THE ECONOMICS AND LAW OF INVASIVE SPECIES MANAGEMENT IN FLORIDA

By

DAMIAN C. ADAMS

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2007

ACKNOWLEDGMENTS

I would like to thank my committee chair, Dr. Michael Olexa for his guidance and encouragement over the last several years. While I was languishing in the intellectual desert that is law school, Dr. Olexa provided a welcome oasis. Working with him as researcher for the Agricultural Law Center rekindled my interests in agriculture and inspired me to pursue a Master's degree in the Food and Resource Economics Department. Without Dr. Olexa, I might never have headed down the PhD path. For that and for the time he has spent helping me navigate the PhD coursework and dissertation red tape, I sincerely thank him.

I would also like to thank my committee co-chair, Dr. Donna Lee. Dr. Lee has provided countless hours of input and guidance on my research into the economics of invasive species. Dr. Lee has had a very big impact on my development as a researcher and an economist. Chapters two and three of this dissertation were wholly inspired by a course that she taught. She also helped me secure grant funding for the aquatic plants research, and we have since collaborated on other grant-funded projects. Dr. Lee is a wonderful researcher, a keen thinker, and a friend. I value her advice and admire her outlook on life, and hope to mirror her success.

I also thank Dr. Richard Kilmer, who is a wonderful mentor and perhaps the most industrious person I know. I have enjoyed our conversations on myriad topics very much, and hope to be even half as productive as he has been.

I would also like to thank Dr. John VanSickle. His feedback and his time are greatly appreciated. I benefited from hearing his perspective on this topic (and others) very much.

I also thank Dr. Roy Carriker. Dr. Carriker provided me with my first teaching opportunity, for which I am eternally grateful. He has also been a wonderful source of information on Florida water policy and law issues over the years. His time and input is appreciated.

I would like to thank Dr. Ricky Telg. Dr. Telg has invaluable feedback on my dissertation and has helped me to greatly improve its quality.

Lastly, I would like to that those outside of the UF campus who have helped me keep my sanity while writing my dissertation. These include my mom and other family members who have supported me and provided endless joke material; my friends, who were always there to make sure I did not get too mired in schoolwork; my golden retriever, Glen, a great companion; and Alison Lutz, who provided so much feedback on my dissertation that she should have been on the committee.

I am eternally indebted to all of them.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

THE ECONOMICS AND LAW OF INVASIVE SPECIES MANAGEMENT IN FLORIDA

By

Damian C. Adams

May 2007

Chair: Michael T. Olexa
Cochair: Donna J. Lee
Major: Food and Resource Economics

Invasive species impact Florida's ecology and economy across multiple dimensions. This dissertation examines the impacts of five invasive species in Florida, and evaluates management responses that follow. It first discusses potential infestation of Lake Okeechobee by invasive zebra mussels over twenty years using a bioeconomic model. Next, it estimates invasive aquatic plants' impacts on freshwater fishing in Florida. Lastly, it analyzes the legal foundations for state control efforts with respect to invasive species.

Zebra mussels are a serious threat to Lake Okeechobee, which is vital to agricultural producers and anglers and provides numerous ecosystem services. A bioeconomic model in a stochastic dynamic simulation framework estimates the impact of zebra mussels on recreation, surface water users, and ecosystem services over 20 years. Without state intervention it is $349.34 million. Policy responses were simulated. The cost-minimizing choice is to invest in arrival prevention and early warning, which reduces costs by 70.91% and is the only policy choice with positive returns ($247.71 million) compared to no control of zebra mussels. Post-establishment eradication yields large losses. This study indicates that investment in arrival prevention is more cost effective than post-arrival eradication.

Invasive plants have significant negative impacts on water-based recreation. Despite the high impacts, little economic research has quantified these impacts in a way useful to invasive species managers. Economic research conducted on aquatic invasive species usually focuses on a single lake, or is too abstract for managers. Data are usually unavailable for larger-scale studies. This study uses unpublished data to estimate the impact of plant coverage on fishing activity on 13 Florida lakes using a bioeconomic model. Policy response simulations estimate the impacts over five years. The results suggest that the optimal management policy is maintenance control with respect to hydrilla, water hyacinth, and water lettuce.

The dissertation then examines the failure of the state's Citrus Canker Eradication Program (CCEP). The CCEP cases are precedent for subsequent pest eradication program challenges. The State's power to take property, due process, and just compensation are reviewed. Lessons for subsequent eradication programs are provided.

CHAPTER 1
INTRODUCTION

The relatively free and rapid movement of people and goods across the globe has led to an increase in the invasion rate of many brittle ecosystems by prolific and destructive plants and animals (Vitousek et al., 1996; Mack, 2000). Once introduced to new areas, some of these species become "invasive," causing a significant proportion of environmental changes worldwide. Invasive species in the United States pose serious ecological and economic problems (Evans, 2003).

An invasive species is defined as a non-native species whose introduction "causes or is likely to cause economic or environmental harm or harm to human health" (Executive Order 13112, 1999). Invasive species are a particular problem for the tropical and subtropical areas of Florida, where physiographic, climatic and geographic characteristics make it relatively easy for non-indigenous species to establish (Simberloff, 1997; Fox [personal communication], 2007). Florida has a high rate of non-native species introduction, with the Port of Miami receiving about 85% of non-native plant shipments each year (OTA, 1993). For example, the entire United States has about 50,000 established non-native plant and animal species, with Florida alone having over 25,000 as exotic ornamentals (Pimentel, 2003); over 1,300 have established in natural areas, and 124 of these are destructive to natural areas (FLEPPC, 2006). By comparison, Florida only has 2,500 native plant species, and the US has 18,000 native species.

Invasive species are a growing economic concern. Today, there are an estimated 5,000 to 6,000 invasive species in the United States (Pimentel, 2003; Burnham, 2004), and invasive plants are invading about 700,000 hectares/year of natural areas in the US (Pimentel et al., 2000).

The detrimental problems resulting from invasive species have multiple dimensions. Adverse ecological impacts, such as the displacement of native species (both related and unrelated), leading to a reduction in the loss of native bio-diversity may cause severe disruption of complex natural ecosystems. They can have devastating ecological impacts, and may be the primary cause of biodiversity loss (Mack, 2000).

Economic impacts can follow close behind such detrimental ecological changes, affecting both the quality (and/or quantity) of public goods, and the interests of private entities. For example, the reduction of recreational benefits derived from public waterways (and the costs of managing offensive invasive species) highlights the public good dimension. Other effects, such as a reduction in property values and/or incurred mitigation costs, have an impact on private citizens and businesses, as well. Economic damages from invasive species are estimated to be $137 billion/year excluding ecosystem impacts (Pimentel et al., 2000). About 25% of US agricultural production is lost to non-native pests or to their associated control costs (Simberloff, 2002). When considering the well-documented impacts of certain invasive species, such as damages caused by *Hydrilla verticillata* in Florida, or the zebra mussel in the Great Lakes, it is clear that invasive species can have dire economic consequences.

With continuing increases in both global trade and the domestic and international migration of people to Florida, the rate of arrival of non-native species is rising. Invasive species management is fast becoming a high priority for the protection of Florida's agricultural and natural systems (Schardt [personal communication], 2007). Yet, despite the large economic and ecosystem harms associated with invasive species, there exists little empirical analysis of invasive species problems in a way that would help policy makers or resource managers (Schardt [personal communication], 2007). There are very few invasive species studies in the economics literature, and most of those are distinctly theoretical and too technical or abstract for use by policy makers or resource managers. Few empirical studies have evaluated the impact of invasive species. The issue of invasive species is one that much more attention (and perhaps budgetary expenditures) will likely be focused on in the near future.

In 2002, the US Governmental Accounting Office reported that "existing studies on the economic impact of invasive species in the United States are of limited use for guiding decision makers formulating policies for prevention and control" (USGAO, 2001). Damages to ecosystems, benefits from alternate controls, risks from future introductions, and multi-sector analyses have been lacking. More comprehensive approaches are needed to help decision makers identify potential invaders, quantify prevailing threat, and prioritize resources for mitigating damages. There is a great deal about invasive species growth, transmission, and other important information that is unknown. Perhaps this explains the lack of accessible economic studies on the topic. Unfortunately, despite these unknowns, given the serious risks to agriculture and natural resources posed by invasive species, policy makers will be called upon to allocate scare public resources in defense of natural and agricultural systems. Studies such as these, though based on several assumptions that have not yet been tested, provide important information to the discourse on invasive species management.

The purpose of this research is to examine the economic impacts of selected invasive species in Florida, and evaluate the management responses that follow. The specific objectives of the research are 1) to provide much needed empirical economic research on invasive species management; and 2) to examine the impact of litigation on invasive species management by state agencies.

Zebra Mussels

Chapter Two discusses the potential infestation of Lake Okeechobee by a fresh water mollusk, the zebra mussel. Zebra mussels (*Dreissena polymorpha*) are small freshwater mussels native to southeast Europe. They first arrived in the US in the Great Lakes region in the mid-

1980s, probably as free-swimming larvae in the ballast water of a transatlantic ship (Hebert et al., 1989; Griffiths et al., 1991; Thorp et al., 2002). Within a few years of introduction, zebra mussels (ZM) were in many major rivers and lakes in the eastern US (Hebert et al, 1989). Lacking significant competition or predation (New York Sea Grant, 1997) and possessing unique characteristics among freshwater mussels (Borcherding, 1991), the spread of ZM across North America has been rapid (Drake and Bossenbroek, 2004; NationalAtlas.gov, 2007; USGS, 2007). Their spread was greatly accelerated by recreational and commercial boating in and around the Great Lakes (Johnson and Carlton, 1996). Zebra mussels now inhabit waters in twenty eastern and southern states and continue to spread (USGS, 2007).

I construct a bioeconomic model to simulate the expected impacts of the zebra mussel (ZM) on the lake based on assumed transmission vectors (recreational boating), habitat suitability from a previous study (Hayward and Estevez, 1997), and effectiveness of ZM mitigation and prevention methods. I include assumed lake-related ecological and recreational values to construct an estimate of the total economic impacts with respect to a ZM infestation. I then apply state probabilities (in a stochastic dynamic simulation format) to arrive at a long-run economic impact analysis of ZM in Lake Okeechobee. I report present value results of the expected economic impacts over 20 years, including costs and damages to surface water use, recreational anglers, and users of ecosystem services, as well as budgetary costs. The results from this study indicate that investment in arrival prevention is much more cost effective than attempting to control or eradicate invasive species post-arrival.

Hydrilla, Water Lettuce, and Water Hyacinth

Chapter Three estimates the impact of the invasive aquatic plants hydrilla, water lettuce, and water hyacinth on freshwater fishing in Florida. Hydrilla is a submerged aquatic plant probably introduced as an aquarium plant in the 1950s, and first detected in Florida water bodies in 1960 (University of Florida, 2001; Langeland, 1996). Its rapid growth rate and suitability to Florida waters allowed it to spread rapidly throughout the state. By the early-seventies, hydrilla could be found in all major drainage basins in Florida. By 1995, hydrilla spread to over 40,000 hectares on 43% of the public lakes in the State (Langeland, 1996). It is believed that 98% of hydrilla is under maintenance control in 193 of the 288 water bodies where it is found in Florida (FDEP, 2003).

Water hyacinth and water lettuce are floating aquatic plants. Water hyacinth, native to South America, was introduced to Florida as an ornamental pond plant in 1885. Its rapid reproduction led to it being discarded into the St. John’s River and it spread quickly to neighboring water bodies (Schmitz et al., 1988). Water lettuce has been in Florida much longer, perhaps since the 16th century, and is also believed to be a native of South America (Schmitz et al). These plants are believed to be under maintenance control in Florida.

The problems with hydrilla, water hyacinth and water lettuce are multidimensional—ecological, economic, public and private. Ecological impacts include displacing native flora (both submersed and floating), altering habitat of native fauna, and disrupting of ecosystems processes. These invasive plants grow in thick monoculture mats which block sunlight to and out-compete native plants, especially in the increasingly nutrient-rich lakes and rivers of Florida as population growth increases nitrate and phosphate runoff. Dense monocultures can contribute to reduced fish populations, and when large mats of plants decompose, the reduced dissolved oxygen levels in a lake can cause massive fish kills. These plants also harm non-aquatic species by covering nesting and egg laying areas, and blocking access to water, shelter, and food sources.

Economic impacts follow close behind ecosystem loss. Hydrilla, water hyacinth and water lettuce can hinder boating, swimming, and fishing activities in lakes and rivers. Reduced sport fish populations coupled with access problems significantly reduce sport fishing activities. The reduction of recreational benefits derived from public waterways (and the cost of managing the weeds) highlights the public loss from invasive aquatic plants. They also affect private citizens and businesses, blocking power generators and agricultural irrigation water intake pipes, jamming water turbines and dams, and clogging canals and ditches. Infestations in private ponds and poorly managed public water bodies can reduce recreational and aesthetic value of waterfront property. Hydrilla has been difficult to eradicate because the plant produces underground tubers which generate new plants each year. Likewise, water hyacinth and water lettuce are extremely prolific, propagating both by seeding and by creating daughter plants vegetatively.

According to the FDEP (2002), "Insufficient management funding allowed hydrilla to expand from 50,000 to 100,000 acres during the middle 1990s." During this time period there was sufficient funding to continue water hyacinth (and water lettuce) control, which was considered of primary importance. Various aquatic plant control strategies have been considered, including mechanical removal, lake draw-down, application of various herbicides and biological control—both with insect and herbivorous fish species. Lake draw-down prevents most recreational use, and biological control remains difficult to control, leaving the use of herbicides as the primary management strategy for most lake managers (FDEP, 2006). Whatever method of control is chosen, there seems to be consensus that keeping invasive aquatic plant populations very low, known as maintenance control, is the most economically efficient funding strategy (Schardt, 1997). Florida has considerable experience fighting invasive aquatic plants (especially water hyacinth), yet Langeland (1996) asserts that lack of adequate and consistent funding for many invasive plants (especially hydrilla) continues to be the biggest barrier to effective management and the efficient use of public resources over time.

The economics of aquatic plant management in Florida have been examined, but only on one or two lakes at a time (Burruss Institute, 1998; Milon and Welsh, 1989; Milon et al., 1986). This study examines the impact of invasive plants on multiple lakes. I use unpublished data on plant coverage, angler effort, and lake physiographic and amenities to estimate a bioeconomic model of the impact of plant coverage on fishing activity on 13 Florida lakes. Using the bioeconomic model of invasive aquatic plants, I then simulate the single-year costs and benefits of six policy scenarios for aquatic plant control. Over five years, the estimated economic value of the 13 lakes is $76.4 million, and lapses in invasive plant control may jeopardize that value. These results suggest that the optimal management policy is maintenance control with respect to hydrilla, water hyacinth and water lettuce.

Legal Basis for State Control of Invasive Species

Chapter 4 discusses the legal foundations for state control efforts with respect to invasive species. Florida is no stranger to agricultural disease, particularly those affecting its citrus industry. Florida has twice successfully eradicated the invasive citrus canker (Division of Plant Industry, 2006). Citrus canker was first detected in Florida in 1910 and declared eradicated in 1947. However, in 1986, a highly aggressive Asian strain of the citrus canker was detected in Florida (Timmer, Graham, and Chamberlain, 2006).

In 1995, the Asiatic strain of citrus canker reappeared in Florida. Soon after, the state of Florida, in conjunction with the United States Department of Agriculture, began a citrus canker eradication program. As part of the program, residential owners of citrus trees suspected to harbor canker innoculum were compensated up to $55 per tree destroyed by the state. Angry homeowners sued to prevent further takings of their trees, and from 2000 to 2004 there were two 18-month lapses in the eradication program.

Subsequent to the lapses, there were five major hurricanes that helped spread the canker innoculum throughout the state, potentially crippling the commercial citrus industry (Albrigo et al., 2005). The hurricanes that passed over Florida in 2004 (Charley, Frances, Ivan, and Jeanne) spread citrus canker from these residential trees to such an extent that 80,000 commercial acres of citrus were subsequently slated for destruction. Concentrated efforts by governmental officials reduced this to 32,000 acres when Hurricane Wilma made landfall in 2005. Due to the spread of the citrus canker pathogen with Wilma, officials faced the task of destroying an additional 168,000 to 220,000 acres of commercial citrus (USDA, 2006). The inability of the State's canker eradication program to continue unabated meant the USDA canker eradication program was largely ineffective. On January 10, 2006, the federal government stated that citrus canker "is so widely distributed that eradication is impossible" and pulled the funding for the USDA's citrus canker eradication program (USDA, 2006). This change in policy came on the heels of a number of judicial decisions upholding the legality of Florida's citrus canker eradication program, but too late to save the USDA eradication program. Though the CCEP was repealed in January 2006 (Timmer et al., 2006), these judicial decisions will be precedential to potential challenges to similar State programs designed to manage and control pests like citrus canker and citrus greening (Salisbury, 2006). This portion of the research examines the legal framework that allowed these lapses, and provides suggestions for the creation of a program to combat a new invasive threat—citrus greening.

Summary

This chapter contains a broad overview of the significance and relevance of invasive species in Florida. In addition, the chapter addresses important background introductory information for each of the three topics included in this series. The first focus area for this series is the economic impact of invasive species in Florida, and its relationship with management practices and strategies. The second focus in the series examines the influence invasive aquatic plants have on the recreation and tourism industry in Florida, specifically in terms of freshwater fishing. Finally, the series concludes with an investigation into the issue of legal foundations for Florida's control of invasive species that may threaten agricultural production or harm natural areas. An overview of the State's use of police power to protect agriculture is addressed in conjunction with legal decisions that balance the exercise of this power with the constitutional mandates of due process and just compensation. These three issues are clearly germane to Florida's economy, environment, and law.

CHAPTER 2
OPTIMAL INVESTMENT IN PREVENTION AND CONTROL OF A POTENTIAL INVADER: THE CASE OF ZEBRA MUSSELS IN FLORIDA WATERWAYS

Introduction

Zebra mussels are a serious threat to several Florida waterways, particularly Lake Okeechobee. The lake is vitally important to agricultural producers and recreational anglers. It also provides numerous ecosystem services. We employ a stochastic dynamic simulation method with a bioeconomic model to estimate the impact of zebra mussels on recreation, surface water users, and ecosystem services. We estimate the present value of zebra mussel-related impacts without state intervention to be $349.34 million over 20 years. We simulated several potential policy responses. The overall cost minimizing choice is to invest in arrival prevention and early warning, which would reduce present value costs by 70.91%. This is also the only policy choice that netted positive returns ($247.71 million) as compared with doing nothing to control or prevent zebra mussels in the lake. Policies that include post-establishment eradication yield large losses ($414.98 million, $603.36 million). The results from this study indicate that investment in arrival prevention is much more cost effective than attempting to control or eradicate invasive species post-arrival. As with many invasive species, a great deal about zebra mussel biology, transmission, and other important variables is unknown. Unfortunately, zebra mussels and other invasive species pose serious risks to agriculture and natural resources. Despite the unknowns, policy makers will be called upon to allocate scarce public resources in defense of natural and agricultural systems. Studies such as this one, though based on several assumptions about zebra mussels that have not yet been tested, provide important information to the discourse on invasive species management.

Background on Invasive Species in the United States

The relatively free and rapid movement of people and goods across the globe has led to an increase in the invasion rate of many brittle ecosystems by prolific and destructive plants and animals (Vitousek et al., 1996; Mack, 2000). Once introduced to new areas, some of these species become "invasive," causing a significant proportion of environmental changes worldwide. Invasive species are non-native species that may cause economic, environmental or human health problems (Federal Register, 1999). In the US, production losses, control costs, and other associated costs related to invasive species is estimated to exceed $137 billion per year (Pimentel et al., 1999). About 25% of US agricultural production is lost to nonnative pests or to their associated control costs (Simberloff, 2002). They can also have devastating ecological impacts, and may be the primary cause of biodiversity loss (Mack, 2000).

In 2002, the US Governmental Accounting Office reported that "existing studies on the economic impact of invasive species in the United States are of limited used for guiding decision makers formulating policies for prevention and control." Damages to ecosystems, benefits from alternative controls, risks from future introductions, and multi-sector analyses have been lacking. More comprehensive approaches are needed to help decision makers identify potential invaders, quantify prevailing threats, and prioritize resources for mitigating damages. This chapter helps quantify the prevailing threat from an invasive aquatic mussel to a large Florida lake—Lake Okeechobee. We examine four policy responses and report the relative impacts on recreation, surface water use, and ecosystem services.

The Invasive Freshwater Zebra Mussel

Zebra mussels (Dreissena polymorpha) are small freshwater mussels native to southeast Europe. They first arrived in the US in the Great Lakes region in the mid-1980s, probably as free-swimming larvae in the ballast water of a transatlantic ship (Hebert et al., 1989; Griffiths et al., 1991; Thorp et al., 2002). Within a few years of introduction, zebra mussels (ZM) were in many major rivers and lakes in the eastern US (Hebert et al, 1989). Lacking significant competition or predation (New York Sea Grant, 1997) and possessing unique characteristics among freshwater mussels (Borcherding, 1991), the spread of ZM across North America has been rapid (Drake and Bossenbroek, 2004; NationalAtlas.gov, 2007; USGS, 2007). Their spread was greatly accelerated by recreational and commercial boating in and around the Great Lakes (Johnson and Carlton, 1996). Zebra mussels now inhabit waters in twenty eastern and southern states and continue to spread (USGS, 2007; Figure 2-1).

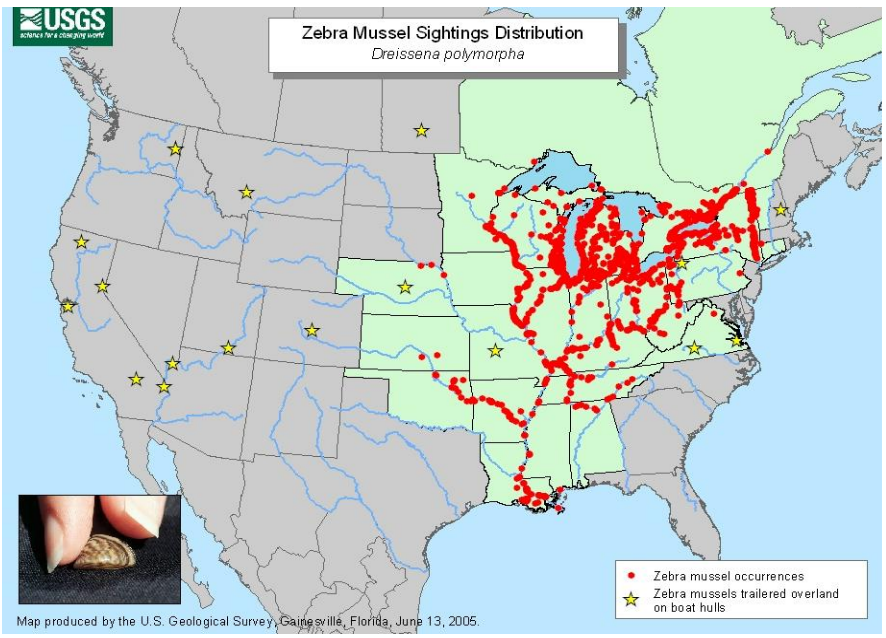


Figure 2-1. 2006 US Geological Survey map of zebra mussels in the United States.

Zebra mussels obstruct and foul man-made structures, impair water-based recreation, and disrupt aquatic ecosystems. They are often found on natural substrates such as submerged plants, logs, rocks, the shells of other animals, and on manmade structures such as bridge abutments, water intake pipes, and boat hulls. When colonies become large, ZM clog water intake pipes, accelerate corrosion, and sink buoys. In areas of the country where ZM have become established, water users face higher maintenance costs to remove mussels and restore water flows, and prevention costs, such as applying antifouling paint to submerged structures. From 1985 to 1995, expenditures for controlling zebra mussels in the United States totaled $69 million, and have since risen to over $60 million per year (Deng, 1996; USGAO, 2002).

Zebra mussels also cause ecosystem damages by disrupting native flora and fauna. Principally, they compete for food sources and habitat, and hamper movement of other species. Their success as invaders can be attributed to their rapid reproduction—females produce between 40,000 and one million eggs per year (USCACE, 2003). Because zebra mussels reproduce in large numbers, natural predators such as turtles, crustaceans, catfish, drum, and ducks have little effect on populations (Strayer, 1999). In areas invaded by zebra mussels, endangered native mussel species are at risk. By 2010, zebra mussels are expected to contribute to the decline in native mussel populations by 50%. Without further control efforts, 140 indigenous mussel species could be lost (USGAO, 2002). Cumulative damage from zebra mussels in the US including direct and indirect economic costs is estimated to be $3.1 to $5 billion from 2002 – 2011 (USGAO, 2002 and USGS, 2000).

Will Zebra Mussels Invade Florida?

North American ZM distribution forecasts are based on various environmental conditions, primarily water temperature (Drake and Bossenbroek, 2004). Initially, ZM were not expected to colonize warm waters due to their intolerance of high water temperatures (McMahon, 1991; Mihuc et al., 1999), but more recent studies report that they are able to withstand higher temperatures (Drake and Bossenbroek, 2004; Lewandowski and Ejsmont-Karabin, 1983; Jenner and Jansen-Mommen, 1993; Orlova, 2002) and may be adapting to local conditions (Marsden et al., 1996; Muller et al., 2001). ZM recently collected from warmer regions have higher heat tolerance than those from northern locations (Elderkin and Klerks, 2005).

ZM are now found in the lower Mississippi River and parts of Alabama (Allen et al., 1999; USGS, 2007), and are expected to spread to Florida (Hayward and Estevez, 1997; Drake and Bossenbroek, 2004). Two studies have predicted the suitability of Florida waters to ZM infestation; both report several lakes and rivers that are highly vulnerable to ZM. Drake and Bossenbroek (2004) use a machine-learning algorithm to predict spread based on several environmental factors. According to their model, North Florida has a high and South Florida a moderate likelihood of being infested by ZM. Hayward and Estevez (1997) calculate habitat suitability indices for Florida waters based on biology and demography studies. Several economically significant Florida water bodies are vulnerable to ZM invasion, including the St. Johns River and Lake Okeechobee (Hayward and Estevez, 1997).

Early studies also suggested that ZM would not colonize southern waters due to the relative lack of hard substrates and ZM inability to colonize soft sediments (Nalepa et al., 1995). Recent studies show that they have adapted well to soft sediments (Strayer and Malcom, 2006; Burlakova et al., 2006) and will colonize sand and mud if hard substrates are unavailable (Strayer, 1999). Floating and submersed aquatic plants also provide suitable hard substrates, but were not considered by earlier ZM distribution forecasts. Florida lakes and rivers, and specifically Lake Okeechobee, have abundant plant life that could provide suitable substrate for the invading mussels.

Model of Lake Okeechobee Zebra Mussel Infestation

Lake Okeechobee is a shallow, 448,000-acre lake located in South Florida. It is the second-largest lake wholly contained within the US. The lake is an important commercial shipping route, a valuable source of water supply, and a major economic and recreation resource (FDEP, 2001). It is the site of several major fishing tournaments each year, and supports commercial fishing operations. Lake Okeechobee draws 1.3 million anglers annually and supports a $117 million/year fishing industry (Lakeokeechobee.org, 2007). Five counties surround the lake, all of which pump lake water for agricultural, industrial, potable, and other uses.

Lake Okeechobee supplies a substantial percentage of freshwater used by municipal, industrial and agricultural sectors in the five-county region surrounding the lake (Table 2-1). In these counties, surface water makes up a large percentage of the water supply, predominantly for agricultural irrigation. For example, 94.49% of lake withdrawals are for agricultural irrigation, and municipal, power plant, mining, and industrial users make up 2.64%, 1.60%, 0.81%, and 0.42% of lake withdrawals, respectively. A ZM infestation would greatly increase the costs of these water users, as well as impact recreational and commercial fishing, and other environmental services provided by the lake; however, ZM would primarily affect agricultural surface water users.

Zebra Mussel Spread and Distribution

Zebra mussels exhibit three types of spread—diffusive (within a lake), advective (within a watershed), and jump dispersal (between watersheds) (Johnson and Carlton, 1996; Johnson and Padilla, 1996). Diffusive and advective spread of ZM occurs by free-swimming planktonic larvae according to population dynamics (Stoeckel et al., 1996). ZM spread and distribution studies have examined infestation of connected riverine areas or lakes within short distances of infested waters using reaction-diffusion models (Buchan and Padilla, 1999). Reaction-diffusion models allow range expansion of species that disperse and reproduce simultaneously, assuming constant dispersal velocity and intrinsic growth rate. Reaction refers to a change in local population (Holmes, 1993). A reaction-diffusion model may apply to ZM within a connected river ecosystem, or over short distances, but Lake Okeechobee falls into neither of these categories. The lake is distinctly isolated and would not be colonized by ZM without external assistance.

