Bioeconomic modeling of floating aquatic weeds in the Sacramento–San Joaquin River Delta

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ABSTRACT

This study develops a preliminary bioeconomic model that links an aquatic weed growth model to an economic model to evaluate the cost of alternative weed management policies in the Sacramento–San Joaquin Delta (Delta). During the past decade the costs to manage both floating and submerged invasive weeds in the Delta between 2013 and 2017 was estimated to be at least $60 million. The bulk of the costs are incurred by the California Division of Boating and Waterways (CDBW), whose areawide weed management program is a public good that influences the costs of aquatic weed management for all other public and private agencies on the Delta. One of the main aquatic weeds managed by CDBW is water hyacinth. Normally, weed control activities can begin in March in areas in the southeast portion of the Delta, and in June elsewhere. This study examines the relative costs incurred by CDBW of starting all weed control in March under three different weed growth model assumptions, and two herbicide efficacy assumptions. Costs fall by 16.4% under the slowest growth rate model and by 73% under the fastest growth rate model. Environmental concerns over the protection of native fish spawning areas may prevent the earlier adoption of herbicide control; however, the results show that investments in control methods that are both fish friendly and effective at controlling weed populations may reap substantial weed management cost savings.

Key words: costs, *Eichhornia crassipes* (Mart.) Solms, policy analysis, water hyacinth.

INTRODUCTION

The Sacramento–San Joaquin Delta (hereafter Delta) is an estuary in northern California formed by the confluence of the Sacramento River from the north and the San Joaquin River from the south. Approximately 500,000 people on 1,100 square miles call the Delta home and engage in a variety of commercial and recreational activities (Environmental Protection Agency [EPA] 2012). Agricultural crops including corn, grapes, pears, and so on are grown on the islands, protected by levees. Commercial cargo ships transport goods to and from ports in Stockton and Sacramento. People enjoy recreational boating, fishing, water skiing, and other water sports from one of the over 55 marinas that dot the rivers' edges. The Delta provides the lifeline of water to agricultural and urban users further south (Moran et al. 2020) as the source of water for California's extensive aqueduct system. In addition, California's native tule plants (*Schoenoplectus acutus* (Muhl. Ex Bigelow) A. Love & D. Love) grow there, and the Delta supports wildlife such as the endangered Delta smelt (*Hypomesus transpacificus* McAllister). All this is increasingly at risk from the threat of invasive, aquatic weeds.

The California State Parks and Recreation Division of Boating and Waterways (hereafter CDBW) is directed, authorized and funded by law to manage invasive plants that obstruct the function and use of the Delta. Currently, nine species have been approved for management activities by CDBW. Of these, five are submersed aquatic plant species: Brazilian waterweed (*Egeria densa* Planch.), curlyleaf pondweed (*Potamogeton crispus* L.), Eurasian watermilfoil (*Myriophyllum spicatum* L.), coontail (*Ceratophyllum demersum* L.), and fanwort (*Cabomba caroliniana* A. Gray). Two are mat-forming emergent plants: alligatorweed, *Alternanthera philoxeroides* (Mart.) Griseb, and Uruguay waterprimrose (*Ludwigia hexapetala* (Hook. & Arn.) Zardini, H. Y. Gu & P. H. Raven). The remaining two species are free-floating aquatic weeds: water hyacinth (*Eichhornia crassipes* (Mart.) Solms) and South American spongeplant (*Limnobium laevigatum* (Humb. & Bonpl. ex Willd.) Heine). Of the nine species mentioned above, the majority of management activities focus on either water hyacinth (floating) or Brazilian waterweed (submersed).

The effectiveness of the CDBW invasive aquatic weed management program is a public good that influences the costs to all other agencies and private enterprises in the Delta. A public good has two characteristics (Mas-Colell et al. 1995) The first is that public goods are nonexclusionary. Nonexclusionary means that people cannot be prevented from using the good or the benefits of the service. Clean air and a successful classical biological control program are two examples. No one can be excluded from breathing the air. Once a successful classical biological control agent is released, it spreads throughout the environment without regards for political boundaries or property rights, and permanently manages the insect or plant pest below economically damaging levels (Schwarzländer et al. 2018). Indeed, it is this characteristic that makes a classical biological control agent attractive for areawide management of exotic, invasive pests. The second characteristic of a public good is that use by one entity does not reduce the use

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Table 1. Cost of invasive weed control (in $1,000) by entity and in the Sacramento/San Joaquin River Delta of California for 2013–2017.

