Journal of Agricultural and Applied Economics, 39(October 2007):111–124

Multiregional Invasive Species Management: Theory and an Application to Florida's Exotic Plants

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This research develops a multiregional optimal control model that incorporates regional allocation of a public budget for controlling invasive plants when regionally differential recreation demand functions and species control costs are present. Our equimarginal condition for optimal budget allocation equates the relative marginal economic benefits per dollar spent across regions. The model was applied to Florida Public Conservation Land regions, and results indicate that the magnitude of an annual management budget affects its distribution among species management regions, but the size of the intrinsic growth rate does not affect the pattern of budget allocation among regions.

Key Words: budget allocation, equimarginal condition, Florida invasive species, invasive plants, optimal control

JEL Classifications: B41, C02, Q51, Q57

Public Conservation Land in Florida serves the critical roles of protecting upland natural resources, providing wildlife habitat, and serving a multibillion dollar ecotourism industry. Threats to those resources include the encroachment and spread of alien invasive plants. Over 1 million acres of Florida's 8.5 million acres of Public Conservation Lands have been invaded by the "10 most unwanted" upland exotic plants, including the Melaleuca (*Melaleuca quinquenervia*), commonly known as "Paperbark Tree," the Brazilian pepper (*Schinus terebinthifolius*), commonly known as "Florida Holly," the Australian pine (*Casuarina* spp.), the Old World climbing fern (*Lygodium microphyllum*), and the Chinese Tallow (*Triadica sebifera*). Furthermore, as of 2003, upland invasive weeds have infested ~15% of Public Conservation Lands statewide (Florida Department of Environmental Protection [DEP]).

This ongoing alien invasion has degraded and diminished Florida's natural areas, affected agricultural production, and reduced outdoor recreation and ecotourism. Accordingly, the Florida DEP, through its Bureau of Invasive Plant Management, began combating invasive plants in the late 1990s with program funding of $6 million per year. With a statewide perspective already established in its

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The authors thank the two anonymous JAAE reviewers and Vince Breneman, Economic Research Service, USDA, for their valued and helpful suggestions. The views expressed are those of the authors and do not necessarily represent the policies of the U.S. Department of Agriculture or the University of Florida.

aquatic weed control program, the DEP's Bureau of Invasive Plant Management merely needed to expand its focus to terrestrial weeds to fulfill its charge; therefore, the Upland Invasive Exotic Plant Management (Upland Weeds) Program was established within the bureau in 1997 (Florida DEP). The Upland Weeds Program funds individual invasive exotic plant control projects on Public Conservation Lands. Program funds are allocated *equally* across 11 working groups composed of federal, state, and local government agencies, which fund the highest priority projects based upon available funds (Florida DEP). As of 2003, 110,000 plant acres were under program management control.

Given the complexity and the magnitude of adverse economic and ecological impacts of invasive plants infestation, researchers have employed at least two different bioeconomic dynamic models to evaluate the economics of invasive plant management (see Olson for a review). The first approach maximizes the net economic benefits from managing invasive plants without consideration of the spatial variation of invasive plants. Eiswerth and van Kooten used a dynamic programming model for managing the Yellow Star thistle weed that infests rangelands in Nevada and California. Odom et al. extended the model used in Eiswerth and van Kooten by including a budget constraint for managing the Scotch Broom (*Sytisus scoparius L.*) plant in Barrington Tops National Park in Australia, but they did not consider budget allocation in their study.

Meanwhile, the second approach minimizes costs of managing invasive plants, while considering the spatial variation of invasive plants. Taylor and Hastings applied a structured model in which the population of the invasive *Spartina* was partitioned at a relatively small spatial scale in order to investigate density-based eradication strategies. A similar model was used by Burnett and Kaiser to control *Miconia calvescens* in Hawaii. While Taylor and Hastings partitioned their study area based on local conspecific density, Burnett and Kaiser divided Oahu into an arbitrary number of plots (cells) of equal size. Both studies assumed that the cost of managing invasive plants per unit area was constant. As Settle and Shogren pointed out, public policy for managing invasive species derived from cost minimization may result in economically inefficient decisions about managing invasive plants. Furthermore, the assumption of constant marginal costs of managing invasive plants per unit area may reduce the benefits of considering the spatial variation of invasive plants.

For this study, increasing demands for public funds coupled with increasing environmental degradation of a multiregion public recreation resource create the necessity to employ logical rationale for the allocation of limited public land-management resources. Florida's Wildlife Management Areas provide for a variety of recreation services, and therefore, management of invasive plants provides economic values to these areas. Accordingly, the Florida Fish and Wildlife Conservation Commission conducted an economic study to estimate the economic values associated with invasive species management for five Wildlife Management Areas (Harding and Thomas).

The objectives of our study include the following: first, we present a multiregional bioeconomic dynamic model of invasive plant management involving the allocation of limited species management resources (i.e., a budget) among alternative regional exotic plant control project areas. The dynamic framework accounts for alternative recreation demand functions and per day recreation expenditures, as well as regionally differential species control costs. The economic framework evaluates the dynamic maximization of the consumer surpluses associated with multiregional recreation demands. Second, we estimate economic benefits resulting from the implementation of an optimal regional "resource" allocation policy for managing invasive plants across the resource management areas. Third, we present concluding remarks.

The Model

Following Huffaker and Cooper, and Kim, Wang, and Yang, we assumed a logistic invasive species–infested acreage growth function for an ith regional exotic control project area infested with exotic plants as follows:

$$(1) \quad \frac{\partial A_i}{\partial t} = g_i A_i \left[1 - \frac{A_i}{V_i}\right] \quad \text{for } i = 1, 2, \ldots, n,$$

where A_i represents infested acreage in the ith regional exotic control project area, g_i represents the intrinsic growth rate for the infested acreage with invasive plants in the ith project area, and V_i represents the maximum possible acreage for infestation, and t = time. It is implicitly assumed in Equation (1) that no control measures have been implemented to reduce infested acreages. Eiswerth and Johnson, and Kim et al. (2006) used modified logistic growth functions, which did not really represent logistic growth relationships. So, here, we introduce a logistic growth function of infested acreage associated with management control measures.

