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Allocation of invasive plant management expenditures for conservation: Lessons from Florida, USA

Drew Hiatt[1] | Kristina Serbesoff-King[2] | Deah Lieurance[1,3] | Doria R. Gordon[4,5] | S. Luke Flory[1,3]

[1]Agronomy Department, University of Florida, Gainesville, Florida
[2]The Nature Conservancy, West Palm Beach, Florida
[3]Center for Aquatic and Invasive Plants, University of Florida, Gainesville, Florida
[4]Environmental Defense Fund, Washington, DC
[5]Department of Biology, University of Florida, Gainesville, Florida

Correspondence
S. Luke Flory, Agronomy Department, University of Florida, PO Box 110500, Gainesville, FL 32611.
Email: flory@ufl.edu

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Florida Fish and Wildlife Conservation Commission, Invasive Plant Management Section

Abstract

Although the ecological impacts of biological invasions are well studied, comprehensive analyses of spending on invasive species management are lacking. Such analyses could inform both effective resource allocation and management planning. We evaluated long-term invasive plant management expenditures and their potential geographic, economic, and ecological drivers for freshwater and terrestrial conservation areas in Florida, USA. Average expenditures for managing invaders were approximately US$45M annually, with over 90% of funding provided by the state. Our model showed that expenditures were best predicted by the prevalence of waterways and abundance of invaders, indicating that funding was allocated towards asset protection in highly invaded aquatic and terrestrial habitats. Higher spending was directly correlated with reduced area invaded for the costliest invader (*Hydrilla verticillata,* ~$10M/year), demonstrating management efficacy and constructive use of resources. Our study highlights that significant funding is required to manage plant invaders in Florida and that greater funding would likely limit the extent of invasions. Additional analyses of management cost-effectiveness for Florida and other regions would benefit from consistent collection and reporting of high-resolution management data. Given the exponential rate of spread of many invaders, additional and sustained management funding is needed for early detection and rapid, effective control of invasive species.

KEYWORDS
aquatic, control, costs, economic, invader, terrestrial

1 | INTRODUCTION

Invasive species, and plant invaders in particular, are widely recognized as leading drivers of global environmental change because they can have profound impacts on biodiversity and ecosystem functions (Pyšek et al., 2012). The ecological impacts of invasive plants on native ecosystems have been increasingly quantified (Stricker, Hagan, & Flory, 2015), but relatively few studies have focused on the economic impacts of invasions. Estimates based on a subset of species suggest the annual cost of invasive plants in the United States alone is at least US$27B (Pimentel, Zuniga, & Morrison, 2005). Despite being widely cited, the focus of this estimate on only a few species indicates the rarity of reporting management expenditures, particularly for non-agricultural weeds. When we consider the number of invasive species in the United States, it is probable that this estimate undervalues the full costs. Moreover, most efforts to estimate management expenditures for invasive species have focused only on a subset of protected areas and expenditures by individual agencies (Iacona, Price, & Armsworth, 2014) or for specific species (Foxcroft, Pyšek, Richardson, Pergl, & Hulme, 2013). Evaluating management at the landscape scale and a broader group of species provides a more accurate understanding of the efficacy of invasive species control because management may be more successful if coordinated broadly (e.g., Glen, Pech, & Byrom, 2013). In addition, managers must determine whether to focus invasive species control efforts on protecting assets at the core of the invasion or targeting outlying incipient populations to reduce spread (Adams & Setterfield, 2015), which requires broader analyses. Overall, a more comprehensive analysis of management expenditures could highlight the economic scale of the invasive species problem (Foxcroft et al., 2013), illustrate the need for additional preventative measures (e.g., biosecurity screening, risk assessment), inform decision-making (Wu & Boggess, 1999), and spur the development of cost-effective management strategies (Rejmánek, 2000).

The state of Florida, USA makes a significant contribution to global species richness because of its high proportion of endemic taxa (Stein, Kutner, & Adams, 2000). In parallel, the state ranks behind only Hawaii and California in the United States in having the highest number of threatened and endangered plant and animal species (USFWS, 2017). A primary threat to native species in Florida is non-native species invasions, which are prevalent because the state has climate zones that range from sub-tropical to temperate, multiple global shipping ports, and significant agricultural and horticultural industries (Colunga-Garcia, Haack, Magarey, & Borchert, 2013). Consequently, Florida has invested significantly in invasive plant control for many years (Iacona et al., 2014) and, therefore, serves as a model for a more comprehensive assessment of invasive species management expenditures.