Table 2-1. Lake Okeechobee surface water supply by sector and county, year 2000.

	Counties Served by Lake Okeechobee						
	Glades	Hendry	Martin	Okeechobee	Palm Beach	Lake Okeechobee Total	Florida Total
Population (1000s)	10.58	36.21	126.73	35.91	1131.18	1340.61	12388.42
% population drinking water from surface sources	0.00	79.87	0.00	75.78	15.35	15.92	11.83
Irrigated acres (1000s)	25.21	169.58	59.81	23.14	446.85	724.59	1691.69
% Irrigation water from surface sources	72.07	61.71	87.14	15.71	93.80	80.75	51.41
% power plant, mining and livestock water from surface sources	100.00	100.00	100.00	100.00	69.90	78.06	23.76
% of total freshwater from surface sources	100.00	100.00	100.00	100.00	74.70	83.13	44.47

Source: USGS (2006).

Critical levels of connectivity help determine whether an invasive species will reach suitable habitats (With, 2002). Large gaps in habitat may be the reason why some species ranges are restricted (Holt et al., 2005). When these gaps are bridged by external forces, then reaction-diffusion models are insufficient because they fail to account for rare long-distance transmission events (Holmes, 1993; Hastings et al., 2005). For many invasive species, humans are the primary vector of transmission (Suarez et al., 2001; Jules et al., 2002; Buchan and Padilla, 1999). This can lead to species' geographic ranges greatly exceeding their natural dispersal abilities (Holt et al., 2005). For example, Higgins and Richardson (1999) estimate that a 0.01% of seeds moving considerable distances (1 – 10 km) can increase the spread rate of a plant species by an order of magnitude. Similarly, a reconstruction of the invasion of the Argentine ant (*Linepithema humile*) over the last century reveals a maximum and fairly constant local dispersal rate, with annual jump distances three times that rate (Suarez et al., 2001). Human-mediated jump dispersal is a concern that must be addressed by invasive species modelers.

The combination of local and human-mediated jump dispersal may result in a lack of agreement between linear models and empirical data (Hengeveld, 1994; Suarez, 2001). Velocities estimated from linear spread models may appropriately provide an upper bound for species spreading within a homogenous system (Holmes, 1993; Hastings et al., 2005), but will likely underestimate spread when human transportation is involved and jump dispersal occurs. Buchan and Padilla (1999) underestimated observed ZM spread rates by almost half due to a failure to account for long-distance dispersal. Neubert and Caswell (2000) provide other examples of underestimated spread rates due to human interaction. The probabilities associated with jump dispersal may be very low and difficult to estimate. Despite these small probabilities, they appear to be the driving factor for migration patterns for many species (Allen et al., 1991;

Lonsdale, 1993; Dwyer et al., 1998; Bossenbroek et al., 2001; Suarez et al., 2001; Hasting et al., 2005), and should not be ignored.

Three studies of ZM dispersion specifically addressed the issue of human-mediated jump dispersal. Bossenbroek et al. (2001) developed a ZM gravity model based on data on registered recreational boats per county. A similar study used lake surface area as a proxy for relative lake attractiveness in Indiana, Michigan, Wisconsin and Illinois (Kraft and Johnson, 2000). They found that small lakes (those with less than 100 hectares) had lower rates of infestation. Kraft et al. (2002) conducted spatial analysis using Ripley's *K* statistic to estimate the probability that invaded lakes would be found within a particular distance of invaded lakes. ZM-invaded lakes in the United States are found to be aggregated at less than 50 kilometers and segregated at greater than 200 kilometers (Kraft et al., 2002). These findings confound simple diffusion models and suggest that ZM dispersal is better defined by long-distance dispersion events and subsequent spread within lakes or connected lake systems.

The likely human-mediated vectors of ZM transmission to lakes over long distances are recreational boating, commercial boating (of ships not obeying existing ballast water procedure laws), and intentional introduction (Carlton, 1993). Commercial vessels are required by federal law to empty their ballast water prior to entering Lake Okeechobee. These efforts have been effective and are credited with a large slowing of the rate of ZM spread. Here, we assume that ZM spread by commercial vessels will not occur. Intentional introduction is not uncommon with invasive species that are perceived to improve the productive or recreational value of land and water bodies (e.g., water hyacinth, hydrilla, and *Melaleuca*). ZM are known to clarify the water column, so there is a possibility of intentional introduction. However, the probability of such an introduction is unknown but we assume (and hope) that current educational efforts will prevent an intentional introduction of ZM to Lake Okeechobee.

Recreational boating is the likely overland transmission vector for ZM, and has been shown to be the primary transmission vector of unconnected water bodies in and around the Great Lakes region (Johnson and Carlton, 1996; Buchan and Padilla, 1999; Bossenbroek et al., 2001). For example, about 25% of recreational boat trailers leaving ZM infested lakes in Michigan carry adult ZM (Ricciardi et al., 1994). Johnson and Carlton (1996) estimated that 7.8 ± 9.2 of trailers at public boat ramps transported entangled vegetation with 2.7 ± 2.0 mussels attached on trailers leaving infested lakes. In addition, they estimated that 1/275 trailers inspected entering uninfested lakes had ZM living on entangled macrophytes. ZM are commonly found at 1000 adult mussels per meter of aquatic plant stem length. For the purposes of this study, we assume that any transmission of ZM to Lake Okeechobee will be unintended, and by recreational boaters.

Bioeconomic Model of the Zebra Mussel Threat to Lake Okeechobee

We use a Markov approach to forecast the likelihood of ZM infestation in Lake Okeechobee and to estimate the long term expected public and private cost under alternative policy scenarios.

Lake Okeechobee is not connected to any watershed known to be infested with zebra mussels. The river system in the Florida Panhandle is the closest distance to ZM-invaded waters, but the water chemistry in this system is inhospitable to ZM. Any ZM invasion to Florida is likely to come in the form of the human-mediated movement of water (with larvae) or submerged objects (with juvenile or adult mussels) over long distances. For ZM to reach Lake Okeechobee, a dispersal barrier of nearly 1200 km must be jumped. The stress of overland transport (Ricciardi et al., 1995) and the low numbers of mussels transported during a single dispersal event (Johnson and Padilla, 1996) make the overland transmission of ZM a rare event, but one that should not be ignored. Here, we use a stochastic dynamic simulation approach to estimate the potential ZM invasion within a gravity model of jump dispersal based on boater behavior.

We assume that new ZM introduction occurs when a boater travels to an infested lake and then to Lake Okeechobee within a short enough time for ZM to survive the transmission. ZM become established when the mussels reproduce and populate the lake to carrying capacity. At carrying capacity ZM masses will be sufficiently large to cause both environmental and economic damage. Thus, there are four distinct states regarding zebra mussel masses in the Lake Okeechobee Waterway: not invaded (s_1), arrived (s_2), growing (s_3), and carrying capacity (s_4).

At present time t = 0, the state is "not invaded," thus

(1) $$S_0 = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}.$$

At time t in the future, St is given by

(2) $$S_t = A^t S_0$$

where A is a 4x4 matrix of transition probabilities

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

A is composed of a_{ij}, the probability of transitioning from state j to i in a single time period.

At any time t, S_t is

$$(4) \qquad S_t = \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix}_t \quad where \quad 0 \le s_i \le 1$$

The expected future costs of mitigating the threat and infestation of zebra mussels is C_t where C_t is a function of the state S_t and the choice of management methods X. For ZM we consider two types of public management: (1) "prevention" which entails both screening and education measures to reduce the probability of arrival, and monitoring to provide local water uses with early warning information ($x_1 = 1$); and (2) "eradication" which involves use of a molluscicide to effectively kill all ZM in the lake ($x_2 = 1$). The annual cost of management C_t is expressed as the product of management (X), zebra states in compact form (θ), and unit cost of management (q):

$$(5) \qquad C_t = X' \, \theta_t \, q$$

Where X, θ_t and q are

$$(6) \qquad X = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$(7) \qquad \theta_t = \begin{bmatrix} s_1 & 0 \\ 0 & s_4 \end{bmatrix}_t$$

$$(8) \qquad q = \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$$

Direct use damages from zebra mussel infestation include losses to recreation uses and increased maintenance costs due to ZM fouling. In equation (9), d_i are annual ZM damages in state i

(9) $$D = \begin{bmatrix} 0 \\ d_2 \\ d_3 \\ d_4 \end{bmatrix}$$

Ecosystem service losses from zebra mussel infestation include diminished ecosystem functions such as wildlife habitat and aquatic food supply. In equation (10), e_i are annual ZM ecosystem losses in state *i*

(10) $$E = \begin{bmatrix} 0 \\ e_2 \\ e_3 \\ e_4 \end{bmatrix}$$

The management objective is to choose a management strategy bundle X to minimize Z, the present value of total expected costs from the threat of ZM infestation:

(11) $$Z = \sum_{t=0}^{T} (1+r)^{-t} \left(C_t(X, S_t) + S_t^{'}(D + E) \right)$$

In equation (11), r is the annual discount rate and T is number of years in the planning time horizon.

Empirical Approach

Parameters of the transition probability matrix (Eq. 3) are estimated using ZM arrival, survival, and population dynamics studies in conjunction with Lake Okeechobee environmental information and data on boating activity. For example, the probability of a ZM establishment (a_{12}) is a function of the number of boats arriving at the lake from ZM infested waters, ZM survival during the trip and after introduction, and the length of time it takes for ZM to establish a viable colony. Once established and growing, ZM survival, population dynamics, and control efforts define the probabilities of the ZM population becoming endemic and causing high levels of damages (a_{34}), being established without causing significant harm (a_{33}) or being effectively nullified (a_{32}). Large economic and ecological damages occur when ZM populations reach carrying capacity in the Lake in state 4. Determining the above parameter values, as well as damage and cost estimates, is a difficult task that requires an exhaustive review of ZM experiments and studies. In the following sections, we present and discuss the parameter estimates and data derived from previous ZM research.

Arrival and Survival

ZM rate of arrival to Lake Okeechobee is assumed from recreational boating data. While most recreational boating activity is local, a small percentage of freshwater boaters in the United States travel very long distances within short periods of time (Buchan and Padilla, 1999). For example, 26% of Wisconsin boaters visit a lake or river during any given 2-week period, 8.4% trailer their boats more than 50km, 3.4% more than 106km, and 0.8% more than 261km.

General boating patterns and number of interstate fishing trips involving Lake Okeechobee are unknown, but there are several fishing tournaments and circuits that draw participants from the entire US, Canada, and even Japan to parts of Florida and from Florida to parts of the Southeastern US with known ZM populations. We use fishing tournament data as a proxy for the arrival rate of boats with ZM veligers or adult mussels. We surveyed angler competition rosters from three national fishing tournaments to determine frequency of participation in tournaments by anglers from states known to have ZM. According to a 2006 USGS map of ZM distribution (USGS, 2007), ZM are found in 24 states. Of the 926 anglers participating in three national tournaments on Lake Okeechobee from 2006 – 2007, 50.45% were from one of these states (Carson, 2007; Eads, 2007). Results confirm Buchan and Padilla's (1999) findings and indicate that tournament participants travel long distances often within short periods of time. We assume that 900 anglers per year fishing on Lake Okeechobee would have come into contact with ZM prior to fishing on the lake.

We must also account for the environmental stresses on ZM during the long-distance trip, as well as seasonal timing. Adult mussels are known to survive out of water for long periods of time, on average 3 – 5 days under temperate summer conditions (Ricciardi et al., 1994; Griffiths et al., 1991) and up to a few weeks in wet fishing nets in Europe (Buchan and Padilla, 1999). Large (21 – 28mm) mussels can easily survive >5 days out of water, and a small percentage of large adult ZM (10%) can withstand 10 days exposure under ideal conditions (Ricciardi et al., 1994). Live wells hold the greatest risk of ZM dispersal. Larvae are discovered in 83% of boat live wells, with densities of 111 ± 222 (1 sd) larvae/liter. A typical boat has a 38-L live well, for an average transportation potential of 4,200 larvae (Johnson and Carlton, 1996).

The timing of dispersal can influence the spread rates on invasive species (van den Bosch et al., 1992). Given environmental stressors, ZM may arrive at Lake Okeechobee several times before a successful colonization occurs. This may explain why Johnson et al. (2001) overestimated ZM colonization of Wisconsin lakes, as they assumed “suitable” lakes would be suitable at all times of the year. Also, they ignored seasonal boating patterns. Boating in the Great Lakes region occurs mostly from April to October, with the warm summer months seeing most of the activity (Penaloza, 1991). June – August averages between 1.25 – 1.69 million boater-days, while October and April only averages 0.56 and 0.24 million boater-days, respectively. Similar, but seasonally reversed, patterns of boating behavior may be found in Florida, when hot and humid summer months create uncomfortable conditions for boaters and reduce fish activity. Florida’s main fishing tournament season begins in February of each year and ends in June (Eads, 2007). Mussels are actively settling or are active as larvae during about 5 months of the year. ZM generally have two spawning periods: 1) from April to July, and 2) in August (Haag and Garton, 1992; Griebeler and Seitz, 2006; Jantz and Neumann, 1998). During these times, free-swimming veligers are abundant in water that may be transported to Lake Okeechobee. Only when both boaters and ZM are active do they pose a significant threat of infestation to Lake Okeechobee.

We apply estimates of Lake Okeechobee habitat suitability to estimate ZM survival upon arrival. Hayward and Estevez (1997) estimated habitat suitability indices (HSI) for zebra mussels based on seven environmental variables: temperature, dissolved oxygen, pH, Secchi depth, salinity, calcium, and sediment size. They conducted a meta-analysis on ZM life-cycle studies and calculated HSI that ranged from 0.0 ("perfectly unsuitable") – 1.0 (optimal) using 281,780 data records from the US Environmental Protection Agency's STORET database for 9,028 sites in Florida and calculated composite HSI for each site. They estimated that 21% of the sites had composite HSI over 0.5, and 3% of sites had HSI above 0.8. Composite HSI were calculated for western Lake Okeechobee (very shallow, high aquatic plant density) and for the lake proper (open water). The HSI were 0.91 and 0.83, respectively, making the lake highly suitable to ZM (Hayward and Estevez, 1997).

Based on the above, we assume a 3.5% annual probability of ZM introduction and establishment. This probability is in line with Bossenbroek et al. (2001), who estimated the probability that a single boat would cause colonization in states surrounding the Great Lakes to be between 0.0000118 – 0.0000411 per arrival by infested boat, or up to about 3.7% chance when a lake experiences 900 arrivals by boats in contact with ZM-infested waters.

Reproduction and Spread

An appropriate estimate of the rate of spread within a water body depends on assumptions about the population dynamics. The life history of ZM has been reviewed by several studies

(McMahon, 1991; Ackerman et al., 1994; Mackie and Schloesser, 1996; Nichols, 1996). ZM development is very quick. Eggs develop into larvae for 1 day if fertilized (Sprung, 1987; Borcherding, 1991; Ackerman et al., 1994). ZM need between 2.5 and 4 weeks to reach the juvenile stage (Borcherding and de Ruyter van Stevenick, 1992; Griebeler and Seitz, 2006; Sprung, 1987). Several studies estimate ZM survival rates for various life cycle stages (Stoeckel et al., 2004; Orlova, 2002; Sprung, 1993; Thorp et al., 2002). During the ZM larvae (free-swimming) stage, mortality is high (Orlova, 2002). Sprung (1993) estimates an egg to adult mortality of 0.999913. Within about two months of spawning, juveniles will "settle" and attach to substrates. Once settled, mussels quickly mature. Females produce between 40,000 and one million eggs per year (USCACE, 2003).

Initial invasion studies indicate that ZM reach carrying capacity 2 – 3 years after detection (Nalepa et al., 1995; Strayer et al., 1996; Burlakova, Karatayev, and Padilla, 2006; Borcherding and Sturm, 2002; Lauer and Spacie, 2004). Average carrying capacity is about 10,000 ZM/m^2 over a representative lake (Griebeler and Seitz, 2006). Once carrying capacity is reached, about half of ZM populations will vary from 10 – 30% each year, while the other half periodically crash and recover, typically in 4-year cycles (Ramcharan et al., 1992). Whether stable or cyclic, ZM populations reproduce very quickly. The Hudson River experienced 4000/m^2 by the end of 1992 after a first detection in May 1991 (Strayer et al., 1996). Akcakaya and Baker (1998) report ZM density on the upper Mississippi River from first detection in December 1991 – October 1995 in three locations. In December 1991, ZM were at less than .1/m^2. The populations grew at a steady exponential rate, reaching about 3000/m^2 by October 1995. Beckett et al. (1997) reported ZM densities on dam locks from 50,000 – 75,000 individuals per m^2 within three years of first detection in the Lower Mississippi River. For our calculations, we assume that ZM may reach their carrying capacity within 2 years of introduction.

Direct Economic Costs and Damages

ZM is a known hazard that the state of Florida has taken steps to curb, including low-power radio alerts warning travelers near the Florida border, and criminal fines—bringing ZM into Florida is a 2nd degree misdemeanor with a $500 fine and up to 60 days in jail (University of Florida News, 1999). One federal agency—the US Army Corps of Engineers (USACE) is also working to prevent the introduction of ZM. In 2003, they proposed a monitoring plan to detect the introduction of zebra mussels in the Okeechobee Waterway (see Figure 2-2). The monitoring plan would include (1) education materials (alert/identification cards, pamphlets, and posters) distributed to boaters, homeowners, and businesses along the waterway to involve the community in detecting zebra mussels when they first arrive, and to enlist boaters' help in preventing ZM spread by cleaning boat live wells and trailers before entering the lake; (2) underwater inspections conducted by divers in conjunction with existing inspections of manatee screens and lock gates; and (3) substrate sampling to detect settlement of juvenile zebra mussels four times per year. Dive inspections at each of the 5 major structures to survey for ZM would cost approximately $25,000 per inspection. The USACE proposed inspection plan calls for quarterly inspections, costing approximately $100,000/yr. Additional costs would be about $700/inspection for USACE labor (Crossland, 2007). We further assume that educational efforts would cost $50,000/yr, for a total monitoring plan cost of $152,800/yr. Early detection measures afford surface water users time to retrofit their equipment pre-invasion, and prevention efforts may be effective at reducing the probability of ZM introductions.

Unlike other invasive species commonly found in Florida, there may not be a feasible method of controlling the spread of ZM once widely established within a lake system. Control alternatives include potassium chloride, molluscicide carbon dioxide (to reduce dissolved oxygen), chlorine, lower pH, increasing salinity, dewatering, and copper sulphate (VDGIF, 2007). Of these, only potassium and molluscicide are considered to have negligible effects on the long run health of the aquatic environment. Both potassium and molluscicide have similar costs per treatment ($2,028 versus $1,778 per million gallons, respectively), but potassium levels will provide long-run protection against ZM whereas molluscicide applications do not.

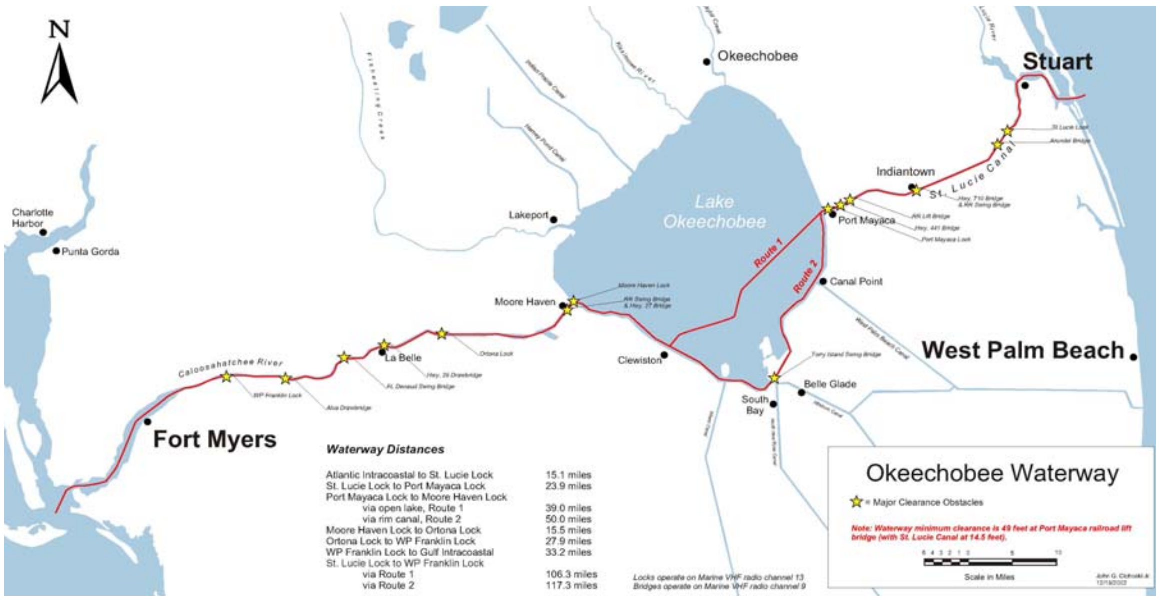


Figure 2-2. Lake Okeechobee waterway.

There is only one known instance of ZM eradication. The Virginia Department of Game and Inland Fisheries successfully eradicated ZM on Millbrook Quarry using high levels of potassium chloride (98 – 115 parts per million) over several weeks at a cost of $365,000 (VDGIF, 2007). They used 174,000 gallons of the chemical over three weeks in January and February, 2006, at a concentration of 100 parts per million. This is twice what is expected to kill 95% of the ZM, but below what would create serious human health or environmental concerns. It is estimated that the potassium levels now found in the quarry will not significantly impact fish or human health, and will protect the quarry from further ZM infestation for approximately 33 years.

Millbrook Quarry is a 12-acre, 93-ft deep quarry (approximately 180 million gallons). By contrast, Lake Okeechobee is a 448,000 acre lake with an average depth of 9 feet (approximately 1.31 trillion gallons). Lake Okeechobee is 3,613 times larger (in water volume) than Millbrook Quarry. A potassium treatment on Lake Okeechobee similar to Millbrook Quarry would require 628.6 million gallons of potassium at a cost of $1.32 billion based on Millbrook Quarry treatment levels and costs.

Recall that almost 95% of surface water withdrawals from Lake Okeechobee are for agricultural irrigation. ZM on Lake Okeechobee would clog surface water intake pipes. Surface water impacts of ZM are more likely to be in form of cost increases rather than lost revenue or production losses. Only 6.3% of respondents to a 1996 study of Great Lakes surface water users reported production losses (Hushak, 1996b), and electric utilities and industry report a 0.0045 percent output loss (Hushak and Deng, 1997). Therefore, we focus on the potential increases in maintenance costs rather than calculating production losses to agricultural surface water users.

Several studies report the impacts of ZM on surface water users (O'Neill, 1996; Deng, 1996; Park and Hushak, 1996; Phillips et al., 2005). O'Neill (1996) reports average costs per water use facility for a wide range of water users—industrial, public supply, power generation, and others. Deng (1996) provides estimates of variable ZM maintenance and control costs as a function of gallons of water used for five ZM control technologies for private and public water utilities, and other industrial users. Park and Hushak (1999) surveyed large surface water users from 1994 – 1995 regarding their annual ZM monitoring, control and research costs. Utility and industry users were classified as small (0 – 10 million gallons/day), medium (11 – 300 mgd), or large (>300 mgd) water users. The average control and monitoring costs to industry facilities were $10,000, $92,000, and $439,000 for small, medium, and large water users, respectively. Hushak (1996b) estimates total ZM expenditures average $0.43 million/facility over 5 years. Small facilities (<5 million gallons/day) have expected costs <$20,000 per year; large facilities (>300 million gallons/day) can expect ZM to cost them $350,000/year (Hushak, 1996b). ZM-impacted industries in the US reported mean ZM-related expenditures of $167,030 per facility for 60.3 mgd average capacity. Mean expenditures on prevention were $92,833, on planning were $37,190 per facility, on monitoring were $14,393, on retrofit were $48,200, and on mechanical or other control technologies were $6,406 (O'Neill, 1997). Currently, the average maintenance cost for annual cleaning of water intake screens costs $6,240, but would increase 7-fold following ZM infestation (O'Neill). Chemical treatment of zebra mussels by industrial facilities has an average cost of $1.13 per million gallons of water treated for the least cost alternative—chlorine (Deng, 1996). This method has up to 95% effectiveness, but only relatively large surface water users are likely to employ this due to the technical challenges. Non-industrial surface water users will likely opt for physical and thermal treatments, which cost $4.90/mgd.

Using variable and percentage increase in total costs estimates from O'Neill (1996), Deng (1996), Park and Hushak (1996a, 1996b), Hushak (1999), Hushak and Deng (1997), and Phillips (2005), we employ a cost-transfer methodology to estimate the potential impact of a ZM infestation to Lake Okeechobee surface water users (Rosenberger and Loomis, 2001). According to the most recent available data, surface water withdrawals from the lake average 1541.34 million gallons per day (USGS, 2006). We apply an average cost of $4.90 per million gallons for physical and thermal treatments according to Deng (1996) to arrive at an estimated average maintenance cost increase of $2.76 million per year for agricultural surface water users following a full ZM infestation in Lake Okeechobee.

Phillips (2005) reports the estimated ZM prevention-related costs on hydropower facilities. Application of anti-fouling paint, including labor, was estimated to cost hydropower facilities $25.56 per square foot in year 2005 dollars. It is not known how long the paint will remain effective against ZM before needing to be reapplied, but we assume that the paint will remain effective for 10 years. Water use and permit records are maintained by the South Florida Water Management District. We obtained records of the 2003 permit holders, which included permits for 504 surface water intake pipes. We conducted a telephone survey (Appendix A) of these users from May – August, 2006 and achieved a 7.1% response rate, largely due to stale contact information. The survey included questions regarding average annual maintenance costs, surface water use, location, presence of invasive aquatic plants (which are likely to impact maintenance costs), average daily withdrawal, frequency of maintenance (times per year), whether the maintenance was contracted out or performed in-house, type of maintenance (physical, chemical, or other removal method), the location of the facility (county), and questions regarding their knowledge of ZM. Mean annual maintenance costs are reported to be $8,936 (sd = $3,913) and they have average water intake pipe diameter and length of 1.91ft (sd = 0.35) and 50.14 ft (sd = 27.23), respectively. This provides a mean intake pipe surface area of 300.58 ft. Assuming 504 intake pipes for the lake, we estimate a total cost for anti-fouling paint of $3.87 million.

Ecological and Recreational Damages

In addition to the impacts on surface water users, a ZM infestation may negatively impact recreation and lake ecology. Following a ZM infestation, lake ecology will change dramatically. ZM can reduce plankton populations by 85% (USACE, 1995), increase water clarity, double phosphate levels, and significantly reduce native mussel populations (Caraco et al., 1997;

Strayer, 1999). In the Upper Mississippi River, native mussel populations dropped with the introduction of ZM; declines in native mussels included two federally listed species (Whitney et al., 1995). ZM in the Hudson River were >70% of the zoobenthic biomass, filtering the equivalent of the entire water column per day (Strayer et al., 1996). Adult ZM can filter up to 1 gallon of water per mussel/day (USGS, 2000). ZM can remove up to 62% of a lake's primary littoral production (Ramcharan et al., 1992), fundamentally altering the aquatic food chain (Caraco et al., 1997). Stoeckmann and Garton (1997) estimate that ZM populations in the range of 10,000 to 50,000 mussels/m² consume 10% to 50% of summertime primary lake production.

Studies of the effects of ZM on fishing are mixed. On one hand, the number of fishing trips was seen to decline dramatically in the Great Lakes following the ZM. In the Great Lakes region, 78.5% of respondents who said that ZM affected the amount of time spent on Lake Erie reported spending less time on the lake, with a decline in fishing trips from 11.2 to 6.3 from 1990 – 1992 (Hushak, 1996a). On the other hand, field studies of fish stocks in the Hudson and Great Lakes regions report a significant decline in open water fish species, but a significant increase in littoral fish species, which are responsible for all of the recorded recreational fishing activity on Lake Okeechobee. Strayer et al. (2004) examine 26 years of data on fish populations on the Hudson River to ZM effects on littoral and open water fish species. The median decline in open water fish species was 28%, while littoral species experienced a median increase of 97% (Strayer et al., 2004). Many of these species were of recreational importance. Open water species of recreational importance included herring, shad, striped bass, and perch, and littoral species included carp, shiner, bluegill, smallmouth bass, largemouth bass and darters. Overall biodiversity and fish biomass fell after ZM arrival (Strayer et al., 2004). According to unpublished fishing effort data from the Florida Fish and Wildlife Conservation Commission, there are four recreationally significant fish groups on the lake—black crappie, catfish, largemouth bass, and pan fish. These species are all littoral zone species.

