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Title: Integrating social and ecological research to control invasive species: fostering collective action among private and public stakeholders

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Project Summary

1. **Project objectives**

Our interdisciplinary team will integrate biophysical and social science approaches to tackle the problem of *Phragmites australis* control. We will implement new treatment and monitoring protocols, and conduct retrospective monitoring of invaded sites with known treatment histories to determine the biophysical factors that predict improved management. We also will investigate social and cultural barriers to collective action for invasive species control. We will develop better tools for outreach communications and ensure that both the cultural values and scientific knowledge of diverse stakeholders are incorporated into a regional strategy for *Phragmites* control. We anticipate that our integrated, multidisciplinary approach to the problem will not only promote better management of an aggressive wetland invader but also will serve as a model framework for addressing other management problems in the Delta that are socioecological in nature. Our specific objectives and approaches are to:

1) Establish an integrated pest management (IPM) approach for Phragmites control efforts in Suisun Marsh

- Evaluate revegetation as a best management practice after herbicide spraying.
- Implement consistent monitoring in sites where *Phragmites* treatment methods are being tested, and conduct retrospective analyses in sites with a known *Phragmites* control history to evaluate the longer-term effectiveness of control.

2) Assess landowner perceptions of Phragmites and Phragmites control and identify strategies for increasing their likelihood to engage in collective action

- Assess private and public landowners' perceptions of current *Phragmites* spread and its invasion risks, factors influencing their *Phragmites*-related decision-making processes, and their willingness and ability to engage in different types of collective action for controlling *Phragmites*.
- Develop a strategic communication framework built on institutional values to expand upon existing motivations for collective action.
- Solicit technical input from land managers, agency staff, and recreational stakeholders about the criteria to be used in prioritizing resource allocation for control of *Phragmites*.

3) Synthesize results to produce a spatial prioritization and inform a regional coordination plan

- Use results from Objectives 1 and 2 as inputs to a spatial prioritization model incorporating multiple factors that predict successful *Phragmites* control, both from the biophysical environment and from the social environment
- Develop a plan for a regional coordination network based on IPM for *Phragmites*, informed by results from Objectives 1 and 2 and other successful regional invasive control efforts.

2. Project methodology

Our proposed work will move first through separate disciplinary phases rooted in established methodologies from the biophysical and social sciences, and then into an integrated, multidisciplinary phase that synthesizes and builds on our results.

The biophysical phase is aimed at establishing an integrated pest management (IPM) approach for *Phragmites* that relies on the best available science, underpinned by rigorous testing and monitoring. IPM is a holistic approach, based on ecological principles, to minimize pests and their impacts over the long term. We will test the benefit of active revegetation (hydroseeding, plantings) in small herbicide-treated *Phragmites* patches across several wetlands. We will also retrospectively review the effectiveness of past treatment approaches through analysis of 20 years of historical cost-share program records and available imagery.

The social science phase is aimed at assessing risk perceptions and communication preferences among private and public landowners and other stakeholders to identify potential barriers to and opportunities for collective action around *Phragmites* control. Suisun Marsh features a diverse, spatially intermingled group of public and private landowners whose perception of the problem and willingness to participate in *Phragmites* control appear to vary, setting up a unique challenge in coordinating natural resource management. We will use a small number of targeted, semi-structured interviews, followed by broadly distributed surveys, to assess landowners' perception of the risk *Phragmites* invasion poses on their properties, their assessment of the past and ongoing control efforts, and their willingness and ability to engage in collective action. Building on this information, we will develop strategic communication tools to overcome barriers to action and influence adoption of both individual best management practices and collective action. Finally, we will use technical input workshops to elicit stakeholder opinion on the assets and values that must be captured when allocating scarce resources towards *Phragmites* control.

In the integrative phrase, our multidisciplinary team will come together to produce two outcomes that incorporate results from the prior work. The first is a spatially explicit prioritization model that layers in biophysical factors that predict successful native plant restoration after *Phragmites* control from our monitoring and retrospective analysis, technical input from on-site managers and wetland invasion experts, and information about stakeholder needs and landowner willingness to participate in control. The second is a plan for a regional coordination strategy around IPM for *Phragmites*, informed by our collective findings, that can overcome barriers to collective action and spend resources wisely and efficiently.

3. Project rationale

The Bay-Delta estuary is highly urbanized and invaded, with a large number of non-native species affecting its wetland ecosystems. Alteration of natural systems is so extensive that most are "novel" ecosystems, requiring careful management to provide the greatest ecological and social value. Although there have been widespread and costly efforts to control the spread of invasive plants in the Bay-Delta, most are conducted with limited understanding of the role that social institutions, civic culture, and trust play in shaping engagement of all parties to maximize their collective action.

A case study that demonstrates this problem is the invasion of *Phragmites* in Suisun Marsh. A troublesome wetland invader, *Phragmites* creates impenetrable areas impeding fish and wildlife navigation, limiting site access and views, reducing navigation, and creating a fire hazard. Control has been attempted throughout the marsh under a cost-share program for private landowners (defunct since 2018) and via inconsistently funded efforts on publicly managed lands. Despite these attempts at control, the extent of *Phragmites* has increased >400% in the Marsh over the past 2 decades. Sporadic and uncoordinated monitoring has made the effects of the expansion difficult to calculate, and hindered understanding of what treatments are most effective. Since no single herbicide or management approach has consistently reduced the spread of the invader, an Integrated Pest Management (IPM) approach that prioritizes post-control native plant establishment appears warranted, but information about the success of treatment alternatives in Suisun Marsh is lacking.