Here, we let the infested acres managed with chemical and/or mechanical control measures, a_i, be represented by $a_i = k_i(Q_i)A_i$, where k_i is a fractional coefficient such that $0 \leq k_i \leq 1$, and Q_i represents a control measure adopted in the ith region. The rate of change of infested acreage associated with the adoption of a control measure is then represented as follows:

$$(2) \quad \frac{\partial A_i}{\partial t} = g_i A_i \left[1 - \frac{A_i}{V_i}\right] - g_i k_i(Q_i) A_i \left[1 - \frac{k_i(Q_i) A_i}{V_i}\right]$$
$$= g_i(1 - k_i(Q_i)) A_i \left[1 - \frac{(1 + k_i(Q_i)) A_i}{V_i}\right],$$
$$\text{where } \frac{\partial k_i(Q_i)}{\partial Q_i} > 0 \quad \text{for } i = 1, 2, \ldots, n.$$

Next, we denote the inverse demand function for recreation for the ith project area as a linear function represented as follows:

$$(3) \quad P_i = \alpha_i - \beta_i D_i^*$$
$$= \alpha_i - \frac{\beta_i V_i}{[V_i - (1 - k_i(Q_i)) A_i]} D_i,$$
$$\text{where } D_i = D_i^* \left[1 - \frac{(1 - k_i(Q_i)) A_i}{V_i}\right]$$
$$\text{for } i = 1, 2, \ldots, n,$$

where P_i is expenditures per day, D_i^* is the number of *potential* recreation days without acreage infested with invasive plants on the public lands, D_i is the number of *actual* recreation days, and α_i and β_i are parameters. The recreation demand function in Equation (3) assumes that the number of recreation days declines proportionally to the ratio between the infested acres and the total acres of the recreation site. The net social benefits (NSB) associated with recreation activities for the ith project area are then represented as follows (where the argument for the variable k_i is hereafter omitted):

$$(4) \quad NSB_i = \int_0^{D_i} \left[\alpha_i - \frac{\beta_i V_i}{V_i - (1 - k_i) A_i} x\right] \delta x - P_i D_i$$
$$= (\alpha_i - P_i) D_i - \left(\frac{\beta_i V_i}{2(V_i - (1 - k_i) A_i)}\right) D_1^2.$$

The dynamic optimization problem is to

$$(5) \quad \text{Max } M = \int_0^{\infty} \exp(-rt) \sum_{i=1}^{n} \left\{ (\alpha_i - P_i) D_i - \left(\frac{\beta_i V_i}{2(V_i - (1 - k_i) A_i)}\right) D_i^2 - C_i(Q_i) \right\} \delta t$$

subject to Equation (2) and an invasive species management budget constraint, such that

$$(6) \quad \sum_{i=1}^{n} C_i(Q_i) \leq B(t),$$

where r is the rate of discount, C_i represents the cost function of implementing species control measure Q_i, and $B(t)$ represents the total annual budget allocated for invasive plants management across all project areas.

The Lagrangian–Hamiltonian equation is represented as follows:

$$(7) \quad H = \exp(-rt) \sum_{i=1}^{n} \{ (\alpha_i - P_i) D_i - \left(\frac{\beta_i V_i}{2(V_i - (1 - k_i) A_i)}\right) D_i^2 - C_i(Q_i) \}$$
$$+ \sum_{i=1}^{n} \lambda_i g_i (1 - k_i) A_i \left[1 - \frac{(1 + k_i) A_i}{V_i}\right]$$
$$+ \mu \left[B(t) - \sum_{i=1}^{n} C_i(Q_i)\right],$$

where λ_i ($i = 1, 2, \ldots, n$) represents adjoint variables, μ is the Lagrangian multiplier, D_i is a decision variable, Q_i is a control variable, and A_i is a state variable. The necessary conditions for optimality, which hold for all i, are as follows:

$$(8)\quad \frac{\partial H}{\partial D_i} = (\alpha_i - P_i) - \frac{\beta_i V_i}{V_i - (1-k_i)A_i} D_i = 0,$$

$$(9)\quad \frac{\partial H}{\partial Q_i} = \exp(-rt) \times \left[\left(\frac{\beta_i A_i V_i}{2(V_i - (1-k_i)A_i)^2} D_i^2 \right) \left(\frac{\partial k_i}{\partial Q_i} \right) - \frac{\partial C_i}{\partial Q_i} \right] - \lambda_i g_i A_i \left(1 - \frac{2k_i A_i}{V_i}\right) \left(\frac{\partial k_i}{\partial Q_i} \right) - \mu \frac{\partial C_i}{\partial Q_i} = 0,$$

$$(10)\quad -\frac{\partial H}{\partial A_i} = \exp(-rt) \left[\frac{\beta_i (1-k_i) V_i}{2(V_i - (1-k_i)A_i)^2} D_i^2 \right] - \lambda_i g_i (1-k_i) \left[1 - \frac{2(1+k_i)A_i}{V_i} \right] = \frac{\partial \lambda_i}{\partial t},$$

$$(11)\quad \frac{\partial H}{\partial \lambda_i} = g_i (1-k_i) A_i \left[1 - \frac{(1+k_i)A_i}{V_i} \right] = \frac{\partial A_i}{\partial t},$$

$$(12)\quad \frac{\partial H}{\partial \mu} = \left[B(t) - \sum_{i=1}^{n} C_i(Q_i) \right] \geq 0 \text{ and } \mu \left[B(t) - \sum_{i=1}^{n} C_i(Q_i) \right] = 0,$$

$$(13)\quad \lim_{t \to \infty} \lambda_i = 0 \quad \text{and} \quad \lim_{t \to \infty} \lambda_i A_i = 0,$$

Equation (8) represents the inverse recreation demand function. Equation (9) states that the present value of the marginal net economic benefits, which measures the consumer surplus associated with recreation activities less the marginal invasive species control costs, resulting from the adoption of invasive species management control measures, Q_i, must equal the sum of the marginal user costs and the marginal opportunity costs of adopting the species control measures. Equation (10), representing the adjoint equation, states that the infested acreages create the value associated with user costs. Equation (11) is the equation of motion, while Equation (12) represents a complementary slackness condition and Equation (13) represents the conventional transversality condition.

