

Developing the capacity to monitor climate change impacts in Mediterranean estuaries

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ABSTRACT

Background: Under predicted climate change scenarios, estuaries and deltas face increased threats to biological sustainability. The Sacramento-San Joaquin Delta in California, USA forms the upstream component of the largest estuary on the Pacific coast of the Americas. It is a Mediterranean system in steep ecological decline under threat from current and potential climate changes.

Goal: Illustrate how climate change impacts on an already fragile system can be monitored with new, advanced remote sensing methods. Describe how remote sensing data can improve monitoring of ecosystem changes. Use examples from the Sacramento-San Joaquin Delta in California to illustrate some of the types of ecosystem changes that are expected with climate change, such as changing species composition and dominance, changes in environmental conditions like salinity, water and air temperatures, and precipitation patterns. Show how imaging spectroscopy can provide information about the dynamics of native and invasive estuarine plant communities.

Data: Airborne HyMap imaging spectroscopy data of the Sacramento-San Joaquin Delta collected in June for the years 2004 through 2008. Approximately 65 flightlines covered the Delta each year with 3×3 m spatial resolution. Concurrent field data recorded geographical locations and phenology of different aquatic plant species. Airborne LiDAR data rasterized at 1×1 m, collected in winter 2007 for the entire Delta, was used to calculate light interception by riparian tree canopies.

Analysis method: We used hyperspectral image analysis in various classification algorithms to perform vegetation type and species mapping, and estimate plant densities and functional traits. A radiative transfer model was applied to LiDAR data to estimate the effects of riparian tree canopies on the irradiance budget of the surface waters of the Sacramento-San Joaquin Delta as a surrogate for potential water temperature increases.

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Results: New remote sensing techniques and data detected and measured the density and other functional traits of plant communities and species in this delta. Examining the year-to-year locations of pixels containing invasive species shows that they have high rates of persistence, and that the predicted increases in water temperature may improve the habitat conditions for invasive aquatic plant species. Other changes, such as altered precipitation patterns, may affect the hydrograph of the Sacramento-San Joaquin Delta and its turbidity that could further improve the habitat for non-native species, although sea level rise and increasing upstream salinity might produce the opposite effect.

Conclusions: The Sacramento-San Joaquin Delta and Estuary face ecosystem problems that are characteristic of most Mediterranean estuaries. Interactions between the biological and physical conditions in the Delta affect the trajectory of dominance by native and invasive aquatic plant species. Trends in growth and community characteristics associated with predicted impacts of climate change (sea level rise, warmer temperatures, changes in the hydrograph with high winter and low summer outflows) do not provide simple predictions. Individually, the impact of specific environmental changes on the biological components can be predicted, however it is the complex interactions of biological communities with the suite of physical changes that make predictions uncertain. Systematic monitoring of these estuarine environments is critical to achieving sustainable management of these ecosystems and providing the data needed to document and understand change and to identify successful adaptation strategies.

Keywords: canopy structure, hyperspectral remote sensing, imaging spectroscopy, mapping invasive and native aquatic plant species.

INTRODUCTION

Globally, estuaries and deltas face unprecedented disturbances and threats to their biological and ecological sustainability (Bianchi and Allison, 2009). Threats come from a variety of detrimental changes, including upstream water diversion, changing sedimentation patterns (both enhanced and reduced), agricultural runoff and industrial pollution, massive land use changes and land conversion, which have led to the marked loss of native species and introduction of invasive species (see, for example, Klausmeyer and Shaw, 2009; Syvitski *et al.*, 2009; Underwood *et al.*, 2009). Today, climate change adds new threats ranging from altered precipitation and runoff patterns, and warmer air and water temperatures, to sea level rise (Ericson *et al.*, 2006), as well as increasing pressure to meet human needs for water and food security (Vorosmarty *et al.*, 2010). The adaptation challenge for estuaries is to meet the dual (and sometimes competing) ecosystem service goals of supporting biodiversity and ecosystem processes while provisioning fresh water resources for human use. These forces will profoundly change the composition, functioning, and ecosystem services of Mediterranean estuaries.

Mediterranean climates are particularly vulnerable to the combined effects of climate change and variability, land use changes, and species invasions. The strong seasonality and extreme variability in precipitation that is characteristic of Mediterranean climates results in highly seasonal estuarine circulation patterns with strong inter-annual variation in river flow, ocean exchange, and stratification (Gasith and Resh, 1999). Human intervention, such as reclamation, diking, levees, and water extraction, significantly change the flow regime in these estuaries, leading to changes in circulation and turbidity, increased stratification and bottom hypoxia (Hearn and Robson, 2001), increased temperatures, and loss of freshwater habitat, which together negatively affect the reproduction of native species (e.g. Moyle *et al.*, 2013). When combined with other human activities that cause changes in sedimentation, water pollution,

increased nutrient inputs, and species introductions, the consequence is often loss of native species, increased rates of invasion, and cascading trophic impacts (e.g. MacQueen *et al.*, 1986; Chapin *et al.*, 1997; Zavaleta *et al.*, 2001). Nonetheless, in some cases natural tidal marshes have been resilient to changes in the physical environment, for example sea level rise and changes in sediment loads (Orr *et al.*, 2003).

Most rivers fan out as they near the ocean and velocity decreases allowing sediment deposition. The Nile River is a classic example of this type of delta (Stanley, 1988). Mediterranean rivers that form typical deltas, in addition to the Nile, are the Po, Rhône, Ebro, and the Guadalquivir Rivers of Europe (Stanley, 1997), while other Mediterranean rivers have not formed deltas, including the River Torrens and the Swan River that flow through Adelaide and Perth, Australia, respectively, and the Loa River, the main waterway through the Atacama Desert in Chile. Regardless, each of these Mediterranean climate rivers experiences tidal flows, which will be affected by sea level rise and corresponding salinity increases (Stanley, 1997; Syvitski *et al.*, 2009), and each experiences some or all of the suite of environmental problems that are found in the Sacramento-San Joaquin River Delta of California, USA today.

The Sacramento-San Joaquin River Delta (hereafter the SSJ Delta) forms the upstream component of San Francisco Bay, the third largest tidal estuary in the USA and the largest on the Pacific Coast of North and South America. In California, the junction of the Sacramento and San Joaquin Rivers forms an inverted delta, a type where the river divides into multiple branches before eventually rejoining and reaching the sea. The SSJ Delta is located inland of the Carquinez Straits, the passage that connects San Pablo Bay (the northern extent of San Francisco Bay) and the Pacific Ocean.

The SSJ Delta covers an area of nearly 3000 square kilometres, consisting of 1770 km of waterways (www.water.ca.gov/swp/delta.cfm) that are bordered by 1800 km of earthen levees that have created about 57 reclaimed islands and tracts. Forty percent of California's water supply flows through the delta, putting water supplies for more than 30 million people at risk [two-thirds of the fresh water consumed in California comes from the SSJ Delta (Lund *et al.*, 2008)], together with millions of acres of farmland that support a 42.6 billion dollar agricultural industry. Like many estuaries, the SSJ Delta is an 'ecosystem in steep decline' (Draft Bay Delta Conservation Plan, 2013), marked by a precipitous decline in several pelagic fish species (MacNally *et al.*, 2010) and species invasions (Cohen and Carlton, 1998; Winder *et al.*, 2011), and sustainment of its ecological and hydrological services is in serious doubt. The SSJ Delta has been brought to this crisis by 150 years of levees, dam, and reservoir construction, dredging and flood control that has drastically modified natural flows and flooding, as shown in Fig. 1 (Katibah, 1984; Whipple *et al.*, 2011). The competing demands for water have made the current system unsupportable and subject to potentially catastrophic failures from earthquakes and its ageing earthen levees (Casas *et al.*, 2011; Draft Bay Delta Conservation Plan, 2013).