Nearly 1,500 non-native plant species have been documented as established in Florida (Wunderlin, Hansen, Franck, & Essig, 2018). Over 150 of these species are invaders in natural areas (UF/IFAS, 2017), where they suppress biodiversity and alter ecosystems (Gordon, 1998). Invaders can have costly impacts on agriculture, navigation, and infrastructure, and invasions in Florida's high-quality natural areas threaten both revenues and biodiversity. Over US$50B per year in revenue is generated from natural resource-based sectors of the Florida economy (Hodges, Rahmani, & Court, 2017), so plant invaders are a critical concern. Given the scale of the invasive plant problem, an analysis of management expenditures across species and among geographical, economic, and ecological predictors in Florida is integral to inform current and future funding allocation patterns for invasive plant management. Findings from such an analysis could highlight the historical prioritization of invasive plant management and the strategic allocation of funds across a large geographic area (Adams & Setterfield, 2015).

Using 6 years of data from state and federal agencies, we investigated the allocation of expenditures for invasive plant management in Florida's publicly-held conservation areas. We evaluated the following: (a) trends in federal and state agency expenditures over time; (b) patterns in spending, including geographic distribution, for more than 20 aquatic and terrestrial invasive plant species; (c) geographic, economic, and ecological drivers that best predict patterns in invasive plant management expenditures (Table 1); and (d) efficacy of management spending for the costliest plant invader in Florida.

2 | METHODS AND MATERIALS

We collected 6 years (2009–2014) of data on invasive plant management expenditures from state and federal agencies that manage at least 10,000 ha of conservation area, which represented 90% of all conservation areas in Florida. In total, we account for over US$265M in management expenditures across the state for the 2009–2014 time period. All data were adjusted for inflation and converted to 2014 US dollars ($) to facilitate comparison among years. Data were analyzed based on the original funding source to eliminate double counting of funds that passed from one agency to another or were shared during inter-agency collaborations. We tabulated average yearly spending for individual species and for all aquatic and terrestrial species combined. We also evaluated the geographic distribution of spending at the county level for the top five invaders in terms of expenditures.

To determine the primary factors associated with allocation of funds among Florida counties (Table 1), we fit general linear mixed effects models of aquatic, terrestrial, and total invasive plant spending to geographic, economic, and ecological predictors (R Core Team, 2016). We conducted analyses at the county level ($n = 67$) because data for many of the predictor variables (per capita income, population density, numbers of federally listed threatened or endangered [T/E] plant and animal species) were available only for entire counties (Table S1). Spending per county was log transformed to meet assumptions of normality, and all predictors were standardized so that effect sizes could be compared. We utilized spatial data from the U.S. Census (U.S. Census, 2017) to delineate the area of fresh or brackish navigable waterways in each county (Figure S1). The amount of conservation land area per county was calculated using data

TABLE 1 Predictors and associated hypotheses to explain geographical patterns in invasive plant management expenditures across counties in Florida, USA

Category	Predictor	Hypotheses
Geographic	Navigable waterways	Counties with more navigable waterways allocate greater expenditures to aquatic invasive species management to protect waterways for conservation[a] and recreation.[a,b]
	Conservation land	Counties with higher amounts of conservation land spend more to manage terrestrial invasive species to protect biodiversity[c,e] and recreation assets.[c,d]
	County area	More expenditures occur in counties with larger areas because of greater area for species to invade.
	Latitude	At lower latitudes, counties have more suitable habitat for non-native species originating in tropical climates[f,g] and therefore require greater management expenditures.
	Longitude	Counties farther east in the state of Florida are likely allocated more to both aquatic and terrestrial invasive plant management due to the arrival of invaders through the major cargo ports of Florida.[h,i]
Economic	Per capita income	More expenditures occur in counties of higher economic status because more intensely landscaped residences contain more non-native species, increasing propagule pressure for surrounding conservation areas.[j,k]
	Population density	Counties with higher population densities have more disturbances and higher invasive plant propagule pressure, requiring greater management expenditures.[f,j,l]
Ecological	Invasive plant abundance	Higher invasive plant abundance requires more expenditures for early detection[m], maintenance control, and long-term monitoring.[n]
	T/E plant species	More expenditures in counties with abundant T/E plant species to reduce the threat from invasive plants.[o]
	T/E animal species	Greater invasive plant management expenditures in counties with more T/E animal species to preserve critical habitat.[p]