Entity	2013	2014	2015	2016	2017	Total
CA Division of Boating and Waterways	7,124	6,804	13,718	12,545	12,545	52,736
CA Department of Water Resources		821			484	1,305
Bureau of Reclamation	343	833	921	658	215	2,970
Marinas	169	576	943	310	21	2,020
Port of Stockton	51	306	168	0	0	524
Mosquito Control District–San Joaquin County	223	73	37	155	11	499
Mosquito Control District–Contra Costa	74	0	0	0	0	74
All	7,984	9,413	15,787	13,669	13,277	60,129

Source: Except for marinas information represents budgetary data provided by the organization. The information from the marinas was obtained from annual telephone and in-person surveys of marina owners and harbormasters.

by another. For example, treatment of floating and submerged aquatics in a marina does not benefit one boat owner but all boat owners. A boat moving through weed-free water does not prevent a second boat from moving through weed-free water.

Between 2014 and 2017 the total cost to manage invasive aquatic weeds, both floating and submerged, by select agencies was about $60 million (Table 1; Jetter and Moran 2019). At $52.7 million, the budgetary costs of the CDBW aquatic weed management program account for the majority of costs. However, as described above, the CDBW management program is a public good, and its objective is to keep costs low for all other agencies and users of the Delta. Other agencies with large aggregate costs from 2014 through 2017 include the U.S. Bureau of Reclamation at $2.97 million, marinas at $2.02 million, mosquito control districts at $573 thousand, and the Port of Stockton at $524 thousand (Table 1).

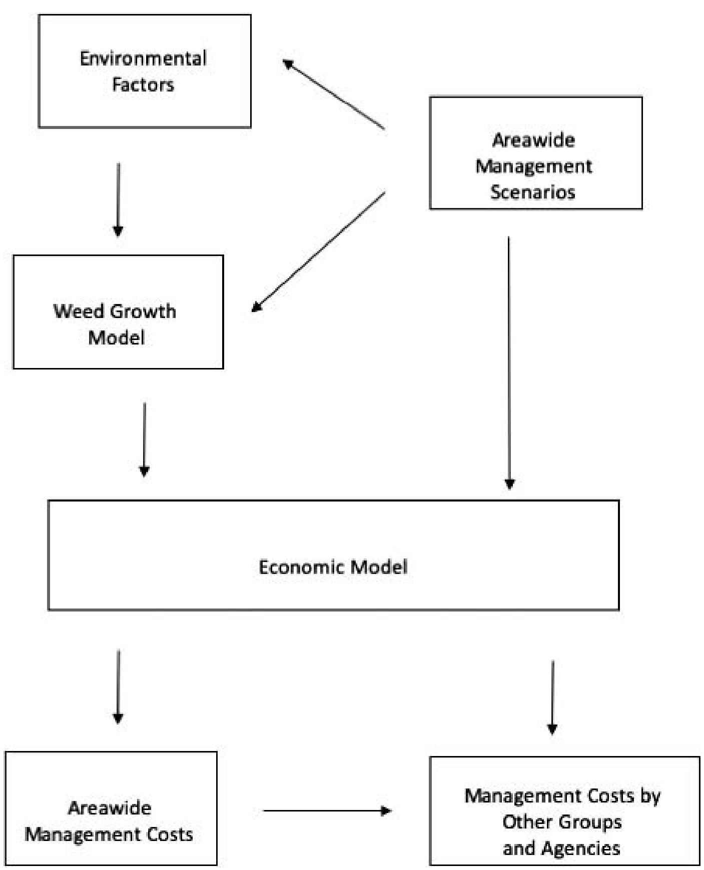

Figure 1. Linkages between components of the bioeconomic model.

Management costs for all agencies peaked in 2015, the year when the 2011–2017 drought was at its most severe in northern California. Total costs for all agencies were nearly $16 million. The majority of those costs were to treat very extensive infestations of water hyacinth (Jetter and Nes 2018). In 2015, the budget for the CDBW was doubled in order to improve capacity to manage vast infestations of water hyacinth and other invasive weeds in the Delta. By 2017 the costs for the agencies that are affected by the CDBW management programs to reduce aquatic weed infestations had fallen by 77% for the U.S. Bureau of Reclamation, 98% for marinas, 100% for the Port of Stockton, and 59% for the mosquito control districts compared to peak costs in 2015. Although total costs have fallen, the majority of expenditures have shifted from water hyacinth control to Brazilian waterweed control.

Aquatic weed management in the Delta is a heavily regulated activity. There are regulations for when control can begin and stop, what herbicides can be applied where and when, and restrictions due to endangered species, such as the valley elderberry longhorn beetle (*Desmocerus californicus dimorphus* Fisher; CDBW and U.S. Department of Agriculture Agricultural Research Service [USDA ARS] 2017; U.S. Fish and Wildlife Service [USFWS] 2019). Each of these regulations has a cost and benefit associated with it. For example, costs may change significantly depending upon when CDBW can begin treatments. In general, with all invasive weed management, the earlier the treatment can occur, the better because the spread of an invasive pest, disease or plant is typically exponential, instead of linear (Arim et al. 2006). This exponential growth will also cause management costs to increase exponentially.