As with other Mediterranean deltas and estuaries, the SSJ Delta faces significant simultaneous impacts from sea level rise, declining sediment transport, agricultural and industrial pollution, invasive species, and many other factors that affect the quality and quantity of its water resources (Mount and Twiss, 2005; Casas *et al.*, 2011). Predicted climate changes include increased temperatures, changes in total precipitation and its seasonal patterns, including extreme periods of drought and floods (Hanak and Lund, 2008). Predicted temperature increases range from 2°C (under the PCM-B1 scenario) to 4°C (under the GFDL-A2 scenario) by 2060 (Knowles and Cayan, 2004). Changes in total precipitation are less clear, except that the predicted significant 30–90% reduction in winter snowpack in the Sierra

Nevada Mountains (Knowles and Cayan, 2004) will have a major impact on freshwater flows through the SSJ Delta. Precipitation is today highly variable from year to year. In the last 10 years, total statewide precipitation has exceeded both 30% more and less than average (www.water.ca.gov/watercondition/droughtinfo.cfm). The peak hydrograph will shift from spring to late winter because of increased rainfall precipitation, decreased snowpack, and warmer temperatures (Knowles and Cayan, 2002).

Climate change predictions show high variability in weather with years of extreme drought conditions. Sea level in San Francisco Bay is predicted to increase 20–80 cm (Cayan *et al.*, 2008). Significantly higher winter flows and lower summer flows are predicted (Knowles and Cayan, 2004). Decreased flows (Cloern *et al.*, 2011) will result in higher water temperatures in the river and SSJ Delta and increased salinity from higher tidal inflows. Lower summer flows are also expected to further threaten the water supply and the people of California, its economy, and the ecosystems that depend on its services.

The impacts of climate and land use changes on the SSJ Delta are emblematic of global estuaries in general, and Mediterranean ecosystem deltas and estuaries in particular. The size of the SSJ Delta and complexity of its ecosystems and hydrologic flows prevents easy comprehensive conservation management (Wright, 2001; Norgaard *et al.*, 2009; Madani and Lund, 2012). In this review, we first provide an overview of the SSJ Delta environment and its history, followed by case studies that focus on ecosystem processes relevant to climate change predictions. We show how advanced remote sensing technologies can aid in understanding the horizontal (floating), vertical (submerged, emergent, and riparian), and temporal dynamics that comprise the functional types of these wetland-aquatic plant communities.

THE SSJ DELTA ENVIRONMENT AND HISTORY

The landscape reconstruction of the San Francisco Bay-Delta system, produced by the San Francisco Estuary Institute (SFEI), shows that a very different delta existed in the nineteenth century (Fig. 1A). Originally, the entire SSJ Delta was a network of freshwater to brackish wetlands within a meandering system of rivers and sloughs. The increasing need for water and agricultural land at the turn of the twentieth century began an era of land reclamation that required draining the SSJ Delta wetlands and constructing levees to regulate river paths (Katibah, 1984; Pincetl, 1999). The newly created islands were dedicated to agriculture (Whipple *et al.*, 2011), although now much of this land is of marginal value. Over the past 100 years, there has been little acquisition of conservation land within the SSJ Delta (Fig. 1B), with the exception of the recent conservation easements (Santos *et al.* 2014a, 2014b). Today, the SSJ Delta has a very different set of environments from its historic flows, which are now in geomorphologically fixed rivers and channels and sloughs with little or no bank erosion (Florsheim *et al.*, 2008), have low connectivity to their riparian habitat, and are dredged and regulated via levees and gates. River flows are highly altered and are controlled by upstream dams and water diversion gates in the SSJ Delta.

Human activities have introduced non-native species, accidentally and intentionally, which has had a significant impact on the current composition of the vegetation community and its dynamics. The reclamation and regulation of rivers at the beginning of the twentieth century led to a wetland-aquatic plant community with low richness, but dominated by native plant species. The increase in commercial boating, especially transcontinental routes, and the growing commercial aquarium industry accelerated the introduction of non-native species. Since the 1980s, there has been a huge increase in non-native plant species that now

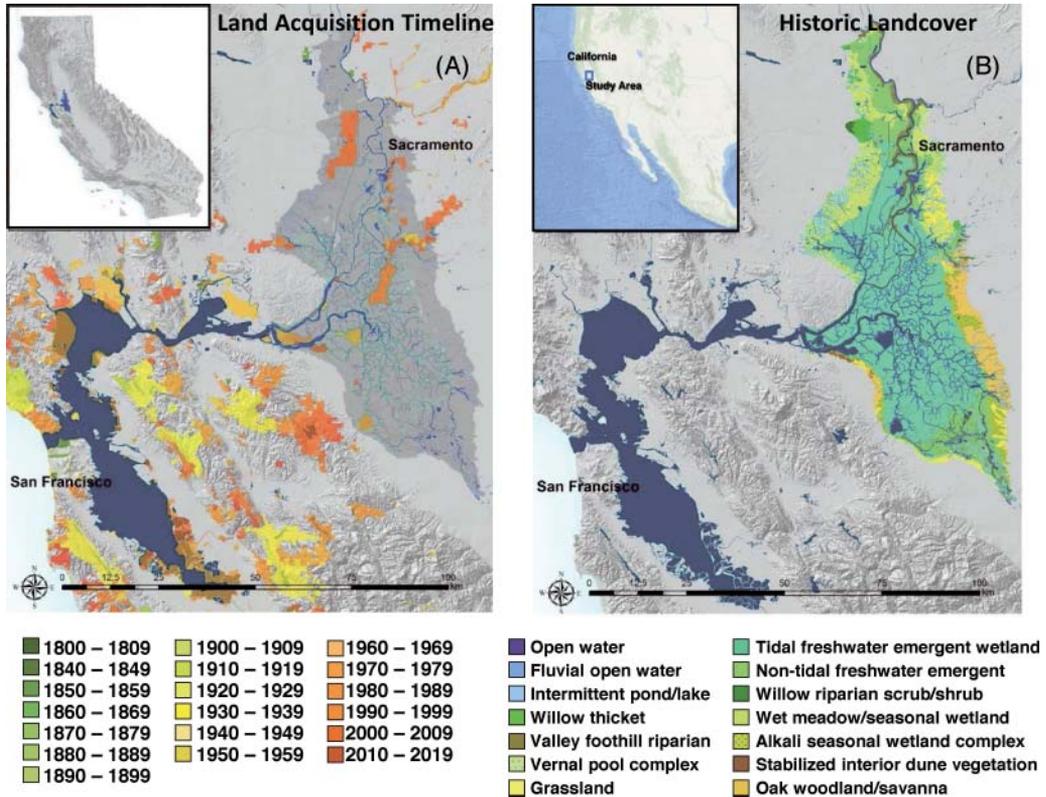


Fig. 1. Reconstruction of the historic vegetation of the delta and history of land acquisition for conservation. (A) History of land acquisition for conservation for the San Francisco estuary region and SSJ Delta (Santos *et al.*, 2014a, 2014b). Inset shows location of the SSJ Delta on a grey-scale relief map of California. (B) Sacramento-San Joaquin River Delta in California extends east of Suisun Bay and shows historic land cover (SFEI, 2013). Inset shows location of the SSJ Delta on a map of western North America.

occupy virtually all of the horizontal and vertical strata of the SSJ Delta’s ecosystems. Today’s wetland-aquatic plant community has increased richness due to the number of invasive species (Cohen and Carlton, 1998), which are now approximately equal in number to native species (Santos *et al.*, 2012), are widespread throughout the SSJ Delta, are highly productive, and dominate total aquatic plant biomass. Massive weed control programmes have been undertaken to control the spread and reduce persistence of *Egeria densa* (Brazilian waterweed) and *Eichhornia crassipes* (water hyacinth). The State of California specifically mandated control of Brazilian waterweed and water hyacinth by the late 1990s (Santos *et al.*, 2009). Predicted climate impacts from warmer water temperatures to changing flow patterns will likely add to the impacts in this already heavily modified ecosystem.

