2016. The Water Boards should adopt and begin implementation of nutrient objectives, either narrative or numeric, where appropriate, in the Delta... by January 1, 2018.

Potential nutrient related problems identified in the Delta Plan for evaluation are:

1. Decreases in algal abundance and shifts in algal species composition,
2. Increases in the abundance and distribution of macrophytes, including water hyacinth and Brazilian waterweed, and
3. Increases in the magnitude and frequency of cyanobacterial blooms

To provide better scientific grounding for the study plan, the Water Board commissioned three literature reviews centered on these three potential areas of impairment. This document provides a synthesis of literature on submersed and floating macrophytes in the Delta.

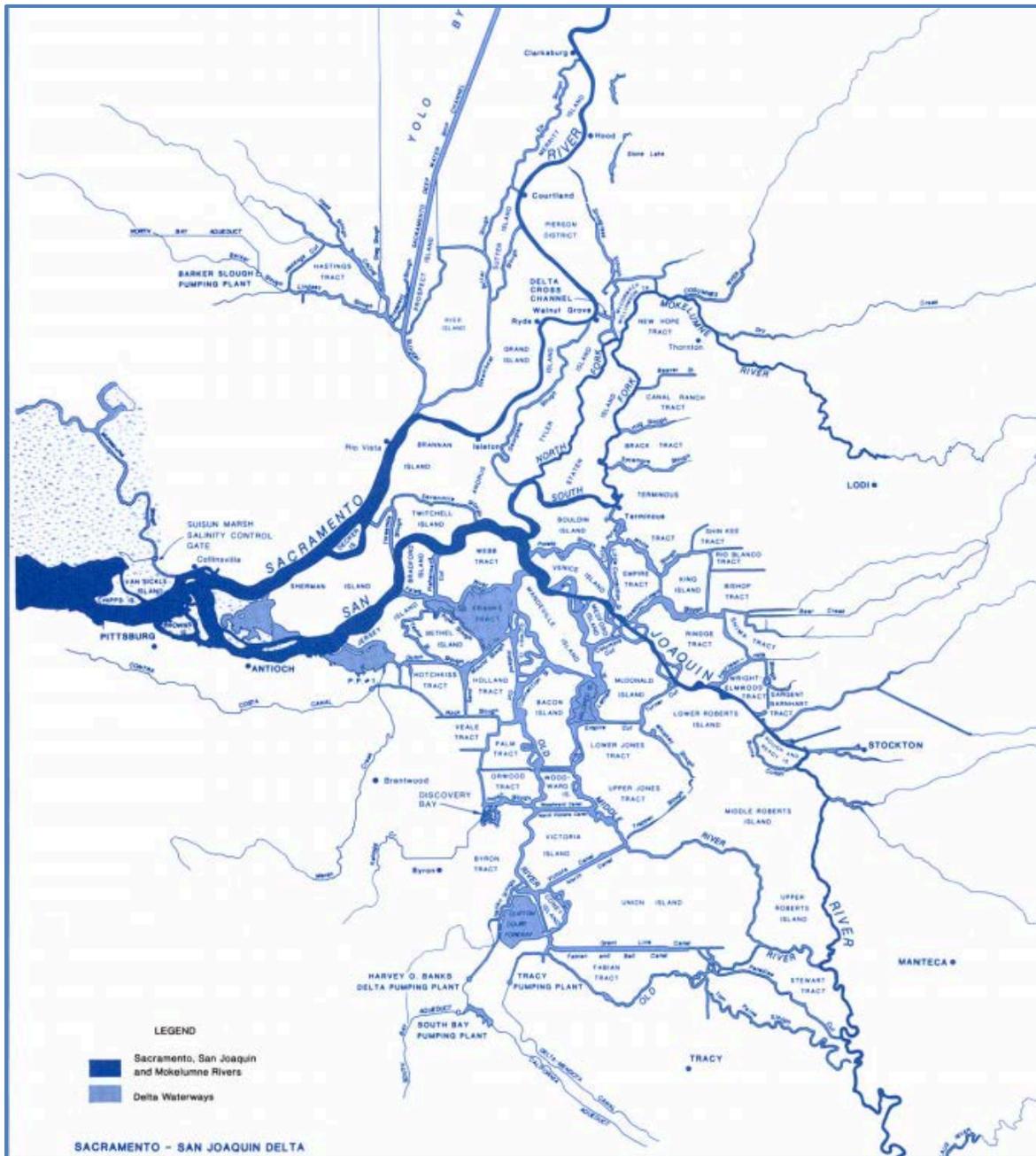


Figure 1.1 The Sacramento-San Joaquin Delta Region

## 1.2 Goal and Organization of Macrophyte Literature Review

This review aims to assess whether there is evidence that the perceived increase in the abundance and distribution of submersed or floating aquatic macrophytes in the Delta is the result of long term changes in nutrient or organic matter loading relative to other factors and to ascertain whether management of nutrient loads might be used to remedy the problems associated with these macrophytes. This review will be evaluated and utilized by a Science Working Group to develop recommendations for a research plan to resolve outstanding questions regarding the need for nutrient management to reduce the impacts of invasive aquatic macrophyte species; a Stakeholder and Technical Advisory Group (STAG) will review and contribute to the research plan.

This review addresses the following key questions:

- 4) How does submersed and floating aquatic vegetation support or adversely effect ecosystem services and related beneficial uses?
- 5) What is known about the spatial and temporal trends in submersed and floating aquatic vegetation in the Delta?
- 6) What is the relative importance of nutrients and organic matter accumulation versus other factors in promoting observed trends in submersed and floating aquatic vegetation in the Delta?
- 7) What are the key data gaps and recommended future studies?

The document is organized as follows:

Section 1: Introduction, Purpose and Organization of the Review

Section 2: General Ecology and Trends in the Distribution of Submersed and Floating Aquatic Vegetation in the Delta

Section 3: Role of Submerged and Floating Aquatic Vegetation in Supporting Ecosystem Services

Section 4: Factors Contributing the Prevalence of submersed and floating aquatic vegetation in the Delta

Section 5: Key Data Gaps and Research Recommendations

Section 6: Literature Cited

## 2. General Ecology and Trends in the Distribution of Submersed and Floating Aquatic Vegetation in the Delta

### 2.1 Classification of Aquatic Vegetation and Scope of Review

This review pertains to the fully aquatic vegetation in the Delta, including those submersed and rooted plant species in the sediments and those floating on the surface. It does not include emergent species such as sedges, rushes, and broad-leaved forbs that are rooted along the Delta's shores. The focus is on the most common species and especially the prolific invaders for which management measures leading to a reduction in abundance and distribution, if feasible, would be deemed acceptable and desirable to resource agencies, scientists, and the general public. We consider only the vascular plants; macro- and microalgae are outside of the scope of this review, although they are mentioned in terms of their relationship to submersed vascular plants.

### 2.2 Overview of Species Found in the Delta

There are about eighteen species of submersed or floating aquatic plants in the Delta (Table 2.1) as identified in the peer-reviewed and grey literature (Anderson 1990; Anderson 2011; Jassby and Cloern 2000; Santos et al. 2011; Khanna et al. 2012; Boyer et al. 2012, 2013; Cohen et al. 2014). About half of those species are rooted and submersed beneath the water surface except at low tides. Nearly half of these were introduced rather than native species.

No studies have estimated abundance of all these species Delta-wide, but patterns in relative abundance have been evaluated within particular regions. Two studies (Santos et al. 2011; Boyer et al. 2013) used a rake method in which the number of tines occupied by each species is used to determine relative abundance of submersed species (Kenow et al. 2007). *Egeria densa* was by far the most abundant species found in the central Delta study, with detections at 70-90% of sampling points (Santos et al. 2011; Fig. 2.1). Similarly, *E. densa* was detected up to 100% of the time within the submerged vegetation beds sampled at four west Delta locations (Boyer et al. 2013; Fig. 2.2). Other studies report that *E. densa* makes up nearly 85% of submersed vegetation biomass in the Delta (Hestir et al. 2010), covering over 2000 hectares or roughly 10% of Delta waters (Santos et al. 2009). Other submersed, non-native species are typically much less abundant at present (Fig. 2.1, 2.2).

*Ceratophyllum demersum* (coontail) was the most frequently encountered native species within both the central Delta and west Delta studies described above, and was more common than all the introduced species other than *E. densa* (Fig. 2.1, Santos et al. 2011; Fig. 2.2, Boyer et al. 2013). In the same central Delta region that harbored 383 hectares of *E. densa* in fall 2007, *C. demersum* covered 284 hectares (Fig. 2.1). We know of no Delta-wide estimates of acreage for this species.

**Table 2.1. Submersed and floating vegetation in the Sacramento-San Joaquin Delta. N = Native, I = Introduced. \* Indicates the most abundant introduced and native species, on which this review is focused.**

Species	Common name	Submersed/ Floating	N/I
<i>Cabomba caroliniana</i>	Carolina fanwort	Submersed	I
<i>Egeria densa</i> *	Brazilian waterweed	Submersed <sup>1</sup>	I
<i>Eichhornia crassipes</i> *	Water hyacinth	Floating	I
<i>Limnobium laevigatum</i>	South American sponge plant	Floating	I
<i>Ludwigia hexapetala</i>	Uruguay water primrose	Floating	I
<i>Ludwigia peploides</i>	Water primrose	Floating	I <sup>2</sup>
<i>Myriophyllum spicatum</i>	Eurasian watermilfoil	Submersed	I
<i>Potamogeton crispus</i>	Crisped or curly-leaf pondweed	Submersed	I
<i>Azolla</i> sp.	Water fern	Floating	N
<i>Ceratophyllum demersum</i> *	Coontail	Submersed <sup>3</sup>	N
<i>Elodea canadensis</i>	Common waterweed	Submersed	N
<i>Hydrocotyle umbellata</i>	Marsh pennywort	Floating	N
<i>Lemna</i> sp.	Duckweed	Floating	N
<i>Potamogeton foliosus</i>	Leafy pondweed	Submersed	N
<i>Potamogeton nodosus</i>	Long-leaf or American pondweed	Submersed <sup>4</sup>	N
<i>Ruppia maritima</i>	Widgeongrass	Submersed	N
<i>Stuckenia</i> sp.*	Sago and fine-leaf pondweed (+ hybrids?)	Submersed	N

1 *E. densa* is typically rooted but fragments can form floating mats.

2 There is confusion over the identification of native and non-native species of water primrose; this species has been designated as introduced in this review as it has by other authors (e.g., Khanna et al. 2012).

3 *C. demersum* is the one submersed species that is not rooted in the sediment; it often attaches to other plants.

4 *P. nodosus* is rooted in the sediment but its leaves float at the surface of the water.

In addition, *Stuckenia* sp. (*S. pectinata* and *filiformis*, and possibly their hybrids: Boyer et al. 2012; Patten and Boyer, unpublished) was relatively common in the Delta sites (Fig. 2.1, Santos et al. 2011) and is typically the only aquatic plant species found within the open Suisun Bay (Fig. 2.2; Boyer et al. 2012, 2013). A rough estimate of acreage, based on mapping only in the west Delta and the assumption that patches are small within the rest of the Delta (smaller than the 3m<sup>2</sup> pixel size used by Santos et al. 2012), is 350 hectares within the Delta and another 200 hectares within the open Suisun Bay (Boyer et al. 2015). *Stuckenia* occurring in island interior sloughs and in Suisun Marsh have not been mapped.

As for floating species, *Eichhornia crassipes* (water hyacinth) has become notorious for its role in clogging channels, marinas, and water supply pipes within the Delta (see Literature Cited for many recent articles centered around the Stockton area). Worldwide, it is ranked as one of the worst invaders (OTA 1993). While it is not nearly as abundant as *Egeria*, covering 160-300 hectares of the Delta, depending on the year (1-2% of the water area; Santos et al. 2009), its prevalence and nuisance effects in areas of high human activity have led to high interest in understanding factors that control it.

Number of detections, relative frequency (in percent) from point samples, area (ha) and percent cover of the submersed aquatic plant species detected in the Sacramento-San Joaquin River Delta (waterways area is 639.89 ha)

Scientific name	Code	Status	Fall 2007			Summer 2008		
			Detections (%)	Area (ha)	% cover	Detections (%)	Area (ha)	% cover
<i>Egeria densa</i>	EGDE	Non-native	339 (89)	382.49	59.77	300 (69)	99.64	15.6
<i>Cabomba caroliniana</i>	CACA	Non-native	1 (0.3)	NA	NA	36 (8)	1.41	0.2
<i>Myriophyllum spicatum</i>	MYSP	Non-native	32 (8)	68.03	10.6	78 (18)	20.4	3.2
<i>Potamogeton crispus</i>	POCR	Non-native	52 (14)	50.8	7.9	53 (12)	10.03	1.6
Total			424	382.9	59.8	467	174.08	27.2
<i>Ceratophyllum demersum</i>	CEDE	Native	107 (28)	283.77	44.3	180 (41)	59.14	9.2
<i>Potamogeton nodosus</i>	PONO	Native	1 (0.3)	NA	NA	10 (2)	6.04	0.9
<i>Elodea canadensis</i>	ELCA	Native	19 (5)	34.28	5.36	10 (2)	18.29	2.9
<i>Stuckenia</i> spp.	STSP	Native	24 (6)	73.02	11.4	32 (7)	69.84	10.9
Total			151	294.29	45.9	232	157.04	24.5
Total submersed species			575	388.35	60.7	699	239.6	37.4

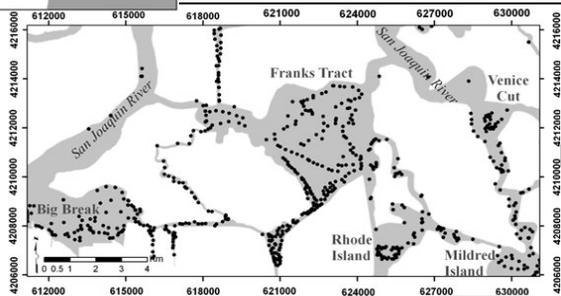


Figure 2.1. Rake detections and other data on abundance of submersed species at sampling points within the central Delta (left). Excerpted from Santos et al. 2011

