Remote sensing applications for invasive species management in the Delta

Authors

Thomas Jabusch – Lead Author and Editor
Sacramento – San Joaquin Delta Conservancy / California Department of Fish and Wildlife

Shruti Khanna
California Department of Fish and Wildlife

Aaron Haiman
Sacramento – San Joaquin Delta Conservancy

Rachael Klopfenstein
Delta Science Program - Delta Stewardship Council

Suggested Citation

Delta Interagency Invasive Species Coordination Team. 2020. Remote sensing applications for invasive species management in the Delta.

Acknowledgements

The following reviewers greatly improved this document by providing comments and edits on draft versions:

Gina Darin (California Department of Water Resources)

Iryna Dronova (University of California, Berkeley)

Louise Conrad (Delta Science Program – Delta Stewardship Council)

Susan Ustin (University of California, Davis)

David Bubenheim (National Aeronautics and Space Administration – Ames Research Center)

Contents

Summary

This paper captures the key messages of the 2019 Delta Invasive Species Symposium: Remote sensing applications for management. The aim of the symposium was to explore how remote sensing tools can help resource managers in the Delta better tackle the pervasive problem of biological invasions. Remote sensing offers a big and diverse toolbox for resource managers dealing with invasive species, and the symposium agenda reflected that. Another key aspect of the symposium was to provide an opportunity for coordination for the diverse community of participants, which included resource managers dealing with invasive species problems, remote sensing experts and users, and those wanting to learn more. Dr. Louise Conrad, the Deputy Executive Officer of the Delta Stewardship Council (Council)'s Delta Science Program opened the symposium by asking some compelling questions for resource managers to consider: "What if we knew in reasonable time, or even real time, where the worst invaders are, where the leading edge of invasion is, and how we can address the problem in a targeted way?"

The paper summarizes the symposium "take homes" and is organized around 5 key topics of interest that emerged from the presentations and discussions:

1. **Using remote sensing to map invasive species.** Remote sensing technologies provide powerful tools to map and monitor the progression of biological invasions in the Delta region and assess the success of control strategies over time.
2. **Moving beyond mapping: Using the maps and ancillary data to understand invasion ecology and curtail spread.** The true value of remote sensing lies in the information that the maps can provide when examined across seasons and years and combined with other kinds of data or models.
3. **Mapping invasives other than plants through remote sensing.** Remotely sensed data are used widely for mapping, monitoring, as well as modeling and forecasting invasions of plant species. However, some remote sensing tools are also useful in mapping animal invaders such as nutria.
4. **Finding synergy with other uses for the data.** This includes leveraging multiple funding sources and making better use of remote sensing data. Sometimes it is not a new tool that brings added benefits but a new way of using the information provided by the tool. An example is the use of habitat maps of nutria for assessing risk and forecasting the spread of nutria.

5. **Finding and coordinating cost-sharing opportunities to monitor the Delta.** A consistent funding source is needed to ensure the continued acquisition of remote sensing data. Cost-sharing is the recommended path forward to ensure that high-quality remote sensing data continues to be collected at the desired frequency. Investing in rich, informative, and high-quality remote sensing datasets can benefit multiple users in the region.

Introduction

The Sacramento – San Joaquin Delta (Delta) is a major conduit for biological invasions into California with a rising rate of invasion (Cohen and Carlton, 1998). Over the past 3 years, the California State Parks Division of Boating and Waterways (DBW) has spent 45 million dollars treating aquatic invasive weeds to keep Delta waterways navigable (Jetter and Nes 2018). State agencies and local groups also put in considerable money, time, and effort to control invasive plant species on levees, in wetlands and restoration sites, and on agricultural lands.

In the symposium opening presentation, Dr. Iryna Dronova from the University of California, Berkeley (UC Berkeley) explained that remote sensing became an important part of the invasive species management toolbox just around the beginning of the 21st century (Figure 1). Invasive species science started in the late 1950s with the first publications discussing the ecology of invasions by animals and plants. Since then, the ecological science of invasions has been advancing, and so have various invasive species management methods. Before the 1970s, the most widely available remote sensing technology was aerial photography, and not all the of the generated imagery was available to the public. However, with the beginning of Earth satellite observations in the 1970s, environmental applications of remote sensing data started to progress. Numerous ecosystem monitoring tools based on remote sensing data were developed in the 1970s, 1980s, and 1990s, but there were relatively few applications towards invasive species science and management. These earlier applications of remote sensing tools consisted mostly of mapping plant species such as palm trees or leafy spurge. Since the early 2000s, there has been a major shift. A larger assortment of remote sensing tools is now available for invasive species detection, mapping, and monitoring. In addition, remote sensing applications are no longer just considered for mapping but are finding additional uses such as modeling. For example, remote sensing tools are being used for modeling the risk of invasions for certain species and sites.