While many long-term changes have affected the SSJ Delta ecosystem, the emergence of high spatial and temporal resolution remote sensing techniques that can monitor the horizontal, vertical, and temporal dynamics of such a system is very recent. Nonetheless, even looking at recent changes can contribute to elucidating the effects of the historic legacy

of land cover and land use, as well as inform conservation managers on how to respond to current and future challenges imposed by climate change. Here we show patterns of recent dynamics that were recorded annually over a period of five years (from 2004 to 2008), including two years (2005 and 2007) when both summer and fall data were acquired. These data show how invasions of aquatic and wetland plant species together with altered hydrologic processes have simultaneously affected the SSJ Delta system. Monitoring such changes will eventually lead to better understanding and prediction of future conditions under climate change. We used state-of-the-art airborne imaging spectroscopy and LiDAR remote sensing data to analyse and map the horizontal and vertical distributions of submerged, floating, emergent, and riparian communities and we assessed the vertical interactions among and between these communities and examined how various abiotic factors such as sediments and irradiance may facilitate or inhibit these changes.

AIRBORNE REMOTE SENSING CAN INFORM CONSERVATION MANAGEMENT ABOUT THE RESPONSE OF PLANT COMMUNITIES TO CLIMATE CHANGE

Imaging remote sensing data provide wall-to-wall mapping (100% spatial sampling) over a systematic grid that can be quantitatively analysed, linking the physiological properties of plants with the physical radiometric values that are measured. The spatial resolution that can be measured from airborne systems is fine enough (typically from 1 m² to 25 m²) to map narrow sloughs and ecological zones, which is critical to distinguishing aquatic species or vegetation types. Imaging spectrometry – that is, remote sensing imagery that measures a detailed spectrum for each pixel – is an essential technology to characterize the spectral properties of plants that provide the unique identification needed for species and community type mapping. Spectroscopy can measure biochemical canopy properties such as chemical composition related to photosynthesis and transpiration, and canopy scale features such as leaf area index, plant size, gap size, and plant spacing. These together provide unprecedented information about ecosystem structure and function over a fine spatial scale. Capturing the full distribution of canopy vertical structure requires a different technology, Light Detection and Ranging or LiDAR. We provide several case studies that demonstrate the types of information about the state of health and composition of estuaries and deltas that can be provided by these remote sensing technologies. Figure 2 shows a composite image, composed of 65 flightlines that cover the SSJ Delta. The SSJ Delta is structured by the 57 islands that were created by the levee system, and the land is largely used for agriculture, as seen by the rectangular fields in the image. Each site discussed in the text is shown in the named boxes on this figure.

Typical data requirements are:

1. *Spatial resolution*: sufficiently fine to map very narrow sloughs and water–land borders where submerged plants can be interspersed with emergent wetland species, and also to identify the distributions of different plant communities. In our examples, we used an imaging spectrometer with a pixel size of about 9 m² (3 × 3 m) and found it sufficient to detect composition changes even in narrow strips of submerged vegetation (Hestir *et al.*, 2008). Today's airborne imaging spectrometers can acquire data at 1 m² pixels or even better at high signal-to-noise ratios. To use these effectively, positioning errors must be small enough (≤ 1 pixel) that temporal changes can be detected at the pixel resolution (Khanna *et al.*, 2011).

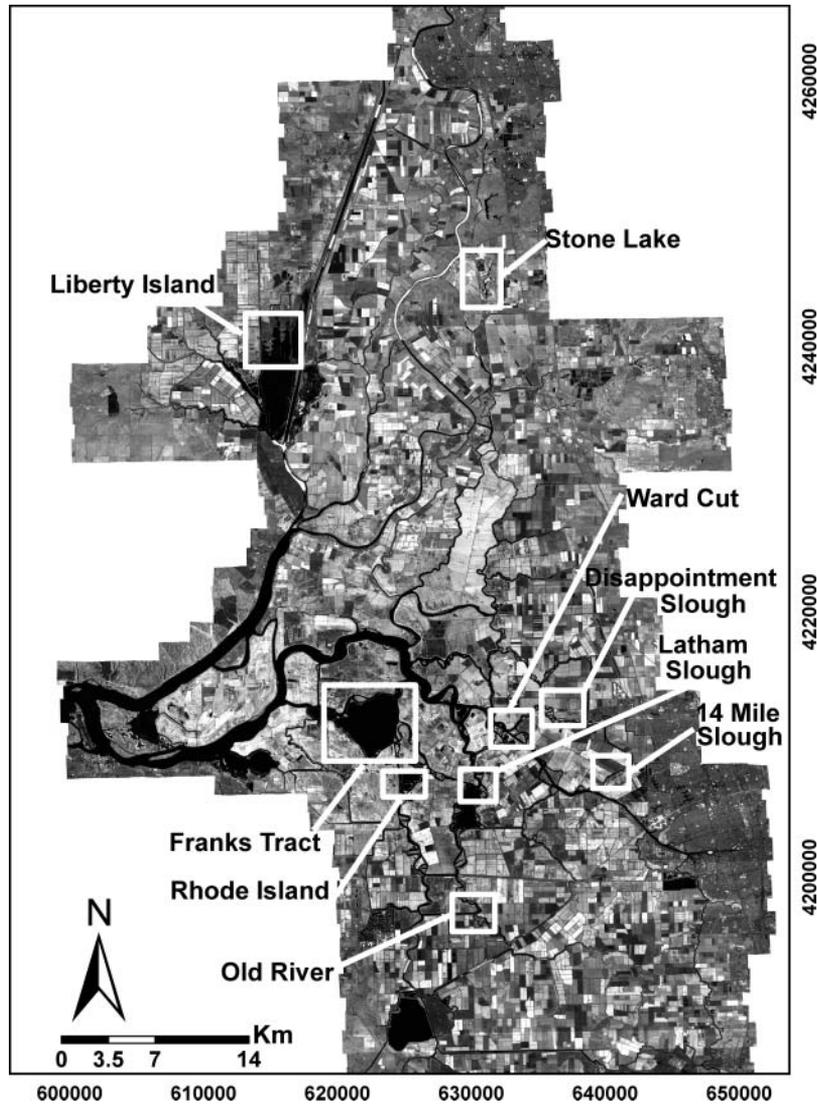


Fig. 2. Composite image of the SSJ Delta; boxes indicate the locations shown in Figs. 3–6. Figure shows the delta channel system (black) that bounds the 57 islands that comprise the delta. The region is rural and the density of agricultural fields can be seen throughout the delta region. The urban area east of 14 Mile Slough is the city of Stockton.

