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Invasive Aquatic Vegetation in the Sacramento-San Joaquin Delta and Suisun Marsh: The History and Science of Control Efforts and Recommendations for the Path Forward

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ABSTRACT

Invasive aquatic vegetation (IAV) is a management challenge in the Sacramento–San Joaquin Delta and the Suisun Marsh that has commanded major resource investment for 4 decades. We review the history and supporting science of chemical, biological, and mechanical control of IAV in the Delta and Suisun March, and in flowing waters outside the region. Outside the Delta, there is a significant history of research on IAV control in lotic systems, but few studies come from tidal environments, and we found no investigations at a spatial scale like that of the Delta. The science of control efforts in the Delta is nascent but has seen marked growth over the recent decade. Since 1983, control of invasive submerged and floating species has been centralized within the California State Parks Division of Boating and Waterways (CDBW). The program relies on herbicides, with an annual budget that has exceeded $12.5 million since 2015. However, the results have been mixed because of the challenge of applying herbicides effectively in a tidal system. In parallel, biological control agents for water hyacinth (*Eichhornia crassipes*) and giant reed (*Arundo donax*) have been released but have not provided an appreciable control benefit, likely because they are not suited for the temperate Delta climate. Over recent decades, regulatory complexity has increased, hampering efforts to innovate alternative methods or respond quickly to new invaders. Control efforts for giant reed and common reed (*Phragmites australis*), the main invasive emergent plants, have not been coordinated under a central program, and studies to investigate control strategies have only recently been permitted. As a result, no local studies have been published on control outcomes for these species. Based on this history and our review of the science, we develop

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recommendations for leadership and science actions to proactively manage IAV.

KEY WORDS

Egeria densa, *Eichhornia crassipes*, invasive aquatic vegetation, herbicide, biological control, fluridone, glyphosate, mechanical removal, non-target effects

INTRODUCTION

Estuarine systems are part of a global trend of the increasing spread of invasive aquatic vegetation (IAV; Planty–Tabacchi et al. 1996; Havel et al. 2015). For humans, these invasions often impede ecosystem services, including commercial vessel travel and recreational uses (Villamagna and Murphy 2010; Keller et al. 2018). Many IAV species are ecosystem engineers, altering fundamental ecosystem processes and setting off cascades of changes to biological communities (Guy–Haim et al. 2018; Emery–Butcher et al. 2020). Natural resource managers have been using chemical, mechanical, and biological strategies to control aquatic plant invaders for decades (Hussner et al. 2017). Controlling these aquatic plant invaders is often elusive and is highly dependent on the context and tailored approach to individual areas of infestation (Simberloff 2021), but lentic systems have seen some successes (Getsinger et al. 2002; Madsen et al. 2002; Parsons et al. 2009). Estuarine and other flowing water systems, such as the Sacramento–San Joaquin Delta (Delta), have received less attention. Invasive plants are more difficult to control in these systems because the hydrology is more complex, involving both tidal and riverine dynamics that complicate control methods and are a source of IAV propagules. Control efforts in estuaries have the common added challenge of a complex regulatory framework. At the interface between aquatic and terrestrial, freshwater, and marine ecosystems, estuaries support high biodiversity, including rare or endangered species (Naiman et al. 1988; Naiman and Decamps 1997). As centers for commerce and recreation, estuaries are also highly susceptible to invasions (Cohen and Carlton 1998; Ruiz et al. 2000). The co-existence of IAV and protected species can introduce multiple permitting requirements to control programs (Williams and Grosholz 2008), which can unintentionally raise barriers to advancing science to control IAV in these systems.

The Delta and adjacent Suisun Marsh is a prime example of a highly modified, complex, and invaded system. The list of floating, submerged, and emergent aquatic plant invaders has grown over recent decades (Christman et al., this issue). Some of the globe's most pernicious invaders now dominate the aquatic vegetation community. For example, *Ludwigia* spp. (water primrose) quadrupled its coverage between 2004 and 2016, overtaking open water, submerged vegetation, and emergent marsh habitat (Khanna, Santos, et al. 2018). *Eichhornia crassipes* (water hyacinth), which is invasive worldwide with numerous social-ecological effects (Kleinschroth et al. 2021) is a major species in the Delta's floating aquatic vegetation (FAV) community and has been the focus of control efforts since 1983. Coverage of submerged aquatic vegetation (SAV) has increased: maps produced from aerial imagery have shown more than a 2-fold increase in some regions between 2004 and 2018 (Ustin et al. 2019). The SAV community is dominated by *Egeria densa* (Brazilian waterweed; Santos et al. 2011; Conrad et al. 2016), which is notable for its ecosystem engineering effects (Yarrow et al. 2009). In the emergent aquatic vegetation (EAV) community, *Phragmites australis* (common reed), a Eurasian native that is commonly found in brackish-water areas of anthropogenic or natural disturbance (Hazelton et al. 2014), has increased more than 200% in Suisun Marsh over the past 2 decades (Boul et al. 2018). *Arundo donax* (giant reed) is present in many waterways in the Delta after its introduction to California for use as housing thatch and erosion control in the 1700s and 1800s (Dudley 2000).

Invasive plants in the Delta hinder recreational and commercial boat navigation, operation of critical water infrastructure, and environmental sampling efforts (Boyer and Sutula 2015; Ta et al. 2017; Khanna et al. 2019). Furthermore, their recent spread into Delta regions slated for tidal wetland restoration makes these future projects highly susceptible to invasion, which critically threatens the intended ecological benefits of these projects (Brown et al. 2016; Khanna, Santos, et al. 2018). Notably, however, efforts to control IAVs and restore habitat occur in the context of a system with a lengthy history of modification that involves extensive land reclamation and altered hydrology, because the system serves as the hub of California's water infrastructure (Lund et al. 2010). Control efforts typically do not attempt to eradicate IAVs or restore the system to historical conditions. Instead, as we will discuss, control efforts are targeted at maintaining the services of water supply, recreation, and local economy that the Delta affords. Even with these general goals, however, IAV management has only grown more challenging; therefore, strategic and cost-effective control methods are urgently needed.

Here, we focus on the history of IAV management in the Delta and Suisun Marsh and the latest relevant scientific understanding. The ecology and effects of IAV species are addressed in Christman et al. (this issue). We limit our geographic scope to the Delta and Suisun Marsh and do not include control efforts for IAV species in the San Francisco Bay. In that region, significant attention has been devoted to control of *Spartina alterniflora* (smooth cordgrass), and those efforts are summarized elsewhere (Williams and Grosholz 2008; Rohmer and Kerr 2021). Additionally, while there are numerous invasive plant species in high marsh and terrestrial habitats (e.g., pepperweed *Lepidium latifolium*, Russian thistle *Kali tragus*), we focus on freshwater and brackish aquatic habitats within the high-water zone of the tidal wetlands and subtidal areas.

We begin with an overview of the particular challenges of controlling IAV in tidal and flowing waters. With this broad context established, we summarize the history of IAV management in the Delta and Suisun Marsh and examine the state of the science for the target and non-target outcomes of control efforts. We include a description of the regulatory context because it often sets the boundaries for research and development of control technologies. Finally, we present recommendations for enhanced leadership and key science actions to advance progress for adaptive management of IAV control actions, which is critically needed as the system responds to a changing climate and shifting, growing human demands (Norgaard et al. 2021).

OVERVIEW OF IAV CONTROL IN TIDAL AND FLOWING WATER SYSTEMS

Generally, there are four main methodologies for IAV control: chemical treatment with herbicides, mechanical removal, physical barriers that prevent growth or spread, and biological control via the introduction of herbivores (Hussner et al. 2017). Applying any of these approaches in highly dynamic systems such as estuaries brings additional challenges because the hydrologic forces at play can impede the treatment agent, and because plant propagules produced during control efforts can often spread and establish new populations elsewhere in the system.

Chemical (Herbicide) Approaches

Submerged IAV species are the most challenging to treat with herbicides in tidal and flowing waters because the plants must absorb a critical dose of the chemical for a long enough time (concentration and exposure time, or CET) to kill the plant. Contact herbicides used for submerged plants have short exposure-time requirements (hours to days), and their mode of action involves direct contact with target plants. In contrast, systemic herbicides have much longer time requirements (weeks to months) because their mode of action involves plant uptake to impede functions critical for growth and survival. In riverine and tidal systems, untreated water constantly enters the treatment area, and dilutes the herbicide, making the required CET very difficult to achieve (Patten 2003; Skogerboe et al. 2006), particularly for systemic herbicides. In some lotic systems, customized application techniques have been developed from dye-based assessments of herbicide dissipation rates (Getsinger et al. 1996; Getsinger and Netherland 1997; Sisneros et al. 1998). For example, in tidal canals infested with *Hydrilla verticillata* (hydrilla)

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in the Crystal River, Florida, researchers achieved longer-lasting control when herbicides were applied using weighted hoses or as granules at the bottom of the water column (Fox and Haller 1992; Fox et al. 1994).

In 1986, the US EPA registered fluridone, a slow-acting, systemic herbicide that can effectively control invasive SAV in lake systems when applied at low concentrations over long exposure periods of 60 to 120 days (Madsen et al. 2002; Parsons et al. 2009). Fluridone was developed specifically for rooted aquatic plants, and functions by inhibiting formation of carotenoid pigments necessary for photosynthesis (Arnold 1979). It requires sustained exposure to achieve control, and can result in total plant death over a period of multiple months (Sprecher et al. 1998; Puri et al. 2006). This tool has been chosen for multiple systems because of its low toxicity profile for non-target organisms (Getsinger et al. 2008). Notably, however, evidence is lacking in the published literature for effective use of fluridone (or other herbicides) in large estuarine systems with regional-scale invasive SAV populations, as in the Delta.

For FAV and EAV, chemical controls can be applied in the same way that they are for lentic systems. The main added difficulty is that truly floating species (e.g., *E. crassipes*) can be mobile in flowing waters, and when plant fragments break off of a main population, they can evade treatment (Clements et al. 2012). For floating species, 2,4-Dichlorophenoxyacetic acid dimethylamine salt (2,4-D)—a systemic herbicide specific to dicotyledonous plants and a long-standing agent for weed control for cereal crops (Grossmann 2010; Song 2014; Peterson et al. 2016)—has historically been the most common herbicide used for *E. crassipes* and *Alternanthera philoxeroide*s (alligator weed) (Gangstad 2017). However, glyphosate, a non-selective, systemic herbicide that acts by inhibiting synthesis of aromatic amino acids (Jaworski 1972) is now the main herbicide used because 2,4-D application near crops and irrigation systems can cause significant agricultural damage (Hemphill and Montgomery 1981; Egan et al. 2014). Glyphosate was first registered for commercial use in 1974, and its use increased rapidly with the inception of glyphosate-tolerant crops in 1996, to become the most widely applied herbicide on the globe (Benbrook 2016). However, multiple studies suggest concerns for non-target, sublethal effects on aquatic flora and fauna, with examples of toxicity across a diversity of animals (Gill et al. 2018). There are also health concerns for applicators (Agostini et al. 2020; e.g., Hardeman v. Monsanto 2021). These concerns and increasing limits on glyphosate necessitate successful models for integration of control methodologies to reduce herbicide use (Jadhav et al. 2008).