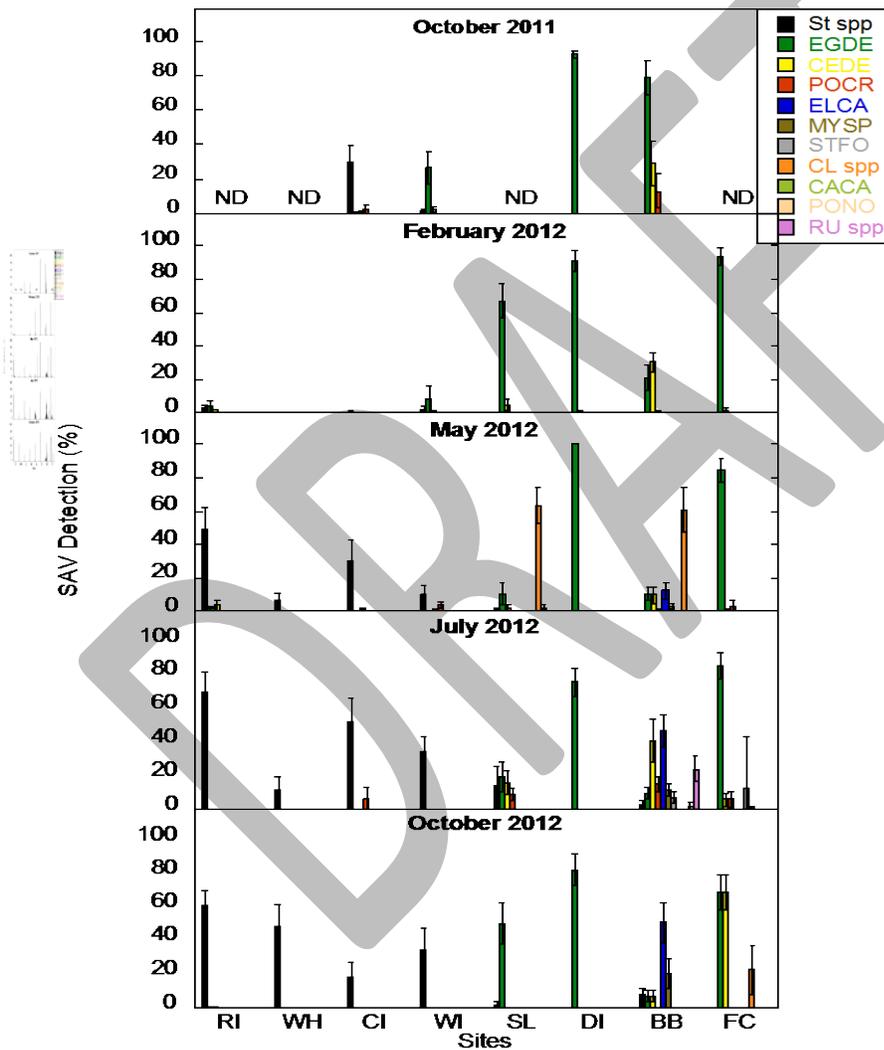
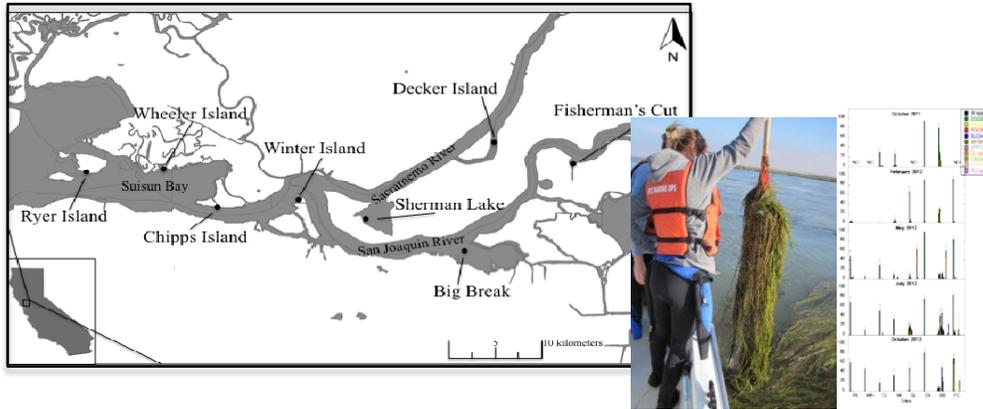


Figure 2.2. Relative abundance of submersed plant species in the west Delta and Suisun Bay (see map inset to interpret site abbreviations from west to east) in 2012 as estimated with a rake sampling method (Kenow et al. 2007). Species abbreviations as in Fig. 2.1, with the addition of *Stuckenia foliosus* (STFO), the green alga *Cladophora* (CL), and *Ruppia* sp. (RU). (Figure from Boyer et al. 2013)

The four species, *E. densa*, *Eichhornia crassipes*, *Ceratophyllum demersum* and *Stuckenia* sp., will be the focus of this review, due to their abundance and/or human interest (Fig. 2.3). A botanical description of each of these species is given below (from the Jepson Manual and Flora of North America, plus taxonomic work on *Stuckenia* spp. described in Boyer et al. 2012, 2015).



Figure 2.3. Species central to this review. Top: Two abundant non-native aquatic species, *Egeria densa* (left, photo Katharyn Boyer) and *Eichhornia crassipes* (right, photo Bob Case). Bottom: Two abundant native species, *Ceratophyllum demersum* (left, photo Ron Vanderhoff) and *Stuckenia* sp. (right, photo Katharyn Boyer).

***Egeria densa*** (Brazilian waterweed) is a submersed species native to warm temperate South America in southeastern Brazil, Argentina, and Uruguay. It grows with trailing stems up to 5 m long, producing roots at intervals along the stem. Although it is typically rooted in the sediment, it can also form mats of detached fragments. The leaves are produced in whorls of four to eight, 1–4 cm long and 2–5 mm broad, with an acute apex. It is dioecious, with male and female flowers on separate plants; however, all plants outside the native range, including California, are believed to be male, with reproduction accomplished through fragmentation. The flowers are 12–20 mm diameter, with three broad, rounded, white petals, 8–10 mm long.

***Eichhornia crassipes*** (water hyacinth) is a free-floating perennial aquatic plant native to tropical and sub-tropical South America. With broad, thick, glossy, ovate leaves, water hyacinth may rise above the surface of the water as much as 1 meter in height. The leaves are 10–20 cm across, and float above the water surface on long, spongy and bulbous stalks. The feathery, freely hanging roots are purple-black. An erect stalk supports a single spike of 8-15 conspicuously attractive flowers, mostly lavender to pink in color with six petals. When not in bloom, water hyacinth may be mistaken for the smaller South American sponge plant (*Limnobium laevigatum*), recently discovered in the Delta (Anderson 2011). One of the fastest growing plants known (a mat of 10 plants can produce 650,000 in one growing season; Penfound and Earle 1948), water hyacinth reproduces primarily by way of runners or stolons, which eventually form daughter plants. In addition, each plant can produce thousands of seeds each year, which can be viable for decades.

***Ceratophyllum demersum*** (coontail) is a submersed, native perennial that grows in still or very slow-moving water. The stems reach lengths of 1–3 m, with numerous side shoots making a single specimen appear as a large, bushy mass. The leaves are produced in whorls of six to twelve, each leaf 8–40 mm long, simple, or forked into two to eight thread-like segments edged with spiny teeth; they are stiff and brittle. It is monoecious, with separate male and female flowers produced on the same plant. The flowers are small, 2 mm long, with eight or more greenish-brown petals; they are produced in the leaf axils. The fruit is a small nut 4–5 mm long, usually with three spines, two basal and one apical, 1–12 mm long. *C. demersum* is not rooted; it can be found free-floating beneath the water or attached to other plants.

***Stuckenia pectinata*** (sago pondweed) and ***S. filiformis*** (fineleaf pondweed) are monocot, perennial rhizomatous herbs native to California with outwardly similar morphology: long stems (2-4 m in summer) and a submersed canopy of thin leaves near the water surface. Neither was known from the open waters of the San Francisco Estuary until very recently but either or both have been present for at least several decades according to review of current and past aerial imagery (see Boyer et al. 2012, 2015). *S. pectinata* was historically an important food for Canvasback ducks in ponds within Suisun Marsh (Jepson 1905). *S. filiformis* is much more rare in California (included in the California Native Plant Society Inventory of Rare and Endangered Plants as *rare, threatened, or endangered in CA; common elsewhere*). Available keys describe *S. filiformis* as having little to no secondary branching, leaves frequently > 1.5 mm and often 2-3 mm or more wide (with extremes to 3.7 mm) and perhaps olive in color and blunt-tipped, and small fruits (2-3 mm) with style and stigma reduced to a broad flattened disk at the top of fruit. In contrast, *Stuckenia pectinata* should have a forking “zig-zag” (wide branch angle) pattern of branching, multiple orders of very leafy branches, with leaves 1 mm wide or less and seldom exceeding 1.5 mm, perhaps brighter green in color with more acutely-pointed leaf tips, and large fruits (2.5-5 mm) with pronounced beaks resulting from persistent styles. Many specimens observed to date do not precisely match either species, and the few fruits available have been intermediate between the two species (large but not beaked) (Boyer et al. 2015); thus, we use “*Stuckenia* sp.” to encompass these two closely related species and the possible hybrids between them.

### 2.3 Habitat Types in Which They are Characteristically Found

*Egeria densa* is found throughout the Delta in areas of moderate and low flow, along the margins of larger sloughs and in more protected areas such as smaller sloughs and breached islands (e.g., Sherman Lake, Franks Tract: Fig. 2.4). It can be found as far west as the confluence of the Sacramento and San Joaquin Rivers around Winter Island (Boyer et al. 2013). It grows densely throughout the water column in waters up to 7 m deep (Parsons and Cuthbertson 1992), but also appears to have an affinity for the water surface as indicated by a strong growth response under experimental conditions of red light (Boussard et al. 2000). Typically it is rooted in the substratum throughout its distribution but it can also be found as a free-floating mat (Boussard et al. 2000). It occurs in a wide variety of conditions at a range of depths and in both turbid and clear water (Santos et al. 2011).

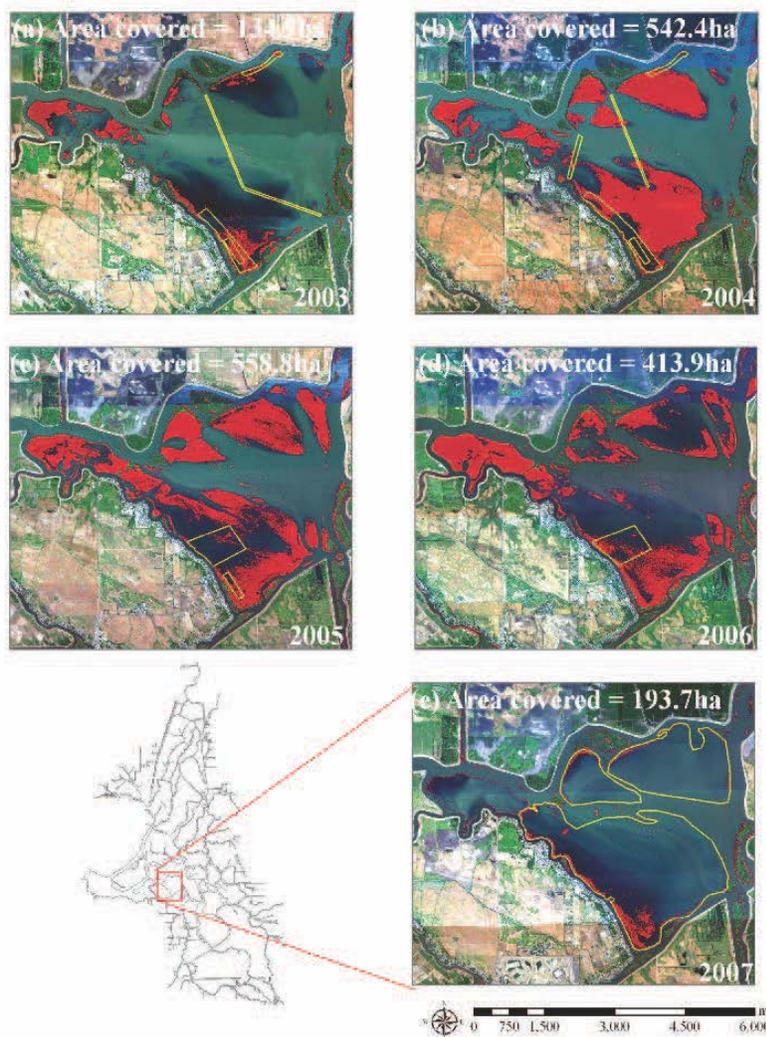


Figure 2.4. Submersed vegetation (primarily *E. densa*) coverage of up to 560 hectares within Franks Tract in the central Delta, 2003-2007 (figure from Santos et al. 2009)

*Eichhornia crassipes* is found throughout the Delta in calm waters, but can be seen rafting through open waters during windy periods, with its stout leaves acting as sails (Boyer, pers. obs.). It has been extremely abundant near the city of Stockton in the last several years (see Literature Cited for many news articles). It is typically found along channel edges with more stable flow conditions, thus minimizing wash out, or in narrow channels or low flow basins (e.g., marinas, breached island interiors) where there is protection from higher velocity flows. Water depth alone is not a limitation since it does not root in the sediment.

*Ceratophyllum demersum* has been documented as abundant in the west and central Delta in areas of low flow (Santos et al. 2011; Boyer et al. 2013). This species was found with roughly half the frequency of *Egeria densa* within the central Delta region in one study (Santos et al. 2011). As it is free-floating or attached to other species of submerged vegetation, it more often occurs along with other species such as *E. densa* than on its own (Santos et al. 2011).

*Stuckenia sp.* is less commonly found in the Delta than the other species described above, but still more common than all other native species besides *Ceratophyllum demersum*. It was found at about 25% of the frequency of *C. demersum* in a survey of the central Delta (Santos et al. 2011). With high salinity tolerance (Borngis and Boyer, in revision), it forms large beds in the west Delta (e.g., Sherman Lake) and along shoals and island shores throughout much of the open Suisun Bay, as well as in sloughs interior to islands and the Suisun Marsh (Fig. 2.5; Boyer et al. 2015).

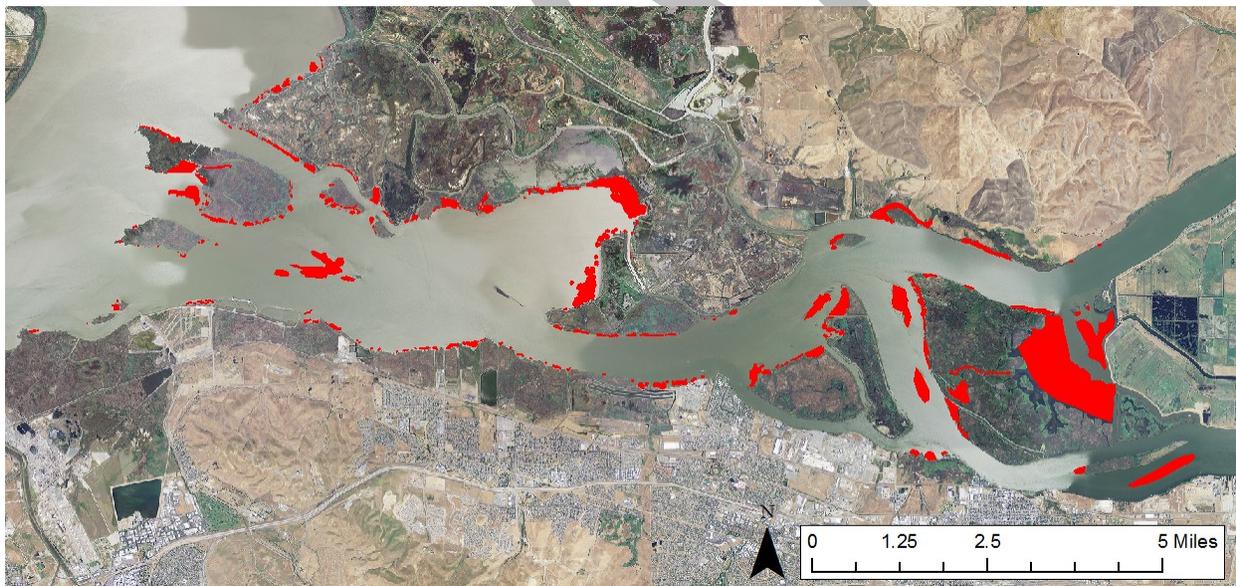


Figure 2.5. Spatial distribution of *Stuckenia sp.* from Ryer Island in Suisun Bay to Sherman Lake in the west Delta, as determined from digitizing and ground truthing aerial imagery (Google Earth), 2012. Coverage is estimated to be ~ 500 hectares in this region. Image unpublished, based on data in Boyer et al. 2015.