2. *Temporal resolution*: sufficiently repetitive to assess changes in environmental variability and management. In our case, we used a yearly repeat interval because the goal was to assess the composition and extent of the aquatic plant community (Hestir *et al.*, 2008), and whether the yearly management activities resulted (or not) in changes in the extent of invasive species (Santos *et al.*, 2009, 2011).
3. *Spectral resolution*: sufficiently detailed to measure the fine spectral structure that provides the information to differentiate species. This is necessary since plants share a

common metabolism that differs primarily only in the relative concentration of minerals and organic compounds. In our case, we used airborne image spectroscopy data (HyMap, 126 narrow bands, covering the 400–2500 nm wavelength region), which allowed us to differentiate all species within the class of floating species (Khanna *et al.*, 2011) and within the class of submerged species (Santos *et al.*, 2012). Measuring the full spectral interval was found to be essential to mapping these species and the various mixtures they are found in.

4. *Vertical resolution*: sufficiently fine vertical and horizontal information to detect small differences in microtopography and plant canopy structure. We examined tree canopy structure on levees, using height to determine whether riparian trees were present, and then used this information to account for shading on the water's surface, which then improved the accuracy of the estimates of submerged aquatic vegetation. We used LiDAR tree canopy data in three-dimensional radiative transfer models to understand how the canopy of riparian trees might modify surface water temperature (Greenberg *et al.*, 2012).

We provide examples of how fusing products from both image spectroscopy and LiDAR technologies produce a more complete picture of the community dynamics in the SSJ Delta, their interactions with the physical environment, and to what extent we can use such information to aid understanding of ecosystem responses to predicted climate change. We start by describing how to detect emergent, floating, and submerged plant communities, and then we describe the dynamics of the different vegetation communities with the physical environment and each other.

Case study I: Mapping the dynamics of invasive species

Floating macrophytes

Invasion and extinction of species and changing floristic composition are likely consequences of climate change impacts in Mediterranean deltas and estuaries. The invasion of aquatic communities by non-native species can have cascading impacts on the entire ecosystem. Monitoring such changes over time and developing effective management actions is key to retaining a functioning ecosystem. One of the most important invasive species in the SSJ Delta is water hyacinth. It can form dense mats that completely fill canals and smaller channels, preventing recreational and commercial use of the waterways for swimming and boating (Santos *et al.*, 2009). The environmental niche of water hyacinth, an invasive floating species, is adjacent to the riparian shoreline and emergent vegetation (Khanna *et al.*, 2012). It co-occurs with other floating species and is either free-floating or anchored at the bottom or to other vegetation. The floating 'mobility' of this invasive species makes it additionally challenging to assess whether changes in its distribution have occurred. Furthermore, all stages of its life cycle may be present in the same spatial location at any given time throughout the summer, including wracks of dead plant debris. Khanna *et al.* (2011) developed a binary classification tree scheme that differentiates water hyacinth from other floating and emergent species (Fig. 3). Despite close spatial proximity among the species, the classifier is able to identify them with an overall mapping accuracy of 71–88%, depending on species and year (Khanna *et al.*, 2011).

Figure 3 illustrates three patterns of change over the five-year period. Although each region experiences the same overall hydro-climate regime, the interactions resulted in differ-

ent successional patterns. Ward Cut (Fig. 3A) shows a progression from floating species to submerged aquatic vegetation (SAV) species, although we see inter-annual turnover within the floating species, mainly water hyacinth and pennywort (Khanna *et al.*, 2011). Initially, emergent wetlands and a mixed floating community in the channels dominate 14 Mile Slough (Fig. 3B). By the end of the period, the native pennywort dominates the floating community. In Stone Lake (Fig. 3C), the SAV community is progressively replaced by water hyacinth. Different successional patterns depend on the local site conditions, with changing dominance between communities and species (Khanna *et al.*, 2011). Although the region has received active management of the water hyacinth patches, they returned to the same general locations each year, suggesting the aquatic weed management programme had little effect on its abundance (Santos *et al.*, 2009). It is difficult to predict where changes in composition will occur, so as environmental conditions change with climate, this type of monitoring capability is needed to track changes in biodiversity and habitat conditions and to evaluate the efficacy of any management actions.

Submerged aquatic macrophytes

The SSJ Delta also hosts a set of invasive species in the submerged habitat. Mapping and monitoring of submerged plant communities is more difficult compared with vegetation at the water surface because of the added complexity of light absorption and attenuation by the water column. Thus the total reflectance from the water's surface is only a few percent of the incident light, meaning the measurable signal is much smaller (approximately three times smaller) than for vegetation types at the water surface. In addition, because these plants are embedded within the water column, their spectral signal becomes mixed with dissolved organic matter, sediment, and algae that are also present in the water column. Hestir *et al.* (2008, 2012) overcame these technical mapping challenges and successfully detected and mapped submerged aquatic vegetation despite turbidity and variable water depth at high accuracy (79–86%, depending on year; Fig. 4). Furthermore, Santos *et al.* (2012) showed that the SAV community as a whole and the individual species – both native and invasive – can be differentiated using their spectral properties.

Of the four native and four non-native SAV species, only Brazilian waterweed was abundant and commonly found throughout the SSJ Delta. For the years we catalogued SAV species composition for the full SSJ Delta, we found Brazilian waterweed alone or dominant in 60.5% of 967 field data points randomly located in the delta in 2007, while in 2008 it was 59% of 350 points and in 2014 it was 66.4% of 329 points. Brazilian waterweed has a suite of traits that make it particularly competitive, including high growth rates, overwintering shoots that are rooted at the bottom of the water column, and establishment both from plant fragments and from seed (Santos *et al.*, 2012). The annual distribution patterns of the SAV community in the SSJ Delta are dependent on preceding winter and spring temperatures, runoff through the delta, and the management actions from the previous year (Santos *et al.*, 2009). To monitor changing food webs and other ecosystem functions under climate change, it will be necessary to account for changes in composition and density of the SAV community.

Figure 4 illustrates an example for mapping of SAV at the community level at four sites. The SAV community in Frank's Tract (Fig. 4A) declined each year after 2004, increased during the middle years in Latham Slough (Fig. 4B), had similar distributions each year in Old River (Fig. 4C), and declined in the last two years in Rhode Island (Fig. 4D). Reasons for the different patterns undoubtedly relate to the conditions at each site. However, eradication of SAV at Frank's Tract was a management focus, especially in 2007 and 2008.

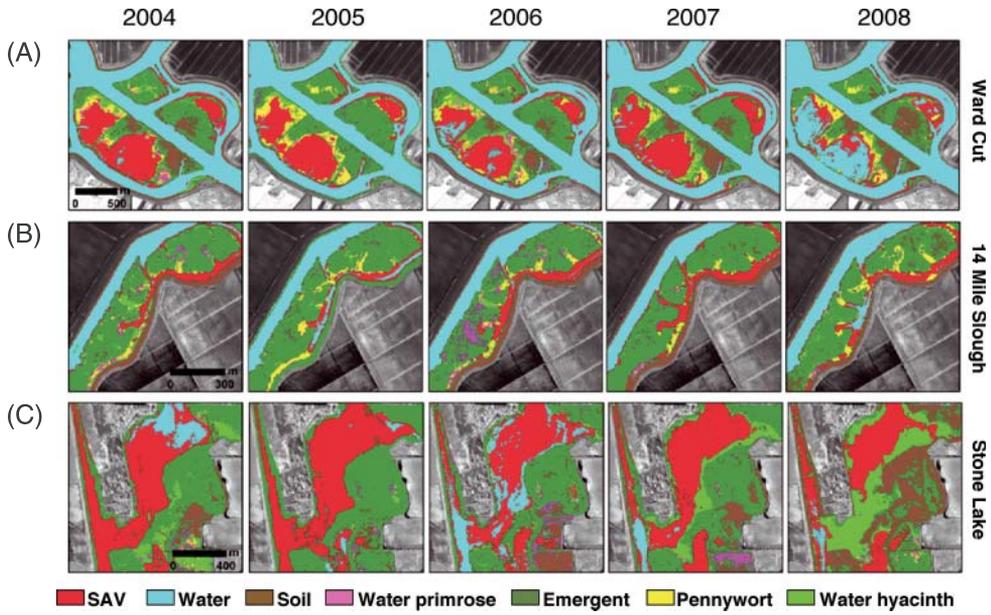


Fig. 3.

