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Estimating the Value of Invasive Aquatic Plant Control: A Bioeconomic Analysis of 13 Public Lakes in Florida

Damian C. Adams and Donna J. Lee

We present a bioeconomic model of three invasive aquatic plants (hydrilla, water hyacinth, and water lettuce) in 13 large Florida lakes, and simulate one-year and steady-state impacts of three control scenarios. We estimate that the steady-state annual net benefit of invasive plant control is $59.95 million. A one-year increase in control yields steady-state gains of $6.55 million per year, and a one-year lapse causes steady-state annual losses of $18.71 million. This model shows that increased control of hydrilla, water hyacinth, and water lettuce is optimal.

Key Words: aquatic plants, bioeconomics, invasive species, lakes, maintenance control

JEL Classifications: Q57, Q26, Q28, Q51, Q25

Florida's vast tropical and subtropical areas are major attractions to visitors and residents alike, but they have also become home to 124 category I or II "invasive species" that have displaced native species and are destructive to Florida's ecosystems (Florida Exotic Pest Plant Council). In 2001, about 1.5 million acres of Florida's state lands were infested with invasive plants (Florida Department of Environmental Protection [FDEP]b).

The primary invasive species problem in Florida is invasive aquatic plants, which pollute 96% of Florida's public lakes and rivers. During summer months, they can cover aquatic areas, drive fish away, limit access by water users, and negatively impact camping, hiking, birding, and other nature-based activities. Florida has over 1.27 million acres of lakes and rivers, 7,700 lakes and ponds, and 1,400 rivers and streams (FDEPa). Recreation on these waters is extremely valuable to the state. In 2001, anglers spent over 48.41 million days fishing, worth over $7.8 billion in year 2003 dollars (United States Fish and Wildlife Service). Without adequate and consistent control efforts, the negative economic impacts of these plants may be substantial.

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Invasive aquatic plant control is becoming a high priority for the protection of Florida's natural systems (Schardt). Public funding to control invasive plants in natural areas is $32 million per year, of which $25.7 million is designated for freshwater invasive plants (FDEPa). State resource managers are under constant pressure to justify these expenditures, which is difficult given the lack of economic studies of invasive aquatic plants (Schardt). Florida policy makers seem primarily concerned about recreation impacts; yet, only a handful of studies have examined this dimension of invasive species (e.g., Bell et al.; Colle et al.; Milon and Welsh; Milon, Yingling, and Reynolds; Newroth and Maxnuk). These studies used state preference surveys to elicit anglers' willingness to pay to reduce invasive aquatic plant coverage. No previous study has examined the impacts of invasive aquatic plant control over broad geographic regions.

This paper contributes to the literature on recreation-based economic impacts and control costs of invasive species by examining three invasive aquatic plants in Florida (hydrilla, water hyacinth, and water lettuce) in 13 public lakes. We estimated an empirical bioeconomic model of the lakes using observations on plant coverage, control costs, fishing activity, and lake characteristics, and then simulated the impacts of three control strategies over both the short-term (one year) and the long-term (steady-state conditions).

Invasive Aquatic Plants: Background

There are 11 invasive aquatic plant species in Florida waters, but very few are actively controlled (Schardt). The state's top control priorities are *Hydrilla verticillata* (hydrilla), *Eichhornia crassipes* (water hyacinth), and *Pistia stratiotes* (water lettuce) due to their high propagation and growth rates and their interference with water use. Resource managers have actively managed these plants for decades, yet they persist as serious problems for the state. In 2002, 175 of Florida's 454 public lakes and rivers were infested with hydrilla, water hyacinth, and/or water lettuce (FDEPb). One third of these had more than 10 acres of hydrilla, and 71 had over 10 acres of floating plants (37 with water hyacinth, and 34 with water lettuce) (FDEPb).

The recreation-based impacts of invasive aquatic plants can be significant. They displace native plants, alter habitat, and disrupt ecosystem processes (Haller and Sutton). In the summer months, they can grow into dense monoculture mats where over half of the biomass is in the upper 0.5 m of the water column (Haller and Sutton). Dense mats contribute to reduced fish populations, and when large mats decompose, block oxygen exchange, or have high respiration rates during summer months, the reduced dissolved oxygen levels cause fish mortality (Bowes, Holaday, and Haller). They also hinder boating, swimming, and fishing activities in lakes and rivers and reduce the aesthetic value of natural areas (Colle et al.; Milon and Joyce). Reduced sport-fish populations coupled with access problems significantly reduce fishing activities (Colle et al.; Milon and Joyce; Milon and Welsh). For example, Colle et al. reported a nearly 85% decrease in angler activity on Orange Lake, Florida, when hydrilla coverage increased from near 0% to 95% of the lake's open-water region. Over time, populations of several recreationally important fish species became skewed to young individuals (Colle et al.; Tate et al.).