[a]Zavaleta (2000); [b]Lovell, Stone, and Fernandez (2006); [c]Serbesoff-King (2003); [d]Lee, Adams, and Kim (2009); [e]Hejda, Pyšek, and Jarošík (2009); [f]Marini, Gaston, Prosser, and Hulme (2009); [g]Pyšek and Richardson (2006); [h]Congress, U. S. Office of Technology Assessment (1993); [i]Florida's Seaports (2017); [j]Gavier-Pizarro, Radeloff, Stewart, Huebner, and Keuler (2010); [k]Hope et al. (2003); [l]Iacona et al. (2014); [m]Geissler and Latham (2014); [n]Blossey (1999); [o]Gurevitch and Padilla (2004); [p]Wilcove (2010)

from the Florida Natural Areas Inventory (FNAI, 2018) (Figure S2). County area also was included in the model to help account for variation in county size. All economic data were obtained from the Bureau of Economic Analysis (BEA, 2017); per capita income was averaged over 2009–2014 and then converted to 2014 US dollars; and population density was calculated using the average population (2009–2014) divided by county area.

We estimated the abundance of aquatic and terrestrial invasive plant species (based on state lists of prohibited species) using recorded observations for a 15-year timeframe (2000–2014) in the online EDDMapS database (EDDMapS, 2018) (Figure S3). EDDMapS is a web-based platform for reporting invasive species occurrences that combines records from non-profit and professional organizations with volunteer observations that are verified by regional experts. Although this data set is not comprehensive and very likely underestimates the total occurrences of invasive species, it includes over 115,000 verified observation records for 50 species and over 70% of the records are from field surveys by expert botanists and ecologists from the FNAI. We included observations of invasive plants before our expenditure data range (2009–2014) to better evaluate if expenditures were allocated where there was a known history of long-term monitoring and invasions. The number of federally listed threatened and endangered (T/E) plant species in each county was determined using herbarium records from the University of Florida Herbarium (FLAS, 2017), University of South Florida Herbarium (Wunderlin et al., 2018), and the Florida State University's Robert K. Godfrey Herbarium (Robertson, Nelson, Bugher, et al., 2010). The number of threatened and endangered animal species was obtained using known or predicted range information from the U.S. Fish and Wildlife Service Environmental Conservation Online System (USFWS, 2017). In total, our data set included records for 64 T/E plant species and 60 T/E animal species. To determine if more management spending was focused where there was a high ratio of invasive to threatened species, we conducted bivariate regressions between management spending and the ratio of invader occurrence (i.e., presence of prohibited terrestrial or aquatic invasive plant species) to the occurrence of T/E plant or animal species.

To evaluate management efficacy for the invader associated with the greatest expenditures, hydrilla (*Hydrilla verticillata*), we extracted data from the 2014–2015 Florida Fish and Wildlife Conservation Commission (FWC) aquatic plant management annual report (Phillips, 2015), which tabulates the majority of management expenditures for this species statewide. There were probably additional private management efforts for hydrilla that are not captured by the FWC data but because private expenditures are expected to be relatively small compared with expenditures reported by FWC, it is unlikely they would have qualitatively changed our results for management efficacy. These data were used to build a linear regression to evaluate the relationship between total annual treatment expenditures for 25 years (1991–2015) and the area invaded 2 years after treatment. The persistence of hydrilla and germination rates of propagules decline sharply beginning 14 months post-treatment (Van & Steward, 1990), thus we hypothesized that the area invaded 2 years after treatment would best reflect long-term responses to management.

3 | RESULTS

In total, we collected over 87,000 invasive plant management treatment records for Florida's conservation areas, with 64% of the records categorized at the species level, including 78 non-native aquatic plant species and 157 terrestrial plant species (total = 235 plant species). Total average annual expenditures for invasive plant management on Florida's conservation lands for state and federal agencies were \$44.9 ± 1.9M (mean ± *SE*, range: \$38.9–50.1M, Figure 1). State agencies (\$40.8 ± 1.9) spent over 10 times more than federal agencies (\$4.0 ± 0.4M, Figure 1a), on average, even though state and federal agencies manage 58 and 42% of conservation area, respectively, across Florida (Figure 1b).

Agencies spent 57% more funds managing aquatic plants than terrestrial plants (Figure 2) with the bulk of annual spending allocated to only five species, including the aquatic plant hydrilla (\$9.7 ± 1.3M) and the terrestrial tree *Melaleuca quinquenervia* (\$3.6 ± 0.4M). Among the five species with the highest management expenditures, the geographic distribution of spending varied by county with some significant patterns emerging: spending on aquatic plant management was concentrated in non-coastal central Florida counties, and terrestrial spending was focused in the southeastern region of the peninsula (Figure 2).