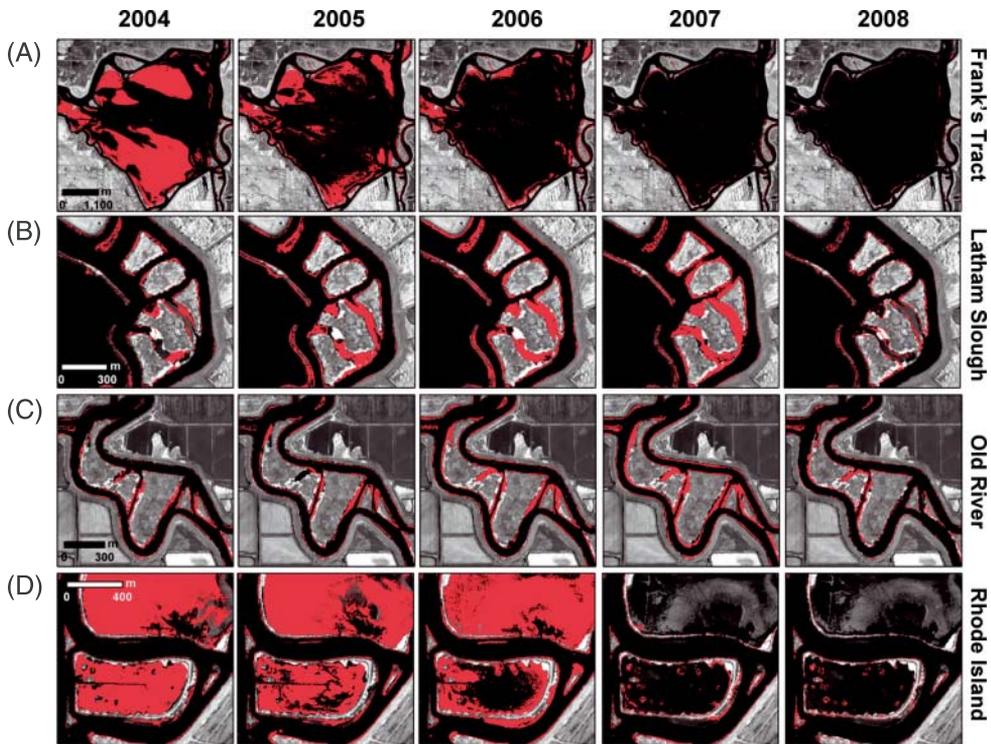


Fig. 4.

Frank's Tract is a shallow flooded island that experiences high tidal flows twice daily. Consequently, it has served as a nursery for invasive weeds into the surrounding waterways. Closest to Frank's Tract is Rhode Island, which showed a marked fall in SAV in 2007, next closest is Latham Slough, with Old River the farthest removed; consequently, any effect of management at Frank's Tract will have delayed the effect at the other sites.

Temporal changes within these environments can be monitored at the pixel scale (here, 9 m²) by overlaying multi-date maps to assess the patterns of growth, spread, persistence, and decline of these submerged communities. Figure 5 reveals the extent of change in SAV distributions from 2004 to 2008 in two environments found in the SSJ Delta, showing both persistence (Fig. 5A and C) and spread (Fig. 5B and D). Starting in 2004, we show where SAV was present in Disappointment Slough and Ward Cut. Then, by colour-coding, we show where SAV persisted in the same pixels each year after that to 2008 (M.J. Santos *et al.*, in preparation). Disappointment Slough (Fig. 5A) is a shallow channel meandering between islands, hence has protection and SAV persists here longer than in open waterways. The most sheltered areas have persistence lasting the five years of the study. Ward Cut (Fig. 5C) is a flooded island protected by levees and offers protection that allows multi-year persistence of SAV. Here we see three- to four-year persistence of SAV. In contrast, over the entire delta we find about 50% of the SAV area in one year persists to the next year.

Figure 5B and D show the expansive spread of SAV during this five-year period. For Disappointment Slough, SAV spreads outward into the channel from sites already occupied, with the most new growth occurring in 2007. In Ward Cut, SAV spreads further into the flooded island each year, impacting the floating community. Even if SAV does not expand beyond its current distribution, its impact on food webs and wildlife habitat will continue to be significant. Brazilian waterweed has the potential to act as an ecosystem engineer, as it can form dense stands under nutrient-rich conditions, warmer waters, and high light intensity. Such stands encourage sediment deposition and provide highly suitable habitat to non-native fish and other organisms (McGowan and Marchi, 1998; Brown, 2003).

Despite some future climate scenarios (warmer temperatures) that seem to favour SAV, others may be less favourable to these invasive species. Under high light when summer temperatures exceed 30°C (as expected in slow-moving shallow channels of the eastern SSJ Delta), the SAV species will likely be stressed (Cook and Urmi-Konig, 1984). Furthermore, low summer flow rates also raise the possibility that increasing summer salinity will penetrate farther upstream and this may have a greater impact on the assemblage of invasive species than on the natives (Knowles and Cayan, 2004). Predicting the actual impact of climate change and other anthropogenic influences on these communities requires that the full extent of the vertical and horizontal dynamics be taken into consideration. Different weightings and perhaps opposing effects of changing environmental and physical conditions will determine

Fig. 3. Figure mapping the distribution of and dynamics between floating and submerged aquatic vegetation (SAV) species over the period 2004–2008 for (A) Ward Cut, (B) 14 Mile Slough, and (C) Stone Lake: floating water hyacinth and water primrose (invasive), pennywort (native). Note that the scale of the panels varies as shown by the scale bar in the 2004 panels.

Fig. 4. Figure mapping the distribution of the submerged aquatic vegetation (SAV) community in four areas of the delta over the period 2004–2008: (A) Frank's Tract, (B) Latham Slough, (C) Old River, and (D) Rhode Island. The location of the SAV community is shown in red for each year. Note that the scale of the panels varies as shown by the scale bar in the 2004 panels.

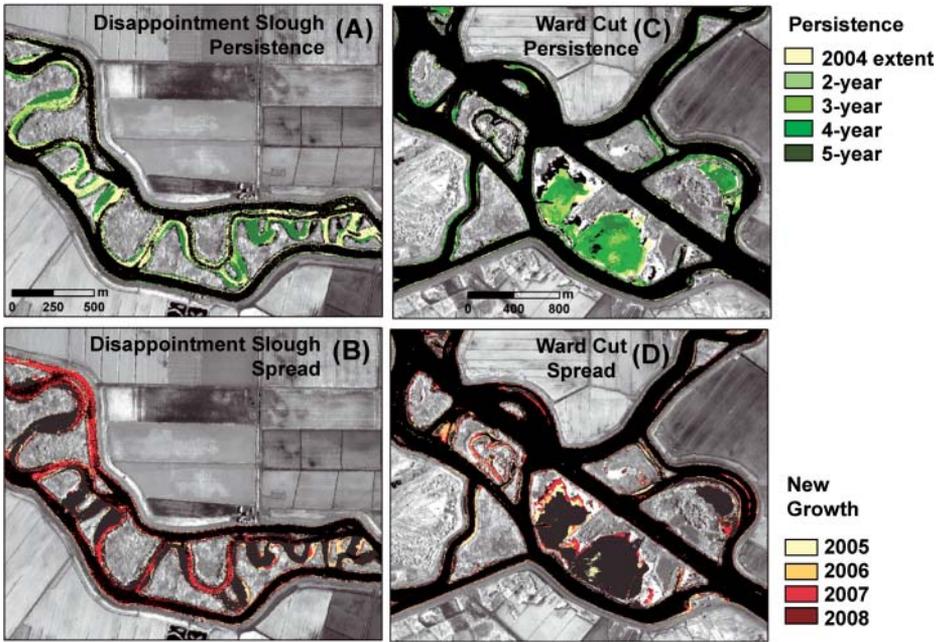


Fig. 5.

