RESEARCH ARTICLE

Using Fire and Herbicide to Control *Lygodium microphyllum* and Effects on a Pine Flatwoods Plant Community in South Florida

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ABSTRACT: *Lygodium microphyllum* (Cav.) R. Br. is a non-native invasive fern that has become a serious problem in many habitats in southern Florida. The effectiveness of fire and/or triclopyr ester in killing *L. microphyllum*, the time and amount of herbicide required for inspections and re-applications, and the effects of these treatments on a southern Florida pine flatwoods community were examined. These treatments were: (1) herbicide application with bimonthly inspection and re-application if necessary, (2) herbicide application with biannual inspection/re-application, (3) prescribed fire to reduce *L. microphyllum* biomass followed by biannual inspection and herbicide application, and (4) untreated controls. All fire and/or herbicide treatments killed standing *L. microphyllum*, and the prescribed fire reduced by about one-half the amount of subsequent herbicide, but not the time, required to kill regrowth. No treatment prevented *L. microphyllum* regrowth, and every treatment had at least one new frond at the end of the three-year study. Fire and/or herbicide treatments did not permanently decrease native species cover, richness, evenness, or diversity (Shannon's *H'*), and native species cover increased following biannual herbicide and fire/biannual herbicide treatments. Two-month inspection/retreatment intervals were not more effective than six-month intervals. *Lygodium microphyllum* can return to former amounts of biomass and cover within a few years of burning. Waiting too long to inspect and retreat negates the benefits of using fire to reduce *L. microphyllum* biomass.

Index terms: fire, herbicide, invasive plant, *Lygodium microphyllum,* Old World climbing fern

INTRODUCTION

Lygodium microphyllum (Cav.) R. Br., Old-World climbing fern, is an indeterminately twining fern found throughout much of the Old World tropics (Pemberton 1998), where it is frequently described as "weedy" (Tagawa and Iwatsuki 1979; Singh and Panigrahi 1984). It was first reported as a naturalized species in Florida (Martin County) in 1965 (Beckner 1968), and concern about the spread of *L. microphyllum* in central Florida was voiced as early as 1978 (Nauman and Austin 1978). This species has now become a recognized threat to native plant communities throughout southern Florida (Pemberton 1998; Pemberton and Ferriter 1998). Extent of *L. microphyllum* in southern Florida was calculated (aerial survey) to be 11,213 ha in 1993, 15,892 ha in 1997, 17,410 ha in 2001, and 48,878 ha in 2005, and estimated to be 74,090 ha in the entire southern Florida region in 2005 (Ferriter and Pernas 2006). The exponential nature of this increase can be seen by plotting the survey data collected by Ferriter and Pernas (2006) and in a more focused examination of spatial distribution of *L. microphyllum* over time in the Everglades region of southern Florida (Wu et al. 2006). The potential distribution of *L. microphyllum* in the Everglades (Volin et al. 2004) and more generally in North and South America has been examined as well (Goolsby 2004).

In its native Old World range, *L. microphyllum* only very infrequently covers more than small patches of ground (R. Pemberton, research entomologist, United States Department of Agriculture, pers. comm.), and does not dominate its plant community (Goolsby et al. 2003). In Florida, however, the rapid spread of the species has been compounded by the establishment of large nearly monospecific stands. The extensive indeterminate growth of single compound fronds of *L. microphyllum* can create dense accumulations of light-blocking biomass covering and killing herbaceous and shrub layers, and can even lead to the death of mature trees as the fern twines into the overstory canopy (Pemberton and Ferriter 1998). Plant communities in Florida infested by *L. microphyllum* include bald cypress (*Taxodium distichum* [L.] Rich.) swamps, pine flatwoods, wet prairies, saw grass (*Cladium majaicense* Crantz) marshes, mangrove stands, Everglades tree islands, and disturbed areas (Pemberton and Ferriter 1998).