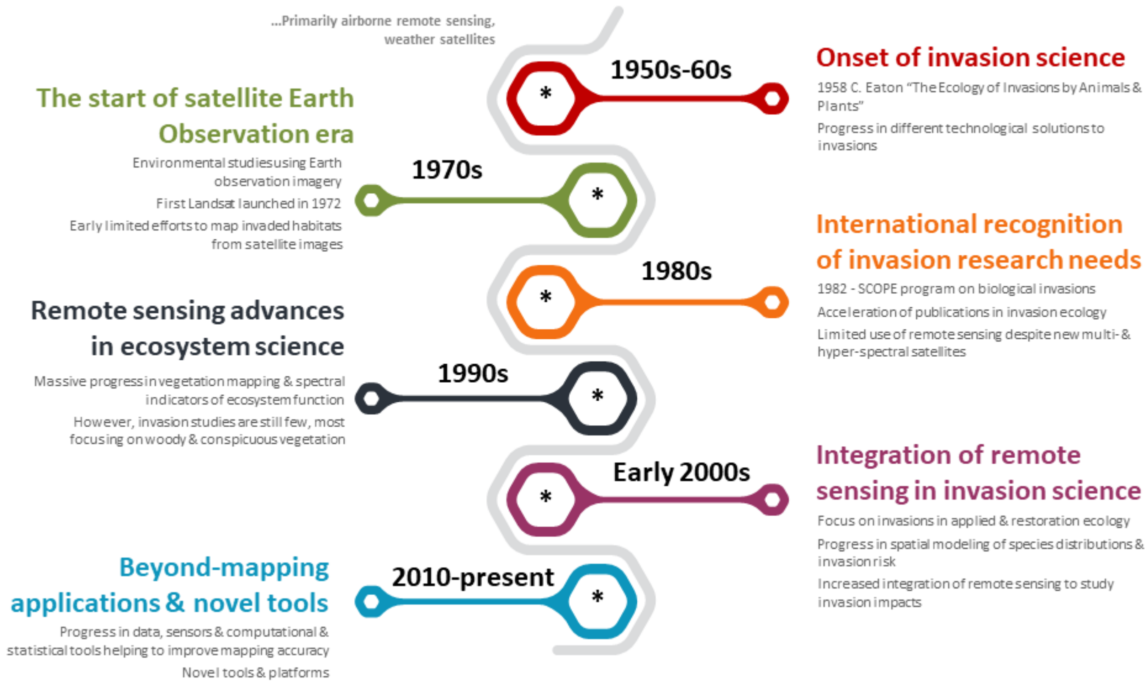

Figure 1. *The evolution of invasive species ecology and remote sensing tools.*

Dr. Dronova introduced four common types of sensor platforms that were discussed in the following presentations:

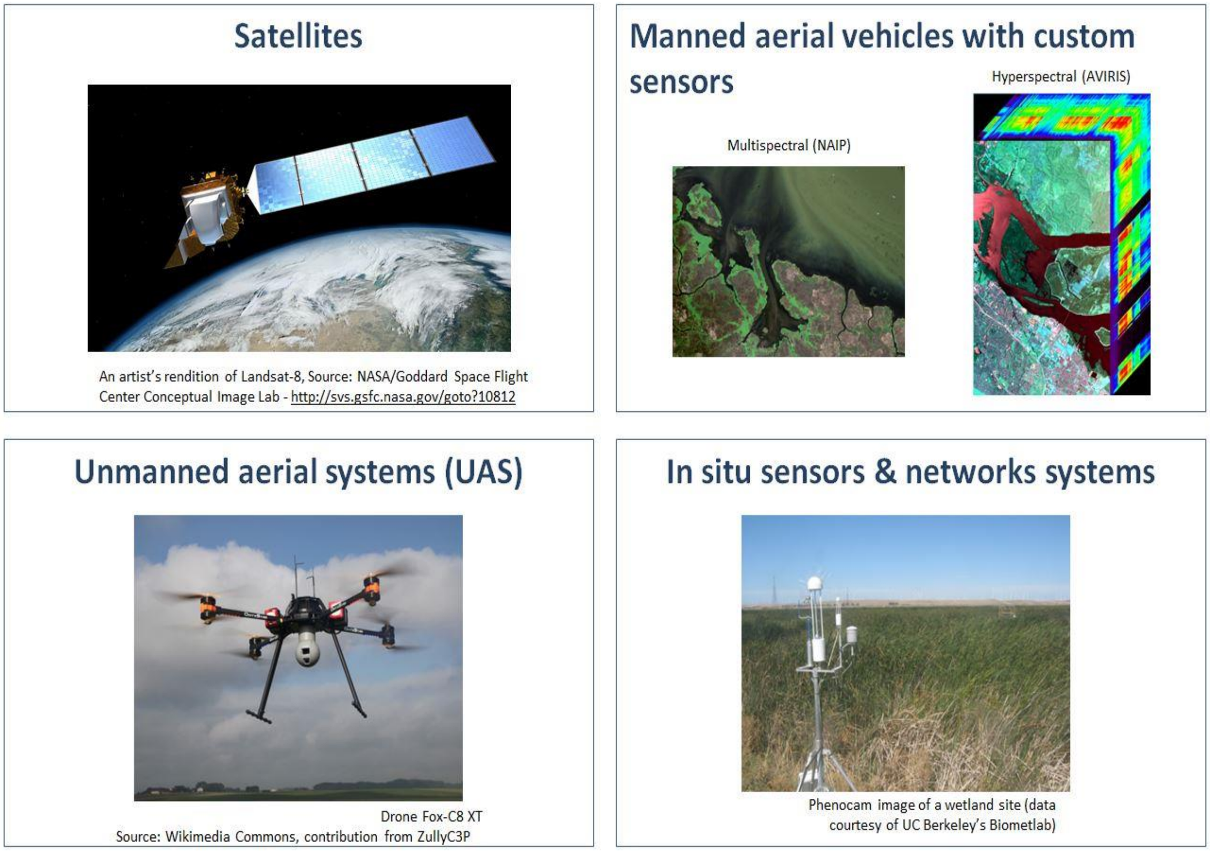

Figure 2. *Remote sensing platforms.*

The most common platforms for remote sensing are 1) satellites, 2) manned aerial vehicles with custom sensors, 3) Unmanned Aerial Systems (UAS), and 4) in-situ sensors, fixed cameras, and network systems. These four sensor types are briefly introduced below. The Aquatic Vegetation Monitoring Framework of the Interagency Ecological Program (Khanna et al. 2018) provides more detailed information on the monitoring toolkit for remote sensing, including the strengths and weaknesses of each tool.

Satellite monitoring typically involves moderate resolution sensors such as Landsat (30m) and Sentinel-2 (10-30m), which offer high frequency (2-26 days) and freely available imagery (Khanna et al. 2018). Typical satellite monitoring applications include the tracking of changes in vegetation and land cover.