#### 2.4 Spatial and Temporal Trends in their Distribution and Abundance

A regular, comprehensive mapping program for aquatic vegetation does not exist for the Delta region. Several grant-funded efforts to conduct remote sensing have provided valuable information, and have

led to improvements in mapping techniques. In particular, recent work to incorporate hyperspectral imagery has aided in the distinction of some of the native submersed species (*Ceratophyllum demersum* and *Potamogeton nodosus*) from non-native ones (*Egeria densa*, *Myriophyllum spicatum*, *Potamogeton crispus*). However, distinction among the non-native species was not well achieved, especially in the western region of the Delta where green algae obscured the spectral signal of *Egeria densa* and *Myriophyllum spicatum* was confused with *E. densa* (Santos et al. 2012). Further, although the native *Stuckenia* sp. had a distinct spectral signature in greenhouse tanks, patches were too small to be detected by remote sensing in the area of the Delta studied (Santos et al. 2012). Mixed species stands are also problematic for remotely determining species presence and extent. Hence, on the ground monitoring is necessary to complement the remote sensing work.

Below, we summarize what is known of the spatial and temporal extent of each of the four species emphasized in this review, primarily resulting from individual grant-funded efforts that provided a window into the distribution over, at most, a few years at a time.

*Egeria densa* is thought to have been introduced to the Delta in 1946 (Light et al. 2005) through aquarium dumping and has spread throughout the region, covering more than 2000 hectares (Anderson 1990; Foschi et al. 2004; Santos et al. 2009). It may have replaced native submersed aquatic plants in much of this area (Lund et al. 2007). One study documented a greater acreage of and percent cover in the central Delta in fall (October 2007) than in the summer (June 2008) (Santos et al. 2011, see Fig. 2.1). Though its biomass declines in winter, it maintains aboveground shoots (Pennington and Systma 2009; Boyer et al. 2013, see Fig. 2.2). *Egeria* coverage expanded during the years between 2003 and 2007 (Santos et al. 2009). Active management (spraying with herbicide by the California Department of Boating and Waterways, now the CA Department of Parks and Recreation Division of Boating and Waterways) in areas such as Franks Tract has the potential to reduce acreages locally, especially if conducted in spring (Santos et al. 2009; see Fig. 2.4, acreage was reduced by >50% after fluridone spraying in April 2007, as opposed to spraying after July 1 in the other years). However, a very small proportion of the Delta is included in the management program, with the most area sprayed in any year covering only 2% of the Delta waterways (CDBW 2005; Santos et al. 2009). During periods of drought, this species shifts further east into the Delta (Boyer, pers. obs.), as its survivorship is very low at salinities of 5 and above (Borgnis and Boyer, in revision; see Section 4).

*Eichhornia crassipes* was introduced to the Sacramento River in 1904 by horticulturalists (Finlayson 1983; Cohen and Carlton 1998; Toft et al. 2003) or perhaps through garden escape (Light et al. 2005). Although it was noted to have declined in coverage in the recent past due at least in part to management activities (CDBW 2005; Santos et al. 2009), there has been massive population growth since 2011 (although we have not seen estimates of acreage), which may be partly attributable to a delay in spraying over several years owing to permitting issues (Breitler 2014). Positions of colonies can shift within a season and from year to year due to drifting (Santos et al. 2009).

*Ceratophyllum demersum* was documented to change in abundance seasonally, with greater acreage and percent cover in October 2007 (284 ha, 44% cover of the waterways sampled) than in June 2008 (59 hectares, 9%) within the same central Delta region (Fig. 2.1, Santos et al. 2011). A similar pattern was

found at Fisherman’s Cut, with rake detections at 70% in October 2012, but little to no presence in February, May, and July 2012 (Fig. 2.2, Boyer et al. 2013). However, its frequency of occurrence at Big Break varied considerably seasonally, with 40, 10, 30, and 5% detection over the four sampling periods in 2012, respectively. In the same study there were no detection at Decker Island, and less than 10% detection at Sherman Lake in any season (Fig. 2.2, Boyer et al. 2013). We found no records of *C. demersum* variation in abundance over longer periods of time.

*Stuckenia* sp. appears to have increased in acreage over the last several decades (Fig. 2.6, from Boyer et al. 2015). Comparing digitized imagery, there was little change in acreage between 1993 and 2002; however, there was about a 30% increase in acreage (43 hectares) in the Suisun Bay region between 2002 and 2012, with many new, mostly small beds occurring along nearly every stretch of shoreline and large increases in acreage in the cove on the southwest side of Ryer Island and along the south sides of Simmons and Chipps Islands. In the west Delta, a similar increase in acreage (37 hectares) appears to have occurred over the decade ending in 2012, a 13% increase since 2002. Biggest gains in this region were in Sherman Lake, offshore and to the west of Sherman Island, and to the west of Winter and Browns Islands (Fig. 2.7).

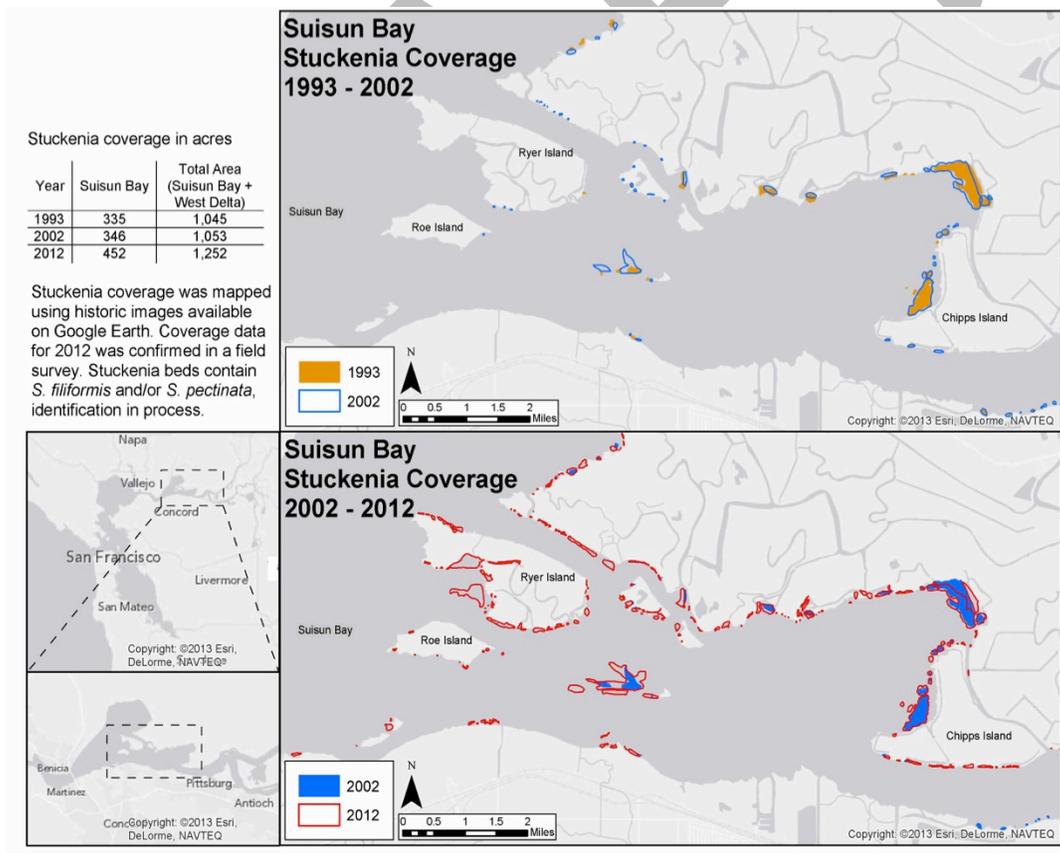


Figure 2.6. Decadal changes in coverage of *Stuckenia* sp. within Suisun Bay, as mapped using digitized and ground-truthed Google Earth images. From Boyer et al. 2015

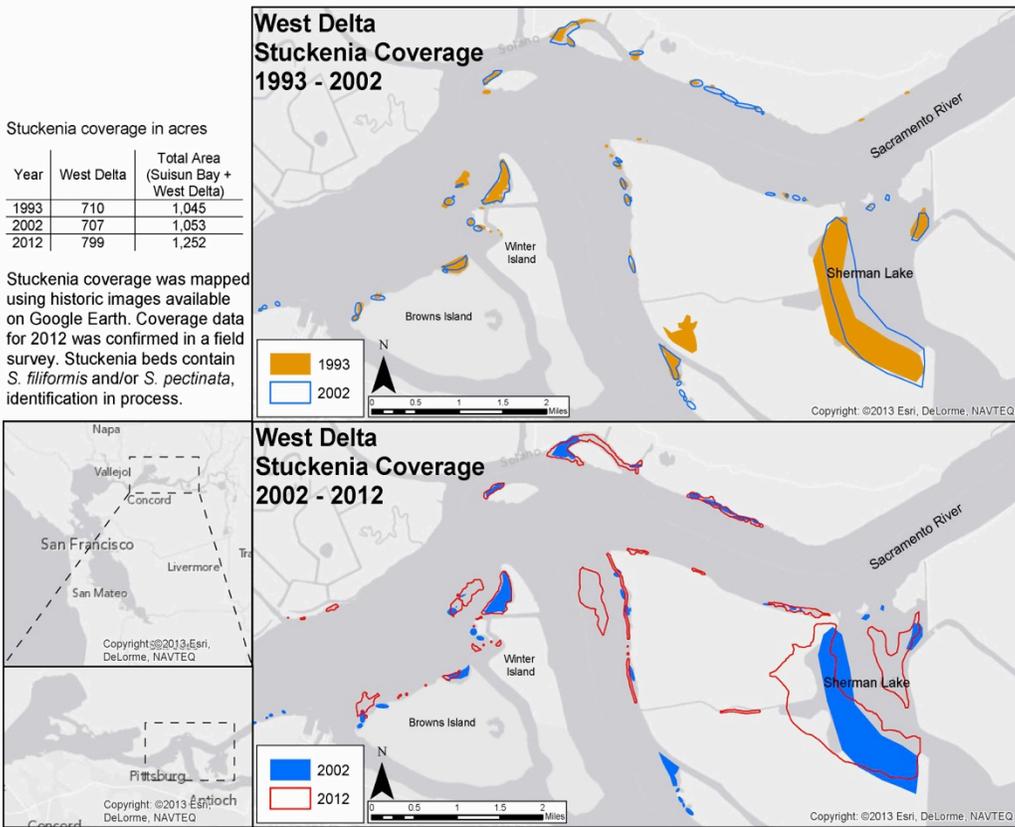


Figure 2.7. Decadal changes in coverage of *Stuckenia* sp. within the western portion of the Delta, as mapped using digitized and ground-truthed Google Earth images. From Boyer et al. 2015

### 3. Role of Submersed and Floating Aquatic Vegetation in Supporting Delta Ecosystem Services

Submersed and floating aquatic vegetation are natural components of estuaries, providing benefits in the form of carbon storage, uptake of nutrients, oxygenation of waters, trophic support through direct consumption by grazers or contributions to the detrital food web, provision of surfaces for algal and invertebrate attachment (also providing trophic support), and predation refuge for small fish. Negative effects tend to emerge in the case of non-native species that have invaded large areas and that have characteristics unlike those of the native species, thus leading to undesirable changes in a number of factors, including nutrient dynamics and food web support. Here we review both the positive and negative effects of submersed and floating vegetation, based on the published literature from other regions as well as local studies where available.

#### 3.1 Conceptual View of Positive and Negative Effects of Submersed and Floating Aquatic Vegetation on Ecosystem Services.

Anderson (2008) proposed a draft conceptual model of the effects of submersed, floating, and emergent vegetation on water quality and fish habitat in the Delta (Fig. 3.1). In general, sparse, open canopies of any species are expected to have fewer negative effects, and native submersed species (e.g., *Stuckenia* sp.) are thought to have many positive effects. In contrast, dense canopies of floating plants (primarily *Eichhornia crassipes*) shade phytoplankton and exclude submersed native plants such as *Stuckenia*. Dense stands of submersed plants (primarily *Egeria densa*) can draw down oxygen at night, increase water temperatures by increasing water residence time, increase pH to the benefit of plants that can utilize bicarbonate as a carbon source (e.g., *E. densa*, see Section 4.1.4), and harbor large non-native fish in the shadows of the canopy, leading to predation on smaller adult and juvenile native fish. In contrast, the open water beneath sparse canopies of native *Stuckenia* sp. may provide a more stable dissolved oxygen setting, ample and accessible invertebrate food resources, a paucity of large predator hiding places – in all, a more suitable habitat for native fish species (Fig. 3.1). Below, we detail a number of adverse effects documented for *Egeria densa* and *Eichhornia crassipes* when they become dense and widespread in invaded regions. These include excessive organic matter accumulation, a decline in phytoplankton and native plants, a change in the physical structure of the habitat, alterations of trophic interactions, changes in water quality, impediments to navigation and industry, and visual impacts.

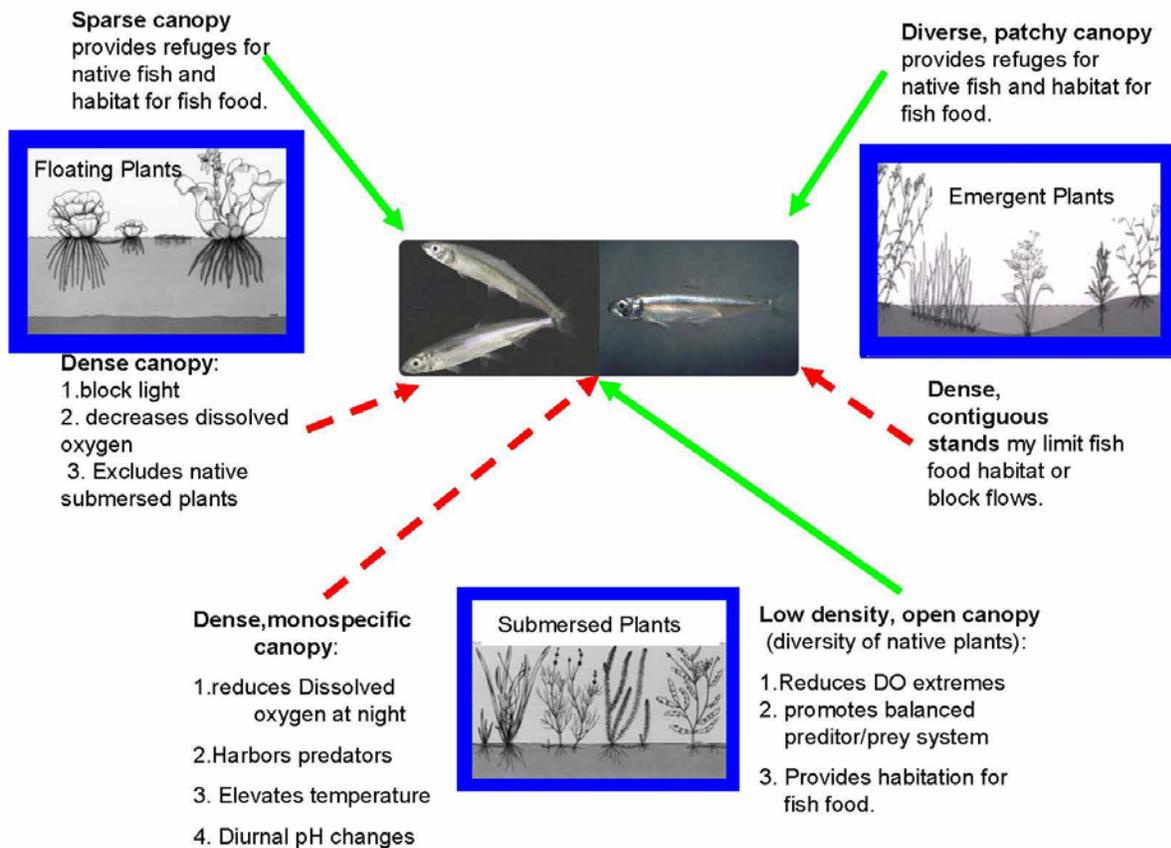


Figure 3.1. Conceptual model of the effects of Delta macrophyte canopy structure on provision of fish habitat. Arrows show direction and primary effect caused by interaction of each “ecological type” of aquatic plant on fish (red, dashed = negative effect, green, solid = positive effect. From Anderson 2008

### 3.1.1 Organic matter subsidy/accumulation

When aquatic vegetation sheds leaves and other tissues, especially during winter senescence or following herbicide application, this material contributes organic matter to the system, and specifically to the sediments over time. While detritus fuels a portion of the food web, excess organic matter can constitute a ready supply of nutrients that further fuels blooms of aquatic vegetation. Natural senescence of *Eichhornia crassipes* is generally slow and occurs during fall and winter (Carignan and Neiff 1992; Pinto-Coelho and Greco 1999; Battle and Mihuc 2000). *E. densa* sheds some biomass in winter but does not fully senesce (Fig. 2.2). For both species, high abundances increase the seasonal contribution of organic matter to the system. Further, control methods that leave the chemically-treated or shredded material in place contribute to the organic matter and nutrients available in other times of the year than natural senescence typically occurs (e.g., spring or summer) (Greenfield et al. 2006). This organic matter becomes a labile source of nutrients through remineralization to inorganic forms, which are then available to rooted plants through the sediments or floating plants through diffusion into the water column. As aquatic vegetation expands in coverage, this large contribution of organic matter from both natural senescence and management of these abundant plants represents

eutrophication. Defined as an increased rate of organic matter supply in an ecosystem (Nixon 1995), eutrophication is manifested by this vascular plant source of organic matter in the Delta, even though more typically-identified signs of eutrophication such as macroalgal and phytoplankton blooms are minimal.