Efforts to eradicate these plants from broad geographic regions have been unsuccessful. Hydrilla can produce millions of underground tubers that generate new plants each year (Haller, Miller, and Garrard; Spencer et al.). Likewise, water hyacinth and water lettuce are extremely prolific and are easily transported to other waters. Florida Statute 369.22(3) mandates the Bureau of Invasive Plant Management to achieve "maintenance control" (defined as keeping the invasive plant population at the lowest feasible levels for the foreseeable future) rather than attempt eradication for established populations. Currently, the preferred method of controlling invasive aquatic plants is the use of herbicides to achieve maintenance control (FDEPa). Inadequate funding has been the biggest barrier to sustaining maintenance control of these plants (Langeland). Funding lapses have allowed the plants to quickly colonize new areas and persist for years from accumulated seed banks. In 2001–2002, total spending on hydrilla and floating invasive plants (water hyacinth and water lettuce) was \$17.3 million and \$3.1 million, respectively (FDEPb). The state spent most of the hydrilla budget on about 20 to 25 lakes where high populations had become established from insufficient control in the mid-1990s (FDEPb).

Bioeconomic Model of Invasive Aquatic Plants

Recently, economists have turned to bioeconomic models to help guide policy decisions. These models relate the biology of invasive species (e.g., population growth) to their economic impacts. For example, Knowler and Barbier modeled lost profits from invasion of a fishery by comb-jelly; Settle and Shogren modeled impacts on wildlife viewing, fishing, and indirect values from invasive trout; Buhle, Margolis, and Ruesink examined the cost-effectiveness of control methods for invasive species with different biological characteristics; and Huffaker and Cooper used a bioeconomic model of rangeland invasives to measure the impact on grazing. To our knowledge, no study has specified a bioeconomic model of invasive aquatic plants.

The essential components of a bioeconomic model of invasive aquatic plants include three linkages: (1) plant control and plant populations, (2) plant populations and lake use, and (3) lake use and lake-based value. Invasive plant coverage on lake L in time t for plant i is assumed to include only hydrilla, $H_{i=1,L,t}$ and floating invasive plants (water hyacinth and water lettuce), $H_{i=2,L,t}$. Coverage is measured in acres of lake surface area. These plants may grow up to the carrying capacity of the lake at a lake-specific intrinsic growth rate, $r_{i,L,t}$. To mitigate their effects, the state may apply aquatic herbicides at time $t = \tau_1$. To determine the amount of herbicidal control needed for the following year, the state will survey the plant acreage at some time $t = \tau_2$. Using observations on aquatic plant control at τ_1 and survey at τ_2, we model invasive aquatic plant coverage as:

$$(1) \quad H_{i,L,t} = f_{1,L}(H_{i,L,0}, \Delta H_{i,L,\tau_1}, \Delta H_{i,L,\tau_2}) \quad \text{for } i = 1, 2,$$

where $\Delta H_{i,L,\tau 1}$ is the acreage controlled at time τ_1, and $\Delta H_{i,L,\tau 2}$ is the change in plant coverage between τ_1 and τ_2. The total budgetary cost of aquatic plant control over all Florida lakes is:

$$(2) \quad TC = \sum_L f_{2,L}(\Delta H_{i,L,\tau_1}) \quad \text{for } i = 1, 2.$$

In north Florida, over 65% of boating activities are related to fishing (Thomas and Stratis); therefore, changes in fishing activity should capture much of the recreational impact of invasive aquatic plants on Florida lakes. Assumptions include that anglers derive direct value from the number of hours spent fishing, that lake use is open access, and that associated costs are essentially fixed (e.g., boat payments), with the exception of opportunity costs. Anglers will regulate their activity level according to individual marginal benefit calculations, which may be affected by invasive plant acreage and lake biophysical characteristics, such as lake size. Angler activity is a function of invasive aquatic plant coverage, $H_{i,L,t}$:

$$(3) \quad F_{L,t} = f_{3,L}(H_{i,L,t}) \quad \text{for } i = 1, 2.$$

The total amount of fishing activity in Florida is the summation of angler activity over the total number of lakes over 365 days per year:

$$(4) \quad TF = \sum_L \sum_t (F_{L,t}).$$

The statewide benefit of freshwater fishing over the course of a year is:

$$(5) \quad TB = f_4(TF).$$

If the value space only includes recreational fishing benefits and control efforts by the state, then the annual net benefit of the lake is Equation (5) minus Equation (2):

$$(6) \quad NB = TB - TC.$$

A comparison of net benefits can be calculated under various invasive aquatic plant control scenarios to estimate the net benefit of a change in control strategies.

Data and Parameters

We parameterized this bioeconomic model (Equations [1–6]) using data on invasive plant coverage, invasive plant control, rate of plant control effectiveness, angler activity, average angler value, and lake biophysical characteristics for 13 large public lakes in Florida.

Invasive Plant Growth and Control

Invasive aquatic plant studies show that time of year is a very good estimator of growth (Best and Boyd).[1] To estimate invasive plant growth, we used four plant acreage data points for each observation year to estimate three growth parameters. These data included acres treated at time $t = \tau_1$ and acres identified by surveys at time $t = \tau_2$, and the beginning and ending of each year, times $t = 1$ and $t = 365$, for which we assumed no invasive plant coverage. Invasive aquatic plants grow in stages throughout the year (Reddy and DeBusk; Wolverton and McDonald). In January, there are typically no plants remaining in the lake from the previous year (Best and Boyd). Once water temperatures reach 3°C, new plants emerge from underground tubers and seeds (Spencer et al.). Growth is rapid through September, when tuber and seed production typically begins (Bowes, Holaday, and Haller). The plants become senescent or dormant as temperatures cool (Best and Boyd).