Sensors on manned aerial vehicles include multispectral and hyperspectral sensors used for airborne optical imagery. Airborne imagery is typically higher cost than satellite imagery and used for more complex remote sensing applications such as mapping species, measuring water quality, or tracking disease infestations. Additional sensor systems used on manned vehicles include Light Detection and Ranging (LiDAR) and Radio Detection and Ranging (RADAR), which are less commonly used for invasive species monitoring. LiDAR is good at measuring 3D canopy structure and can be used to differentiate between Floating Aquatic Vegetation (FAV), Emerging Aquatic Vegetation (EAV), and riparian trees. RADAR can record vegetation surface roughness and is used to detect inundated wetlands and flooded areas under a vegetation canopy.

UASs include fixed-wing Unmanned Aerial Vehicles (UAVs) and hovering (helicopter-type) small platforms referred to as “drones”. UAVs or drones can be mounted with regular photographic cameras, infrared cameras, or multispectral and hyperspectral sensors. UAVs are lower cost, offer high spatial resolution, and on-demand image collection. A typical application is monitoring of individual restoration sites (Taddeo and Dronova 2018).

In-situ sensors and cameras include tools such as fixed cameras, motion detectors, or light sensors at selected sites. These tools and other systems like hydroacoustic sensors are less commonly used for standalone monitoring purposes. They might provide helpful low-cost options in addition to other methods.

1. Using remote sensing to map invasive species

Status of remote sensing data and applications

Dr. Dronova summarized remote sensing data that have been applied or could potentially be used for mapping and studying invasive species in the Delta at a regional scale. These data were or are being collected with different sensor platforms and technologies:

Example datasets & programs	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
HyMap (airborne hyperspectral)							Multiple plant invasion studies by CSTARS group, UC Davis & CDBW														*
AVIRIS (airborne hyperspectral)																	Drought studies		*	*	
VegCAMP & Delta/ Suisun veg mapping			*			*			*	Delta		*			*			*			
NAIP (aerial multi-spectral, 1m, USDA)																					
Landsat (satellite multi-spectral)	L-5,7	L-5,7	L-5,7	L-5,7	L-5,7	L-5,7	L-5,7	L-5,7	L-5,7	L-5,7	L-5,7	L-5,7	L-5,7	L-5,7	L-7	L-7,8	L-7,8	L-7,8	L-7,8	L-7,8	L-7,8
Sentinel-2 (satellite multi-spectral)																					
Commercial high-res multi-sp. satellites																					
Lidar (airborne)		Used in *Lepidium* studies (Andrew & Ustin 2008-2010) & discrimination of EAV & FAV (Khanna et al. 2011)												Suisun							
Satellite & airborne radar (var. res.)									ALOS PALSAR	ALOS PALSAR	ALOS PALSAR	ALOS PALSAR	ALOS PALSAR	ALOS PALSAR			Sent-1	Sent-1	Sent-1	Sent-1	Sent-1
UAS radar (UavSAR)																					

Figure 3. *Selected remote sensing data relevant to invasion studies & management in the Suisun-Delta region. * indicates datasets that do not cover the entire Delta region. L-5,7 = Landsat 5 and 7. L-7 = Landsat 7. L-7,8 = Landsat 7 and 8. ALOS PALSAR = Advanced Land Observing Satellite (ALOS) equipped with Phased Array type L-band Synthetic Aperture Radar (PALSAR). Sent-1 = Sentinel 1.*

For example, an upcoming Surface Biology and Geology (SBG) mission (not listed in the table above) by the National Aeronautics and Space Administration (NASA) holds great potential for mapping invasive species at the genus level using multi-spectral imagery. Dr. Erin Hestir from UC Merced highlighted the potential of LiDAR technology for improving detection of invasive species, especially when used in conjunction with other remote sensing data. For example, Andrew and Ustin (2009) used LiDAR microtopography data coupled with identification of perennial pepperweed (*Lepidium latifolium*) from hyperspectral remote sensing to identify optimal habitat for this invasive weed in Suisun Marsh.

The continued improvement in sensors, flight technology, and processing software for UASs is creating new opportunities for cost-effective surveying and management of invasive species. UASs allow observation of difficult to access habitats such as densely vegetated and tidally influenced wetlands or mudflats in the Delta. They can supplement field efforts by collecting imagery concurrent with field work, thus reducing the amount of effort required as well as the footprint of a sampling effort on a sensitive ecosystem. UAS imagery can also be used for validating airborne or satellite imagery when mapping species in large areas or an entire region.

Mapping invasives in the Delta through remote sensing

Resource managers and researchers started mapping invasive plants in the Delta with remote sensing tools in the late 1990s. For example, the California Department of Fish and Wildlife (CDFW) mapped Suisun Marsh vegetation every three years starting in 1999 using fine spatial resolution aerial imagery. This mapping has been critical in documenting a many-fold increase of non-native *Phragmites* in the marsh.

Submerged aquatic vegetation (SAV) and the two dominant FAV species in the Delta, water hyacinth (*Eichhornia crassipes*) and water primrose (*Ludwigia* species), have been mapped since 2004 using hyperspectral airborne imagery. This mapping was done at the Center for Spatial Technologies And Remote Sensing (CSTARS) at the University of California, Davis (UC Davis) and has been funded by various agencies through the years, including DBW, CDFW, California Department of Water Resources (DWR), DSC, and State Water Contractors (SWC). Initially, from 2004 to 2008, SAV and FAV were mapped every summer. After that, there was a six-year funding gap where no imagery was collected. Since 2014, the imagery acquisition has resumed across a third of the Delta area, with Suisun and the entire legal Delta Boundary only being imaged some of the years. This long dataset of distribution of Delta invasives has, over the years, yielded valuable information about their impacts on the ecosystem, growth, competition, turnover, control efficacy, and invasion success (Andrew and Ustin 2008; Hestir et al. 2008; Khanna et al. 2012, 2018; Santos et al. 2009, 2010, 2012, 2016). Hyperspectral data collected during and following the drought (2014-2018) showed water primrose encroaching on and spreading into marsh habitat (Khanna et al. 2018).