Unfortunately, control efforts in Suisun Marsh have been held back by the lack of regional coordination involving the intermixed private and public stakeholders. In particular, there has been no systematic investigation of the decision-making processes that affect stakeholders' willingness to participate in *Phragmites* control, nor research into approaches that would facilitate their adoption of an IPM program.

We see the problem as fundamentally socio-ecological. Successful invasive species management requires more than understanding biophysical drivers of invasion and deploying effective techniques of control; it also depends on understanding and overcoming the social and cultural barriers to collective action. Clearly, the current mosaic of *ad hoc* treatment efforts by individual private or public landowners is not working. The challenge is to develop a plan that is more strategic, more coordinated, and more thoroughly based on evidence from the ecological and social sciences. In this proposed work, we take an approach inspired by the concept of adaptive management: examining current intents and motivations as well as past failures and successes, and suggesting new approaches that promise better management in the future.

Project Narrative

Introduction and Background

The San Francisco Bay-Delta is known as a highly urbanized and invaded estuary with a large number of non-native species affecting the functioning of its ecosystems, including its wetlands (Nichols et al. 1986; Cohen and Carlton 1995, 1998). Alteration of the natural systems is so extensive that most are now considered "novel" ecosystems that require careful management to provide the greatest ecological and social values (Moyle et al. 2014). This includes working with numerous stakeholders to implement integrated pest management (IPM; i.e., a holistic approach based on ecological principles to minimize pests and their impacts over long timescales), that can be coordinated regionally to provide long-term, effective control of wetland invaders.

Although there have been widespread and costly efforts to control the spread of invasive plants in the Bay-Delta (Ta et al. 2017, Conrad et al. 2019), most have been conducted by a single agency or landowner with limited understanding of the role of social institutions, civic culture, and trust in shaping engagement of all parties to maximize their collective action. **We see the problem of wetland plant invasions as fundamentally a social-ecological challenge that requires addressing barriers to collective action as well as the biophysical factors involved in the spread of the invader**. In this project, we propose to tackle the problem of the ongoing rapid spread of the invasive common reed (*Phragmites australis*) in the brackish Suisun Marsh region of the Delta (Fig. 1), using an integrative approach rooted in both the biophysical and social sciences.

Suisun Marsh encompasses more than 10% of California's remaining natural wetlands; it has high value as a resting and feeding ground for migrating birds in the Pacific Flyway and is also home to a wide variety of fish, invertebrates, and plants. It is a major recreational area for hunters, birdwatchers, and boaters and supports both subsistence and commercial fisheries. Although there are native *Phragmites* in North America, genetic analyses suggest that most plants in the American West, and all plants in Suisun Marsh, are the Eurasian strain of nonnative invasive *Phragmites australis* (Saltonstall 2003), which is one of the most aggressive invaders of marshes in North America (Bains et al. 2009). Nonnative *Phragmites* does have a few positive benefits to humans, such as sequestering carbon, but its effects on wetland ecosystem services are largely negative. Invasion by *Phragmites* creates an impenetrable area that impedes navigation, limits site access and views, reduces wildlife movement, and creates a fire hazard (Kettenring et al. 2012). For example, in the fall of 2018, eight fires burned across Suisun Marsh, causing widespread environmental and structural damage. *Phragmites* also has negative impacts on habitats and biodiversity, by

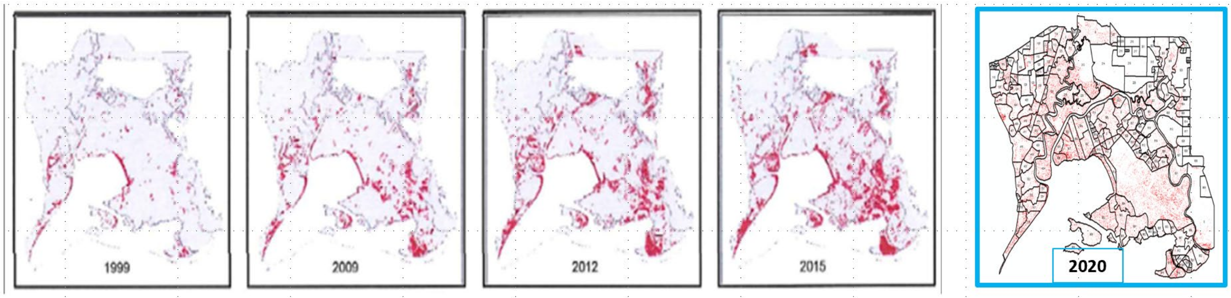

Fig. 1. Manual classification of Phragmites expansion from 1999-2015 (Boul et al. 2018) and with a new automated classification in 2020 (Casa2100).

crowding out native fish and waterbirds, and providing low levels of food for wildlife populations (Chambers et al. 1999, Able and Hagen 2000, Kettenring et al. 2012).

Phragmites has increased rapidly over the past two decades in Suisun Marsh. Monitoring with an older image classification method indicated 325% growth (693 to 2,947 acres) between 1999 and 2015 (Boul et al. 2018; Darin et al. 2018). A recent unsupervised classification algorithm from 2020 indicated the expansion has continued (to 4,300 acres; C. Potter, Casa 2100; unpubl. data). An especially worrisome trend is the rapid colonization by *Phragmites* of newly restored tidal wetland sites, which doubled in size over the last 20 years (Boul et al. 2018; Darin et al. 2018), undermining the potential of restoration projects to improve conditions for wildlife. Several methods, including different herbicide applications, have been used in attempts to control *Phragmites* across North America (Hazelton et al. 2014), but extensive efforts have not been effective in eradicating the invasion in Suisun Marsh over the last 25 years. Programs for control of *Phragmites* and other wetland invaders in restored tidal marshes have been complicated by uncertainty about the effect of herbicides and vegetation removal on sensitive species (Casazza et al. 2016) such as the salt marsh harvest mouse (*Reithrodontomys raviventris*) and California Ridgway's rail (*Rallus obsoletus*).