Mechanical Approaches

Mechanical removal or shredding is appealing as an alternative to chemical control. Approaches include a variety of equipment, from large harvesters and specialized shredders, to suction devices used by divers, or simple hand removal (Hussner et al. 2017). For emergent species *Phragmites australis* and *Arundo donax*, mowing, disking of rhizomes, and burning are common mechanical approaches (Lawson et al. 2005; DiTomaso et al. 2013; CA–IPC 2020). Removal approaches have had numerous successes in reducing *E. crassipes* (Thiemer et al. 2021). However, the approach presents challenges by being labor intensive, costly, and unrealistic for large infestations (Eichler et al. 1993; Alexander et al. 2008). Furthermore, it often disperses plant fragments, causing further spread. The disposal of copious amounts of decaying plant biomass produced by removal operations is an added complication (Elenwo and Akankali 2019), causing precipitous drops in dissolved oxygen if left in the aquatic environment. Bringing dead plant biomass onto land can also be problematic because it may introduce fire hazards or occupy prohibitive amounts of space; though these issues can be partially offset by the growing practice of innovatively using plant material to produce energy (Kleinschroth et al. 2021).

Physical Approaches

Physical approaches to control IAV differ from mechanical methods because they do not involve plant removal or shredding, but rather containing plants with booms or curtains for floating species, or benthic barriers for rooted plants to deprive them of light. Controlled experiments that compared responses of multiple SAV species to different benthic mats showed varying responses across species as a result of differences in morphology and the plant's ability to pass through the matting material (Hofstra and Clayton 2012). Additionally, studies in stream systems with emergent species have observed high rates of reinfestation after barriers are removed, and colonization on top of barriers when sediment accumulates (Eichler et al. 1995; Laitala et al. 2012; Collins et al. 2019). Benthic barriers can also harm invertebrate communities and interfere with nutrient and oxygen exchange processes where water and sediment meet (Ussery et al. 1997). Still, in small infestations where chemical control is not feasible or desirable, physical control may present an option, maintaining IAV at low levels.

Biological Approaches

After herbicides, mechanical, and physical control, the fourth mode of controlling IAV is biological, which involves introducing herbivores to reduce target plants. Candidate biological control agents are tested rigorously in lab settings for their specificity to consume only targeted IAV species, and this step typically requires multiple years of work before the agents are allowed to be released in the field. The most common form of biological control for IAV species is the introduction of herbivorous insect species that co-evolved with the target plant species in its native range (Schwarzländer et al. 2018). The approach often has variable results, largely because of climate mis-matches between the identified biocontrol agent and its release locations (Harms et al. 2021). Still, in some examples with floating IAV, biological control has been highly effective. In the 1960s, three insects were released to manage *A. philoxeroide*s in the southeastern US. The insects readily established and the resulting suppression of the plants remains one of the most compelling examples of biological control of FAV worldwide (Tanveer et al. 2018). Other successes include control of the *Azolla filiculoides* (red waterfern) in South Africa after the 1990 release of a frond-eating weevil *Stenopelmus rufinasus* (McConnachie et al. 2004), leading to extirpation of *A. filiculoides* in South Africa (Zachariades et al. 2017).

Aquatic insects that feed on SAV are less common and less diverse than their terrestrial counterparts, and to date there are no examples of species–specific SAV control from a biological agent (Cuda et al. 2008; Hussner et al. 2017). Several fly species have been identified and released to control *H. verticillata* in the southern US but established populations did not provide significant control (Purcell et al. 2019). Grass carp (*Ctenopharyngodon idella*), made triploid and sterile by pressure treatment of eggs, have been used to control *H. verticillata* across the US and in other countries (Chilton and Muoneke 1992), including in canal systems of the Imperial Valley of California (Stocker and Hagstrom 1986). However, these fish feed non-selectively on SAV species and are often caged within a specific water body to avoid damage to desirable vegetation.

For key invasive emergent species, *P. australis* and *A. donax*, efforts are also underway to enhance control through biological agents. Agents have been tested for *P. australis* (Blossey et al. 2018), but none are approved for release in the US. The shoot-tip galling wasp *Tetramesa romana* has been introduced to riparian areas of the Rio Grande river in Texas, resulting in well-established populations that achieve substantial control (Moran et al. 2017; Marshall et al. 2018). Similarly, the shoot-feeding armored scale *Rhizaspidiotus donacis*, is also established in Texas and can provide substantial control (Goolsby and Moran 2019). These two agents have also been released in California, and ongoing work is assessing their effect on *A. donax* (Pratt et al. 2021). A third agent, a leaf-mining fly *Lasioptera donacis,* is permitted for release in the US and may tolerate cold better than the wasp (Goolsby et al. 2017; Marshall et al. 2018). Its suitability for release in California is under evaluation.

Generally, each of the four modes of control have trade-offs regarding cost, labor, occupational

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hazards, and efficacy; and these trade-offs vary among IAV growth forms. Notably, a review of efforts to control IAVs recently concluded that successful eradication or even maintenance management of freshwater aquatic plants is uncommon (Simberloff 2021). Because of the trade-offs across control methodologies and the unique circumstances presented in every infestation example, particularly in tidal and flowing waters, integrated approaches are the best positioned for effecting any control (Hussner et al. 2017). Adaptive, coordinated, and proactive leadership is essential to addressing invasions in dynamic systems (Williams and Grosholz 2008), as is allowing experimentation with emerging techniques so the control toolbox continues to grow. Along these lines and despite the seemingly intractable and growing problem of IAV infestations in these dynamic environments, there is ongoing research to develop new innovative techniques, including those based on molecular genetics (Simberloff 2021).

THE HISTORY AND PRACTICE OF IAV CONTROL IN THE DELTA AND SUISUN MARSH

General Regulatory Context

Since 1983 for floating species, and since 2000 for submerged species, the California Department of Parks and Recreation, Division of Boating and Waterways (CDBW) has primarily led and implemented IAV control in the Delta. Control of EAV, in contrast, has not been centralized through any entity, and each effort to control EAV that includes aquatic habitats must be individually permitted. This lack of centralization for EAV control efforts has resulted in slower, dispersed, and more limited progress in the science of control methodology for the region.

FAV control began after 1982 state legislation established the Water Hyacinth Control Program (WHCP; Figure 1). From 1983 to 1999, CDBW treated approximately 65 to 1,100 hectares per year (CDBW 2001). Control efforts for SAV began in 2001, after 1996 legislation authorized CDBW to initiate the *Egeria densa* Control Program (EDCP, Figure 1). Between 2001 and 2018, it has been necessary to grow the list of species that CDBW is permitted to treat, and today nine species are included in the program's permit (FAV: *E. crassipes*, *Limnobium laevigatum* (spongeplant), *Ludwigia* spp., and *A. philoxeroide*s; SAV: *E. densa*, P. *crispus*, *M. spicatum*, and *Ceratophyllum demersum* (coontail) Figure 1). However, the addition of new species invokes a bureaucratic process. Before 2013, CDBW was required to add a new species to its program through a lengthy consultation process with federal agencies that required a year or more. To increase efficiency, the process changed in 2013 so that CDBW could request that the California Department of Fish and Wildlife (CDFW) conduct a risk assessment protocol that leverages the US Aquatic Weed Assessment scoring tool (Gordon et al. 2012). If the scoring indicates a likelihood of economic or environmental harm, then eradication or control measures can proceed, within the regulations of existing environmental permits, such as the Biological Opinions (BOs). Even with a more systematic protocol, the process still requires months of time. The risk assessment tool allowed *A. philoxeroide*s to be added to the CDBW program in March 2018 after its discovery in the Delta in 2017. A new submerged invader, *Vallisneria australis* (Australian ribbonweed), was formally identified in the Delta in 2017 and is of concern because of its spread on other continents, including New Zealand and Europe (Madsen 2022). The request for its risk assessment was submitted in November 2021 and CDFW provided a response to CDBW in September 2022 to classify the species as invasive and allow treatment to begin. (2022 personal communication between M. Volkhoff and JLC, unreferenced, see "Notes").

Regulatory complexity for CDBW control has increased substantially over time, and the current program must comply with standards for eight different state and federal authorities, and many of these standards have associated reporting requirements (Caudill et al. 2021). Species' listings for the Delta Smelt (*Hypomesus transpacificus*) and the Sacramento Winter-run Chinook salmon (*Oncorhynchus tshawytscha*), among others, necessitate Endangered Species Act permits, or BOs, include limitations on treatment approaches to minimize effects on protected species. Until

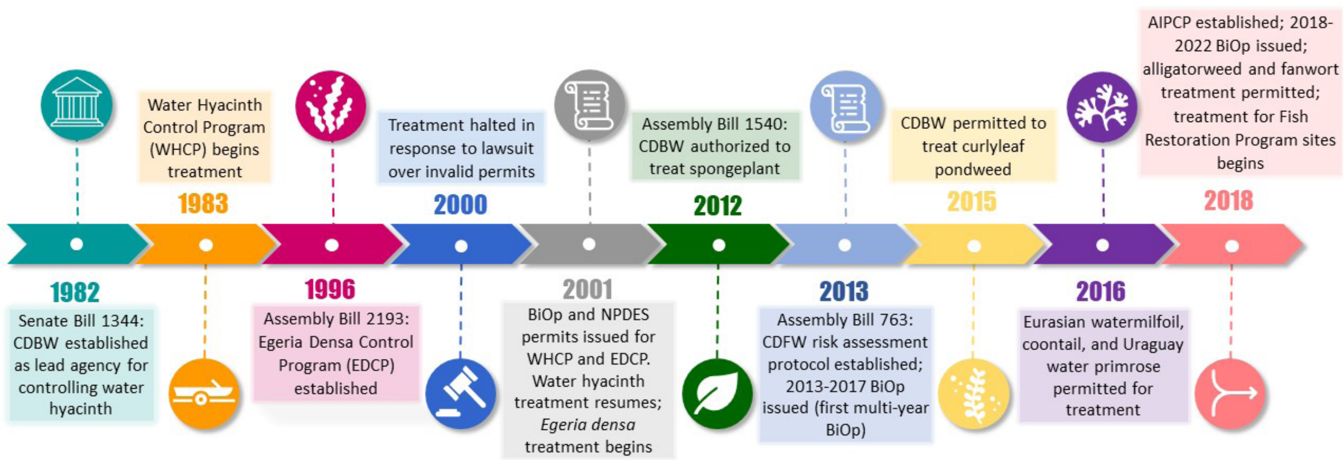

Figure 1 Timeline of enabling legislation and permitting milestones for the CDBW control program for SAV and FAV in the Delta. BO = Biological Opinion, issued to the CDBW control program to ensure sensitivity to species listed on the Endangered Species Act. NPDES = National Pollutant Discharge Elimination System; AIPCP = Aquatic Invasive Plant Control Program.

2013, BOs for treatment of each aquatic plant species were issued annually, resulting in variability for when treatment began each year (Caudill et al. 2021). In 2018, CDBW underwent a major consolidation of BOs, effectively combining the previously separate FAV and SAV programs into a single permitted program, the Aquatic Invasive Plant Control Program (AIPCP; Figure 1). The current BO permits an annual treatment of up to 6,000 total hectares (ha) of SAV and FAV. Additionally, this BO established Demonstration Investigation Zones (DIZs), which are relatively small plots (<8 ha) for the express purpose of evaluating newly proposed treatment methods (e.g., new herbicides, physical controls) before they are adopted at a programmatic scale (USFWS 2019). Until completion of this BO, experimentation with new methods had to be permitted separately from the overall program, and was a significant barrier to conducting control methodology research.

Even as the permitting approach has been evolving to adopt a more streamlined approach, new invaders or changing habitat present new demands for control. Notably, tidal wetland restoration is required for State and Central Valley Water Project compliance with federal and state Endangered Species Acts at a scale of over 3,000 ha. A long-standing concern is that the new shallow-water areas will provide additional habitat for IAV, which would compromise the intended benefits of the restored areas for food webs and native fishes (Brown et al. 2016). Indeed, invasive plants have expanded significantly in the North Delta in areas adjacent to planned restoration sites, making this a pressing concern for investment in restoration actions (Ustin et al. 2019; Conrad et al. 2020). These large shallow-water areas are different from typical CDBW treatment areas (channels, slough, marinas), and developing successful control strategies will require innovation.