Equimarginal Condition

To derive the efficient allocation of a limited public resource for multiple regions to control exotic invasive plants, Equation (9) is rewritten as follows:

$$(14)\quad L_i = \left\{ \exp(-rt) \left[\frac{\beta A_i V_i}{2(V_i - (1-k_i)A_i)^2} D_i^2 \right] \left(\frac{\partial k_i}{\partial Q_i} \right) \right\} \Big/ \left\{ \lambda_i g_i A_i \left(1 - \frac{2k_i A_i}{V_i} \right) \left(\frac{\partial k_i}{\partial Q_i} \right) + [\exp(-rt) + \mu] \left(\frac{\partial C_i}{\partial Q_i} \right) \right\}$$
$$\text{for } i = 1, 2, \ldots, n,$$

where the co-state variable $\lambda_i(t)$, which is obtained from solving the first-order differential Equations in (10), is represented by[1]

$$(15)\quad \lambda_i(t) = \frac{-\exp(-rt)}{r - g_i(1-k_i)[1 - 2(1+k_i)A_i/V_i]} \times \left(\frac{\beta_i (1-k_i) V_i D_i^2}{2(V_i - (1-k_i)A_i)^2} \right),$$

and the invasive species infested acreage, obtained from solving the first-order differential Equations in (11), is represented by

$$(16)\quad A_i(t) = [A_i(0)] / \{ \exp[-g_i(1-k_i)t] + [1 - \exp(-g_i(1-k_i)t)] [(1+k_i)A_i(0)/V_i] \},$$

where $A_i(0)$ represents infested acreage in the ith region during the base period.

The numerator in Equation (14) represents the marginal economic benefits resulting from the adoption of invasive species control measures, and the denominator represents the marginal costs associated with the adoption of control measures. The optimal condition in Equation (9) requires that L_i in Equation (14) be equal to one. The allocation of a limited public resource (budget) across regions is economically optimal when the equimarginal condition is met, that is, when $L_i = L_j$ for all i and j. For the case where $L_i > L_j$, for example, more of the management resource will be allocated for control measures

[1] The constant of integration is assumed to be zero in the derivation of Equation (15).

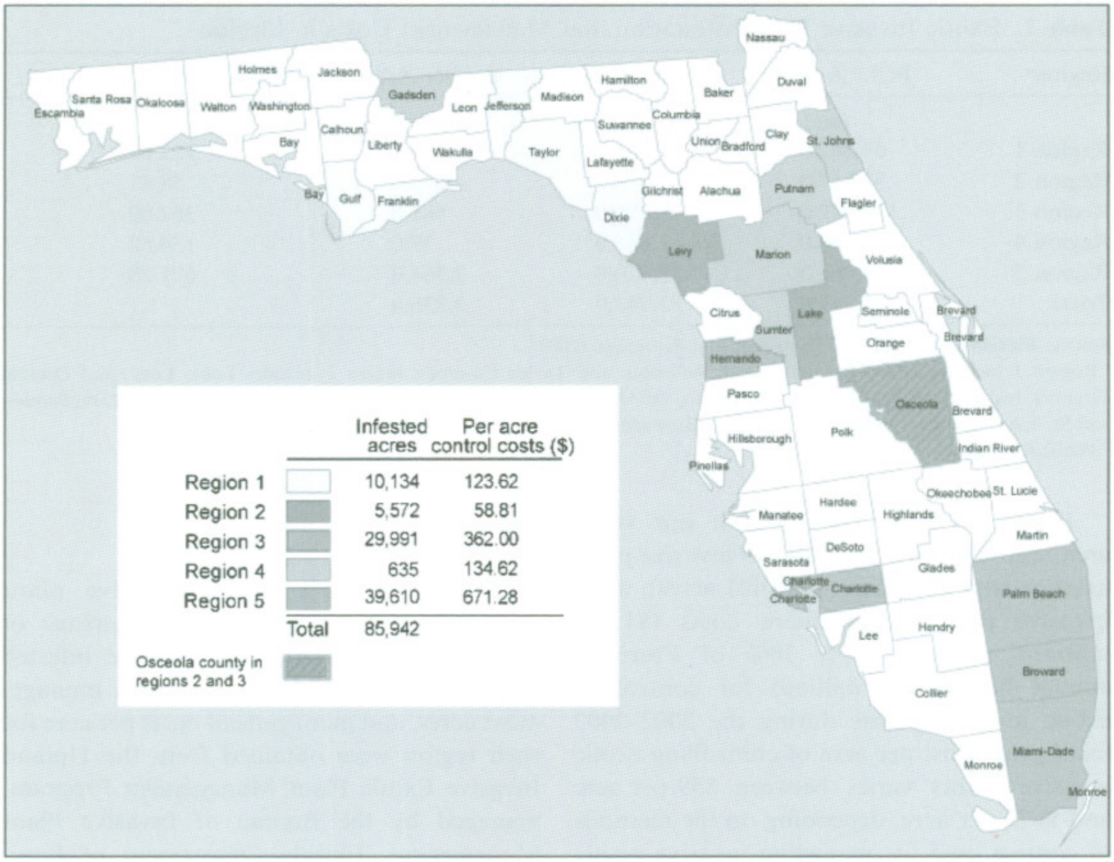


Figure 1. Invasive Species–Infested Acres and Control Costs by Florida Management Region

in the ith region until the equimarginal condition is reached.