For some lake systems, the reduction in phytoplankton accompanying a ZM introduction may increase also mitigate the impacts of eutrophication (Ulanowicz and Tuttle, 1992).

We must also consider the potential for other invasive species to flourish following a ZM infestation, and the negative impacts that would have on fishing effort. Increased water transparency can cause the increased abundance of submersed aquatic plants, as was the case in Lake Huron (Skubinna et al., 1995). This may exacerbate invasive aquatic plant problems on Lake Okeechobee. Snail populations may also significantly increase following a ZM introduction (Strayer, 1999), and may include the invasive apple snail that is threatening Florida waters. Given the above, we assume an increase in fishing effort of 10% following a ZM infestation. The average total hours spent fishing on Lake Okeechobee from 1983 – 2002 was 4,316 hours/day (FFWCC, 2003). Assuming that effort has a direct and linear relationship to available fish species, we expect an increase in fishing effort by 431.6 hours/day. According to the Florida Fish and Wildlife Conservation Commission, freshwater anglers on Florida lakes spent an average of $20.65 in 2002 dollars (FFWCC, 2003). This equates to a $3.25 million gain per year.

There is also the potential for fundamental changes to aquatic plant life that would hamper the functioning of wetlands. Lake Okeechobee has 29,000 acres of Audubon Society wetlands, and a further 31,000 are assumed from visual inspection of aerial maps. Costanza et al. (2003) estimate a per hectare value of lake services of $8,498. Of this, $439 per hectare was for wetland services. We assume that 60,000 acres of wetlands connected to the lake are vulnerable to injury from ZM infestation, and a 2% inflation rate for the Costanza et al. value.

Effectiveness of Management Methods

There are two methods x_1 and x_2 that may be employed singly or jointly to mitigate ZM-related damages. Investment in prevention is given by $x_1 = 1$ which includes efforts to detect and prevent the arrival of ZM and provide water users early warning of ZM establishment in the lake. These efforts may include brochures, posters and pamphlets alerting the public to the ZM threat, and boating regulations requiring that hulls be free of mussels and macrophytes, and live wells be empty prior to entering Lake Okeechobee. It also includes the USACE monitoring program that would provide early warning to surface water users at a cost of $152,800 per year. We assume that the USACE monitoring program will reduce annual probability of arrival by 75%, or from 3.5% to 0.875%. Sensitivity analyses of this parameter are included in the results section.

Investment in ZM eradication is given by $x_2 = 1$. ZM were effectively eradicated from Millbrook Quarry, VA using potassium chloride. The same protocol for Lake Okeechobee would cost $1.32 billion chemicals and labor costs and would provide an additional 30 years of protection from future introductions.

A cost mitigating measure is the application of anti-fouling paint on the interior of surface water intake pipes which would effectively reduce the cost of keeping pipes free of fouling organisms including ZM. Paint and labor costs are $25.56 per square foot of pipe and each application is good for 10 years. We assume water users would apply anti-fouling paint after they detect ZM which would occur post-establishment. With an early warning system in place, water users would apply antifouling paint before ZM is established thereby avoiding maintenance expenditure due to ZM clogged pipes. If ZM are eradicated, antifouling paint application becomes unnecessary.

We assume that once ZM are introduced into Florida waters, the mussels would become "established" i.e., they begin reproducing in one year. After two years the mussel population would reach the carrying capacity of the lake. If an early monitoring program were in place (x_1), then surface water users would have sufficient time to prepare. Without early warning, initial ZM damages will be 10% higher due to a lag in x_3 application similar to the findings of O'Neill (1997), Deng (1996) and others. In the Great Lakes region, it took about 6 years following ZM introduction for costs to stabilize, largely due to initial ZM spread rates and late adoption of retrofitting. Small water users (0 – 10 million gallons per day) did not begin retrofitting water intake pipes and other equipment until 3 years after ZM were detected, largely due to a lack of appreciation for the potential impacts of the mussels. This lag in uptake of antifouling measures caused ZM-related costs to jump from \$2,000 per facility to about \$15,000 per facility from the 3rd to 4th years following ZM introduction. Within 2 years after retrofitting began, control costs fell by over 73% (O'Neill, 1997). We assume ZM-related maintenance costs will be \$2.76 million with antifouling paint applied before ZM reach carrying capacity. Without the early warning system, the lag in application of anti-fouling paint will increase maintenance costs by 27.75%, or \$3.37 million. We also assume that once ZM have arrived, monitoring and prevention costs will fall to zero. A summary of parameter values used in the ZM model are reported in Table 2-2.

Policy Scenarios and Results

At present, there is no State plan in place to monitor, prevent, or eradicate ZM in Florida. Thus, to examine the widest range of plausible options we constructed the following four scenarios. Policy scenario I is the current policy being pursued by the state—do nothing with respect to ZM. Policy II provides state funding for labor and technology to prevent introduction of ZM to Lake Okeechobee and to monitor the lake and its entry points to detect the presence of live ZM. Policy III foregoes prevention with a plan to eradicate ZM as soon as it is detected.

Table 2-2. Zebra mussel model parameter values.

Symbol	Definition	Value
a_{11}	Annual probability of ZM not arriving to Lake Okeechobee	0.965
a_{21}	Annual probability of ZM arrival/year without x_1 (arrival prevention and early warning)	0.035
a_{21}	Annual probability of ZM moving from state 4 (carrying capacity) to state 1 (not invaded) with eradication	1
a_{32}	Annual probability of ZM moving from state 2 (arrived) to state 3 (growing) without eradication	1
a_{43}	Annual probability of ZM moving from state 3 (growing) to state 4 (carrying capacity) without eradication	1
a_{44}	Annual probability of ZM staying in state 4 without eradication	1
Other a_{ij}	Annual probability of ZM moving from state j to state i	0
c_1	Annual cost of arrival prevention and early warning	\$152,800
c_2	Total cost of eradication	\$1.32 billion
c_3	Total private mitigation (anti-fouling paint) costs	\$3.87 million
d_2	Annual ZM-related surface water use maintenance costs in state 2	0
d_3	Annual ZM-related surface water use maintenance costs in state 3	0
d_4	Annual ZM-related surface water use maintenance costs in state 4	\$2.76 million
e_2	Annual per-hectare ZM-related ecological services losses in state 2	0
e_3	Annual per-hectare ZM-related ecological services losses in state 3	0
e_4	Annual per-hectare ZM-related ecological services losses in state 4	\$439

Source: USGS (2006)

Since no monitoring is in place, detection is most likely to occur after ZM have become established. Policy IV invests in arrival prevention measures, early warning and eradication measures if necessary. Budgetary and private mitigation costs for the four policy scenarios are reported in Table 2-3.

Table 2-3. Present value estimates of zebra mussel policy scenarios (20 year, 2006 $ million)

	Public policy action			Private action	
Policy	Monitor, prevent arrival	Eradicate upon detection	Budgetary cost of policy	Long run mitigation	Mitigation costs
I	no	no	0.00	yes	10.83
II	yes	no	2.33	yes	3.02
III	no	yes	872.90	no	0.41
IV	yes	yes	696.36	no	0.11

We estimate cumulative probabilities of ZM being in each of the four states (S_t) and employ the parameter estimates (Table 2-2) in equation 11 to arrive at the expected present value of ZM infestation in Lake Okeechobee under the four policy scenarios. We assume a 2% discount rate.

The state expenditures vary widely by policy. If the state only pursues arrival prevention and an early warning system, then policy costs are $2.33 million, compared to a very costly $872.90 million for an "only eradicate" policy, or $696.36 million for a combination of the two. ZM-related maintenance costs borne by surface water users are $10.83 when the state employs long term management only, compared to $3.02 million for the arrival prevention/early warning system is in place, $0.41 million when only eradication is used, and $0.11 when both are used simultaneously.

Policy costs, maintenance costs, recreation losses, and ecosystem gains are reported in Table 2-4 as a comparison to Policy I—do nothing. Introduction of ZM to the lake will improve fishing recreation by $1.09 million, compared with $0.31 for the arrival prevention/early warning system, $0.25 for only eradication, and $0.22 when both are pursued. ZM prevention and control policies will invariably reduce fishing recreation. The losses range from $0.78 to $0.87 million in present value over 20 years. These gains are very small when compared to the increases in maintenance costs or ecosystem impacts.

Table 2-4. Simulation results compared to Policy I (Do nothing) (present value, 2006 $ million).

	II	III	IV
	Monitor, prevent arrival, provide early warning of arrival $x_1 = 1, x_2=0$	Eradicate upon detection $x_1=0, x_2=1$	Prevention and eradication $x_1=1, x_2=1$
Policy Costs	2.33	872.9	696.36
Reduction in Maintenance Costs	7.81	10.42	10.72
Recreation Impacts	-0.78	-0.84	-0.87
Ecosystem Impacts	243.02	259.96	271.54
Maintenance and Recreation Impacts	7.03	9.58	9.85
Maintenance, Recreation and Ecosystem Impacts	250.05	269.54	281.39
Policy, Maintenance and Recreation Impacts	4.7	-863.32	-686.51
All Values	247.71	-603.36	-414.98

Wetland losses and associated damages are $339.61 million when the state does nothing. If the state employs ZM policies, it can prevent significant losses to ecosystem services. When the state invests in arrival prevention and early warning, the net gains to ecosystem services are $243.02 million. They are even higher when the policy includes eradication. When only eradication is used, ecosystem service gains are $259.96, and when both strategies are used jointly, there are gains of $271.54 million.

Some policy makers may question the validity of including ecosystem service values because the values are too indirect. When only considering direct economic impacts—recreation, and maintenance costs—the returns to ZM policies are all positive. They are $7.03 million for arrival prevention and early warning, $9.58 million for eradication, and $9.85 when both are used together. When ecosystem impacts are included, the returns to ZM control and prevention strategies are very large. Net direct impacts are $250.05 million, $269.54, and $281.39 for arrival prevention and early warning, eradication, and a combination of the two, respectively.

The impacts of the ZM policies change dramatically when considering the budgetary demands of the ZM policies. When only considering direct impacts and budgetary costs, Policy II (arrival prevention and early warning) provides the only positive return— $4.7 million. Eradication is very expensive, with Policy III (eradication) having total direct impacts of $-863.32 million, and Policy IV (combination of Policies II and III) with net direct impacts of $-686.51. The relatively small price tag associated with Policy II is very effective at reducing the present value costs of eradication.

If ecosystem service values are included, the results are still not supportive of eradication. When considering the policy, maintenance, recreation and ecosystem impacts, Policy II is still the clear favorite, with net benefits of $247.71 million. By comparison, Policy III (eradication) and Policy IV (arrival prevention, early warning, and eradication) yield losses of $603.26 and $414.98 when compared with doing nothing.

Given our assumptions, the overall cost and damage-minimizing choice is to invest in Policy II, arrival prevention and early warning. The total net costs and damages of this policy are 70.91% less than Policy I (do nothing), 89.34% less than Policy III (eradication), and 86.71% lower than Policy IV (arrival prevention, early warning, and eradication). Investing in prevention and early detection also place a smaller budgetary burden on the state—less than 0.03% of the budgetary costs of the other two policies. This is due to the very high cost of eradication, and the large gains realized by delaying the arrival of ZM. A relatively small amount of spending to prevent the arrival of ZM has a large impact on reducing the probability that ZM will infest the lake (See Figure 2-3). Without monitoring and prevention (x_1), there is a 45.42% probability of ZM fully infesting Lake Okeechobee by 2026. With monitoring and prevention, this probability is greatly reduced even if eradication is not attempted.

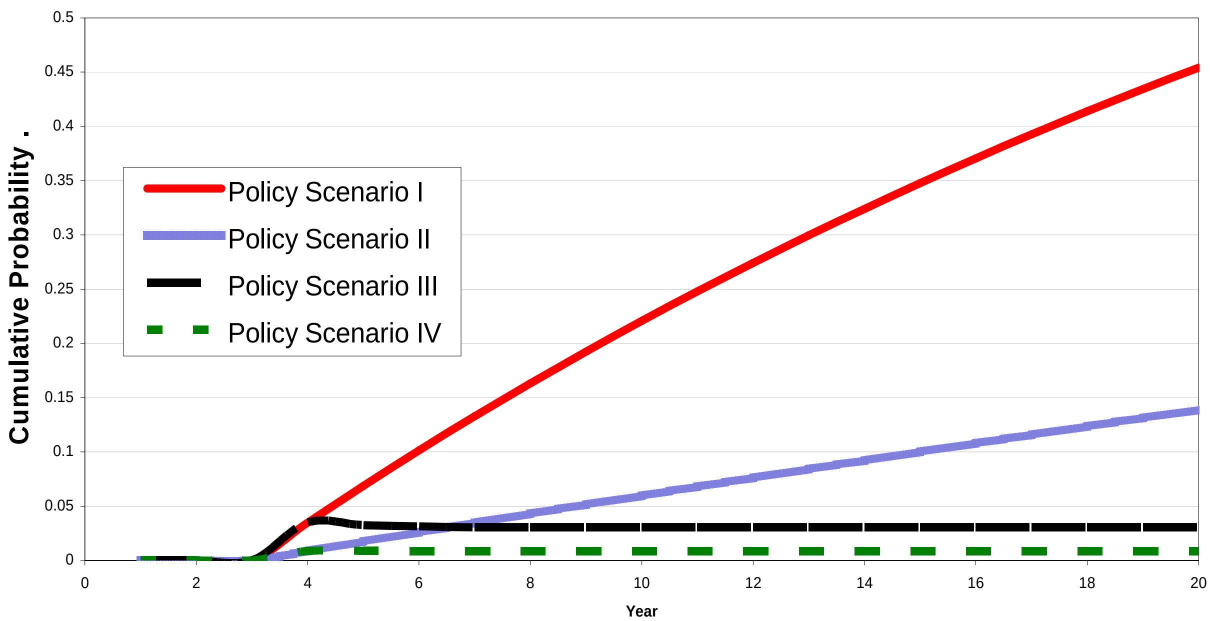


Figure 2-3. Zebra mussel policy impacts on cumulative probability of infestation.

From the standpoint of both surface water users and environmental protection groups, Policy IV—the combination of arrival prevention, early warning, and eradication—is preferred. The ZM-related maintenance cost for this policy is only 98.99% lower than Policy I, as compared to 72.22% lower than Policy II, and 96.22% lower when only eradication is used (Policy III). Ecological damages to the lake are also lowest when a combination of policies is used, but by much closer margins than with surface water maintenance costs. Ecosystem damages are also much lower under Policy IV as compared with Policy I. Policy II, III and IV provide 71.55%, 76.54%, and 79.99% less ecosystem services losses than Policy I.

Recreational anglers would prefer that the state not prevent or eradicate ZM. Policy I (do nothing) provides 495.45% more fishing-related benefits than the combination of management tools which is most effective at minimizing ecological and maintenance costs. Arrival prevention and early warning, and eradication respectively provide 140.91% and 113.64% of the fishing-related benefits of the combination of management practices.

We conducted sensitivity tests on key parameters that are expected to have large impacts on policy outcomes—arrival rate, fishing-related benefits, ecosystem valuation, and eradication costs. The results are reported in Appendix B. Assuming that the ZM arrival rate is half of our original assumptions, the total costs and damages of a ZM infestation are still minimized by choosing arrival prevention and early warning. Costs and damages under this policy are now $53.18 million instead of $101.64 million when arrival was assumed to be 3.5% without policy intervention. Similar savings are found for maintenance costs, but ecosystem losses and fishing gains are reduced to a point where results from Policy I (arrival prevention and early warning) and Policy IV (arrival prevention, early warning, and eradication) are nearly equivalent; the original policy rankings still stand. We then simulated a loss of 10% instead of a gain of 10% in fishing benefits following a ZM infestation. This did not change the original policy rankings. We also estimated what the per-acre ecosystem damage and the eradication costs would have to be to make policy makers ambivalent between preventing and eradicating ZM. If ecosystem values were 51.25 times higher or if eradication costs were reduced by 97.5% then policymakers would be ambivalent between prevention and eradication. This provides support for our original ranking of the policies.

These results set up an interesting dilemma for the state. Surface water users and environmental groups are expected to prefer a very costly combination of ZM management methods, while fishermen may prefer to have no state-funded efforts to prevent or mitigate ZM costs. The social planner, however, would clearly prefer to invest only in arrival prevention and early warning, but legislators may instead prefer to do nothing as that response puts the least budgetary burden on the state. The only Policy that may be excluded by all groups is the decision to only eradicate. Depending on the relative influence that budgetary pressures and interest groups have on legislators, the state would choose to do nothing, only invest in arrival prevention and early warning, or provide a combination of the prevention and detection measures as well as eradication.

Our estimates of the economic effects of a ZM infestation suggest that pre-planning is essential to reducing the overall impacts of the mussels. Despite the very low probabilities of ZM establishment on the lake, the expected costs and damages of such an infestation are very high—up to $349.34 million over 20 years if nothing is done. Eradication of ZM on the lake would be extremely expensive, and perhaps more than the state of Florida would want to spend. This would not be uncommon, as there is only one example of ZM eradication, and that was in a very small water body in Virginia of very high recreational significance. Proactive measures, such as an early warning system and arrival prevention efforts can significantly reduce ecosystem damages, maintenance costs, and state expenditures on a policy response to the ZM problem. Compared with the other policy options, the policy of arrival prevention and early warning is 3.43 to 9.37 times more cost effective than other available policy options.

Conclusion

The Zebra mussel (*Dreissena polymorpha*) is a serious threat to recreation, surface water use, and ecosystem services in lakes and rivers in the United States. The zebra mussel is expected to reach Florida waters, but state and federal agencies currently have no program to deal with zebra mussel arrival. The United States Army Corps of Engineers have proposed an arrival prevention and education program for recreational boaters, as well as a zebra mussel early monitoring and warning system, but these have not been funded. Costly eradication of the mussel post-establishment is also an option. Here, we estimate and compare the impacts of zebra mussel policies on recreation, surface water use, and ecosystem services on Florida's largest lake—Lake Okeechobee.

We construct a bioeconomic model to simulate the expected impacts of the zebra mussel (ZM) on the lake. We first estimate ZM introduction into the lake based on assumed transportation vectors (recreational boating), habitat suitability from a previous study (Hayward and Estevez, 1997), and effectiveness of ZM mitigation and prevention methods. We surveyed Lake Okeechobee surface water users and applied our results to existing estimates of changes in ZM-related maintenance costs for surface water users. We include assumed lake-related ecological and recreational values to construct an estimate of the total economic impacts with respect to a ZM infestation. We then apply state probabilities (in a stochastic dynamic simulation format) to arrive at a long-run economic impact analysis of ZM in Lake Okeechobee. We report present value results of the expected economic impacts over 20 years, including costs and damages to surface water use, recreational anglers, and users of ecosystem services, as well as budgetary costs (Table 2-4).

Our model of the economic impacts of zebra mussels on Lake Okeechobee, Florida offers some insight into the cost-effective management of this and other invasive species threats. A zebra mussel infestation in Lake Okeechobee has expected net economic costs and damages of $349.34 million over 20 years if nothing is done. Recommended best practices for managing invasive species threats are prevention, control, and eradication (where economically feasible) (Hulme, 2006). In aquatic systems, eradication and control is particularly difficult (Floerl and

Inglis, 2005). A comparison of ZM policy scenarios reveals that zebra mussel prevention is more desirable than post-invasion efforts given the high cost of eradication. For example, the present value policy costs of eradication would be $872.9 million over 20 years, but with even modest funding on arrival prevention and early warning ($2.33 million), significant savings are achieved. With arrival prevention, early warning and eradication combined, the present value policy costs fall to $696.36 million.

In addition to budgetary costs of a ZM policy, policy makers must balance the expected impacts on surface water use, recreation, and damages to freshwater ecosystems. An active ZM policy of arrival prevention and early warning, eradication, or a combination of the two would provide significant reductions in agricultural surface water users' maintenance costs ($7.81 million – $10.72 million) and very high savings to ecosystem services ($243.02 million – $271.54 million). Zebra mussels are expected to benefit fishing on the lake, but angler-related gains from ZM are not expected to be large compared to other impacts. With active ZM policies, fishing benefits would fall by $0.78 million – $0.84 million over 20 years. Ecosystem services are difficult to measure, and some policy makers may be wary of using such values. Without considering ecosystem services, the clear cost-minimizing ZM policy is arrival prevention and early warning, which yields a net gain of $4.7 million. By comparison, large losses are associated with policies that include eradication ($686.51 million, $863.32 million). The inclusion of ecosystem services does not impact the relative performance of ZM policies. With arrival prevention and early warning, net gains are much larger ($247.71 million). Policies that include eradication still yield large losses ($414.98 million, $603.36 million).

The results from this study indicate that investment in arrival prevention is much more cost effective than attempting to control or eradicate invasive species post-arrival. As with many invasive species, there is a great deal about ZM biology, transmission, and other important variables that are unknown. Unfortunately, ZM and other invasive species pose serious risks to agriculture and natural resources, and despite the unknowns, policy makers will be called upon to allocate scare public resources in defense of natural and agricultural systems. Studies such as this one, though based on several assumptions about ZM that have not yet been tested, provide important information to the discourse on invasive species management.

CHAPTER 3
BIOECONOMIC MODEL OF INVASIVE AQUATIC PLANTS HYDRILLA VERTICILLATA (HYDRILLA), EICHHORNIA CRASSIPES (WATER HYACINTH), AND PISTIA STRATIOTES (WATER LETTUCE) FOR FLORIDA LAKES

Introduction

Invasive aquatic plants can have significant negative impacts on water-based recreation, such as fishing, wildlife viewing, and boating. Despite the high potential impacts, little economic research has attempted to quantify these impacts across spatial scales that would be useful for invasive species management decisions. The little economic research that has been conducted on aquatic invasive species usually focuses on a single lake, or is too abstract to be applied. This is the case because often very little data are available for larger scale studies. This study uses unpublished data on plant coverage, angler effort, and lake physiographic and amenities to estimate the impact of plant coverage on fishing activity on 13 Florida lakes. Using the bioeconomic model of invasive aquatic plants, I then simulate the single-year costs and benefits of six policy scenarios for aquatic plant control. I estimate that the total economic value of the 13 lakes over $64.78 million, and lapses in invasive plant control may jeopardize that value. These results suggest that the optimal management policy is maintenance control with respect to hydrilla, water hyacinth and water lettuce.

Invasive Species Background

Invasive species in the United States pose serious ecological and economic problems (Evans, 2003). An invasive species is defined as a non-native species whose introduction "causes or is likely to cause economic or environmental harm or harm to human health" (Executive Order 13112, 1999). Invasive species are a particular problem for the tropical and subtropical areas of Florida, where physiographic, climatic and geographic characteristics make it relatively easy for non-indigenous species to establish (Simberloff, 1997; Fox [personal communication], 2007). Florida has a high rate of non-native species introduction, with the Port of Miami receiving about 85% of non-native plant shipments each year (OTA, 1993). For example, the entire United States has about 50,000 established non-native plant and animal species, with Florida alone having over 25,000 as exotic ornamentals (Pimentel, 2003); over 1,300 have established in natural areas, and 124 of these are destructive to natural areas (FLEPPC, 2006). By comparison, Florida only has 2,500 native plant species, and the US has 18,000 native species.

Invasive species are a growing economic concern. Today, there are an estimated 5,000 to 6,000 invasive species in the United States (Pimentel, 2003; Burnham, 2004), and invasive plants are invading about 700,000 hectares/year of natural areas in the US (Pimentel et al., 1999). Economic damages from invasive species are estimated to be $137 billion/year excluding ecosystem impacts (Pimentel et al., 1999). When considering the well-documented impacts of certain invasive species, such as damages caused by hydrilla verticillata in Florida, or the zebra mussel in the Great Lakes, it is clear that invasive species can have dire economic consequences.

With continuing increases in both global trade and the domestic and international migration of people to Florida, the rate of arrival of non-native species is rising. Invasive species management is fast becoming a high priority for the protection of Florida's agricultural and natural systems (Schardt [personal communication], 2007). Yet, despite the large economic and ecosystem harms associated with invasive species, there exists little empirical analysis of invasive species problems in a way that would help policy makers or resource managers (Schardt [personal communication], 2007). There are very few invasive species studies in the economics literature, and most of those are distinctly theoretical and too technical or abstract for use by policy makers or resource managers. Few empirical studies have evaluated the impact of invasive species, and very few have examined their impact on recreation (Singh et al., 1984;

Milon et al., 1986; Milon and Joyce, 1987; Colle et al., 1987; Milon and Welsh, 1989; Newroth and Maxnut, 1993; Henderson, 1995; Bell et al., 1998, et al.). The issue of invasive species is one that much more attention (and perhaps budgetary expenditures) will likely be focused on in the near future.

Hydrilla, Water Hyacinth, and Water Lettuce Past Management

The present level of expenditures devoted to the management of a handful of invasive plant species is inadequate, even for those few being managed. There are 18 invasive aquatic plant species in Florida waters, but very few of these are actively managed. Due to their extremely high propagation and growth rates, the Florida Department of Environmental Protection (FDEP) has targeted *Hydrilla verticillata* (hydrilla), *Eichhornia crassipes* (water hyacinth) and *Pistia stratiotes* (water lettuce) as among its top management priorities. These plant pests have been the focus of management efforts in Florida for decades; however, additional research is needed to assess economically efficient strategies for managing them.

Hydrilla is a submerged aquatic plant introduced as an aquarium ornamental in the 1950s, and first detected in Florida water bodies in 1960 (University of Florida, 2001; Blackburn et al., 1969). Its rapid growth rate and suitability to Florida waters allowed it to spread rapidly throughout the state. By the early 1970s, hydrilla could be found in all major drainage basins in Florida. By 1995, hydrilla spread to over 40,000 hectares on 43% of the public lakes in the state (Langeland, 1996).

Hydrilla eradication efforts have not been successful. The high growth rates and other unique characteristics of hydrilla and other invasive plants make them virtually impossible to eradicate. The Bureau of Invasive Plant Management's current official policy on invasive plants is to achieve "maintenance control," defined as keeping the invasive plant population at very low levels for the foreseeable future. In 2002, 175 Florida public water bodies were infested with hydrilla, with 1/3 having more than 10 acres. Hydrilla is under maintenance control in 96% of Florida waters, but most of the hydrilla budget is spent on about 25 lakes (FDEP, 2004). Total spending on hydrilla was $17.3 million in fiscal year 2001-02 (FDEP, 2004).

Water hyacinth and water lettuce are floating aquatic plants. Water hyacinth, a native to South America, was introduced to Florida as an ornamental pond plant in 1885. Its rapid reproduction led to it being discarded into the St. John's River, and it spread quickly to neighboring water bodies (Schmitz et al., 1988). Within a few years, it was credited with blocking boat traffic on the St. John's River (Schmitz et al.). Water lettuce has been in Florida much longer, perhaps since the 16th century, and is also believed to be a native of South America (Schmitz et al.). In 2002, water hyacinth and/or water lettuce were found in 244 public waters inventoried (57%), and were considered to be under maintenance control in 95% of Florida's waters (FDEP, 2004). Of these, 71 had over 10 acres of floating plants (37 with water hyacinth, and 34 with water lettuce) (FDEP, 2004). Total state control spending on floating plants in fiscal year 2001-02 was $3.1 million (FDEP, 2004).

The problems with hydrilla, water hyacinth and water lettuce are multidimensional—ecological, economic, public and private. Ecological impacts include displacing native flora (both submersed and floating), altering habitat of native fauna, and disrupting ecosystem processes (Haller and Sutton, 1975). These invasive plants grow in thick monoculture mats where over half of the plant biomass is found in the upper 0.5m of the water column (Haller and Sutton, 1975). These mats block sunlight to and out-compete native plants (Hofstra, Clayton, Green, et al., 1999; Sutton, 1986), especially in the increasingly nutrient-rich lakes and rivers of Florida. Hydrilla may also outcompete other submerged invasive aquatic plants, such as Elodea densa and Ceratophyllum demersum (De Kozlowski, 1991; Chambers et al., 1993). Dense monocultures can contribute to reduced fish populations, and when large mats of plants decompose, the reduced dissolved oxygen levels in a lake can cause massive fish kills (Bowes et al., 1979).