To limit plant growth, the state applies herbicides at a time, τ_1, that is expected to have maximal effectiveness (around $t = 60$). The actual date of herbicide application is determined by the FDEP in consultation with regional FDEP biologists and the Florida Fish and Wildlife Conservation Commission to ensure that herbicide application has minimal impacts on recreational fishing. Although the actual dates of herbicide application were not available, we assumed that they occurred at time $\tau_1 = 60$ based on discussions with lake managers at the FDEP. Herbicide applications are highly effective, leaving very little living plant biomass following an application. Van, Steward, and Conant found that herbicides are over 95% effective for dioecious (Florida) hydrilla. We assumed a 99% efficiency rate for the sake of providing conservative estimates of expenditures and losses associated with invasive plant control.

The FDEP and U.S. Army Corps of Engineers (USACE) conduct annual visual assessment surveys of invasive aquatic plants to record total acreage. Plant surveys are conducted at a time that is expected to reveal maximal population (around day 270) (Haller; Ludlow; Schardt). Based on discussions with aquatic plant managers, we assumed that the plant survey date and the date of maximal invasive aquatic plant acreage is time $\tau_2 = 270$. We obtained unpublished plant coverage data on 51 Florida lakes from 1983–2002 from FDEP and USACE. Of these lakes, only 13 had sufficient data to be used in the bioeconomic model.

For each lake, we estimated lake-specific annual growth functions for hydrilla and floating plants (water hyacinth and water lettuce together):

$$(7) \qquad H_{i,L,t} = \begin{cases} H_{i,L,t}e^{(r_{i,1,L})t} & \text{for } 1 \le t \le \tau_1 \\ H_{i,L,t}e^{(r_{i,2,L})(t-\tau_1)} & \text{for } \tau_1 < t \le \tau_2 \\ H_{i,L,t}e^{(r_{i,3,L})(t-\tau_2)} & \text{for } \tau_2 < t \le 365, \end{cases}$$

where $r_{i,1,L}$, $r_{i,2,L}$, and $r_{i,3,L}$ are lake-specific growth (and decline) parameters for days 1–60, 61–270, and 271–365, respectively. We parameterized Equation (7) using five years of annual invasive plant coverage and control

[1] We tested the assumption that t is a good predictor of growth using the most recent lakewide study of hydrilla growth in Florida (Bowes, Holaday, and Haller). Bowes, Holaday, and Haller measured the level of hydrilla biomass on Orange Lake, Florida, in 1977. Using this data, we estimated a growth function for hydrilla with time as the explanatory variable (statistically significant at $p = 0.01$, with an adjusted $R^2 = 0.975$, suggesting high explanatory power).

Table 1. Hydrilla and Floating Plants Growth Function Parameter Estimates

	Hydrilla			Water Hyacinth and Water Lettuce		
Lake	r_{11}	r_{12}	r_{13}	r_{21}	r_{22}	r_{23}
George	0.014	0.014	0.04	0.018	0.018	0.04
Griffin	0.034	0.016	0.009	0.059	0.02	0.033
Harris	0.047	0.016	0.017	0.035	0.02	0.018
Istokpoga	0.122	0.029	0.093	0.12	0.007	0.041
Jackson	0.091	0.023	0.058	0.082	0.02	0.047
Kissimmee	0.131	0.026	0.092	0.102	0.013	0.044
Lochloosa	0.063	0.014	0.023	0.03	0.02	0.015
Okeechobee	0.03	0.03	0.085	0.141	0.014	0.072
Orange	0.095	0.028	0.074	0.085	0.01	0.026
Osborne	0.078	0.014	0.032	0.059	0.02	0.033
Poinsett	0.102	0.02	0.06	0.088	0.012	0.033
Sampson	0.078	0.028	0.063	0.045	0.011	0.003
Weohyakapka	0.133	0.023	0.086	0.072	−0.005	−0.015

data for 13 lakes (George, Griffin, Harris, Istokpoga, Jackson, Kissimmee, Lochloosa, Okeechobee, Orange, Osborne, Poinsett, Sampson, and Weohyakapka). Parameter values $r_{i,1,L}$, $r_{i,2,L}$, and $r_{i,3,L}$ were interpolated as follows. $\tilde{H}_{i,L,\tau 1}$ is the average reported acres of invasive aquatic plants controlled on lake L on day $\tau_1 = 60$, and $\tilde{H}_{i,L,\tau_2}$ is the average observed plant acres on lake L on day $\tau_2 = 270$. We use these as proxies for the changes in plant coverage, $\Delta H_{i,L,\tau_1}$ and $\Delta H_{i,L,\tau 2}$, in Equation (1). The estimated early season growth rate, $r_{i,1,L}$ is obtained by:

$$(8) \quad r_{i,1,L} = \ln(\tilde{H}_{i,L,\tau_1})/\tau_1.$$

Assuming a 99% rate of control efficacy, the peak-season growth rate, $r_{i,2,L}$ and late-season decay rate, $r_{i,3,L}$ are:

$$(9) \quad r_{i,2,L} = \ln(\tilde{H}_{i,L,\tau_2})/(\tau_2 - \tau_1)$$

$$(10) \quad r_{i,3,L} = \ln(\tilde{H}_{i,L,\tau_2})/(365 - \tau_2).$$

The parameter estimates appear in Table 1. Figure 1 provides an example of invasive plant coverage on Florida lakes when all available plant acreage is treated, and Figure 2 depicts plant coverage when no acreage is controlled. We assumed initial plant coverage from estimated initial steady-state conditions.