One way to compare the costs and benefits of alternative regulatory policies is with a bioeconomic model. A bioeconomic model links weed management policy alternatives to a model of weed growth and spread, and then to an economic model (Figure 1). The management alternatives may govern what herbicides can be applied and when they can be applied; restrictions due to environmental factors; or different budget constraints that define treatment capacity. For the Delta, the cost equations would include costs by

CDBW for areawide management, and local costs to other agencies as applicable. Because control by the CDBW is a public good, management by CDBW influences the costs incurred by other agencies.

A complete bioeconomic model would incorporate weed management policy alternatives; changes in weed populations because of spread between sites and in situ growth over time; areawide management by public agencies such as CDBW; and economic costs with respect to control costs and damages to local business, agencies, or environment depending on the level of control achieved by the areawide management. Developing the entire bioeconomic model was beyond the scope of the current project. This study reports the results of the phase 1 development of the modeling process. This model links weed management policy, and in situ changes in weed populations to the economic costs of areawide management.

MATERIALS AND METHODS

The current bioeconomic model focuses on the management of the primary floating aquatic weed, water hyacinth. It proposes a change in weed management policy, and analyzes the relative costs under each option. Water hyacinth is an invasive free-floating aquatic weed introduced from South and Central America, and has been described as "the world's worst aquatic weed" (Holm et al. 1977). Water hyacinth forms rosettes from a central stem base, with leaves radiating around the stem base. New plants are formed predominantly by apical bud formation on the end of a stolon (Penfound and Earle 1948). Stolons and leaves have air-holding aerenchyma, which provides buoyancy. Apical buds are formed prolifically at the early stages of colonization to increase mat density, and decline as the growth of individual rosettes increases (Madsen 1993). Biomass formed in a single season can be as much as 2,500 g dry weight m^{-2} (Center and Spencer 1981, Madsen 1993).

Water hyacinth was first introduced to the United States as part of the 1884 New Orleans Cotton Exposition, and was under intensive management in waterways in Louisiana and Florida by 1899 (Penfound and Earle 1948, Holm et al. 1969). Its current distribution includes North, Central and South America, Africa, Europe, Asia, Australia, and New Zealand, and it forms nuisance growths throughout much of its range (Kriticos and Brunel 2016). It was first observed in California in 1904, and has spread throughout the San Joaquin and Sacramento River drainages and elsewhere in California (Bock 1968). In the Delta, it begins its growing season in March or April and continues through the winter until the first freezing event, typically in December or January (Spencer and Ksander 2005). Dense growths of water hyacinth cause numerous economic and ecological impacts, including obstructing waterways and navigation, decreasing water quality and dissolved oxygen, and adversely affecting native plant and animal communities (Holm et al. 1969, Mullin et al. 2000, Villamagna and Murphy 2010, Getsinger et al. 2014, Madsen et al. 2020).

Weed management policy proposal

Under current regulations CDBW may only treat weed infestations with herbicides in the Delta during certain times of the year (Figure 2). In the crosshatch area (zone 2) CDBW is able to treat from March 1 through November 30. In the diagonal lined area (zone 1) CDBW is able to start treatments only at the beginning of June. Because CDBW may only begin to treat weeds in June, infestations present before June 1 are able to continue to grow and spread, thereby increasing both the costs and resources needed to manage the infestation.

The greater restrictions in zone 1 are because of protections for native fish that are spawning, or migrating upstream to spawn, during the winter and early spring (CDBW 2017). During this time, as a precautionary measure to protect juvenile fish, the spraying of herbicides is barred. This analysis will compare the costs to treat weed infestations under the current March and June start date protocols to a protocol where all sites can begin treatments in March. The results will be discussed within the context of fish protection concerns.

In situ weed population dynamics

Label directions for the application of herbicides are based on acreages. Weed acreage at site j at time t will depend on the amount of acreage at the start of the growing season, how quickly the weed grows at that site, how large an infestation is when a treatment is triggered, and how well a particular herbicide reduces a weed population.

Starting weed values. The starting weed patch size, in acres, was estimated from two sources. The first was satellite imagery using NASA's Harmonized Landsat Sentinel-2 (HLS) satellite data (Claverie et al. 2018). HLS data provide a satellite image at 10 m per pixel. For patch sizes of 50 m^2, the patch registers as infested with floating aquatic vegetation (FAV) if more than 50% of the pixels within the patch have FAV. Total infested acreage is then estimated by adding up the number of infested patches in each site.