These invasive aquatic plants also harm non-aquatic species by covering nesting and egg laying areas, and blocking access to water, shelter, and food sources (FDEP, 2004). Endangered species are impacted by invasives—about 400/958 endangered or threatened species are "at risk" primarily due to invasive species competition or predation (Wilcove et al., 1998).

Economic impacts follow close behind ecosystem losses. Hydrilla, water hyacinth and water lettuce can hinder boating, swimming, and fishing activities in lakes and rivers, and reduce the aesthetic value of natural areas (Milon and Joynce, 1987; Colle, Shireman, Haller, et al., 1987). The reduction of recreational benefits derived from public waterways (and the cost of managing the weeds) highlights the public loss from invasive aquatic plants. Florida's 454 public lakes and rivers comprise 1.27 million acres (FDEP, 2004). In total, Florida has 1.5 million acres of lakes and rivers, with 7,700 lakes and ponds, and 1,400 rivers and streams (FDEP, 2004). Freshwater fishing lures over 34 million participants to Florida who spend in excess of $35 billion/year (Lee [personal communication], 2006). Reduced sport fish populations coupled with access problems significantly reduce sport fishing activities (Colle et al., 1987; Milon and Joyce, 1987; Milon and Welsh, 1989). For example, Colle et al. (1987) reported a nearly 85 percent decrease in total angler effort on Orange Lake, when hydrilla coverage increased from near 0 to almost 95% of the historically open-water region of the lake.

Populations of several recreationally-important fish species, such as largemouth bass, bluegill, redear sunfish, and black crappie become skewed to young individuals (Colle et al., 1987; Tate, Allen, Myers, et al., 2003). They also affects private citizens and businesses, blocking power generators and agricultural irrigation water intake pipes, jamming water turbines and dams, and clogging canals and ditches (FDEP, 2004). Infestations in private ponds and poorly managed public water bodies can reduce recreational and aesthetic value of waterfront property.

Invasive Aquatic Plant Control

Florida has considerable experience fighting invasive aquatic plants (especially water hyacinth), yet Langeland (1996) asserts that lack of adequate and consistent funding for many invasive plants, (especially hydrilla) continues to be the biggest barrier to effective management and the efficient use of public resources over time. According to the FDEP (2004), "insufficient management funding allowed hydrilla to expand from 50,000 to 140,000 acres during the middle 1990s." During this time there was sufficient funding to continue water hyacinth (and water lettuce) control, which was considered of primary importance due to their higher growth rates. Lapses in invasive plant control are particularly harmful to Florida's natural and agricultural systems because the invasive plants reproduce very quickly, and have prolific seed banks. Hydrilla has been difficult to eradicate because the plant produces underground tubers which generate new plants each year (Spencer, Ksander, Madsen et al., 2000; Haller, Miller and Garrand, 1976; Van, 1989). Likewise, water hyacinth and water lettuce are extremely prolific, propagating both by seeding and by creating daughter plants vegetatively.

Various aquatic plant control strategies have been considered (Bowes et al., 1979; Chambers, Barko and Smith, 1993; Nichols, 1991), including mechanical removal, lake draw-down, application of various herbicides (Van, Steward, and Conant, 1987; Gangstad, 1978; Klaine and Ward, 1984) and biological control, both with insect and herbivorous fish species (De Kozlowski, 1991; Hestand and Carter, 1978). Lake draw-down prevents most recreational use, and biological control agents lack precision, potentially leading to a depopulation of native as well as invasive plants, or not providing enough control. The primary method of controlling aquatic plants today is the use of herbicides (FDEP, 2004). Whatever method of control is chosen, there seems to be consensus that keeping invasive aquatic plant populations very low and under maintenance control is the preferred state-wide management strategy (Schardt, 1997).

Bioeconomic Modeling of Invasive Species

Recently, economists and natural resource managers have turned to bioeconomic models to help guide resource managers' decisions. Bioeconomic models relate the biology of invasive species—population growth rates, dispersion, predation, etc—to their economic impacts. Some recent studies use bioeconomic models in an optimal control framework to analyze invasive species spread and control (Eiswerth and Johnson, 2002; Eiswerth and van Kooten, 2002; Gutierrez and Regev, 2002), while others emphasize feeback links between the biological and economic systems (Finoff, Shogren, Leung and Lodge, 2005; Settle and Shogren, 2002).

Several studies have used bioeconomic models to estimate costs associated with invasion or to evaluate policy alternatives. For example, Knowler and Barbier (2000) model the invasion of an anchovy fishery by comb-jelly and provide estimates of lost profits due to the invasion. Settle and Shogren (2002) model the impacts of Lake Trout on the native Cutthroat trout, and the subsequent impacts on wildlife viewing, fishing, and indirect values. Buhle, Margolis and Rueslink (2005) examine the relative cost-effectiveness of various control methods for invasive species with different reproductive rates and environmental tolerances. Finnoff and Tshirhart (2005) also examine physiological traits to determine optimal invasive species control and prevention strategies.

Other studies have focused on the changing stochastic and uncertain nature of invasive species arrival, spread, and damages. For example, Leung, Lodge, Finoff, et al. (2002) compare arrival prevention and damage mitigation under uncertainty. Olson and Roy (2002, 2005) examine optimal policy responses under uncertainty and with a stochastically changing invasion. Huffaker and Cooper (1995) use a bioeconomic model of rangeland invasive to measure the impact on grazing. Odom, Cacho, Sinden, et al. (2003) develop a similar model with respect to the invasive scotch broom.

The economics of aquatic plant management in Florida have been examined by willingness to pay studies on specific lakes (Burruss Institute, 1998; Milon and Welsh, 1989; Milon et al., 1986). For example, Milon et al. (1986) estimated a $480,000 annual willingness to pay for hydrilla control on Orange and Lochloosa lakes. They also found that a full hydrilla infestation on the lakes would result in a loss over $5 million per year. Colle et al. (1987) similarly estimated a total economic impact of $900,000 for invasive weed control on Orange Lake. Milon and Welsh (1989) estimated $176,000 willingness to pay for invasive plant management on Harris and Griffin lakes, with a total recreation impact of $1.7 million. Bell et al. (1998) estimated almost $20 million annual willingness to pay for invasive plant management on Lake Tarpon. No work has yet examined impact of various control strategies on budgetary costs.

Empirical Approach

This study examines the impact of invasive plants on management expenditures and recreational activity on 13 Florida lakes. I estimate lake-specific yearly growth functions for hydrilla and floating plants (water hyacinth and water lettuce together) from unpublished FDEP aquatic plant coverage and treatment acreage data. I then quantify the relationship between the invasive plants and fishing activity to capture the economic implications of invasive aquatic plant infestation. In North Florida, over 65 percent of boat trip activities are for fishing (Thomas and Statis, 2001), therefore changes in angler activity will capture much of the recreational impact of invasive aquatic plants on Florida lakes. A linear regression model is specified to measure the impact of invasive aquatic plant coverage on angler effort. Included in the model are lake specific variables that characterize the biological and physical conditions of a lake that also influence angler effort. These include lake trophic state, lake size, season and lake amenities (such boat ramps and parking facilities). Third, I estimate per acre control costs for hydrilla and floating plants based on DEP treatment acreage and cost data. Finally, I simulate the impacts of various invasive plant management strategies on recreational fishing value and compare the costs and benefits for four potential policy responses to aquatic plant infestation on the 13 lakes.

Data Sources and Description

FDEP performs annual aquatic plant surveys and maintains information on the prevalence and coverage of aquatic plants on Florida's public water bodies. Each year, the FDEP conducts grid sampling studies of aquatic plants in which total acreage of each plant discovered is recorded. Unpublished aquatic plant coverage data on 51 Florida lakes from 1983-2002 was obtained from FDEP.

The Florida Fish and Wildlife Conservation Commission (FFWCC) perform "Creel" surveys of angler effort and catch on many Florida lakes. Unpublished Creel data on 45 lakes collected from 1966-2002 were obtained from five regional FFWCC offices. Angler effort is an estimation of the number of hours that anglers on a boat spent fishing, times the number of anglers. For example, if 3 anglers spent 4 hours fishing, the Creel survey would record 12 hours of angler effort. Angler effort is used as a proxy for recreational activity level on Florida lakes. Each Creel survey was performed either in spring, summer, fall, or winter, lasting an average of 3.0 months for winter, 3.0 months for summer, 3.1 months for spring, and 2.9 months for fall. Since Creel surveys reported angler effort over time periods of different lengths, I standardize the data by computing average angler effort per day over the time period of the Creel survey.

I collected data on physical characteristics of the lake that are expected to impact recreation. Included were amenities, lake size, and trophic state. The presence of lake amenities—such as public boat ramps, parking spaces and camping facilities—may influence the demand for recreation on particular lakes. The Florida Fish and Wildlife Conservation Commission operates about 1,300 boat ramps on 454 public lakes and rivers throughout the State that are available for public use, some with additional features such as parking (Thomas and Stratis, 2001). Data on lake amenities were collected from the FFWCC website (FFWCC, 2003).

Lake size is defined as lake surface area. Data on lake surface area were obtained from Florida LAKEWATCH and Florida DEP. Lake access is determined by water level. Water level information were available but excluded from the analysis because Creel surveys often do not occur when water depth is too shallow for boat use. For example, in 2001 there were 46 public waters inaccessible for FDEP plant inventories, and in 2002 there were 26 (FDEP, 2004).

A lake's trophic state indicates the amount of plant and animal life that a lake can support and is typically measured with a trophic state index (TSI). The biological productivity of a lake is expected to impact fish populations and catch rates. Particular trophic states are known to be more beneficial to sport fish production than others. The FDEP uses a Florida-specific trophic state index developed by Brezonik (1984) for surveying water quality. The Florida-specific TSI is based on total nitrogen (mg/l), total phosphorous (µg/l), chlorophyll a (mg/m^3) for planktonic algae, and secchi depth (m) for water transparency (State of Florida, 1996). I computed a long-run Florida-specific trophic state index for each lake. The computed TSI values were used to characterize each lake as Oligotrophic, Mesotrophic, Eutrophic, or Hypereutrophic.[1] The data used in the TSI calculations were obtained from the University of Florida's LAKEWATCH program for the period 1991-2002. Data prior to 1991 were unavailable.

---

[1] It is known that trophic state changes with population growth. Future work will test the assumption that trophic state can be held constant in the regression and still yield consistent results.

Expenditures for invasive aquatic plant management for years 1998 to 2002 were obtained from Florida FDEP (Ludlow, 2005). These data include the number of acres, date, and cost of herbicide treatment for Florida lakes managed by the FDEP. Data prior to this were largely unavailable.

Data were compiled into an Excel spreadsheet. Included were hydrilla, water hyacinth and water lettuce coverage at the time of the FDEP's annual aquatic plant survey, control costs, lake specific amenities and surface area, and angler effort per day. Excluded were lakes that did not have both Creel survey and invasive plant survey data for the same years, or lakes that lacked calculable trophic state index numbers. Of the 45 lakes for which there were Creel data, 38 lakes remained in the spreadsheet. Of these, 13 had FDEP invasive aquatic plant coverage over 100 acres during the 1998-2002 period for which I also have acres treated data (George, Griffin, Harris, Istokpoga, Jackson, Kissimmee, Lochloosa, Okeechobee, Orange, Osborne, Poinsett, Sampson, and Weohyakapka).

Hydrilla and Floating Plants Growth Models

The FDEP conducts annual aquatic plant surveys primarily from July through December, with most surveys occurring in September. Fishing and Creel surveys however take place at various times throughout the year. Hydrilla in warm southern waters of the United States are the typically emerge beginning in mid-August, with maximal new plant sprouting in October (Spencer et al., 2000). Hydrilla biomass is generally highest in November (Bowes et al., 1979). Water hyacinth and water lettuce have similar growth patterns (Wolverton and McDonald, 1979). Since plant coverage changes throughout the year, it was necessary to estimate their coverage during the whole year to match plant coverage with Creel survey data.

Current herbicide applications used to control invasive aquatic plants are effective at eliminating most of the existing aboveground biomass (Van, Steward, and Conant, 1987), but after herbicide application these plants regenerate from underground tubers, seeds, and the small percentage of remaining plant material. Most hydrilla plant biomass can be effectively killed using aquatic herbicides, but hydrilla tubers can not (Steward, 1980; Steward and Van, 1987). It is estimated that hydrilla tubers covered 108,980 acres of public water bodies in 2002, clearly presenting a persistent management problem (FDEP, 2004). Seeds from floating plants are also pervasive (Schardt, 2007). I could not, however, include tuber or floating plant seed banks in the model of plant growth as these data are unavailable. Assuming static tuber and seed bank numbers, I was able to estimate single year growth rates for hydrilla and floating plants.

Hydrilla grows in stages. At the beginning of the calendar year, there are typically no living hydrilla plants remaining from the previous year when the plants naturally lose their ability to carry out basic physiological functions. Once water temperatures reach 3 degrees Celsius, new plants sprout leaf material from the underground tuber bank. Growth is rapid through about day 270, or early September (Bowes et al., 1979). As the temperature begins to cool, the plants return to their senescent state following tuber production (Best and Boyd, 1996). Water hyacinth and water lettuce follow similar growth stages (Wolverton and McDonald, 1979).

Annual plant growth is a function of numerous variables, including water temperature, solar radiation, nutrient levels, available space, water turbidity, lake depth, trophic state, plant predation and competition, and many other factors (Best and Boyd, 1996; Van, Haller, and Garrard, 1978; Bowes, Holaday, and Haller, 1979; Best, Buzzelli, Bartell, et al., 2001). For the purposes of this study, I make several simplifying assumptions. First, I assume that only lake surface area, time, and herbicide applications affect plant growth. I tested this assumption using the most recent lake-wide study of hydrilla growth in Florida (Bowes et al.,1979). Bowes et al.,

(1979) measured the level of hydrilla biomass on Orange Lake, Florida in 1977. Using the Bowes et al. data, I estimated a temporal growth function for hydrilla with time as the explanatory variable (statistically significant at $p = 0.01$, with an adjusted R^2 greater than 0.975, suggesting a good fit).

Second, I assume that the date of the FDEP aquatic plant survey was day 270 of each year after several communications with State of Florida invasive plant managers (Schardt, 2007, Ludlow, 2005). I also assumed day 270 to be the date of maximum surface area coverage for hydrilla, water hyacinth and water lettuce based on the hydrilla literature (Best and Boyd, 1996; field studies of water hyacinth and water lettuce growth were not available) and calculations from Bowes et al. (1979). Third, I assume that the date of herbicide application is day 60 of each year, a time when tubers and seeds have sprouted and the rapid plant growth encourages uptake of herbicides (Schardt, 2007; Ludlow, 2005; Haller, 2006). I was not able to reach consensus regarding initial tuber and seed density on the 13 lakes that are the focus of this study. Future work will factor tubers and seeds into both the growth function estimations and the comparison of the economic efficiency of various management schemes. Here, I assume a static growth function of hydrilla and floating plants, respectively, for each of the 13 lakes.

The growth equations are a function of time, with three distinct growing periods, defined as:

$$H_t = \begin{cases} e^{g_1 t} & for\ 1 < t \le ts \\ H_{ts} e^{g_2 (t-ts)} & for\ ts < t \le tm \\ H_{tm} e^{-b(t-tm)} & for\ tm < t \le 365 \end{cases}$$

Equation 1.

Where H_t is the acreage of the invasive aquatic plant at day t; g_1 is the lake-specific growth parameter for time 0-60, g_2 is the lake-specific growth parameter for time 61 – 270, and b is the lake-specific decay parameter for time 271– 365; ts is the assumed day of plant herbicide spray application (if done), which is assumed to be 60; and *tm* is the assumed day of plant maximum surface area coverage and FDEP survey date, which is assumed to be 270. The parameter estimates are reported in Table 3-1.

Table 3-1. Hydrilla and floating plants growth function parameter estimates.

	Hydrilla			Floating		
Lake	*g*1	*g*2	*b*	*g*1	*g*2	*b*
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

Aquatic Plant Management Scenarios

Several management scenarios are considered for the treatment of the invasive aquatic plants (Table 3-2). Scenario *A* is the status quo, which is calculated from the 1998-2002 FDEP aquatic plant acreage treated data. The status quo treatment is estimated from 5-year averages on the 13 lakes. This is the level of treatment actually pursued by the Florida Department of Environmental Protection. Status quo treatment already provides lake access throughout most of the year on Florida’s 454 public lakes. As long as the lakes remain relatively free of hydrilla and floating plants, most of the lakes’ recreation and ecosystem value will be preserved.

Aquatic plant herbicide application occurs in early to mid-Spring when plants are young and growing vigorously and able to uptake a large percentage of the herbicide (Haller [personal communication], 2006). Treatment in the summer months would result in too much dissolved oxygen depletion due to plant die-off at a time when dissolved oxygen is already low (Haller). For simplicity and tractability of calculation, I assume that treatment will occur at day 60. Van, Steward, and Conant (1987) found that aquatic herbicides are up to 95% effective for the Florida variety of dioecious hydrilla, and Langeland and Pesacreta (1985) found similar effectiveness for the monoecious variety in North Carolina. For the sake of providing conservative estimates of expenditures and losses associated with hydrilla control, I assume a 99% efficacy rate (1% of the plant biomass continues to grow after the herbicide is applied).

For scenario *A*, I use the following invasive aquatic plant coverage function:

Equation 2. $$H_t = \begin{cases} e^{g_1 t} & for\ 1 < t \le ts \\ \varepsilon H_{ts} e^{g_2(t-ts)} & for\ ts < t \le tm \\ H_{tm} e^{-b(t-tm)} & for\ tm < t \le 365 \end{cases}$$

where ε is the percentage of living invasive plant acreage left after treatment, which is assumed to be .01.

Table 3-2. Model assumptions for policy scenarios.

Scenario	First treatment (at day 60)	Second treatment (at day specific to lake)[2]
A	All hydrilla and floating plant acreage	No treatment
B0	No treatment	No treatment
B2	Scenario A, but every other year	No treatment
C20	Same as Scenario A	20% of hydrilla and floating plants acreage

[2] The date of the second treatment is calculated to maximize the effectiveness of treatment. The dates of second treatment are reported in Table 3-3. Note: some calculated dates are greater than 365. In these cases it is assumed that no second treatment occurs.

Table 3-3. Date of second herbicide treatments for *C20*.

	C20 Floating	*C20* Hydrilla
George	223	277
Griffin	210	245
Harris	209	245
Istokpoga	511	163
Jackson	210	193
Kissimmee	294	175
Lochloosa	207	269
Okeechobee	267	161
Orange	362	167
Osborne	210	273
Poinsett	312	210
Sampson	337	167
Weohyakapka	279	190

Scenario *B0* is no treatment, and has the same growth function as Equation 1.

Scenario *B2* is treatment every other year, and has the following growth function:

Equation 3. $$H_t = \begin{cases} 2e^{g_1 t} & \text{for } 1 < t \le ts \\ \varepsilon H_{ts} e^{g_2(t-ts)} & \text{for } ts < t \le tm \\ H_{tm} e^{-b(t-tm)} & \text{for } tm < t \le 365 \end{cases}$$

It is assumed that the initial invasive aquatic plant acreage would double from one year to the next absent treatment. It must be stressed that this assumption has not been tested and may represent unrealistic growth conditions.

For scenario *C20*, the state treats all of the invasive aquatic plant acreage at day 60 plus an additional treatment 20% of the acreage at a later date. The date for second treatment is lake-specific and was calculated to maximize the effectiveness of the treatment. The growth function for scenario *C20* is:

$$\text{Equation 4.}\quad H_t = \begin{cases} e^{g_1 t} & for\ 1 < t \le ts \\ \varepsilon H_{ts} e^{g_2(t-ts)} & for\ ts < t \le ts_2 \\ \varepsilon H_{ts} e^{g_2(t-ts_2)} & for\ ts_2 < t \le tm \\ H_{tm} e^{-b(t-tm)} & for\ tm < t \le 365 \end{cases}$$

where ts_2 is the date of second treatment.

For each of the management scenarios, the corresponding acreages of hydrilla and floating plants were calculated and were used to calculate the changes in both recreational fishing benefits and control costs. The results are discussed in the Economic Effects of Aquatic Plant Management section. For three of the lakes, I provide examples of the impact of management scenarios on aquatic plant coverage (Figure 3-1, Figure 3-2, and Figure 3-3).

Recreational Fishing Effort Model

The benefits associated with invasive aquatic plant management are measured as a change in the amount of hours that anglers spend fishing on that lakes, times an estimate the average willingness to pay for an hour of fishing (Thomas and Stratis, 2001). I refer to “angler effort” as the amount of hours an angler spends fishing on a lake, which is a function of several factors:

Equation 5. $F = f(H, X)$

where F is angler effort, H is hydrilla and floating plants coverage as estimated on the 13 lakes, and X is the matrix of other factors likely to affect fishing effort, including trophic state, season, lake size and lake amenities. Both F and H are per day averages; trophic state, lake size, and amenities are assumed to remain constant.

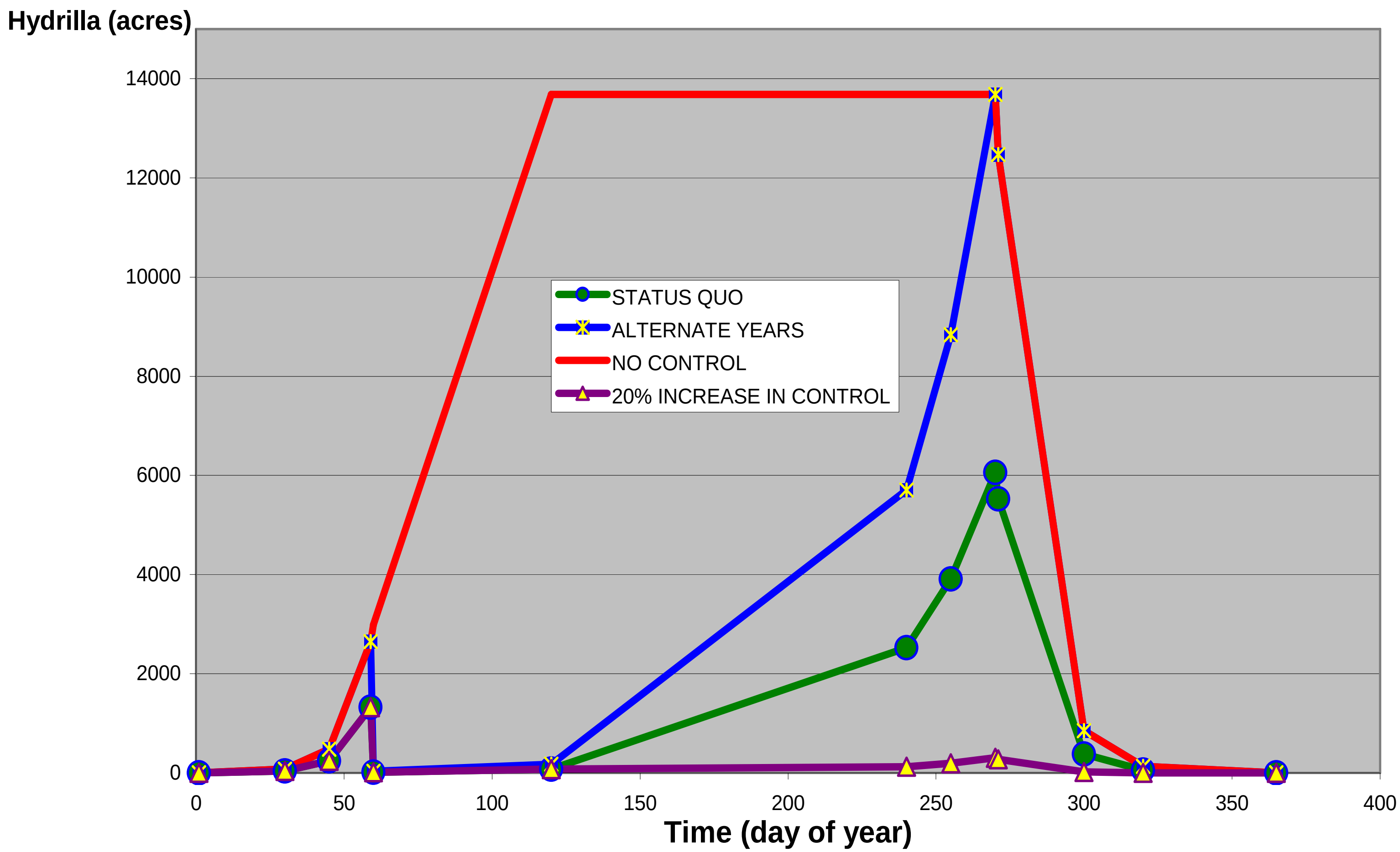


Figure 3-1. Simulated hydrilla coverage in Lake Istokpoga.

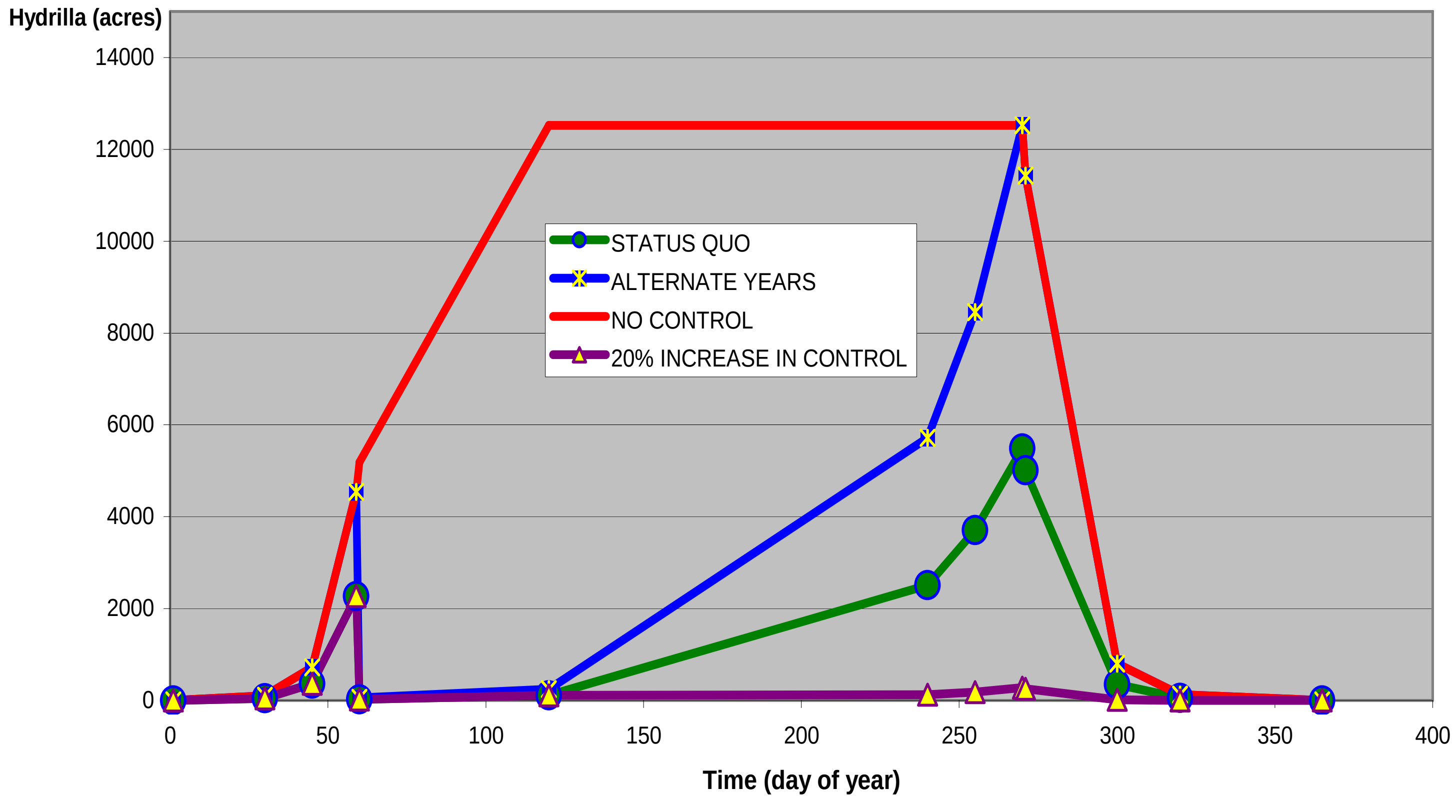


Figure 3-2. Simulated hydrilla coverage in Lake Kissimmee.