Hyperspectral aerial imagery has thus far been the primary, but not the only remote sensing tool for mapping invasive plant species in the Delta. DBW has also been collecting hydroacoustic data to map SAV in selected locations across the Delta where they treat submerged aquatics extensively. DBW collects one set of images at the beginning of the spray season, one during, and one after the completion of the spray season. DBW summarizes results from the SAV mapping in annual monitoring reports. In recent years, NASA scientists have used Landsat and Sentinel satellite multispectral imagery to map FAV in the Delta and provide frequent maps throughout the year. Timely data like these can guide agencies like DBW and California Department of Food and Agriculture (CDFA) in targeting sites and time periods for herbicide application to make the process more streamlined and effective.

UAVs have recently also been used to spray emergent invasives such as *Phragmites* in the field without having to physically navigate into dense emergent vegetation. Types of UAVs include multi-copter, which can hover in place, or fixed wing, which cannot hover, but are faster and better for large sites. Different types of sensors can be mounted on these UAVs from simple cameras to multispectral to hyperspectral sensors. UAVs usually provide not just the sensor data but also accurate geolocation information and digital surface models.

Temporal and spatial dynamics of invasive species

The presenters showed how remote sensing technologies can provide powerful tools to map and monitor the progression of biological invasions in the Delta region and assess the success of control strategies over time. Several speakers also addressed how to select the appropriate platforms and technologies for use, as well as considerations for the appropriate sampling approach. For example, Dronova discussed the frequency of data collection as an important deciding factor, broadly dividing data into “low frequency” (e.g., annual, or seasonal) and “high frequency” (e.g., monthly, weekly, or daily).

“Low frequency” datasets are useful for describing the current state of an invasion and assessing gradual changes in conditions (e.g., year-to-year dynamics). A prime example is hyperspectral aerial imagery. Typical uses include the monitoring of peak biomass or maximum extent coverage of invasive plants each year, and their spread over time (Khanna et el. 2018). Less frequently collected but information-rich (typically costlier) data can also serve to study the response of invasive species to interannual variation in climate and hydrology (droughts, flooding) or to slower-acting treatments (Santos et al., 2009).

“High frequency” datasets are typically cheaper and easier to process. Examples include satellite acquired multi-spectral imagery, such as Landsat or Sentinel-2. High frequency data are often needed to study the processes involved in biological invasions, such as seasonal plant community succession; the timing of biological events such as flowering, leafing, hibernation, reproduction, and migration; or responses to rapid-acting treatments.

Improving invasive species management in the Delta

One of the Lightning Talks at the symposium featured the DBW Aquatic Weed Control Program, which is one of the primary users of remote sensing data for invasive species management in the Delta. The program uses satellite-based FAV mapping primarily for identifying and addressing priority areas for treatment, assessing the efficacy of management actions such as herbicide treatments, and evaluating which long-term strategies to pursue for effective control.

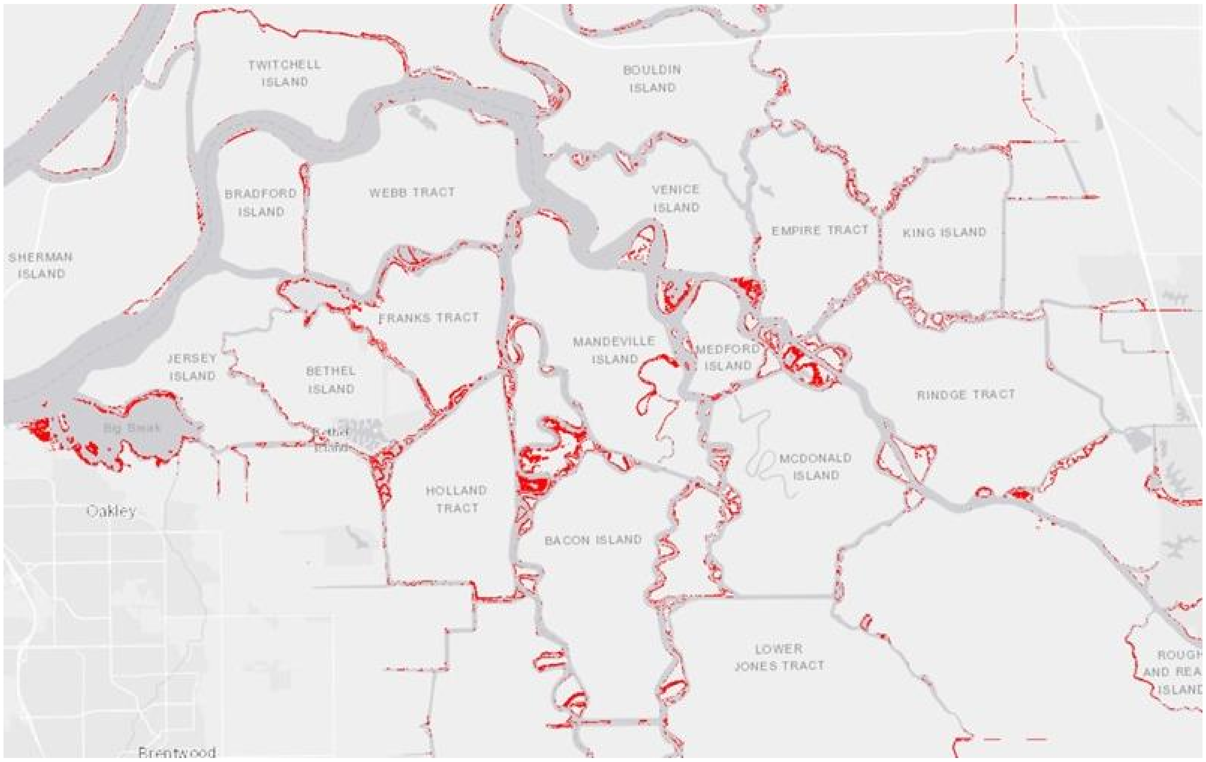

Figure 4. *FAV mapping in the Delta, derived from Landsat multi-spectral imagery.*

2. Moving beyond mapping

Remote sensing data is invaluable in mapping distribution of invasive species and monitoring their spread. However, the true value of remote sensing lies in the information that the maps can provide when combined with other kinds of data or models. Integrating remote sensing data-derived maps with statistical modeling and other spatial, ecological, and environmental data can yield integrated solutions for managing invasive species, forecasting invasion risk, and anticipating future trajectories as a result of climate change (Andrew & Ustin, 2009; Leitão & Santos, 2019).