### 3.1.2 Limitation of microalgae and native submersed and floating macrophytes

Shading of the water column by floating macrophytes or by dense canopies of submerged vegetation can reduce light available to phytoplankton and benthic microalgae. Although the plants can reduce suspended sediment concentrations through baffling of particles out of suspension, shading can cancel out any potential positive effects of sediment removal to these other primary producers. In addition, a number of submersed and floating macrophytes, including *Eichhornia crassipes*, have been noted to have allelopathic effects on algae and microbes (Shanab et al. 2010).

Native species of submerged vegetation may be replaced when an introduced floating or submersed species becomes invasive, taking available space and outcompeting the natives. Native species may be deemed inherently valuable, or may serve particular functions such as in food web support, the loss of which would be considered undesirable (Fig. 3.1, 3.2).

### 3.1.3 Habitat alteration

In general, submersed vegetation has the potential to slow the velocity of water, thereby initiating a positive feedback loop in which the favorable lower flows permit greater growth and spread. The density of the vegetation throughout the water column influences the degree to which water flow is affected (>40% reduction in dense beds; Wilcock et al. 1999) and varies with both plant morphology and density. Submerged plants may also facilitate the

establishment and spread of floating plants through reduction in flow, permitting floating plants to better remain in place and spread locally. Dense submersed vegetation is also capable of reducing suspended sediment, creating clearer water in the vicinity of the plants. Increased water clarity may affect predator-prey interactions within the invertebrate and fish assemblage, as visual predators may be more successful at locating prey. Dense plant canopies may hinder movement of some fish species (Brown 2003).

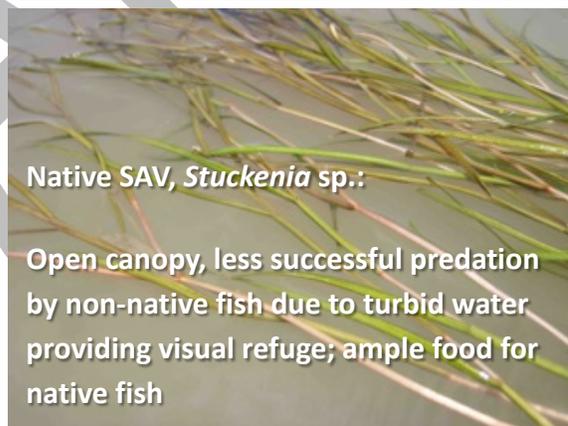


Figure 3.2. Conceptual model hypothesizing loss of function in invasive *Egeria densa* versus native *Stuckenia* sp. beds

Submersed vegetation provides surfaces for the growth of epiphytic algae and attachment points for filamentous algae, which also form mats in water slowed by the submersed vascular plants (Fig. 3.3). These in turn affect the habitat and food availability to invertebrates and fish, and can influence nutrient cycling; e.g., filamentous algae attached to *Potamogeton crispus* was found to increase phosphorus retention of an experimental pondweed assemblage (Engelhardt and Richie 2002). These algae can also



Figure 3.3. Green filamentous algal mats attached to *Egeria densa* in Sherman Lake, May 2012.  
Photo, Katharyn Boyer

be considered nuisance species if they become overly abundant. Observations of thick green algal mats attached to *E. densa* have been made in the west Delta (Santos et al. 2012; Boyer unpublished, Fig. 3.3).

Floating vegetation is less likely to reduce water motion than submerged vegetation, but species that densely cover the water surface, especially with aerial structures, may have the ability to reduce the generation of wind waves across the water surface. Floating species have a great potential to shade the underlying water, especially when they form dense colonies.

#### 3.1.4 Trophic support

Macrophyte invasion can lead to changes in structural complexity of the habitat, altering composition and abundance of invertebrates. Such changes can have cascading effects on higher trophic levels. Direction and magnitude of change are difficult to predict in terms of desirable food for fish; however, thick stands of *Egeria densa* are thought to make access to potential invertebrate food resources difficult for fish, while dark, shadowy hiding places promote ambush of small native fish by larger non-native predatory species. *Egeria densa* impedes the movement of several fish species of concern, including salmonids, splittail, and Delta smelt (Brown 2003). With its thickly growing stems extending throughout the water column, it creates shadowy hiding places where non-native fish may be able to ambush juvenile and small native fish (e.g., juvenile salmon, Delta smelt). Because of these negative effects on the food web, it is a major concern for the restoration of tidal wetlands in Delta habitats in places where it is very abundant (Simenstad et al. 2000).

*Eichhornia crassipes* also modifies the food resources available to higher trophic levels. Floating macrophyte invasion of open water can increase the surface area available for epiphytic invertebrate colonization (Brendonck et al. 2003). However, when native floating macrophytes are replaced, there can be a large shift in species composition of the invertebrate group present. For example, in the Delta, large differences in the epiphytic invertebrate assemblage were found on *E. crassipes* versus the native floating species, pennywort (*Hydrocotyle umbellata*) (Toft et al. 2003). Microcrustacean zooplankton can be more abundant with no vegetation than with *E. crassipes* present (Bredonck et al. 2003). A study in Uruguay found calanoid and cyclopoid copepods to be less abundant at sites with *E. crassipes* than with *Stuckenia pectinata* or no vegetation (Meerhoff et al. 2003). Still, the literature on *E. crassipes* effects on zooplankton are inconsistent, perhaps because there are many factors that might interact to affect zooplankton, including the effects of density of *E. crassipes* on predator abundance (Villamagna and Murphy 2010).

In terms of food web support for fish, consumption of *E. crassipes* appears to be minimal, as it is a nutritionally poor diet choice for herbivorous fish (Cowx 2003). For carnivorous fish, the presence of *E. crassipes* may shift the invertebrate foods available relative to those on native species of aquatic vegetation (Toft et al. 2003). Large drawdowns in dissolved oxygen (see next section) under dense or decomposing mats of *E. crassipes* can be dangerously low for fish, and levels less than 4.8 mg l<sup>-1</sup> are considered detrimental (reviewed by Villamagna and Murphy 2010). The abundance of *E. crassipes* is linked to the value of the habitat it creates for fish; at some (undefined, and probably site-specific) lower level of abundance, adequate light for phytoplankton production to support zooplankton, surfaces for invertebrate attachment, and dissolved oxygen all support fish presence and diets, while at higher abundance these features are diminished or even threatening to fish (McVea and Boyd 1975; Brown and Maceina 2002).

Similarly, for birds, presence of *Egeria densa* or *Eichhornia crassipes* may benefit certain birds through provision of invertebrate or fish prey attracted to the physical structure; however, access to these prey becomes diminished when canopies become excessively dense (Brendonck et al. 2003), and declines in dissolved oxygen (see below) that affect prey would also limit value to birds. Neither of these species is known to be a valuable food source for birds themselves although American coots are known to eat *E. crassipes* (Villamagna 2009). In contrast, *Stuckenia pectinata*, a native species subject to replacement by these two invaders, is a very nutritious food source that was heavily used by canvasback ducks historically (Jepson 1905).

### 3.1.5 Changes in Water Quality

Submersed and floating aquatic vegetation can have large effects on water column nutrients and on dissolved oxygen. *Eichhornia crassipes* is used in a number of regions as a tool to remove nutrients from the water column, which can be effective if the plants are later harvested. In contrast, large contributions of decomposing biomass to sediments can occur where extensive blooms of floating or submersed vegetation occur and are left to sink, which can support a long-term supply of nutrients back to the water column to further fuel vegetation blooms (Greenfield et al. 2007; see Section 3.1.1).

Unlike phytoplankton and submersed vegetation, floating species such as *Eichhornia crassipes* do not contribute measurable amounts of dissolved oxygen to the water column (Meerhoff et al. 2003). In fact, dense mats of *E. crassipes* can lead to large reductions in dissolved oxygen through prevention of gas exchange at the water's surface (Hunt and Christiansen 2000) and through shading photosynthetic species in the water including phytoplankton and submersed vascular plants. Further, decomposition of *E. crassipes* following senescence, or shredding or spraying in control efforts, can lead to chronic drawdown of dissolved oxygen in the water column, creating unfavorable conditions for fish and invertebrates and in extreme cases, fish kills (dissolved oxygen concentration  $<2.3 \text{ mg l}^{-1}$ ; US EPA 1986). In addition, decreased oxygen in the sediments can increase mobility of phosphorus, contributing to nutrient loading (Scheffer and Van Nes 2007). Further, high abundance of submerged macrophytes can lead to increased pH as  $\text{CO}_2$  is drawn down during photosynthesis, leading bicarbonate ( $\text{HCO}_3^-$ ) to become the primary form of DIC available (Sand-Jensen 1989; Santamaria 2002) to the advantage of species that can use bicarbonate efficiently (e.g., *Egeria*, Cavalli et al. 2012).

### 3.16 Navigation and industry

Submersed and floating vegetation both have the capacity to clog navigation channels, marinas, intake pipes for potable water supply, industry, and agriculture. Highly productive aquatic plant beds can have devastating effects on local economies and quality of life for recreational users of waterways. Thick mats of *Egeria densa* hinder a wide variety of recreational and commercial activities, including boating, fishing, swimming and water pumping for potable supply and irrigation (Bossard et al. 2000). *Eichhornia crassipes* can grow so densely on the water's surface that it impedes navigation by recreational motorboats and ships, becomes entrained in water pumps, and chokes irrigation channels (Bossard et al. 2000; Toft et al. 2003).

### 3.1.7 Aesthetics

Some invasive macrophytes are very attractive, but lose their aesthetic appeal when there is a loss of commercial, industrial, municipal, and recreational use. *Eichhornia crassipes*, in particular, has very showy and attractive purple flowers, a likely reason for its original introduction in many areas of the world.

## 4. Factors Contributing to the Prevalence of Submersed and Floating Aquatic Vegetation in the Delta

### 4.1 Conceptual Models of Growth, Propagation and Environmental Characteristics that Enhance or Limit Growth

There are a number of factors known to influence aquatic vegetation in low salinity and fresh regions of an estuary. Anderson (2008) developed a draft conceptual model to describe the ways in which submersed, floating, and emergent vegetation are likely to respond to and modify conditions within the Delta. This effort included a general model for establishment, growth, and dispersal, reprinted here as Fig. 4.1. To briefly review this model, both submersed and floating macrophytes are influenced by light levels, with submersed plants adapted to lower light conditions. Carbon dioxide limits photosynthesis especially for submersed plants in thick stands where drawdown and high pH reduce availability, but many submersed species are capable of substituting bicarbonate as a source of inorganic carbon. Water quality conditions, including nutrient levels, are known to strongly influence growth of these species. Sediment characteristics, including nutrients and grain size distribution affect growth and anchoring of submersed vegetation. Local flow conditions help to maintain floating plants in place and help submersed species to accumulate large quantities of biomass.

Anderson (2008) described “sub models” for submersed and floating species which further detailed important determinants of establishment, growth, and dispersal for each vegetation type. These are reprinted here as Fig. 4.2A and B. Below we review these sub models in detail and the literature supporting each of them.

**Aquatic Plant Resource Requirements for Establishment, Growth and Dispersal**  
 Delta Hydrodynamics: tidal flows; seasonal variations in nutrients, sediment loading and temperature interact with these drivers (See Hydrodynamic Submodels)

Arrows show resources acquired through common driver-pathways (overlapping circles) among the three ecological/ growth forms of aquatic plants: Emergent, Floating and Submersed. Overlaps occur where the plant types share access to resources and where drivers impact both plant types.

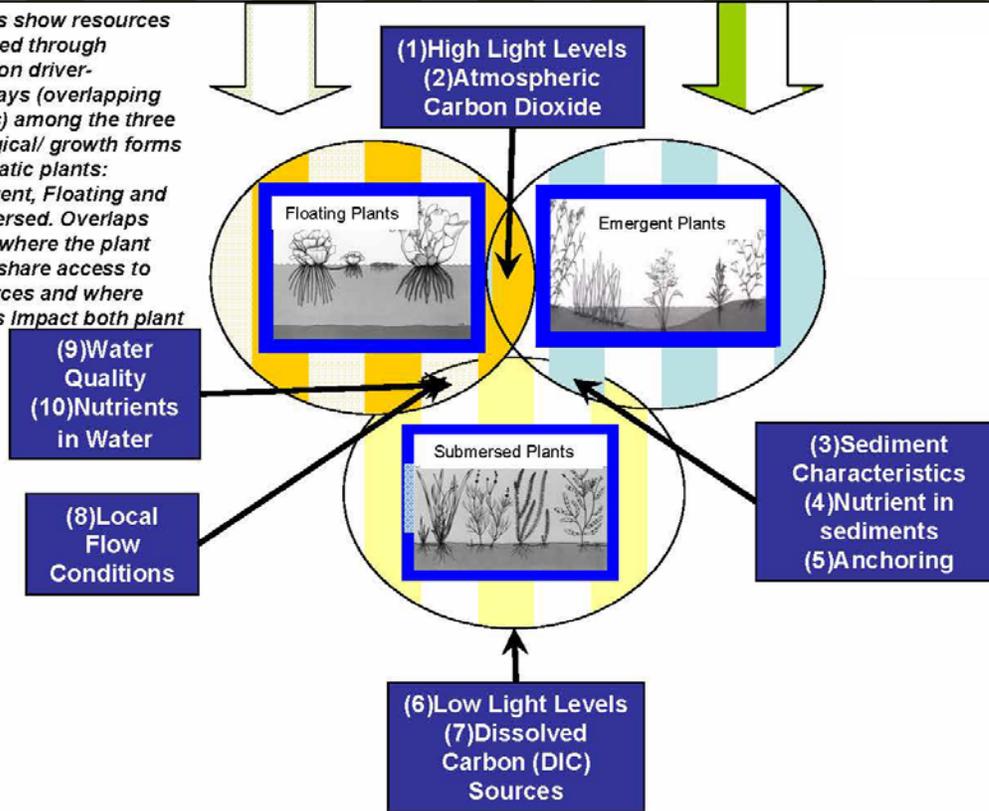


Figure 4.1 Aquatic plant resource requirements for establishment, growth and dispersal, as described in a draft conceptual model by Anderson (2008)



### 4.1.1 Light

Light is essential to photosynthesis in all plants and is generally adequate for floating species such as *Eichhornia crassipes*. Floating species can benefit by shading submerged plants (see Section 4.1.7 below), which frees other resources such as nutrients and favors development of sustainable floating macrophyte populations (Fig. 4.2B).