On privately managed wetlands, the Suisun Resource Conservation District (SRCD) partnered with private landowners through a cost-share program to support ground and aerial herbicide applications starting in 1999, but the foundation grant supporting that effort ended in 2018. On publicly managed and tidal wetlands, control efforts have been less consistent and less frequent, due to state budget constraints. Scarce funding has made it difficult to evaluate the effectiveness of herbicides against *Phragmites* in Suisun Marsh, because little funding has been available to develop and implement a scientifically rigorous monitoring program. Lack of monitoring is a particular blind spot, given that no single herbicide or management approach has ever consistently reduced the expanse of *Phragmites* across North America (Hazelton et al. 2014). This suggests a need for careful attention to the effectiveness of supplementing herbicides with alternative approaches, such as planting native species as a follow-up to repel regrowth or reinvasion.

Beyond these technical challenges, *Phragmites* control efforts in Suisun Marsh have been hindered by a lack of regional coordination that includes both private and public landowners. This is likely due to the fact that the private and public land ownerships are intermixed in Suisun Marsh (Fig. 2), and there is a general lack of understanding of the different perspectives of the private and public landowners and other stakeholders in Suisun Marsh regarding *Phragmites* control. Another possible reason for the lack of regional coordination may be that past control methods have become "sticky" (i.e., difficult to reverse) due to uncertainty about what new control methods might be more effective.

Addressing the lack of regional coordination requires an understanding of the perceived risks associated with *Phragmites* spread among different landowners and other stakeholders in the region. It also requires addressing such risk perceptions through present and future communication efforts in order to promote *Phragmites* control (Drake and Donohue 1996, Rittelmeyer 2020). This is because *Phragmites,* like many invasive plant species, can be conceptualized as a threat to public goods such as biodiversity (Niemiec et al. 2016). Individual landowners who do not manage invasive plants on their properties will inadvertently increase the invasion risk and management costs of their neighbors (Bagavathiannan et al. 2019; Epanchin-Niell et al. 2010; Graham and Rogers 2017; Graham et al. 2019; Perrings et al. 2002). Likewise, when individual landowners manage invasive plants on their properties, their neighbors may indirectly benefit via reduced invasion risk and potential reduced management costs (Ma et al. 2018; Ervin et al. 2019; Hershdorfer et al. 2007; Yung et al. 2015).

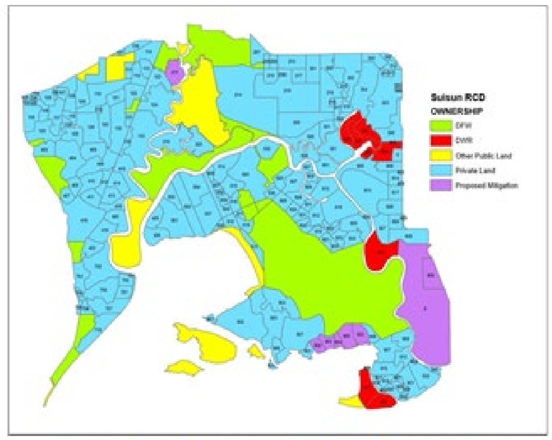

Fig. 2. Intermixed private and public ownerships in Suisun Marsh.

Therefore, the potential success of invasive plant management depends on how much each actor within a social-ecological system would be willing and able to engage in management actions that reduce the overall invasion risks (Graham et al. 2019; Perrings et al. 2002). So far, most research on the human dimensions of invasive plant management has focused on individual landowners' efforts (e.g., Niemiec et al. 2017a). However, collective action has been recognized as more effective than individual efforts by reducing overall invasion risks and management costs and increasing treatment effectiveness (Bagavathiannan et al. 2019; Epanchin-Niell and Wilen 2015; Graham 2013; Graham 2019; McKiernan 2017; Niemiec et al. 2017b).

Consequently, we will collect, analyze, and integrate both biophysical and social data to develop strategies that promote collective action for *Phragmites* control. In developing a conceptual framework for this work (Fig 3), we recognized that successful invasive species management requires more than merely understanding the ecological drivers of invasion and deploying effective techniques of control; it also depends on understanding and overcoming the social and cultural barriers to collective action. Our thinking aligns with the broad recognition that decision-making in the Delta requires a capacity to develop multidisciplinary, interdisciplinary, and transdisciplinary forms of knowledge (Biedenweg et al. 2019). This can be accomplished through "...combining the natural and social science data into integrated models to understand an issue" (Biedenweg et al. 2019).

We propose to work as an interdisciplinary team that will apply both biophysical and social science approaches in tackling the problem, and produce outcomes that truly integrate and synthesize these results. On the natural science side (Fig. 3: blue), we will implement new treatment and monitoring protocols for *Phragmites* in Suisun Marsh. Combined with retrospective monitoring of sites whose treatment history is known, we will determine the ecological factors that have, in the past, predicted successful local control. On the social science side (Fig. 3: yellow), we will investigate the social and