Images were obtained for each of the sites managed by CDBW for March and June from 2016 through 2019. A total of 277 sites were included in the analysis. The number of images per year was determined by the number of times the satellites can obtain a cloud-free image. The number of times images were taken in March varied from one in 2016 to four in 2019. For images taken in June the number varied from two in 2016 to five in 2018. Variations in March are attributable to rain. Variations in June are attributable to coastal fog. The starting values for each time period in the analysis were estimated as the average acreage from 2016 to 2019 for each site by month.

The second source of information used to estimate starting values by site was the daily log data maintained by the CDBW (CDBW 2015, 2016, 2017, 2018). These data record information for every herbicide treatment in the Delta. Information includes, but is not limited to, site treated, start time, end time, acreage treated, type of herbicide applied, amount of herbicide applied, type of

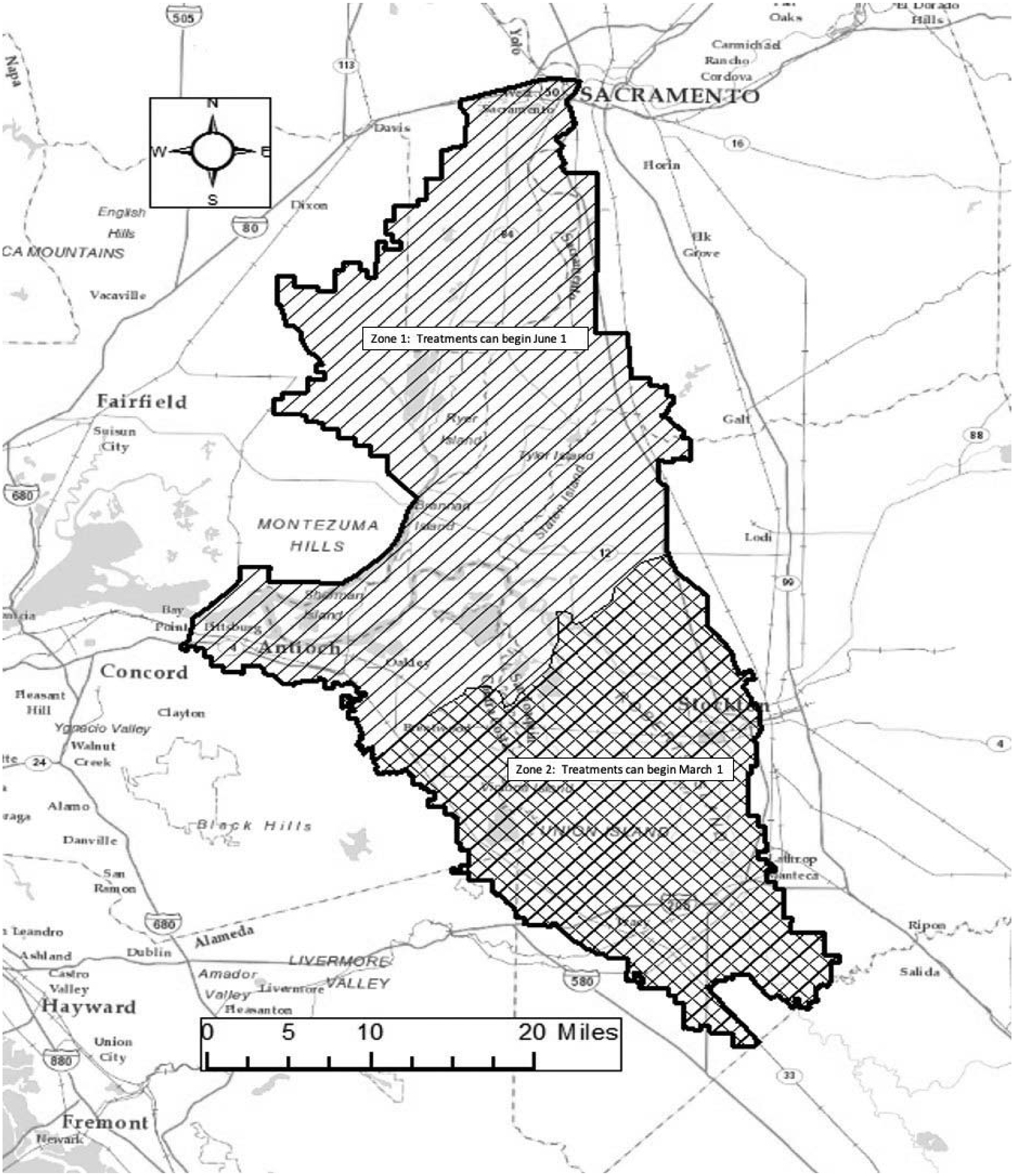

Figure 2. Sacramento/San Joaquin River Delta map of treatment zones used by the California Division of Boating and Waterways. Treatments may only begin June 1 in the diagonal lined treatment zone and March 1 in the crosshatch treatment zone.

any surfactants applied, and the amount of any surfactants applied. Data from 2014 to 2017 (the latest data available at the time of analysis) were copied in from the annual report and analyzed to determine if the site had been treated at any time from 2014 through 2017. Any site that was not treated was recorded as a zero for the start value. This effectively means that that site will never have a weed treatment. All remaining sites had a start value equal to the average acreage size for the beginning of March or the beginning of June as appropriate from the satellite data.