Submersed species must cope with lower light conditions than floating species due to attenuation of photosynthetically-active radiation (wavelengths of 400-700 nm, PAR) through water. PAR is further attenuated by particles in the water, including sediments and phytoplankton. Light availability is very important to establishment of submersed species at the sediment surface (Fig. 4.2A), whether from seeds or turions in *Stuckenia* sp. or fragments in *Ceratophyllum demersum* or *Egeria densa*. After establishment, dense plant growth can lead to self-shading of tissues lower in the water column. However, dense growth of *E. densa* reduces turbidity of the water, leading to greater light penetration (Fig. 4.2A). *Stuckenia* sp. has evolved a canopy of leaves within the upper portion of the water column, which provides access to higher light levels near the surface, and its relatively sparse leaf growth minimizes self-shading. This sparse leaf growth does not appear to reduce the turbidity of the water (Boyer pers. obs.).

Experimental work also supports that light is likely to be quite limiting to lower portions of plant tissue in dense *Egeria densa* beds. In one local experiment testing light effects, *E. densa* had 4-fold lower biomass under conditions comparable to those measured in beds in the Delta at 1 m depth ( $215.5 \mu\text{M}$  quanta  $\text{m}^{-2}\text{s}^{-1}$ ) compared to levels 2x greater (Borgnis and Boyer, unpublished data). In a New Zealand mesocosm study, reduced light (25% reduced from 50% incident level) was found to be a more important factor controlling *E. densa* than was temperature (tested at 20, 26, and 30°C) (Riis et al. 2012). Interestingly, a Brazilian study found that apical shoots of *E. densa* expanded more rapidly than those under high light exposure, suggesting a mechanism by which *E. densa* can extend its canopy upward through the water column (Rodrigues and Thomaz 2010).

### 4.1.2 Temperature

Warm temperatures are expected to favor the establishment and growth of both floating and submersed species and to produce localized warming of waters through reduction in water flow, which in turn should benefit plant growth (Fig. 4.2A-B). However, high water temperatures within the range found currently in the Delta might limit growth of some species, and temperatures are expected to increase with climate warming (Knowles and Cayan 2002). A 2012 experiment testing temperature effects on growth of *E. densa* apical shoot sections in aquaria showed substantial increases in aboveground biomass, total shoot length, and mean root length at a water temperature of 22°C (the average measured in the west Delta in summer) in fresh water, with similar effects at 26°C, although much less of a biomass response (Fig. 4.3, Borgnis and Boyer in revision). In contrast, there were great reductions in all these measures at 30°C (Fig. 4.3), which is within the current range of maximum temperatures measured for the west Delta (Borgnis and Boyer, in revision). Further, testing these temperatures at a salinity of 5, which can be found in the west Delta in drought years (e.g., fall of 2012-

2014), led to reduced root length at all temperatures. At a salinity of 10, the negative effects of high temperature (30°C) were amplified and led to greatly reduced aboveground biomass (Fig. 4.3).

We know of no local experiments testing temperature effects on *Eichhornia crassipes*, *Ceratophyllum demersum*, or *Stuckenia* sp. In other regions, *Eichhornia crassipes* has been shown to benefit from warming above ambient conditions. In China, *E. crassipes* rates of relative growth and clonal propagation increased by 15% with an increase in water temperature from 24 to 26-27°C in mesocosms (You et al. 2014).

#### 4.1.3 Salinity

In general, species in the Delta thrive under current conditions of fresh water maintained through water management practices to support potable, industrial, commercial, and agricultural uses. This is in contrast to the historic condition of brackish waters prior to water management practices. In the past several years of drought, late-summer water salinities of 5 or more have reached east to the Sherman Lake region of the Delta. Salinity could further increase in the Delta through several mechanisms stemming from climate change and water management. Sea-level rise and shifts in magnitude and timing of snowmelt events are projected to increase salinity levels by 1-3 in this region by 2090 (Knowles and Cayan 2002). In addition, extended periods of drought could lead to increased salt penetration not counteracted by reservoir releases during the summer months. There is also potential for levee failures through erosion or earthquakes, leading to a higher volume of saline tidal waters reaching up-estuary. Finally, management actions that inadvertently or deliberately reduce fresh water releases during the dry season could increase salinity in this region. Summer and fall salinity has already increased in the last 25 years due to management of fresh water releases from water control structures (Knowles and Cayan 2002; Contra Costa Water District 2010). C&H Sugar Refining Company (Crockett, CA) has long tracked salinity in order to access fresh water for its refining process;

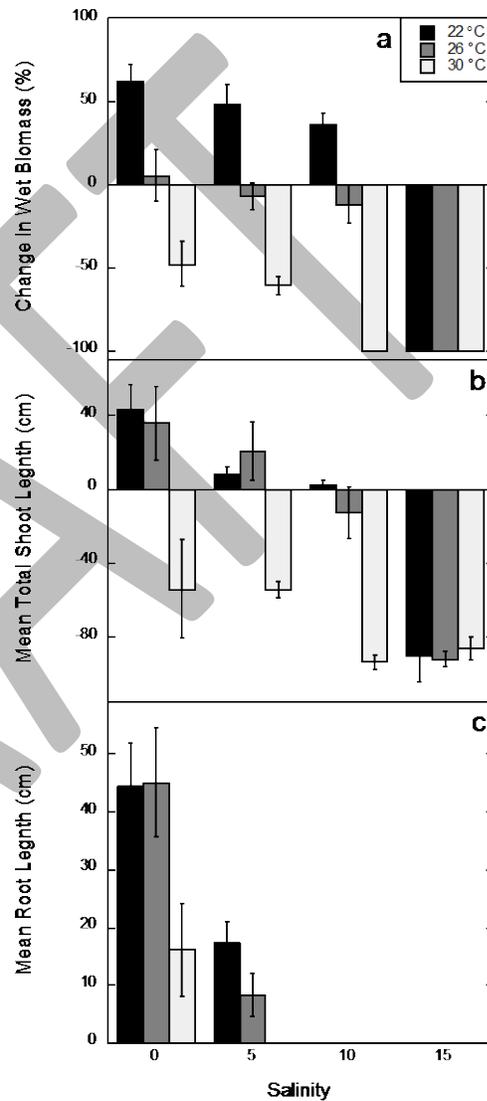


Figure 4.3. Response of *Egeria densa* to a range of temperature conditions applied at increasingly high salinity conditions at the end of 6 weeks in aquaria. From Borgnis and Boyer, in revision

its data show annual salinity intrusion now occurs much earlier in the year in Suisun Bay (beginning of March) compared to the early 1900s (beginning of July) (Department of Water Resources 2010).

As mentioned, *Egeria densa* is strongly limited by salinity in Delta waters. As in the six-week temperature-controlled aquaria experiment described above, a three-month experiment conducted in large tanks in a greenhouse in 2012 showed *E. densa* negative responses to a salinity of 5, with a 5-fold decrease in biomass relative to the freshwater treatment (Fig. 4.4, Borgnis and Boyer, in revision). At salinities of 10 and 15, mortality and decomposition occurred within three weeks. This was in contrast to 5-fold increases in shoot biomass in freshwater over the three months, and nearly 10-fold increases in the number of shoots and in root biomass (Fig. 4.4). Tissue nitrogen (N) concentration stayed constant at salinities of 0 and 5; however, tissue phosphorus (P) increased at a salinity of 5 (and thus N:P also), suggesting that P taken up could not be utilized and thus accumulated in the tissues, perhaps another indication of stress at this higher salinity.

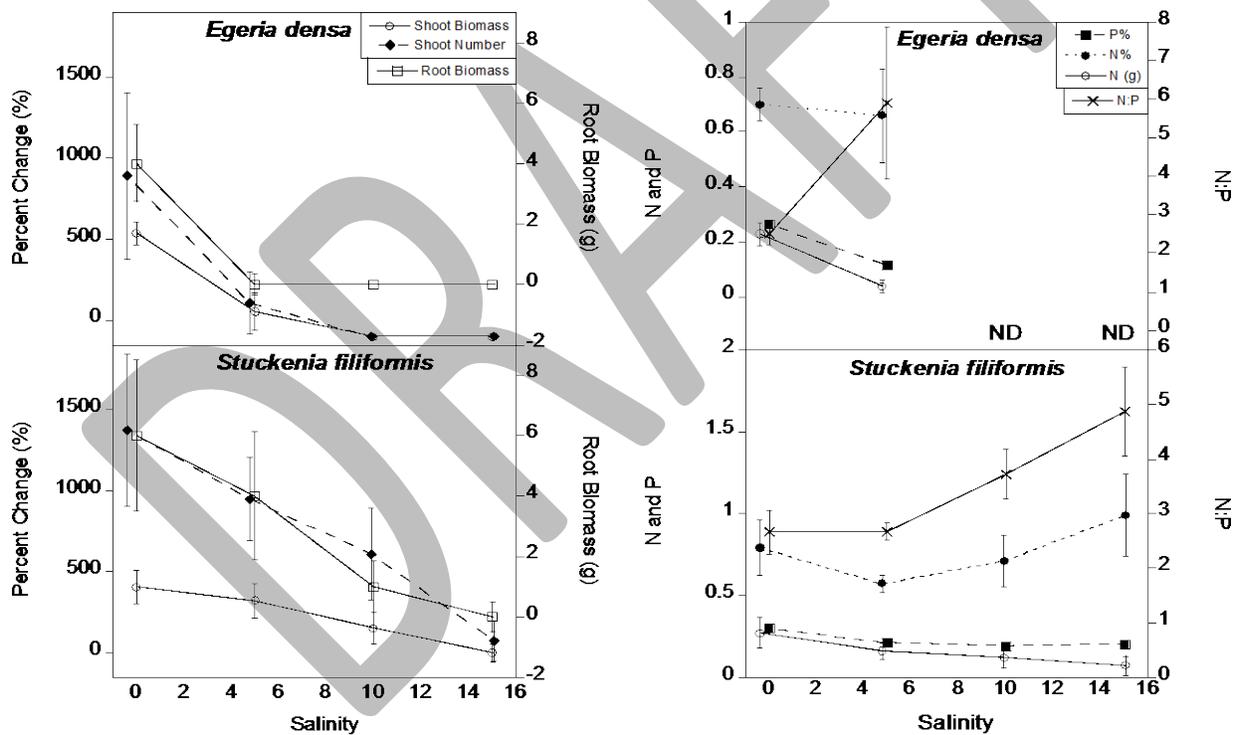


Figure 4.4. Salinity effects on growth characteristics and nitrogen and phosphorus content and ratio of *Egeria densa* and *Stuckenia* sp. (gross morphological characteristics most closely matched *S. filiformis*) at the end of mesocosm experiment that ran June-August 2012. ND = no data; *E. densa* tissue nutrients could not be measured at the higher salinities due to insufficient tissue availability. From Borgnis and Boyer, in revision

Of all aquatic macrophyte species found within the Delta, *Stuckenia sp.* is expected to have the greatest tolerance for salinity. This assumption is due in part to its distribution in waters that can reach salinities of 15 within Suisun Bay. Further, in six weeks in greenhouse mesocosms, *Stuckenia sp.* biomass accumulated greatly (~4x initial) at salinities of 0 and 5, doubled at 10, and was unchanged at 15 (Fig. 4.4; Borgnis and Boyer, in revision). Increases in both N and P concentrations in tissues at higher salinities (Fig. 4.4) suggests an inability to utilize all available nutrients, and perhaps the accumulation of N as “compatible solutes” to balance water potential as is common in saline wetland plants (REF).

We are not aware of any local studies of salinity tolerance on *Ceratophyllum demersum* or *Eichhornia crassipes* but based on distribution, we would surmise that *C. demersum* has some ability to tolerate low salinities (perhaps up to a salinity of 5), and that *E. crassipes* has less.

#### 4.1.4 Dissolved inorganic carbon

Floating vegetation should be able to access adequate carbon dioxide to fuel photosynthesis; however, availability of dissolved inorganic carbon (DIC) can be an important limiting factor to submersed species. The forms of carbon dissolved in the water are determined by pH (Barko and Smart 1981; Sand-Jensen 1989). Although CO<sub>2</sub> is the form of DIC preferred by all autotrophic organisms (Raven 1970), drawdown of CO<sub>2</sub> leads to increased pH. This is because CO<sub>2</sub> in solution is in equilibrium with carbonic acid (H<sub>2</sub>CO<sub>3</sub>), which becomes more common, leading to removal of protons from the water (thus a higher pH). This, in turn, has an effect on the relative concentrations of the other DIC forms in the water and bicarbonate (HCO<sub>3</sub><sup>-</sup>) becomes the primary form of DIC available (Sand-Jensen 1989; Santamaria 2002). Species that can utilize bicarbonate efficiently should have an advantage in the waters of the Delta.

Both *Egeria densa* and *Ceratophyllum demersum* are able to efficiently utilize bicarbonate as a DIC source (Cavalli et al. 2012), which may partly explain their success within the Delta, with the heightened pH in dense beds leading to further advantage over time through positive feedback (Fig. 4.2A). However, one study of *E. densa* in New Zealand experimentally manipulated dissolved carbon, temperature, and light found temperature and light to be more important in limiting *E. densa* relative growth rates than carbon (Hussner et al 2014).

#### 4.1.5 Nutrients

The primary nutrients limiting plant growth are N and P. Limitation is typically determined by adding one or more nutrients to ascertain if the potential rate of net primary production has been achieved (Howarth 1988); in other words, if the plant grows with added nutrients, then it has greater potential for production than what its ambient nutrient environment allows. At temperate latitudes, phosphorus is generally considered the primary limiting element to system primary production in freshwater, and nitrogen is considered the primary limiting element in marine systems, although there is variation in this pattern (Smith 1984). N may be less limiting in freshwater due to a greater importance of N fixation there (Howarth et al. 1995, 1999; Paerl et al. 1995), and a greater efficiency of sediments in sequestering P than in marine systems (Caraco et al. 1990); however, both N and P have been shown to be important in estuaries (McComb et al. 1981; D’Elia et al. 1986) under different conditions and seasonally (Conley 2000).