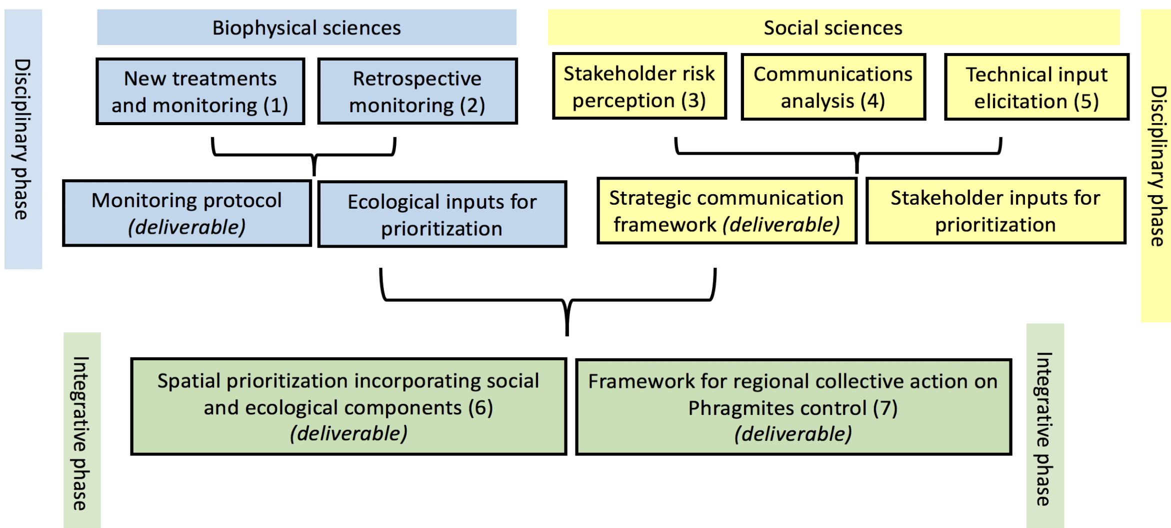

Fig 3: Conceptual model for the project, showing how social and ecological research components begin in separate disciplinary phases and are combined in an integrative phase. Numbers in parentheses correspond to workplan tasks.

cultural barriers to participation in collective action for invasive species control, seeking to understand the role of stakeholders' risk perception and to develop better tools for outreach communications. We also will solicit technical input from local land managers, agency staff, and other stakeholders to set criteria for allocating resources strategically. The integration of natural and social science (Fig 3: green) will come in producing two major deliverables: a spatial prioritization that incorporates the social and biophysical predictors of success to direct interventions towards sites that maximize the potential for successful control, and a framework for regional coordination informed by our collective synthesis. We anticipate that this approach will not only promote effective, coordinated action against this specific invader in this specific place, but will also make a broader intellectual contribution towards solving other collective action problems around common-pool resources and public goods in the Delta and beyond.

Objectives
Our interdisciplinary research team representing SRCD, Utah State University, Santa Clara University, Purdue University, and University of California Davis will integrate biophysical and social science approaches to tackle the problem of *Phragmites australis* control. Our specific objectives and approaches are to:

1) Establish an integrated pest management (IPM) approach for *Phragmites* control efforts in Suisun Marsh
- Evaluate revegetation as a best management practice after herbicide spraying.
- Implement consistent monitoring in sites where *Phragmites* treatment methods are being tested, and conduct retrospective analyses in sites with a known *Phragmites* control history to evaluate the longer-term effectiveness of control.

2) Assess landowner perceptions of *Phragmites* and *Phragmites* control and identify strategies for increasing their likelihood to engage in collective action
- Assess private and public landowners' perceptions of current *Phragmites* spread and its invasion risks, factors influencing their *Phragmites*-related decision-making processes, and their willingness and ability to engage in different types of collective action for controlling *Phragmites*.
- Develop a strategic communication framework built on institutional values to expand upon existing motivations for collective action.
- Solicit technical input from land managers, agency staff, and recreational stakeholders about the criteria to be used in prioritizing resource allocation for control of *Phragmites*.

3) Synthesize social-ecological results to produce a spatial prioritization and inform a regional coordination plan
- Use results from Objectives 1 and 2 as inputs to a spatial prioritization model incorporating multiple factors that predict successful *Phragmites* control, both from the biophysical environment (*e.g.,* elevation, sediments, application timing) and from the social environment (*e.g.,* stakeholder risk perceptions, values, past experiences, likelihood to participate in different types of collective action).
- Develop a plan for a regional coordination network based on IPM for *Phragmites*, informed by results from Objectives 1 and 2 and other successful regional invasive control efforts.

Work Plan

Methods for Objective 1: Establish an integrated pest management (IPM) approach for Phragmites control efforts in Suisun Marsh
Most control efforts in Suisun Marsh have focused on ground or aerial chemical applications, sometimes combined with mowing of larger patches of *Phragmites* to facilitate biomass breakdown. However, a recent detailed monitoring study of *Phragmites* control effects showed that most patches that exceed several meters in size are rarely, if ever, eradicated (Quiron et al. 2018). Thus, an important part of a control plan is identifying and rapidly treating small patch expansion areas to eradicate them before them become larger.

Task #1: Evaluate revegetation as a best management practice.-- We will test the added benefit of active revegetation of native plants (seeds, seedling plugs, or both) relative to untreated (i.e., not seeded or planted) plots (n $\geq$ 30). These revegetation treatments will occur in areas previously invaded by small (<10 m) *Phragmites* patches across several wetlands. Target native plants will include (1) fast growing native annuals likely to compete initially against *Phragmites* seedlings (e.g., *Leymus triticoides*; creeping wild rye) and (2) slow growing, habitat-forming perennials valued by managers for habitat (e.g., *Schoenoplectus acutus*; hardstem bulrush and *Distichlis spicata*; saltgrass). Seeds will be hydroseeded into research plots with a tackifier to ensure seeds adhere to the soil sufficiently. Plugs will be hand-planted. Sowing and planting densities will reflect common practice for restoration practitioners in the region. We will assess plant emergence (seeds) and survival (seedling plugs) a month after treatment and end of growing season cover after years 1 and 2.