As a California state agency program, CDBW treatments are a public good (Mas–Colell et al. 1995) because they provide services and benefits non-exclusively to stake-holder parties. As a public good, the program engenders diverse expectations among its many stake-holders (Caudill et al. 2021). With the ongoing spread of IAV, and because there are no established numerical targets for control, it is difficult for the program to illustrate progress. Instead, evaluation of the program's performance is left to the measure and perception of its beneficiaries as a public good, which have variable needs and expectations for control (e.g., Gokham 2011; Anderson 2014).

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Costs of SAV and FAV Control

Financial costs are an important point of context for IAV control because they are an obvious factor in evaluating return on investment, and they influence decision-making for treatment plans. From 2013 through 2018, the annual cost of the CDBW program increased from approximately $7.1 million to $14.3 million (Table 1).

While CDBW has the largest control program, other agencies also incur costs to maintain water supply, navigation of commercial and recreational vessels, conduct environmental monitoring, and protect human health (Jetter and Nes 2018; Khanna et al. 2019). The US Bureau of Reclamation uses boats and mechanical sweepers to remove aquatic plants that accumulate at the Tracy Fish Collection Facility, which precedes the Central Valley Project's intakes to the aqueduct system for water supply. Generally, costs of these ancillary control efforts are evened or reduced by the larger CDBW program because of the general service it provides. For example, some marinas will attempt to remove IAV by raking, but most will request control services from CDBW. However, costs increase across entities when SAV and FAV abundance sharply increase, as in the drought years of 2014 and 2015. In these years, the Port of Stockton used mechanical harvesters to remove large infestations of *E. crassipes* (water hyacinth) from their dock areas to enable container ship access (Table 1).

In addition to direct costs, there are important considerations of the public's perception of IAV management, which are unexplored in the scientific literature for the Delta. For example, the public often values alternatives for control methods differently, and, in urban landscapes, is willing to pay a significantly higher amount for biological approaches (Jetter and Paine 2004). In the Delta, studies have not yet been conducted on public perception, preferences, or willingness to pay for alternative IAV control methods, pointing to knowledge gaps that must be filled to help inform appropriate control targets and prioritization of control areas, including the evaluation of the costs and benefits for no-treatment areas where invasive vegetation is allowed to persist if costs or feasibility of successful treatment are prohibitive.

METHODOLOGY TO CONTROL IAV IN THE DELTA

Current methodology for the CDBW AIPCP is well documented by Caudill et al. (2021). We provide a brief overview of the history of control approaches in the Delta for each IAV growth form to illustrate how scientific efforts have been conducted and to set the stage for the current understanding of control outcomes.

History and Practice of IAV Control

SAV: Reliance on Fluridone, a Slow-Acting Systemic Herbicide

The SAV control program has relied exclusively on herbicides throughout its history. Since the inception of the EDCP in 2001, fluridone has been nearly the sole control agent used because of its low toxicity profile, though diquat was used in limited quantities from 2001 to 2005, and again starting in 2018 (Figure 2). To attempt the required long exposure times for fluridone, CDBW

Table 1 2013–2018 IAV control costs in the Delta (*in thousands $USD*). Expanded from Jetter and Nes, 2018 using methods described therein. *Source: Table adapted from Jetter et al. (2021).*

	2013	2014	2015	2016	2017	2018	Total
California State Parks Division of Boating and Waterways	7,124	7,625	13,718	12,545	13,029	14,340	61,257
Port of Stockton	51	306	168	0	0	0	474
US Bureau of Reclamation	343	833	921	658	215	71	2,698
Mosquito and Vector Control District-San Joaquin County	223	73	37	155	11	19	295
Private marinas	169	576	943	310	21	150	2,001
Total	7,910	9,413	15,787	13,669	13,277	14,580	66,725

applies fluridone for 8 to 16 consecutive weeks (Caudill et al. 2021), targeting a consistent water concentration of 1.5 to 3.5 ppb (CDBW 2019a). The current BO allows fluridone application rates up to the rate specified on the product label (75 ppb), though post-treatment water concentrations must remain from 1 to 10 ppb (USFWS 2019). However, CDBW applies fluridone well below label permissions to protect irrigation water from herbicide residue. Recently, to enhance the list of herbicides used to treat SAV, CDBW has used the newly permitted DIZs to pilot the use of contact herbicides. In 2020, after pilot use, diquat use was re-incorporated into the program, though its use remains under temporal and spatial restrictions (Table 2). Demonstration Investigation Zones will be used in future years to investigate the use of endothall for SAV treatment, after promising mesocosm studies and field trials in 2018 that showed endothall effectively treat watermilfoil and coontail (96% and 94% biomass reduction), with a lesser effect on Brazilian waterweed (43% reduction) (Madsen, Morgan, Miskella et al. 2021).

Between 2001 and 2020, SAV treatment was concentrated in the Central Delta, with treatment in the North, East, West, and South Delta regions becoming more common in recent years (Figure 3). Treatment area has increased over time, from fewer than 100 ha in the first years to consistently near or above 1,000 ha in recent years (Figure 2). Despite increasing control efforts, coverage expanded significantly: from 2008 through 2014, SAV and FAV coverage increased by 60%, reaching over 4,500 ha (Ta et al. 2017). Increased spread was associated with drought periods, and was notable in Franks Tract after installation of a temporary salinity control barrier in 2015 that dramatically reduced tidal action, creating favorable conditions for new SAV beds (Kimmerer et al. 2019). Since 2016, CDBW has surveyed SAV biovolume with hydro-acoustic surveys (Sabol et al. 2002; Radomski and Holbrook 2015) to create maps standardized to Mean Lower Low Tide. These surveys have been conducted before and after treatments and are used to inform treatment plans for subsequent years.

With no current candidates for biocontrol, SAV control in the Delta remains limited to a short list of herbicide agents. In the most recent BO, physical approaches to control have recently

Figure 2 Hectares of SAV and FAV treated for each control method, 2001–2021. Suorces: *Data obtained from CDBW annual reports for SAV and FAV control programs available from: http://dbw.parks.ca.gov.*

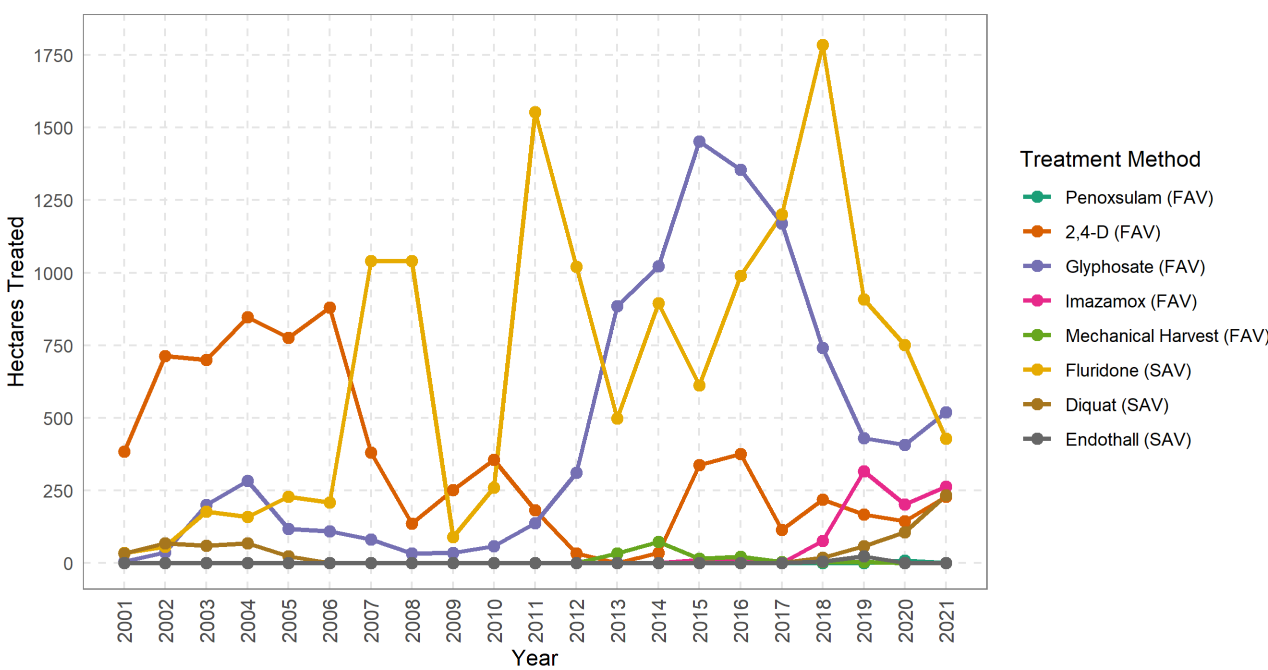

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Table 2 Aquatic Invasive Plant Control Program (AIPCP) methods and conservation measures included in the 2018–2022 USFWS Biological Opinion (BO). (*) indicates new methods. DIZ = Demonstration Investigation Zones; CDPR = California Department of Pesticide Regulation; USEPA = US Environmental Protection Agency. *Source: Adapted from Table 1 in USFWS (2019)*.

Control Method	SAV	FAV	Status or Relevant Conservation Measure
Chemical Control Agents			
2, 4-D		▪	Limited to June 15 through September 15, to avoid juvenile and sub-adult life stages of Delta smelt
Glyphosate		▪	Primary FAV control method
Fluridone	▪		Maximum application rates of 40 ppb, below product label rates
Diquat	▪	▪	Limited to 550 acres of treatment in areas outside Delta Smelt habitat between April 30 and November 30.
Penoxsulam	▪	▪	USEPA Reduced Risk Herbicide
Imazamox	▪	▪	USEPA Reduced Risk Herbicide. For SAV applications, maximum target concentration of 125 ppb
***Imazapyr**		▪	USEPA Reduced Risk Herbicide. Initial use limited to DIZ locations
***Carfentrazone-ethyl**	▪	▪	For use only in tank mixes and in DIZ locations; pending CDPR approval
***Endothall**	▪		Initial use limited to DIZ locations
***Flumioxazin**	▪	▪	For use only in tank mixes and DIZ locations
***Florpyrauxifen-benzyl**	▪	▪	USEPA Reduced Risk Herbicide; Initial use limited to DIZ locations, pending CDPR approval
***Tank mixes**	▪	▪	Mix of fast-acting contact herbicides and slow-acting systemic herbicides to target plants with multiple modes of action
Physical and Mechanical Methods			
Hand removal		▪	Historically used on a limited and localized basis.
Mechanical harvesters		▪	Limited to 80 ha per year
Cutters, shredders		▪	Timing, location must minimize impacts on protected species
***Benthic mats**	▪		For use in small areas (<1 hectare), and only outside of habitat historically used for Delta smelt spawning and rearing.
***Diver assisted suction removal**	▪		May not be used in areas where Delta smelt are likely to be present, to avoid entrainment in suction devices
***Booms and floating barriers**	▪	▪	Flexible barges or balloons used to contain infestations, or in conjunction with harvesters, cutters, curtains, screens, or herbicide treatment to enhance efficacy
***Curtains and screens**	▪	▪	Permeable (screens) and non-permeable (curtains) barriers extending 1 m below water surface and used in conjunction with harvesters that cause plant fragmentation and dispersal, used only in locations that would not impeded boat navigation
Biological Control (Water Hyacinth only)			
***Neochetina* sp.**		▪	Present in the Delta since first introduction in 1982, formal inclusion as a control method in 2019 BO
Plant Hopper (*M. scutellaris*)		▪	Present in the Delta since first introduction in 2011, formal inclusion as a control method in 2019 BO.