Remote sensing data-derived invasive species and plant community maps have been used in conjunction with ecological modeling to determine species and community turnover. Biological invasions and their control can provide exceptional opportunities for researchers to better understand ecosystem dynamics in the Delta. For example, successful control strategies may force invasive species to constantly vacate their ecological niche, allowing competitors to enter (Khanna et al. 2012). Andrew and Ustin (2009) used maps from hyperspectral remote sensing data and multiple environmental context layers to produce a habitat occupancy model for perennial pepperweed and also to forecast invasion risk of the species in Suisun Marsh based on the model. Santos et al. (2016) used the 2004-2008 SAV maps to derive growth rates and persistence, showing that each year about half the SAV extent was new growth and half had persisted from the previous year. By studying differences between the spectral data of native and non-native species, Santos et al. (2012) could identify biophysiological characteristics of invasive plants that made them successful in their adopted ranges, such as a specialized carbon fixation mechanism that allows many invasive SAV species to take advantage of low- and high-light conditions.

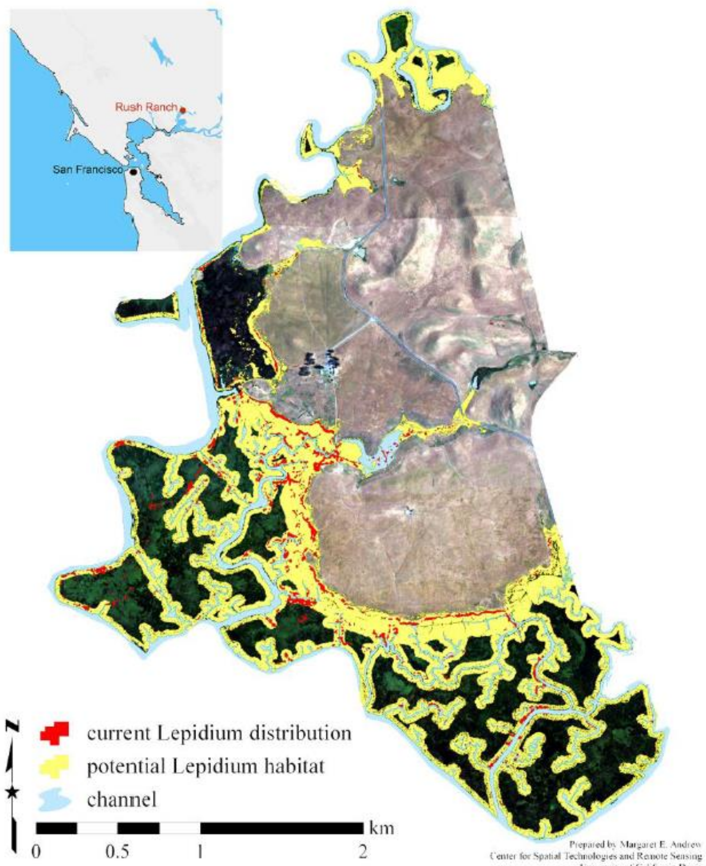

Figure 5. *Current and predicted distribution of perennial pepperweed at Rush Ranch from remote sensing data-derived mapping combined with modeling analysis. (With permission Wiley and Sons, Andrew and Ustin (2009) Diversity and Divisions 15(4): 627-640).*

3. Mapping invasives other than plants through remote sensing

Symposium presenters Avery Scherer (Cramer Fish Sciences) and Valerie Cook (CDFW) outlined potentially powerful remote sensing tools for monitoring animal species invasions and how they can increase the likelihood of successful control or eradication efforts. Specifically, they discussed tools and techniques used in monitoring the impacts of invasive predatory fish and the spread of nutria (Myocastor coypus).

Figure 6. *Judas nutria outfitted with Iridium satellite/global positioning system (GPS) collar.*

In addition, Katie Senft from the UC Davis Lake Tahoe Research Center gave a lightning talk on using Sonar (sound navigation ranging) technology to survey non-native Mysis shrimp in Lake Tahoe. The sonar surveys are possible because Mysis form large vertical bands on their nightly migration from the lake bottom to the surface.

Invasive predatory fish

Dr. Avery Scherer (Cramer Fish Science) highlighted remote sensing tools and techniques that have potential for mapping and assessing the impacts of invasive predatory fish. These include shipboard sampling platforms, video sampling platforms, and predation tethering. Application of these tools in the monitoring of invasive predatory fish and their effects on the environment is a new and emerging technology with extensive potential yet to be explored.

The shipboard sampling platform employed by Cramer Fish Science is a framed net mounted on a boat where fish are funneled into an observation area that is actively monitored with video cameras. After passing through the observation area, fish are then funneled back into the habitat without any direct interactions with observers or equipment. This technique allows for the identification of a large range of fish species (native and invasive), can be paired with abiotic characteristics to determine habitat correlations and preferences of invasive fish, and can be used in management decisions to reduce habitat favorability for invasive fish species. Shipboard sampling has been used to track how inland silverside (Menidia beryllina) move through a series of habitat types as they increase in size. This can help to identify the habitat types where inland silversides pose the greatest threats to Delta Smelt (Hypomesus transpacificus).