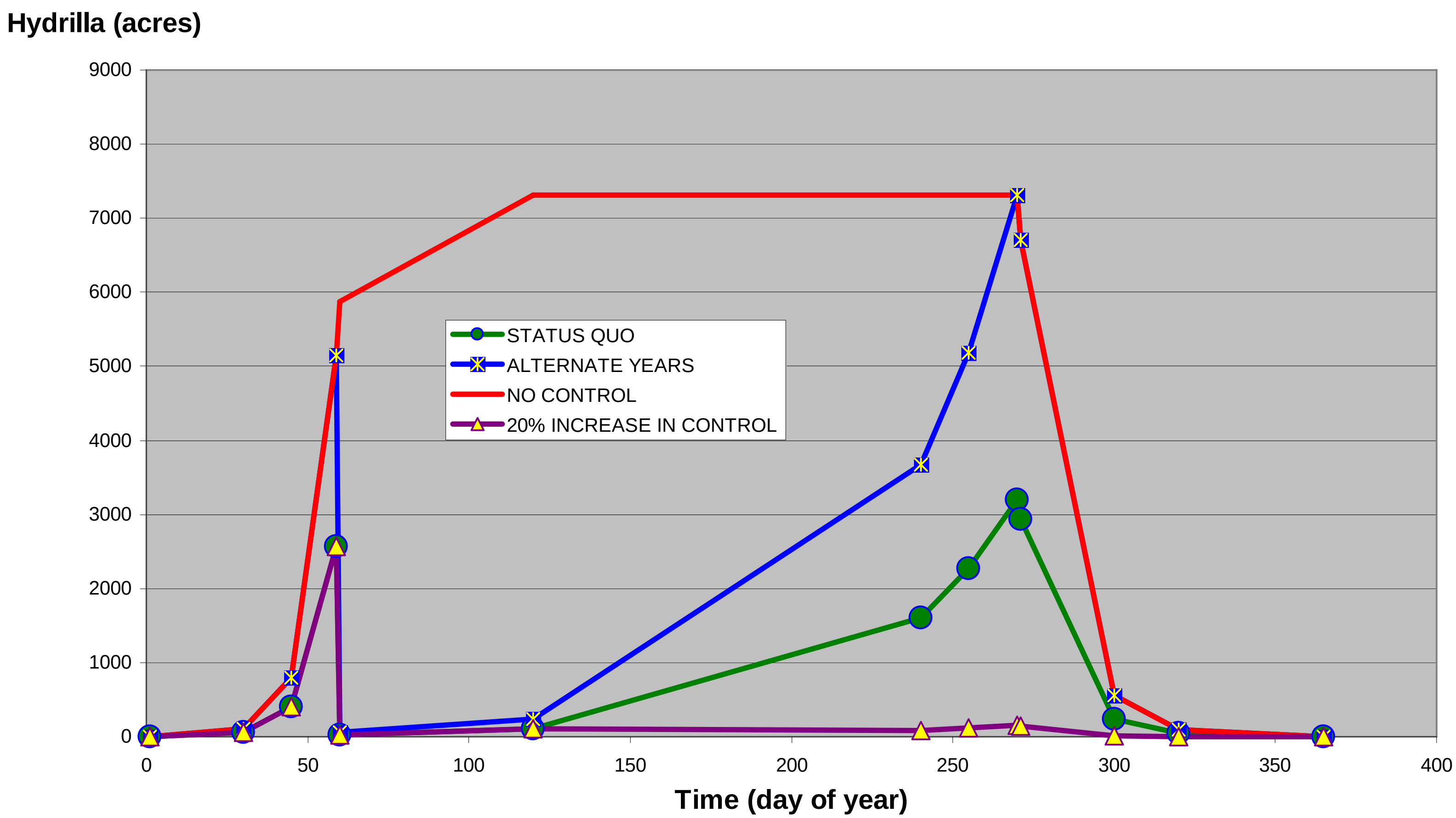


Figure 3-3. Simulated hydrilla coverage in Lake Weohyakapka.

A regression analysis was conducted on the above variables using data collected on the 13 lakes over 20 years (from 1982 – 2002). These data are unbalanced panel data (Greene, 2004). I used Limdep 8.0's panel data analysis tool for unbalanced panel data to perform regression analyses. I conducted several specification tests, including 1) to determine whether hydrilla and floating plant acreage variables should be raised to a higher power to provide better parameter estimates; 2) to check whether I needed an interaction variable to capture the combined effects of invasive aquatic plant acreage and lake size; and 3) pooling tests were conducted to check whether intercept and slope coefficients could be assumed to be the same for all lakes. While there were not enough degrees of freedom to test for lake-specific slope parameters, the partial F-test for lake-specific intercept terms indicates no statistically significant difference (Greene, 2004). The amenity variables Ramps and Parking were perfectly correlated, and were redefined as one variable (Ramps+Parking). There was no variation in the variable Camping, so it was excluded from the model. The model parameter estimates are reported in Table 3-4.

All variables except Summer are significant at the 95% level of confidence or higher. The model significance was high ($F = 42.02$, significance of $F = 0.0000$), with the regression equation providing a relatively good fit to the sample data (Adj. $R^2 = 0.7836$). There were no obvious model problems. Neither White's test nor the Breush-Pagan test for heteroscedasticity revealed any problems, and the Durbin-Watson statistic was 1.96, signifying no significant problem with autoregression.

Lake size, and ramps+parking have a positive impact on fishing effort. The positive sign on WACRES suggests that angler effort is greater on larger lakes. Larger lakes likely have fewer conflicts between anglers and other recreational boaters, leading to a better fishing experience and perhaps better fishing. More fishing sites, larger fish may explain this phenomenon, and proximity of large lakes to large population areas are other explanations. I estimate that for each additional 1000 acres of lake surface area, there will be 7.01 additional hours of fishing effort per

Table 3-4. Angler effort regression model parameters.

	Coefficient	P-value
Intercept	-406.426	0.002525
Hydrilla^2**	4.25E-07	0.030062
Floating^2**	4.68E-07	0.026767
(Hydrilla+Floating)x(wacres)**	-2.90E-07	0.030224
WACRES***	0.00701	2.36E-33
Ramps+Parking***	5.305605	7.79E-07
Oligotrophic**	440.4176	0.037645
Eutrophic***	377.5538	0.005022
Hypereutrophic***	615.6091	5.08E-05
SPRING***	504.9197	1.38E-05
WINTER***	430.8179	0.000372
SUMMER	155.1794	0.205076

* significant at the 90% level of confidence
** significant at the 95% level of confidence
***significant at the 99% level of confidence

day on that lake. This may suggest that larger lakes are a more valuable natural resource for recreational use, and may warrant higher priority for funding to control invasive aquatic plants.

Likewise, ramps and parking have a positive impact on fishing effort. The availability of ramps, and safe, maintained parking areas are likely to improve the fishing experience. Here, I estimate that the presence of both parking and ramps adds almost 5 hours of angler effort per day. An interesting interpretation, when taken together with the aquatic weed effects (discussed below), is that building parking spaces and providing ramp access may overcome a certain amount of invasive aquatic plant coverage, at least while lake access is possible through the aquatic weeds.

Interpretation of the trophic state parameters is less obvious, perhaps because there are competing forces at work. On the one hand, scientific findings suggest a reduction in fish species and fish weight for some sport fish with an increase in Florida lake trophic state (Bachmann et al., 1996; Hoyer et al., 2005). On the other hand, lake eutrophication is advanced by increased runoff from larger population centers. This model shows mixed results with respect to trophic states' effects on fishing effort. The parameters for oligotrophic, eutrophic and hypereutrophic lakes are positive, while the parameter on the excluded variable mesotrophic is interpreted as being negative; Hypereutrophic lakes attract more fishing effort than eutrophic, which is greater than mesotrophic. One interpretation is that oligotrophic lakes attract anglers for the clarity of the water that may improve the fishing experience. As lake clarity falls with the increased trophic state, the dominant force may then be population center effect, i.e. lakes become eutrophic because they are near population centers and receive more nutrient loads. And because the lake is near a population center it is fished more frequently despite the higher trophic state.

The aquatic plant parameter estimates suggest that invasive aquatic plant coverage has a negative impact on fishing effort when including the interaction effects of lake size. For example, a lake of 10,000 acres that goes from no invasive aquatic plants to 10 acres of hydrilla and 10 acres of floating plants (water hyacinth and water lettuce) would cause the loss of 0.057 hours of angler effort per day. Going from 10 to 50 acres of hydrilla and floating plants, respectively, would cause the loss of 0.287 hours of fishing effort per day. Figure 3-4 shows the impacts of increased hydrilla and floating plants coverage (in equal amounts) on fishing effort for a 10,000 acre lake. This finding is consistent with the literature on hydrilla coverage and angler effort. Colle et at. (1987) report a significant negative correlation between hydrilla coverage and harvestable bluegill and redear sunfish populations on Orange Lake, Florida. Colle et al. also reported an 85% decrease in total angler effort on Orange Lake when hydrilla coverage increased from 0% to 95%.

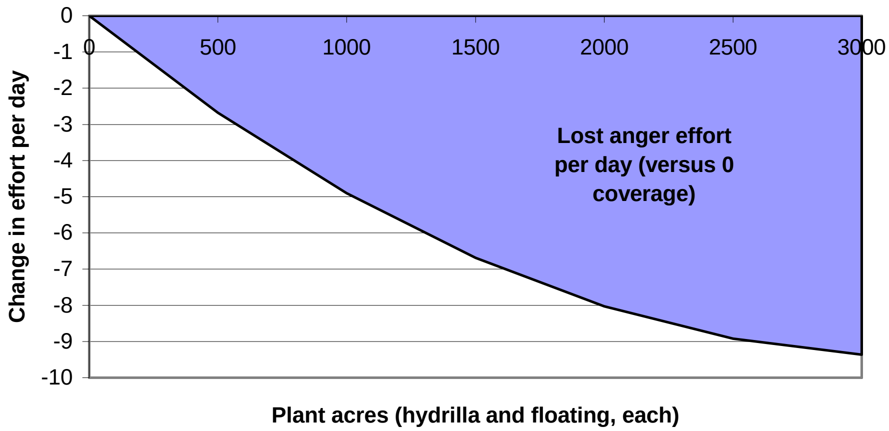


Figure 3-4. Daily fishing effort lost to invasive aquatic plants for a 10,000 acre lake in Florida.

Hydrilla, Water Hyacinth, and Water Lettuce Treatment Cost Model

The lack of common knowledge of hydrilla growth rates may have contributed to drastic reductions in State funding for invasive plant control in the mid 1990s. Without adequate funding for control, hydrilla grew rapidly and took over entire lakes. Control of lakes was eventually regained in subsequent years, but at a very high cost. The total cost of controlling hydrilla, water hyacinth and water lettuce in any given year is modeled as a function of acres treated during that year assuming constant costs:

Equation 6. $C = c_1 Hydrilla + c_2 Floating$

where C is the total cost of treating invasive plants, c_1 is the per acre cost of treating hydrilla, *Hydrilla* is the total number of acres treated, c_2 is the per acre cost of treating water hyacinth and water lettuce, and *Floating* is the total acres of water hyacinth and water lettuce treated. Equation 6 was estimated from the 5 year averages of per acre treatment costs for the 13 lakes included in this study using data obtained from FDEP for 1998-2002 (Ludlow [personal communication], 2005); the five year average for c_1 is \$561 and c_2 is \$107.

Angler Effort Value Model

According to the Florida Fish and Wildlife Conservation Commission, freshwater anglers on Florida lakes spent \$18.20 per hour fishing in 1996 or \$20.65 in 2002 dollars (Thomas and Stratis, 2001; FFWCC, 2003). Applying \$20.65 and assuming a fishing day is 6 hours, the empirical angler value equation is

Equation 7. $V = p\,F$

where V is the value of fishing, p is the per hour angler value in dollars and F is the number of hours spent fishing.

Economic Effects of Invasive Aquatic Plant Management

Using the actual treatment and surveyed acreage data from FDEP for the 13 lakes, I simulate the economic effects of each of the treatment scenarios (*A*- status quo, *B0*- no treatment, *B2*- treatment every other year, and *C20*- second treatment at 20%). Recall Equations 1-4, the growth equations for the invasive aquatic plants for each treatment scenario. Angler effort, F, is a function of invasive aquatic weed acreage, H, and other lake characteristics, X (i.e., lake size, parking, trophic state, and season) such that

Equation 8. $F = f(H, X)$

and the change in angler effort with respect to a change in invasive plant acreage from a particular scenario is

Equation 9. $\dfrac{\partial F}{\partial H} = \dfrac{\partial f(H, X)}{\partial H}$.

Angler effort can be summed over several years as

Equation 10. $F^1 = F^0 + \dfrac{\partial f(H, X)}{\partial H} dH$

and generalized as

Equation 11. $dF = F^1 - F^0$.

The same generalization can be made of treatment costs and invasive aquatic plant acreage as

Equation 12. $dH = H^1 - H^0$

Equation 13. $dC = C^1 - C^0$.

The net benefit for each scenario is calculated as

Equation 14. $$NB = \sum_{L=1}^{13}\left(\sum_{t=1}^{365}\left(p \ \frac{\partial f(H_{L,t}, X_L)}{\partial H_{L,t}} dH_{L,t}\right) - dC(H_{L,t})\Big|_{t=ts}\right)$$

where *NB* is net benefit from the treatment strategy, *L* is the subject lake (George, Griffin, Harris, Istokpoga, Jackson, Kissimmee, Lochloosa, Okeechobee, Orange, Osborne, Poinsett, Sampson, and Weohyakapka), *t* is the day of the year, *p* is the per hour value of fishing, *H* is invasive aquatic plant coverage, and *C* is treatment costs.

The acreage of hydrilla, water hyacinth and water lettuce changes throughout the year. In the warm summer months, when the photoperiods are longer, aquatic plants can infest almost all of the available lake acreage absent control. While it is widely accepted that high levels of aquatic plants can block recreational access to Florida lakes, only one study has measured the relationship between invasive plant coverage and fishing. Colle et al. (1987) report an 85% decrease in total angler effort on Orange Lake when hydrilla coverage increased from 0% to 95%. In Florida, many 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. Here, I assume that only 15% of the otherwise expected fishing effort would remain when invasive aquatic plant coverage is above 80% of available lake surface area.

I simulate the impacts of the invasive plant management scenarios using General Algebraic Modeling System (GAMS) 2.5A software. The results are reported in Table 3-5, with an example for 4,000-acre Lake Jackson in Figure 3-5. One very useful result is the estimation of the total value of the 13 lakes—over $64.78 million, with about 3.13 million total fishing hours. These results are similar to those found by other studies on Florida lakes. For example, Milon et al. (1986) estimated a $480,000 annual willingness to pay for hydrilla control on Orange and Lochloosa lakes. They also found that a full hydrilla infestation on the lakes would result in a loss over $5 million per year. Colle et al. (1987) similarly estimated a total economic impact of $900,000 for invasive weed control on Orange Lake.

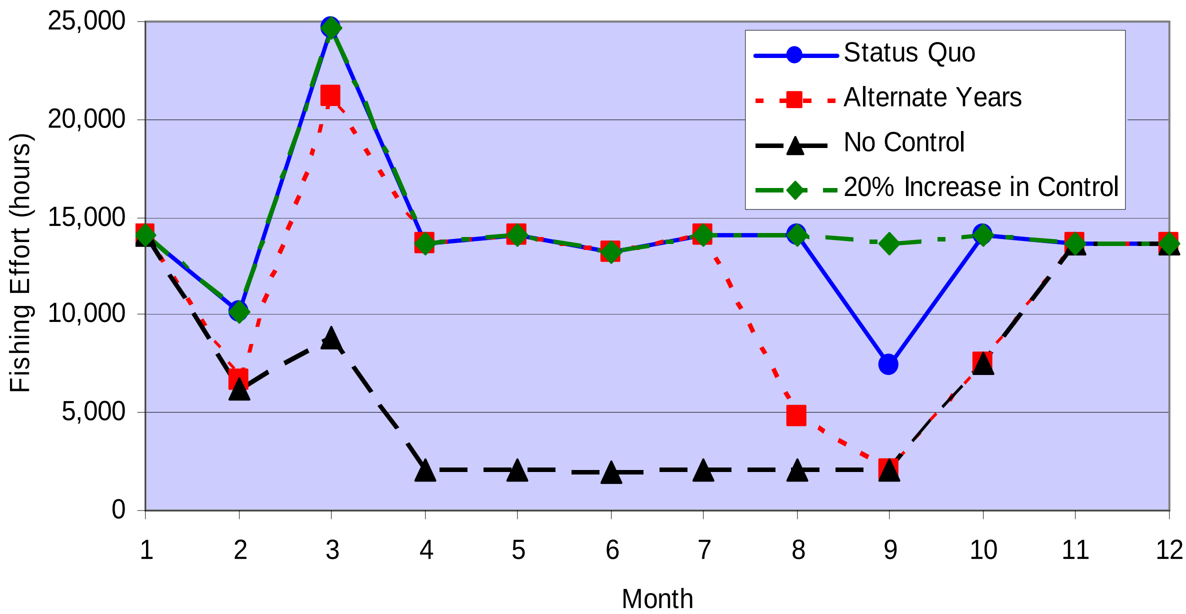
Table 3-5. Annual economic impact of invasive aquatic plant management on 13 lakes.

	A- Status quo	*B2*-Alternate year control	*B0*-No control	*C20*-Second treatment at 20%
Fishing Effort (hours)	3,135,966	2,426,774	1,369,516	3,359,053
Treated Acres	13,785	31,285	0	16,542
Peak Acres	21,085	43,620	43,620	4,304
Total Value $^{\eta}$	64,783,832	50,133,107	28,291,923	69,392,436
Total Control Costs $^{\eta}$	4,828,254	10,938,970	0	5,793,905
Net Benefit $^{\eta}$	59,955,578	39,194,966	28,291,923	63,598,531
Change in NB $^{\eta}$	0	-20,761,440	-31,663,655	3,642,954

$^{\eta}$ Value per year, $ 2006 millions

Milon and Welsh (1989) estimate $176,000 willingness to pay for invasive plant management on Harris and Griffin lakes, with a total recreation impact of $1.7 million. Bell et al. (1998) estimated almost $20 million annual willingness to pay for invasive plant management on Lake Tarpon.

Compared with the status quo treatment strategy, reducing treatment to every other year, or halting treatment altogether will lead to significant recreational and ecosystem losses, largely due to access problems. Alternative year control (*B2*) results in a 23.61% reduction in fishing hours,



99Figure 3-5. Impact of invasive plant control on fishing effort (Lake Jackson example)

and no control (*B0*) yields a 56.33% loss in angler effort. A 20% increase in control (*C20*) increases fishing hours by 7.11%.

Peak and treated acreage of invasive plants vary widely by control policy. Decreasing treatment more than doubles the peak acreage. Alternate year control (*B2*) and no control (*B0*) cause annual peak acreage to increase by 106.88% (the lake maximum), and treated acreage to increase by 126.95% for alternate year control. Increasing treatment substantially decreases the peak acreage and the total acres treated. For example, moving from the status quo to strategy *C20* reduces the peak acres by 79.59% (see Figure 3-1, Figure 3-2, and Figure 3-3). This may be extremely important to the ecology of the lakes and for the preservation of native plant species.

Control costs also vary widely by policy. The status quo (*A*) control costs are $4,828,254. These costs rise by 126.56% with the alternate year control (*B2*), and by 20% for the 20% increase in control (*C20*).

The state of Florida must balance the benefits and costs of invasive species-related public policies. The total recreation-related losses associated with no control (*B0*) are \$33,663,655 per year. Using this as a baseline for return on investment calculations, I estimate that status quo control (*A*) yields a 655.80% return on the investment of \$4,828,254 in invasive aquatic plant investment. In terms of rate of return, status quo ranks the highest, but in terms of absolute net benefit, increasing control is preferred. Increasing control by 20% from status quo will increase fishing-related benefits by \$3,642,953. *B2* yields a 609.37% return on investment, which is lower than the 655.80% rate of return to the status quo policy. Alternate year control (*B2*) results in a loss in fishing-related benefits as compared to the status quo, but yield 99.67% rate of return as compared to do nothing (*B0*). In the mid-1990s, the state of Florida significantly reduced the FDEP's invasive plant management budget, and hydrilla growth went unchecked. These results confirm the high costs associated with such a lapse in funding.

Treatment of invasive aquatic plants should be continued, either at their current levels or at slightly increased levels of control, depending on relative demands on state monies. However, these results may be too conservative as they do not consider the impacts of invasive aquatic plant control on seed and tuber bank numbers or ecosystem brittleness that may result from prolonged aquatic weed monocultures. These simulations are restricted to a 5 year period on 13 lakes. Using the FDEP plant coverage data (n = 997), I estimate a mean hydrilla coverage of 9.36%, with a standard error of 0.61%, and a range of 0 to 100% of the lake surface area. I also estimate mean floating plant coverage of 0.07%, with a standard error less than 0.1% and a range of 0 to 51.92% of lake surface area. At these levels, tuber and seed banks are at relatively low numbers. Given several years of no control, these numbers would be much higher and could vastly increase control costs and recreational losses in subsequent years. Treatment strategies *B0* (no treatment) and perhaps *B2* (treatment every other year) could produce such an event, at which point a substantial portion of the total benefit of these 13 lakes would be lost for four years or more. The loss of recreation on these 13 lakes may have a devastating impact on certain regional economies.

Maintenance control of these aquatic species at low levels is more economically efficient than allowing them to grow rampantly or infrequently controlling them. Indeed, the comparison of the status quo scenario *A* to the every other year treatment scenario *B2*, it is apparent that control costs rise substantially and net benefits fall substantially due to sporadic control. Even brief lapses in funding, like what occurred during the mid-1990s, are very costly. In Florida there are 1.05 million acres of lake surface area on lakes with over 1,000 acres (FFWCC, 2005). When considering the economic implications on lakes throughout the State, continued and perhaps increased treatment of invasive aquatic plants may be in the public's best interest.

Lapses in maintenance control may also have long run consequences. In 2000, it was discovered that hydrilla was becoming resistant to flouridone herbicide, apparently due to random mutations (FDEP, 2004). For example, in 2002 the 19,000-acre Lake Tohopekaliga had 15,000 acres of herbicide-tolerant hydrilla. If mutation rate is a function of population size, then brief lapses in hydrilla control that lead to large plant populations may provide for more mutations and higher rates of herbicidal resistance. There is no close substitute to fluoridone for large-scale hydrilla control; lake managers must be vigilant against large hydrilla populations.

One important final note about the results is that while they may be robust over the 5-year period and the 13 lakes I examined, they may not be robust for predicting the economic effects of invasive aquatic plant management for future time periods. An important impact of consistent treatment of these plants is on reducing their tuber and seed banks. Seed banks indicate the potential future biomass (Winton and Clayton, 1996). The presence of tuber and seed banks may exacerbate the differences between the various levels of treatment. Future work will include tuber and seed banks for hydrilla, water hyacinth, and water lettuce.

Conclusion

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. Recreational freshwater fishing in Florida lures over 3 million anglers with annual expenditures exceeding $3.8 billion. 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 run cost-effective management of these invasive species requires consistent control efforts, yet the State's funding has fallen short in the past. Using data collected on 13 lakes with more than 100 acres of invasive plant coverage at any point during 1998-2003, I estimate the growth of hydrilla, water hyacinth, and water lettuce for each lake as well as per acre control costs for hydrilla and floating plants. Using fishing effort data collected over 20 years, I also estimate the effects of hydrilla, water hyacinth, water lettuce, and other lake characteristics on fishing effort. I combine plant growth, angler effort, and control costs into a bioeconomic model of hydrilla, water hyacinth and water lettuce and fishing effort. The bioeconomic model is used to estimate the value of various invasive aquatic plant management regimes.

Model results show that over 5 years, the value of fishing activity on the 13 lakes is in excess of $64.78 million, with about 3.13 million total fishing hours. Compared with the status quo treatment strategy, reducing treatment to every other year, or halting treatment altogether will lead to significant recreational and ecosystem losses, largely due to access problems. The status quo (*A*) control costs are $4,828,254. These costs rise by 126.56% with the alternate year control (*B2*), and by 20% for the 20% increase in control (*C20*).

Peak and treated acreage of invasive plants vary widely by control policy. Decreasing treatment more than doubles the peak acreage. Increasing treatment substantially decreases the peak acreage and the total acres treated.

The total recreation-related losses associated with no control (*B0*) are high—$33,663,655 per year. By comparison, status quo control yields 655.80% return on investment for control expenditures of $4,828,254 per year. In terms of absolute net benefits, increasing control by 20% will increase fishing-related benefits by $3,642,953, but at a lower rate of return— 609.37%. Alternate year control (*B2*) results in a loss in fishing-related benefits as compared to the status quo, but yield 99.67% rate of return as compared to do nothing (*B0*).

A few clear conclusions follow from the results: 1) Florida lakes have very high economic values that are at risk from invasive aquatic plants; 2) maintenance control of invasive aquatic plants is the preferred cost-minimizing control policy; and 3) lapses in maintenance control, even if brief, can significantly increase subsequent invasive aquatic plant control costs.

CHAPTER 4
THE LEGAL BASIS FOR REGULATORY CONTROL OF INVASIVE AGRICULTURAL PESTS IN FLORIDA

Introduction

Florida is no stranger to agricultural disease, particularly those affecting its citrus industry. Florida has twice successfully eradicated citrus canker (Division of Plant Industry, Florida Department of Agriculture and Consumer Services, 2006). Citrus canker was first detected in Florida in 1910 and declared eradicated in 1947. However, in 1986, a highly aggressive Asian strain of the citrus canker was detected in Florida[3] (Timmer, Graham, and Chamberlain, 2006). Some speculate that the 1986 strain was not a reintroduction but a perennial holdover from the 1910 *Xanthomonas axonopodis* pv. *citri* introduction (Schubert and Sun, 2001). The 1986 strain was declared eradicated in 1994, but was found again in 1995 in residential and commercial sites, including the Miami International Airport in Miami-Dade County (Gottwald et al., 2002). Florida has a high rate of non-native species introduction, with the Port of Miami receiving about 85% of non-native plant shipments entering the US each year (OTA, 1993).

Facing potentially devastating effects to the citrus industry as well as Florida's economy, the US Department of Agriculture and the State of Florida implemented major dual-track citrus canker eradication programs (CCEP). Both programs required the removal of all trees within 1,900 feet (initially 125 feet) of an infected tree. The USDA administered and provided compensation to commercial citrus growers whose trees were taken, while the state of Florida administered and provided compensation to residential tree owners whose trees were taken. Under the USDA program, commercial growers were compensated $26 per tree. Residential tree owners were provided $55 per tree, and some counties supplemented this compensation. For

[3] Haire v. Florida Dept. Of Agriculture And Consumer Services, 870 So.2d 774 (Fla. 2004).

example, in Broward County tree owners were given $45 Wal-Mart gift certificates for the first tree taken (good for Garden Center purchases only). Legal challenges to the state and federal eradication programs happened almost immediately after the first tree was taken (Regina, Olexa, and McGovern, 2004)

In 2000, residential citrus tree owners of suspicious trees were granted temporary injunctions against the State's canker eradication program. From 2000 to 2004, there were two 18-month gaps during which the State was enjoined from cutting down healthy trees within 1,900 feet of infected trees and canker innoculum increased and was largely undetected on residential trees. Since that time, Florida experienced five major hurricanes (Albrigo et al., 2005). The hurricanes of 2004, Charley, Frances, Ivan, and Jeanne, spread citrus canker from these residential trees to such an extent that 80,000 commercial acres of citrus were subsequently slated for destruction. Concentrated efforts by governmental officials reduced this to 32,000 acres when Hurricane Wilma hit in 2005. Due to the spread of the citrus canker pathogen with Wilma, officials faced the task of destroying an additional 168,000 to 220,000 acres of commercial citrus (USDA, 2006). The inability of the State's canker eradication program to continue unabated meant the USDA canker eradication program was largely ineffective. On January 10, 2006, the federal government stated that citrus canker "is so widely distributed that eradication is impossible" and pulled the funding for the USDA's citrus canker eradication program (USDA, 2006). This change in policy came on the heels of a number of judicial decisions upholding the legality of Florida's citrus canker eradication program, but too late to save the USDA eradication program. Though the CCEP was repealed in January 2006 (Timmer et al., 2006), these judicial decisions will be precedential to potential challenges to similar State programs designed to manage and control pests like citrus canker and citrus greening (Salisbury, 2006).