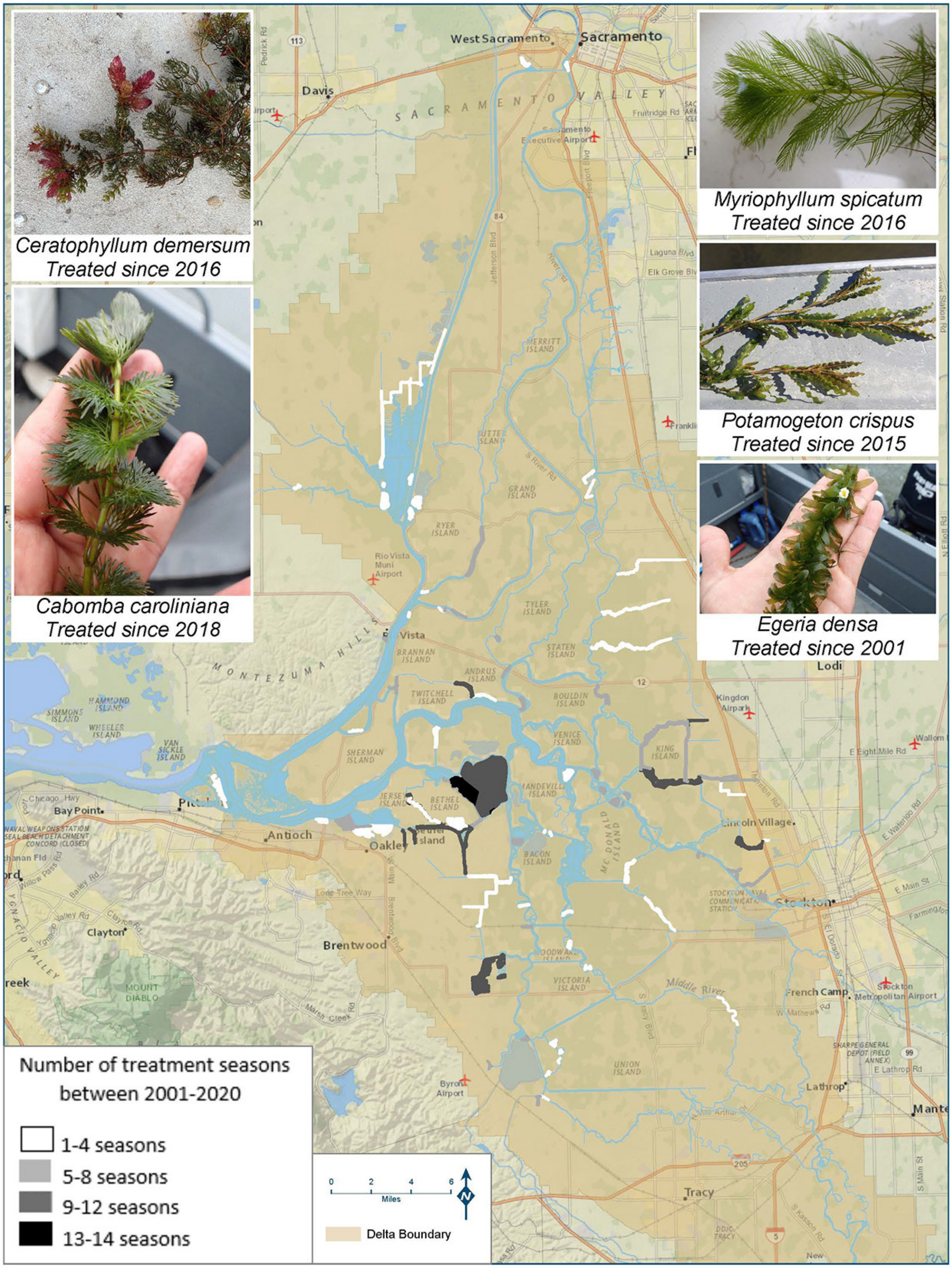

Figure 3 SAV treatment sites and target species 2001–2020 (*photo insets at right*). Sites are *shaded* by the number of treatment seasons each site received. SAV treatment sites generally represent 8 to 16 weeks of fluridone application. *Photo credits: Patricia Gilbert, Lydia Kenison, and Jose Martinez , CDBW*.

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been permitted for investigation (Table 2) and may be useful in conjunction with herbicides to maintain target CET levels in treatment areas. Other permitted tools (e.g., diver-assisted suction removal, or benthic barriers), are only appropriate for small-scale infestations, and require significant manual labor.

FAV: Chemical Control with Ancillary Mechanical and Biological Methods

Like the SAV program, the CDBW program for FAV relies primarily on herbicide treatments, but the chief chemical agents have changed, and the program also incorporates mechanical and biological control methods. From 1983 through 1999, 2,4-D was used almost exclusively, with diquat and glyphosate used in limited quantities and only when 2,4-D was inappropriate because of potential damage to adjacent crop fields (CDBW 2012). From 2001 through 2011, 2,4-D was still the main herbicidal agent, but glyphosate was used with increasing frequency (Figure 2), and it is now the primary herbicide agent. This change was motivated by toxicity concerns with 2,4-D for Delta Smelt and protected salmonids, and the need to protect sensitive crops near treatment areas (USFWS 2013). 2,4-D use continues today, but with more limited applications and seasonal restrictions (Table 2; Caudill et al. 2021). Since 2014, systemic herbicides imazamox and penoxsulam have also been used on a very limited basis (Figure 2). Their addition to the CDBW program helps diversify the herbicide portfolio to reduce the risk of target plants developing resistance to the dominant herbicides. Between 2003 and 2020, FAV treatment has occurred mostly in central and eastern Delta regions, with fewer treatments in western and northern regions (Figure 4).

Since 2013, CDBW has included mechanical harvest at a small scale relative to herbicide treatment (Figure 2), and usually only in emergencies or when herbicide treatment is not possible or appropriate. As in other systems, the challenges with this method have included the difficulty of locating and paying for spoil sites for the harvested vegetation (Greenfield et al. 2006), which includes consideration of contaminants absorbed and concentrated in *E. crassipes* tissue (Greenfield et al. 2007).

Efforts to diminish FAV with biological control agents in the Delta began at approximately the same time as herbicide treatments. The first releases of biological control agents targeted *E. crassipes* and occurred between 1982 and 1985, led by the US Army Corps of Engineers (Corps) with assistance from the US Department of Agriculture (USDA) Agricultural Research Service (ARS) and the California Department of Food and Agriculture (CDFA). Two weevils were released (*Neochetina bruchi* Hustache and *Neochetina eichhorniae* Warner), which are the same agents that have provided beneficial control in Florida (Tipping et al. 2014) and South Africa (Wilson et al. 2007). A leaf-boring moth, *Niphograpta albiguttalis* (Warren) was also released in the same period (Akers et al. 2017). Both weevils established populations (Stewart et al. 1988), but only *N. bruchi* became widespread in the Delta (Hopper et al. 2017), and the leaf-boring moth did not establish any populations. In 2011, the CDFA released the planthopper *Megamelus scutellaris* Berg, targeting *E. crassipes*, in the western and southern Delta, but the planthopper did not become established (Moran et al. 2016; Hopper et al. 2017). Recently, biological control efforts have expanded because they are permitted under the 2018–2019 Biological Opinion for the CDBW program (Pratt et al. 2021). *Megamelus scutellaris* was released between 2018 and 2020. Current monitoring efforts will determine establishment.

Biological control agents for *A. philoxeroide*s and *Ludwigia* spp. are being researched for release in the Delta. Three agents for *A. philoxeroide*s—the leaf-feeding flea beetle (*Agasicles hygrophila* Selman and Vogt), the leaf- and stem-feeding thrips (*Amynothrips andersoni* O'Neill), and the stem-boring moth (*Arcola malloi* Pastrana)—established in the southeastern US in the early 1970s (Coulson 1977) and are under investigation for release in the Delta. Biological control for *Ludwigia* spp. has been proposed multiple times over the last 5 decades, but scientists have been skeptical about the probability of discovering an herbivore that is sufficiently host-specific to not

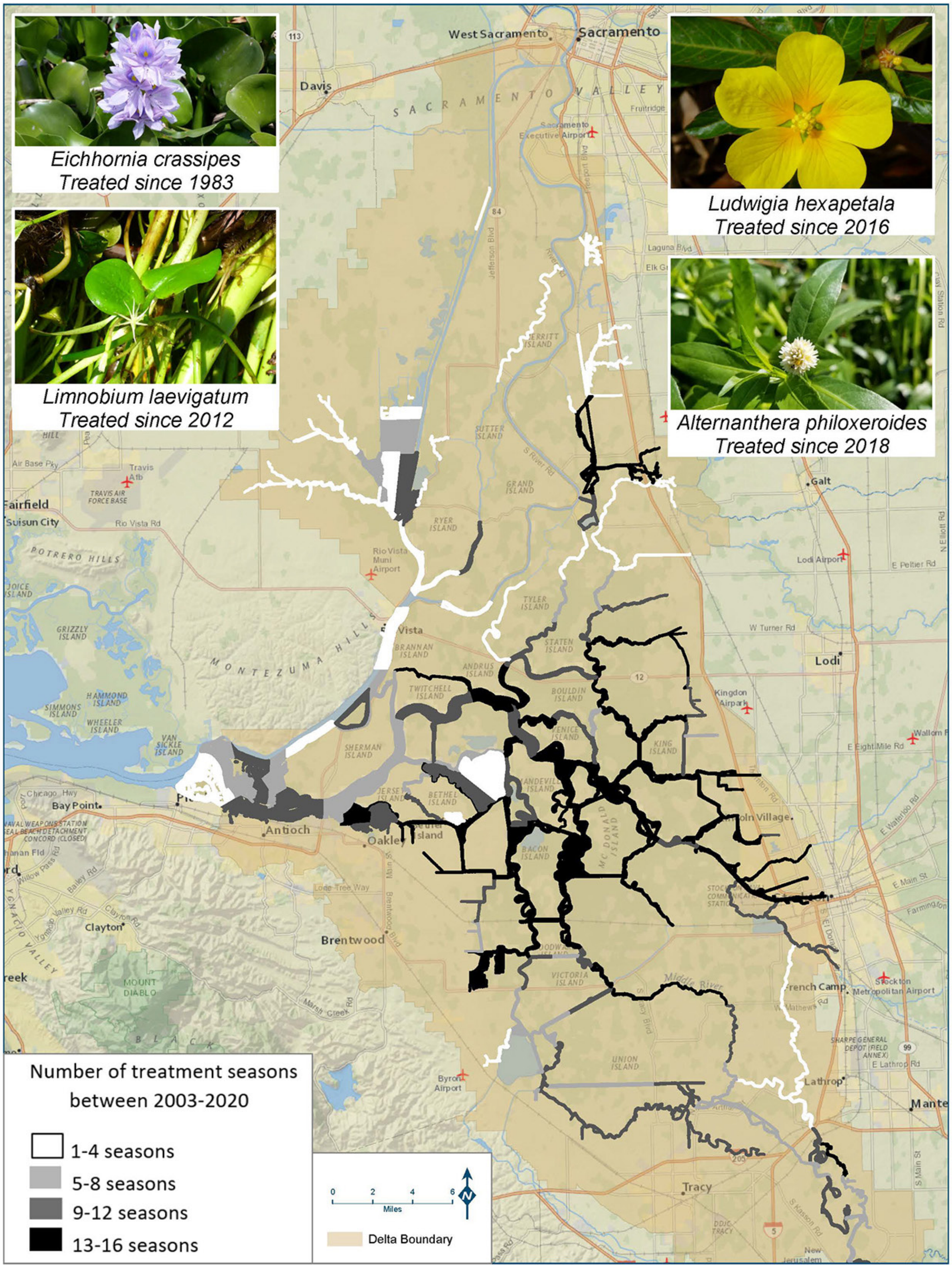

Figure 4 FAV treatment sites and target species, 2003–2020. Sites are *shaded* by the number of treatment seasons each site received within each time-period. *Photo credit: Michael Kwong, CDBW.*

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represent a threat to US native congeners. To date, three insects have been tested for specificity to the same phylogenetic section (*Jussiaea*) but all were unacceptable because they can complete their development on native *Ludwigia* (Reddy et al. 2020). Host range testing of other candidate biological control agents of exotic *Ludwigia* spp. is ongoing (Reddy et al. 2021).