The San Francisco Estuary is an example of a system replete in both N and P, and yet depauperate in phytoplankton production (Cloern 2001). The annual loading rates of both N and P are higher in San Francisco Estuary than in the Chesapeake, and yet large phytoplankton blooms and mortality common in Chesapeake, followed by large drawdowns in dissolved oxygen concentration, do not typically occur in the San Francisco Estuary (Cloern et al. 2001). Thus, San Francisco Estuary is not considered to be a eutrophic system in terms of algal production; phytoplankton may be limited by high levels of turbidity, abundant consumers including introduced clams (Jassby and Cloern 2000), and possibly by the ratios of species of N available (i.e., ammonium versus nitrate, Wilkerson et al. 2006).

High nutrient availability is often cited as at least partly responsible for the extensive growth of the invasive *Egeria densa* and *Eichhornia crassipes* within Delta waters. *Egeria densa* is able to take up nutrients through its leaves and roots, thus accessing water column nutrients from both the water column and the sediment. Studies differ on whether it preferentially take ups nutrients from its roots (Barko and Smart 1980) or shoots (Feijoo et al. 2002). *Eichhornia crassipes* accesses nutrients through its roots hanging at the surface of the water column (Klumpp et al. 2002; Rommens et al. 2003). Although many experiments have tested the effects of nutrients on phytoplankton growth under different scenarios of light, temperature and other variables (e.g., Wilkerson et al. 2006), we know of no comparable local experiments conducted on aquatic macrophytes. Further, although there are current efforts to document nutrient conditions inside and outside of submersed macrophyte beds (Boyer, unpublished), we are aware of no previous studies that have monitored macrophyte bed nutrient concentrations in the Delta.

In other regions, studies of nutrient limitation on *Egeria densa* have shown mixed results. A Florida mesocosm experiment repeated in two different seasons in Florida (April-June and October-December) found no effects of fertilizer (N:P:K of 15-9-12 in slow release fertilizer added to the sediment in a range of concentrations from 0 to 4 kg/g sediment on *E. densa* biomass (Mony et al. 2007). However, in *E. densa*'s native range in Argentina, biomass and nutrient content were positively correlated with nutrient concentrations (phosphate and ammonium) in the water and in sediments (as total N) (Feijoo et al. 1996). An experiment by that same group found ambient levels of phosphate ( $0.3 \text{ mg l}^{-1}$ ) led to significantly greater biomass than phosphate at half of ambient concentrations (Feijoo et al. 2002). In a separate experiment, they found that ammonium was absorbed more readily than nitrate (added at ambient concentrations of  $6 \text{ mg DIN l}^{-1}$ , separately), leading to higher concentrations of tissue N with ammonium; however, this did not translate to differences in biomass (Feijoo et al. 2002). A comparison across the two experiments found phosphate was more readily absorbed by *E. densa* than nitrogen in either form, and that water column uptake was greater than from sediments (Feijoo et al. 2002). A study in Florida also found *E. densa* to prefer ammonium over nitrate when both were present in the water in equal amounts at concentrations considered to be non-limiting ( $10.5 \text{ mg l}^{-1}$  of each DIN source, plus phosphate at  $3 \text{ mg l}^{-1}$ , as found in sewage effluent, Reddy et al. 1987). In a separate experiment, these authors varied concentration of ammonium and phosphate (range of 1-4 mg N and 0.2 to 0.8 mg P  $\text{l}^{-1}$ , respectively); although they did not report biomass data, they noted that biomass was *greater* at low nutrient concentrations than at high. N and P removal rates were estimated to be  $186\text{-}408 \text{ mg N m}^{-2} \text{ day}^{-1}$

<sup>1</sup> and 122-228 mg P m<sup>-2</sup> day<sup>-1</sup> from the water column (Reddy et al. 1987). Importantly, *E. densa* uptake of both nutrients was similar in summer and winter experiments.

To summarize our review of studies on *Egeria densa* in relation to nutrients, there is not a clear link between biomass of this species and nutrient availability. Although N and P are essential nutrients, we cannot point to a threshold in water column nutrient supply that leads to large blooms of this species based on the literature. One factor that complicates the relationship of this species' abundance to nutrients is that organic loading of sediments, after years of invasive macrophyte contributions, is likely to provide an ample supply of remineralizable nutrients to rooted macrophyte growth, with perhaps little correlation to availability of nutrients in the water column. Further, the positive feedback of declines in dissolved oxygen making sediment-bound P more available suggests that this important nutrient will continue to be sourced from the sediments as large mats of decomposing macrophyte tissues continue to be incorporated into the sediments. A rooted species like *E. densa* with the capability of accessing nutrients from both the water column and the sediments would be very difficult to manage by simply reducing water column nutrient supply.

*Eichhornia crassipes*, with access to nutrients only from the water column, is perhaps a simpler case. In a mesocosm study on *E. crassipes* in China, nutrient additions to oligotrophic lake water (0.6 mg l<sup>-1</sup> total N and 0.05 mg l<sup>-1</sup> total P), raising N to 5 mg l<sup>-1</sup> (using NH<sub>4</sub>NO<sub>3</sub>) and P to 0.5 mg l<sup>-1</sup>, led to 30% increases in both relative growth rate and clonal propagation rate (You et al. 2014). Notably, the same elevated N level combined with a much higher P enrichment (1.0 mg l<sup>-1</sup>) led to 150% increases in these measures relative to the oligotrophic conditions simulated. In that same study, warming by 2-3 degrees had a much smaller positive effect on growth rate (15%, see above) and some effects of elevated temperature (increased shoot:root and foliar N) were found only when nutrient levels were also elevated (You et al. 2014).

Although water column nutrients are the only source available to *E. crassipes*, supply from the water column is still influenced by the deposition of organic matter to the sediments and fluxes to the water column of both N and P (the latter enhanced by low oxygen conditions). Hence, while management of water column nutrient supply might seem to be a straightforward solution that could reduce *E. crassipes* abundance, perhaps more easily than for *E. densa*, biogeochemical coupling with the sediments makes the implementation of such a strategy for either species a challenging proposition.

#### 4.1.6 Flow

Flow velocity and residence time of water within a given area are expected to influence both floating and submersed species. Propagules need to be able to stay in place to initiate bed establishment, which succeeds to a greater degree in more protected areas. Development of an aquatic plant bed slows flow in the immediate vicinity, a positive feedback loop that further supports bed development. Although the draft conceptual model of Anderson (2008) indicates the importance of substrate stability, it does not indicate the importance of this positive feedback (Fig. 4.2A). Densely growing submersed macrophytes like *Egeria densa* can reduce flow by 40% (Wilcock et al. 1999; Champion and Tanner 2000), favoring their continued presence and spread within the area. However, higher flow is important

to dispersal of propagules of all aquatic macrophytes to new areas (Fig. 4.2A) and water movement is essential for growth by bringing nutrients and CO<sub>2</sub> (and other inorganic carbon forms) to the leaves by mass transport.

#### 4.1.7 Chemical, mechanical, and biological control

Herbicide application has been the most common means of attempted control for both *Egeria densa* and *Eichhornia crassipes* to date (Anderson 1990, CDBW 2004). Legal challenges to herbicide control have led to new permitting and monitoring requirements (Siemering et al. 2005), leading to a re-evaluation of alternative control methods (Greenfield et al. 2006).

Mechanical removal of *Egeria densa* has been attempted in the Delta, but tends to produce fragments that then can become propagules for further spread locally and in distant locations through water movement (Anderson 2003). Mechanically gathering and harvesting *Eichhornia crassipes* can be effective in limited areas, but it is expensive to remove the heavy masses of plants with very high water content (Gopal 1987). Shredding of this species using shredder boats and leaving the plant material in place may be one option, although the resulting biomass and source of remineralizable nutrients as well as dissolved oxygen implications are both concerns (Greenfield et al. 2006; see above).

There is an extensive literature on the use of biological agents, including weevils and mites, as controls for *Eichhornia crassipes*. There are two commonly used weevil species from the plant's native range, in the genus *Neochetina* (Sosa et al. 2012). Typically, mechanical or chemical treatment is used first, making initial conditions more manageable for biological control (Adekoya et al. 1993). There is currently a project at the US Department of Agriculture labs in Albany, CA to investigate the possible use of a variety of biological control agents, including an ephydrid fly larva, on *Egeria densa* (David DuBose, pers. comm.). To our knowledge, no biological control methods have been attempted in the Delta to date. Although such methods may be desirable to avoid the concerns of non-target species effects of chemical application, the resulting biomass is still a major issue to contend with. *Neochetina* spp. weevils are used to reduce buoyancy of *Eichhornia crassipes* (Wilson et al. 2007), making it sink to the bottom and decompose; presumably any biological control method would result in large contributions of decomposing tissues to draw down oxygen and supply recycled nutrients to the sediments and water column, unless the treated plants are harvested.

#### 4.1.8 Interactions with other submersed or floating species

A factor not summarized in the draft conceptual models of Anderson (2008) is interactions among species of aquatic macrophytes. Several recent studies suggest these could be quite important in determining the abundance of some species or guilds of species. For example, experimental work in mesocosms suggests that *Egeria densa* has strong negative effects on *Stuckenia* sp. growth under fresh water conditions. When grown together with *Egeria densa* in fresh water, *Stuckenia* sp. produced 75% less biomass than in monoculture, and significantly more nodal roots, suggesting increased nutrient foraging (Fig. 4.5, Borgnis and Boyer in revision). At a salinity of 5, a decline in *E. densa* performance (see above) coincided with a doubling of *Stuckenia* sp. shoot density. These results suggest that *Stuckenia* sp. might be more abundant in the fresh waters of the Delta in places where *E. densa* currently dominates.

There may be other possibilities of important interactions within the submersed plant community. In one study, *Ceratophyllum demersum* was found to occur more frequently with other species, especially *Egeria densa*, than it occurred on its own (Santos et al. 2011). *C. demersum* can grow on its own, forming large mats or balls of stems, but also attaches to other plants, perhaps facilitating its growth and spread.

In addition, remote sensing data tracking changes in the coverage of the floating species *Eichhornia crassipes* indicated a large loss of submersed species with an increase of 25% in *E. crassipes* and conversely a large increase in submersed species with 25% decrease (Fig. 4.6, Khanna et al. 2012). However, there were no consistent effects on other floating species: the native *Hydrocotyle umbellata* or the introduced *Ludwigia* spp. (Fig. 4.6). A conceptual model was developed to show the hypothesized relationships between *E. crassipes* and submersed vegetation with succession and treatment (Fig 4.6).

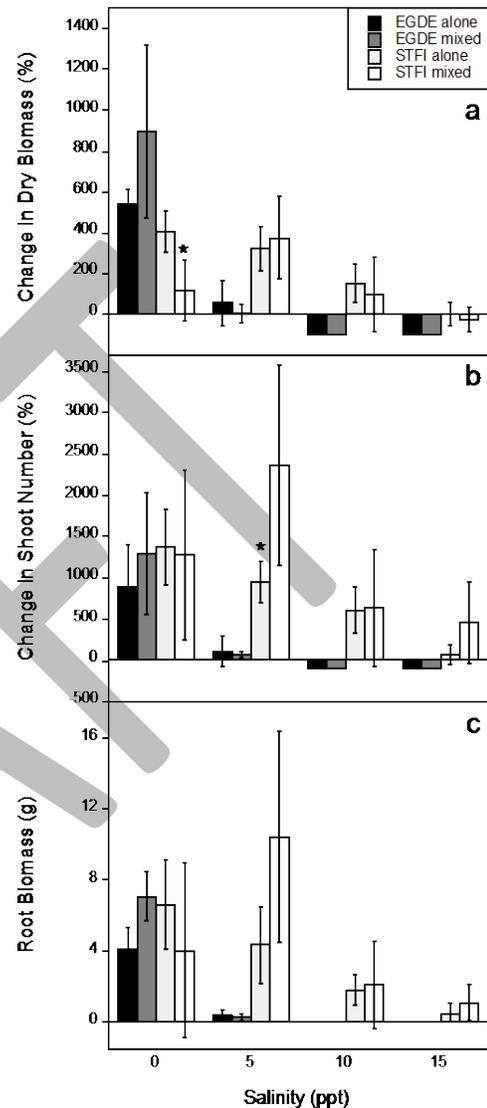


Figure 4.5. Effects of salinity on growth characteristics of *Egeria densa* (EDGE) and *Stuckenia* sp. (presumed to be *S. filiformis* based on gross morphological characteristics, STFI), grown separately and together, at the end of a mesocosm experiment running June-August 2012. From Borgnis and Boyer, in revision

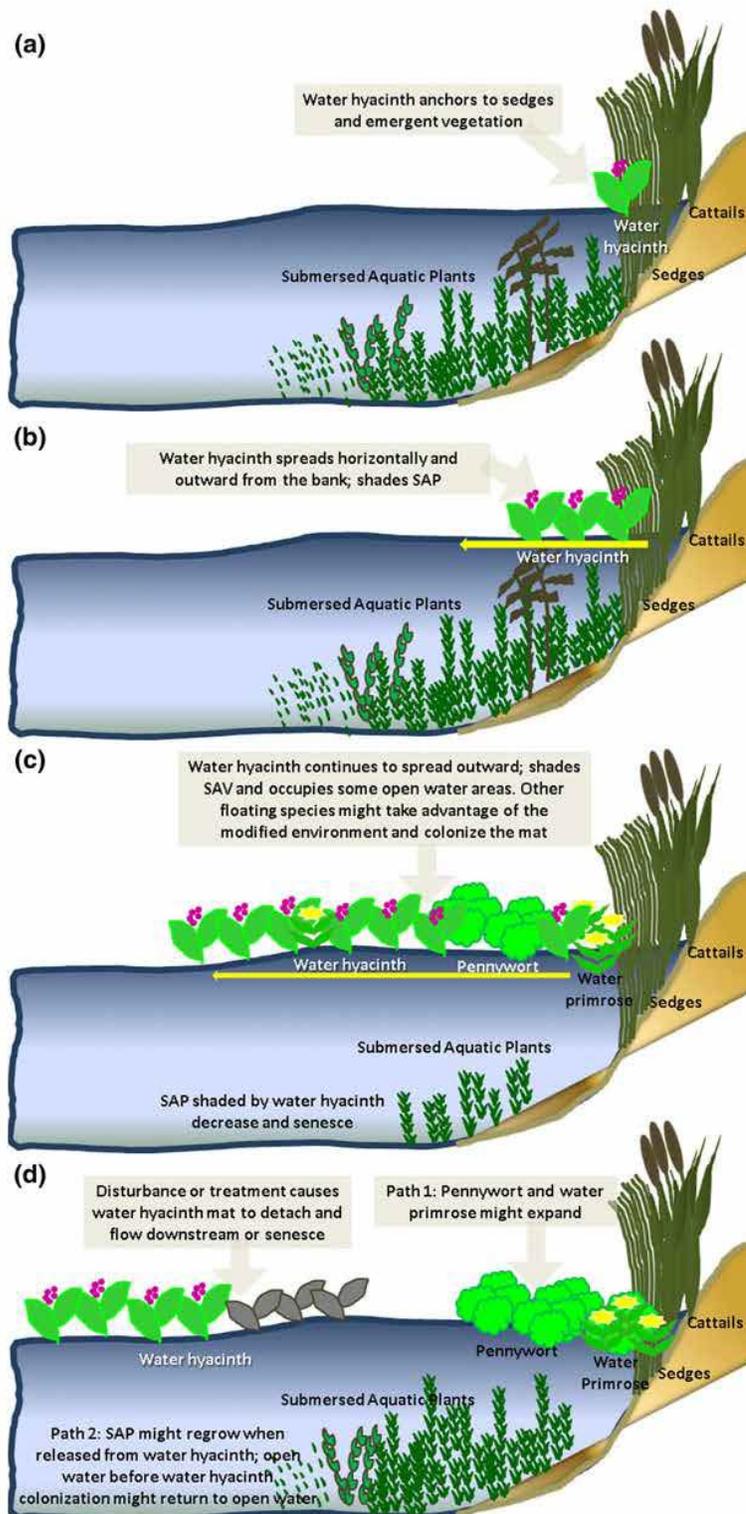
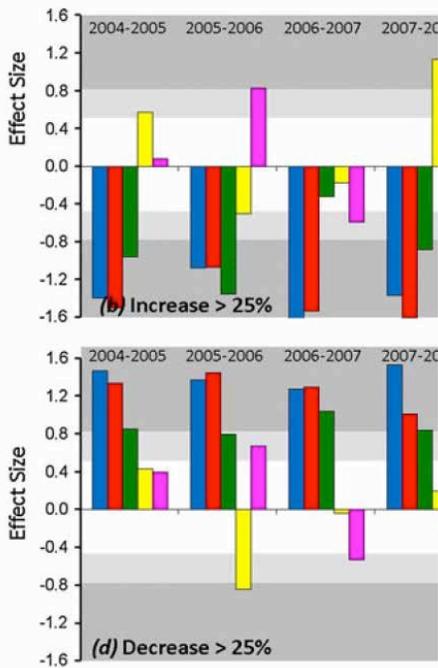


Figure 4.6. Left: Effect sizes reflecting change in coverage with 25% increases or decreases in water hyacinth (*Eichhornia crassipes*) from remote sensing data (dark region of background indicates a strong effect). Changes are shown for water (blue), submerged aquatic vegetation (red, predicted to be primarily *Egeria densa*), emergent and senescent plants (green), native pennywort *Hydrocotyle umbellata* (yellow), and introduced water primrose (*Ludwigia* spp.). Right: Conceptual model of successional pathways of *E. crassipes* growth and expansion, with effects on other floating and submersed plants. From Khanna et al. 2012

#### 4.1.9 Additional factors

Depth and slope of shores can also limit submersed species (Fig. 4.2A). *Egeria densa* can grow to depths of 6 m (Carrillo et al. 2006) and 40% slope, but this seems to be the extreme (in tropical, high elevation lakes). *Eichhornia crassipes* is not limited by depth since it does not root in the sediments, but it tends to accumulate along shores due to greater protection from washing out.