Spray treatments will include ground applications or use of spray-drones to deliver herbicide effectively to small areas. Spray treatments will include ground applications or use of UAS with 3.5 gallon tanks (spray-drones: PrecisionVision 35, Leading Edge Aerial Technologies) that can deliver herbicide effectively to small areas (Takekawa, in prep.). We will treat areas in 2022 and 2023 with assessment a month after treatment and the following 1-2 years.

Task #2: Implement consistent monitoring and conduct retrospective analyses in sites with known Phragmites control history.-- Monitoring of invasive *Phragmites* control efforts in Suisun Marsh to allow for learning and adjusting management accordingly has been at best neglected and at worst ignored. However, monitoring has been called the most important element to achieving positive management outcomes (Martin and Blossey 2013). We propose to develop and test effective approaches for monitoring the results of control efforts and to undertake a retrospective analysis on historical private landowner treatments through analysis of SRCD records on treatment areas and available imagery.

We propose to examine RGB and near-infrared imagery from aircraft or unmanned aerial systems (UAS) to provide a basis for estimating the Marsh-wide extent of *Phragmites* and the success of control efforts. For example, ground and helicopter spraying have been conducted over 20 years, but systematic, follow-up monitoring has not been implemented. Imagery taken for triennial vegetation analyses of endangered species habitats has allowed the opportunistic tracking of the invasion at a marsh scale (Boul et al. 2018), but a quantitative assessment of results has not been implemented at individual sites. We have recently worked with a remote-sensing specialist (Dr. Christopher Potter, Casa 2100 Systems) to develop an unsupervised classification approach (ISODATA, ENVI) that can identify major plant species in a square meter from high resolution (60 cm) color images taken for the National Agricultural Imagery Program (NAIP). These images are taken every other year and are available for no or low cost, and the triennial vegetation survey often are taken during intervening years. The algorithm calculates four band class means evenly distributed in the data space and iteratively clusters remaining pixels using minimum distance techniques (Tou and Gonzalez 1974).

In addition, we have used UAS with 4K cameras flying surveys to test seamless stitched images for analyses, and this has proven effective to examine sites that are 10s to 100s of acres. Also, we propose to test simple ground vegetation survey transects of treatment areas (% cover) immediately after treatment and in following years to see if we can document effects of treatments of smaller sites. Finally, we will review archived records of private landowner treatments over the 25 years of the SRCD cost-share program to examine longer-term effects of treatments relative to the biophysical conditions (*e.g.,* elevation, soils) of the habitats. We also will examine GPS routes from aerial helicopter treatments in the past 3 years as a retrospective analysis of control results a few years post-treatment.

Methods for Objective 2. Assess landowner perceptions of Phragmites and Phragmites control and identify strategies for increasing their likelihood to engage in collective action:

Suisun Marsh has 120+ private landowners, >20,000 acres under public ownership, and a diverse set of state and federal agencies directly involved in conservation within its boundaries. SRCD works closely with all of the landowners in Suisun Marsh and hosts twice annual workshops that are attended by both private and public landowners and staff of other public agencies and organizations in the region. Following a pilot study investigating effective communication about tidal restoration in Suisun Marsh (Simon et al. 2014; Bales et al. 2015), and building upon the existing relationships between SRCD and private landowners, we have developed a research approach that uses a combination of qualitative interviews, focus groups, and surveys to achieve our objective, divided here into three tasks.

Task #3: Assess private and public landowners' perceptions of current Phragmites spread and its invasion risks, factors influencing their Phragmites-related decision-making processes, and their willingness and ability to engage in different types of collective action for controlling Phragmites.-- Private landowners in Suisun Marsh include individuals and families, waterfowl associations and hunting clubs, and nonprofit conservation organizations. Public landowners in the area include the Department of Fish and Wildlife and the Department of Water Resources. There is a small but growing literature on collective action to manage invasive species (Bagavathiannan et al. 2019; Graham et al. 2019; Marshall et al. 2016; Niemiec et al. 2016). So far, there is no consensus about how many or what types of landowners need to be working together to constitute collective action. In fact, many studies simply use the term "neighbors" to describe participating landowners in their studies of collective management of invasive plants.

Other studies have associated community-led collective action for managing invasive plants with local farmers participating in a cooperative integrated pest management program (Stallman and James 2015), neighboring farmers engaging in herbicide-resistant weed management (Ervin et al. 2019), private landowners teaching their neighbors about invasive plants (Niemiec et al. 2016), or landowners sharing information and applying social pressure on others to control weeds (Graham 2013; Graham and Rogers 2017). A review of empirical research found that collective action for managing invasive species could be classified as externally led, community-led, comanaged, or managed by organizational coalitions (Graham et al. 2019). In this proposed project, we define collective action as one actor (private and public landowners and other stakeholders) in the region supporting, coordinating, or directly working with at least one other actor to control *Phragmites* on their properties with or without external leadership (Graham et al. 2019).

Our research will use a mixed-method approach to collect and analyze data from both private and public landowners. We will not start our data collection process until we obtain approval from the appropriate Institutional Review Boards. For qualitative data collection, the research team will conduct semi-structured interviews of private landowners to gain a preliminary understanding of their understanding about the current spread of *Phragmites*, perceived risks to their property and enjoyment/use of their properties associated with the current and potential spread of *Phragmites*, current management practices, the challenges and needs associated with effective *Phragmites* control.

We will use purposive sampling to recruit interviewees (Neuman 2011). Purposive sampling is a non-probabilistic sampling approach that is often used in qualitative research to recruit necessary cases in order to generate rich descriptions of complex situations, events or relationships, to reveal distinctive characteristics of people and the social settings, and to deepen understanding of processes (Corbin and Strauss 2008; Neuman 2011). The way in which study participants are selected is determined by their relevance to the research topic rather than their representativeness of the overall population (Neuman 2011). Specifically, through SRCD, we will first identify a list of private landowners who have actively and less actively managed *Phragmites*. We will also ask each interviewee to identify other private landowners we could interview who may have similar or different levels of engagement with *Phragmites* control. The research team will stop the interview process when data saturation is reached.