EAV: Disparate Herbicide Control Efforts for Giant Reed and Common Reed C-head

P. australis and *A. donax* are the primary EAV invasive species to be controlled in the Delta and Suisun Marsh. As described above, there is no central organizing entity in the region to control EAV, and EAV has often been controlled through private entities. Herbicide (glyphosate) is the primary control method, but other approaches have included physical, biological, and mechanical. Conducting experimental work on EAV control in tidal wetlands requires individual, case-by-case permitting that is difficult or impossible because there is insufficient information on risks of treatments to protected species.

A. donax populations in the legal Delta were mapped in 2014 by the Sonoma Ecology Center and the Sacramento–San Joaquin Delta Conservancy (SSJDC), revealing 39 ha of coverage, with the most severe infestations along the lower Sacramento River corridor, the confluence area, and the Cache–Slough Complex (CAL–IPC 2020; SSJDC 2020). Significant populations are also present in Suisun Marsh, and the most recent estimate obtained in 2018 estimated coverage at 77 ha in that region (Ustin et al. 2019). The SSJDC has been the main agency confronting the *A. donax* invasion, and—in partnership with the USDA–ARS and the California Department of Water Resources (CDWR)—is developing an integrated biological and chemical control program. In the 2015–2019 Cache Slough Complex Pilot Project to control *A. donax* , patches were treated with a blend of glyphosate and imazapyr. Post-treatment evaluations suggested that while complete death of *A. donax* patches occurred in fewer than half the sites, cover was often reduced to 2.5% or less. However, sustained control required continuous follow-up treatment. This project noted the challenges of continual introduction of rhizomes from upstream regions, and recommended updated mapping, including for upstream watersheds, so that these populations can be strategically treated to minimize propagules entering the Delta (Sonoma Ecology Center 2019; SSJDC 2020).

A. donax is also the subject of biological control efforts in the Delta. The shoot-tip galling wasp *Tetramesa romana* and the shoot-feeding armored scale *Rhizaspidiotus donacis* were released at multiple sites in the western Delta and in the upper Sacramento and San Joaquin watersheds in 2017 (Pratt et al. 2021), with additional wasp releases in 2020. Early monitoring results suggest that the wasp has established in the western Delta and two established populations were observed in upstream watersheds in 2021 (PM, personal observation; Pratt et al. 2021). The armored scale was released as mature females between 2018 and 2020 and has established at low densities in the western Delta (Pratt et al. 2021).

P. australis, most commonly found in Suisun Marsh, has been expanding in coverage over recent decades, with most recent estimates showing minimum coverage of approximately 2,400 ha within Suisun Marsh (Ustin et al. 2019). This estimate suggests significant continued invasion since regional coverage was estimated at approximately 280 ha in 2000 (Boul et al. 2018). Glyphosate has been the most common herbicide applied to control *P. australis* in the managed wetlands of Suisun Marsh, and control efforts have been ongoing since 1998. The managed wetland impoundments are treated after they are drained for the summer season, and applications are accomplished through aerial (helicopters, unmanned aerial vehicles or UAVs) or ground vehicles. Recently, aerial applications with UAVs have been tested as an effective and precise means of treating smaller patches of up to a few hectares before they become established (2019 data file from J. Takekawa, T. Edmunds, and W. Reynolds, unreferenced, see "Notes"). However, continuing challenges to control *P. australis* in Suisun Marsh are a lack of consistent funding and a lack of coordination among public and private land-owners.

In recent years, however, a pair of studies is currently underway to improve cohesion in the control approach for the region and to identify effective control measures. The first study, led by the CDWR on Blacklock Island, aims to develop effective chemical and mechanical treatment strategies that can then be permitted more generally for management of tidal wetland restoration sites. Preliminary results from this work suggest that all experimental herbicide and mowing treatments significantly reduced the *P. australis* growth as compared to untreated sites, and water quality analysis indicated herbicide levels well below the levels of concern (2021 data file from GSD, unreferenced, see "Notes"). The second study, led by the Suisun Resources Conservation District in collaboration with a national team of plant ecologists and social scientists, is following a social-ecological approach to examine attitudes toward coordinated control efforts, while also investigating active re-vegetation with native species after herbicide applications. The results from these two projects may help bring cohesion to the currently fragmented approach to controlling *P. australis*.

Current Understanding and Knowledge Gaps on Target and Non-Target Effects of IAV Control Methods

Relative to the 40-year history of IAV control in the Delta, scientific publications on the topic are nascent, with the first peer-reviewed article appearing in 2006. Since then, 40 articles about the Delta have been published or are in review, with nearly three-quarters of those publications occurring within the last decade (Figure 6). Much of this activity can be attributed to the formation of collaborative science groups centered on IAV control (Ta et al. 2017). For example, the Delta Region Areawide Aquatic Weed Project (DRAAWP) was a group comprising state and federal agencies that was funded from 2014 through 2018 by the USDA–ARS Areawide Pest Management Program. The formation of this group galvanized a suite of research projects that included investigation of new chemical and biological control tools, bioeconomic modeling, and monitoring methodology, all with the goal of advancing knowledge to develop an integrated management program. These efforts resulted in a dedicated special issue in the Journal of Aquatic Plant Management in 2021 (summarized in Moran et al. 2021). DRAAWP scientists and their research were instrumental in the development of the 2018 BO for DBW that consolidated SAV and FAV control programs into a single program, with a permitting structure that afforded investigation of new control tools. The Interagency Ecological Program (IEP) formed an Aquatic Vegetation Project Work Team in 2016, providing a continuing and essential platform for coordination among managers and scientists.

Of the published papers on IAV control in the Delta, nearly one-third have focused on monitoring methods or have provided general reviews of how IAV is managed in the system (Figure 6). In this area, significant progress has occurred in the use of remote-sensing technology to provide synoptic maps of IAV coverage for the full region (Hestir et al. 2008; reviewed in Hestir and Dronova, this issue), something that is not possible with land-based methods. Recent monitoring advancements include the ability to map FAV species at the genus level using satellite data that has a high frequency of collection which establishes the potential to create maps intra-annually to inform management (Ade et al. 2022).

Early research on specific control methodologies included a focus on mechanical techniques (David et al. 2006). This body of work included documentation of water-quality concerns associated with shredding approaches (Greenfield et al. 2007; Rajan et al. 2008), and contrary to expectations, some of this work showed that the cuttings were alive and remained in the area for more than a month (Spencer et al. 2006). Other specific research on control methodologies has focused on chemical and biological methods for SAV and FAV, but few studies evaluate the efficacy of tools that have been in use for decades—particularly for FAV—at the full regional scale of the Delta. Without these landscape-scale analyses, it is difficult to assess how control efforts are affecting IAV populations over time, or whether there is greater efficacy in specific habitats or sub-regions of the Delta. Also, the existing literature on the Delta does not cover physical controls such as benthic mats and floating barriers, but the opportunity for investigating these tools only recently became available with their incorporation in the 2019 BO for the CDBW program. Notably, we did not find any published studies on the control methodology for *P. australis* or *A. donax* in the Delta. In the sections below, we summarize the current understanding of target and non-target chemical and biological tools; Figure 5 also depicts this understanding via conceptual model.

Herbicide Treatments: Challenges of the Tidal Environment of the Delta and the Need for New, Low-Toxicity Tools

As expected from the general literature on IAV control in tidal and flowing waters, the available literature from the Delta shows higher efficacy of herbicide treatments for FAV than for SAV. However, only two studies have specifically examined treatment outcomes for *E. crassipes*, and using herbicides only recently permitted for experimental use, to compare with the long-standing agents 2,4-D and glyphosate, and to investigate the use of blends of herbicides (Madsen and Kyser 2020; Kyser et al. 2021). In field trials within the Delta, these studies showed promise for increased efficacy of newly permitted herbicides compared to the 80% control observed for the main agents used by CDBW (2,4-D and glyphosate) and suggest that these new agents be introduced as part of a rotation of herbicides that target *E. crassipes*. Still, herbicide efficacy in the Delta across the common or newly invasive FAV species (examining *Ludwigia* spp. and *A. philoxeroides*) has not been compared.

Studies on herbicide treatments of SAV have revealed both significant barriers to maintaining required CET (particularly for fluridone, the slow-acting systemic herbicide), and limited efficacy

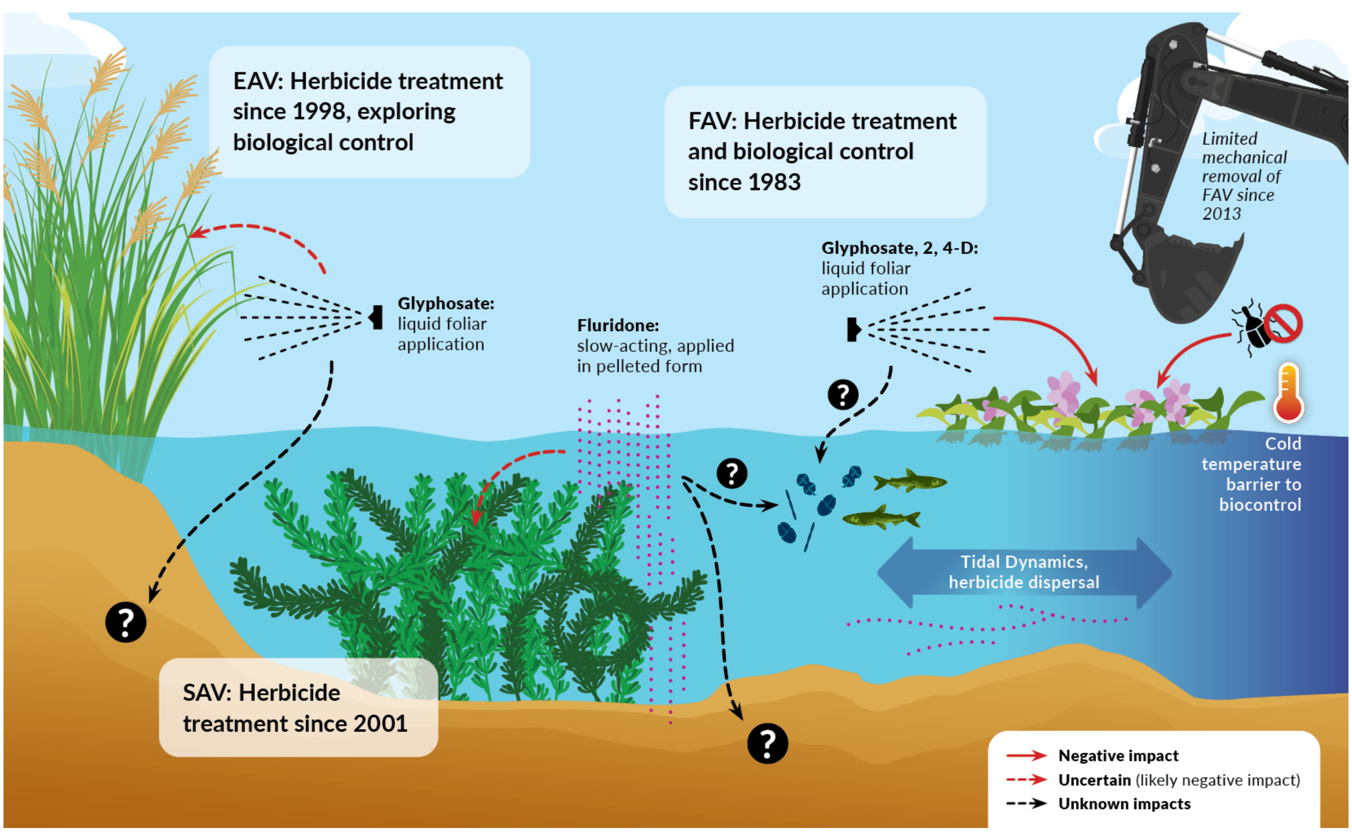

Figure 5 Conceptual model of common IAV control methodologies in the Delta and Suisun Marsh, with relative knowledge of their target and non-target effects. *Credit: Illustrated by Vincent Pascual with the California Office of State Publishing.*