General linear mixed effects models were able to explain 49, 71, and 62% of the variation for aquatic, terrestrial, and total spending, respectively, at the county level. No economic metrics were significant predictors of the spatial distribution of invasive plant management expenditures (Figure 3). Of the geographic factors (Table 1), area of navigable waterways was a strong positive predictor for aquatic (p = .01) and total spending (p = .005), relative to terrestrial spending (p = .055), exemplifying the higher allocation to aquatic species management. County longitude was the strongest positive predictor of spending on terrestrial invasive plant species (p < .001, i.e., spending increased from west to east), and a marginal predictor for total spending (p = .051). Of the ecological factors (Table 1), total records of prohibited terrestrial plant species per county best predicted both terrestrial (p = .024) and total spending (p = .002). Total records of prohibited aquatic plant species was a strong positive predictor for the allocation of aquatic expenditures (p = .029). The total amount of threatened/endangered plant species was a marginal negative predictor for terrestrial spending (p = .096). The number of threatened/endangered animals was a positive predictor for terrestrial invasive plant management (p = .028).

There was a positive relationship between terrestrial management spending and the ratio of occurrence of terrestrial invasive plant species and the occurrence of T/E animal species (t = 1.92, p = .06, Figure S4b). There was also a positive relationship between aquatic spending and the ratio of occurrence of aquatic invasive plant species and the occurrence of T/E animal species (t = 3.33, p = .01, Figure S4d), but neither model had much explanatory power.

Over a 25-year period (1991–2015) both the area invaded by hydrilla (8,500–39,000 ha) and expenditures to control invasions varied widely (\$3.1–\$17.6M per year, Figure 4a). Higher expenditures were associated with less area invaded 2 years after management, whereas the extent of hydrilla invasions was greater following years with lower management expenditures. As a result, regression analysis showed a strong negative relationship between spending and area invaded 2 years after treatment (R^2 = 0.35, Figure 4b).

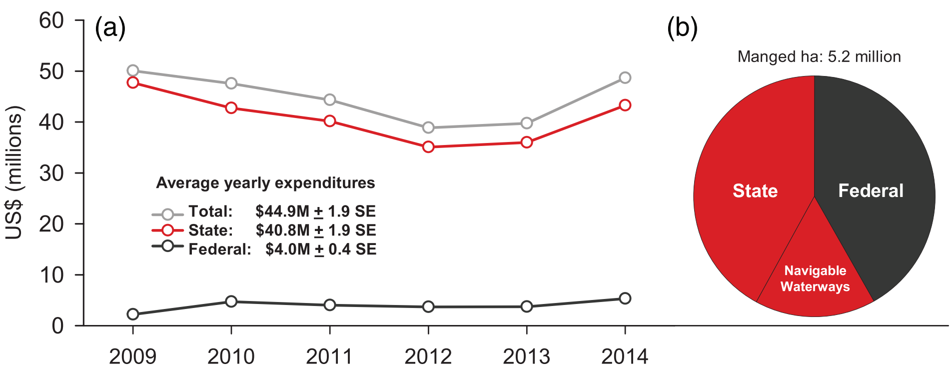

FIGURE 1 (a) Total, state, and federal invasive plant management expenditures on conservation lands in Florida 2009–2014, and (b) total hectares managed by state and federal agencies. Note that the state of Florida owns all navigable waterways in the state

