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Optimal Management of a Potential Invader: The Case of Zebra Mussels in Florida

Donna J. Lee, Damian C. Adams, and Frederick Rossi

Dominant users of Lake Okeechobee water resources are agricultural producers and recreational anglers These uses will be directly affected, should the lake become infested with zebra mussels. We employ a probabilistic bioeconomic simulation model to estimate the potential impact of zebra mussels on consumptive water uses, recreational angling, and wetland ecosystem services under alternative public management scenarios. Without public management, the expected net economic impact from zebra mussels is −\$244.1 million over 20 years. Public investment in prevention and eradication will yield a net expected gain of +\$188.7 million, a superior strategy to either prevention or eradication alone.

Key Words: cost transfer, fishing, invasive species, probability transition matrix, surface water, wetlands

JEL Classifications: C63, Q25, Q52, Q57, Q58

Zebra mussels (*Dreissena polymorpha*) are a small freshwater species native to southeastern Europe. In suitable water, zebra mussels become successful invaders. Mature females can produce up to 1 million eggs per year (USACE). The zebra mussel most likely crossed the Atlantic Ocean as larvae on a transatlantic ship (Griffiths et al.; Hebert, Muncaster, and Mackie; Thorp, Alexander, and Cobbs) and disembarked into the Great Lakes. The mussels multiplied rapidly and began spreading. Today, populations are found in 24 states, as shown in the map in Figure 1 (USGS 2007).

The problem with zebra mussels is that they colonize on any submerged surface, including boat hulls, navigational buoys, bridge abutments, and water intake pipes. Their dense mats will accelerate the rate of corrosion, sink navigational buoys with their weight, and obstruct water flow in pipes. United States' expenditure for the upkeep required to maintain boat bottoms, docks pilings, locks, gates, and pipes is estimated to be \$60 million per year (USGAO). Because zebra mussels are spreading, damages are expected to rise. Future damages are estimated to be between \$3.1 and \$5 billion for the period 2002 to 2011 (USGAO; USGS 2000).

Zebra mussels compete with native flora and fauna for food and space, alter the composition of the water column, and transform lake bottoms. They will biofoul rocks, logs, submerged plants, and the shells of other mussels. In the United States, more than half

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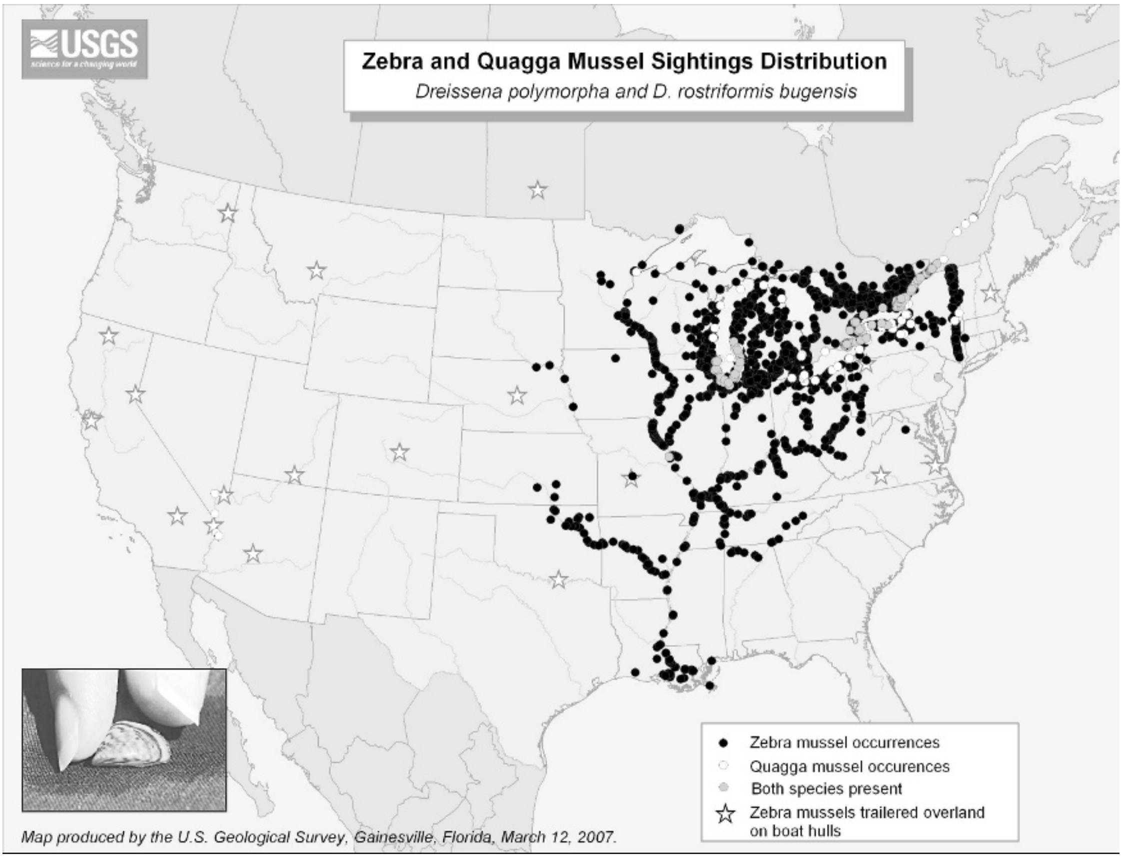