Substrate stability is necessary for submersed plant establishment and persistence, and larger grain size (sand) can lead to less stable bed conditions, especially under higher flow regimes (which can lead to larger grain size to start with).

#### 4.2 Relative Importance of Nutrient Subsidies Versus Other Factors in Promoting Observed Trends

Our review indicates that there are a number of important factors that are likely to be affecting the biomass and distribution of nuisance aquatic species in the Delta. Nutrients are certainly important to the growth of all plant species and the high nutrient levels currently found in the Delta are probably not limiting these plants. Studies of nutrient addition to *Eichhornia crassipes* show clear signs of a direct relationship of water column nutrients to accumulation of biomass as well as clonal propagation. However, studies of *Egeria densa* biomass response to nutrients are very limited and conflicting, and thus do not provide convincing evidence that a reduction in water column nutrients will result in a reduction in *E. densa* production. Further, for both these species, we have very limited understanding of the relative importance of remineralizable nutrients from organic matter in sediments, which these macrophytes continue to contribute through natural senescence or control methods that do not harvest the plants.

## 5. Recommendations

The goal of this review is to synthesize available information to provide insight into major factors controlling the expansion of invasive floating and submerged aquatic vegetation in the Delta. The review addressed three major questions:

1. How does submersed and floating aquatic vegetation support or adversely affect ecosystem services and related beneficial uses?
2. What is known about the spatial and temporal trends in submersed and floating aquatic vegetation in the Delta?
3. What is the relative importance of nutrients and organic matter accumulation versus other factors in promoting observed trends in submersed and floating aquatic vegetation in the Delta?

This review found that the lack of routine monitoring of aquatic macrophytes greatly hindered our ability to summarize, with confidence, the status and trends of floating and SAV in the Delta (Question 2), and to what extent nutrients versus other factors were controlling their occurrence (Question 3). Given this finding, our recommendations are focused on three principal actions:

1. Strengthen routine monitoring.
2. Develop and use a biogeochemical model, coupled with routine monitoring and special studies, to understand the spatial and seasonal nutrient and organic carbon budgets vis a vis major sources of nutrients fueling floating and SAV growth.
3. Conduct a literature review and a pilot research program in floating and SAV control programs.

**R1: Implement Routine Monitoring of Invasive Floating and Submersed Aquatic Vegetation.** Routine monitoring of floating and submersed aquatic vegetation should be undertaken to assess trends over time and to support ecosystem modeling of the Delta. Monitoring should be comprised of a combination of remotely-sensed areal coverage and field-based transects to estimate biomass and characterize species composition. Despite recent advances in remote sensing to include image spectrometry (i.e., hyperspectral remote sensing), problems with misclassification among non-native SAV as well as poor detection of species that occur in smaller patches (e.g., *Stuckenia* sp.) suggest that transect and quadrat monitoring is also needed to follow trends in species composition in space and time. Estimates of biomass and areal cover should be conducted in combination with measures of the major factors that control growth of these primary producers. Early actions should include: 1) the development of a workplan to lay out the key indicators and cost estimates required for monitoring and 2) existing remote sensing data should be used in an attempt to thoroughly estimate areal coverage spatially and over time.

**R2: Develop a Biogeochemical Model of the Delta, focused on Nutrient and Organic Carbon Fate and Transport.** Understanding of factors controlling floating and SAV is critically hampered by the lack of information on nutrient and carbon budgets for the Delta and its subregions. In particular, it's important to quantify the storage in the compartments of the ecosystem (i.e. water, sediment, plant biomass, etc.) and fluxes or exchanges between compartments at varying seasonal and spatial scales. This information will provide an understanding of whether management of "new" nutrients can be effective in controlling floating and SAV relative to the contribution of nutrients recycled from sediment organic matter. To step into model development, three actions should be taken: 1) examine existing models already available to determine suitability for this task, 2) develop a work plan that lays out the modeling strategy, model data requirements, and implementation strategy, and 3) conduct special studies and other monitoring needed to support model development. This includes special studies that quantify N, P, and OC associated with ecosystem compartments as well as uptake, release and flux rates. These analyses should inform hypotheses that can be tested through model development as well as potential future scenarios.

**R3. Investigate control strategies for both *E. densa* and *E. crassipes* that include, among other strategies, mechanical removal.** Depending on the outcome of R2, nutrient management may be ineffective in controlling invasive floating and SAV. While monitoring, modeling and special studies are underway, research to determine more effective removal strategies should be conducted. This work should begin by: 1) conducting a literature review of control strategies to identify potential measures that may be useful in the Delta, and 2) funding research projects that pilot these strategies.

## 6. Literature Cited

### 6.1 Peer-reviewed literature and grey literature (reports)

Anderson, L. 2011. Spongeplant: A new aquatic weed threat in the Delta. Cal-IPC News, Spring 2011.

Bini, L. M. and S. M. Thomaz. 2005. Prediction of *Egeria najas* and *Egeria densa* occurrence in a large subtropical reservoir (Itaipu Reservoir, Brazil-Paraguay). *Aquatic Botany* 83:227-238.

Borgnis, E. and K. E. Boyer. Salinity tolerance and competition drive distributions of native and invasive submerged aquatic vegetation in the upper San Francisco Estuary. In revision at *Estuaries and Coasts*.

Boussard et al 2000 from Hestir

Boyd, C. E. 1970. Vascular aquatic plants for mineral nutrient removal from polluted waters. *Economic Botany* 23(1):95-103.

Boyd, C. E. 1976. Accumulation of dry matter, nitrogen and phosphorus by cultivated water hyacinths. *Economic Botany* 30(1):51-56.

Boyer, K. E., J. Lewis, W. Thornton and R. Schneider. 2012. San Francisco Bay Expanded Inventory of Submerged Aquatic Vegetation (Part 1). Final Report for NOAA National Marine Fisheries, Southwest Region Habitat Conservation Division.

Boyer, K. E., E. Borgnis, J. Miller, J. Moderan, and M. Patten. 2013. Habitat Values of Native SAV (*Stuckenia* spp.) in the Low Salinity Zone of San Francisco Estuary. Final Report prepared for the Delta Science Program.

Boyer, K.E., J. Miller, M. Patten, J. Craft, J. Lewis, and W. Thornton. 2015. San Francisco Bay Expanded Inventory of Submerged Aquatic Vegetation, Part 2: Trends in Distribution and Phenotypic Plasticity. Final Report for NOAA/National Marine Fisheries Service, Southwest Region, Habitat Conservation Division.

Brown, L. R. 2003. Will tidal wetland restoration enhance populations of native fishes? *San Francisco Estuary and Watershed Science* 1(1):1-42.

Brown, L. R. and D. Michniuk. 2007. Littoral fish assemblages of the alien-dominated Sacramento– San Joaquin Delta, California, 1980–1983 and 2001–2003. *Estuaries and Coasts* 30(1):186-200.

Carignan, R. and J. J. Neiff. 1992. Nutrient dynamics in the floodplain ponds of the Parana River (Argentina) dominated by the water hyacinth *Eichhornia crassipes*. *Biogeochemistry* 17:85-121.

Carr, G. M., H. C. Duthie, and W. D. Taylor. 1997. Models of aquatic plant productivity: a review of the factors that influence growth. *Aquatic Botany* 59:195-215.

Carrillo, Y., A. Guarin, and G. Guillot. 2006. Biomass distribution, growth and decay of *Egeria densa* in a tropical high-mountain reservoir (NEUSA, Colombia). *Aquatic Botany* 85:7-15.

Casabianca, M.-L. and T. Laugier. 1995. *Eichhornia crassipes* production on petroliferous wastewaters: Effects of salinity. *Bioresource Technology* 54:39-43.

Cavalli, G., T. Riis, and A. Baattrup-Pedersen. 2012. Bicarbonate use in three aquatic plants. *Aquatic Botany* 98:57-60.

Center, T. D. and F. A. Dray Jr. 2010. Bottom-up control of water hyacinth weevil populations: Do the plants regulate the insects? *Journal of Applied Ecology* 47:329-337.

Choudhury, M. I., X. Yang, and L.-A. Hansson. 2014. Stream flow velocity alters submerged macrophyte morphology and cascading interactions among associated invertebrate and periphyton assemblages. *Aquatic Botany* 120:333-337.

Clary Jr., R. F. and H. A. George. 1983. Ten years of testing for waterfowl food plants in California. *Cal-Neva Wildlife Transactions* 1983:91-96.

Coetzee, J. A., M. Byrne, and M. P. Hill. 2007. Impact of nutrients and herbivory by *Eccritotarsus catarinensis* on the biological control of water hyacinth, *Eichhornia crassipes*. *Aquatic Botany* 86:179-186.

Cohen and Carlton 1995 from Hestir

Cohen, R. A., F. P. Wilkerson, A. E. Parker, and E. J. Carpenter. 2014. Ecosystem-scale rates of primary production within wetland habitats of the northern San Francisco Estuary. *Wetlands* 34:759-774.

Finlayson 1983 from Hestir

Cornwell, D. A., J. Zoltek Jr., C. D. Patrinely, T. deS. Furman, and J. I. Kim. 1977. Nutrient removal by water hyacinths. *Journal of the Water Pollution Control Federation* 49(1):57-65.

DeBusk, T. A. and F. E. Dierberg. 1989. Effects of nutrient availability on water hyacinth standing crop and detritus deposition. *Hydrobiologia* 174:151-159.

Desougi, L. A. 1984. Mineral nutrient demands of the water hyacinth (*Eichhornia crassipes* (Mart.) Solms) in the White Nile. *Hydrobiologia* 110:99-108.

Engelhardt, K. A. M. and M. E. Ritchie. 2002. The effect of aquatic plant species richness on wetland ecosystem processes. *Ecology* 83:2911-2924.

Enright, C. and S. D. Culbertson. 2010. Salinity trends, variability, and control in the northern reach of the San Francisco Estuary. *San Francisco Estuary and Watershed Science* 7(2):1-28.

Feijoó, C., M. E. García, F. Momo, and J. Toja. 2002. Nutrient absorption by the submerged macrophyte

*Egeria densa* Planch.: Effect of ammonium and phosphorus availability in the water column on growth and nutrient uptake. *Limnetica* 21(1-2):03-104.

- Ferreiro, N., C. Feijoo, A. Giorgi, and L. Leggieri. 2011. Effects of macrophyte heterogeneity and food availability on structural parameters of the macroinvertebrate community in a Pampean stream. *Hydrobiologia* 664:199-211.
- Foschi, P. G., G. Fields, G., and H. Liu. 2004. Detecting a spectrally variable subject in color infrared imagery using data-mining and knowledge-engine methods. *PRRS04-018*.
- Frost-Christensen, H. and K. Sand-Jensen. 1995. Comparative kinetics of photosynthesis in floating and submerged *Potamogeton* leaves. *Aquatic Botany* 51:121-134.
- Gantes, H. P. and A. S. Caro. 2001. Environmental heterogeneity and spatial distribution of macrophytes in plain streams. *Aquatic Botany* 70:225-236.
- Grace, J. B. and R. G. Wetzel. 1978. The production biology of Eurasian Watermilfoil (*Myriophyllum spicatum* L.): A review. *Journal of Aquatic Plant Management* 16:1-11.
- Greenfield, B. K., G. S. Siemering, J. C. Andrews, M. Rajan, S. P. Andrews Jr., and D. F. Spencer. 2007. Mechanical shredding of water hyacinth (*Eichhornia crassipes*): Effects on water quality in the Sacramento-San Joaquin River Delta, California. *Estuaries and Coasts* 30(4):627-640.
- Grimaldo, L. F., A. R. Stewart, and W. Kimmerer. 2009. Dietary segregation of pelagic and littoral fish assemblages in a highly modified tidal freshwater estuary. *Marine Coastal Fisheries: Dynamics, Management & Ecosystems Sciences* 1:000-000.
- Gruber, R. K. and W. M. Kemp. 2010. Feedback effects in a coastal canopy-forming submersed plant bed. *Limnology and Oceanography* 55(6):2285-2298.
- Gunnarsson, C. C. and C. M. Peterson. 2007. Water hyacinths as a resource in agriculture and energy production: A literature review. *Waste Management* 27:117-129.
- Haller, W. T. and D. L. Sutton. 1973. Effect of pH and high phosphorous concentrations on growth of waterhyacinth. *Hyacinth Control Journal* 11:59-61.
- Heard, T. A. and S. L. Winterton. 2000. Interactions between nutrient status and weevil herbivory in the biological control of water hyacinth. *Journal of Applied Ecology* 37:117-127.
- Henninger, T. O., P. W. Froneman, N. B. Richoux, and A. N. Hodgson. 2009. The role of macrophytes as a refuge and food source for the estuarine isopod *Exosphaeroma hylocoetes* (Barnard, 1940). *Estuarine, Coastal and Shelf Science* 82:285-293.
- Hestir, E. L., S. Khanna, M. E. Andrew, M. J. Santos, J. H. Viers, J. A. Greenberg, S. S. Rajapakse, and S. L. Ustin. 2008. Identification of invasive vegetation using hyperspectral remote sensing in the California Delta ecosystem. *Remote Sensing of Environment* 112:4034-4047.
- Hill, J. M. 2014. Investigations of growth metrics and  $\delta^{15}\text{N}$  values of water hyacinth (*Eichhornia crassipes*, (Mart.) Solms-Laub) in relation to biological control. *Aquatic Botany* 114:12-20.