Specifically for qualitative research, conducting and analyzing interviews will occur simultaneously. For a generally non-controversial topic with a demographically homogeneous population, the research team expects to detect data saturation around 12 interviews (Guest et al., 2006). Each interview will be audio recorded with the consent of the interviewee, and supplemental notes will be taken by the primary interviewer. Each interview will be transcribed and analyzed using NVivo (QSR Intl.), a qualitative computer coding software. The research team will develop the initial coding framework using a combination of inductive and deductive methods to categorize interview data into codes (i.e., themes; DeCuir-Gunby et al. 2011). This process will allow deductive codes to be derived from questions in the interview protocol and additional codes to emerge from the interviews.

Building upon the interview data, our research team will further develop a survey instrument and administer it via online software Qualtrics and/or mail following the well-established Tailored Design Method (Dillman et al. 2014). The population of interest for the survey will be the private and public landowners in Suisun Marsh. Due to the size of our population of interest, instead of using a probabilistic sample strategy, the research team plans to survey all the willing landowners in the area. The survey will address similar topics as covered in the semi-structured interviews. Additional questions will be added to collect information about the characteristics of private landowners, their land characteristics, communications that occurred or are occurring regarding *Phragmites* control, their communication preferences, their interest in engaging in collective action with other private and public landowners, and their interest in participating in the development of a regional coordination plan for *Phragmites* control.

For both private and public landowners, the survey will also contain questions that are relevant for Task #4 in order to reduce survey fatigue (see below for details about Task #4). In the cases of public and private landowners with previous collaboration experience, additional questions will be asked about the nature of their collaboration with other private and public entities and the factors that facilitated or inhibited their collaborative experiences. The survey will take approximately 30 minutes to complete and will be kept anonymous.

Descriptive statistics and cluster analysis will be used to analyze the characteristics, attitudes, risk perceptions, and behaviors of individual vs. cooperative managers of *Phragmites*. Multivariate regression models may be used to explore the relationships among landowners' characteristics, attitudes, risk perceptions, past behaviors, and their interest in engaging in *Phragmites*-focused collective actions (both in terms of actual control practices and interest in participating in a regional coordination planning process).

Task #4: Develop a strategic communication framework built on institutional values to expand upon existing motivations for collective action.-- In order to alter individual risk perceptions to facilitate collective action, strategic framing of communication among landowners and from land managers must be employed. Framing allows diverse peoples to converge on a shared understanding of an issue or topic through the activation of cultural values and literal "frames of mind" (Price et al. 1997; Miller 2000; Chong and Druckman 2007). Framing also allows for the effective explanation of biophysical science best practices to diverse audiences, bringing all stakeholders to a common ground of understanding (Bunten and Arvizu 2013). Additionally, a solutions-oriented framing approach allows for targeted communication of stakeholder-specific actions to advance a unified goal (Lindenberg and Steg 2013). This strategic framing approach has been successful in achieving increased levels of community-led civic action in the public (Geiger et al. 2017). Few efforts in framing literature have been made beyond one-way communication from specialized/skilled groups to broad audiences: here we seek to facilitate two-way communication among non-expert stakeholder groups with actionable outcomes for species management. In doing so, we increase both knowledge of ecological issues and the tools with which landowners and land managers can communicate and coordinate about species management in their own backyards.

After establishing the state of existing collective action in this group of landowners in Task #3, we also seek to alter these perceptions using strategic communication techniques that both facilitate the explanation of best ecological practices and motivate community-driven collective actions. The proposed communications research targets the role of language and cultural values in motivating collective action. We will employ a research framework rooted in framing theory and cognitive science research (Brewer and Gross 2005; Lakoff 2006; Borah 2011) to address the role of historical stewardship and cultural values specific to private and public landowners in communications in increasing individual agency in a collective solution. Our research framework will follow a three-stage approach: 1) identification of existing communication tools, 2) landowner survey, and 3) semi-structured qualitative interviews. We aim to produce public vs. private-specific sets of values, metaphors (key phrases), and solutions to advance collective action among private and public landowners.

In the first stage, we will consult existing written materials distributed by the SRCD regarding invasive plant control and consult with local science writers to determine the starting material for stage two survey contents. In the second stage survey, we will align our efforts across Tasks #3 and #4 to reduce survey fatigue. The contents of this survey will be framing elements (values, metaphors, solutions), specifically geared towards facilitating the explanation of new ecological best practices, developed in Objective 1, as well as developing nuanced suggested actions for each type of landowner. Restoring agency built upon cultural and institutional values (e.g., stemming from identities including historic duck clubs, ranchlands, or public restoration projects) is important for strengthening collective action (Geiger et al. 2017; Swim et al. 2018). For example, we will first identify whether *Phragmites* control, or the control of invasive species at large, is one of these existing values.

Following the analysis of the survey data (as described in Task #3), we will conduct another set of semi-structured interviews with individuals from the targeted stakeholder groups. In these interviews, we will follow a pre- and post-framing evaluation of trust, knowledge, and willingness to engage in advocacy. First, we will ask a series of open-ended questions for the interviewee to tell us what they know about specific topics in invasive species management, and what they believe their role is. Next, we will deliver a frame set (value, metaphor, solution) for each topic, and follow up with an open-ended period for the interviewee to explain the scientific topic again in their own words, and express how they believe they can play a role in future actions or decision-making. Interviews will be recorded and transcribed, at which point they will be anonymized by demographic identification only for long-term storage.