The custom-built video sampling platform used by Cramer Fish Science is pulled along a cable stretched across a waterway to form an established transect and to allow for fish sampling to occur in that area. Video sampling along established transects allows for repeated sampling in otherwise inaccessible areas. The lack of observer involvement during the sampling allows for sampling of secretive fish that may evade sampling techniques that involve higher levels of human disturbance. Measurements collected by the platform (fish numbers, fish species composition, water quality, water depth, substrate characteristics, etc.) can be combined to determine habitat preferences and the impacts of biotic and abiotic characteristics on invasive and native fish.

Predation tethering is a technique where prey fish are tethered to anchors imbedded in the substrate. Tethered fish can be left in place for set periods of time. For short periods of time, video cameras can be setup to monitor predation rates of the tethered fish. For longer periods of time, tethered fish can be re-checked, and missing fish can be assumed to have been eaten and so provide estimates of predation rates.

The combination of tethered prey fish and video cameras allows observation and comparison of predation behaviors of native and invasive species. Sacramento pikeminnow (Ptychocheilus grandis) are a native fish with a slow and less efficient attack. Largemouth bass (Micropterus salmoides) are an invasive fish with a fast and highly efficient attack. This type of observation can indicate both the number of predators and the species of predator, which both may be significant in determining impacts to native fish. A potential issue with this technique is that tethered fish may present an artificially easy target and so may bias predation rates and predator species. Also, cameras have some limitations in high turbidity situations.

Nutria

Valerie Cook (CDFW) described the role of remote sensing tools and techniques in the mapping, tracking, and eradication of nutria in California. These include mapping of potentially suitable habitat, infrared-triggered cameras, and the tracking of Iridium satellite GPS collared individuals.

Mapping of potentially suitable habitat for nutria has been undertaken using some of the same remote sensing datasets used for plant mapping.

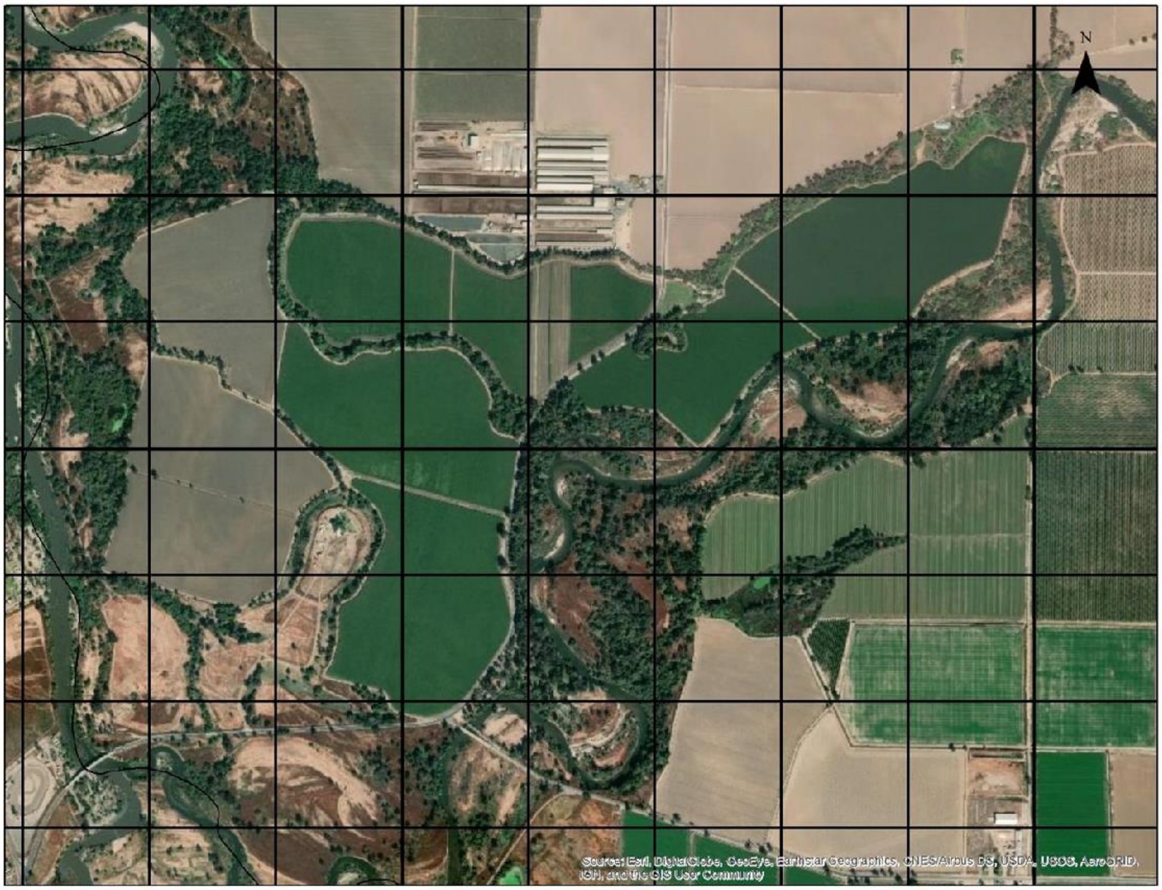

Figure 7. *The CDFW Nutria Eradication Program employs a 5-phase strategy that consists of (1) survey (for presence of nutria or suitable habitat), (2) knock-down trapping, (3) mop-up removals, (4) verification, and (5) surveillance. Remote sensing data are critical to all phases, including the mapping of suitable habitat and present nutria. The spatial framework for implementing the 5-phase strategy is the 40-acre project grid shown above. The goal is "every animal must be put at risk" (Valerie Cook, CDFW).*

Infrared-triggered cameras have been used extensively by CDFW's nutria eradication program to detect animals and monitor implementation success. Infrared-triggered cameras are deployed overlooking baited platforms (feeding beds of vegetation or floating rafts) that serve as attractants in known or suspected areas of nutria infestation. They allow for behavioral and demographic observations, which help in planning proportional control strategies. Use of infrared-triggered cameras increases the geographic area covered, frequency of observations, and the detection rate, and decreases the cost of other survey efforts that utilize human observers.