Figure 1. Zebra Mussels in the United States (USGS 2007)

of all native freshwater mussel species are either threatened or endangered. Recovery efforts are significantly hindered by the presence of zebra mussels (Ricciardi, Neves, and Rasmussen; USGAO).

Will Zebra Mussels Invade Florida?

Zebra mussels were first sighted in Florida in 1998 during an inspection of a bait and tackle shop (University of Florida). Fortunately, a fast-acting official collected and destroyed the animals before they could spread. No other sightings have occurred since, but in the past decade, zebra mussels have made their way south, creeping ever closer to the Florida border. Populations are thriving in Arkansas, Alabama, Kentucky, Louisiana, Mississippi, Missouri, Tennessee, and West Virginia (USGS 2007). According to estimates by Drake and Bossenbroek, zebra mussels are bound to reappear in Florida. The authors estimate that, in the coming years, there is a "high" likelihood that zebra mussels will reach north Florida and a "moderate" likelihood that zebra mussels will reach south Florida. Suitability of Florida's warm waters was examined by Hayward and Estevez. They judged the rivers in the Florida panhandle (north Florida) unsuitable for zebra mussel propagation because the water is acidic and contains few minerals. The St. Johns River in north-central Florida and Lake Okeechobee in south Florida have low acidity and high mineral content and are judged suitable for sustaining zebra mussels.

This study examines the potential for Lake Okeechobee to become infested with zebra mussels, describes a simulation model, proffers a series of management scenarios, presents results, and offers sensitivity tests on key model parameters. Novel contributions include the quantification of potential future damages from zebra mussels, economic tradeoffs between public management expenditures and public and private gains, and comparisons of management alternatives with respect to prevention and eradication.

Lake Okeechobee

Lake Okeechobee is an important commercial shipping route, a valuable source of freshwater, a major recreational resource, and, at 448,000 acres, the second largest lake entirely within the United States (FDEP). Five counties around the lake pump water for irrigation, industry, and household uses. Affected services from an infestation of zebra mussels would include water supply, water recreation, and wetland ecosystem services.

The Lake Okeechobee waterway is presently free of zebra mussels, and the nearest populations are 750 mi. away. Most likely, zebra mussels will make the journey by clinging to the stems of aquatic weeds entwined in a boat propeller or snagged on a trailer. Although the possibility may seem remote, it is worth noting that zebra mussels can survive for several days out of water. In the Great Lakes region, aquatic weeds covered with live zebra mussels were observed on one of every 275 boats in parking lots while owners were preparing to launch into uninfested lakes (Johnson and Carlton).

Lake Okeechobee is a popular destination for local and out-of-state sport fishers and recreational boaters and is host to several major fishing tournaments each year. Out-of-state boaters and returning Florida boaters are likely vectors for transporting zebra mussels to Lake Okeechobee.