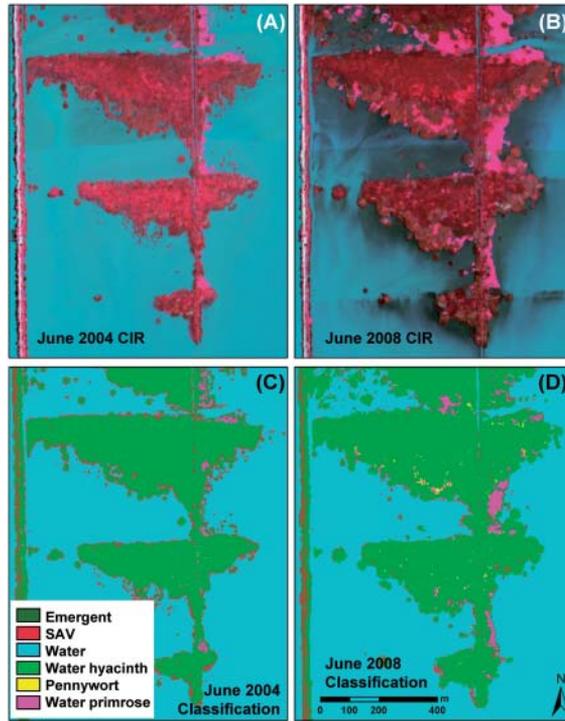


Fig. 6.

the establishment and spread of SAV, making the net effect of future SSJ Delta conditions on their distributions unclear. To reduce this uncertainty, a monitoring strategy is needed that can effectively track changes that will allow us to develop appropriate mitigation plans and quantify the effectiveness of mitigation strategies.

Case study II: Interactions between submerged and floating species

Changes in the composition of plant functional types will likely have cascading effects on the other aquatic communities in the aquatic environment of the SSJ Delta. Such changes are expected to be part of the changing composition of ecosystems in response to climate change. In the aquatic environment, light limitations affect the structure of emergent, floating, and submerged plant communities, since the first has its canopy above the water's surface, the second is at the surface of the water column, and the third within or at the bottom of the water column. Shading and light limitations by the first two have significant impacts on the growth and survival of the latter. Light limitations on the submerged aquatic communities in particular can result from the invasion of water hyacinth as it expands over the near-shore environment that is suitable for SAV species (Khanna *et al.*, 2011).

Temporal dynamics among these functional types can be followed using imaging spectroscopy by monitoring their changes in distribution. Figure 3 provides an example of changing dominance patterns from three locations in the SSJ Delta. In Ward Cut, most of the pennywort was replaced by water hyacinth, while at the same time the SAV community was encroaching on the distribution of the floating community. In contrast, 14 Mile Slough experienced an expansion of the native pennywort (*Hydrocotyle ramunculoides*) with significant reductions in SAV, water hyacinth, and water primrose (*Ludwigia* spp.). During the five years observed, Stone Lake changed from being dominated by SAV to being dominated by water hyacinth (Khanna *et al.*, 2011). Each of these species is functionally distinct, driving resource use in different trajectories for trophic interactions, fluxes of carbon, nutrients, water, etc. In the case of 14 Mile Slough (Fig. 3), removal of two invasive species resulted in the release of pennywort, a native species that then expanded to cover channels previously dominated by water hyacinth and water primrose (Khanna *et al.*, 2011). The native pennywort, adapted to the historic SSJ Delta, which had much higher variability in salinity, might reclaim more of its traditional habitat as water hyacinth retreats. Thus, specific

Fig. 5. Panels (A) and (C) show changes in persistence of submerged aquatic vegetation (SAV) species over the period 2004–2008 at two sites: Disappointment Slough and Ward Cut. Persistence is the continued presence of SAV in the pixels where it was identified as being present in 2004. Panels (B) and (D) show locations where new growth of SAV occurred in each year after 2004. New growth represents an expansion of SAV into pixels where it was not present in the previous year.

Fig. 6. Changes in the distribution of a tule-dominated landscape in the flooded lake of the former Liberty Island between 2004 and 2008. Panels (A) and (B) are colour infrared images that show vegetated pixels dominated by emergent species, mainly tule and cattails (dark red) or macrophytes (SAV or floating species in pink). Panels (C) and (D) show the vegetation classification by functional type and species for these two years. The figure shows the expansion of the emergent wetland into the lake during this 5-year period.

predictions about the outcome of future wetland and aquatic system species compositions, given the likely impacts of climate change should be considered uncertain, but with monitoring predictions will become more accurate. The ability to track ecosystem changes at these very fine spatial and temporal scales, as demonstrated here, provides spatially explicit information not previously available for conservationists to monitor change. To effectively respond to the effects of climate change, we need to develop automated cost-effective observational methods, spatial analytical tools, and models that will allow more effective monitoring of ecosystem functioning and improve our understanding of the significance of such changes on the larger estuary.

Case study III: Re-establishment of native emergent wetland from a flooded agricultural tract

Rise in sea level, less predictable climates, and other components of climate change will have significant impacts on future land use in Mediterranean estuaries. One consequence is likely to be abandonment of marginal agricultural lands in deltas and estuaries and subsequent regeneration of marshes and wetlands, especially as a mitigating strategy to prevent erosion and restore ecosystem function. Agricultural practices on many of the islands in the SSJ Delta have resulted in significant subsidence, with elevations ~8 m below sea level (Mount and Twiss, 2005; Miller *et al.*, 2008; Brooks *et al.*, 2012; Deverel *et al.*, 2014). In the western SSJ Delta, gas removal from the large Rio Vista Gas Field has also led to significant subsidence (Deverel *et al.*, 2014). Liberty Island in the north SSJ Delta is a freshwater, naturally restored tidal wetland of ~2100 ha that was created by flooding a reclaimed agricultural tract following a levee breach in 1998 (Lehman *et al.*, 2010a). Flooding has produced a shallow wetland with large spatial gradients in tides and flow, with highly variable seasonal and yearly fluctuations in water levels, depending on the upstream freshwater supplies (Whitley and Bollens, 2014). Annual changes in areal cover of the emergent wetland vegetation were highly variable, perhaps because 2006 was an extremely wet year (139% normal Sierra Nevada snowpack; California Snow survey, <http://cdec.water.ca.gov/snow/>) with high flows, which likely limited the growth of these species.