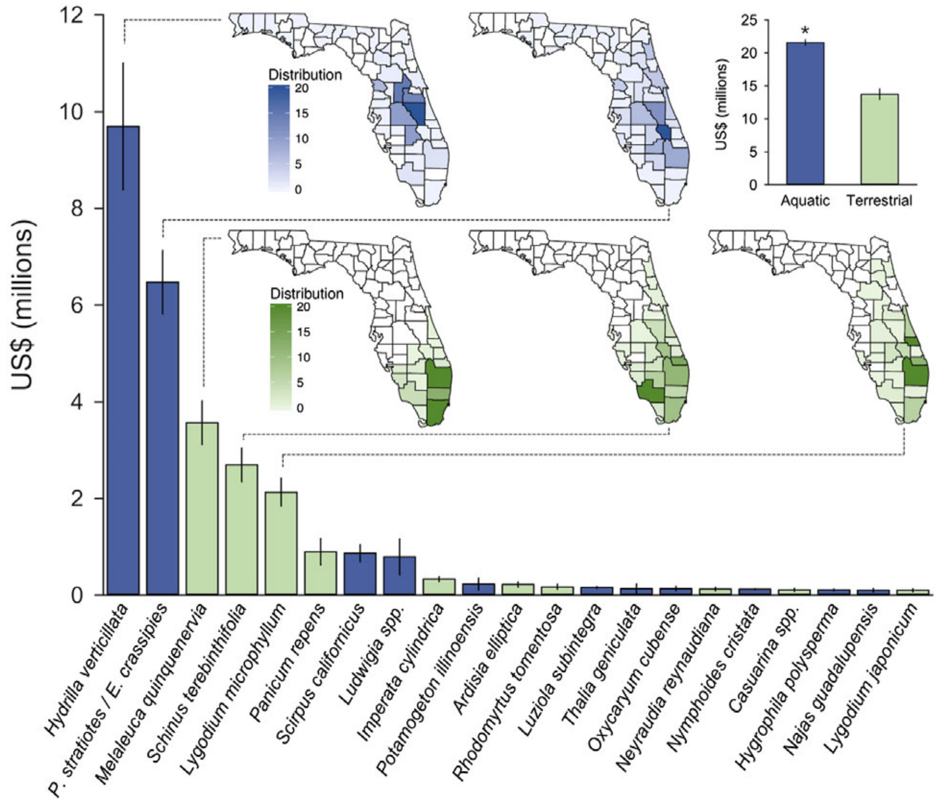

FIGURE 2 Mean ± *SE* yearly expenditures on conservation lands and waters for non-native aquatic (blue) and terrestrial (green) plant species in Florida. Inset maps show the distribution (% of mean yearly expenditures) by county for the five plant invaders with the highest expenditures per year and inset bar chart illustrates the allocation of annual spending for aquatic and terrestrial plant species