Aquatic Plant Control Costs

We estimated per acre control costs for hydrilla, water hyacinth, and water lettuce based on five years (1998–1992) of FDEP and USACE control acreage and cost data. The current control policy is to treat all invasive aquatic plants at time τ_1 (day 60). The total budgetary cost of controlling hydrilla, water hyacinth, and water lettuce in any given year is a function of acres treated during that year, assuming scale-independent costs calculated from five-year averages:

$$(11) \quad C_L = c_1 H_{1,L,\tau_1} + c_2 H_{2,L,\tau_1},$$

where c_1 is the per acre cost of controlling hydrilla, and c_2 is the per acre cost of controlling water hyacinth and water lettuce. We estimated c_1 to be \$564 and c_2 to be \$107.

Impacts of Invasive Aquatic Plants on Fishing

In a previous study, Adams estimated angler activity, $F_{L,t}$ as a function of acres of invasive plant coverage, $H_{i,L,t}$, and lake biophysical characteristics that are expected to impact recreation on the 13 lakes that we used in our analysis. Adams' regression model used angler effort data collected by the Florida Fish and Wildlife Conservation Commission standard-

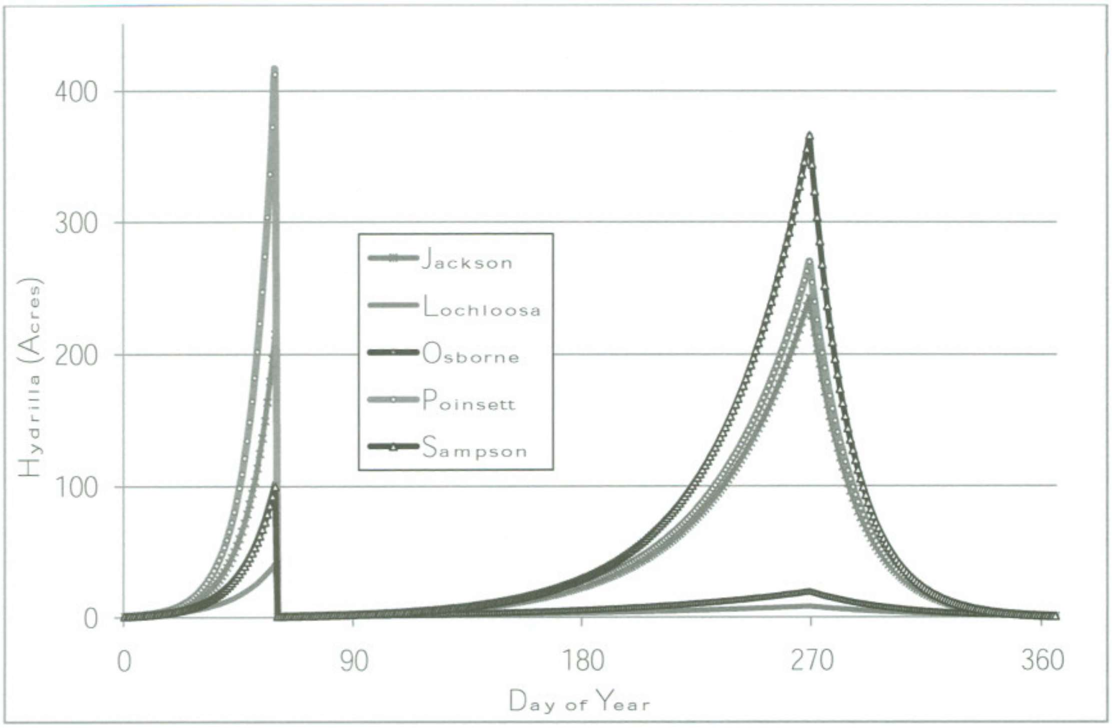

Figure 1. Simulated Hydrilla Coverage on Select Florida Lakes with Maintenance Control

ized as per day averages, and the following lake biophysical variables: lake biological productivity (trophic state index[2]), lake surface area (acres), season (indicator variables), and lake amenities (boat ramps and parking spaces indicator variable). The parameter estimates for the invasive plants variables were significant above the 95% confidence level, except for one season indicator variable. The overall model significance was high (F = 42.02, significance of F = 0.0000), and the estimated regression equation provided a relatively good fit to the sample data (adjusted R^2 = 0.7836). Adams reported no obvious model problems.

From Adams' empirical model, we obtained the following lake-specific empirical expression for aggregate daily angler activity as a function of average invasive aquatic plant coverage (acres):

$$F_{L,t} = \alpha_L - \beta_{1,L} H_{1,L,t} - \beta_{2,L} H_{2,L,t}. \tag{12}$$

Table 2 reports the lake-specific parameters for the empirical model of angler activity.

Aquatic plant parameter estimates suggest that invasive plant coverage negatively impacts angler activity. For example, if 35,000-acre Lake Kissimmee goes from 400 to 2,000 acres of invasive plant coverage (hydrilla and floating plants in equal amounts), on average, there will be 3.77 fewer hours of angler activity on the lake per day.