Our equimarginal condition presented in Equation (14) differs from the equimarginal benefits condition presented in earlier studies (Kim et al. (1989); Koundouri and Christou), where the marginal benefits resulting from multiple crop production were also equated at the optimum, but where marginal costs were the same across multiple crop production. In our Equation (14), the marginal cost, as well as the marginal benefit, associated with the recreation activities varies across regions. Therefore, our equimarginal condition compares the relative economic benefits per dollar spent across regions.

Empirical Study

The Upland Invasive Exotic Plant Management (Upland Weeds) Program was established in 1997, and it was formed by the Regional Invasive Plant Working Groups (RIPWG), which are composed of federal, state, and local agencies, nongovernmental organizations, and other interested stakeholders in 11 areas of the state encompassing all of Florida's 67 counties (Florida DEP). Meanwhile, there are 37 diverse and varied Wildlife Management Areas (WMA) in Florida, which provide a variety of recreational services, including hunting, fishing, and wildlife viewing, for the state's residents and vistors. The Florida Fish and Wildlife Conservation Commission conducted a recreation survey over the period August 2001–July 2002 to collect visitor count and trip data for five selected WMA (Harding and Thomas). However, regional designations for the RIPWG and WMA were not consistent, and, therefore, for this study we have selected five regions overlapping both the RIPWG and WMA (Figure 1).

Table 1. Exotic Invasive Plant Infestation and Management Costs in Florida

Region[a]	PCL[b] Acres	Infested Acres	Project Acres	Per Acre Control Costs
	(ac.)	(ac.)	(ac.)	($)
Region 1	67,562.0	10,134.0	177.0	123.62
Region 2	37,147.0	5,572.0	675.0	58.81
Region 3	199,942.0	29,991.0	581.0	362.00
Region 4	4,230.0	635.0	39.0	134.62
Region 5	264,066.0	39,610.0	2,364.0	671.28
Total	572,947.0	85,942.0	3,836.0	

Source: Florida Department of Environmental Protection (2003).

[a] Region 1 includes Dixie, Franklin, Gulf, Jefferson, and Taylor Counties; region 2 includes Lake, Levy, and Osceola Counties; region 3 includes Charlotte, Hernando, and Osceola Counties; region 4 includes Gadsden, Marion, Putnam, Sumter, and St. John Counties; and region 5 includes Broward, Dade, and Palm Beach Counties.

[b] Public Conservation Land area.

Project acres (3,836 acres) in our study area represent 13% of Florida's invasive plant management project area (29,421 acres), while invasive plant management costs ($1.864 million) represent over 30% of Florida's annual budget ($6 million) for controlling exotic invasive plants during the 2002–2003 fiscal year. Cost per acre of controlling exotic invasive plants varies between $59 per acre and $671 per acre, depending on the methods of control used for managing invasive plants and the number of invasive plants per acre (Table 1). Controlling invasive plants with herbicides is the most researched and economical method of use in Florida (Laroche and McKim), where ground herbicide treatment, for instance tree injection, is estimated to be $538 per acre. Aerial treatment is less effective and can cause more damage to nontarget plant species, since seed release is accelerated among trees stressed by herbicide, and new infestations are created by dispersal of these seeds (Florida DEP). Mechanical removal may not be appropriate in natural areas because of the disturbance to soils and nontarget vegetation. However, it is the only effective way to quickly remove dense monocultures of species such as the Brazillian pepper and Australian pine (Florida DEP). Mechanical removal of a moderately thick stand, 400 trees per acre, is estimated to cost $842 per acre. Therefore, the management costs per acre vary across regions depending on the variety of exotic invasive plants in each region.

Data Sources

Data on Florida's exotic invasive plant management program, including acreage of Public Conservation Land, acreage infested with exotic invasive plants, control management acres, and management costs per acre for each region were obtained from the Upland Invasive Exotic Plant Management Program, managed by the Bureau of Invasive Plant Management, Florida Department of Environmental Protection (Table 1).

Recreation data by WMA, including the number of recreation site visitations, average recreation expenditures per visit, and the price elasticity of recreation demand were obtained from Harding and Thomas.[2] Even though the recreation survey was conducted across five recreation sites (including Aucilla, Andrews, Babcock/Webb, Half Moon, and J.W. Corbett), Harding and Thomas identified twelve transfer-site WMA with similar resources and conditions. The site where the data are collected and the analysis is performed is typically called the *study* site, while the site to which the data are transferred is called the *transfer* site. Therefore, the estimated recreation demand function on each site is based on

[2] Harding and Thomas estimated the price elasticities of consumptive activities (fishing and hunting) and nonconsumptive activities (wildlife viewing, biking, and hiking). Therefore, our price elasticity is a weighted average of the price elasticities of consumptive and nonconsumptive recreation demands.

Table 2. Characteristics of the Florida Recreation Sites

Recreation Sites	Study & Transfer Sites	Number of Visitations	Elasticities	Expenditures per Visit
				($)
Region 1 (Aucilla)	Dixie, Franklin, Gulf, Jefferson, Taylor	207,437.0	0.2175	93.00
Region 2 (Andrews)	Levi, Lake, Osceola[a]	5,555.0	0.3956	161.00
Region 3 (Babcock/Webb)	Charlotte, Hernando, Osceola[b]	171,554.0	0.1346	140.00
Region 4 (Half Moon)	Gadsden, Marion, Putnam, Sumter, St. Johns	29,487.0	0.2505	149.00
Region 5 (J.W. Corbett)	Broward, Dade, Palm Beach	738,983.0	0.2786	299.00

Source: Bureau of Invasive Plant Management, Florida Department of Environmental Protection (2003).
[a] Northern part of Osceola County.
[b] Southern part of Osceola County.

the sum of the study site and the transfer site in our study (Table 2 and Figure 2).

The rate of change of infested acreage associated with the adoption of a control measure, presented in Equation (2), requires knowledge about the intrinsic growth rate for infested acreage in each of the project areas. No data are available for the intrinsic growth rates of Florida's exotic plants, and therefore, we applied an estimating procedure proposed by Voronov as shown in Equation (17).