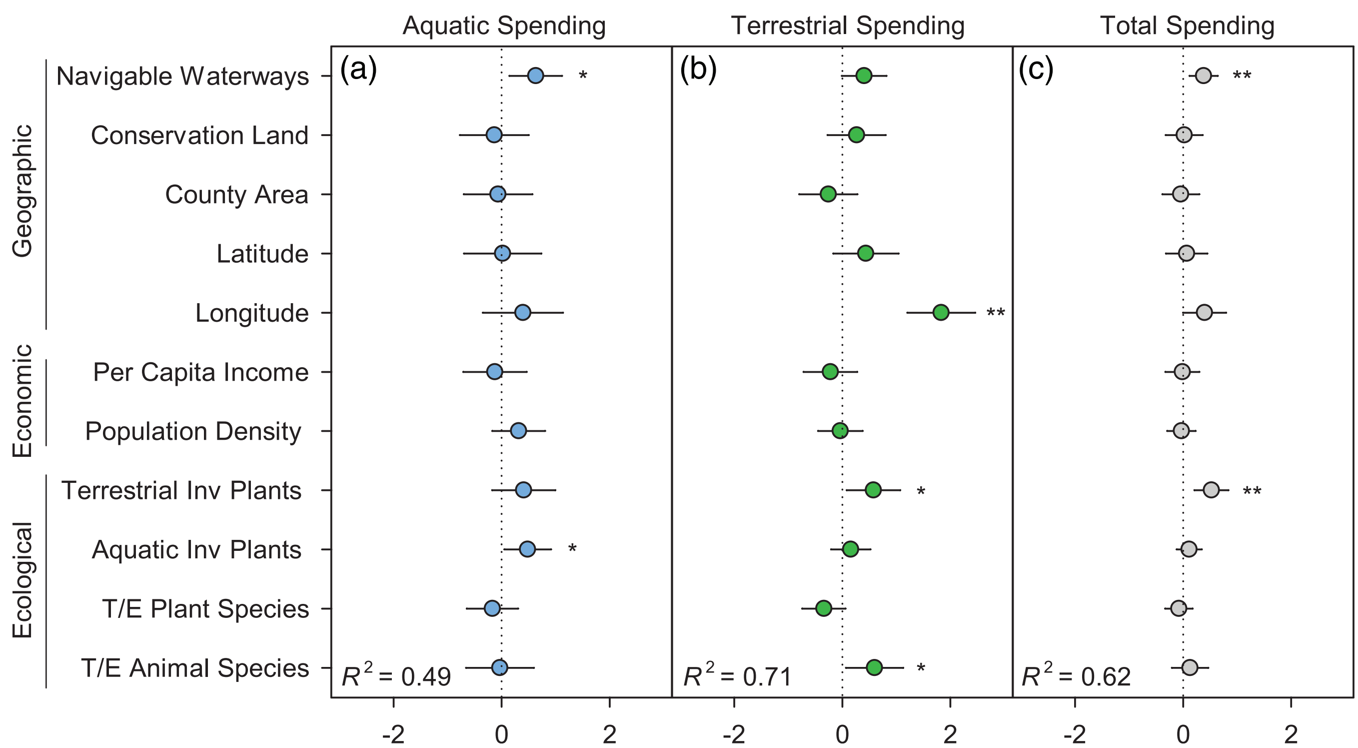

FIGURE 3 Coefficient plots (effect size ± 2 *SE*) of geographic, economic, and ecological predictors of expenditures on invasive plant management at the county level for (a) aquatic plant species, (b) terrestrial species, (c) and all species expenditures. Asterisks denote statistical significance (**p* < .05, ***p* < .01)

4 | DISCUSSION

Our study shows that substantial financial resources (approximately \$45M/year) were used to manage plant invaders on conservation areas in the state of Florida, USA during 2009–2014. More funds were directed to aquatic than terrestrial invaders, and expenditures were primarily allocated based on prevalence of waterways and abundance of invaders. Collectively, our model suggests that the state of Florida has focused on asset protection by allocating invasive plant management funds where problematic invasive plant species are most abundant and causing impacts in conservation areas (Adams & Setterfield, 2015; Gurevitch & Padilla, 2004; Lee et al., 2009). In addition, we show that management expenditures had a strong negative relationship with area invaded for the costliest species (hydrilla), demonstrating the efficacy of management and the importance of persistent control of this problematic invader. More broadly, our study highlights the need for consistent reporting by agencies of invasive plant management expenditures, including area invaded, retreatment history, and other explanatory variables, to facilitate analysis of management efficacy and efficiency across multiple taxa.

While the expenditures reported here might be perceived as high, spending on invasive plant management in natural areas is dwarfed by agricultural weed management costs (Pimentel et al., 2005). For comparison, it is estimated that Florida's farmers spend US\$91M annually (\$110M in 2014 USD) on agricultural weed control, demonstrating significant concern and investment in this land use as well (Gianessi & Reigner, 2006). Similarly, for the country of Australia, 90% of total invasive plant management expenditures (\$3.5B in 2011–2012) were directed toward agricultural weeds (Hoffmann & Broadhurst, 2016). Thus, the impacts of non-native plant species and increasing need for investment in management are a shared burden between agriculture and conservation.

State agency spending accounted for over 90% of total expenditures per year, on average, for the conservation lands assessed in this study, highlighting Florida's relatively high level of commitment to invasive plant management. A survey conducted in California in 2008 also showed higher state (\$26M) than federal (\$21M) agency spending (Cal-IPC, 2008) on invasive plant control in natural areas, despite federal ownership of 40% of the total land area compared with state ownership of 2% (Vincent, Hanson, & Argueta, 2017). However, in both Florida and California it is unclear if current spending levels are sufficient to inhibit the establishment of new non-native species or forestall the spread of current invaders. In Florida, spending was significantly greater on aquatic compared with terrestrial species and was primarily focused on five species. The aquatic invader with the highest expenditures was the widespread hydrilla, which is known to significantly alter native plant communities and affect fish populations (Langeland, 1996), and the terrestrial invader *M. quinquenervia,* which can alter hydrology and fire regimes and reduce native biodiversity (Gordon, 1998). The concentrated spending on aquatic invaders in the central portion of the state is likely driven by control of invasive plants in interconnected high-value residential and fishing freshwater bodies (Figure S1). The negative relationship between expenditures and area invaded for hydrilla suggests that, for example, every \$5M spent on management would result in approximately 5,500 less hectares (13,600 acres) invaded. This apparent effectiveness is due to both consistent funding and coordinated control efforts (Schardt, 1997). Thus, if other species respond similarly to management as hydrilla, coordinated management of invaders can result in more efficacious use of management funds. More broadly, the cyclic spending and area invaded pattern suggests that consistent and sufficient allocations of management expenditures are more effective than reducing spending when populations appear low.