The State of Florida, as other states in the US, has a duty to protect its agricultural and natural resource interests from invasive plant, animals, and other species. The power to exercise protective measures originates from the police power inherent in Florida's sovereignty.[4,5] The use of police power to protect Florida's agricultural interests is delegated by the Legislature to the Director of the Division of Plant Industry within the Department of Agriculture and Consumer Services.[6]

This chapter provides an overview of the State's use of police power to protect agriculture in conjunction with legal decisions that balance the exercise of this power with the constitutional mandates of due process and just compensation. These cases demonstrate how the courts apply these constitutional limitations in challenges to measures involving a burrowing nematode (spreading decline) in comparison with the measures taken in controlling an aggressive strain of citrus canker.

Use of Police Power to Take Private Property

The State of Florida has the power to take private property for a public purpose as an incident to its sovereignty and requires no constitutional recognition.[7] One form of this power is when Florida uses its police power to take property for the purpose of protecting "public safety, public welfare, public morals, or public health.[8]" "Police power" is sometimes used to only

[4] Boom Co. v. Patterson, 25 L.Ed 206, 98 U.S. 403 (U.S. 1878).

[5] Department of Agriculture and Consumer Services v. Bonanno, 568 So.2d 24 (Fla. 1990).

[6] Fla. Stat. §581.031(7) (2002).

[7] See *infra* note 3; see also note 4.

[8] Sweat v. Turpentine & Rosin Factors, Inc., 15 So.2d 267 (Fla. 1943).

describe activities that do not require compensation. However, the exercise of police power may require compensation.[9]

It should be noted that it is difficult to discern the boundary line between the actions that are compensable under the police power and compensable actions under eminent domain.[10] The distinction is that eminent domain involves taking a property for a public use, where police power involves the destruction of such property to prevent its use in a manner that is detrimental to the public interest (Gottwald, Timmer, and McGuire, 1989). Broadly speaking, the courts will consider six factors when deciding whether State action is a valid exercise of police power or a compensable taking:[11]

1. "Whether the State physically invaded the property."
2. Whether the State's actions "precludes all economically reasonable use of the property."
3. "The extent to which the regulation curtails investment-backed expectations."
4. Whether the regulation "confers a public benefit or prevents a public harm."
5. Whether the regulation "promotes the health, safety, welfare, or morals of the public."
6. Whether the regulation is "arbitrarily and capriciously applied."

In the canker and spreading decline cases, the determinations that cutting healthy, yet suspect citrus trees were compensable takings largely depended on whether the State's action conferred a public benefit or prevented a public harm, and these cases preceded the legislature's 2002 statutory compensation scheme for trees cut after 1995.[12] After *Patchen v. Dept. of Agriculture and Consumer Services*, an owner of a healthy residential citrus tree that was cut by

---

[9] Department of Agriculture and Consumer Services v. Mid-Florida Growers, Inc., 521 So.2d 101, 101-4 (Fla. 1988), cert. denied, 488 U.S. 870, 109 S.Ct. 180, 102 L.Ed.2d 149 (1988); see also Department of Agriculture and Consumer Services v. Polk, 568 So.2d 35 (Fla. 1990); see also Graham v. Estuary Properties, Inc., 399 So.2d 1374 (Fla. 1981) cert. denied, 454 U.S. 1083 (1981); see also State Plant Board v. Smith, 110 So.2d 401 (Fla. 1959).

[10] 16A Am. Jur. 2d Constitutional Law § 318 (1998).

[11] See *infra* note 7.

[12] See Department of Agriculture and Consumer Services v. Mid-Florida Growers, Inc., 521 So.2d 101, 101-4 (Fla. 1988), cert. denied, 488 U.S. 870, 109 S.Ct. 180, 102 L.Ed.2d 149 (1988); see also Patchen v. Dept. of Agriculture and Consumer Services, 906 So.2d 1005 (Fla. 2005).

the State no longer has to prove that the State's actions constituted a taking.[13] However, the question of whether the statutory compensation is enough is unresolved. The following section addresses this question.

Limitations on Police Power

The Florida Constitution limits the use of police power to control agricultural disease. Private property cannot be destroyed without "due process of law" and "just compensation.[14]"

Substantive Due Process and Procedural Due Process

Due process includes both substantive and procedural elements (Gottwald et al., 1989). Substantive due process protects individual rights, such as life, liberty or *property*, and the exercise of a police power that infringes one of these rights must bear a "reasonable relationship" to a legitimate objective.[15] The courts have long held that the protection of agriculture is a legitimate objective for the use of the State's police power.[16] So long as the legislative decision bears a reasonable relationship to protecting agriculture, the court will not substitute its own judgment. Procedural due process ensures that process is fair when these substantive rights are at issue.[17] A procedural due process consideration relevant to the control of agricultural disease is the "opportunity to be heard" on whether the destruction is proper.[18]

---

[13] 906 So.2d 1005 (Fla. 2005).

[14] Fla. Const. Art. I, §9; see also Fla. Const. Art. X, §6.

[15] See Lochner v. New York, 198 U.S. 145 (1905); see also Griswold v. Connecticut, 381 U.S. 479 (1965).

[16] Department of Agriculture and Consumer Services v. Mid-Florida Growers, Inc., 521 So.2d 101, 101-4 (Fla. 1988), cert. denied, 488 U.S. 870, 109 S.Ct. 180, 102 L.Ed.2d 149 (1988).

[17] See Herrera v. Collins, 506 U.S. 390 (1993).

[18] State Plant Board v. Smith, 110 So.2d 401 (Fla. 1959)

Just Compensation

The Florida Supreme Court stated that, "the absolute destruction of property is an extreme exercise of police power and is justified only within the narrowest limits of actual necessity, unless the state chooses to pay compensation."[19] However, the State is not compelled to compensate for property that is "valueless, incapable of any lawful use, and a source of public danger," such as "diseased cattle, unwholesome meats, decayed fruit or fish, infested clothing, obscene books or pictures, or buildings in the path of a conflagration."[20] This provision can be rephrased to say that the state remains obligated to provide "just compensation," but that the amount of compensation is a nullity because the property is without value.

Comparing the Limitations on the Use of Police Power: Spreading Decline versus Citrus Canker

The following lines of cases demonstrate how the facts of the case play a key role in determining the limitations when agricultural crops are destroyed through the exercise of police power. These cases both deal with the diseases that affect citrus trees, spreading decline and citrus canker.

Spreading Decline

Spreading decline is caused by the burrowing nematode, *Radopholus similis*, a microscopic worm that damages the feeder roots of citrus trees (Suit and DuCharme, 1953). Over time, the root system deteriorates, causing the tree's foliage and productivity to deteriorate (Suit and DuCharme, 1953). Infected trees are rendered commercially unprofitable under ordinary market conditions. The burrowing nematode travels very slowly through the soil.

---

[19] Corneal v. State Plant Board, 95 So.2d 1 (Fla. 1957); see also Department of Agriculture and Consumer Services v. Polk, 568 So.2d 35 (Fla. 1990)

[20] See *infra* note 16; see also note 17; see also Department of Agriculture and Consumer Services v. Mid-Florida Growers, Inc., 521 So.2d 101, 101-4 (Fla. 1988), cert. denied, 488 U.S. 870, 109 S.Ct. 180, 102 L.Ed.2d 149 (1988).

The eradication program called for the destruction all of the citrus trees affected by the nematode and the first four trees past the last visibly affected tree.[21] Because spreading decline spreads so slowly, it is not considered an immediate threat and procedural due process requires a hearing before, rather than after, the actual destruction.[22]

The destruction of *diseased* trees does not require compensation.[23] Even though it is justified under the police power as necessary to protect neighboring property, destruction of trees only *suspected* of being affected by the nematode does require compensation.[24] The state does have to give compensation for the destruction of healthy but suspect trees because, although infected, suspect trees do retain some value.[25]

Citrus Canker

Florida implemented a more aggressive program in its attempt to eradicate Asian strain of citrus canker. This strain of citrus canker is caused by the bacterium *Xanthomonas axonopodis* pathovar *citri*. The bacterium causes defoliation, dieback, blemished fruit, reduced fruit quality, and premature fruit drop (Schubert and Sun, 2001). Unlike the slow spreading decline, citrus canker spreads rapidly by wind driven rain, flooding, air currents, insects, birds, human movement within the groves, and movement of infected plants and seedlings (Schubert et al., 2001). Symptoms may manifest as early as seven to fourteen days after infection[26] (Schubert et al., 2001), but may take up to 60 days or more to appear (Schubert et al.). However, the

[21] See *infra* note 17.

[22] See *infra* note 16.

[23] See *infra* note 17.

[24] Id.

[25] Id.

[26] Florida Department of Agriculture & Consumer Services v. City of Pompano Beach, 792 So.2d 539 (Fla. 4th DCA 2001); 829 So. 2d 928 (Fla. 4th DCA. 2002).

maximum visualization does not occur until approximately 107 to 108 days after infection (Gottwald et al., 2002).

In 2002, the Citrus Canker Law amendments —584.184 and 933.07(2), Florida Statutes, required the destruction of all citrus trees within 1,900 feet of an infected tree and allow area-wide search warrants.[27,28] This enlarged the existing statutory 125- foot buffer zone that was based on a study conducted in Argentina (Gottwald et al., 2002). Destruction of all citrus trees within the 125-foot buffer had survived a number of court challenges. Citrus canker was determined to be an imminent threat, which justified destruction of trees prior to a hearing.[29,30] In cases that examined the legality of the USDA's eradication program, the courts also determined that all *healthy but suspect commercial trees within the 125 feet of an infected tree* did not require compensation because they were "incapable of any lawful use, it is of no value, and it is a source of public danger."[31,32]

A study by Gottwald et al. (2002) determined that the 125-foot radius was inadequate because it only captured 30-41% of infection spreading from a diseased tree (Gottwald et al., 2002; Gottwald et al., 1989). Based on the Gottwald study, the Florida legislature ultimately concluded that an enlarged 1,900-foot buffer was necessary and amended section 584.184, Florida Statutes.[33] Procedurally, section 584.184, Florida Statutes requires that owners be

---

[27] Fla. Stat. §933.07(2) (2002).

[28] Fla. Stat. §581.184 (2002).

[29] Denney v. Conner, 462 So.2d 534 (Fla. 1st DCA 1985).

[30] Nordmann v. Florida Department of Agriculture and Consumer Services, 473 So.2d 278 (Fla. 5th DCA 1985).

[31] See Department of Agriculture and Consumer Services v. Polk, 568 So.2d 35 (Fla. 1990).

[32] State Dept. of Agriculture and Consumer Services v. Varela, 732 So.2d 1146 (Fla. 3rd DCA 1999).

[33] See *infra* note 24.

notified of the impending destruction by order.[34] The owner has the option to ask for a stay of destruction in an appellate court where the only issues are whether the tree itself is infected and whether the tree is within 1,900 feet of an infected tree.[35] Since the disease spreads at a fast rate, the court held that the state had adequate reason to not conduct a full hearing prior to eradicating an "imminent danger."[36] The owners may opt for a hearing after destruction.[37] The hearing determines if the destruction of exposed but healthy residential trees constitutes a taking and, if so, the amount of compensation required.[38] These hearings will determine if trees within the 1,900-foot buffer zone require compensation beyond the $55 provided by the statute.[39] The USDA program offered $26 per destroyed commercial tree.

Enlarging the buffer zone from 125 to 1,900 feet reignited legal challenges. In several citrus canker takings cases, homeowners alleged that the FDACS was conducting unreasonable searches of their property and taking trees within the 1,900-foot radius without allowing the homeowner any "opportunity to be heard." Specifically, they alleged 1) that the 1,900-foot rule established by the legislature did not establish probable cause of a tree being infected and therefore did not provide any basis to search a property suspected of harboring an infected tree, and 2) area-wide search warrants requested by the FDACS constituted an unreasonable search of

---

[34] See *infra* note 26.

[35] Id.

[36] Id.

[37] Id.

[38] Id.

[39] Id.

properties for which probable cause was not established. The area-wide search warrants included properties that did not necessarily harbor citrus trees within 1,900 feet of an infected tree.[40]

In *Florida Dept. Of Agriculture and Consumer Services v. Haire,* the court was asked to determine the constitutionality of section 584.184 and 933.07(2), Florida Statutes[41] (Gottwald et al., 1989). Procedurally, the court upheld previous decisions declaring that citrus canker was an "imminent danger" and justified destruction prior to an "opportunity to be heard" for trees within the 1,900-foot zone (Gottwald et al., 2002; Gottwald et al., 2006), but that area-wide warrants were unconstitutional and a violation of the Fourth Amendment to the US Constitution's prohibition against unreasonable searches and seizures.[42] Following these rulings, the FDACS will still be able to seek warrants to search residential properties, but probable cause must be established for each individually identified property.

In its examination of substantive due process, the court determined that the 1,900-foot buffer zone bore a "reasonable relationship" to protecting the citrus industry (Gottwald et al., 1989). The court noted that restricting the legislature to acting only in areas of scientific certainty would result in a level of supervision hostile to our basic principles of government (Gottwald et al., 1989). It is the charge of the elected legislative representatives, not the courts, to decide the proper course of action to protect the public (Gottwald et al., 1989). The courts can only overturn a legislative exercise of police power if it lacks a "reasonable relationship" to the legitimate objective (Gottwald et al., 1989). Here, judicial intervention was not warranted because the legislature based its actions on the advice of a Technical Advisory Committee and a peer-reviewed and published study (Gottwald et al., 1989).

---

[40] See *infra* note 1.

[41] See *infra* note 29.

[42] See *infra* note 1.

While the Haire court found the legislative action valid, the court reiterated that this did not relieve the State from paying "just compensation" (Gottwald et al., 1989). The compensation in the statute provided a floor value guaranteed to the affected owner, even if the tree was valueless (Gottwald et al., 1989). This was valid because the homeowner still had the opportunity to have a judicial determination of what was "just compensation" for the tree beyond this floor value.[43]

In *Patchen v. Dept. of Agriculture and Consumer Services,* the Florida Supreme Court was asked whether *healthy but suspect residential trees within 1,900 feet of an infected tree* were without value.[44] Previously, in *Department of Agriculture and Consumer Services v. Polk,* the court held that healthy *commercial* trees within a 125-foot buffer zone were without value and a source of public danger.[45] The court in *Patchen* was asked to address whether this rationale extended to the 1,900-foot buffer zone, particularly within a residential context.[46] The court neglected to answer this question, holding that the legislature had already decided that homeowners who met the statutory requirements were entitled to a minimum level of compensation, essentially conceding the point of whether cutting healthy trees amounted to a taking.[47] The court again reiterated that this does not prevent the homeowner from bringing a judicial action to determine whether trees within 1,900 feet are of greater value than the $55 floor prescribed by the legislature, affirming that "what constitutes 'just compensation' was a judicial function which could not be preempted by the legislature."[48]

---

[43] Id.; see also Rich v. Dept. of Agriculture and Consumer Services, 898 So.2d 1163 (Fla. 2nd DCA 2005).

[44] See *infra* note 11.

[45] See *infra* note 29.

[46] Patchen v. Dept. of Agriculture and Consumer Services, 906 So.2d 1005 (Fla. 2005).

[47] Id.

[48] See *infra* note 1; see also note 11.

The control of citrus canker, like spreading decline, justifies the exercise of police power. In both instances, the legislature eradication programs were valid because they bore a "rational relationship" to protecting the citrus industry. However, the procedural due process requirements are different for citrus canker. Citrus canker, unlike spreading decline, poses an imminent danger, thus justifying the lack of a full hearing prior to destruction. It is likely that citrus greening would have a similar status.

The one remaining unsettled legal issue regarding the CCEP concerns compensation, even with respect to canker-infected trees. The state does not have to give compensation for canker infected *commercial* trees because they are without value, but the status of residential tree value is still unsettled. However, unlike spreading decline, healthy but suspect trees may or may not be subject to compensation under common law, yet it appears that the Florida courts are willing to consider destruction of healthy trees as a compensable taking.

Currently, there is an apparent conflict in the law between the 3rd and 4th appellate districts. The 3rd District Court of Appeal has held that trees exposed to canker have "'no marketable value' and therefore, no damages can be awarded."[49] The 4th District Court of Appeal, which includes Broward, Indian River, Okeechobee, Palm Beach, St. Lucie, Martin counties, has allowed homeowners in Broward County to move forward with a class action suit that contends that the FDACS must provide replacement costs for their mature citrus trees, including all ancillary costs, even for infected trees.[50] Currently there are nine plaintiffs representing a potential class of about 100,000 residential citrus owners in Broward County[51] (Parsons, Adorno, and Yoss, 2006). It is still an open question as to whether a *healthy but suspect tree within 1,900*

[49] See *infra* note 30.

[50] See *infra* note 24.

[51] Id.

feet of an infected tree may have value beyond the $55 floor value assigned by the legislature, and whether an infected residential tree has value in the 4th Appellate District.

Lessons for Citrus Greening

Like citrus canker, citrus greening (Huanglongbing) is a fast-spreading and highly destructive disease that is of great concern to Florida citrus growers and the FDACS. Citrus greening is caused by the bacteria *Candidatus Liberibacter spp.* spread by two species of psyllids (Chung and Brlansky, 2006). Unlike citrus canker, citrus greening causes rapid decline and death of citrus trees within a few years rather than a mere drop in productivity (Halbert and Keremane, 2004). To prevent use of residential citrus trees as host plants for psyllid populations in areas testing positive for greening, the state of Florida may need to begin removing residential trees once again.

The spreading decline and citrus canker cases have paved the way for a more effective Citrus Greening Control Program (CGCP) that may not fall prey to costly injunctions. To survive legal challenges, a CGCP must first establish a radius of likely infection based on a scientific study similar to the Gottwald et al. studies (2006; 1989). Warrants that list specific property addresses and provide probable cause to search suspect premises will be required. Being within the radius established by the scientific study will suffice for probable cause. Since citrus greening is fatal, unlike citrus canker, courts will likely allow FDACS to destroy infected trees without compensation, if indeed the biological justification for tree removal still remains (it may be too little too late). This would be the case even for the 4th Appellate District. However, suspect trees taken within the designated radius will likely be judged to have value, requiring compensation. The level of compensation can not be legislated. The law regarding agricultural pests and the defensive taking of trees is relatively settled. It is likely that a citrus greening eradication program, should one ever be deemed necessary, would survive legal challenges and help protect the multi-billion dollar citrus industry in Florida. Once the Broward County compensation cases are settled, there will be a better understanding of how Florida courts would assess the value of trees potentially affected by citrus greening, helping policy makers estimate the potential costs of a citrus greening program.

Conclusion

The state is allowed flexibility in its exercise of police power so long as there is a "reasonable relationship" to protecting agriculture. This flexibility was evident in the cases upholding the destruction of all trees within 1,900 feet of a tree infected with citrus canker. One must keep in mind that the constitutional limitations are just that – limitations. Statutes may extend benefits beyond the limitations of the constitution. Many statutory schemes allow for compensation of both diseased and non-diseased trees alike. For instance, although courts have held that diseased trees are without value, section 581.1845 of the Florida Statutes requires compensation to homeowners for the destruction of their trees in the amount of $55 per tree.[52] The state, by compensating for diseased trees, extends a benefit beyond what is required by the Florida Constitution. It is still an open question as to whether healthy but suspect trees within 1,900 feet of a tree infected with citrus canker have a value beyond $55, and whether infected residential trees have any value in the 4th Appellate District, but this issue should be settled in early 2007.

The legislature must balance a number of factors in its decisions to protect agriculture and Florida's economy. While it may be authorized to destroy all trees within 1,900 feet of a tree infected with citrus canker, the rapid spread of citrus canker in the 2004-5 hurricane seasons rendered the program impracticable. Faced with a lack of federal funds and a statute calling for

[52] Fla. Stat. § 581.1845 (2002).

the destruction of 25% of Florida's current citrus crop, the citrus canker eradication program was ended in January, 2006 in favor of a series of best management practices for citrus producers called the Citrus Health Response Plan that does not require the removal of infected trees (Timmer et al., 2006). As the Florida citrus industry braces itself for a new invasive plant pest—citrus greening—lessons from the citrus canker cases may help guide policy makers should they decide to create a citrus greening eradication program.

CHAPTER 5
SUMMARY AND CONCLUSIONS

Introduction

This dissertation focuses on the economic and legal aspects of controlling invasive species in Florida. Invasive species are fast becoming an important issue for many state and federal agencies charged with protecting agricultural and natural systems.

The increase in global trade, tourism and emigration has led to an increase in the invasion rate of many brittle ecosystems by prolific and destructive plants and animals. Once introduced to new areas, roughly 10% of these species become invasive, causing a significant proportion of environmental changes and economic losses worldwide. Florida has about 124 invasive species. In the US, production losses, control costs, and other associated costs related to invasive species is estimated to exceed $137 billion per year (Pimentel et al., 1999). About 25% of US agricultural production is lost to nonnative pests or to their associated control costs (Simberloff, 2002). They can also have devastating ecological impacts, and may be the primary cause of biodiversity loss (Mack, 2000).

Despite the large economic and environmental damages associated with exotic species invasion, little empirical economic research has been produced on the topic. Much of the economics literature on invasive species is too abstract or technical for policy application. Unfortunately, zebra mussels, invasive aquatic plants, and pathogens like citrus canker and citrus greening pose serious risks to agriculture and natural resources. Despite the unknowns, policy makers will be called upon to allocate scarce public resources in defense of natural and agricultural systems. These studies provide much needed information to the discourse on invasive species management even though they are based on untested assumptions about invasive species biology, propagation, spread, and impacts.

Invasive species are a particular problem for tropical and subtropical states like Florida, given that the physiographic, climatic and geographic characteristics of these states make them relatively more vulnerable to the establishment of non-indigenous species than for other states. When considering the well-documented impacts of certain invasive species, such as damages caused by the zebra mussel, hydrilla, and citrus canker, it is clear that the economic consequences of this issue resound with enormous potentiality.

With continuing increases in both global trade and the domestic and international migration of people to Florida, it is reasonable to assume that such transmission pathways will keep contributing to the invasive species problem. This is particularly so with regard to water-borne organisms which are carried in the ballast water of ships plying international trade routes.

This dissertation focuses on three aspects of Florida's interaction with invasive species. The first aspect is the potential economic implications of the infestation of Lake Okeechobee by zebra mussels. The second aspect is the impact of invasive species on recreation. Specifically, I estimate the recreation impacts associated with three types of invasive aquatic species currently found in Florida: water hyacinth, water lettuce, and hydrilla. The third aspect addressed in this series is the legal issues associated with Florida's control and management of invasive species. The state's handling of citrus canker and spreading decline are examined to provide lessons for another pest—citrus greening. This chapter provides a summary of the dissertation topics.

Summary and Conclusions Regarding the Potential Infestation of Zebra Mussels in Florida

Zebra mussels have radically changed ecosystems and increased the cost of surface water withdrawals in the Great Lakes region over the last two decades. They are prolific reproducers, and possess unique biological characteristics that enable them to spread very quickly via human contact. Recreational boaters can unwittingly aide the spread of zebra mussels over long distances. This is a particular concern for the state of Florida, which has a multi-billion dollar recreational fishing industry.

Zebra mussel arrival prevention and eradication measures have been selectively attempted throughout the United States. The US Army Corps of Engineers have proposed an arrival prevention and early warning system for zebra mussels in Lake Okeechobee, FL, but have not received funding to support the program. Given the long-distances that anglers travel to fish on Lake Okeechobee, and the very high potential economic impacts associated with zebra mussels in the Great Lakes, it is worth estimating the expected impacts of zebra mussels in Florida to provide information useful to policy making.

I constructed a bioeconomic model to simulate the potential damages from a zebra infestation on Lake Okeechobee. I first estimated the rate of zebra mussel arrival based on transportation vectors (recreational boating), and then estimated survival assuming habitat suitability from a previous study (Hayward and Estevez, 1997). The results of my survey of surface water users on Lake Okeechobee were applied to existing estimates of changes in maintenance costs of water intake pipes from areas known to be infested with ZM. I report an expected economic impact of ZM over 20 years, including costs and damages to surface water use, angling, ecosystem services, and budgetary cost. I applied state probabilities in a Stochastic Dynamic Simulation format to arrive at a long-run analysis of ZM in Lake Okeechobee.

I found zebra mussel-related impacts without state intervention to be $349.34 million over 20 years. I simulated several potential policy responses to delay or mitigate zebra mussel infestation—arrival prevention and early warning, eradication, and a combination of the two. The arrival prevention and early warning policy that I simulated is the same as proposed by the US Army Corps of Engineers for the lake. Eradication has only been successfully attempted on one small pond in the United States—Millbrook Quarry, VA. Lake Okeechobee is over 3,200 times larger than Millbrook Quarry, and eradication would be very costly—$1.32 billion based on Millbrook Quarry control costs on a volume basis. Arrival prevention and early warning are relatively cheap—$152,800 per year. Arrival prevention reduces the probability of zebra mussels arriving at Lake Okeechobee, and an early warning system provides surface water users with enough advance warning to apply mitigation measures (anti-fouling paint) that reduce the economic impact of an infestation.

The overall cost minimizing choice is to invest in arrival prevention and early warning, which would reduce present value costs by 70.91%. This is also the only policy choice that netted positive returns ($247.71 million) as compared with doing nothing to control or prevent zebra mussels in the lake. Policies that include post-establishment eradication yield large losses ($414.98 million, $603.36 million).

A model of the economic impacts of a potential invasion of Lake Okeechobee by zebra mussels offers some insight into management of this and other invasive species threats. Lessons from this study include

1. Invasive species become endemic and virtually impossible to eradicate once established
2. Post-establishment eradication is much costlier than arrival prevention. Zebra mussels have no known cost-effective control measure, unlike is available for controlling aquatic plants. Scarce public resources are much more effectively spent to prevent the establishment and where cost-effective, control the population of invasive species, rather than attempt eradication
3. Much more data and empirical economic studies are needed to help evaluate invasive species funding demands

Summary and Conclusions Regarding Invasive Aquatic Plants in Florida

Hydrilla verticillata (hydrilla), *Eichhornia crassipes* (water hyacinth), and *Pistia stratiotes* (water lettuce) have been established in Florida's lakes and rivers for over half a century. 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 run cost-effective management of these invasive species requires consistent control efforts, yet the state's funding has fallen short in the past.

In this chapter, I evaluate the status quo maintenance control policy with other potential hydrilla and floating plant control policies. I specify a bioeconomic model of invasive aquatic plants using unpublished data on angler effort, plant coverage, and lake physiographic features and amenities. I first specify plant growth models for hydrilla and floating plants using data collected on 13 lakes with more than 100 acres of invasive plant coverage at any point during 1998-2003. I then simulate the impact of four different control policies for the plants—no control, 99% eradication once every other year, 99% eradication once every year (status quo maintenance control), and 99% eradication once every year with follow-up partial eradication (20%) later in the year. Next, I estimated the impact of invasive aquatic plant coverage on angler effort as well as per acre control costs for hydrilla and floating plants. The bioeconomic model was used to estimate the value of various invasive aquatic plant management regimes.

Model results show that over five years, the value of fishing activity on the 13 lakes is in excess of $64.78 million, with about 3.13 million total fishing hours. Compared with the status quo treatment strategy, reducing treatment to every other year, or halting treatment altogether will lead to significant recreational and ecosystem losses, largely due to access problems. The status quo (*A*) control costs are $4,828,254. These costs rise by 126.56% with the alternate year control (*B2*), and by 20% for the 20% increase in control (*C20*).

Peak and treated acreage of invasive plants vary widely by control policy. Decreasing treatment more than doubles the peak acreage. Increasing treatment substantially decreases the peak acreage and the total acres treated.

The total recreation-related losses associated with no control (B0) are high—$33,663,655 per year. By comparison, status quo control yields 655.80% return on investment for control expenditures of $4,828,254 per year. In terms of absolute net benefits, increasing control by 20% will increase fishing-related benefits by $3,642,953, but at a lower rate of return— 609.37%. Alternate year control (*B2*) results in a loss in fishing-related benefits as compared to the status quo, but yield 99.67% rate of return as compared to do nothing (*B0*).

A few clear conclusions follow from the results:

- Florida lakes have very high economic values that are at risk from invasive aquatic plants
- Maintenance control of invasive aquatic plants is the preferred cost-minimizing control policy
- Lapses in maintenance control, even if brief, can significantly increase the costs associated with subsequent invasive aquatic plant control.

Also apparent from the research is the lack of understanding of the biological and economic relationships involving invasive plants. Little data is available, and very few models and even fewer empirical economics studies address invasive plants. Given the risks to agricultural and natural systems from invasive plants, improvements in data collection and modeling are desperately needed.