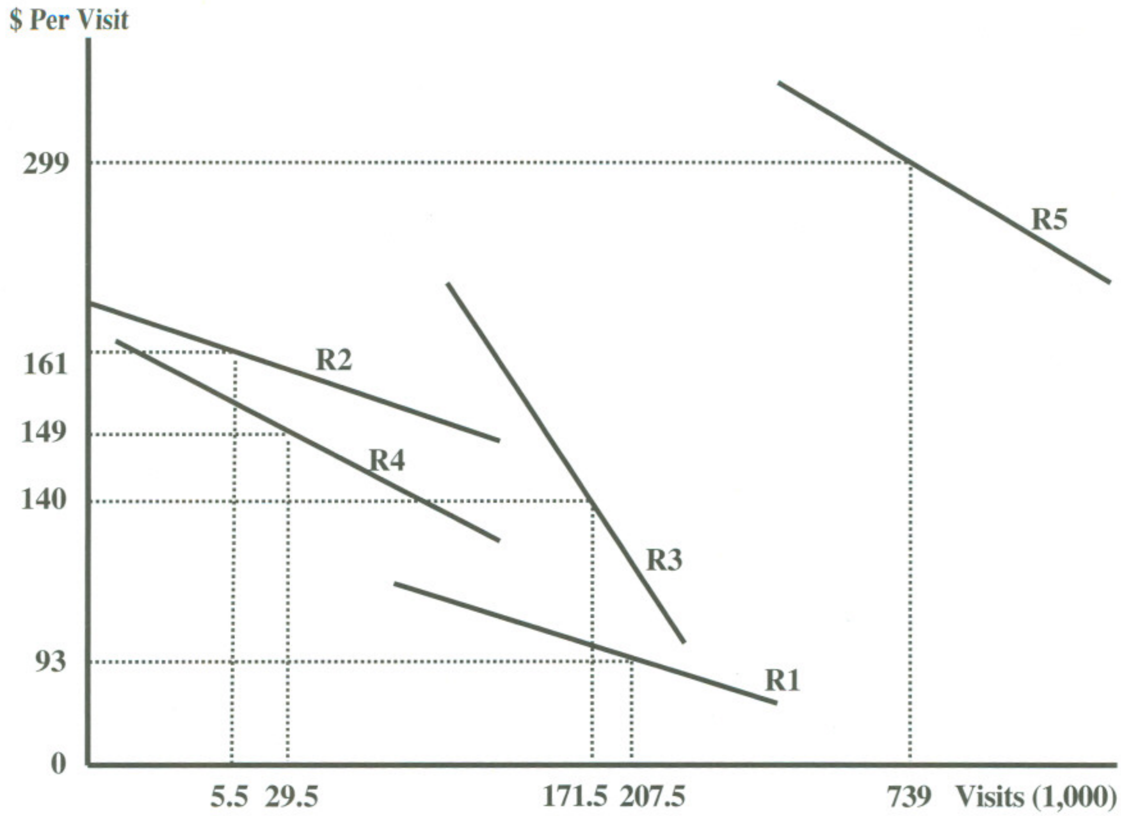
$$(17)\quad g_i \approx \frac{\ln[\left(\frac{A_i(t_2)}{V_i} - \frac{A_i(t_1)}{V_i}\right) \times 100\%]}{(t_2 - t_1)},$$

where t_1 and t_2 represent the initial and terminal time periods, respectively.

Dates of species introduction to Florida vary among the invasive exotic plants like the Australian pine (*Casuarina*), which was introduced in the early 1900s (Wikipedia—Casuarina), the Melaleuca (*Melaleuca quinquenervia*), which was also introduced into southern Florida in the early 1900s, the Brazilian pepper, which was introduced to Florida by, at the latest, 1891 (Wikipedia—Brazilian pepper), the Chinese Tallow, which was introduced into Florida in the 1700s (National Invasive Species Information Center), and the Old World climbing fern (*Lygodium microphyllum*), which was first discovered in Florida in 1958. Among these "unwanted" invasive exotic plants, acres infested with the Melaleuca and Brazilian pepper, which were controlled between 1998 and 2003, represent nearly 80% of total project acres (Florida DEP). Since both the Melaleuca and Brazilian pepper were introduced into Florida around 1900, and there is no information on acreage infested with each of these invasive exotic plants, our simulation analysis is based on aggregate average intrinsic growth rates of $g_i = 0.02$ and $g_i = 0.05$ (where $A_i(t_2) = 85{,}942$, $A_i[t_1] = 0$ and $V_i = 572{,}947$ from Table 1 and $t_2 - t_1 = 110$).

Simulation Results

Nearly 87% of the management budget during the base period (of nearly $2 millon) was allocated to region 5 during the 2002–2003 period, where the number of recreational visitations and the expenditures per visit are the largest, while per acre control costs of managing exotic invasive plants are also the largest. Meanwhile, nearly 12% of the annual management budget was allocated to region 3, where per acre control costs are the second highest, but the number of recreational visitations is third, and the expenditures per visit rank fourth among the five regions. We evaluated these base-period budget allocations by conducting 10-year period simulation analyses for several scenarios with our model.



Source: Bureau of Invasive Plant Management, Florida Department of Environmental Protection (2003).

Figure 2. Characteristics of the Florida Recreation Sites

Simulation Scenarios

Using data presented in Tables 1 and 2, simulation analyses were conducted for six scenarios using General Algebraic Modeling System (GAMS) software. Scenario 1 assumes that no species control measures are adopted, where $g_i = 0.02$ and $r = 0.03$. Scenario 2 is the same as scenario 1, except that the rate of intrinsic growth is increased by 250% to $g_i = 0.05$. Scenario 3 assumes that a nominal budget of $2 million is allocated for controlling infested acres in each year, where $g_i = 0.02$ and $r = 0.03$. Scenario 4 is the same as for scenario 3, except that the annual budget is raised to $4 million. Scenario 5 is the same as for scenario 3, except that the rate of intrinsic growth increases to $g_i = 0.05$ from $g_i = 0.02$. Meanwhile, scenario 6 is the same as for scenario 4, except that the rate of intrinsic growth increases to $g_i = 0.05$ from $g_i = 0.02$. (Table 3 summarizes scenario criteria changes for each of the simulation analyses.)