Iridium satellite GPS collars will be used to track the movement of individual nutria, referred to as Judas nutria. Judas nutria are nutria that have been trapped, sterilized, fitted with satellite GPS collars, and then released into areas of interest, as well as to aid in confirming absence during the later verification and surveillance phases. This technique exploits nutria's tendency to search out other nutria on a landscape, which will help to detect and locate nutria more efficiently and identify areas where eradication efforts should be focused. The areas where Judas nutria may be released include places where nutria are not yet known to occur, that are difficult for humans to access and survey, where dispersing/roaming individuals are known to occur but difficult to locate, and in post-trapping locations where the mop-up and verification must occur with increased efficiency. Given the potential dispersal distances and daily rate of movement nutria area capable of exhibiting, the satellite GPS collars used in CDFW's Judas nutria project are necessary for collecting and transmitted data remotely and over much larger areas than the VHF (Very High Frequency) transmitters that are commonly used in tracking animal movements.

Dispersal and spatial ecology information gained from Judas nutria can be paired with the use of infrared-triggered cameras to confirm the presence and status of nutria establishment in an area. Information from Judas nutria can also be paired with biotic and abiotic factors such as water levels, water condition information, and habitat conditions and types to better understand how nutria utilize and move across a landscape.

4. Find synergies with other uses

Symposium presenters showcased several examples of how remote sensing data have been effectively used for multiple management purposes. This includes opportunistic uses of data products for management purposes that were not necessarily anticipated when they were generated. Dr. Shruti Khanna (CDFW) highlighted in her presentation the multiple ways that invasive plant community maps derived from aerial hyperspectral imagery have also been used for other purposes. For example, these maps were also used to evaluate the potential of a drought control barrier to prevent salinity intrusion into the Delta (Kimmerer et al. 2019). In another example, the same LiDAR dataset used to assess invasion risk by perennial pepperweed was also used to calculate levee stability and assess conformation of levees with U.S. Army Corps of Engineers standards (Casas et al. 2012, Greenberg et al. 2012).

Moving forward, Delta organizations should prioritize ways to utilize remote sensing datasets for various management needs. With greater coordination amongst agencies, remote sensing data may become more cost effective and widely used. Remote sensing of aquatic weeds has been successfully coordinated in the Delta and sporadically used for other purposes but has not been successfully leveraged. Additional uses of remotely sensed datasets in the Delta may include comparing imagery before and after large projects (e.g., drought barrier placement and habitat restoration), mapping of harmful algal blooms and riparian zone species, monitoring ecosystem change or dynamics of animal invasions, and assessing agricultural water demands, levee stability, and land subsidence.

5. Finding and coordinating cost-sharing opportunities to monitor the Delta

Funding challenges

A consistent funding source is needed to ensure the continued acquisition of remote sensing data. Several speakers identified inconsistent data collection as a main barrier to using remote sensing tools more effectively. For example, no hyperspectral imagery was collected in the Delta between August 2008 and November 2014, resulting in a 6-year gap that includes the years before and at the beginning of California's historic drought. The 6-year gap now makes it difficult to analyze the effects of management actions on invasive vegetation in the region under a range of hydrologic conditions. This analysis would be needed to inform an adaptive management strategy for aquatic invasive weeds based on water year. Hyperspectral imagery acquisition of the Delta has continued each year since 2014 using several different sensors (AVIRIS-NG from 2014 to 2017, HyMap in 2018 and 2019, and FENIX in the summer of 2020), but there is currently no dedicated funding to extend data acquisition beyond 2020. Several funding commitments and proposals are currently on the table to continue hyperspectral imaging beyond 2020, but they depend on collaborations and cost-share partners that have not yet materialized.

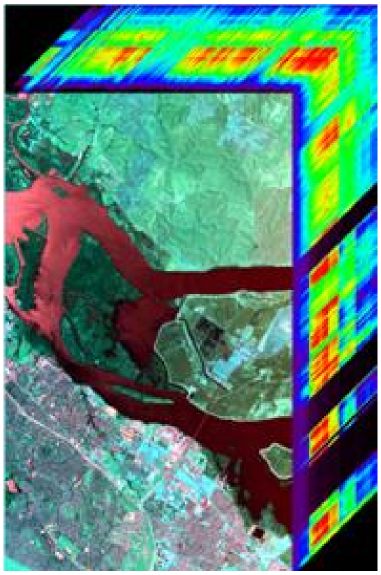

Figure 8. *Hyperspectral imagery yields information on plant species composition, health, or density based on rich spectral signals sensitive to local variation in these characteristics.*

Cost-sharing opportunities

Several speakers recommended cost-sharing as a path forward to ensure that high-quality remote sensing data continues to be collected at the desired frequency. They also indicated that cost-sharing opportunities for remote sensing are not fully realized. Cost-sharing benefit can be realized when the same remote sensing data can be used by multiple partners and projects for multiple purposes, for example by utilizing the same hyperspectral imagery for invasive species management as well as for agricultural purposes and water quality assessments. Dr. Susan Ustin (UC Davis) stated in her summary presentation that the Delta data user community needs to "make better use of remote sensing data to get maximum value" [through data- and cost-sharing]. However, Dr. Ustin also acknowledged that different users of a data product may have different specific data requirements. These may result in different individual interests for the season and frequency, spatial scale, or tidal phase of data collection. Such specialized data needs have historically posed a challenge to the sharing of remote sensing data.