Summary and Conclusions Regarding the Regulatory Basis for Controlling Invasive Agricultural Pests in Florida

The state is allowed flexibility in its exercise of police power so long as there is a "reasonable relationship" to protecting agriculture. This flexibility was evident in the cases upholding the destruction of all trees within 1,900 feet of a tree infected with citrus canker. One must keep in mind that the constitutional limitations are just that – limitations. Statutes may extend benefits beyond the limitations of the constitution. Many statutory schemes allow for compensation of both diseased and non-diseased trees alike. The state, by compensating for diseased trees, extends a benefit beyond what is required by the Florida Constitution. It is still an open question as to whether healthy but suspect trees within 1,900 feet of a tree infected with citrus canker have a value beyond what they are legally assigned.

The legislature must balance a number of factors in its decisions to protect agriculture and Florida's economy. While it may be authorized to destroy all trees within 1,900 feet of a tree infected with citrus canker, the rapid spread of citrus canker in the 2004-5 hurricane seasons rendered the program impracticable. Faced with a lack of federal funds and a statute calling for the destruction of 25% of Florida's current citrus crop, the citrus canker eradication program was ended in January, 2006 in favor of a series of best management practices for citrus producers called the Citrus Health Response Plan that does not require the removal of infected trees (Timmer et al., 2006).

Close examination of the litigation surrounding citrus canker and spreading decline eradication programs can provide valuable lessons for regulating other invasive agricultural pests, such as citrus greening. These lessons include

1. Establish a radius of likely infection based on scientific study
2. The radius will provide probable cause for searching a property for the pest, but individual search warrants will be needed
3. If the disease or pest that is the subject of eradication is fatal, it is unlikely that the state will have to compensate residential owners for taken trees. If it is not fatal, the courts may yet support compensation
4. Trees merely suspected of harboring the pest, but not testing positive for it, have value that is determined by the courts

5. Fast-spreading agricultural pest eradication efforts can be devastated by litigation that leads to injunctions. Instead of delaying litigation, the state should fast-track early challenges by certifying the cases as dealing with issues of high public importance. This will move the court cases to the front of the docket list

6. The state should consider litigation alternatives and involve citizens in the regulatory process with town meetings or informal hearings. Homeowners were put aback by their lack of participation in the regulatory process and their inability to have a hearing about tree removal. This alienation led to anger and ultimately litigation. Instead, the state should have considered educating the citizens about the dangers of citrus canker, and provided public forums for citizens to have their say. The state should also have considered mediation as an alternative to costly litigation, which may have avoided the CCEP injunctions that allowed canker innoculum to build up prior to the 2004-2005 hurricanes.

Conclusion

This chapter served as a summation of a series of the three research topics—bioeconomic modeling of zebra mussel impacts on Lake Okeechobee, bioeconomic modeling of invasive aquatic plants on Florida lakes, and the limits to regulatory action to control invasive agricultural pests in Florida. Invasive species are an important concern for the state of Florida, yet there exists little useful empirical economics research on the topic. In Chapter Two and Chapter Three, bioeconomic models are used to estimate the impacts of invasive aquatic plants and mussels. Simulations were run on potential policy responses, and relative impacts of the invasive species under each policy were reported and discussed. One clear conclusion from the results reported in Chapters Two and Three is that it is much more cost-effective to keep invasive species populations at very low levels or prevent their arrival. Once endemic, economic and ecosystem damages are very large. Chapter Four examines the regulatory framework for controlling agricultural pests. I first examine two past regimes—spreading decline and citrus canker, with primary focus on canker. Recent developments in the law regarding citrus canker are discussed, and lessons for future regulatory control of agricultural pests are discussed. The citrus canker eradication program failed because it ran afoul of procedural due process and compensation requirements that could have been avoided by appropriate legislative action.

The implications regarding these findings are that the state of Florida has a good chance of designing control efforts that would survive legal challenges and would work to protect the state’s significant tourism and recreation industries, specifically in terms of fresh water fishing and state park and public recreational area usage.

APPENDIX A
ZEBRA MUSSEL INFORMATION SURVEY

University of Florida
Food and Resource Economics Department

Welcome to the Zebra Mussel Information Survey homepage. The zebra mussel is an invasive species not yet established in Florida, but it does have the potential to be a future threat to our state. This survey will confidentially acquire information from selected surface water users in Florida, in order to estimate future costs associated with a potential zebra mussel infestation of Florida waters.

To start this survey, all you need is the assigned Personal Identification Number (PIN) sent to you by mail. We sent each business or public utility asked to participate in this survey a unique identification number (PIN) to establish the confidentiality and validity of this survey. Please enter your PIN in the space below to begin.

SUBMIT

Section A
This section contains a few questions about some invasive species. Throughout this survey, the term "your facility" refers to the private business or public utility that: 1) is your employer; and 2) is under permit to withdraw surface water in Florida.

Question #1:

Water Hyacinth is an invasive aquatic plant found in many parts of Florida. Have you ever heard of this plant?

- Yes coded: A1Y
- No A1N

Question #2:

Hydrilla is another invasive aquatic plant that is also found in many parts of Florida. Have you ever heard of this plant?

- Yes coded: A2Y
- No A2N

Question #3:

Has either of these aquatic plants ever impeded the surface water withdrawals of your facility, to the degree that it required action from a maintenance crew?

- Yes coded: A3Y
- No: click here to skip to Question #5 A3N

Question #4:

Which of the following aquatic plants is most responsible for causing water flow impediments at your facility?

-
- Hydrilla coded: A41
- Water Hyacinth A42
- Other aquatic plant A43
- Don't know A44

Question #5:

Do you have any knowledge regarding the presence of zebra mussels in the Great Lakes, the Mississippi River, or elsewhere in the United States?

- Yes coded: A5Y
- No A5N

- Answering yes to Question #5 will send you to the next page
- Answering no will send you to Section D

SUBMIT

Section A Notes: Use radio buttons to record all responses

Section B
This section contains a few questions about attitudes towards zebra mussels.

Question #1:

Please tell us how you know about zebra mussels in the United States. Check all of the boxes that apply.

- Trade publication coded: B11
- Water management district publication or employee B12
- Other state agency publication or employee B13
- Internet website B14
- Newspaper or magazine article B15
- Family member, friend or neighbor B16
- Other source B17

Question #2:

Given your knowledge of zebra mussels: what level of concern, if any, do you have about the possibility of zebra mussels being introduced into Florida?

- Very concerned coded: B21
- Concerned B22
- Slightly concerned B23
- Not concerned: click here to skip to Question #5 B24

Question #3:

The concern you have for zebra mussels is primarily related to:

- Environmental issues coded: B31
- Economic issues B32
- Political issues B33
- Some other issue B34

Question #4:

Do you think the state government should spend money to prevent zebra mussels from being introduced into Florida?

- Yes coded: B4Y
- No B4N

Question #5:

Do you think the concern for zebra mussels shown by various U.S. Government agencies is primarily related to:

- Environmental issues coded: B51
- Economic issues B52
- Political issues B53
- Some other issue B54

Question #6:

Do you think the concern for zebra mussels shown by the general public of the United States (of those persons aware of the issue) is primarily related to:

- Environmental issues coded: B61
- Economic issues B62
- Political issues B63
- Some other issue B64

Question #7:

Has your facility made any contingency plans for dealing with zebra mussels should they become established in Florida?

- Yes coded: B7Y
- No B7N

- Answering yes to Question #7 will send you to the next page
- Answering no will send you to Section D

SUBMIT

Section B Notes: Use check boxes for Question #1
Use radio buttons to record all other responses

Section C
The following questions ask you about your contingency plans to deal with zebra mussels, should they become established in Florida.

Question #1:

Please tell us how your facility plans to combat zebra mussels if faced with this problem in the future. Check all that apply.

• Increase routine maintenance	coded: C11
• Retrofit equipment	C12
• Chemical treatment	C13
• Other strategy: please specify below	C14
	C15

Question #2:

As a result of such planning, has your facility actually spent money on any of these strategies?

• Yes	coded: C2Y
• No	C2N

Question #3:

If you answered Yes: please tell us the total amount of money spent for each type of activity being planned. (example: $10,000 for purchase of chemicals).

• Increase routine maintenance	___________________	C31
• Retrofit equipment	___________________	C32
• Chemical treatment	___________________	C33
• Other strategy	___________________	C34

SUBMIT

Section D

This section asks some questions regarding the maintenance of your facility's surface water intake structures. Specifically, we us the word maintenance to refer to the routine cleaning and upkeep of water conveyance systems, in order to ensure there are no impediments to the flow of water. Such impediments resulting from the growth of organisms have been referred to as "bio-fouling."

Question #1:

Does bio-fouling caused by native mussels, and/or other native organisms require your facility to perform regularly scheduled maintenance of its' surface water intake structures?

- Yes — coded: D1Y
- No: click here to skip to Question #6 — D1N

Question #2:

How often is such maintenance performed on the surface water intake structures of your facility, because of the bio-fouling caused by native mussels, and/or other native organisms?

- Twice a year — coded: D21
- Once a year — D22
- Once every two years — D23
- Other frequency: please specify below — D24

D25

Question #3:

Which of the following is the main cause of the bio-fouling at your facility?

- Native mussels — D31
- Other native organism — D32
- Not sure — D33

Question #4:

For maintenance performed to remove the bio-fouling, does your facility contract this work out to another firm?

- Yes — coded: D4Y
- No: click here to skip to Question #6 — D4N

Question #5:

Please tell us the method(s) of maintenance that your maintenance crews use to combat the bio-fouling of surface water intake structures. Check all that apply.

- Physical removal: scraping coded: D51
- Physical removal: pressure washing D52
- Chemical treatment(s) D53
- Backflushing D54
- Other method: please specify below D55

D56

Question #6:

In the contact letter we sent by mail informing you of this survey, we included data obtained from your facility's surface water permit. Please review that information now.
Is the data we mailed to you correct?

- Yes: click here to skip to Question #7 coded: D6Y
- No D6N

If you answered No, please make the appropriate corrections in the box below:

Permit No.	ID No.	Average Daily Withdrawal Amount (Gallons)	Intake Size (Inches)	Intake Location (County)
Example:				
00001	01	2000000	12	Hillsborough

NOTE: If possible, this box pops up only if respondent answers No to Question #6.

Question #7:

Please use the following box to tell us about the maintenance costs for each location of surface water intake structures owned by your facility. "Maintenance cost" refers to the approximate value of costs incurred each time maintenance is performed ("Visit"), regardless of whether it was contracted to other firms, or performed by your employees. We would also like to know the approximate length of the intake(s).

Permit No.	ID No.	Maint. Cost ($ per Visit)	Frequency (Visits per time frame)	Intake Length (Feet)	Surface Water Body (i.e., Lake Tarpon, St Johns River, etc.)
Example:					
00001	01	$1000	1 per 2 yrs	1500	Crystal River

SUBMIT

(Exit page: reached upon final submission)

Thank you very much for participating in this survey. All information is strictly confidential. For more information about zebra mussels, use the following links.

APPENDIX B
SENSITIVITY ANALYSIS OF ZEBRA MUSSEL PARAMETERS

Table B-1. Sensitivity analysis of zebra mussel parameters.

Base Results	Policy I (Do nothing)	Policy II (Arrival prevention and early warning)	Policy III (Eradication)	Policy IV (Combination of Policies II and III)
Net Losses	349.30	101.60	952.70	764.30
Policy Cost	0.00	2.33	872.90	696.40
Maintenance Impacts	-10.83	-3.02	-0.41	-0.11
Ecosystem Impacts	-339.6	-96.60	-79.65	-68.07
Recreation Impacts	1.09	0.31	0.25	0.22
Sensitivity Test A- Reduce arrival rate by half to 0.035/2				
Net Losses	174.70	53.19	918.40	518.80
Policy Cost	0.00	2.41	838.50	472.10
Maintenance Impacts	-5.41	-1.54	-0.26	-0.04
Ecosystem Impacts	-169.80	-49.39	-79.91	-46.86
Recreation Impacts	0.54	0.16	0.25	0.15
Sensitivity Test B- Loss (instead of gain) to recreational uses = 10% of 3.25				
Net Losses	351.50	102.30	953.20	764.80
Policy Cost	0.00	2.33	872.90	696.40
Maintenance Impacts	-10.84	-3.02	-0.41	-0.11
Ecosystem Impacts	-339.60	-96.60	-79.65	-68.07
Recreation Impacts	-1.09	-0.31	-0.25	-0.22
Sensitivity Test C- Increase value ecosystem loss to 51.25x$439/ha in $1994				
Net Losses	17,415	4,955	4,955	4,185
Policy Cost	0	2.33	872.90	696.40
Maintenance Impacts	-10.84	-3.02	-0.41	-0.11
Ecosystem Impacts	-17,405	-4,951	-4,082	-3,489
Recreation Impacts	1.09	0.31	0.25	0.22
Sensitivity Test D- Reduce eradication costs to 2.5% of $1.32 billion				
Net Losses	349.30	101.60	101.60	87.65
Policy Cost	0.00	2.33	21.82	19.68
Maintenance Impacts	-10.84	-3.02	-0.41	-0.11
Ecosystem Impacts	-339.60	-96.60	-79.65	-68.07
Recreation Impacts	1.09	0.31	0.25	0.22

LIST OF REFERENCES

Ackerman, J.D., B. Sim, S.J. Nichols, and R. Claudi. "A Review of the Early Life History of Zebra Mussels (*Dreissena polymorpha*): Comparisons with Marine Bivalves." *Canadian Journal of Zoology* 72 (2004):1169 – 1179.

Akcakaya, R., and P. Baker. *Zebra Mussel Demography and Modeling: Preliminary Analysis of Population Data from Upper Midwest Rivers*. Washington, D.C.: US Army Corps of Engineers Report EL-98-1, 1998. Internet site: http://el.erdc.usace.army.mil/elpubs/pdf/crel98-1.pdf (Accessed August 13, 2006).

Albrigo, L.G., R.S. Buker, J.K. Burns, W.S. Castle, S. Futch, C.W. McCoy, R.P. Muraro, M.E. Rogers, J.P. Syvertsen, J.P. Timmer, A. John, K. Bowman, K.W. Hancock, M.A. Ritenour, P.D. Spyke, and R.C. Vachon. "The Impact of Four Hurricanes in 2004 on the Florida Citrus Industry: Exeriences and Lessons Learned." *Proceedings of the Florida State Horticultural Society*, 2005. 118:66-74.

Allen, L.J.S., E.J. Allen, C.R.G. Kunst, and R.E. Sosebee."A Diffusion Model for Dispersal of *Opuntia imbricata* (cholla) on Rangeland." *The Journal of Ecology* 79 (1991):1123 – 1135.

Allen, Y.C., B.A. Thompson, and C.W. Ramcharan. "Growth and Mortality Rates of the Zebra Mussel, *Dreissena polymorpha*, in the Lower Mississippi River." *Canadian Journal of Fisheries and Aquatic Sciences* 56 (1999):748 – 759.

Animal and Plant Health Inspection Service. *United States Department of Agriculture, Citrus Canker Emergency Program Overview*. Washington, D.C.: Statement of the Inspector General before the House Appropriations Committee on Agriculture, Rural Development, Food and Drug Administration and Related Agencies, 1999. Internet site: http://www.aphis.usda.gov/ppq/ep/citruscanker/background.html (Accessed August 15, 2006).

Bachmann, R.W., B.L. Jones, D.D. Fox, M. Hoyer, L.A. Bull, and D.E. Canfield, Jr. "Relations Between Trophic State Indicators and Fish in Florida (U.S.A.) Lakes." *Canadian Journal of Fisheries and Aquatic Sciences* 53(1996): 842–855.

Beckett, D.C., B.W. Green, and A.C. Miller. *Changes in Zebra Mussel Densities in the Upper Mississippi River: 1995 Update*. Chicago, IL: Illinois Natural History Survey Triannual Unionid Report No. 11, 1996. Internet site: http://ellipse.inhs.uiuc.edu/FMCS/TUR/TUR11.html#p15 (Accessed May 9, 2006).

Bell, F.W. *The Economic Value of Lake Tarpon, Florida, and the Impacts of Aquatic Weeds.* A.L. Burruss Institute of Public Service, Kennesaw State University, 1998.

Best, E.P.H., C.P. Buzzelli, S.M. Bartell, R.L. Wetzel, W.A. Boyd, R.D. Doyle, and K.R. Campbell. "Modeling Submersed Macrophytes Growth in Relation to Underwater Light Climate: Modeling Approaches and Application Potential." *Hydrobiologia* 444(2001): 43-70.

Best, E.P.H., and W.A. Boyd. 1996. *A Simulation Model for Growth of the Submersed Aquatic Macrophyte Hydrilla (Hydrilla verticillata (L. f.) Royle*). Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station, Technical Report A-96-8, 1996.

Borcherding, J. "The Annual Reproductive Cycle of the Freshwater Mussel *Dreissena phlymorpha* Pallas in Lakes." *Oecologia* 87(1991):208 – 218.

Borcherding, J., and E.D. de Ruyter van Steveninck. 1992. "Abundance and Growth of *Dreissena polymorpha* Larvae in the Water Column of the River Rhine During Downstream Transportation." *The Zebra Mussel Dreissena polymorpha: Ecology, Biological Monitoring and First Applications in Water Quality Management.* D. Neumann, and H.A. Jenner, eds. Stuttgart; New York: G. Fischer, 1992.

Borcherding, J., and W. Sturm. "The Seasonal Succession of Macroinvertebrates, in Particular the Zebra Mussel (*Dreissena polymorpha*) in the River Rhine and Two Neighboring Gravel-Pit Lakes Monitored Using Artificial Substrates." *International Review of Hydrobiology* 87(2002):165 – 181.

Bossenbroek, J.M., C.E. Kraft, and J.C. Nekola. "Prediction of Long-Distance Dispersal Using Gravity Models: Zebra Mussel Invasion of Inland Lakes." *Ecological Applications* 11(6)(2001):1778 – 1788.

Bowes, G., A.C. Holaday, and W.T. Haller. "Seasonal Variation in the Biomass, Tuber Density and Photosynthetic Metabolism in Three Florida Lakes*." Journal of Aquatic Plant Management* 17(1979), 61-65.

Brezonik, P.L. 1984. *Trophic State Indices: Rational for Multivariate Approaches*. Knoxville, TN: Lake and Reservoir Management, EPA 440/5-84-001 U.S. E.P.A., 441-445.

Buchan, L.A.J., and D.K. Padilla. "Estimating the Probability of Long-Distance Overland Dispersal of Invading Aquatic Species." *Ecological Applications* 9(1)(1999): 245 – 265.

Buhle, E.R., M. Margolis, and J.L. Ruesink. "Bang for the Buck: Cost Effective Control of Invasive Species with Different Life Histories." *Ecological Economics* 52(2005):355 – 366.

Burlakova, L.E., A.Y. Karatayev, and D.K. Padilla. "Changes in the Distribution and Abundance of *Dreissena polymorpha* Within Lakes Through Time." *Hydrobiologia* 571(2006):133 – 146.

Burnham, M. *Front Lines of Battle Against Invaders Increasingly Local.* Washington, D.C.: Environmental and Energy Publishing, 2004. Internet site: http://www.eenews.net/Landletter/Backissues/02120404.htm (Accessed June 23, 2006).

Burruss Institute of Public Service. *The Economic Value of Lake Tarpon, Florida and the Impact of Aquatic Weeds.* Kennesaw State University and Department of Economics, Florida State University, 1998.

Caraco, N.F., J.L. Cole, P.A. Raymond, D.L. Strayer, M.L. Pace, S.E.G. Findlay, and D.T. Fischer. "Zebra Mussel Invasion in a Large, Turbid River: Phytoplankton Response to Increased Grazing." *Ecology* 78(2)(1997):588 – 602.

Carlton, J.T. 1993. "Dispersal Mechanisms of the Zebra Mussel (*Dreissena polymorpha*)." *Zebra Mussels: Biology, Impacts, and Control* . T.F. Nalepa and D.W. Schloesser, eds. Boca Raton, LA: Lewis, 1993.

Carson, R. Personal Communication. FLW Outdoors, February 2007.

Chambers, P.A., J.W. Barko, and C.S. Smith. "Workshop Summaries—Evaluation of Invasions and Declines of Submerged Aquatic Macrophytes." *Journal of Aquatic Plant Management* 31(1993):218 – 220.

Colle, D.E. et al. "Influence of Hydrilla on Harvestable Sport-Fish Populations, Angler Use, and Angler Expenditures on Orange Lake, Florida." *North American Journal of Fisheries Management* 7(1987):410 – 417.

Chen, D., M.B. Coughenour, D. Eberts, and J.S. Thullen. "Interactive Effects of CO2 Enrichment and Temperature on the Growth of Dioecious Hydrilla verticillata." *Environmental and Experimental Biology* 34(4)(1994):345 – 353.

Chung, K.R., and R.H. Brlansky. *Citrus Diseases Exotic to Florida: Huanglongbing (Citrus Greening).* Gainesville, FL: Plant Pathology Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, 2005. Internet site: http://edis.ifas.ufl.edu/PP133 (Accessed March 8, 2006).

Colle, D.E., J.V. Shireman, W.T. Haller, J.C. Joyce, and D.E. Canfield, Jr. "Influence of Hydrilla on Harvestable Sport-Fish Populations, Angler Use, and Angler Expenditures at Orange Lake, Florida*." North American Journal of Fisheries Management* 7(1987):410-417.

Crossland, J. Personal Communication. US Army Corps of Engineers, South Florida Operations Office, January 2007.

De Kozlowski, S.J. "Lake Marion Sterile Grass Carp Stocking Project." *Aquatics* 13(1991):13 – 16.

Deng, Y. "Present and Expected Economic Costs of Zebra Mussel Damages to Water Users with Great Lakes Intakes." PhD dissertation, The Ohio State University, August 1996.

Division of Plant Industry. *Florida Department of Agriculture and Consumer Services Comprehensive Report on Citrus Canker Eradication Program in Florida through 14 January 2006.* Tallahassee, FL: Florida Department of Agriculture and Consumer Services, pp. 1-25, 2006. Internet site: http://www.doacs.state.fl.us/pi/canker/pdf/cankerflorida.pdf (Accessed April 3, 2006).

Drake, J.M., and J.M. Bossenbroek. "The Potential Distribution of Zebra Mussels in the United States." *BioScience* 54(10)(2004): 931 – 941.

Dwyer, G., J.S. Elkinton, and A.E. Hajek. "Spatial Scale and the Spread of a Fungal Pathogen of Gypsy Moth." *The American Naturalist* 152(1998):485 – 494.

Eads, B. Personal Communication. Fishers of Men Tournament, February 2007.

Eiswerth, M.E. and G.C. van Kooten. "Uncertainty, Economics, and the Spread of an Invasive Plant Species." *American Journal of Agricultural Economics* 84(5)(2002):1317 – 1322.

Eiswerth, M.E. and W.S. Johnson. "Managing Nonindigenous Invasive Species: Insights from Dynamic Analysis." *Environmental and Resource Economic*s 23(2002):319 – 342.

Elderkin, C.L., and P.L. Klerks. "Variation in Thermal Tolerance Among Three Mississippi River Populations of the Zebra Mussel, *Dreissena polymorpha*." *Journal of Shellfisheries Research* 24(1)(2005):221 – 226.

Evans, E.A. "Economic Dimensions of Invasive Species." *Choices* 2nd Quarter(2003): 5 – 9.

Federal Register, Feb 3 1999, Executive Order 13112, 64(25):6183-86. 2/8/199.

Fegan, R.M., M.T. Olexa, and R.J. McGovern. "Protecting Agriculture: The Legal Basis of Regulatory Action in Florida." *Plant Disease* 88 (9)(2004):1040-1043.

Finoff, D., J.F. Shogren, G. Leung, and D. Lodge. "The Importance of Bioeconomic Feedback in Invasive Species Management." *Ecological Economics* 52(2005):367 – 381.

Finoff, D. and J. Tschirhart. “Identifying, Preventing, and Controlling Invasive Plant Species Using Their Physiological Traits.” *Ecological Economics* 52(2005):397 – 416.

FLEPPC. *Florida Exotic Pest Plant Council*. Fort Lauderdale, FL: Florida Exotic Pest Plant Council, 2006. Internet site: http://www.fleppc.org (Accessed November 8, 2006).

Floerl, O., and G.J. Inglis. “Starting the Invasion Pathway: The Interaction Between Source Populations and Human Transport Vectors.” *Biological Invasions* 7(2005):589 – 606.

Florida Department of Environmental Protection. *2001-2002 Aquatic Plant Management Report.* Washington, D.C.: Department of Environmental Protection, 2002. Internet site: http://www.dep.state.fl.us/lands/invaspec/2ndlevpgs/Aquaticplnts.htm (Accessed January 27, 2006).

Florida Department of Environmental Protection. *2003-2004 Aquatic Plant Management Report.* Tallahassee, FL: Florida Department of Environmental Protection, 2004. Internet site: http://www.dep.state.fl.us/lands/invaspec/2ndlevpgs/pdfs/Aquatic%202003-04.pdf (Accessed February 6, 2005).

Florida Department of Environmental Protection. *Status of the Aquatic Plant Maintenance Program in Florida Public Waters.* Washington, D.C.: Department of Environmental Protection. Internet site: http://dep.state.fl.us/lands/invaspec/2ndlevpgs/pdfs/Aquatics 2002-2003.pdf (Accessed January 27, 2006)

Florida Department of Environmental Protection. *Plant Management in Florida Waters: Aquatic Herbicidal Control.* Washington, D.C.: Department of Environmental Protection. Internet site: http://plants.ifas.ufl.edu/guide/herbcons.html (Accessed January 27, 2006).

Florida Fish and Wildlife Conservation Commission. *Florida Lakes, 1000 Acres or Larger*. Washington, D.C.: Florida Fish and Wildlife Commission. Internet site: http://www.floridaconservation.org/fishing/lakes.html (Accessed October 15. 2005.).

Florida Fish and Wildlife Conservation Commission. *Boat Ramps*. Tallahassee, FL: Florida Fish and Wildlife Conservation Commission, 2003. Internet site: http://www.floridafisheries.com/ramps/ (Accessed Aug 3, 2003).

Florida Department of Environmental Protection, Division of Water Resource Management. *Basin Status Report—Lake Okeechobee*. November 2001.

Gangstad, E.O. “Chemical Control of Hydrilla.” *Journal of Aquatic Plant Management* 16(1978):38 – 40.

Garton, D.W., and L.E. Johnson. “Variation in Growth Rates of Zebra Mussel, *Dreissena polymorpha*, Within Lake Wawasee.” *Freshwater Biology* 45(2000):443 – 451.

Gottwald, T.R., X. Sun, T. Riley, J.H. Graham, F. Ferrandino, and E.L. Taylor. “Geo-Referenced Spatiotemporal Analysis of the Urban Citrus Canker Epidemic in Florida. *Phytopathology* 92(2002):361-377.

Gottwald, T.R., L.W. Timmer, and R.G. McGuire. “Analysis of Disease Progress of Citrus Canker in Nurseries in Argentina. *Phytopathology* 79(1989):1276-1283.

Greene, W.H. *Econometric Analysis* (4th ed.). Upper Saddle River, New Jersey: Prentice Hall, 2004.

Griebeler, E.M., and A. Seitz. 2006. “Effects of Increasing Temperatures on Population Dynamics of the Zebra Mussel *Dreissena polymorpha*: Implications From an Individual-Based Model.” *Oecologia*. Published online 10 November 2006.

Griffin, M.L. Personal Communication. Unpublished Climate Data, The Florida Climate Center, Florida State University, July 2005.

Griffiths, R.W., D.W. Schloesser, J.H. Leach, and W.P. Kovalak. “Distribution and Dispersal of the Zebra Mussel (*Dreissena polymorpha*) in the Great Lakes Region.” *Canadian Journal of Fisheries and Aquatic Sciences* 48(1991):1381 – 1388.

Gutierrez, A.P. and U. Regev. “The Bioeconomics of Tritrophic Systems: Applications to Invasive Species.” *Ecological Economics* 52(2005):383 – 396.

Haag, W.R., and D.W. Garton. “Synchronous Spawning in a Recently Established Population of the Zebra Mussel, *Dreissena polymorpha*, in Western Lake Erie, USA.” *Hydrobiology* 234(1992):103 – 110.

Halbert, S.E., and L.M. Keremane. “Asian Citrus Psyllida (Sternorrohyncha: Psyllidae) and Greening Disease of Citrus: A Literature Review and Assessment of Risk in Florida.” *Florida Entomologist* 87(3)(2004): 330-353.