Zebra Mussel Model

In a previous study, Leung et al. used stochastic dynamic programming to model the probability of a zebra mussel invasion as a decreasing function of prevention effort. Zebra mussel growth was captured with a logistic function. Damages were expressed in terms of lost productivity due to reduced water flow. The optimal solution was to reduce the probability of arrival by 10% with prevention measures. Finnoff et al. applied a stochastic dynamic programming model following Leung et al. to examine the economics of preventing zebra mussel damages in a Midwest lake. They questioned the importance of including feedback links and the conditions under which omission would make a difference. One interesting finding was that overinvestment or underinvestment in control could result, depending on how the public manager believes the private entity will respond to the invasion. To compare management alternatives for eradicating the oyster drill (*Ocinebrellus inornatus*), an invasive marine mollusk, Buhle, Margolis, and Ruesink employed a Markov approach. The authors specified a 2 × 2 transition matrix to capture two of the animals' three life stages and ascertained that control efforts targeting the adult animals would be more cost-effective than control efforts targeting the bright egg masses.

For Lake Okeechobee, we assume there is a real threat of zebra mussel introduction. Once introduced, the small critters are unlikely to be noticed until dense mats are formed or piles of razor-sharp mussel shells wash up onshore. By the time they are detected, the economic and environmental damage will already be significant. To characterize this system, we use a stylized model comprising the following four "states of nature": (1) none, (2) introduced, (3) propagating, and (4) critical mass. The probability that the lake will be in any of the four states at time t in the future is s_{it}. At present, there are no zebra mussels; thus, $s_{1t=0} = 1$, and it follows that $s_{2t=0} = s_{3t=0} = s_{4t=0} = 0$. An additional description of the variable s_{it} appears in Table 1.

The s_{it} state probabilities are brought together to form the elements of vector variable S_t:

$$(1)\quad S_t = \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix}_t \quad \text{where} \quad 0 \leq s_{it} \leq 1 \quad \text{and} \quad \sum_{i=1}^{4} s_{it} = 1.$$

Table 1. Description of Zebra Mussel States in Lake Okeechobee

i	Probability of State i at Time t	Description of State i	Economic and Ecosystem Damages?
1	s_{1t}	No zebra mussels	No
2	s_{2t}	Zebra mussels recently introduced	No
3	s_{3t}	Zebra mussels propagating	No
4	s_{4t}	Zebra mussels at critical mass	Yes

At present, the lake has no zebra mussels; thus, at $t = 0$,

$$(2) \qquad S_0 = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}_{t=0}.$$

To derive future state values S_{t+1}, we define the transition probability a_{ij}, which represents the probability of changing to state i from state j in a single time period. In matrix form, a_{ij} comprises the elements of A_0, the 4 × 4 matrix of transition probabilities under a natural progression of zebra mussels:

$$(3) \qquad A_0 = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}.$$

S_{t+1} is defined as the product of A_0 and S_t from Equations (3) and (1):

$$(4) \qquad S_{t+1} = A_0 S_t.$$

Each element of S_{t+1} can be obtained:

$$(5) \qquad s_{i,t+1} = a_{i1}s_{1t} + a_{i2}s_{2t} + a_{i3}s_{3t} + a_{i4}s_{4t} \quad \text{for } i = 1 \ldots 4.$$

Because the natural progression of zebra mussels may be undesirable, prevention measures are available to reduce the probability of introduction and propagation. Letting f_1 measure the effectiveness of a prevention program, the transition probability matrix A_p with a prevention program in place is expressed by

$$(6) \qquad A_p = \begin{bmatrix} a_{11} - a_{21}f_1 & a_{12} & a_{13} & a_{14} \\ a_{21}(1 - f_1) & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}.$$

Propagation can be thwarted with early eradication, which is defined as the action required to destroy all zebra mussels as soon as they are detected. With monitoring as a component of the prevention program, we assume early eradication takes place in state 3 before the zebra mussels can cause significant damage or loss. The transition probability matrix A_m is represented by

$$(7) \qquad A_m = \begin{bmatrix} a_{11} - a_{21}f_1 & 1 & 1 & 1 \\ a_{21}(1 - f_1) & a_{22} & a_{23} & a_{24} \\ a_{31} & 0 & a_{33} & a_{34} \\ a_{41} & a_{42} & 0 & 0 \end{bmatrix}.$$

Without a prevention program in place, we assume that there would be no monitoring and that therefore zebra mussels would be detected with the onset of economic damages, i.e., in state 4. Late eradication is defined to be the measures taken to destroy all zebra mussels in Lake Okeechobee after reaching state 4. The transition probability matrix A_r is expressed by

$$(8) \qquad A_r = \begin{bmatrix} a_{11} & 1 & 1 & 1 \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & 0 & a_{33} & a_{34} \\ a_{41} & a_{42} & 0 & 0 \end{bmatrix}.$$