Angler Value

According to a recent statewide recreation study, freshwater anglers spend an average of \$20.65 per hour of fishing in 2002 dollars (Thomas and Stratis; FFWCC). We applied this value to Equation (5) to estimate the value of fishing on each lake. We made one final adjustment to the bioeconomic model to account for known abrupt changes in lake access. Invasive plant acreage changes

[2] A lake's trophic state indicates the amount of plant and animal life that it can support and is typically measured with a trophic state index (TSI). Particular trophic states are known to be more beneficial to sport fish production than others.

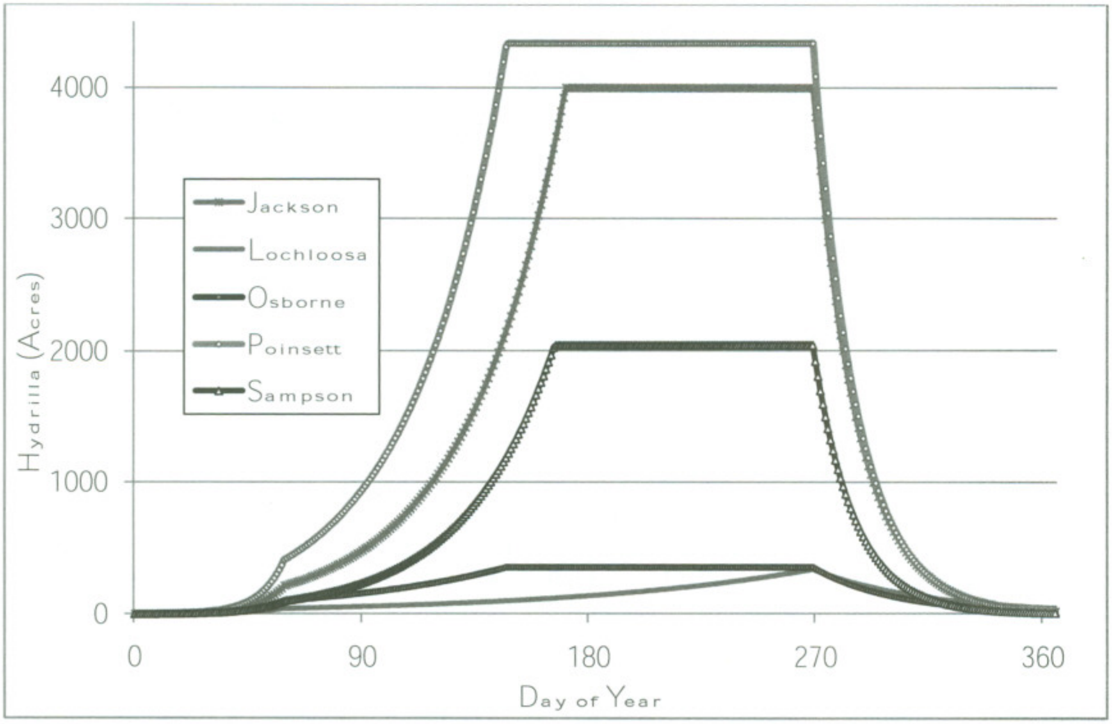

Figure 2. Simulated Hydrilla Coverage on Select Florida Lakes with No Control

throughout the year and can infest almost all available lake surfaces in summer. Plant surveys are not conducted when lakes are inaccessible. It is widely accepted that aquatic plants can block access to lakes, yet only one study reports the impact of high levels of invasive plant coverage on fishing. Colle et al. observed an 85% decrease in angler activity on Orange Lake when hydrilla coverage increased from 0% to 95%. Many Florida anglers use shallow-draft fan boats that are not hampered by aquatic plants, which may explain the persistence of some fishing effort at high levels of plant coverage. To account for abrupt changes in fishing from access problems, we assumed that only 15% of the otherwise predicted fishing effort would remain when invasive aquatic plant coverage is above 80%

Table 2. Empirical Angler Activity Model Parameters

Lake	α	β_1	β_2
George	380.0	3.5190×10^{-5}	1.3205×10^{-4}
Griffin	641.0	1.9125×10^{-6}	2.0592×10^{-5}
Harris	710.0	4.0460×10^{-6}	5.0731×10^{-6}
Istokpoga	473.2	5.1485×10^{-3}	4.5995×10^{-5}
Jackson	455.1	2.0655×10^{-4}	7.7651×10^{-5}
Kissimmee	1,224.6	4.6674×10^{-3}	5.6066×10^{-5}
Lochloosa	325.0	7.0550×10^{-6}	4.0061×10^{-6}
Okeechobee	4,324.8	2.6129×10^{-3}	8.2705×10^{-4}
Orange	516.9	8.5255×10^{-4}	1.1082×10^{-5}
Osborne	283.0	1.6660×10^{-5}	2.0117×10^{-5}
Poinsett	181.1	2.2950×10^{-4}	2.0667×10^{-5}
Sampson	140.1	3.1110×10^{-4}	1.2730×10^{-6}
Weohyakapka	554.7	2.7192×10^{-3}	2.2464×10^{-7}