Haller, W.T. and D.L. Sutton. “Community Structure and Competition Between Hydrilla and Vallisneria.” *Hyacinth Control Journal* 13(1975):48 – 50.

Haller, W.T., J.L. Miller, and L.A. Garrard. “Seasonal Production and Germination of Hydrilla Vegetative Propagules.” J*ournal of Aquatic Plant Management* 14(1976):26 – 29.

Hastings, A.K., K.F. Cuddington, C.J.Davies, S.E. Dugaw, A. Freestone, et al. "The Spatial Spread of Invasions: New Developments in Theory and Science." *Ecology Letters* 8(2005):91 – 101.

Hayward, D., and E.D. Estevez. *Suitability of Florida Waters to Invasion by the Zebra Mussel (Dreissena polymorpha)*. Mote Marine Laboratory Technical Report No. 495, 1997.

Hebert, P.D.N., B.W. Muncaster, and G.L. Mackie. "Ecological and Genetic Studies in *Dreissena polymorpha* (Pallas): A New Mollusk in the Great Lakes." *Canadian Journal of Fisheries and Aquatic Sciences* 46(1989):1587 – 1591.

Henderson, J.E. *Use of Economic Information in the Evaluation of Aquatic Plant Control Programs: The Lake Guntersville Recreation Study.* US Army Corps of Engineers Waterways Experiment Station, A-95-3, 1995.

Hengeveld, R. "Small-Step Invasion Research." *Trends in Ecology and Evolution* 9(1994):339 – 342.

Hestand, R.S. and C.C. Carter. "Comparative Effects of Grass Carp and Selected Herbicides on Macrophytes and Phytoplankton Communities." J*ournal of Aquatic Plant Management* 16(1978):43 – 45.

Higgins, S.I., and D.M. Richardson. "Predicting Plant Migration Rates in a Changing World: The Role of Long-Distance Dispersal." *The American Naturalist* 153(5)(1999):464 – 475.

Hofstra, D.E., J. Clayton, J.D. Green, and M. Auger. "Competitive Performance of Hydrilla verticillata in New Zealand." *Aquatic Botany* 63(1999):305 – 324.

Holmes, E.E. "Are Diffusion Models Too Simple? A Comparison with Telegraph Models of Invasion." *The American Naturalist* 142(5)(1993):779 – 795.

Holt, R.D., T.H. Keitt, M.A. Lewis, B.A. Maurer, and M.L. Taper. "Theoretical Models of Species' Borders: Single Species Approaches." *Oikos* 108(1)(2005):18 – 27.

Hoyer, M.V., C.A. Horsburgh, D.E. Canfield, Jr., and R.W. Bachmann. "Lake Level and Trophic State Variables Among a Population of Shallow Florida Lakes and Within Individual Lakes." *Canadian Journal of Fisheries and Aquatic Sciences* 62(2005):2760-2769.

Hulme, P.E. "Beyond Control: Wider Implications for the Management of Biological Invasions." *Journal of Applied Economics* 43(2006):835 – 847.

Hushak, L. *Zebra mussels Cost Great Lakes Water Users an Estimated $120 Million.* Columbus, OH: Aquatic Nuisance Species Update, Ohio Sea Grant, 1996. Internet site: http://www.glc.orgt/ans/ansupdate/pdf/ansv2n1.html (Accessed May 4, 2004).

Hushak, L.J. “Present and Expected Costs of Zebra Mussel Damages to Water Users with Great Lakes Water Intakes: Socio-Economic Analysis.” Sea Grant Zebra Mussel Report. Ohio Sea Grant, 1996.

Hushak, L.J., and Y. Deng. *Costs of alternative zebra mussel control strategies: The case of Great Lakes surface water users*. Technical Summary OHSU-TS-042, Ohio Sea Grant College Program Technical Summary Series, 1997.

Jantz, B., and D. Neumann. “Shell Growth and Aspects of the Population Dynamics of *Dreissena polymorpha* in the River Rhine.” *The Zebra Mussel Dreissena polymorpha: Ecology, Biological Monitoring and First Applications in Water Quality Management.* D. Neumann, and H.A. Jenner, eds. Stuttgart; New York: G. Fischer, 1992.

Jantz, B., and D. Neumann. “Growth and Reproductive Cycle of the Zebra Mussel in the River Rhine as Studies in a River Bypass.” *Oecologia* 114(1998):213 – 225.

Jenner, H.A., and J.P.M. Jansen-Mommen. “Monitoring and Control of *Dreissena polymorpha* and Other Macrofouling Bivalves in the Netherlands.” *Zebra Mussels: Biology, Impacts, and Control.* T.F. Nalepa and D.W. Schloesser, eds. Boca Raton, FL: Lewis, 1993.

Johnson, L.E., and J.T. Carlton. “Post-Establishment Spread in Large-Scale Invasions: Dispersal Mechanisms of the Zebra Mussel *Dreissena polymorpha*.” *Ecology* 77(6)(1996):1686 – 1690.

Johnson, L.E., and D.K. Padilla. “Geographic Spread of Exotic Species: Ecological Lessons and Opportunities from the Invasion of the Zebra Mussel *Dreissena polymorpha*.” *Biological Conservation* 78(1996):23 – 33.

Jules, E.S., M.J. Kauffman, W.D. Ritts, and A.L. Carroll. “Spread of an Invasive Pathogen over a Variable Landscape: A Nonnative Root Rot on Port Orford Cedar.” *Ecology* 83(2002):3167 – 3181.

Karatayev, A.Y., L.E. Burlakova, and D.K. Padilla. “Growth Rate and Longevity of *Dreissena polymorpha* (Pallas): A Review and Recommendation for Future Study.” *Journal of Shellfish Research* 25(1)(2006):23 – 32.

Klaine, S.J., and C.H. Ward. “Environmental and Chemical Control of Vegetative Dormant Bud Production in Hydrilla verticillata.” *Annals of Botany* 53(1984):503 – 514.

Kraft, C.E., P.J. Sullivan, A.Y. Karatayev, L.E. Burlakova, J. Nekola, L.E. Johnson, and D.K. Padilla. “Landscape Patterns of an Aquatic Invader: Assessing Dispersal Extent from Spatial Distributions.” *Ecological Applications* 12(3)(2002):749 – 759.

Kraft, C.E., and L.E. Johnson. "Regional Differences in Rates and Patterns of North American Inland Lake Invasions by Zebra Mussels (*Dreissena polymorpha*)." *Canadian Journal of Fisheries and Aquatic Sciences* 57(2000):993 – 1001.

LakeOkeechobee.org. *Lake Okeechobee fact sheet*. Internet site: www.lakeokeechobee.org (Accessed April 17, 2005).

Langeland, K.A. "Hydrilla verticillata (L.F.) Royle (Hydrocharitaceae): The Perfect Aquatic Weed*." Castanea* 61(1996):293-304.

Lauer, T.E., and A. Spacie. "Space as a Limiting Resource in Freshwater Systems: Competition Between Zebra Mussels (*Dreissena polymorpha*) and Freshwater Sponges (Porifera)." *Hydrobiologia* 517(2004):137 – 145.

Leung, B., D.M. Lodge, D. Finoff, J.F. Shogren, M.A. Lewis, and G. Lamberti. "An Ounce of Prevention or a Pound of cure: Bioeconomic Risk Analysis of Invasive Species." *Proceedings of the Royal Society of London B: The Biological Sciences* 269(1508)(2002): 2407 – 2413.

Lonsdale, W.M "Rates of Spread of an Invading Species: *Mimosa pigra* in Northern Australia." *Journal of Ecology* 81(1993):513 – 521.

Mack, R.N., D. Simberloff, W.M. Lonsdale, H. Evans, M. Clout, and F.A. Bazzaz. "Biotic Invasions: Causes, Epidemiology, Global Consequences, and Control." *Ecological Applications* 10(2000):689 – 710.

Mackie, G.L., and D.W. Schloesser. "Comparative Biology of Zebra Mussels in Europe and North America: An Overview." *American Zoologist* 36(1996):244 – 258.

Marsden, J.E., A.P. Spiedle, and B. May. "Review of Genetic Studies of *Dreissena* spp." *American Zoologist* 36(1996):259 – 270.

McMahon, R.F. "Mollusca: Bivalvia." *Ecology and Classification of North American Freshwater Invertebrates.* Thorp, J.H. and A.P. Covich, eds. New York, NY: Academic Press, 1991.

Mihuc, T.B., J.M. Battle, J.R. Mihuc, and C.F. Bryan. "Zebra Mussel (*Dreissena polymorpha*) Seasonal Colonization Patterns in a Sub-Tropical Floodplain River." *Hydrobiologia* 392(1999):121 – 128.

Miller, J.L., L.A. Garrard, and W.T. Haller. "Some Characteristics of Hydrilla Tubers Taken from Lake Ocklawaha During Drawdown." *Journal of Aquatic Plant Management* 14(1978):29 – 31.

Milon, J.W., and R. Welsh. "An Economic Analysis of Sport Fishing and the Effects of Hydrilla Management in Lake County, Florida." Economics Report 118, Food and Resource Economics Department, University of Florida, Gainesville, 1989.

Milon, J.W., J. Yingling, and J.E. Reynolds. “An Economic Analysis of the Benefits of Aquatic Weed Control in North-Central Florida.” Economics Report 113, Food and Resource Economics Department, University of Florida, Gainesville, 1986.

Milon, J.W. and J.C. Joyce. “Sportanglers’ Perceptions and Economic Valuation of Aquatic Weed Management.” *Aquatics* 9(4)(1987):8 – 12.

Muller, J., S. Woll, and A. Seitz. “Genetic Interchange of *Dreissena polymorpha* Populations Across a Canal.” *Heredity* 86(2001):103 – 109.

Nalepa, T.F., J.A. Wojcik, D.L. Fanslow, and G.A. Lang. “Initial Colonization of the Zebra Mussel (*Dreissena polymorpha*) in Saginaw Bay, Lake Huron: Population Recruitment, Density, and Size structure.” *Journal of Great Lakes Research* 21(4)(1995):417 – 434.

NationalAtlas.gov “Zebra Mussel Dynamic Map.”

National Climatic Data Center. *Climate Atlas of the United States.* Asheville, NC: National Environmental and Satellite Information Service, 2005. Internet site: http://gis.ncdc.noaa.gov/website/ims-climatls/index.html (Accessed July 7, 2005).

Neubert, M.G., and H. Caswell. “Demography and Dispersal: Calculation and Sensitivity Analysis of Invasion Speed for Structured Populations.” *Ecology* 81(2000):1613 – 1628.

Newroth, P.R., and M.D. Maxnuk. “Benefits of the British Columbia Aquatic Plant Management Program.” *Journal of Aquatic Plant Management* 31(1993):210 – 213.

New York Sea Grant. “North American Range of the Zebra Mussel.” *Dreissena* 7(6)(1997):5 – 6.

Nichols, S.A. “The Interaction between Biology and the Management of Aquatic Macrophytes.” *Aquatic Botany* 41(1991):225 – 252.

Nichols, S.J. “Variations in the Reproductive Cycles of *Dreissena polymorpha* in Europe, Russia, and North America.” *The American Zoologist* 36(1996):311 – 325.

Olson, L.J., and S. Roy. “The Economics of Controlling a Stochastic Invasion.” *American Journal of Agricultural Economic*s 84(2002):1311 – 1316.

Olson, L.J., and S. Roy. *On Prevention and Control of an Uncertain Biological Invasion.* Department of Agricultural and Resource Economics, University of Maryland, College Park, WP 05-02, January 2005.

O’Neill, C.R., Jr. “Economic Impact of Zebra Mussels – Results of the 1995 National Zebra Mussel Information Clearinghouse Study.” *Great Lakes Research Review* 3(1)(1997):35 – 42.

Orlova, M.I. "*Dreissena (D.) polymorpha*: Evolutionary Origin and Biological Peculiarities as Prerequisites of Invasion Process." *Invasive Aquatic Species of Europe—Distribution, Impact and Management.* E. Leppakoski, Gollasch, and S. Olenin, eds. Kluwer, Dordrecht, 2002.

Park, J., and L.J. Hushak. *Zebra Mussel Control Costs in Surface Water Using Facilities*. Technical Summary OHSU-TS-028, Ohio Sea Grant College Program Technical Summary Series, 1999.

Parsons, W.R., Adorno, and Yoss, P.A. Personal Communication, August, 2006.

Penaloza, L.J. *Boating Pressure on Wisconsin's Lakes and Rivers: Results of the 1989 – 1990 Wisconsin Recreational Boating Study, Phase 1*. Wisconsin Department of Natural Resources Technical Bulletin No. 174, 1991.

Phillips, S., T. Darland, and M. Systsma. *Potential Economic Impacts of Zebra Mussels on the Hydropower Facilities in the Columbia River Basin*. Pacific States Marine Fisheries Commission Report, 2005.

Pimentel, D. "Economic and Ecological Costs Associated with Aquatic Invasive Species." *Proceedings of the Aquatic Invaders of the Delaware Estuary Symposium*. Malvern, PA, May 20, 2003, pp. 3 – 5.

Pimentel, D., L. Lach, R. Zuniga, and D. Morrison. "Environmental and Economic Costs of Nonindigenous Species in the United States." *Bioscience* 50(1999):53 – 65.

Ramcharan, C.W., D.K. Padilla, and S.I. Dodson. "A Multivariate Model for Predicting Population Fluctuations of *Dreissena polymorpha* in North American Lakes." *Canadian Journal of Fisheries and Aquatic Sciences* 49(1992):150 – 158.

Ricciardi, A., R. Serrouya, and F.G. Whoriskey. "Aerial Exposure Tolerance of Zebra and Quagga Mussels (Bivalvia: Dreissenidae): Implications for Overland Dispersal." *Canadian Journal of Fisheries and Aquatic Sciences* 52(1994):470 – 477.

Rosenberger, R., and J. Loomis. *Benefit Transfer of Outdoor Recreation Use Values: A Technical Document Supporting the Forest Service Strategic Plan (2000 Revision)*. Gen. Tech. Rep. RMRS-GTR-72 Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 2001.

Salisbury, S. *Canker Repeal Tops Legislature's List of Agriculture Priorities*. Palm Beach Post, March 05, 2006.

Schardt J. 1997. "*Maintenance Control in Strangers in Paradise: Impact and Management of Nonindigenous Species in Florida*. Washington, DC: Island Press, 1997.

Schmitz, D.C., B.V. Nelson, L.E. Nall, and J.D. Schardt. 1988. "Exotic Aquatic Plants in Florida: A Historical Perspective and Review of the Present Aquatic Plant Regulation Program." Proceedings of the Symposium on Exotic Pest Plants, pp. 303-326.

Schubert, T.S., and X. Sun. *Bacterial Citrus Canker*. Florida Department of Agriculture & Consumer Service Division of Plant Industry Plant Pathology, Circular No. 377, 2001.

Schubert, T.S., T.R. Gottwald, S.A. Rizvi, J.H. Graham, X. Sun ,and W.N. Dixon. "Meeting the Challenge of Eradicating Citrus Canker in Florida—Again." *Plant Disease* 85 (4)(2001).

Settle, C. and J.F. Shogren. "Modeling Native-Exotic Species within Yellowstone Lake." *American Journal of Agricultural Economics* 84(2002):1323 – 1328.

Simberloff, D. "The Economics of Biological Invasions." *Biodiversity Conservation* 11(2002):553 – 556.

Simberloff, D. "The Biology of Invasions." S*tranger in Paradise: Impact and Management of Nonindigenous Species in Florida*. Simberloff, D., D.C., Schmitz, and T.C. Brown, eds. Island Press:Washington, D.C., 1997.

Singh, K.P. et al. "Economic returns and incentives of lakes rehabilitation: Illinois case studies." *Procedings of the Third Annual Conference of the North American Lake Management Society*. Washington, D.C., 1984.

South Florida Water Management District (SFWMD). *Water management districts permitting portal.* West Palm Beach, FL: South Florida Management District, 2005. Internet site: http://arcimspub.sjrwmd.com/website/permitportal/default.htm (Accessed March 23, 2005).

Spencer, D.F., G.G. Ksander, J.D. Madsen, and C.S. Owens. "Emergence of Vegetative Propagules of Potamogeton nodosus, Potamogeton pectinatus, Vallisneria americanan, and Hydrilla verticillata Based on Accumulated Degree-Days." *Aquatic Botany* 67(2000):237 – 249.

Sprung, M. "Ecological Requirements of Developing *Dreissena polymorpha* Eggs." *Archiv für Hydrobiologie, Supplement* 79(1987):69 – 86.

Sprung, M. "The Other Life: An Account of Present Knowledge of the Larval Phase of *Dreissena polymorpha*." *Zebra Mussels: Biology, Impacts, and Control* . T.F. Nalepa and D.W. Schloesser, eds. Boca Raton, LA: Lewis, 1993.

State of Florida. *Water Quality Assessment for the State of Florida: Section 305(b).* Main Report, Bureau of Water Resources Protection, Division of Water Facilities, Florida Department of Environmental Protection, Tallahassee, Florida, 1996.

State of Florida. *State of Florida Quick Facts*. Orlando, FL: State of Florida.com, 2005. Internet site: http://www.stateofflorida.com/Portal/DesktopDefault.aspx?tabid=95 (Accessed April 3, 2005).

Steward, K.K. "Retardation of Hydrilla (Hydrilla verticillata) Regrowth through Chemical Control of Vegetative Reproduction." *Weed Science* 28(1980):245 – 251.

Steward, K.K., and T.K. Van. "Comparative Studies of Monoecious and Dioecious Hydrilla (Hydrilla verticillata) Biotypes." *Weed Science* 35(1987):204 – 210.

Steward, K.K. "Growth of Hydrilla (Hydrilla verticillata) in Hydrosoils of Different Composition." *Weed Science* 32(1984):371 – 375.

Stoeckel, J.A., K.D. Camlin, K.D. Blodgett, and R. Sparks. *Growth Rates of Zebra Mussel Veligers in the Illinois River: Implications for Larval Dispersal and Settlement Patterns.* Illinois Natural History Survey, 1996.

Stoeckel, J.A., D.K. Padilla, D.W. Schneider, and C.R. Rehmann. "Laboratory Culture of *Dreissena polymorpha* Larvae: Spawning Success, Adult Fecundity, and Larval Mortality Patterns." *Canadian Journal of Zoology* 82(2004):1436 – 1443.

Stoeckmann, A.M., and D.W. Garton. "A Seasonal Energy Budget for Zebra Mussels (*Dreissena polymorpha*) in Western Lake Erie." *Canadian Journal of Fisheries and Aquatic Sciences* 54(1997):2743 – 2751.

Strayer, D.L., J. Powell, P. Ambrose, L.C. Smith, M.L. Pace, and D.T. Fischer."Arrival, Spread, and Early Dynamics of a Zebra Mussel (*Dreissena polymorpha*) Population in the Hudson River Estuary." *Canadian Journal of Fisheries and Aquatic Sciences* 53(1996):1143 – 1149.

Strayer, D.L. "Effects of Alien Species on Freshwater Mollusks in North America." *Journal of the North American Benthological Society* 18(1)(1999):74 – 98.

Strayer, D.L., K.A. Hattala, and A.W. Kahnle. "Effects of an Invasive Bivalve (*Dreissena polymorpha*) on Fish in the Hudson River Estuary." *Canadian Journal of Fisheries and Aquatic Sciences* 61(2004):924 – 941.

Strayer, D.L. and H.M. Malcom. "Long-Term Demography of a Zebra Mussel (*Dreissena polymorpha*) Population." *Freshwater Biology* 51(2006):117 – 130.

Suarez, A.V., D.A. Holway, and T.J. Case. "Patterns of Spread in Biological Invasions Dominated by Long-Distance Jump Dispersal: Insights from Argentine Ants." *Proceedings of the National Academy of Sciences* 98(3)(2001):1095 – 1100.

Suit, R.F., and E.P. DuCharme. "The Burrowing Nematode and Other Plant Parasitic Nematodes in Relation to Spreading Decline of Citrus." *Plant Disease Reptr* 37(1953):379-383.

Sutton, D.L. "Growth of Hydrilla in Established Stands of Spikerush and Slender Arrowhead." *Journal of Aquatic Plant Management* 24(1986):16 – 20.

Sutton, D.L. and K.M. Portier. "Density of Tubers and Turions of Hydrilla in South Florida." *Journal of Aquatic Plant Management* 23(1985):64 – 67.

Sutton, D.L., and K.M. Portier. "Growth of Dioecious Hydrilla in Sediments from Six Florida Lakes." *Journal of Aquatic Plant Management* 33(1995):3 – 7.

Sutton, D.L., T.K. Van, and K.M. Portier. "Growth of Dioecious and Monoecious Hydrilla from Single Tubers." *Journal of Aquatic Plant Management* 30(1992):15 – 20.

Tate, W.B., M.S. Allen, R.A. Myers, E.J. Nagid, and J.R. Estes. "Relation of Age-0 Largemouth Bass Abundance to Hydrilla Coverage and Water Level at Lochloosa and Orange Lakes, Florida." *North American Journal of Fisheries Management* 23(2003):251 – 257.

Thomas, M.H., and N. Stratis. *Assessing the Economic Impact and Value of Florida's Public Piers and Boat Ramps.* Florida Fish and Wildlife Conservation Commission, 2001

Thorp, J.H., J.E. Alexander, and G.A. Cobbs. "Coping with Warmer, Large rivers: A Field Experiment on Potential Range Expansion of Northern Quagga Mussels (*Dreissena bugensis*)." *Freshwater Biology* 47(2002):1779 – 1790.

Timmer, L.W., J.H. Graham, and H.L. Chamberlain. *Fundamentals of Citrus Canker Management.* Institute of Food and Agricultural Sciences, EDIS Fact Sheet PP-153. July 2006.

Ulanowicz, R.E., and J.H. Tuttle. "The Trophic Consequences of Oyster Stock Rehabilitation in Chesapeake Bay." *Estuaries* 15(3)(1992):298 – 306.

University of Florida. *Hydrilla Verticillata*. Gainesville, FL: Non-Native Invasive Aquatic Plants in the United States (website) of the Center for Aquatic and Invasive Plants, University of Florida. Internet site: http://www.plants.ifas.ufl.edu/seagrant/hydver2.html (Accessed March, 4, 2006)

United States Army Corps of Engineers (USACE). *Environmental Effects of Zebra Mussel Infestations.* Technical Note ZMR-1-14, 1995.

United States Department of Agriculture, Letter from Deputy Secretary Chuck Connor to Charles H. Bronson, Commissioner of Agriculture, Florida Department of Agriculture and Consumer Services dated January 10, 2006.

United States General Accounting Office (USGAO). *Invasive Species Clearer Focus and Greater Commitment Needed to Effectively Manage the Problems*. Report to Executive Agency Officials, GAO-03-1, October, 2001.

United States Geological Survey (USGS). *Zebra Mussels Cause Economic and Ecological Problems in the Great Lakes*. GLSC USGS Fact Sheet 2000-6, created August 15, 2000.

United States Geological Survey (USGS). *USGS Real-Time Water Data for Florida*. Reston, VA: United States Geological Survey, 2006. Internet site: http://waterdata.usgs.gov/fl/nwis/rt (Accessed October 10, 2006).

United States Geological Survey (USGS). *Non-indigenous Aquatic Species Database*. Reston, VA: United States Geological Survey, 2006. Internet site: http://nas.er.usgs.gov (Accessed February 14, 2007).

Van, T.K. "Differential Responses to Photoperiods in Monoecious and Diecious Hydrilla verticillata." *Weed Science* 37(1989):552 – 556.

Van, T.K., K.K. Steward, and R.D. Conant. "Responses of Monoecious and Dioecious Hydrilla (Hydrilla verticillata) to Various Concentrations and Exposures of Diquat." *Weed Science* 35(1987):247 – 252.

Van, T.K., W.T. Haller, and L.A. Garrard. "The Effect of Daylight and Temperature on Hydrilla Growth and Tuber Production." *Journal of Aquatic Plant Management* 16(1978):57 – 59.

Van den Bosch, F., R. Hengeveld, and J.A.J. Metz. "Analyzing the Velocity of Animal Range Expansion." *Journal of Biogeography* 16(1992):503 – 540.

Virginia Department of Game and Inland Fisheries (VDGIF). *Millbrook quarry zebra mussel eradication.* Richmond, VA: Department of Game and Inland Fisheries., 2006. Internet site: http://www.dgif.state.va.us/zebramussels/ (Accessed February 5, 2007).

Vitousek, P.M., C.M. D'Antionio, L.L. Loope, and R. Westbrooks. "Biological Invasions as Global Environmental Change." *American Scientist* 84(5)(1996):468 – 478.

Whitney, S.D., K.D. Blodgett, and R.E. Sparks. "Update on Zebra Mussels and Native Unionids in the Illinois River." Illinois Natural History Survey. Rep., LTRMP Field Station, 1995.

Wilcove, D.S., D. Rothstein, J. Dubow, E. Phillips, and E. Losos. "Quantifying Threats to Imperiled Species in the United States." *BioScience* 48(1998):607 – 615.

Winton, M.D., and J.S. Clayton. "The Impact of Invasive Submerged Weed Species on Seed Banks in Lake Sediments." *Aquatic Botany* 53(1996):31 – 45.

With, K.A. "The Landscape Ecology of Invasive Spread." *Conservation Biology* 16(2002):1192 – 1203.

Wolverton, B.C., and R.C. McDonald. "Water Hyacinth (*Eichhornia crassipes*) Productivity and Harvesting Studies." *Economic Botany* 33(1979):1-10.

Woods, C. *New UF Low-Power Radio Stations On I-75 And I-95 Warn Travelers About Zebra Mussels.* Gainesville, FL: University of Florida News. Internet site: http://news.ufl.edu/1999/02/19/zebra/ (Accessed April 14, 2006).

BIOGRAPHICAL SKETCH

Damian Campbell Adams was born in Naples, Florida and spent most of his life living near Gainesville, Florida. As a child, Damian raised prize-winning chickens. At Oak Hall High School, Damian was senior class president, founder of the ecology club, a member of Standing Room Only Players acting troupe, lettered in football and weightlifting, ran track, and was a member of the physics competition team and the Mu Alpha Theta math honor competition team. Damian set the Oak Hall High School record for the triple jump in 1991.

Damian almost entered basic training for the US Marines in the summer of 1993, but instead followed his mother's advice to attend college. Damian applied to only two schools—UF and Florida State University. UF responded first, and so Damian went on to enroll in the University of Florida in 1993. At UF, Damian was active in several student groups, including College Republicans, Rotaract, Alpha Tau Omega fraternity, and even started his own student political party (which came only a few dozen votes short of winning the UF student body presidency). Damian was also an active contributor to the student newspaper—The Independent Florida Alligator. While a student at UF, Damian spent a summer interning in the US Congress for Rep. Cliff Stearns, and also spent several months working as a researcher for Nick Hawkins, MP in the British House of Commons. Damian finished his BS in Business Administration (*Highest Honors*) in December, 1997 and enrolled in UF's law school in 1998.

Damian took an agricultural law course from Prof. M.T. Olexa, who would later become chair of both his Master of Agribusiness and later his PhD committees. Damian began working as a legal researcher for the Agricultural Law Center with Dr. Olexa, and soon enrolled in the Master of Agribusiness program in the Food and Resource Economics Department. In 2001, Damian graduated from both the College of Agricultural and Life Sciences and the UF College of Law with both his MAB and JD. In 2001, Damian was recruited into the PhD program in the

Food and Resource Economics Department with a very generous USDA National Needs Fellowship.

While a PhD student, Damian explored several research topics. In 2002, Damian was asked to teach a course in natural resource and environmental policy, which he enjoyed immensely. This changed his entire career outlook, and he hoped to someday become a professor. In 2003, Damian left UF to earn a Master's degree from Cambridge University in England. Damian was researching an issue that the UK was mired in—genetically modified crops—and he wanted to get first-hand exposure to those conducting the most exciting research on the issue. Cambridge was an amazing experience and Damian returned to Florida in 2004 with a renewed vigor and drive to write a dissertation on the topic of the welfare effects associated with different regulatory regimes for genetic drift from genetically modified crops. Shortly after his return to the US, Damian was offered a faculty job (100% teaching) with the Food and Resource Economics Department, which he began in mid-April, 2005.

Due to data problems on organic crop production in the US (that he needed to measure the welfare effects of GM policies), Damian decided to change dissertation topics in 2006. Fortunately, he had been working on several invasive species projects with Dr. Donna Lee. With wise counsel from his committee, Damian began focusing on the economics and law of invasive species management in October, 2006. About six months later, Damian had finished his dissertation and successfully defended on April 12, 2007. The journey continues.