Expected benefits

Multiple speakers emphasized the advantages of remote sensing data- and cost-sharing. A key take-home message was that investing in rich, informative, and high-quality remote sensing datasets can benefit multiple users in the region. Dr. Ustin (UC Davis) pointed out that remotely sensed data that are acquired to manage aquatic weeds (e.g., hyperspectral imagery or LiDAR) could also help with management problems related to Delta agriculture, water quality, wetlands, habitat conservation planning, wildlife protection, and land use planning.

The Remote Imagery Collaboratory (RIC), which is sponsored by the Delta Science Program, provides a forum for an ongoing conversation on how to keep developing and collaboratively use remote imagery. Dylan Chapple is the lead for RIC and can be contacted at Dylan.Chapple@deltacouncil.ca.gov.

References

Andrew, M. E., Ustin, S.L. 2008. The role of environmental context in mapping invasive plants with hyperspectral image data. Remote Sensing of Environment, V. 112(12), p. 4301–4317.

Andrew, M. E., Ustin, S.L. 2009. Habitat suitability modelling of an invasive plant with advanced remote sensing data. Diversity and Distributions, V. 15(4), p. 627–640.

Aronson, R. B., Heck Jr., K. L. 1995. Tethering experiments and hypothesis testing in ecology. Marine Ecology Progress Series, V. 121, p. 307–309.

Aronson, R. B., Heck Jr., K. L., Valentine, J.F. 2001. Measuring predation with tethering experiments. Marine Ecology Progress Series, V. 214, p. 311–312.

Casas, A., Riaño, R., Greenberg, J. Ustin, S. 2012. Assessing levee stability with geometric parameters derived from airborne LiDAR. Remote Sensing of Environment, V. 117, p. 281–288.

Cohen, A.N., Carlton, J.T. 1998. Accelerating Invasion Rate in a Highly Invaded Estuary. Science, V. 279(5350), p. 555–558. doi:10.1126/science.279.5350.555

Demetras, N.J., Huff, D.D., Michel, C.J., Smith, J.M., Cutter, G.R. Hayes, S.A., Lindley, S.T. 2016. Development of underwater recorders to quantify predation of juvenile chinook salmon (*Oncorhynchus tshawytscha*) in a river environment. Fishery Bulletin, V. 114(2), p. 179–185.

Greenberg, J.A., Hestir, E. L., Riano, D., Scheer, G.J., Ustin, S.L. 2012. Using LiDAR Data Analysis to Estimate Changes in Insolation Under Large-Scale Riparian Deforestation 1. Journal of the American Water Resources Association, V. 48(5), p. 939–948.

Hestir, E.L., Khanna, S., Andrew, M. E., Santos, M. J., Viers, J. H., Greenberg, J. A., Rajapakse, S. S., Ustin, S.L. 2008. Identification of invasive vegetation using hyperspectral remote sensing in the California Delta ecosystem. Remote Sensing of Environment, V. 112(11), p. 4034–4047.

Jetter, K. M., Nes, K. 2018. The cost to manage invasive weeds in the California Bay-Delta. Agricultural and Resources Economics Update, V. 21(3), p. 9–11.

Khanna, S.J., Conrad, J.L., Caudill, J., Christman, M., Darin, G., Ellis, D., Gilbert, P., Hartman, R., Kayfetz, K., Pratt, W., Tobias, V., Wasserman, A. 2018. Framework for aquatic vegetation monitoring in the Delta. Interagency Ecology Program Technical Report 92.

Khanna, S., Santos, M. J., Boyer, J. D., Shapiro, K. D., Bellvert, J., Ustin, S.L. 2018. Water primrose invasion changes successional pathways in an estuarine ecosystem. Ecosphere, V. 9(9), Article e02418.

Khanna, S., Santos, M. J., Hestir, E. L., Ustin, S. L. 2012. Plant community dynamics relative to the changing distribution of a highly invasive species, *Eichhornia crassipes*: A remote sensing perspective. Biological Invasions, V. 14(3), p. 717–733.

Kimmerer, W., Wilkerson, F., Downing, B., Dugdale, R., Gross, E. S., Kayfetz, K., Khanna, S., Parker, A. E., Thompson, J. 2019. Effects of drought and the emergency drought barrier on the ecosystem of the California Delta. San Francisco Estuary and Watershed Science, V. 17(3), Article 2.

Leitão, P. J., Santos, M.J. 2019. Improving models of species ecological niches: A remote sensing overview. Frontiers in Ecology and Evolution, V. 7, Article 9.

Santos, M. J., Anderson, L. W. J., Ustin, S.L. 2010. Effects of invasive species on plant communities: an example using submersed aquatic plants at the regional scale. Biological Invasions, V. 13(2), p. 443–457.

Santos, M. J., Greenberg, J. A., Khanna, S., Hestir, E. L., Ustin, S.L. 2016. Spread and persistence of an invaded community assessed using hyperspectral remote sensing. Ecological Applications, V. 26(6), p. 1733–1744.

Santos, M. J., Hestir, E. L., Khanna, S., Ustin, S.L. 2012. Image spectroscopy and stable isotopes elucidate functional dissimilarity between native and nonnative plant species in the aquatic environment. New Phytologist, V. 193(3), p. 683–695.

Santos, M. J., Khanna, S., Hestir, E. L., Andrew, M. E., Rajapakse, S. S., Greenberg, J. A., Anderson, L. W. J., Ustin, S.L. 2009. Use of hyperspectral remote sensing to evaluate efficacy of aquatic plant management in the Sacramento-San Joaquin River Delta, California. Invasive Plant Science and Management V. 2(3), p. 216–229.

Taddeo, S., Dronova, I. 2018. Indicators of vegetation development in restored wetlands. Ecological Indicators, V. 94, p. 454–467.

DIISC

This publication is based on the outcomes of the 2019 Delta Invasive Species Symposium. The symposium was sponsored by the DIISC, which was formed to foster communication and collaboration among California state agencies that detect, prevent, and manage invasive species and restore invaded habitats in the Sacramento-San Joaquin Delta.