Weed growth. The Delta is made up of rivers, sloughs, islands, and levees. This creates a heterogeneous environment in which determining growth rates areawide can be challenging. Three models were estimated that vary depending on the type of data collected and experiment completed. Collectively these three models provide a range of values that can be used to simulate different representative growth rates.

The first growth rate used in the model was generated from field studies. Three sites were surveyed monthly from May 2015 through December 2017. More details on these field studies are available in this issue (Madsen et al. 2021, this issue). A relative growth rate was calculated using the equation

$$\mathrm{RGR} = (\ln W_2 - \ln W_1)/(t_2 - t_1), \qquad [1]$$

where W_2 is biomass at time 2, W_1 is biomass at time 1, t_2 is the days after start at time 2, and t_1 is the number of days after start at time 1 (Radford 1967). The estimated RGR was 0.008.

The second estimate of RGR was taken from the literature on water hyacinth growth rates in the Delta (Spencer et al. 2006). In a study comparing RGR due to the control of water hyacinth through mowing, the estimated RGR for seven experiments for the control group varied between –0.002 and 0.064. The average value was about 0.03, and this value was used in the simulations for the middle range RGR.

Finally, growth rates for this model were generated from greenhouse studies in which water hyacinth was grown under temperature-controlled conditions at 15, 20, 25, and 30 C for 6 wk, with harvests taken at 1-wk intervals (Madsen and Morgan 2020, this issue). The study was repeated, and each temperature was replicated in four tanks per repetition. More details of the methods and results can be found elsewhere (Madsen and Morgan 2021, this issue).

A simple linear equation was used to develop the growth rate function of RGR versus water temperature, which resulted in the equation

$$\mathrm{RGR} = 0.0118 + 0.00331 * \text{Water Temperature} \qquad [2]$$

where RGR is the relative growth rate and T is the water temperature (Madsen 2018, Madsen and Morgan 2020, this issue). Although greenhouse growth results might tend to overestimate growth rate in situ, the resulting growth rates and calculated doubling times (7–10 d) are consistent with results reported elsewhere for plants grown in situ (Sale et al. 1985, Wilson et al. 2005).

Once the relative growth rates where determined, weed acreage at site j at time t was estimated as

$$dP_j/dt = r * P_{jt} - 1 * \Big(1 - (P_{jt} - 1/K_j)\Big), \qquad [3]$$

where P_j is the size of the infestation measured in acres at site j in time t, r is the relative growth rate, and K is the maximum site size measured in acres as provided by CDBW.

Determining when to treat. Normally many factors are used to determine when to treat an infestation. These may include knowing where there are infestations, favorable climatic conditions, infestations of a certain size, and so on. However, for modeling purposes a criteria needs to be defined that will trigger a treatment. The criteria may be a specific size, or it can be a ratio of infestation size to total site size. The CDBW daily log data were used to determine whether the size of the infestation or ratio of infestation size to site size should be used to trigger a treatment, and what that value should be.

Data on the size of the treated acreage were taken from the CDBW daily log data. Data on site size were provided by the CDBW. The data were separated into quintiles and the average treatment size and ratio of infested acreage treated to site acreage calculated in order to determine if any trends based on site size were evident. Between 2014 and 2017 average aquatic weed treated acreage was about 4.7 acres. An infestation of 4.7 acres is about 4.2%, on average, of total site size. When broken down by quintiles little variation is seen in acreage treated. Average acres treated varies between 4.2 and 4.9. However, there is a significant variation in the treatment ratios. The ratio of treated acreage to total site acreage varies from 7.6% for the bottom quintile to 0.7% for the top quintile. For the current bioeconomic model a treatment is triggered when the size of the infestation is at or passes five acres.

Herbicide efficacy. Once a treatment is triggered, the efficacy of the treatment determines the new start value for the next growth/treatment cycle. Herbicide efficacy was estimated from field plot trials. Although 16 herbicide active ingredients are labeled for use in aquatic systems in the United States by the U.S. EPA, only 10 have been recommended for control of water hyacinth by their registrants (Aquatic Ecosystem Restoration Foundation [AERF] 2017). Of these 10, only 4 active ingredients have been approved by the USFWS and National Marine Fisheries Service for use in the Delta under CBDW's Biological Opinion: 2,4-D, glyphosate, imazamox, and penoxsulam (CDBW and USDA ARS 2017). In addition, foliar treatments with these herbicides requires the use of an aquatic-approved surfactant.