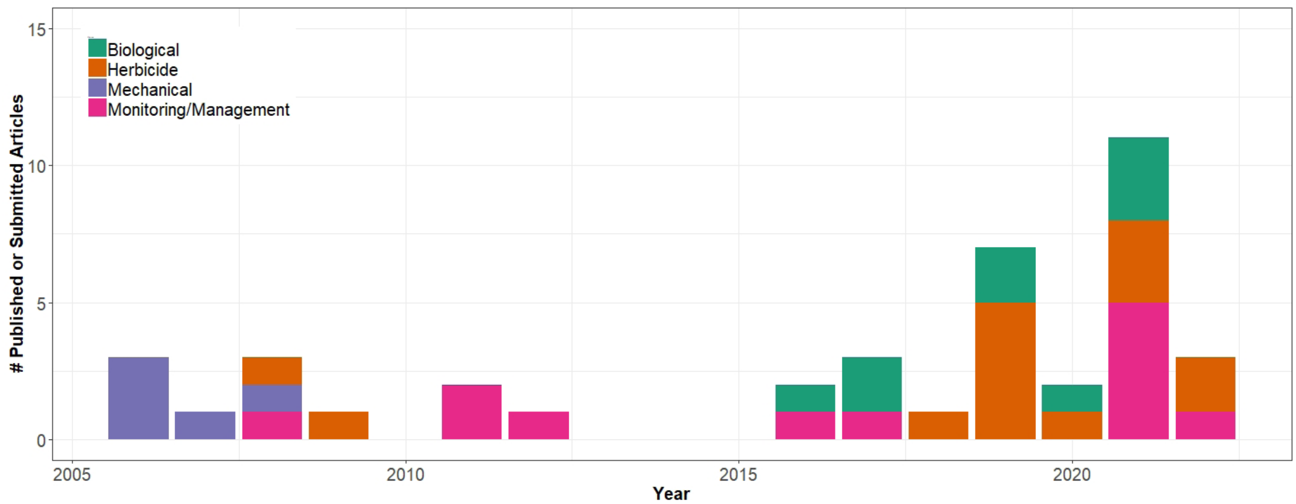

Figure 6 Number of articles that examine IAV management in the Delta and Suisun Marsh, 2005–2022, categorized by control approach. Reports from the gray literature and articles pertaining to IAV biology, ecology, and ecosystem engineering effects are not included. All articles are published in peer reviewed outlets except one article in 2022 that has been submitted for publication.

for reducing SAV coverage, but also that long-term treatment could change the composition of SAV species. Results from CDBW biovolume surveys conducted in recent years have shown that in approximately two-thirds of treated sites (n = 156, 2016–2017, 2019–2020) biovolume decreased or showed no change, and individual site changes ranged from −75% to +46% (CDBW 2016; CDBW 2017; CDBW 2019a; CDBW 2020). In contrast, nearly all diquat-treated sites (n = 29, 2019–2020) showed a decrease in biovolume, with changes ranging from −87% to +24% (CDBW 2019b; CDBW 2020). This survey approach provides valuable site-level data, but the information is not collected at consistent intervals pre- and post-treatment, and the monitoring efforts do not include untreated sites. As a result, it is not possible to decisively determine if changes at treatment sites result from treatment, or from regional changes in coverage, or from phenological changes in plant growth.

Since developing the use of hyperspectral imagery to produce regional-scale SAV coverage maps over the last 2 decades (see Hestir and Dronova, this issue), it has been possible to investigate herbicide efficacy over both seasonal and multi-year time-scales. The first of these analyses (Santos et al. 2009) showed no difference in the rate of SAV spread between treated and untreated sites after the treatment season, regardless of the herbicide used (diquat or fluridone). Fluridone, however, produced modest reductions in SAV coverage (5% on average) in sites treated for 2 consecutive years, and particularly if treatment was initiated in the spring rather than the summer (Santos et al. 2009). Recent analyses from Khanna et al. (submitted) have investigated multi-year fluridone efficacy using SAV coverage maps, treatment records, and have modeled water current speed, and suggest that fluridone's effect is lessened with increasing water-current speeds, and that consecutive years of treatment did not reduce the probability of SAV coverage. Results from these studies using landscape-scale analyses are consistent with results from the field: Rasmussen et al. (2022) observed SAV species composition and density over 18 months and two to three sets of multi-week fluridone applications, and found no change compared to untreated areas. The null result was likely from rapid dilution of fluridone over the tidal cycle, because automated water sampling included in this study showed that herbicide concentrations were negatively associated with tidal stage and were commonly below the minimum target level of 1 ppb.

Over longer periods of fluridone treatment, however, changes in species composition may occur: sites in Franks Tract, a large body of open water in the Central Delta, received fluridone treatments up to 14 times between 2001 and 2020, and one recent analysis using SAV species frequency data suggests that this focused treatment has gradually resulted in a change in SAV species composition such that *E. densa* decreased and a native pondweed, *Potamogeton richardsonii* increased in frequency (Caudill et al. 2019). The authors suggest that this change may be the result of species-specific responses to fluridone; however, they were unable to compare Franks Tract species trends to untreated areas for the same period.

Overall, as SAV coverage in the system at large continues to expand—poorly deterred by the apparently modest effect of fluridone—the need for development of effective control tools for SAV is evident. In a recent investigation of additional tools to control SAV in the Delta, application of a new herbicide (endothall) resulted in greater than 90% treatment efficacy for *M. spicatum* and *C. demersum* over a 6-week study period, but 43% efficacy for *E. densa* (Madsen Morgan, Miskella, et al. 2021). While this work is a start, the challenge of controlling SAV needs significantly more attention, including a robust cost–benefit evaluation of treatment or leaving some regions untreated so that resources can be focused in a particular area where invasive SAV is particularly undesirable.

Biological Control in the Delta: Negligible Efficacy of Current Agents and Continued Research to Improve Contributions to Control

The published literature on biological control methods includes multiple articles on potential new control agents for use in the Delta (e.g., Moran et al. 2016; Pratt, Herr et al. 2019; Reddy et al. 2020), as well as investigations into why control agents only inefficiently control water hyacinth (Hopper et al. 2017; Reddy et al. 2019; Hopper et al. 2021). Despite establishment throughout the Delta of the weevil *Neochetina bruchi*, it controls water hyacinth only negligibly (Hopper et al. 2017; Pratt et al. 2021). Field surveys and laboratory trials have shown that underperformance is largely from a mis-match in winter temperatures in the Delta and optimal temperatures for *N. bruchi* population growth (Hopper et al. 2021). Efforts by the USDA–ARS to re-introduce *N. eichhorniae*, which was originally introduced in the early 1980s along with *N. bruchi*, started with an evaluation of cold tolerance of imported populations from South America, South Africa, and Australia. This research revealed that the Australian population may better tolerate Delta water temperatures than the current Delta population (Reddy et al. 2019), and the USDA–ARS is pursuing permits for release of the Australian population in the Delta. As described above, investigations are underway for biological control of *A. donax* and *Ludwigia* spp., but there is no effective control for either of these species to date.

Non-Target Effects of SAV and FAV Control Measures

Some of the available published literature from the Delta addresses non-target effects of herbicide or mechanical control efforts; however, publications are few, so better understanding of non-target effects is needed. Non-target, direct effects of herbicides may include damage to native macrophytes and phytoplankton, and indirect effects may occur for non-plant life, such as zooplankton, fish, benthic and epibenthic macroinvertebrates, and microorganisms in the sediment. Investigations are continually needed to fully understand lethal and sublethal non-target effects, particularly as the list of herbicide products grows, and it is important that evaluations include investigations for unintended effects that occur below regulatory benchmarks (Hasenbein et al. 2017).

In the Delta, much of the research on non-target effects of herbicides has been conducted in the laboratory as a required element for permitting their use in the habitat of protected species. Findings are primarily documented in unpublished technical reports and cited within the BO (e.g., USFWS 2019). In the published literature, Jin et al. (2018) investigated sublethal effects of glyphosate, fluridone, imazamox, and penoxsulam on Delta Smelt. They observed evidence for endocrine disruption at environmentally relevant concentrations of glyphosate and fluridone. Responses to imazamox and penoxsulam showed no signal of endocrine disruption, but exposed Delta Smelt expressed inhibited brain acetylcholinesterase (AChE) activity. In a separate study on food web effects, Lam et al. (2020) conducted a laboratory study to assess the growth responses of phytoplankton taxa to fluridone, glyphosate, and imazamox. They observed that fluridone was the only herbicide to inhibit phytoplankton growth at low concentrations, specifically for the diatom species assessed (*Thalassiosira pseudonana*) when concentrations were below 10 ppb. This study also demonstrated the potential for *M. aeruginosa* to be inhibited by fluridone at the higher concentrations (30 ppb) that are most likely to occur after initial application. These findings illustrate that fluridone—one of the most widely applied herbicides in the Delta—may have detrimental effects on both beneficial (diatom) and harmful (cyanobacteria) taxa illustrate the complexity of understanding how herbicide applications affect food webs.

Few studies have used ambient Delta water to examine non-target effects of herbicides. This gap is noteworthy because of the potential for synergistic effects on non-target organisms with other, non-herbicidal constituents existing in Delta waters. One recent study attempting this approach showed that *T. pseudonana* exhibited significantly reduced cell growth in all water collected from the Delta compared to clean laboratory water, whether the source Delta waters had been treated or not, and regardless of whether or how much fluridone was added as an amendment (Rasmussen et al. 2020). The results suggested that other, non-fluridone constituents at the Delta sites inhibited *T. pseudonana* growth, and that further study on sources of toxicity in ambient water may be warranted to fully understand inhibitions to phytoplankton growth.

Because CDBW applies fluridone in a pelleted form that sinks to the bottom of the water column, an additional and largely unexplored area of non-target effects is in the sediment. Field assessments have revealed elevated sediment concentrations of fluridone and diquat compared to the water, by up to an order of magnitude (Hosea 2005), and similar results for fluridone have been observed in recent monitoring at both treated and untreated Delta sites (Rasmussen et al. 2020). These field observations are consistent with laboratory evaluations that compare fluridone and glyphosate concentrations in sediment leachate: glyphosate concentrations in sediment diminish rapidly after initial washes; fluridone concentrations remain high after consecutive washes (Pandey et al. 2019). Further study has shown that degradation of sediment-bound fluridone is faster with increasing exposure to ultra-violet light, increasing temperature (greater than 20 °C), and higher clay content in the sediment matrix (Wickham et al. 2020).