Posteradication, we assume the treated lake would be free of zebra mussels for a period of n years, during which time the transition probability matrix becomes

$$(9) \qquad A_n = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

With prevention, the zebra mussel state equation when there are no zebra mussels

Table 2. Four Management Alternatives

	$x_p = 0$	$x_p = 1$
$x_r = 0$	I Do nothing (status quo)	II Invest in prevention (prevention)
$x_r = 1$	III Eradicate when zebra mussels become problematic (late eradication)	IV Invest in prevention and eradicate before zebra mussels become problematic (prevention and early eradication)

(state 1) and after they are introduced (state 2) is defined as

$$(10)\qquad S_t = A_p S_{t-1}.$$

We assume zebra mussels will be detected after they begin propagating (state 3). In this state, prevention would no longer be practical; thus, prevention measures would be halted after state 3. While zebra mussels are propagating (state 3) and when they reach critical mass (state 4), the transition matrix is A_0, and the state equation reverts to Equation (4).

With prevention and early eradication, the state equation while there are no zebra mussels and after they are introduced and propagating is

$$(11)\qquad S_t = A_m S_{t-1}.$$

With late eradication, the state equation while there are no zebra mussels and after they have been introduced, are propagating, and have reached critical mass is

$$(12)\qquad S_t = A_r S_{t-1}.$$

For the remainder of the planning horizon, after early eradication and after late eradication, the state equation is

$$(13)\qquad S_t = A_n S_{t-1}.$$

Economic comparison of the management choices requires estimates of the expected benefits and costs. For this problem, the management choice variable X is a (4×4) vector composed of the elements x_p and x_r.

$$(14)\qquad X = \begin{bmatrix} x_p & x_p & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & x_p x_r & 0 \\ 0 & 0 & 0 & x_r \end{bmatrix}$$

The decision to invest in prevention is given by $x_p = 1$ and $x_r = 0$. The decision to invest in prevention and early eradication is given by $x_p = 1$ and $x_r = 1$. The decision to invest in late eradication is given by $x_p = 0$ and $x_r = 1$. The four management alternatives are shown in Table 2.

Combining the two management choices yields a vector of four management alternatives:

$$(15)\qquad u(X) = \begin{bmatrix} (1 - x_p)(1 - x_r) \\ x_p(1 - x_r) \\ (1 - x_p)x_r \\ x_p x_r \end{bmatrix}$$

The unit costs of implementing the management choices x_p and x_r are c_p and c_r, which comprise the (2×1) management cost vector q.

$$(16)\qquad q = \begin{bmatrix} c_p \\ 0 \\ c_r \\ c_r \end{bmatrix}$$

The cost of management C_t at time t is the product of unit cost q, management choice X, and zebra mussel state S_t from Equations (16), (14), and (1):

$$(17)\qquad C_t = q' X S_t.$$

Economic damage from zebra mussel infestation is d, an X-dependent variable of increased maintenance expenditure by consumptive water users in Lake Okeechobee. Ecosystem service loss with zebra mussel infestation e includes diminished wetland functions, loss in wildlife habitat, and reduced aquatic food supply in state 4. The benefit from zebra mussel infestation b is the added value to recreational and sport fishers from improved water clarity and increased catch rates due to zebra mussel filter feeding. In this model, cost, damage, and loss are expressed as negative values, and benefit is expressed as a positive value. The objective is to choose a management strategy X that maximizes Z, the present value of total expected cost, damage, loss, and benefit with the threat of zebra mussel infestation. The objective is to

$$\text{(18)} \quad \max Z = \sum_{t=0}^{T} (1 + r)^{-t} (q' X S_t + (e' + b') S_t + u(X)' d(X)' S_t),$$

subject to Equations (1) through (17). In Equation (18), r is the annual discount rate, and T is the number of years in the planning horizon.