Neither per capita income nor the population density of a county was related to the allocation of resources in our model, suggesting that financial resources for invasive plant management were not directed primarily to protect conservation areas near affluent, densely inhabited counties as might be predicted. This result contradicts previous research in Florida using a much smaller dataset, which showed that the density of surrounding households was particularly important for predicting spending on invasive plant management (Iacona et al., 2014). Instead, we found that the distribution of expenditures was more closely tied to multiple county-level ecological and geographic attributes. For example, first, the abundance of invasive plant species was a significant positive predictor of spending on both aquatic and terrestrial species, demonstrating that expenditures were allocated based on the extent of invasions. This finding highlights the importance of continued monitoring and search effort, because counties that detect and report invasions were more likely to receive state funding for invasive plant management. Second, funds were spent on protection of critical wildlife habitat, evidenced by the fact that the occurrence of threatened or endangered animal species was a positive predictor for the allocation of terrestrial expenditures. These patterns demonstrate the commitment of Florida agencies to prevention of imminent loss by managing where invasions are most dense, prioritization of management to protect critical wildlife habitat, and focused spending where there is a high ratio of invaders to threatened and endangered animals (Figure S4; Leung et al., 2002; Januchowski-Hartley, Visconti, & Pressey, 2011).

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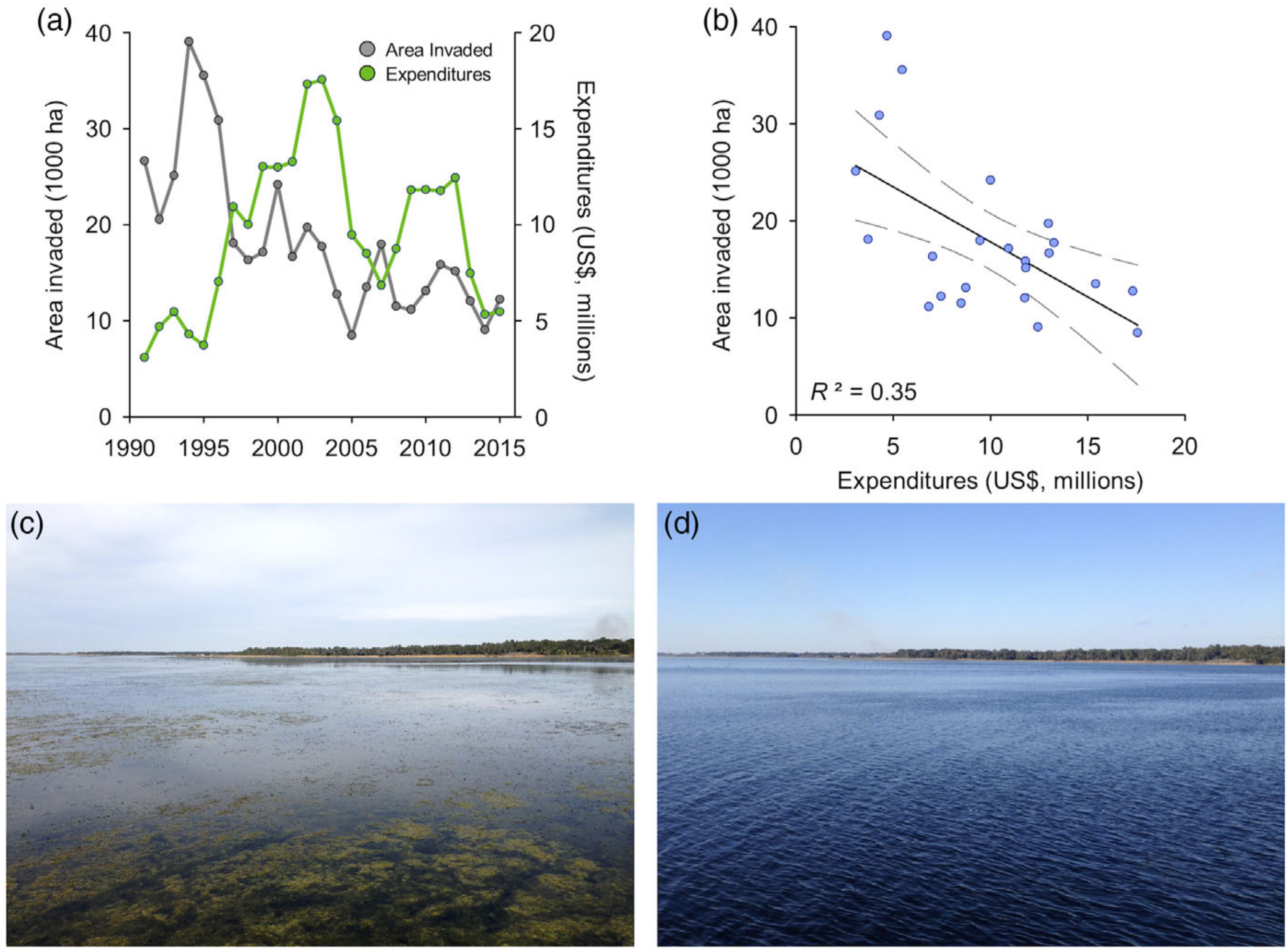