Under scenario 1, assuming no management control budget, infested acres increase from 15% of Public Conservation Lands in the base year to 18% over the 10-year period (Table 4). Accordingly, total recreation days decline by 37,000 days to 1,116,000 days from 1,153,000 days, which leads to economic benefit losses of $217 million during the same time period. Under scenario 2, which also assumes no control budget, but where $g_i = 0.05$ and $r = 0.03$, infested acres increase to 22% of Public Conservation Lands, and total recreation days decline to 101,000 days, which leads to economic benefit losses of $341 million over the 10-year period (Table 5). That is, as the rate of intrinsic growth of species infested acres increases to $g_i = 0.05$,

Table 3. Alternative Simulation Analyses

Simulation Scenario	Management Budget	Intrinsic Growth Rate (g_i)	Rate of Discount (r)
Scenario 1	No budget	0.02	0.03
Scenario 2	No budget	0.05	0.03
Scenario 3	$2 million	0.02	0.03
Scenario 4	$4 million	0.02	0.03
Scenario 5	$2 million	0.05	0.03
Scenario 6	$4 million	0.05	0.03

recreation days would decline by up to 64,000 days, which would lead to economic losses of $12.4 million per year on average.

Under scenario 3, an annual management budget (of $2 million) is allocated among regions 1, 4, and 5 during the first three years, but the budget allocation to regions 1 and 4 then declines as infested acreage for these regions declines, while the budget allocation increases for region 5 (Table 6). It should be noted that there would be no management of exotic plants in regions 2 and 3, while all of the annual budget is allocated to region 5 after the fourth year of controlling exotic plants for the study area. These results imply that region 5 receives most of the economic benefits from the invasive plants management program. Even though the control costs per acre in region 2 are the lowest across the study area, the number of recreation visitations is so small so that it is not economically worth controlling exotic plants in region 2. This result indicates that cost minimization models may lead to different policy decisions. The present value of net economic benefits resulting from the adoption of species management controls implemented under an annual $2 million program (measured as increased consumer surplus less invasive plant management costs) is estimated to be $308 million during the 10-year study period.

If the annual management control budget is raised to $4 million, scenario 4 results demonstrate that almost all of the increased budget is allocated to region 5 (Table 7). However, as exotic invasive plants near

Table 4. Present Values of Consumer Surpluses Associated with Recreation Activities and the Estimated Exotic Invasive Plant–Infested Acres with No Control, where $g_i = 0.02$ and $r = 0.03$

	Consumer Surplus	Infested Acres[a]					Recreation Days[a]				
		R1	R2	R3	R4	R5	R1	R2	R3	R4	R5
	($mil)			(acres)					(1,000 d.)		
Base Year	540	10,134	5,572	29,991	635	39,610	207.4	5.6	171.6	29.5	739.0
1	507	10,306	5,667	30,501	646	40,283	206.8	5.5	171.0	29.4	736.8
2	491	10,481	5,763	31,018	657	40,966	206.2	5.5	170.5	29.3	734.5
3	475	10,658	5,860	31,542	668	41,658	205.5	5.5	170.0	29.2	732.2
4	459	10,838	5,959	32,073	679	42,360	204.9	5.5	169.5	29.1	729.9
5	444	11,020	6,059	32,612	690	43,071	204.2	5.5	168.9	29.0	727.6
6	430	11,204	6,160	33,158	702	43,792	203.6	5.5	168.4	28.9	725.2
7	416	11,391	6,263	33,711	714	44,523	202.9	5.4	167.8	28.8	722.8
8	402	11,580	6,367	34,271	726	45,263	202.2	5.4	167.2	28.7	720.4
9	389	11,772	6,473	34,839	738	46,013	201.5	5.4	166.7	28.6	717.9
10	376	11,967	6,580	35,415	750	46,773	200.8	5.4	166.1	28.5	715.4
Sum = $4,389											

[a] R1 includes Dixie, Franklin, Gulf, Jefferson, and Taylor Counties; R2 includes Lake, Levy, and Osceola Counties; R3 includes Charlotte, Hernando, and Osceola Counties; R4 includes Gadsden, Marion, Putnam, Sumter, and St. John Counties; and R5 includes Broward, Dade, and Palm Beach Counties.

Table 5. Present Values of Consumer Surpluses Associated with Recreation Activities and the Estimated Exotic Invasive Plant–Infested Acres with No Control, where $g_i = 0.05$ and $r = 0.03$

	Consumer Surplus	Infested Acres[a]					Recreation Days[a]				
		R1	R2	R3	R4	R5	R1	R2	R3	R4	R5
	($mil)			(acres)					(1,000 d.)		
Base Year	540	10,134	5,572	29,991	635	39,610	207.4	5.6	171.6	29.5	739.0
1	505	10,565	5,809	31,266	662	41,293	205.9	5.5	171.3	29.3	733.4
2	486	11,010	6,054	32,584	690	43,035	204.3	5.5	168.9	29.0	727.7
3	468	11,471	6,307	33,948	719	44,836	202.6	5.4	167.6	28.8	721.8
4	450	11,947	6,569	35,357	749	46,697	200.9	5.4	166.1	28.6	715.6
5	433	12,439	6,839	36,813	779	48,619	199.1	5.3	164.7	28.3	709.3
6	416	12,946	7,118	38,314	811	50,603	197.3	5.3	163.2	28.0	702.8
7	400	13,470	7,406	39,863	844	52,648	195.4	5.2	161.6	27.8	696.1
8	384	14,009	7,703	41,459	878	54,756	193.4	5.2	160.0	27.5	689.1
9	369	14,564	8,008	43,102	913	56,926	191.4	5.1	158.3	27.2	682.0
10	354	15,135	8,322	44,752	948	59,159	189.4	5.1	156.6	26.9	674.6
Sum =	$4,265										

[a] R1 includes Dixie, Franklin, Gulf, Jefferson, and Taylor Counties; R2 includes Lake, Levy, and Osceola Counties; R3 includes Charlotte, Hernando, and Osceola Counties; R4 includes Gadsden, Marion, Putnam, Sumter, and St. John Counties; and R5 includes Broward, Dade, and Palm Beach Counties.