Table 3. Empirical Bioeconomic Model Variables and Parameters

Variables	Description	
C_L	Cost of invasive aquatic plant control per lake, per species	\$
$F_{L,t}$	Hours of fishing activity on lake L in time t	hr.
$H_{1,L,t}$	Acreage of hydrilla on lake L in time t	acres
$H_{2,L,t}$	Acreage of water hyacinth and water lettuce on lake L in time t	acres
L	Florida lakes	1–13
NB	The net of fishing benefits and invasive aquatic plant control costs	\$
t	Day of year	1–365
TB	Total benefit of invasive plant control	\$
TC	Annual total cost of invasive plant control	\$
Parameters		
α_L, $\beta_{1,L}$, $\beta_{2,L}$	Empirical angler activity model parameters	see Table 2
c_1	Per acre cost of controlling hydrilla	\$564
c_2	Per acre cost of controlling water hyacinth and water lettuce	\$107
p	Average per hour value of freshwater fishing	\$20.65
$r_{i,1,L}$, $r_{i,2,L}$, $r_{i,3,L}$	Hydrilla and floating plant growth function parameters	see Table 1
τ_1	Assumed date of herbicide application	60
τ_2	Date of plant survey; assumed date of maximal coverage	270

of lake surface area. Finally, we summed the angler activity over all 13 lakes and 365 days to estimate total angler activity (hours) per year and estimated the net recreational benefits of invasive aquatic plant management according to Equation (6). Descriptions of the variables and parameters included in the empirical bioeconomic model are provided in Table 3.

Simulation of Invasive Aquatic Plant Control Strategies

We simulated the economic impacts of three invasive aquatic plant control strategies for 13 Florida lakes using the bioeconomic model. Recall that hydrilla largely relies on a tuber bank to sustain its population following control efforts. Sustained hydrilla control in a lake is expected to reduce the tuber bank, which will reduce future acreage, *Ceteris paribus*. Water hyacinth and water lettuce are prolific vegetative and seed reproducers that easily move within and between water bodies. Similar efforts against floating plants are not expected to achieve long-term population reductions due to the high level of cross-contamination of lakes with water hyacinth and water lettuce by recreational boaters. Our bioeconomic model assumed that deviations from status quo hydrilla acreage would result in proportional declines in tuber production, with tubers remaining viable for four years (Best and Boyd). For example, a regime that allows peak plant coverage on a lake to increase by 32% will cause 32% more tubers to be produced, which would fully infest the lake much faster in future years. We also assumed that hydrilla populations would be maintenance managed at new peak levels from the following year forward. Thus, early changes in hydrilla control would lead to sustained changes in invasive plant acreage, whereas control efforts would probably impact only within-year populations of floating plants.

Several control scenarios were considered for invasive aquatic plants (see Table 4). Scenario A is the status quo, which was calculated from five-year averages of the 1998–2002 FDEP and USACE data. Status quo control maintains fishing access throughout most of the year. Most of the lakes' recreation and ecosystem value would be preserved as long as the state maintained hydrilla and floating plants at relatively low levels. Scenario B simulated the effect of skipping a year of control, and scenario C simulated adding one follow-up herbicide application in year one. For these scenarios,

Table 4. Model Assumptions for Control Scenarios

Scenario	Treatment at Day 60	Second Treatment
A (status quo)	All hydrilla and floating plant acreage	None
B	None in year 1, then maintenance control in subsequent years	None
C	Maintenance control in subsequent years	20% additional control during mid-summer (actual date varies by lake), then maintenance control in subsequent years

we assumed that aquatic plant growth follows Equation (7).

We calculated an initial steady state of invasive plant coverage based on our assumptions about hydrilla tubers and plant control after five years of consistent control (scenario A). If plant control is increased (Scenario C), then the steady state would be altered. Consistent control reduces tuber banks, which may exacerbate the differences between the various levels of control. Less vegetation means fewer tubers, so in subsequent years, there would be less acreage to treat. If plant control is reduced (scenario B), then more tubers would result in more acreage to treat each year in order to maintenance manage the invasive plants.

We simulated the short-term (one year) and steady-state impacts of scenarios A, B, and C using General Algebraic Modeling System (GAMS) 2.5A software.

The short-term (year 1) impacts of these scenarios are reported in Table 5. The long-term steady-state implications of the scenarios are reported in Table 6. Scenario A (status quo) estimates the annual value of the 13 lakes—over $64.78 million (average $4.98 million per lake), with about 3.13 million total fishing hours. Assuming that an average fishing trip lasts six hours (Thomas and Stratis), this equates to 521,667 fishing trips each year. Compared with the status quo, a lapse in control (scenario B) would lead to significant recreational losses, largely due to access problems. Missing one year of control would raise steady-state peak plant coverage to 43,620 acres on the 13 lakes. This would also result in a long-term annual reduction in fishing hours by 20.67%, with lost angler benefits totaling $13.38 million per year. We also estimated the steady-state number of days per year that the lakes will have invasive aquatic plant coverage above the 80% level (Table 6). Under the status quo scenario, we estimated that there would be approximately 88 days per year that the lakes are largely inaccessible. A one-year lapse in control would cause the number of access days lost to

Table 5. Year 1 Cost of Altering Invasive Plant Control on 13 Lakes

Scenario	A	B	C
Total Acreage Treated (acres)	13,785	0	16,776
Treatment Costs ($m)	$5.78	0	$4.90
Change in Control Cost[a] ($mn)	0	–$5.78	+$0.07

[a] Versus status quo scenario A.