Figure 6 shows the mapped locations of emergent wetland species in a subsection of Liberty Island. The dominant emergent species in this wetland include tule (*Schoenoplectus acutus*, *S. californicus*), cattail (*Typha latifolia*, *T. angustifolia*), and common reed (*Phragmites australis*). Dominant floating plant species include the invasive water primrose, water hyacinth, and native pennywort. Even though the overall emergent wetland vegetation cover was variable from year to year, the locations they occupy have expanded into the open water habitat, following an outward trajectory of recolonization each year. Figure 6 shows the differences after five years of restoration-mediated recolonization of the shallower areas of Liberty Island by the tule-dominated emergent tidal wetland. The triangular shapes of the initial wetland units are the original agricultural access roads between fields, with deposition starting along this edge and filling outward, as seen in the colour difference on the colour infrared images (Fig. 6A and B), while the classified images (Fig. 6C and D) show the distribution by vegetation type. These recovered wetlands now support a year-round habitat for the endangered delta smelt (Sommer *et al.*, 2011). This example illustrates progress in the recovery of native wetlands and their ecosystem functions, showing that it is possible but that it is a slow process. Because climate change will be expressed as a suite of changing conditions, which may represent new environmental

combinations, our new wetlands are unlikely to duplicate today's species distributions. Careful monitoring of species' responses to these new conditions will provide templates for expected future distributions.

Case study IV: Submerged plants and sediment

Climate change will bring changes in the physical aquatic environment. The warmer winter temperatures and precipitation regime will likely lead to more frequent winter flooding and summer droughts. Such patterns may significantly impact other aspects of hydrologic processes, including erosion and sediment transport in winter and tidal salinity intrusions in summer. The interaction between water movement, sediment deposition, and aquatic plants is complex (Hestir, 2010). When the submerged vegetation is sparse, water velocity is high, and sediment re-suspension is high, the high turbidity produces an environment where light limits submerged vegetation growth. In the alternate state, submerged vegetation is abundant, thus reducing water velocity, and consequently reducing sediment re-suspension and increasing clarity, which then promotes SAV growth (Crooks, 2002; Schulz *et al.*, 2003). Additional factors further strengthen these feedback loops. High current velocity changes bed composition and induces shear stress on plants (Madsen *et al.*, 2001). Conversely, vegetation beds trap sediment and accrete organic matter, which improves bed composition and nutrient content, and thus promotes plant growth (Jones *et al.*, 2012). These positive feedbacks permeate the trophic structure of aquatic ecosystems, affecting nutrients, algae, zooplankton, and fish (Schriver *et al.*, 1995; van Donk and van de Bund, 2002).

Using our maps of SAV distribution, Hestir (2010) showed that high water velocity significantly limited the cover of SAV. When the SAV community maps were coupled with historic observations of SAV distribution (Attwater *et al.*, 1977; Brown and Michniuk, 2007) and long-term suspended sediment monitoring data, there was evidence of a state shift in turbidity and SAV feedback in the SSJ Delta (Hestir, 2010). The SSJ Delta experienced a significant step decrease in suspended sediment in 1983, which seems to have favoured the initial period of SAV expansion (Hestir *et al.*, 2013). By the late 1990s, SAV had expanded across most of the SSJ Delta, and although its total areal cover fluctuates annually, the expansion phase seems to have stabilized and its distribution is now partially limited by channel velocity (Hestir, 2010; Hestir *et al.*, 2012), while suspended sediment supply continues to decline (Wright and Schoellhamer, 2004; Hestir *et al.*, 2013; Schoellhamer *et al.*, 2013). The expansion of SAV in the SSJ Delta is positively correlated with the decline in suspended sediment, contributing between 21% and 70% of the total trend in decreased suspended sediment. The SSJ Delta has now transitioned into a sediment supply-limited system, possibly ending light as the limiting factor for SAV growth. However, in addition to increasing SAV, phytoplankton biomass also has shown positive trends over the past decade (Jassby, 2008). Cyanobacterial blooms (*Microcystis aeruginosa*) first appeared in the SSJ Delta in 1999 and have increased in abundance and toxicity each year (Lehman *et al.*, 2005, 2008, 2010b). Increases in water temperature associated with climate change may favour increased phytoplankton blooms, particularly toxic cyanobacteria (Paerl and Paul, 2012), and expansion of algae and bacterial mats near the water surface could create a new source of light limitation for bottom-rooted SAV and create an upwards cascading trophic effect that may yet initiate another state shift in the SSJ Delta. Cyanobacterial blooms are readily identified in imaging spectroscopy data because their phycocyanin pigments produce distinctively different spectral signatures compared with the chlorophyll a and b and carotenoids of higher plants. The evolving suite of physical environmental variables

under a changing climate will produce new successional patterns and reassemble community composition because of their location-specific interactions.

Case study V: Implications of levee management decisions to the aquatic environment

As we move into an era of mitigation for climate change, it is essential to have tools to monitor management actions and determine their efficacy. The US Corps of Engineers is responsible for preventing failure of the earthen levees in the SSJ Delta. Consequently, they plan to remove the riparian forest trees and other vegetation from the levees (US Army Corps of Engineers, 2009) to prevent roots from creating channels for water transport through the levees, which can lead to failure. However, there are other consequences to removing all tree and vegetation cover from levees in a Mediterranean climate, such as enhanced winter erosion from the bare soil and increased summer water temperatures, by removing canopy shade from shallow channels. Greenberg *et al.* (2012) investigated the impact of increased solar radiation on the water surface in summer months using a three-dimensional radiative transfer model, after simulating removal of the riparian forest. They used LiDAR data to quantify the vertical distribution of the tree and shrub canopies in the riparian zone, and then used a radiative transfer model of the radiation intersecting the water surface for the summer months. They compared this to the simulated radiance that would intersect the water surface if the canopy were removed. They found that the narrow, shallow channels in the eastern SSJ Delta experienced the greatest potential increase in radiation (Fig. 7), which would, in the absence of other factors, lead to an increase in water temperature, thus affecting the growth rate of SAV and habitat for fish and other wildlife. The implications of this are that in the shallow waters occupied by SAV species, the increased water temperatures should benefit the spread and density of aggressive invasive species like Brazilian waterweed and other invasive SAV species such as Eurasian watermilfoil, *Myriophyllum spicatum* (Santos *et al.*, 2011). In terms of future conditions caused by climate change, this study demonstrates that a change in plant functional type (here loss of the riparian forest) or a decline in its cover fraction can have significant impacts on other aspects of the ecosystem, cascading through trophic levels and biodiversity [e.g. increased water temperatures will be extremely detrimental to the native fish assemblage of the SSJ Delta (Thomson *et al.*, 2010)].

DISCUSSION

The impacts of climate change on Mediterranean ecosystems are mediated by the complexities of the interactions between the species and their physical environment. In this review, we report patterns of recent dynamics in aquatic plant species that were recorded annually over a period of five years. These examples show how invasions of aquatic and wetland plant species and changes in hydrologic processes have simultaneously affected the SSJ Delta system in just a few years. What are the implications of such short-term dynamics to long-term effects of climate change?