FIGURE 4 (a) Twenty-five years of total annual expenditures and hectares invaded for hydrilla, (b) relationship between area invaded 2 years after treatment and expenditures, (c) Goblet's cove (Osceola County, Florida) pre-treatment and (d) Goblet's cove post-treatment. *Source:* photos courtesy of Michael Netherland

Finally, our relatively high-resolution data allowed us to examine spatial patterns in management expenditures and determine that terrestrial spending was best predicted by county longitude, with greater expenditures allocated to counties in the eastern part of the state. This pattern was driven in part by high levels of terrestrial plant management spending in the counties near major cargo ports (i.e., those that accept cargo containers) of Florida (PortMiami and Port Everglades) where propagule pressure, disturbance, and ideal climate conditions likely coincide to drive invasions in conservation areas (Congress, U.S., 1993; Florida's Seaports, 2017; Pyšek & Richardson, 2006). In addition, the unique shape of the state of Florida, where the counties farthest east are also many of the counties that are farthest south, may have contributed to this result. Overall, although it is unclear if total expenditures are adequate to effectively manage invasive plants over the long term, expenditures appeared to be appropriately allocated to the conservation areas that are most critically threatened by invaders.

There has been a long-standing desire to better quantify the economic impacts of invasive species to demonstrate the overall impacts of invaders, motivate policy changes, and encourage sufficient spending on management. Most studies have documented the economic impact of invasive species through bio-economic models or estimations of future economic losses and have demonstrated potential losses of billions of US$ per year from invasions (Leung et al., 2002; Pimentel et al., 2005). Our results expand on such studies by evaluating not only the distribution of resources based on geographic, economic, and ecological factors, but also the efficacious use of management funds to reduce invader abundance. Furthermore, we evaluated spending across 235 species, broad geographic areas, and multiple possible predictors of spending patterns. This effort was only possible because most conservation related agencies in Florida maintain historical databases on the amount of funding and the source of funds, as well as species targeted for control and location of treatment. These data are critical for understanding patterns in management spending over time and space and can ultimately aid broader efforts to manage invasive species and conserve natural areas. We urge all agencies to maintain consistent databases of funds spent on invasive species management, including the source of funds, the timing, location, and identity of species treated, and the effectiveness of control and necessity for retreatment, and to make those data readily available to researchers and other managers. Only then will we better understand patterns in Florida and if they are indicative of those across broader geographic areas.

Given increasing global travel and trade, the introduction of species to non-native ranges shows no sign of slowing down (Seebens et al., 2017). Accordingly, expenditures for managing invasive species to reduce their economic and ecological effects are expected to escalate over time. Our study demonstrates the need for continued and sustained management funding to efficiently address the growing problem of invasions. Furthermore, given the exponential rate of spread of some invaders following establishment (Hastings et al., 2005), these findings also highlight the need for funding to target early detection and rapid, persistent control of invasive species. We urge researchers and managers to continue seeking cost-effective invasive species removal and native species restoration methods, and we encourage decision-makers to increase designated funding for risk assessment, early detection, rapid response, and maintenance control of invaders (McConnachie, Cowling, Van Wilgen, & McConnachie, 2012). Moreover, we emphasize that collection and dissemination of high-resolution management data can be particularly useful for resources managers to evaluate if management efforts are cost-effective and for decision makers to assess management efficacy and resource allocation.

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AUTHOR CONTRIBUTIONS

S.L.F. conceived the idea and developed the project along with K.S.K., D.L., and D.R.G. D.H. led the data collection with contributions from K.S.K. D.H. conducted all analyses and modeling, created figures, and wrote the initial manuscript draft. All authors designed the study approach, interpreted results, and contributed to writing and editing the manuscript.

DATA ACCESSIBILITY STATEMENT

Data are freely available through the Dryad Digital Repository (doi:10.5061/dryad.jh5n738).

ETHICS STATEMENT

All research was conducted according to the laws and regulations of the state of Florida and the United States.

ORCID

Drew Hiatt https://orcid.org/0000-0001-9514-9585
Doria R. Gordon http://orcid.org/0000-0001-6398-2345
S. Luke Flory https://orcid.org/0000-0003-3336-8613

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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