Empirical Model Parameters

Transition Probabilities

Recreational and sport boats are the primary vector for transporting zebra mussels from infested lakes to Lake Okeechobee. We examined data from three national tournaments on Lake Okeechobee during 2006–2007 (Carson; Eads) and observed that half of the 926 anglers were from states with zebra mussel–infested waters. The potential for trailered boats to vector zebra mussels was shown by Bossenbroek, Kraft, and Nekola. They estimated that trailered boats in the Great Lakes area could convey enough live zebra mussels to colonize an uninfested body of water in a nearby state with a probability of between 1.18×10^{-5} and 4.11×10^{-5}. We used an intermediate probability of 3.78×10^{-5} per boat, multiplied by 926 boats per year, to obtain an annual probability of zebra mussel introduction of 3.5% per year ($a_{21} = 0.035$).

Upon introduction to Lake Okeechobee, zebra mussels would prosper, according to Hayward and Estevez. The scientists computed habitat suitability indices (HSI) of 0.83 and 0.91 for open water and shallow water containing dense aquatic plants. Given the high HSI values for Lake Okeechobee and the large expanse of suitable habitat, we assumed introduced zebra mussels would become established and propagate until critical mass was reached with a probability of 100% ($a_{32} = a_{43} = a_{44} = 1.0$).

Time to reach carrying capacity according to Borcherding and Sturm; Burlakova, Karatayev, and Padilla; Lauer and Spacie; Nalepa et al.; and Strayer et al. is 2–3 years after detection. For our model, we assume zebra mussels will grow to produce dense mats sufficient to cause damages 2 years after introduction; thus, the time lag between states 2 and 3 and between states 3 and 4 is 1 year.

Private Economic Damage

In the Great Lakes area, both O'Neill and Deng estimated the annual expenditure for chemical, mechanical, and thermal maintenance. For a zebra mussel infestation in Lake Okeechobee, we assume water users would employ mechanical and thermal means to clear clogged intake pipes and spend \$4.90 per million gallons pumped, as reported by Deng. Mean water withdrawal from Lake Okeechobee is 562,589 million gallons per year (USGS 2006). Multiplying annual water use by average unit expenditure, we arrived at economic damage of \$2.76 million per year to consumptive water users ($d_2 = 2.76$). As most pipes in the Great Lake region are pretreated with antifouling paint, we apply this damage estimate to treated pipes.

Antifouling paint helps reduce maintenance expenditures by inhibiting zebra mussel colonization. In the Columbia River Basin, water users applied antifouling paint to interior pipe surfaces at a cost of \$25.56 per ft^2 (Phillips, Darland, and Systsma). According to Adams, the average interior surface area of intake pipes drawing from Lake Okeechobee is 300.58 ft^2, and there are 504 major water users on the lake. Total intake pipe surface area is estimated to be 151,492 ft^2, which would cost \$3.87 million to treat with antifouling paint. Assuming the paint treatment lasts 10 years, annualized mitigation damage is \$0.387 million ($d_3 = 0.387$).

We assume antifouling paint treatment saves water users about 22% in maintenance expenditures. Thus, without treatment, Lake Okeechobee consumptive water users would pay \$5.98 per million gallons per year pumped to maintain pipes. Annual damage to untreated pipes is \$3.37 million ($d_1 = 3.37$).

Public Ecosystem Service Loss

Surrounding Lake Okeechobee are 29,000 acres of Audubon Society wetlands and 31,000 acres of unnamed wetlands for a total of 60,000 acres of wetlands. Costanza et al. estimated the value of wetland services to be \$1,083 per acre per year. Multiplying \$1,083 by 60,000 acres yields a wetland damage estimate of \$64.98 million per year ($e = 64.98$).

Private Economic Benefit

Between 1983 and 2002, anglers spent an average of 1,575,340 hours on Lake Okeechobee each year (FFWCC). The Florida Fish and Wildlife Conservation Commission reported an average spending of \$20.65 per hour in 2002 (FFWCC). Using total expenditures to estimate the recreational value of freshwater fishing, we multiplied hours fished by value per hour to obtain a total recreational value of \$32.5 million per year. Assuming an increase in water clarity attributable to zebra mussels would yield a 1% increase in fishing hours. The benefit from zebra mussels is \$0.325 million per year in state 4 ($b = 0.325$).

Management Cost

A plan to monitor and prevent zebra mussels from entering Lake Okeechobee was proposed in 2003 (USACE). The plan included inspecting underwater structures, sampling waterway sediments, and distributing education alert materials to boaters, lake homeowners, and businesses. The cost of implementing the proposed plan is \$152,800 per year ($c_p = 0.1528$).