The herbicide 2,4-D has been widely used in managing water hyacinth throughout the United States because of its effectiveness and low cost (Madsen 2000). 2,4-D is a synthetic auxin, mimicking the action of indol acetic acid (IAA) and causing uncontrolled growth. Prior to 2010, 2,4-D was used proportionately more than glyphosate to control water hyacinth in the Delta, but after that date glyphosate was more commonly used (Madsen and Kyser 2020).

Glyphosate was first developed as an agricultural herbicide in 1974, and has become the single most used herbicide in the world (Woodburn 2000, Duke and Powles 2008).

Table 2. Herbicide active ingredient, rate in English units and in SI units, biomass of water hyacinth at 8 wk after treatment, and percent control calculated as percent reduction in biomass. Superscript number next to active ingredients refers to the Sources of Materials information. Results derived from Madsen and Kyser (2020).

Herbicide	Rate (oz. formulation $acre^{-1}$)	Rate (g a.i. ha^{-1})	Biomass (g dry weight m^{-2})	% Control
Untreated			2,021	0.00
2,4-D[1]	64	2,116	1,051	48
2,4-D[1]	32	1,058	358	82
Glyphosate[2]	96	4,511	676	67
Glyphosate[2]	48	2,256	256	87
Imazamox[3]	48	418	391	81
Imazamox[3]	24	209	144	93
Penoxsulam[4]	5	87	106	95
Penoxsulam[4]	3	52	114	94

Glyphosate is an EPSPS inhibitor, which disrupts the shikimic acid synthesis pathway and prevents the production of three amino acids: phenylalanine, tryptophan, and tyrosine. Glyphosate was registered for aquatic use in 1977, and was widely adopted for use in aquatic systems because it is perceived to be safe for the environment and is relatively inexpensive cost (Netherland 2014).

Imazamox is an acetolactate synthase (ALS) inhibitor in the imidazolinone family that was initially labeled for rice production and use with genetically modified resistant crops (Shaner 2014). It was labeled for aquatic use in 2008, and has seen moderate use for control of water hyacinth and several emergent species (Netherland 2014). Penoxsulam is another ALS inhibitor that was initially released for use in rice production (Shaner 2014). It was labeled for aquatic use in 2007 for use on hydrilla and other submersed weeds, though it has a fairly broad range of susceptibility (Netherland 2014). Both of these ALS inhibitors were labeled through the US EPA conventional Reduced Risk Pesticide program (Fishel 2016).

Estimates of the efficacy of these four herbicides are based on field trials completed in the summer and fall of 2016 (Madsen and Kyser 2020). Forty experimental plots were constructed of 5-cm diameter (2-in.) PVC with each being plot being 1 m^2 (10.9 ft^2). Plots were "planted" with small rosettes of water hyacinth to 50% cover, and allowed to grow for 2 wk before treatment. Plots were then treated with 50 and 100% rates of the maximum allowed concentration of 2,4-D,[1] glyphosate,[2] imazamox,[3] and penoxsulam.[4] All treatments also included a nonionic surfactant[5] at 0.25% v/v. Water hyacinth was subsampled 8 wk after treatment from each plot. The efficacy of control from this experiment indicated 90 to 95% control from all four herbicides (Table 2). In the model only glyphosate was used, as it the most common herbicide used by CDBW in managing waterhyacinth and other floating aquatic weeds. It is the standard to which the other herbicides are compared.

Incorporating herbicide efficacy into Equation 4 results in

$$dP_j/dt = r * P_{jt} - 1 * \left(1 - (P_{jt} - 1/K_j)\right) - \varepsilon * A_{jt-1}, \quad [4]$$

where ε is the herbicide efficacy rate and A_{jt} is the amount of acreage treated at site j in time t.

Economic costs. For the current bioeconomic model only the variable labor and material costs are included in the analysis. Total variable costs for areawide treatments by the CDBW were calculated as

$$\mathrm{TVC} = \sum_{j=1}^{J} \sum_{t=1}^{365} (w_h h + w_s s) * A_{jt} + w_l * \widehat{L_{jt}}, \quad [5]$$

where w is the per-unit cost of herbicides, surfactants, or labor, h is the application rate of the herbicide glyphosate per acre, s is the application rate of the surfactant per acre, and A_{jt} is the amount of acreage treated at site j at time t, L is the labor hours per treatment based on the estimated minutes on water it takes to treat an infestation. The model is run daily for 1 yr.

The price of herbicides and surfactants were taken from supplier costs in the area. The price of glyphosate is \$0.20 per ounce and the price of Agridex is \$0.125 per ounce. The amount of acreage treated was equal to the actual weed infestation size from the growth model on the day it passed 5 acres. The labor rate was set at \$15 an hour. The amount of labor used depends on the amount of time on water needed to treat the infestation.