While several herbicides are able to kill *L. microphyllum* (Stocker et al. 1997), the rapid spread of this species makes it unlikely that herbicide-only programs will be able to contain the plant, nor lead to its eventual control. A statewide management plan recommends biological control combined with herbicide treatments as the best strategy for long-term management and control (Pemberton et al. 2006). The biological control program is well underway (Goolsby et al. 2003), and the first biological control agent (*Austromusotima camptonozale* [Lepidoptera: Crambidae; Yen et al. 2004]), a frond-feeding musotimine moth, was released in 2005. It is possible that several different biological control agents will be necessary, and until a more diverse biological control program is implemented, herbicides will remain the most effective readily available management tool.

The importance of fire in the evolution of Florida's plant communities and the use of prescribed fire to manage habitats for native plant diversity (Wade et al. 2000) suggest that fire might offer an additional management tool to control *L. microphyllum*, except for three very important factors: (1) fire alone does not kill *L. microphyllum* (Maithani et al. 1986; Roberts 1996; Stocker et al. 1997), (2) *L. microphyllum* regrows very quickly after fire (Goolsby et al. 2003), and (3) fire may provide open sites for establishment of new populations (Langeland and Hutchinson 2006). Fire can, however, reduce both living and dead standing *L. microphyllum* biomass, possibly reducing the amount of herbicide required for subsequent treatment of regrowth and unburned plants, and make access to sites much easier for management personnel (Langeland and Hutchinson 2006). In small demonstration plots, spot fires have been used to burn *L. microphyllum* climbing into overstory trees. Herbicide (glyphosate) applications to regrowth three to four months after the fire were effective, with little regrowth seen (J. Hutchinson, graduate student, University of Florida, pers. comm.). While spot burning followed by herbicide may not be suitable for larger infestations, it may be an effective tool in nascent populations (Langeland and Hutchinson 2006).

Since fire is an important and frequently used tool for vegetation management (Wade et al. 2000), and since wildfires occur regardless of management plans, research is needed to learn more about the interaction of fire and herbicides and the effects of these management tools on invasive species like *L. microphyllum* and on the native plant communities. This study was conducted to assess the effects of herbicide, and a combination of fire and herbicide on control and regrowth of *L. microphyllum*, and the effects of those treatments on a pine flatwoods plant community, one of many plant communities in Florida that require frequent burning to maintain desired native plant diversity and habitat for threatened and endangered plants and animals (Langeland and Hutchinson 2006). Additional objectives included comparing two different frequencies of herbicide re-treatment (every two or six months) and determining time and herbicide requirements for the tested treatments.

METHODS

The study site is a wet flatwoods dominated by *Pinus elliottii* Engelm. (slash pine), located in Palm Beach County, Florida, on the south side of Indiantown Road approximately 1.6 km west of Interstate 95. A fire in 1995 killed many *Taxodium distichum* and *P. elliottii*. *Lygodium microphyllum* recovered very rapidly following the fire, and by 1997 covered much of the herbaceous and shrub layers and many of the standing trunks of dead trees. At the start of the study (December 1997), *L. microphyllum* was estimated to occupy approximately 73 ha of the 176 ha total property area. Since the property was scheduled to be developed into a Palm Beach County natural area and recreational facility, the research was conducted in parallel with a larger restoration effort.

On 3 December 1997, a 20-m x 40-m area was divided into 24 plots, each 2-m x 8-m, with 1-m strips between plots on their long axis and 2-m strips between plot ends. Three 0.25-m^2 square plot frames were randomly located in each plot, from which *L. microphyllum* biomass samples were collected and dried to constant weight in a forced air drying oven. Complete floristic lists, and cover estimates for each understory species, were recorded in five 20-cm x 50-cm sub-plots spaced at 1-m intervals centrally along the long axis of each plot. Estimated cover was reported as one of six unequal size classes (>0-5%, >5-25%, >25-50%, >50-75%, >75-95%, and >95-100%; Daubenmire 1959). Mean cover for each species was calculated from the total (30) of all sub-plots (5) in all replicates (6) of each of four treatments. Data collection was repeated in November 1998 and 1999.