Table 6. Steady-State Long-Term Impact of Invasive Plant Control on 13 Lakes

Scenario	A	B	C
Fishing Hours (hr.)	3,135,966	2,487,857	3,299,093
Acreage Treated (acres)	13,785	23,948	8,193
Peak Acreage (acres)	21,085	43,620	7,163
Fishing Benefit ($m)	$64.78	$51.39	$68.15
Maintenance Costs ($m)	$4.82	$10.15	$1.64
Net Fishing Benefit ($m)	$59.95	$41.24	$66.51
Change in Net Benefit[a] ($m)	0	–$18.71	$6.55
Days Not Fished (d.)	1,153	2,176	802

[a] Versus status quo scenario A.

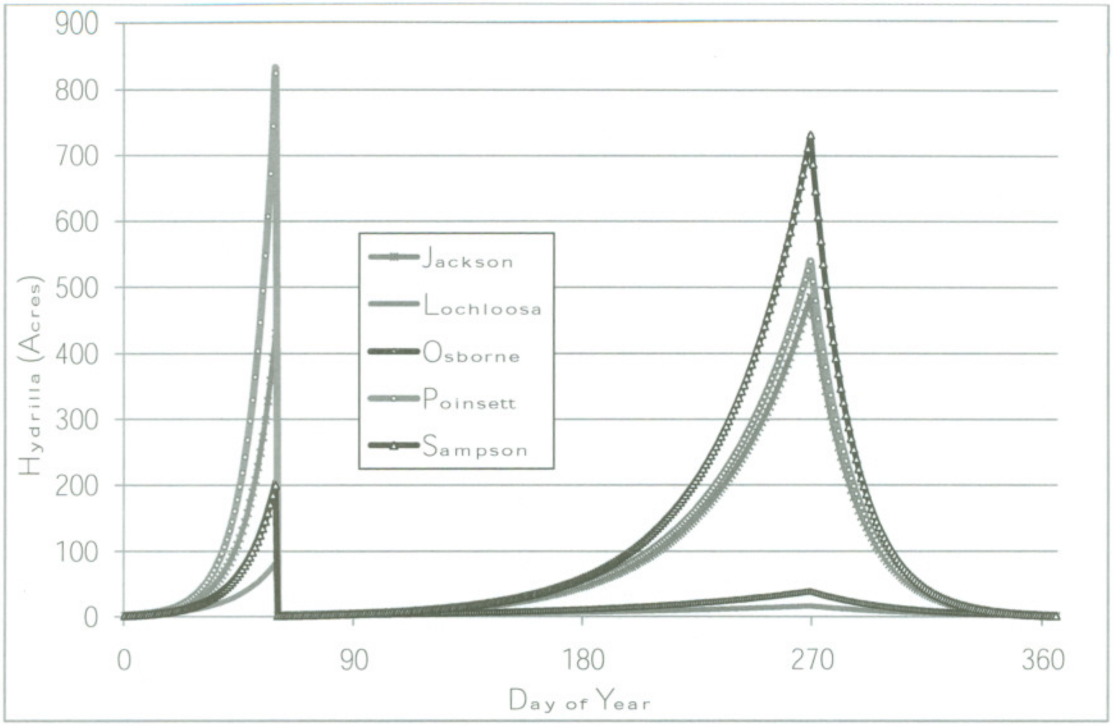

Figure 3. Simulated Impact of Reduced Control on Hydrilla Coverage

increase to an average of 167 days. Implied in the steady-state angler value calculation is the assumption that fish stocks and catch rates will not drastically change beyond what was captured by our bioeconomic model.

A short-term lapse in control (scenario B) leads to short-term cost reductions, but significant increases in long-term control costs. Missing one year of control saves the state \$5.78 million in the first year, but if the state reverts back to maintenance control, annual costs will be higher because there will more acreage of aquatic invasive plants to treat on day 60 (see Figure 3). The steady-state acreage treated increases from 13,785 to 23,948, and steady-state annual maintenance costs are 2.1 times higher (\$10.15 million). When we include changes in control costs and fishing benefits, the lapse causes steady-state annual losses of \$18.71 million.

Increases in control (scenario C) yield large long-term gains. A one-time second herbicide application would reduce steady-state peak acreage from 21,085 to 7,163 on the 13 lakes (see Figure 4). Angler benefits associated with this scenario are \$68.15 million, a 5.20% increase over the status quo. This control strategy would reduce the average number of days when lakes are inaccessible to 61.69, 27.00 days less than the status quo scenario. The gains in fishing come at a higher short-term cost of \$5.78 million; however, acreage of invasive plants treated falls from 13,785 to 8,193, and associated annual control costs are 66.01% lower than the status quo. This scenario leads to a \$6.55 million increase in steady-state annual net benefits. This suggests that, if a second herbicide application were possible, the state could significantly reduce its long-term invasive aquatic plant control burden and increase net benefits with increases in control.