Framing elements that result in the interviewee independently expressing the communication target are deemed most successful at advancing the positive engagement of specific stakeholder groups, and will be used in all further outcomes and deliverables. Data will be analyzed alongside stage two survey communication results in a repeated measures linear mixed model design, controlling for individual differences in communication preferences within landowner type. It is necessary to understand whether a single approach across landowners (public and private) for the communication of best science practices is sufficient to motivate collective action, or whether nuanced language must be developed to increase buy-in from all landowners in Suisun Marsh for individual reasons, towards a common solution.

Task #5: Solicit technical input from local experts on prioritization criteria.-- In this task, we will elicit expert opinions from the most engaged local stakeholders about the best way to allocate resources for *Phragmites* control. Our goal will be to collect and formalize the opinions of on-the-ground managers who have many years of collective experience in treating wetland invaders. These are the people who know "what works where." We will also draw on the values of a diverse group of users of the marsh who can express their perceptions of the cultural and ecological assets or activities that are most important to protect from the spread of *Phragmites*. We will use a workshop format, with participants organized into discussion groups, rather than a probabilistic sample and a formal survey. Expert elicitation will follow a modified Delphi format (IDEA) that structures inputs to avoid contextual bias (Hemming et al. 2017). Participants will be supplied with the best available maps of the current extent of invasion in the marsh, as well as peer-reviewed and gray literature sources of data about *Phragmites* life history and management potential, to inform their discussion. With this approach, we will attempt to build a local consensus about the relative weightings or rankings that should be assigned to criteria in the spatial model (Objective 3).

Methods for Objective 3. Synthesize results from Objectives 1 and 2 to produce a spatial prioritization and inform a regional coordination plan

Task #6: Use results from Objectives 1 and 2 as inputs to a spatial prioritization model that includes multiple factors that predict successful Phragmites control.-- When an invasive species is widespread on a large scale, resources are typically insufficient to control and manage the invasion's full extent. In that situation, we need prioritization and coordination to use resources efficiently. Our team has expertise in devising a spatial prioritization model for the management of *Phragmites* in the vast Great Salt Lake wetlands (Long et al. 2017). This model incorporated both ecological information on the local environmental conditions that were driving *Phragmites* expansion, as well as input from wetland managers regarding what values should be given precedence in prioritization, and where management feasibility might be highest.

For example, although it would be possible to attempt to control *Phragmites* on exterior wetland levees in Suisun Marsh, the plant actually provides value as protection from levee erosion. However, if *Phragmites* on berms or levees is a repeated source of invasion, directing control efforts at the most likely areas where that occurs may be most cost-effective. Trade-offs like these will be decided from model parameterization informed by our results from Objective 2, Task #5. Also, although we will not specifically model climate change effects, the prioritization model should help us better understand how changing ecological conditions may result in a greater potential for invasion. For instance, increasing soil salinities related to diversions and drought may change the areas most vulnerable to invasion.

We also will use our new data on revegetation as an IPM method (Objective 1, Task #1) and our retrospective monitoring (Objective 1, Task #2) to understand how the success and the expense of various forms of control will vary depending on site-specific ecological factors. We will incorporate our knowledge from Objective 2, Task #3 of landowners' willingness to participate which can be construed as a spatial layer, because we will know the characteristics of all landowners and the location of their parcels. Combined with our new understanding of how to target unwilling landowners (Objective 2, Task #4), the model can suggest targeted approaches--and the specific amounts of funding and landowner cooperation that would be needed to accomplish them--for various scenarios of *Phragmites* control.

Task #7: Develop a plan for a regional coordination network informed by results from Objective 1 and 2 and other successful regional invasive control efforts.-- Our final outcome will be the synthesis of all our findings into a framework for using IPM in an evidence-based, socially- and culturally-relevant, regionally coordinated effort to control *Phragmites*. Alongside our own collective knowledge, we will analyze other successful regional programs, such as the Invasive Spartina Project. It is too early to say what form this program will take, but we expect to propose models of governance, techniques for stakeholder engagement, strategies for securing and allocating resources, and other recommendations drawn from our investigations. Although this proposed regional network will focus on *Phragmites* in Suisun Marsh, we believe that our approach--integrating social and biophysical sciences, and focused on local knowledge--could serve as a model for developing similar efforts in and out of the Delta.

Outcomes and Deliverables

Our deliverables will be used proximally by all natural resource agencies concerned with recreation, navigation, and wildlife habitat in Suisun Marsh. Potentially, they could be used as a model for regional coordination on other thorny management issues elsewhere in the Bay-Delta. We anticipate benefits to all recreational users of Suisun Marsh if our plans succeed at improving management of *Phragmites* regionally.

- Quarterly progress reports and invoices (10)
- Annual progress report (3: Jan 2022, Jan 2023, Jan 2024)
- Revised data management plan (Jul 2022)
- Stakeholder engagement plan (Dec 2021)
- Delta Science Tracker updates (2021-2024)
- Stakeholder engagement workshop (2022, 2023)
- Communication strategic plan (2021-2024)
- Presentations at the 2022 State of the Estuary
- Presentations at the 2023 Bay-Delta Science Conference
- New treatment and monitoring protocols (2023)
- Summary results from a retrospective monitoring analysis (2023)
- Consensus results from technical input workshop (2023)
- Spatial prioritization model and outputs (2024)
- Recommendations to inform a regional control plan (2024)
- ≥2 manuscripts submitted to peer-reviewed journals (2024)