- Hofstra, D. E., J. Clayton, J. D. Green, and M. Auger. 1998. Competitive performance of *Hydrilla verticillata* in New Zealand. *Aquatic Botany* 63:305-324.
- Hussner, A., H. P. Hoelken, and P. Jahns. 2010. Low light acclimated submerged freshwater plants show a pronounced sensitivity to increasing irradiances. *Aquatic Botany* 93:17-24.
- Hussner, A., D. Hofstra, P. Jahns, and J. Clayton. 2014. Response capacity to CO<sub>2</sub> depletion rather than temperature and light effects explain the growth success of three alien Hydrocharitaceae compared with native *Myriophyllum triphyllum* in New Zealand. *Aquatic Botany* 120:205-211.
- Jassby, A. D. and J. E. Cloern. 2000. Organic matter sources and rehabilitation of the Sacramento-San Joaquin Delta (California, USA). *Aquatic Conservation* 10:323-352.
- Julien, M. H., M. P. Hill, T. D. Center, and D. Jianqing, eds. 2001. Biological and integrated control of water hyacinth, *Eichhornia crassipes*. **Proceedings of the Second Meeting of the Global Working Group for the Biological and Integrated Control of Water Hyacinth, Beijing, China.**
- Kato-Noguchi, H., M. Moriyasu, O. Ohno, and K. Suenaga. 2014. Growth limiting effects on various terrestrial plant species by an allelopathic substance, loliolide, from water hyacinth. *Aquatic Botany* 117:56-61.
- Kennedy, T. L., L. A. Horth, and D. E. Carr. 2009. The effects of nitrate loading on the invasive macrophyte *Hydrilla verticillata* and two common, native macrophytes in Florida. *Aquatic Botany* 91:253-256.
- Kenow, K. P., J. E. Lyon, R. K. Hines, and A. Elfessi. 2007. Estimating biomass of submersed vegetation using a simple rake sampling technique. *Hydrobiologia* 575:447-454.
- Kim, Y. and W.-J. Kim. 2000. Roles of water hyacinths and their roots for reducing algal concentration in the effluent from waste stabilization ponds. *Water Research* 34(13):3285-3294.
- Lund, J., E. Hanak, W. Fleenor, R. Howitt, J. Mount, and P. Moyle. 2007. Envisioning futures for the Sacramento-San Joaquin Delta. Public Policy Institute of California, San Francisco, California.
- Malik, A. 2007. Environmental challenge vis a vis opportunity: The case of water hyacinth. *Environment International* 33:122-138.
- Marína, V. H., A. Tironi, L. E. Delgado, M. Contreras, F. Novoa, M. Torres-Gómez, R. Garreaud, I. Vila, and I. Serey. 2009. On the sudden disappearance of *Egeria densa* from a Ramsar wetland site of Southern Chile: A climatic event trigger model. *Ecological Modelling* (In press).
- Marlina, D., M. P. Hill, B. S. Ripley, A. J. Strauss, and M. J. Byrne. 2013. The effect of herbivory by the mite *Orthogalumna terebrantis* on the growth and photosynthetic performance of water hyacinth (*Eichhornia crassipes*). *Aquatic Botany* 104:60-69.

- Martin, G. D. and J.A. Coetzee. 2014. Competition between two aquatic macrophytes, *Lagarosiphon major* (Ridley) Moss (Hydrocharitaceae) and *Myriophyllum spicatum* Linnaeus (Haloragaceae) as influenced by substrate sediment and nutrients. *Aquatic Botany* 114:1–11.
- Matheson, F. E., M. D. de Winton, J. S. Clayton, T. M. Edwards, and T. J. Mathieson. 2005. Responses of vascular (*Egeria densa*) and non-vascular (*Chara globularis*) submerged plants and oospores to contrasting sediment types. *Aquatic Botany* 83:141-153.
- Mony, C., T.J. Koschnick, W.T. Haller, and S. Muller. 2007. Competition between two invasive Hydrocharitaceae (*Hydrilla verticillata* (L.f.) (Royle) and *Egeria densa* (Planch)) as influenced by sediment fertility and season. *Aquatic Botany* 86:236–242.
- Nobriga, M. L. 2009. Bioenergetic modeling evidence for a context-dependent role of food limitation in California's Sacramento-San Joaquin Delta. *California Fish and Game* 95(3):111-121.
- Nobriga, M. L., F. Feyrer, R. D. Baxter, and M. Chotkowski. 2005. Fish community ecology in an altered river delta: spatial patterns in species composition, life history strategies, and biomass. *Estuaries* 28(5):776-785.
- Ogg Jr., A. G., V. F. Bruns, and A. D. Kelley. 1969. Response of sago pondweed to periodic removal of topgrowth. *Weed Science* 17(2):139-141.
- Pennington, T. G. and M. D. Sytsma. 2009. Seasonal changes in carbohydrate and nitrogen concentrations in Oregon and California populations of Brazilian *Egeria* (*Egeria densa*). *Invasive Plant Science and Management* 2(2):120-129.
- Petrucio, M. M. and F. A. Esteves. 2000. Uptake rates of nitrogen and phosphorous in the water by *Eichhornia crassipes* and *Salvinia auriculata*. *Revista Brasileira de Biologia* 60(2):229-236.
- Pierini, S. A. and S. M. Thomaz. 2004. Effects of inorganic carbon source on photosynthetic rates of *Egeria najas* Planchon and *Egeria densa* Planchon (Hydrocharitaceae). *Aquatic Botany* 78:135-146.
- Reddy, K. R. 1983. Fate of nitrogen and phosphorus in a waste-water retention reservoir containing aquatic macrophytes. *Journal of Environmental Quality* 12(1):137-141.
- Reddy, K. R. and W. F. DeBusk. 1984. Growth characteristics of aquatic macrophytes cultured in nutrient-enriched water: I. water hyacinth, water lettuce, and pennywort. *Economic Botany* 38(2):229-239.
- Reddy, K. R. and W. F. DeBusk. 1985. Nutrient removal potential of selected aquatic macrophytes. *Journal of Environmental Quality* 14(4):459-462.
- Reddy, K. R. and J. C. Tucker. 1983. Productivity and nutrient uptake of water hyacinth, *Eichhornia crassipes* I. effect of nitrogen source. *Economic Botany* 37(2):237-247.

- Reddy, K. R., J. C. Tucker, and W. F. DeBusk. 1987. The role of *Egeria* in removing nitrogen and phosphorous from nutrient enriched waters. *Journal of Aquatic Plant Management* 25:14-19.
- Riemer, D. N. and S. J. Toth. 1969. A survey of the chemical composition of *Potamogeton* and *Myriophyllum* in New Jersey. *Weed Science* 17(2):219-223.
- Riis, T., B. Olesen, J. S. Clayton, C. Lambertini, H. Brixa, and B. K. Sorrell. 2012. Growth and morphology in relation to temperature and light availability during the establishment of three invasive aquatic plant species. *Aquatic Botany* 102:56-64.
- Ripley, B. S., E. Muller, M. Behenna, G. M. Whittington-Jones, and M. P. Hill. 2006. Biomass and photosynthetic productivity of water hyacinth (*Eichhornia crassipes*) as affected by nutrient supply and mirid (*Eccritotarus catarinensis*) biocontrol. *Biological Control* 39:392-400.
- Rodrigues, R. B. and S. M. Thomaz. 2010. Photosynthetic and growth responses of *Egeria densa* to photosynthetic active radiation. *Aquatic Botany* 92:281-284.
- Rogers, H. H. and D. E. Davis. 1972. Nutrient removal by waterhyacinth. *Weed Science* 20(5):423-428.
- Santos, M. J., L. W. Anderson, and S. L. Ustin. 2011. Effects of invasive species on plant communities: an example using submersed aquatic plants at the regional scale. *Biological Invasions* 13:443-457.
- Shanab, S. M. M., E. A. Shalaby, D. A. Lightfoot, and H. A. El-Shemy. 2010. Allelopathic effects of water hyacinth [*Eichhornia crassipes*]. *PLoS ONE* 5(10): e13200.doi:10.1371/journal.pone.0013200
- Smart, R. M. and J. W. Barko. 1990. Effects of water chemistry on aquatic plants: Interactive effects of inorganic carbon and nitrogen on biomass production and plant nutrition. Department of the Army, Technical Report A-90-4.
- Smith, S. D. P. 2014. The roles of nitrogen and phosphorus in regulating the dominance of floating and submerged aquatic plants in a field mesocosm experiment. *Aquatic Botany* 112:1-9.
- Sosiak, A. 2002. Long-term response of periphyton and macrophytes to reduced municipal nutrient loading to the Bow River (Alberta, Canada). *Canadian Journal of Fisheries and Aquatic Science* 59:987-1001.
- Sousa, W. T. Z., S. M. Thomaz, and K. J. Murphy. 2010. Response of native *Egeria najas* Planch. and invasive *Hydrilla verticillata* (L.f.) Royle to altered hydroecological regime in a subtropical river. *Aquatic Botany* 92:40-48.
- Steinhardt, T. and U. Selig. 2011. Influence of salinity and sediment resuspension on macrophyte germination in coastal lakes. *Journal of Limnology* 70(1):11-20.
- Summers, J. E., R. G. Ratcliffe, and M. B. Jackson. 2000. Anoxia tolerance in the aquatic monocot *Potamogeton pectinatus*: Absence of oxygen stimulated elongation in association with an unusually large Pasteur effect. *Journal of Experimental Botany* 51(349):1413-1422.

- Thomaz, S. M., P. A. Chambers, S. A. Pierini, and G. Pereira. 2007. Effects of phosphorus and nitrogen amendments on the growth of *Egeria najas*. *Aquatic Botany* 86:191-196.
- Thouvenot, L., C. Puech, L. Martinez, J. Haury, and G. Thiébaud. 2012. Strategies of the invasive macrophyte *Ludwigia grandiflora* in its introduced range: Competition, facilitation or coexistence with native and exotic species? *Aquatic Botany* 107:8-16.
- Toft et al. 2003 from Hestir
- Van, T. K., G. S. Wheeler, and T. D. Center. 1997. Competition between *Hydrilla verticillata* and *Vallisneria americana* as influenced by soil fertility. *Aquatic Botany* 62:225-233.
- Vanderstukken, M., N. Mazzeo, W. van Colen, S. A. J. Declerck, and K. Muylaert. 2011. Biological control of phytoplankton by the subtropical submerged macrophytes *Egeria densa* and *Potamogeton illinoensis*: a mesocosm study. *Freshwater Biology* 56:1837-1849.
- Villamagna, A. M., and B. R. Murphy. 2010. Ecological and socio-economic impacts of invasive water hyacinth (*Eichhornia crassipes*): a review. *Freshwater Biology* 55:282-298.
- Weragoda, S.K., N. Tanaka, K. B. S. N. Jinadasa, and Y. Sasaki. 2008. Impacts of plant (*Egeria densa*) density and nutrient composition on nitrogen transformation mechanisms in laboratory microcosms. *Journal of Freshwater Ecology* 24(3):393-401.
- Williams, A. E., H. C. Duthie, and R. E. Hecky. 2005. Water hyacinth in Lake Victoria: Why did it vanish so quickly and will it return? *Aquatic Botany* 81:300-314.
- Williams, A. E., H. C. Duthie, and R. E. Hecky. 2007. Water hyacinth decline across Lake Victoria—Was it caused by climatic perturbation or biological control? A reply. *Aquatic Botany* 87:94-96.
- Wilson, J. R. U., O. Ajuonu, T. D. Center, M. P. Hill, M. H. Julien, F. F. Katagira, P. Neuenschwander, S. W. Njoka, J. Ogwang, R. H. Reeder, and T. Van. 2007. The decline of water hyacinth on Lake Victoria was due to biological control by *Neochetina* spp. *Aquatic Botany* 87:90-93.
- Wilson, J. R., N. Holst, and M. Rees. 2005. Determinants and patterns of population growth in water hyacinth. *Aquatic Botany* 81:51-67.
- Wu, Z., P. Deng, X. Wu, S. Luo, and Y. Gao. 2007. Allelopathic effects of the submerged macrophyte *Potamogeton malaianus* on *Scenedesmus obliquus*. *Hydrobiologia* 592:465-474.
- Xie, Y., M. Wen, D. Yu, and Y. Li. 2004. Growth and resource allocation of water hyacinth as affected by gradually increasing nutrient concentrations. *Aquatic Botany* 79:257-266.
- Xie, Y. and D. Yu. 2003. The significance of lateral roots in phosphorus (P) acquisition of water hyacinth (*Eichhornia crassipes*). *Aquatic Botany* 75:311-321.

Yarrow, M., V. H. Marin, M. Finlayson, A. Tironi, L. E. Delgado, and F. Fischer. 2009. The ecology of *Egeria densa* Planchon (Liliopsida: Alismatales): A wetland ecosystem engineer? *Revista Chilena de Historia Natural* 82: 299-313.

You, I., D. Yu, D. Xie, L. Yu, W. Xiong, and C. Han. 2014. Responses of the invasive aquatic plant water hyacinth to altered nutrient levels under experimental warming in China. *Aquatic Botany* 119:51-56.

Zhang, M., T. Cao, L. Ni, P. Xie, G. Zhu, A. Zhong, J. Xu, and H. Fu. 2011. Light-dependent phosphate uptake of a submersed macrophyte *Myriophyllum spicatum* L. *Aquatic Botany* 94:151–157.

## 6.2 Local and regional press reports

Anderson, L. and P. Akers. 2011. Spongeplant: A new aquatic weed threat in Delta. *Cal-IPC News* 19(1):45.

Breitler, A. 2014, October 22. Bill Wells: Hyacinth a 'disaster,' possible national security threat. *The Record*. Retrieved from <http://www.recordnet.com/>

Breitler, A. 2014, October 24. Legislators: Help us with hyacinth. *The Record*. Retrieved from <http://www.recordnet.com/>

Breitler, A. 2014, October 28. Another hyacinth plan hatches. *The Record*. Retrieved from <http://www.recordnet.com/>

Breitler, A. 2014, November 8. Stockton mayor floats an idea: Bring in manatees. *The Record*. Retrieved from <http://www.recordnet.com/>

Breitler, A. 2014, November 14. Feds, state may join the hyacinth fray. *The Record*. Retrieved from <http://www.recordnet.com/>

Breitler, A. 2014, December 15. Delta: As hyacinth clears out, focus turns to next year. *The Record*. Retrieved from <http://www.recordnet.com/>

Daly, T. 2014, October 27. State claims it's doing everything possible to eradicate water hyacinth. *ABC News10*. Retrieved from <http://www.news10.net/>

Task force to control hyacinth in the delta. *Capital Public Radio*. Retrieved from <http://www.capradio.org/>

Martinez, L. 2014, November 3. Removing hyacinth clogging Port of Stockton a slow process as dry year has plant thriving. *CBS Sacramento*. Retrieved from <http://sacramento.cbslocal.com/>.

Ruhstaller, L. 2014, November 22. Guest view: Solution to weedy problem? *The Record*. Retrieved from <http://www.recordnet.com/>

Theuri, M. 2013. Water hyacinth – Can its aggressive invasion be controlled? **UNEP Global Environmental Alert Service (GEAS)**.

(No author). 2014. Our viewpoint: Green water = problem. *The Record*. Retrieved from [http://www.recordnet.com/article/20141015/OPINION/141019724/101034/A\\_OPINION](http://www.recordnet.com/article/20141015/OPINION/141019724/101034/A_OPINION).

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