Table 6. Present Values of Net Economic Benefits and the Estimated Exotic Invasive Plant–Infested Acres with a Nominal Budget Constraint of $2 Million per Year, where $g_i = 0.02$ and $r = 0.03$

	Net Benefits[a]	Infested Acres[b]					Controlled Acres[b,c]				
		R1	R2	R3	R4	R5	R1	R2	R3	R4	R5
	($mil)			(acres)					(acres)		
Base Year		10,134	5,572	29,991	635	39,610	177	675	581	39	2,364
1	14.1	2,977	5,677	30,501	187	38,689	7,200	0	0	451	1,563
2	18.1	56	5,763	31,018	4	36,898	2,922	0	0	184	2,404
3	21.2	1	5,860	31,542	0	34,505	55	0	0	3	2,969
4	25.2	0	5,959	32,073	0	32,067	1	0	0	0	2,979
5	29.3	0	6,059	32,612	0	29,592	0	0	0	0	2,979
6	33.3	0	6,160	33,158	0	27,079	0	0	0	0	2,979
7	36.4	0	6,263	33,711	0	24,527	0	0	0	0	2,979
8	40.4	0	6,367	34,271	0	21,934	0	0	0	0	2,979
9	43.5	0	6,473	34,839	0	19,298	0	0	0	0	2,979
10	46.5	0	6,580	35,415	0	16,617	0	0	0	0	2,979
Sum = $308 million											

[a] Net benefits represent increasing consumer surplus resulting from the adoption of control measures less invasive plant management costs.

[b] R1 includes Dixie, Franklin, Gulf, Jefferson, and Taylor Counties; R2 includes Lake, Levy, and Osceola Counties; R3 includes Charlotte, Hernando, and Osceola Counties; R4 includes Gadsden, Marion, Putnam, Sumter, and St. John Counties; and R5 includes Broward, Dade, and Palm Beach Counties.

[c] Budget allocations across regions can be obtained by multiplying per acre control costs of each region (Table 1) by control acres of each region.

Table 7. Present Values of Net Economic Benefits and the Estimated Exotic Invasive Plant–Infested Acres with a Nominal Budget Constraint of $4 Million per Year, where $g_i = 0.02$ and $r = 0.03$

	Net Benefits[a]	Infested Acres[b]					Controlled Acres[b,c]				
		R1	R2	R3	R4	R5	R1	R2	R3	R4	R5
	($mil)			(acres)					(acres)		
Base Year		10,134	5,572	29,991	635	39,610	177	675	581	39	2,364
1	20.1	2,977	5,667	30,501	187	35,652	7,200	0	0	451	4,542
2	28.1	56	5,763	31,018	4	30,779	2,922	0	0	184	5,384
3	36.3	1	5,860	31,542	0	25,259	55	0	0	3	5,948
4	45.4	0	5,959	32,073	0	19,641	1	0	0	0	5,959
5	53.5	0	6,059	32,612	0	13,929	0	0	0	0	5,959
6	60.7	0	6,160	33,158	0	8,118	0	0	0	0	5,959
7	68.7	0	6,263	33,711	0	2,220	0	0	0	0	5,959
8	71.8	0	6,367	27,087	0	43	0	0	7,049	0	2,158
9	73.9	0	6,473	16,376	0	1	0	0	10,972	0	42
10	77.0	0	6,580	5,420	0	0	0	0	11,048	0	1
Sum = $535.5 million											

[a] Net benefits represent increasing consumer surplus resulting from the adoption of control measures less invasive plant management costs.

[b] R1 includes Dixie, Franklin, Gulf, Jefferson, and Taylor Counties; R2 includes Lake, Levy, and Osceola Counties; R3 includes Charlotte, Hernando, and Osceola Counties; R4 includes Gadsden, Marion, Putnam, Sumter, and St. John Counties; and R5 includes Broward, Dade, and Palm Beach Counties.

[c] Budget allocations across regions can be obtained by multiplying per acre control costs of each region (Table 1) by control acres of each region.

eradication in region 5 by year 8 (as indicated by the significant decline in infested acres), it then becomes economically efficient to allocate a control budget to manage invasive plants in region 3. These results indicate that an increased annual species management budget does not generate additional economic benefits from regions 1, 2, and 4. Even so, while region 5 contributes the most to the economic benefits of an increased annual management budget, region 3 contributes economic benefits in the latter years of the study period as exotic invasive plants in other regions (except for region 2) are eradicated. Net economic benefits increase to nearly $536 million from $308 million during the 10-year period as a result of increasing the annual management budget to $4 million (while other scenario criteria remain the same).

Scenarios 5 and 6 are concerned with the effects of an increase in the intrinsic growth rate (for species infested acres) at annual management control budgets of $2 million and $4 million, respectively. Results for these scenarios (Tables 8 and 9) may indicate that the magnitude of the rate of intrinsic growth does not significantly affect the economically efficient budget allocation among the study area regions for controlling invasive plants.