Non-target effects of glyphosate have been investigated in some field and in local mesocosm trials. These studies have only begun in recent years and are focused on food web effects. Other areas in need of exploration—including the potential for legacy effects after accumulation in the sediment—have been largely uninvestigated. One field evaluation of glyphosate effects after *E. crassipes* treatment revealed that macroinvertebrate communities were unaffected 1 month after treatment (Marineau et al. 2019). Other work using a mesocosm approach has shown that *E. crassipes* treatments result in enhanced abundance of larval mosquitos, because the decayed plant structures offer even more still-water habitat than the live plants (Portilla and Lawler 2020). Mesocosms populated with untreated *E. crassipes* or *E. densa* plants collected from the Delta and filled with locally-sourced water fostered lower abundances of mosquito larvae (*Culex* spp.) than open-water tanks (Portilla et al. 2021). This result led the authors to suggest that the common practice of treating invasive vegetation to reduce mosquito habitat should potentially be replaced by directly controlling mosquitoes in open-water habitats. Consistent with the recent mesocosm trials, field sampling by the San Joaquin Mosquito and Vector Control District has observed increased densities of larval mosquitos after late-season (post-August) FAV treatments, possibly because of the increase in

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open-water areas (Lucchesi 2018). Additional field evaluations are required to guide best practices for mosquito control using an IAV treatment.

RECOMMENDATIONS FOR ADVANCING IAV CONTROL AND ITS SUPPORTING SCIENCE IN THE DELTA AND SUISUN MARSH

Despite recent advances, leadership in policy and funding areas and additional science actions are needed to ensure proactive and adaptive management and to properly position IAV control in the Delta and Suisun Marsh. To this end, we describe below recommendations for both leadership priorities and critical science actions that together can inform a deliberate and systematic approach to IAV control (Figure 7).

Priorities for Leadership to Support IAV Adaptive Management

Recommendation 1: Set Informed Management Targets for IAV Control Programs

Existing IAV control programs in the Delta and Suisun Marsh do not have quantitative targets to reduce IAV. Without set goals in place, it is difficult to strategically plan, organize, or evaluate control programs. The Delta Stewardship Council established Delta Plan Performance Measures (DSC 2019) that include targets for acreage to be treated (5,000 acres of FAV herbicidal treatment; 2,500 acres of SAV herbicidal treatment) and coverage amounts to be reduced (50% reduction by 2030 from baselines of coverage maps produced between 2003 and 2016). However, joint goals of acreage treated and coverage reduced may not be compatible because the targets for acreage to be treated are unlikely to accomplish the goals to reduce coverage. In the years since baseline data were collected, SAV and FAV coverage has expanded—despite targets for acreage to be treated being met in most years. For *P. australis* and *A. donax* populations, there is even less monitoring than for SAV and FAV populations, making it impossible to track progress toward the target for reduced coverage.

We suggest that targets for control programs should be based on human uses and goals from commercial, recreational, environmental, and

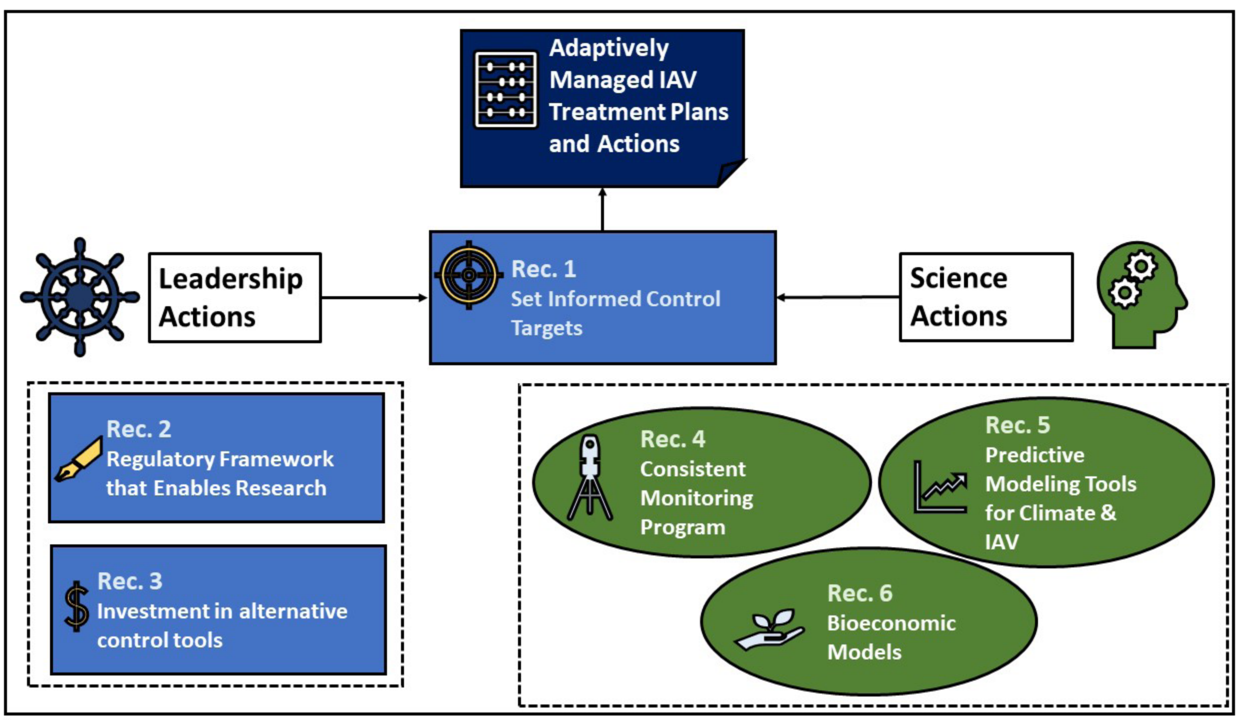

Figure 7 Conceptual diagram of recommended leadership and science actions that mutually would inform development of science-based control targets and adaptive managed IAV treatment strategies

economic standpoints—as well as an ecological basis for the ecosystem functions and species communities that must be protected. It is non-trivial to establish what tolerable coverage levels are, and these levels may not be consistent throughout the Delta and Suisun Marsh regions, or among stake-holder groups. Establishing control targets will require significant social science attention (e.g., surveys, interviews) to determine what costs of control and levels of IAV coverage are acceptable for the public, stakeholders, and government agencies, as well as leadership to synthesize the varied input that would be received during the process. This evaluation must include consideration of intended outcomes of wetland restoration initiatives, and what levels of IAV are acceptable in these habitats intended to benefit native fishes. Given the difficulty and limited success in managing IAV populations in the system, particularly for SAV, developing target levels for control must also be informed by feasibility, by the efficacy of existing control measures, and by weighing the relative benefits of continued treatment in an area with a no-treatment alternative. The question that should be considered—but to our knowledge has not been addressed at a system-wide scale—is: Are there areas that are or can be left untreated, where the costs of allowing IAV to persist are low enough that the best use of resources is to focus them elsewhere, where IAV is more problematic, and control is more feasible? As new research on control strategies continues, the feasibility of achieving targets of acreage to be controlled may change, and periodic evaluation of acceptable IAV coverage amounts would be beneficial.

Recommendation 2: Maintain a Regulatory Framework that Enables Research for Effective Methodologies to Control all IAV Growth Forms

Our review shows a lack of published studies that document the effect of efforts to control *A. donax* and *P. australis* in the Delta and Suisun Marsh. Most of the literature used as a basis for control of these species comes from other regions, some of which are very different ecologically. A major reason for this paucity of studies is that the regulatory framework does not allow for experimental work. Establishing a regulatory framework that allows research on test plots, like the DIZ concept for SAV and FAV in the CDBW 2019 BO, would enable faster attention to areas of management uncertainty, including target and non-target impacts of control measures.

The lack of coordination of EAV control efforts in the Delta and Suisun Marsh has resulted in non-existent or inconsistent assessment of EAV treatments. Enhanced coordination could advance monitoring of control outcomes and coverage of invasive EAV, and sharing results among partners could result in identifying best practices that could then be widely adopted. The current disparate approach with limited applied research is notable because synthetic reviews from other regions have shown that eradication of *P. australis* patches is rare, leading to recommendations that managers shift their goals from eradication to aggressive treatment of nascent patches, and expansion of treatment strategies to the watershed scale (Hazelton et al. 2014; Quirion et al. 2018). Any strategic approach at the full watershed scale of a region like the Delta and Suisun Marsh would require significant coordination across private and public entities, which is in stark contrast to current practices.

Research on non-target effects of existing, currently approved herbicides, as well as other control methods (e.g., mechanical removal), is also ongoing and must continue. This research is essential to informing how and where herbicides can be applied to achieve a control benefit, while also protecting human safety and minimizing ecological effects on non-targets. For glyphosate, the balance of human safety, necessary environmental protections, and the management need for invasive vegetation control has been the subject of significant controversy (Alcántara–de la Cruz et al. 2021; Hardeman v. Monsanto 2021). While glyphosate is banned in some California counties (and elsewhere worldwide), it remains one of few available tools to control invasive EAV and the most widely used tool for FAV in the Delta. Still, there remains scientific debate on glyphosate's non-target effects (Brovini et al. 2021). Likewise, an analysis is needed that compares the ecological harm and human

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safety concerns of herbicides with the harm of maintaining and allowing IAV populations to persist and spread. These evaluations, including use of bioeconomic models (discussed below) to assess the benefits and costs of herbicide applications and other control measures, are necessary to inform appropriate restrictions on herbicide use.

Recommendation 3: Enhance Investments in Researching Physical and Biological Control Approaches and Expanding Herbicidal Tools to Develop Effective Integration of Control Methods

Chemical control is the most widely used tool for managing IAV in the Delta, but it requires significant resource investment, does not consistently yield a control benefit in the case of SAV, and is subject to public controversy. It is generally accepted that integrating multiple control methodologies (chemical, mechanical, physical, and biological control) will facilitate optimization of IAV management. Opportunities for increased integration of methods need to be explored: for example, proactively targeting *E. crassipes* stem bases before the spring growing season with mechanical removal equipment could be rotated into current herbicide treatments, thereby reducing chemical usage.

Along similar lines, biological control can often provide greater benefit when combined with other methods (Tipping et al. 2014; Pitcairn 2018). Efforts to achieve successful biological control may have strong public support because they would reduce reliance on chemical agents (Jetter and Paine 2004). However, increased investment should be considered to match the growing IAV problem, with specific attention to improved climate-matching of biological control agents, development of predictive models to guide biocontrol programs of the future, and the necessary studies for permitting release of control agents (Hoddle et al. 2014). In the Delta, release of control agents that are approved for other US regions requires additional steps to ensure there is minimal risk to threatened or endangered fish. Acquiring those data should be prioritized and expedited so biological control can be deployed as early as possible in the invasion process. This is particularly important for newer invaders, such as *Alternanthera philoxeroides* (alligator weed), which was detected in 2017 and is now expanding its distribution in the Delta. Three *A. philoxeroide*s biological control agents have been approved for release and are widely distributed in the southeastern US but have still not been released in the Delta because resources have not been available to conduct the necessary experiments to permit their release. With the appropriate models and adequate resources in place to address new invasive species, it would be possible to predict the likelihood of establishment and spread of approved biological control agents for *A. philoxeroide*s in the Delta, to rapidly conduct the necessary assessments of risk to protected species, and then as appropriate, to release the agents likely to be successful in the Delta and monitor their control benefit.