Schedule by Task (07/01/21 - 02/01/24)	**Q1** 07/21 - 09/21	**Q2** 10/21 - 12/21	**Q3** 01/22 - 03/22	**Q4** 04/22 - 06/22	**Q5** 07/22 - 09/22	**Q6** 10/22 - 12/22	**Q7** 01/23 - 03/23	**Q8** 04/23 - 06/23	**Q9** 07/23 - 09/23	**Q10** 10/23 - 12/23	**Q11** 01/24 - 02/24
1. Evaluate revegetation as a best management practice			■	■	■						
2. Implement consistent monitoring and conduct retrospective analyses				■	■	■	■	■	■		
3. Assess perceptions, decision-making, and willingness for collective action		■	■	■	■	■	■	■			
4. Develop a communication framework built on institutional values			■	■	■	■	■	■	■	■	
5. Solicit technical input on prioritization criteria			■	■	■	■	■	■	■		
6. Use socioecology results from Obj. 1-2 as inputs to a spatial prioritization model						■	■	■	■	■	■
7. Develop a plan for a regional coordination network							■	■	■	■	■

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Science Action Agenda Relevance

Our plan addresses Science Action Agenda (SAA) Areas 1, 3, and 4.

Under SAA Area 1, "Assess the human dimensions of natural resource management decisions," we will fulfill the priority management needs to "determine how to coordinate and assist adaptive management in the Delta" and "understand human responses to policy and management actions regarding common pool resources." Our approach is inspired by adaptive management because it critically examines past failures and successes with retrospective monitoring, and suggests new approaches that promise better success in the future. The foundation of the work is on improving our understanding of human responses to management actions, and then incorporating this understanding into new approaches that have better potential for uptake and adoption.

Under SAA Area 3, "Develop tools and methods to support and evaluate habitat restoration," our proposal will fulfill the priority management need to "evaluate performance of restored areas on a landscape scale." Our retrospective monitoring will be an evaluation of past performance, and we will develop a new monitoring protocol that will support future restoration. Although our tests of revegetation success will occur in small plots or transects, our examination of the remotely sensed imagery, and our eventual spatial prioritization model that incorporates this information, occur at the landscape scale.

Under SAA Area 4, " Improve understanding of interactions between stressors, managed species, and their communities," our proposal addresses the priority management need to "improve ability to prevent, conduct early detection, rapid response, eradication, and control of non-native and potential invasive species." Our proposed work is specifically aimed at control of invaders. Moreover, we expect that the outcomes of our work will improve other managers' ability to control different Delta and SF Bay invaders in the future.

Finally, our project generally addresses the new 2022-2026 SAA Top Management Questions of large-scale experiment coordination among stakeholders (#1) and better monitoring design (#2) and specifically deals with the desired extent of invasive control (#36) and the understanding of social factors to better design invasive management plans (#51).

Broader Impacts and Vulnerable Communities

We have focused the proposed work on a case study of invasive *Phragmites* control in Suisun Marsh, but we anticipate the results of this study will provide socio-ecological findings that should have broad applications for other invasive species in the Bay-Delta, California, and beyond. This work will complement and follow noxious weed studies that we are completing in Suisun Marsh this quarter supported by the California Department of Food and Agriculture on both Phragmites control and Lepidium where we worked on spray-drone development for treatments. Also, we plan to closely coordinate our work in Suisun Marsh with an ongoing DWR study on treatments in tidal marshes at their Blacklock property and with control efforts on the DFW Grizzly Island Wildlife Area supported by a Wildlife Conservation Board grant.

Our *Phragmites* expert, Dr. Karin Kettenring from Utah State University, has ongoing *Phragmites* research in Great Salt Lake wetlands as well as on Chesapeake Bay, so the proposed work in Suisun Marsh will add to the breadth of North American results. We are not aware of invasive plant studies in the Bay-Delta that have specifically integrated ecological and social sciences as the foundation of the project. Our intended results should help inform a number of invasive species control efforts on how identifying differences among stakeholders in the community may be a key concern for developing an effective program that leads to effective collective action.

In addition, we are proposing to support programs for four scientists and mentor one DSC Science Fellow, two new postdoctoral researchers, and at least four undergraduate Interns to conduct the work. We will advertise for new hires in a variety of venues in order to recruit a diverse pool of candidates, including members of groups underrepresented in science and natural resource management. Importantly, our team--and especially our natural science and social science postdocs, who will work closely together in Tasks #6 and #7--will all gain valuable experience in working in an interdisciplinary group. This will build their capacity to accomplish high-quality, integrated socio-ecological research in the future.

We will attend local (landowner workshops), regional (State of the Estuary and Bay Delta Science Conference), and possibly national scientific meetings (Restore America's Estuaries, Society of Wetland Scientists) to report our findings, and we will develop peer-reviewed publications as well as local landowner newsletters and website updates. Our plans for stakeholder engagement are part and parcel of the research, so we refer the reader to the detailed methodologies in Tasks #3, #4, and #5 for information about the frequency, methods, goals, and audiences for engagement.

We used the Delta Adapts Map Tool to identify vulnerable communities inside the project footprint and within a 5-mile radius of the project boundary. Most census tracts within this adjacent area are considered to have “Moderate” vulnerability to climate change, but to the south of the marsh are several disadvantaged communities rated as “High” or “Highest” vulnerability. These include parts of Pittsburg and unincorporated areas of Contra Costa County, as well as portions of Rio Vista in Solano County. Also, the (DAC Mapping Tool) indicates that Suisun Marsh includes 3 disadvantaged communities in the project footprint, 17 within a 1-mile radius of the project boundary, and 3 within a 5-mile radius. By reducing barriers to navigation and wildlife movement, and improving wildlife populations, *Phragmites* control will benefit recreational users of Suisun Marsh who live in these vulnerable communities, including some who depend on subsistence hunting and fishing in the marsh to supplement household food resources.