The results from the three scenarios indicate that increased and sustained control of invasive aquatic species is more economically efficient than infrequent control. A comparison of the consistent control in scenario A to lapses in control in scenario B reveals a spike in control costs and drop in fishing activity. Just one year of insufficient funding could

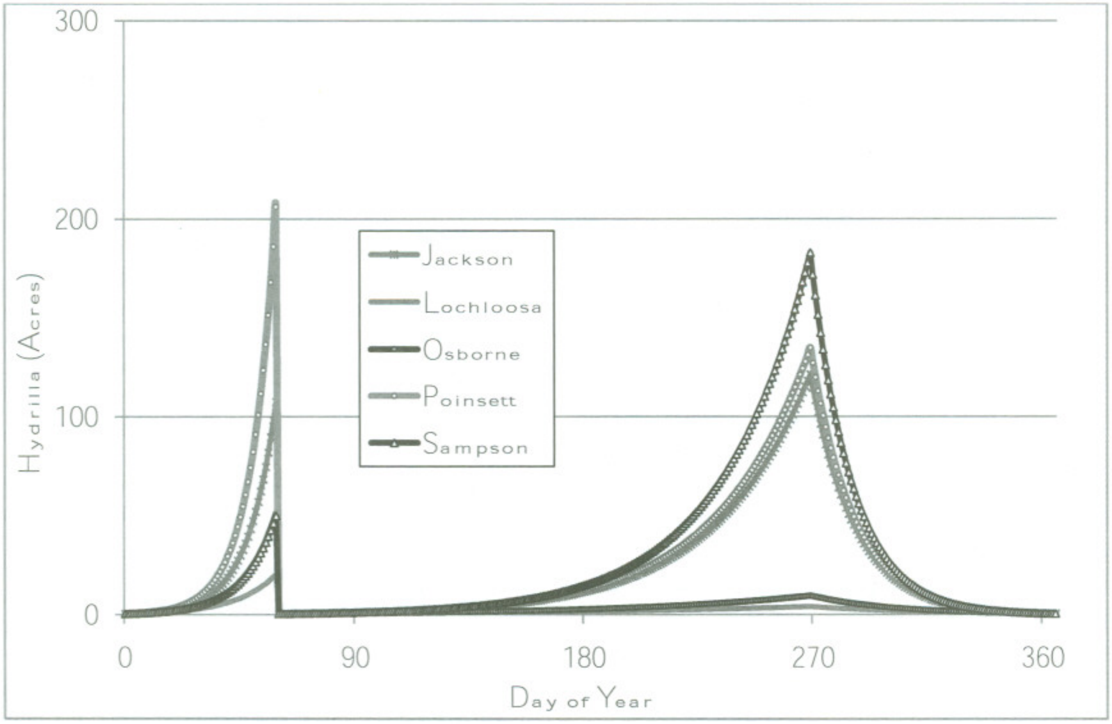

Figure 4. Simulated Impact of Increased Control on Hydrilla Coverage

vastly increase control costs and severely reduce recreation, perhaps devastating local economies. When including scenario C in the analysis, we concluded that continued and perhaps increased control of invasive aquatic plants may be in the public's best interest, considering the economic implications of sporadic aquatic plant control on lakes throughout the state.

Conclusion

The invasive aquatic plants *Hydrilla verticillata* (hydrilla), *Eichhornia crassipes* (water hyacinth), and *Pistia stratiotes* (water lettuce) have long been established in Florida's lakes and rivers. The unique characteristics of these plants allow them to grow rapidly, displacing native flora and fauna and reducing recreational use and enjoyment of many water bodies. Consistent and significant control efforts are required to prevent invasive aquatic plants from eroding the value of Florida's lakes to the state's economy and ecosystems.

Long-term cost-effective control of these invasive species involves consistent control efforts, yet the state's funding has fallen short in the past. We created a bioeconomic model of hydrilla, water hyacinth, and water lettuce using data collected on 13 lakes in Florida. We used this bioeconomic model to estimate the value of three invasive aquatic plant control regimes: the status quo, a one-year lapse, and a one-year increase in control. We estimated the value of fishing activity on the 13 lakes to be in excess of \$64.78 million per year, with about 3.13 million fishing hours per year. The steady-state net benefit of the status quo control strategy is \$59.95 million over the 13 lakes.

Compared with the status quo control strategy, a one-year lapse in control would significantly reduce recreation (20.67% drop) and cause large increases in long-term control costs (2.1 times higher). If the statewide control budget is \$30 million per year, a one-year lapse in funding would require over one third of the state's plant control budget for just 13 of Florida's 454 public lakes and rivers.

This control strategy leads to steady-state losses of $18.71 million.

A one-year increase in control yields large long-term benefits. Steady-state increases in fishing benefits are $4.90 million per year for a second herbicide application in year one, and steady-state maintenance costs fall by $3.18 million (66.01%). The net annual gain is $6.55 million.

Based on the simulation results, we were able to draw a few clear conclusions: (1) Florida lakes have very high economic values that are threatened by invasive aquatic plants; (2) increased control of invasive aquatic plants is the preferred cost-minimizing control strategy; and (3) lapses in maintenance control, even if brief, can significantly increase subsequent invasive aquatic plant control costs and jeopardize fishing benefits, which are worth more than $64.78 million per year on 13 of Florida's public lakes.

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