Predicted temperature increases of 2–4°C (Knowles and Cayan, 2004) and increases in insolation have several implications, given the current composition of the plant communities of the SSJ Delta. Submerged invasive species survive the winter because the temperature is too warm to freeze, which allows them to overwinter and resume their phenological cycle in late winter (Santos *et al.*, 2011). This is hypothesized to give Brazilian waterweed a competitive

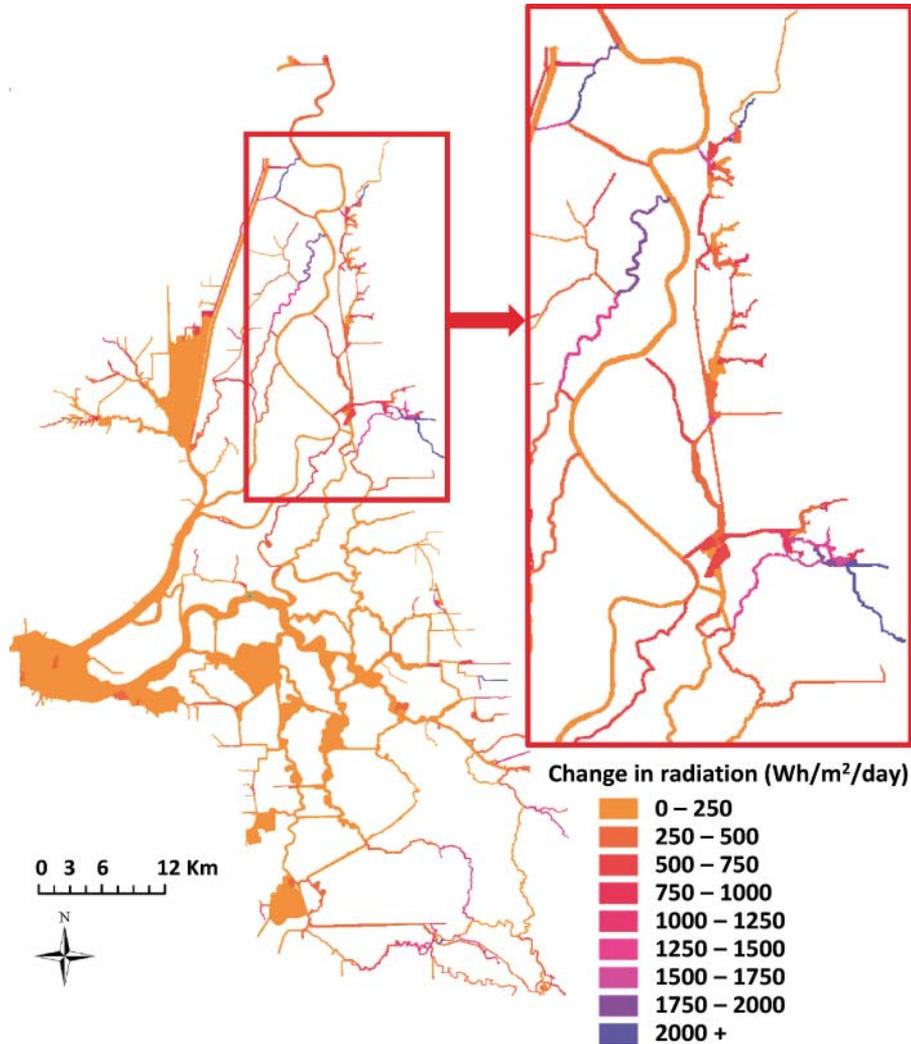


Fig. 7. Difference in daily incident radiance ($W/m^2/day$) over the summer months on the surface water in channels in the SSJ Delta given the current distribution of riparian/levee tree canopies, and the daily incident radiance if riparian trees were removed from the levees (Greenberg *et al.*, 2012).

advantage (Santos *et al.*, 2012). Furthermore, all of the non-native submerged species in the SSJ Delta have the facultative C4 photosynthetic pathway that allows them to take advantage of the high radiation levels at the surface and low radiation levels at the bottom of the water column that are not tolerated by the native species (Santos *et al.*, 2012). The known decline in sediment levels in the SSJ Delta (Hestir *et al.*, 2013), associated with the timing of spread of submerged species (Hestir, 2010; Hestir *et al.*, 2012), and the potential for increased radiation levels (Greenberg *et al.*, 2012), should extend competitiveness for the invasive submerged species compared with the native SAV species.

With warmer water temperatures from climate change, it will become easier for water hyacinth and other floating species to thrive, and since they will not be limited by freezing in

winter and will have optimal growth conditions in summer, their removal and eradication will depend on chemical and/or mechanical treatments (Santos *et al.*, 2009). Floating species tend to re-occur in the same protected locations at the edges of emergent wetlands where they are sheltered from wind and currents, and have access to source populations that are released from the neighbouring agricultural ditches that are seasonally opened to the SSJ Delta (Khanna *et al.*, 2012). The scale of the SSJ Delta will make removal under this scenario unlikely.

Increased winter rainfall due to warming is predicted to substantially change the river hydrograph to a pattern with increased winter flows and decreased summer flows (Knowles and Cayan, 2002), and will also increase the likelihood for more extreme inter-annual drought and flood cycles (Cloern *et al.*, 2011). In contrast to temperature predictions, the higher winter flows are likely to have a negative effect on the floating species, which can wash out of the SSJ Delta system and may also have a detrimental impact on the SAV that can be uprooted and washed out under high-velocity flows. The higher summer temperatures and lower flow rates and lower sediment transport may favour expansion of the invasive species, although this may be mitigated by sea level rise and higher salinity in the interior of the SSJ Delta (Cayan *et al.*, 2008), which should favour native species. The consequences of these changes will cascade through the ecosystem, as several species of threatened fish are already responding to shifts in the submerged plant community and turbidity (Ferrari *et al.*, 2014), as well as changes in other physical properties (Cloern *et al.*, 2011).

The Sacramento-San Joaquin Delta has undergone major ecological changes over the past few decades due to a multitude of anthropogenic stressors (Delta Stewardship Council, 2011), including species invasions (Moyle and Bennett, 2008; MacNally *et al.*, 2010; Thomson *et al.*, 2010), eutrophication from agricultural runoff (Nichols *et al.*, 1986), and declines in turbidity (Schoellhamer *et al.*, 2013). Our case studies show how species invasions have had a profound impact on the current status and future of the SSJ Delta. The current plan by the State of California to mitigate ecological damage to the SSJ Delta and reduce the presence of invasive species is to reduce the flow of fresh water through the delta and create a more brackish environment by transporting Sacramento River water around the SSJ Delta and into the California Aqueduct System (Draft Bay Delta Conservation Plan, 2013). The Conservation Plan includes a coordinated system of *in situ* sensors and regular monitoring by airborne imaging spectroscopy and LiDAR-type sensors to aid adaptive management decisions.

Estuaries in other Mediterranean climate areas are likely to face challenges similar to those described here. The current and planned satellites by the major space agencies will not meet the requirements for high spatial, spectral, and temporal resolution data to adequately monitor these systems. There are a number of commercial imaging spectrometers that are suitable, from small aerial platforms [such as drones with small (<5 kg) instruments, e.g. Headwall Photonics] to moderate size airborne platforms (e.g. the Twin Otter, a popular platform today) and larger but still moderately sized (<100 kg) instruments (e.g. SPECIM's AISA systems). The most recent commercial satellite sensors are approaching the required observation capability, such as WorldView-3, which has eight visible and near-infrared bands at 1.24 m ground resolution and eight shortwave-infrared bands at 3.7 m resolution; however, these sensors are still expensive, may not have the relevant bands for differentiating species, and are not available for routine monitoring. Nonetheless, they demonstrate the potential for developing this observational capacity from space. The German, Italian, Japanese, Indian, and Chinese space agencies are in various stages of developing space-borne imaging spectrometers, but for the foreseeable future, these will not have the spatial resolution or temporal repeat frequency to meet the observational needs in estuaries.

Therefore, drone- or aircraft-based deployments, arranged to coincide with the best observation time, are likely to be the primary option for developing a routine monitoring strategy for Mediterranean estuaries and deltas. Fortunately, the cost of both platforms and instruments has significantly declined in recent years, and thus it is not inconceivable that such instruments can be supported at the local management level.

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