Estimating time on water. A fixed-effects regression model was developed in StataSE (version 16) to estimate how long it would take treat an infestation of a specific size. A fixed-effects regression model assumes that there are unobserved variables that will lead to biased coefficients. It uses techniques that result in unbiased estimates because of the fixed effects of the unobserved variables on the dependent variable. One drawback to this technique is that it excludes independent dummy variables (Bell et al. 2019).

The dependent variable, minutes to treat an infestation, was calculated from the start and end times in the 2014–2017 CDBW daily log data. Information on date of treatment, acres treated, number of boats, and type of herbicide used were also obtained from the CDBW daily log data. Additional variables were included to control for specific time periods such as summer (June–August) and fall (September–November). Because California was in a severe drought in 2014 and 2015, a dummy variable was also used to denote that time period. Finally, site size varies across the Delta so a variable that examines the ratio of acres treated to total site acreage was included.

The final model to estimate time on water is

$$\begin{aligned} \mathrm{TM}_{jt} = {} & 123.5 + 38.31 * A_{tj} - 0.833 * A_{tj}^2 \\ & - 39.34 * \text{glyphosate} - 10.62 * \text{number of boats} \\ & - 13.32 * \text{summer} - 19.88 * \text{fall} \\ & + 13.04 * \text{drought year} - 160.4 * A_{tj}/K_j, \end{aligned} \quad [6]$$

where TM_{jt} is total minutes to treat site j in time t. All variables were significant at $\alpha = 5\%$. Labor hours were then estimated as total minutes divided by 60. The complete bioeconomic model linking the management scenarios to the growth model and finally to the economic model was programmed using Python on a Macbook.

Table 3. Total cost, acres treated, hours on water, and herbicide applied under each scenario.

Scenario	Start Time	Herbicide Efficacy Rate (%)	Total (in 1000s) Cost ($)	Acres Treated	Hours on Water	Herbicides (in gallons)
RGR = 0.008						
1	March and June	90	67	1.23	0.71	1.15
2	All March	90	56	0.69	0.65	0.9
3	March and June	95	61	1.13	0.63	1.06
4	All March	95	51	0.88	0.59	0.83
RGR = 0.03						
5	March and June	90	350	6.73	3.41	6.3
6	All March	90	220	3.5	2.65	3.29
7	March and June	95	310	6.14	3.02	5.75
8	All March	95	180	3	2.24	2.81
RGR = (0.0118 + 0.00331 * Water Temperature)						
9	March and June	90	2,300	48	20	45
10	All March	90	630	9.9	8	9
11	March and June	95	2,200	47	18	44
12	All March	95	570	9	7	8

RESULTS AND DISCUSSION

A total of 12 simulations were run using the 3 growth equations, 2 weed management policy choices, and 2 herbicide efficacy rates (Table 3).

The change in costs due to changes in timing

For the simulation with the lowest RGR of 0.008, the change in total variable costs incurred by the CDBW to treat water hyacinth infestations decreased by 16.4% when the timing to start treatments shifts from the current March/June start dates to all sites being treated in March, and herbicide efficacy was at either 90 or 95%. In absolute terms the estimated costs declined by about $9,000 from $67,000 to $56,000 with an herbicide efficacy of 90%, and by about $10,000 from $61,000 to $51,000 with a herbicide efficacy of 95%.

As the estimated RGR for water hyacinth increased to 0.03, the change in relative costs also increased, as both a percentage and in absolute terms. For example, with a 90% herbicide efficacy rate costs decreased by 37%, or by $130,000. When the RGR was a function of the water temperature, costs fell by 73%, or by $1.67 million dollars.

The main drop in costs was due to a decrease in the amount of acreage being treated (Table 3). Acreage falls by about 22% when the RGR was 0.008, between 48 and 51% when the RGR was 0.03, and between 79 and 81% when the RGR was a function of the water temperature.

Because time spent on water was a nonlinear function of acreage treated, the percentage decrease in hours on water was less than the decrease in acreage treated when the timing of the start of treatments was at the beginning of March for all sites. For a RGR of 0.03 and herbicide efficacy of 90%, acreage declines by 48% when timing moves from the March/June scenario to the all March scenario, while labor hours decline by only 22%. At a herbicide efficacy of 95% acreage decline is 51%, labor hours decline by 26% when treatment timing shifts from the March/June scenario to the all-March scenario. Finally, because herbicides are applied proportionately to the amount of acreage treated, the percentage fall in herbicides was similar to the percentage fall in acreage treated across both herbicide efficacy scenarios (Table 3).