In 2006, an infestation of zebra mussels prompted the Virginia Department of Game and Inland Fisheries to pour 174,000 gallons of potassium chloride into Millbrook Quarry. At 100 ppm, the concentration was double the amount needed to kill zebra mussels but low enough to avoid harming humans or fish. The single treatment is expected to protect the quarry from zebra mussel infestation for 33 years. The cost for chemicals and labor was \$365,000 (VDGIF). A similar treatment for Lake Okeechobee would require 628.6 million gallons of potassium chloride at a cost of \$1.320 billion. This cost annualized over 33 years is \$55.03 million ($c_r = 55.03$).

A summary of the parameter values used in the Zebra Mussel Model appears in Table 3.

Four Management Scenarios

With management I (do nothing), public management costs are zero. Private water users become aware of zebra mussels when they incur damages d_1 in the first year of state 4. In the second year, they will apply antifouling paint, thereby incurring damages d_2 and d_3 in subsequent years. Public ecosystem loss is e for every year the system is in state 4. Public recreation benefit is b for every year the system is in state 4.

With management II (prevention), public management cost is c_p when the system is in states 1 and 2 and zero in states 3 and 4. Private damage is d_3 during the first year that the system is in state 3 and d_2 and d_3 while in state 4. Public ecosystem loss is e for every year the system is in state 4. Public recreation benefit is b for every year the system is in state 4.

With management III (late eradication), public management cost is c_r after the system reaches state 4. Private water users become aware of zebra mussels when they incur damages d_1 during the first year in state 4. In subsequent years, private damages drop to zero because the zebra mussels are eradicated. Public ecosystem loss is e for 1 year while the

Table 3. Zebra Mussel Model Parameter Values

Symbol	Definition	Model Value
a_{11}	Probability of zebra mussel not being introduced to Lake Okeechobee	0.965
a_{21}	Probability of zebra mussel being accidentally introduced to Lake Okeechobee	0.035
a_{32}	Probability of zebra mussel moving from state 2 to state 3	1
a_{43}	Probability of zebra mussel moving from state 3 to state 4	1
a_{44}	Probability of zebra mussel remaining at state 4	1
All other a_{ij}		0
b	Economic benefits from zebra mussel	\$0.325 mil
c_p	Cost of arrival prevention and monitoring (per year)	\$0.1528 mil
c_r	Cost of eradication (annualized)	\$55.03 mil
d_1	Private economic damages without mitigation expenditures (per year)	\$3.37 mil
d_2	Private economic damages with mitigation expenditures (per year)	\$2.76 mil
d_3	Private mitigation expenditures (annualized)	\$0.387 mil
e	Value of wetland services lost with zebra mussels in state 4 (per year)	\$64.98 mil
f_p	Effectiveness of prevention measures	0.75
f_r	Effectiveness of eradication measures	1.00
r	Discount rate	0.02
t	Year	0, . . . , 19
T	Planning horizon	20 years

system is in state 4. Public recreation benefit is b for 1 year while the system is in state 4.

With management IV (prevention and early eradication), public management cost is c_p while the system is in states 1 and 2, c_r when the system is in state 3, and zero otherwise. Private damage is zero. Public ecosystem loss and public recreation benefit are zero, as the system never reaches state 4.

The empirical zebra mussel model was run on GAMS software (GAMS). In the following section, results from the simulation model are presented and discussed. Breakpoint values are provided to show the sensitivity of the results to the model parameter values.

Results

The least costly strategy is management I, in which nothing is done to prevent zebra mussels from entering Lake Okeechobee, and nothing is done to arrest propagation after they arrive. Over 20 years, management cost is \$0. The present value of expected ecosystem damages in terms of lost wetland functions is −\$219.5 million. Private water users sustain −\$25.7 million in expected damages from increased maintenance expenditures, and recreational anglers will gain +\$1.1 million in expected fishing benefits. The net present value of "do nothing" is −\$244.1 million.

The next least costly strategy is management II, in which prevention measures are implemented. Because prevention is only 75% effective, if zebra mussels arrive, we assume that prevention measures would be halted and that no further action would be taken to manage the growing mussel population. Over 20 years, the present value of expected public expenditure on prevention is −\$2.5 million. The present value of expected ecosystem damages in terms of lost wetland functions is −\$62.4 million. Private water users will endure −\$7.2 million in expected damages due to increased maintenance and mitigation expenditures. Recreational anglers will enjoy +\$0.3 million in expected fishing benefits. The net present value of managing the threat of zebra mussel with prevention is −\$71.8 million, a gain of +\$172.2 million over doing nothing.