Devoting this level of enhanced attention and investment will require significant financial and staff resources, possibly diverting those resources from routine treatment. Furthermore, it is necessary for research to occur at an ecosystem-scale to effectively inform management. As we describe above, and despite the long history of control programs in the region for the full Delta (particularly for FAV, Figure 4), few studies investigate the effect of control efforts at a system scale. The Delta is not unique in this way; generally, experimental work in laboratories and mesocosms or small-scale field evaluations are the most common in the scientific literature (Lake and Minteer 2018). However, these small-scale studies are not particularly applicable to determine the direction, priorities, and strategy for a regional infestation problem such as in the Delta. To meaningfully inform adaptive management of IAV control in the Delta, studies are needed that investigate treatment outcomes across multiple sites and compare them with untreated areas. Notably, some of this work is already occurring through synthesis and modeling efforts that leverage historical treatment data (Khanna et al., submitted), and some recent field research has adopted this approach to evaluate fluridone treatment of SAV (Rasmussen et al. 2022). The same approach is needed to investigate whether newer treatment methods can control IAV spread. Because of the scale of the needed shift toward research and development activities, adopting this priority may require its support by policy-makers.

Critical Science Actions to Enable Rapid Response to Changes in IAV Populations

Recommendation 4: Establish a Consistent Monitoring Program for all IAV Growth Forms

A necessary companion to targets for control programs—and essential to their adaptive management—is a consistent monitoring program. Multiple reports have recommended consistent monitoring for SAV and FAV (Boyer and Sutula 2015; Ta et al. 2017; Khanna, Conrad, et al. 2018) that uses a remote sensing approach because it is the only way to produce synoptic coverage maps. A promising approach includes use of satellite-acquired data, which is cheaper and collected more frequently than piloted aircraft (Bubenheim et al. 2021; Ade et al. 2022). Ground-level data is necessary to guide imagery classification, detect new invaders, and can provide species-level information, which is not always possible with remotely sensed data (Hestir and Dronova, this issue). Therefore, a robust monitoring program would deploy both remote-sensing techniques and field-based survey, would be conducted at consistent times on a schedule appropriate for annual IAV management plans, and would include the necessary scientific staff resources needed for data processing, evaluation, and reporting (Khanna, Conrad et al. 2018).

An additional reason to implement a monitoring program is to detect new invaders as early in the invasion process as possible. Specifically, an early detection and rapid response program (Reaser et al. 2020), is needed to be able to quickly respond when a new invasive species enters the system, and this could be part of a consistent monitoring program for the Delta and Suisun Marsh that is also needed to measure progress toward control targets. In addition to new invaders, an early detection emphasis in a monitoring program could identify new areas of spread for existing invaders so nascent populations could be rapidly addressed.

Recommendation 5: Develop Modeling Tools to Enable Prediction and Preparation for a Changing Climate and IAV Community

To equip IAV control efforts for future changes and to appropriately plan resource use, models that integrate IAV species distributions and climate forecasts are needed (Norgaard et al. 2021). For example, population-growth-rate models that integrate climate-change scenarios and associated hydrological patterns could inform long-term management strategies and guide investment. As reported recently by the International Panel on Climate Change (IPCC 2021), climate scenarios over the next 30 years will include more frequent extreme weather events including heat waves, droughts, and flooding. Estuaries will be subject to these extremes, and, in turn, increasingly vulnerable to invasion (Wetz and Yoskowitz 2013). During recent droughts in the Delta, IAV populations have expanded significantly, and the prospect of prolonged and severe droughts in the future indicates that this trend will continue, and the return of wet conditions does not guarantee a clearing of areas newly infested during drought (Flow Alteration and Management Synthesis Team 2020). Species phenology could also change because of increasing temperatures, such that peak growth seasons occur earlier in the year. Currently, many CDBW control efforts are permitted to begin on March 1, but this date may increasingly be after active growth is underway. Having an environmental trigger, such as water temperature, for the start of the control season rather than a fixed calendar date may better position control programs for having a high impact on target plants (Madsen, Morgan, Miskella 2021), though evaluation of non-target impacts of such a change would also be necessary.

Predictive models that integrate the influence of temperature on biological control efficacy can guide research on insect biotypes that are suitable for current and future conditions (Mc Kay et al. 2018; Pratt, Pitcairn et al. 2019; Harms et al. 2021). Investment in predictive models may also

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result in the identification of future IAV species likely to colonize the Delta, which would help to prioritize proactive control efforts. Predictive models could also help improve climate-matching of biological control agents to the regions where they are introduced (Mc Kay et al. 2018; Harms et al. 2021).

Recommendation 6: Develop Bioeconomic Models to Enable Evaluation of the Social-Ecological Trade-Offs Across Management Alternatives

As management challenges in the Delta evolve in response to changes in climate, water demands, protected species, and invasive species, bioeconomic models can provide tools to integrate biological, economic, and policy objectives so the consequences of different assumptions and scenarios can be examined for management (Adams and Lee 2007; Wainger et al. 2018). The cost of IAV control in the Delta is significant and growing, yet benefit-to-cost-trade-off evaluations have not been incorporated into IAV treatment plans. An economic model would estimate costs for area-wide management and would include how the presence of CDBW control may reduce costs incurred by other entities, such as private marinas (Figure 8). Costs of excluding IAV populations from control efforts would also be investigated to compare the costs of treatment with the cost of not treating and allowing IAV to persist. The biological portion of the model would represent IAV spread and incorporate

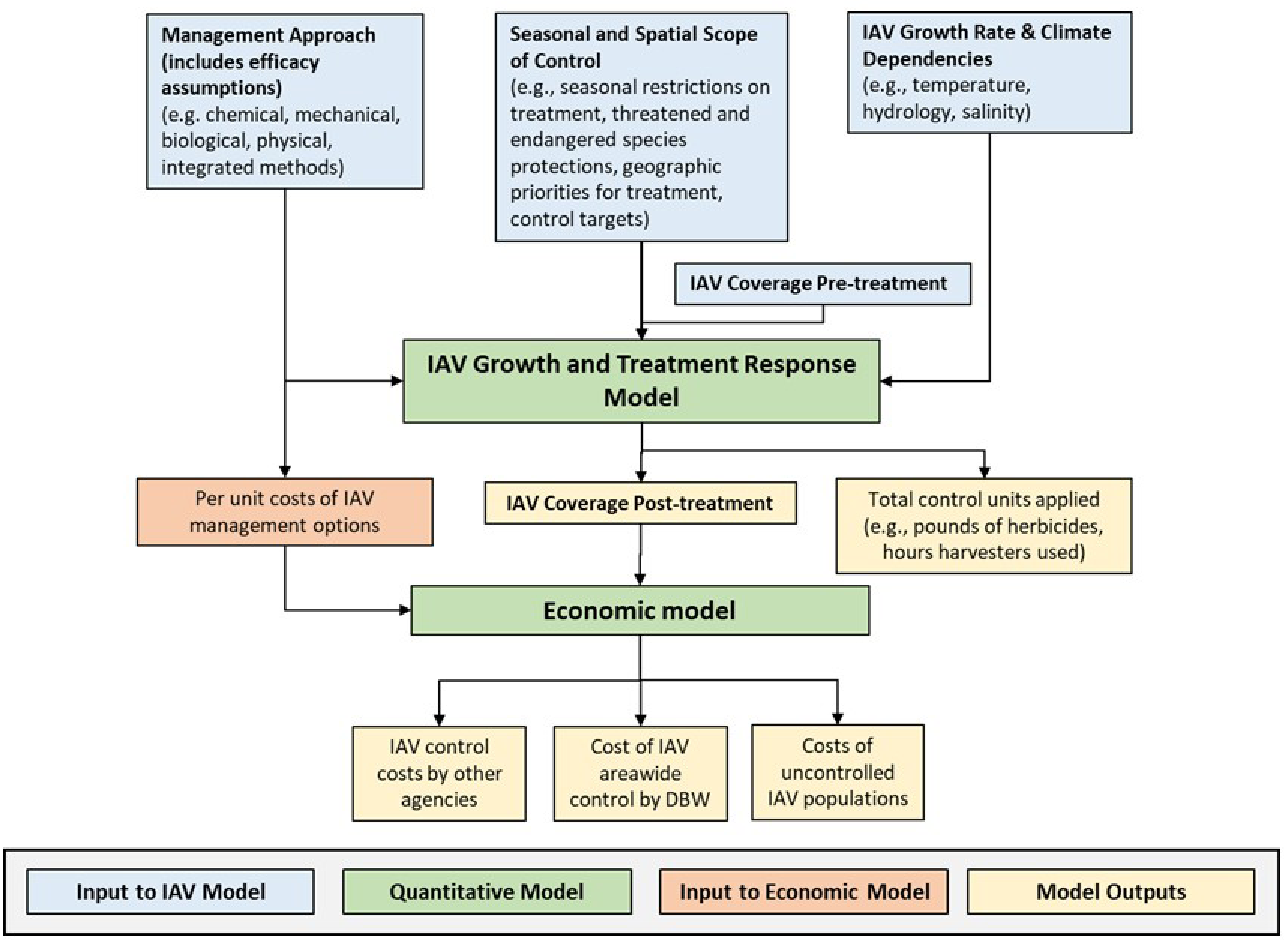

Figure 8 Conceptual diagram of a bioeconomic model that can be used to evaluate treatment outcomes and costs associated with alternative management and climate scenarios

environmental factors that control growth, such as water temperature and salinity, and could leverage existing multi-dimensional models for the system (MacWilliams et al. 2016). Inputs to the IAV growth model must also include the availability of tools and their efficacy, as well as seasonal or spatial restrictions on control efforts (Figure 8). In this way, development of useful bioeconomic models will hinge on robust evaluations of existing and emerging control methodologies (Recommendation 3, above).

In a recent example for *E. crassipes* treatment, Jetter et al. (2021) estimated the costs if all treatments began in March, compared to the current paradigm of some treatments beginning in March and some beginning in June. The authors compared cost estimates across different assumptions for *E. crassipes* growth rates and herbicide efficacy. The results showed that costs, acreage treated, and the volume of herbicides applied were significantly reduced if treatments were initiated earlier rather than later, for all plant growth and herbicide efficacy assumptions. While these results need to be weighed against the risk of additional non-target effects associated with implementing treatments earlier in the season, further development of bioeconomic tools may prove essential to quantitatively assess the best use of limited resources to control IAV.

Expansions upon the initial approach from Jetter et al. (2021) could include some of the recommendations of this review. For example, climate-change drivers could be incorporated into the model as changes in temperatures and salinity, which in turn would affect plant growth rates (Figure 8). With a climate-informed growth model, the effects on control costs could be estimated across different management scenarios or control program targets. Model outputs could also include IAV coverage that results from different management approaches. For example, a bioeconomic model could evaluate the costs of using primarily mechanical control methods early in the year and then switching to chemical controls, and compare them with the current approach of near-total reliance on chemical controls.

CONCLUSION

In summary, developing an informed, adaptive, and systematic approach to IAV control in the Delta and Suisun Marsh will require both research and monitoring activities, and significant leadership to ensure adequate capacity for innovation and enhanced coordination among managers and scientists. This review highlights major knowledge gaps in understanding: (1) the efficacy of current treatment approaches, (2) non-target effects appropriate climate-matching for candidate biological control agents, and (3) a lack of necessary modeling tools to evaluate trade-offs across alternative treatment plans. Additionally, adaptive management of IAV control is currently stymied by the lack of a consistent monitoring program. However, collaborative science for IAV control has been increasing rapidly over the last decade (Ta et al. 2017), and provides the needed platform for discussions among managers and scientists to inform adaptive management. Leveraging the recent progress in collaborative science will be essential to effectively respond to an expanding and evolving ensemble of IAV in the Delta.

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