Herbicide efficacy/growth rates

As herbicide efficacy increased, weed management costs decreased. For example, when the RGR was 0.03, total weed treatment costs declined by about $40,000 when herbicide efficacy increased from 90 to 95% under both timing scenarios. As stated previously, invasive pests spread exponentially. The smaller the initial size of an infestation, the lower the initial growth from that infestation will be. Thus, herbicides that achieve a better control of an infestation and reduce it to its smallest size after treatment will result in slower growth than herbicides that leave larger masses behind.

Fish populations and implications

There are significant benefits to treating weed infestations earlier rather than later; however, the effects on juvenile fish populations and endangered species is unclear at this time. Although the herbicides in use have been determined to have a low risk of damage to fish wildlife (CDBW 2017) a conservative approach to protecting fish wildlife has been adopted that limits herbicide applications when juvenile fish populations are likely to be most vulnerable. It is unlikely that environmental concerns will be relaxed in the near future, and indeed many people have a stated willingness to pay more for the protection of marine endangered species (Lew 2015) but if RGRs are typically closer to the 0.03 or the rates that depend on water temperature (and as noted above the literature indicates that the RGR for water hyacinth is typically much higher than 0.008) it is worth examining the feasibility of nonchemical alternatives, such as biological control methods. A successful classical biological control program should cause the demand for chemical herbicides to fall as the biocontrol agent would reduce weed populations without a potential negative impact on endangered fish populations.

Future model expansion and implications for policy

The model presented here is a basic bioeconomic model. It lays the foundation upon which additional components will be added as they are developed. The key components to add include additional economic values and impacts, weed spread, and additional environmental factors on weed growth.

Economic values

The current economic model just includes the variable labor and material costs to treat weed infestations. Additional costs, including water testing pretreatment, fuel, repairs, and depreciation, need to be added. These will all increase costs. Incorporating the agencies and users who control water hyacinth locally will also increase the costs. The net impact on the cost savings though treating weed infestations earlier is also likely to be larger because of the exponential growth in weeds, and therefore weed management costs, over time.

Spread

The current bioeconomic model estimates weed populations based on in situ growth of weeds only. A population exists at a site and grows without consideration of weeds floating in or weeds floating out. Although one interpretation of a RGR of 0.008 may be that it is a net rate observed after weed spread, that cannot be confirmed at this time. Incorporating how weeds are transported in the Delta will provide better estimates of all impacts of weed control based on timing. The net effect of incorporating spread into the model is ambiguous, however. It could either cause higher costs, and a higher benefit to changing the timing of treatments, or lower costs and a lower benefit. For example, parts of the Delta with strong river currents may have lower costs, as the current may simply wash the water hyacinth out to sea where it cannot survive in the salty water. Other parts of the Delta, such as coves, slow-moving water, dead-end sloughs and marinas, may have higher costs, as weeds are washed into those areas and contribute to larger weed acreage, and management costs, over time.

Environmental factors

Environmental factors may also play a pivotal role in the effective management of invasive weeds in the Delta. Both of the major rivers that enter the Delta, the Sacramento to the north and the San Joaquin to the south, transport nutrients from agricultural runoff into the Delta (Schlegel and Domagalski 2015; Wang et al. 2019). Seasonal fluctuations in this runoff may lead to significant seasonal variation in growth rates throughout the Delta.

Water in the Delta ebbs and flows from changes in river flows because of rain and dam releases, and the tides. Rain and dam releases increase the flow rate of rivers, and incoming tides can even reverse the current in certain areas at certain times of the year, influencing management decisions. For example, rivers can transport weeds out to sea, but calm, dead-end sloughs can provide ideal environmental conditions for weed growth.

Variations in river depths may also affect weed growth rates, and costs. Deep areas with colder water can have slower rates, and shallower areas with water closer to the surface have faster rates. Incorporating real-time temperature measurements into predicting when plant management should begin, and predicting the response time of the plants to management based on water temperature are important considerations in future modeling efforts.

The Sacramento–San Joaquin Delta is vast and vastly heterogeneous. A bioeconomic model needs to include all of that heterogeneity. However, even with the basic model that has been developed to date, it is still possible to gain significant insights on the scope of potential changes in weed management approaches. This will better inform decision making regarding regulatory restrictions on treatment and may lead to improved integrated adaptive aquatic weed management. An additional benefit of this basic model is that it can also be easily adapted to other regions by simply changing the weed growth and economic parameters to reflect local conditions.

SOURCES OF MATERIALS

[1]2,4-D. NuFarm Weedar 64 Broadleaf Herbicide, Nufarm, Inc., St. Joseph, MO.

[2]Glyphosate. RoundUp Custom, Monsanto Company, St. Louis, MO.

[3]Imazamox. Clearcast Herbicide, SePRO Corporation, Carmel, IN.

[4]Penoxsulam. Galleon SC Herbicide, SePRO Corporation, Carmel, IN.

[5]Agri-Dex, Helena Chemical Company, Collierville, TN.

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