The most costly strategy is management III, in which zebra mussels are eradicated from Lake Okeechobee after they begin causing damage. Over 20 years, the present value of expected public expenditure on

Table 4. Zebra Mussel Model Simulation Results

	Management Alternative			
	I Do nothing	II Prevention	III Late eradication	IV Prevention and early eradication
	$ million			
Public management cost	0	−$2.5	−$185.9	−$55.4
Public ecosystem loss	−$219.5	−$62.4	−$23.8	−$0
Private economic damage	−$25.7	−$7.2	−$1.2	−$0
Private recreational benefit	+$1.1	+$0.3	+$0.12	+$0
NPV	−$244.1	−$71.8	−$210.8	−$55.4
ΔNPV	0	+$172.2	+$33.3	**+$188.7**

T = 20 years, r = .02.

eradication is −$185.9 million. The present value of expected ecosystem damage in terms of lost wetland functions is −$23.8 million. Private water users will absorb expected damages of −$1.2 million, and recreational fishers will gain +$0.12 million in expected fishing benefits. The net present value of late eradication is −$210.8 million, a gain of +$33.3 million compared to doing nothing.

The strategy with the smallest public ecosystem loss, the least private economic damage, and the highest expected net present value is management IV, in which both prevention and eradication measures are used to mitigate infestation and resulting damages. Over 20 years, the present value of expected public expenditure on prevention and early eradication is −$55.4 million. Expected loss in ecosystem functions, damage to private consumptive use, and gain to recreational anglers is $0. The net present value from prevention and early eradication is −$55.4, a gain of +$188.7 million compared to doing nothing.

Among the four alternatives, the optimal strategy based on the net present value of expected costs, damages, losses, and benefits over the 20-year planning horizon as defined in Equation (17) is *Management I—Prevention and Early Eradication.* A summary of the simulation model results appears Table 4.

Discussion

Results show large gains to investment in prevention. With an expected outlay of $2.5 million for prevention measures over 20 years, more than $170 million in expected losses and damages can be avoided. If a prevention program is not in place before zebra mussels are introduced and begin causing damages, eradication may be warranted. Over 20 years, the expected expenditure for eradication is −$185.9 million, which would serve to reduce impending damages by −$220 million. If a prevention program is in place and zebra mussels are detected before they can cause damage, early eradication would serve to supplant −$70 million in expected damages for an incremental cost of −$52.9 million over prevention alone.

Breakpoint Parameter Values

To test model robustness, we estimated breakpoint values for key parameters in the model. Here, we define breakpoint value to be the value at which the relative preference of the four management strategies changes based on expected net present value (NPV).

Simulation results show that if the annual probability of zebra mussel arrival were only 0.0004 (rather than 0.035), prevention would not be warranted. The optimal strategy would be to wait for zebra mussels to arrive and eradicate them when they are detected.

If the probability that introduced zebra mussels will propagate and grow to critical mass is 0.052 (rather than 1), prevention would not be warranted. Instead, managers should eradicate zebra mussels when they are detected.

Table 5. Breakpoint Parameter Values for Zebra Mussel Model

Optimal Strategy	Change Parameter	From	To	New Optimal Strategy
Prevention and early eradication	Annual probability of arrival	0.035	0.00040	Late eradication
	Annual probability of zebra mussel establishing	1	0.052	Late eradication
	Benefit (to fishing from zebra mussel)	$0.325 mil	$71.6 mil	Do nothing
	Annual cost of prevention and monitoring	$0.1528 mil	$8.7 mil	Late eradication
	Eradication cost	$55.03 mil	$72.08 mil	Prevention
	Eradication cost (annualized)	$1,320 mil	$1,729 mil	Prevention
	Eradication duration (years)	33	15	Prevention
	Value of wetland services (per year)	$64.98 mil	$48.09 mil	Prevention
	Value of wetland services (per acre)	$1,083	$801.4	Prevention
	Effectiveness of prevention measures	75%	1%	Late eradication

Recreational water users may advocate reduced zebra mussel management. Our simulations show that if the benefit from zebra mussels were instead $71.6 million per year (compared to our assumed value of $0.325 million), the advantages of allowing zebra mussels to enter Lake Okeechobee would outweigh the projected damages. In this case, neither prevention nor eradication would be warranted.