In summary, simulation results presented in Tables 4–9 indicate that for our study area, it is economically efficent to allocate a large portion of an annual management budget designed to control exotic invasive plants to region 5, even though management control cost is the highest for region 5 at $671.28 per - acre (Table 1). Meanwhile, control costs for region 2 are the lowest at $58.81 per acre, but no management budgets are allocated to region 2 under the various scenarios. These results may indicate that minimization of management control costs may result in different policy conclusions. As pointed out by Settle and Shogren, integration of economics within an ecosystem-based modeling framework yields different policy conclusions

Table 8. Present Values of Net Economic Benefits and the Estimated Exotic Invasive Plant–Infested Acres with a Nominal Budget Constraint of \$2 Million per Year, where $g_i = 0.05$ and $r = 0.03$

	Net Benefits[a]	Infested Acres[b]					Controlled Acres[b,c]				
		R1	R2	R3	R4	R5	R1	R2	R3	R4	R5
	(\$mil)			(acres)					(acres)		
Base Year		10,134	5,572	29,991	635	39,610	177	675	581	39	2,364
1	17.1	2,956	5,572	29,991	186	38,043	7,178	0	0	449	1,567
2	25.1	135	5,809	31,266	16	35,617	2,821	0	0	170	2,426
3	31.2	6	6,054	32,584	9	32,663	128	0	0	7	2,954
4	39.2	0	6,307	33,948	9	29,684	6	0	0	0	2,978
5	46.3	0	6,569	35,357	9	26,705	0	0	0	0	2,979
6	53.3	0	6,839	36,813	10	23,726	0	0	0	0	2,979
7	59.4	0	7,118	38,314	10	20,746	0	0	0	0	2,979
8	65.4	0	7,406	39,863	11	17,767	0	0	0	0	2,979
9	71.5	0	7,703	41,459	11	14,787	0	0	0	0	2,979
10	77.5	0	8,008	43,102	12	11,808	0	0	0	0	2,979
Sum = \$486.0 million											

[a] Net benefits represent increasing consumer surplus resulting from the adoption of control measures less invasive plant management costs.

[b] R1 includes Dixie, Franklin, Gulf, Jefferson, and Taylor Counties; R2 includes Lake, Levy, and Osceola Counties; R3 includes Charlotte, Hernando, and Osceola Counties; R4 includes Gadsden, Marion, Putnam, Sumter, and St. John Counties; and R5 includes Broward, Dade, and Palm Beach Counties.

[c] Budget allocations across regions can be obtained by multiplying per acre control costs of each region (Table 1) by control acres of each region.

compared to results derived when only cost minimization or minimized ecosystem effects are considered. These study results also demonstrated that the annual budget allocation does not significantly change as the rate of intrinsic growth changes, but such allocations would change significantly as the annual management budget increases.

Concluding Remarks

This research develops a multiregional optimal control model for managing exotic invasive plants in the context of allocating limited resources (budgets) among spatially separated regions. In our economic framework, the relative allocation of a limited resource (budget) among regions accounts for the systematic transition of invasive species management that would result from our equimarginal condition occurring over time. An obvious strength of our model is the more detailed description of how to allocate an annual budget for managing exotic invasive plants across regions in an intertemporal context. This additional detail naturally enhances the role of economic analysis in public resource policy evaluation. This is especially true in the area of managing invasive species across regions, where society frequently chooses, for example, regulatory approaches to achieving public policy goals when allocating a limited resource.

In our application, these traits include the allocation of an annual budget for managing invasive plants among five Florida conservation management regions. While it is least expensive to manage exotic invasive plants in region 2, our analysis suggests that the allocation of a limited management budget to region 2 would be the most economically inefficient public policy decision. Even though management costs are much higher for region 5, economic efficiency accounts for more than minimization of cost by also taking account of the higher recreation benefits in region 5.

Table 9. Present Values of Net Economic Benefits and the Estimated Exotic Invasive Plant–Infested Acres with a Nominal Budget Constraint of $4 Million per Year, where $g_i = 0.05$ and $r = 0.03$

	Net Benefits[a]	Infested Acres[b]					Controlled Acres[b,c]				
		R1	R2	R3	R4	R5	R1	R2	R3	R4	R5
	($mil)			(acres)					(acres)		
Base Year		10,134	5,572	29,991	635	39,610	177	675	581	39	2,364
1	20.1	3,009	5,809	31,266	189	36,534	7,232	0	0	453	4,536
2	30.2	134	6,054	32,584	9	32,452	2,878	0	0	181	5,393
3	38.3	7	6,307	33,948	0	27,652	131	0	0	8	5,933
4	48.4	0	6,569	35,357	0	22,641	6	0	0	0	5,958
5	57.6	0	6,839	36,813	0	17,426	0	0	0	0	5,959
6	67.7	0	7,118	38,314	0	11,990	0	0	0	0	5,959
7	75.7	0	7,406	39,863	0	6,312	0	0	0	0	5,959
8	85.8	0	7,703	41,459	0	370	0	0	0	0	5,959
9	86.9	0	8,008	32,215	0	18	0	0	10,394	0	354
10	93.0	0	8,322	22,027	0	1	0	0	11,019	0	17
Sum = $603.7 million											

[a] Net benefits represent increasing consumer surplus resulting from the adoption of control measures less invasive plant management costs.

[b] R1 includes Dixie, Franklin, Gulf, Jefferson, and Taylor Counties; R2 includes Lake, Levy, and Osceola Counties; R3 includes Charlotte, Hernando, and Osceola Counties; R4 includes Gadsden, Marion, Putnam, Sumter, and St. John Counties; and R5 includes Broward, Dade, and Palm Beach Counties.

[c] Budget allocations across regions can be obtained by multiplying per acre control costs of each region (Table 1) by control acres of each region.

Results show that net economic benefits from managing exotic invasive plants within our study area increase to $536 million from $308 million over a 10-year period as the annual management budget increases from $2 million to $4 million. With a larger intrinsic growth rate, $g_i = 0.05$, net economic benefits increase to $604 million from $486 million over the 10-year period as the annual management budget increases from $2 million to $4 million. These results show that net economic benefits from controlling invasive plants increase even as the rate of intrinsic growth increases. Furthermore, our sensitivity analyses demonstrate that the magnitude of an annual budget affects its distribution among species management regions, but the size of the intrinsic growth rate does not significantly affect the pattern of budget allocation among regions.

[Received March 2007; Accepted June 2007.]

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