We found that if the annual cost of prevention ballooned to $8.7 million per year (versus our assumed value of $0.1528 million), prevention would be unwarranted, as there would be no advantage over late eradication. There would, however, be a slight advantage to being able to eradicate early versus late. Likewise, if the effectiveness of prevention at reducing the arrival rate fell to 17% (versus 75%), there would be no gain in prevention over eradication. Finally, if prevention cost were $9.7 million per year, early eradication would be unwarranted, and late eradication would be preferred.

If, on the other hand, the annual cost of eradication were $1,729 million per treatment (versus $1,320 million), neither late nor early eradication would be warranted. With high eradication costs, prevention measures take on more importance as a means of mitigating potential damages. As a reference, $1,729 million is equivalent to an annualized cost of $72 million per year for 33 years or the same treatment at $1,320 million lasting for only 15 years.

Estimated breakpoint values and the relative rankings of management alternatives appear in Table 5.

Summary

The zebra mussel is expected to reach Florida in the near future and thus poses a threat to consumptive water uses and wetland ecosystem services. Several years ago, the U.S. Army Corps of Engineers responded to the threat by outlining an education, monitoring, and prevention program for Lake Okeechobee. The program, however, was never funded. Although bringing live zebra mussels into Florida is illegal and punishable by fine, there is no other state or federal program to prevent zebra mussels from entering Florida or Lake Okeechobee. In lieu of prevention, eradication postarrival is an option, albeit a costly one.

This study examined the potential impact of zebra mussels on consumptive water uses, recreational fishing, and ecosystem services in Lake Okeechobee. A probabilistic model was developed to simulate the arrival and spread of zebra mussels and to assess the cost-effectiveness of alternate management strategies. Results indicate that both prevention and eradication of zebra mussels are economically justified for Lake Okeechobee.

These findings are based on the data we used to parameterize the model. Although we used the best data available to the study, some questions undoubtedly remain. To tackle these questions head-on and advance the dialog on this topic, we conducted a series of sensitivity tests around key model parameters. Specifically, we tested the probability that zebra mussels would arrive in Lake Okeechobee and the likelihood that they would survive and reproduce in this new environment. We also tested our assumptions on the effectiveness of a prevention program that would cost only $152,800 per year and brought into question the cost of a prevention program that boasted 75% effectiveness. Because documented eradications of invasive mollusks are few, we reexamined our assumptions regarding how much this action might cost, presuming eradication was technically feasible and environmentally desirable.

The battery of sensitivity tests was presented in the form of breakpoint values (i.e., borderline values of the tested parameters that would cause a change in the relative ranking of the preferred alternatives). Under the baseline model parameters, prevention with early eradication was most preferred, that is, offered the highest expected net present value. Next preferred was prevention alone, followed by late eradication, followed by the status quo, which is to do nothing. Our sensitivity tests showed that the cost-effectiveness of prevention is fairly robust over a wide range of model assumptions. For example, probability of arrival, habit suitability, and prevention effectiveness would have to be many times smaller or the cost of prevention would have to be many times larger to rule out prevention as a worthwhile public investment. In contrast, a mere 30% increase in the cost of eradication would cause this management activity to be ruled out on the basis of cost-effectiveness. Likewise, it would take only a 26% reduction in projected wetland losses due to zebra mussels to conclude that eradication might not be worthwhile.

To evaluate the eradication of zebra mussels from Lake Okeechobee, we used case studies from other locations to infer treatment procedures, chemical dosages, and overall cost. Better information will be required before managers will embark on a venture of this magnitude. Fortunately, the decision to eradicate can be postponed until zebra mussels have arrived, at which time we hope that more will be known. Because of the likely arrival of zebra mussels, their potential to induce economic and environmental damage, and the uncertainty regarding the technical feasibility and cost-effectiveness of eradication, this study provides empirical evidence for prevention as a sensible management option that is economically justified. Although additional scientific study could lend better data to improve the precision of our model estimates, the threat of zebra mussels will loom large until an effective prevention program is in place.

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