Treatments consisted of: (1) initial use of herbicide to kill *L. microphyllum* and herbicide treatment of regrowth at two month intervals (termed bimonthly herbicide), (2) initial use of herbicide to kill *L. microphyllum* and herbicide treatment of regrowth at six month intervals (biannual herbicide), (3) initial use of fire to reduce *L. microphyllum* biomass followed by herbicide treatment at six month intervals (fire/biannual herbicide), and (4) untreated control plots. The final interval in biannual herbicide and fire/bin herbicide plots was four months instead of six. Each treatment was replicated in six plots in a completely randomized design. It is recognized that bimonthly application of herbicide is impractical for most resource management situations, but *L. microphyllum* had recovered quickly from some herbicide applications in demonstration plots, and it was desirable to know if even an impractical bimonthly frequency would successfully kill this species.

Fire was applied to fire/biannual herbicide plots on 14 January 1998. After initial ignition of biomass, the plot was allowed to burn without further assistance unless re-ignition was needed to continue the burn. *Lygodium microphyllum* has very thin pinnae, and fronds readily ignite and support rapid, intense burning. Fire was suppressed with shovels and water when it reached the plot borders. No heat effects, such as curled or scorched leaves, were observed on plants in neighboring unburned plots.

Triclopyr ester (Pathfinder™, 0.09 kg L^{-1} active ingredient) was used for all herbicide applications because it had been effective in killing *L. microphyllum* as a directed spray in unreplicated demonstration plots. All green parts of *L. microphyllum* were treated in a spray-to-wet application by backpack (initial treatments) or hand-held sprayer (retreatments). Initial herbicide was applied on 13 and 17 January 1998. Care was taken to minimize contact to non-target species and avoid drift to adjacent plots. No herbicide effects, such as browned or killed tissue, were observed on plants outside the treated plots.

At the scheduled intervals (two or six times per year), *L. microphyllum* regrowth in all plots (except untreated controls) was treated with herbicide. The time required for inspection and application, as well as amount of herbicide used, were recorded for each plot. Final assessment and treatment were conducted on 2 November 1999 – 22 months after initial treatments. On the following day, three 0.25-m^2 biomass samples were collected from all plots containing *L. microphyllum* for dry weight determination as before.

Data analysis and statistics

To analyze the effects of the treatments on the resident plant community, cover class mid-points for each plant species, by sub-plot, were entered into PC-ORD (McCune and Mefford 1999) for calculation of mean cover, species richness, evenness (Pielou 1969), and Shannon's Diversity Index (*H'*; Shannon 1948). Cover class values (1-6) were then used to calculate an end-point (beginning and ending years only) repeated measures ANOVA with treatment as the "between" factor and sampling year as the "within" factor, using Wilk's Lamda statistic and an all-years ANOVA of contrast variables to compare the second and third year data with pre-treatment data (SAS 1985). Fisher's Protected Least Significant Difference test was used to separate means where the ANOVA F statistic showed significance ($P<0.05$). Separate analyses were conducted on all species, native species, non-native species other than *L. microphyllum*, and *L. microphyllum* alone. Native species categorization followed Wunderlin and Hansen (2004).

To analyze the time and herbicide requirements for the three fire and/or herbicide treatments, one-way analysis of variance (ANOVA; SAS 1982) was performed separately on total time required to inspect and re-treat plots and on total amount of herbicide used.

RESULTS

Pre-treatment mean cover of *L. microphyllum* across all sub-plots (71.9%; SE=2.7) was not significantly different among treatments (P=0.94), and was 56.4% of the total vegetation (all species) cover of 127.5%. (SE=3.7). Mean cover of *L. microphyllum* in control plots was initially 79.8% (SE=2.2; Figure 1) and did not change significantly throughout the study (P=0.09). Cover of *L. microphyllum* in control plots was 62.6, 67.7, and 61.4% of total cover for all vegetation in these plots in 1997, 1998, and 1999, respectively. Pre-treatment mean dry weight of *L. microphyllum* for all sub-plots combined was 181.3 g m^{-2} (SE=15.3), and did not differ among treatments. Final dry weight of *L. microphyllum* was zero in biannual herbicide and fire/biannual herbicide plots, 4.5 g m^{-2} in bimonthly herbicide plots, and 98.8 g m^{-2} in control plots.

Effectiveness of treatments in controlling *L. microphyllum*

Ten months after treatments were initiated, mean cover of *L. microphyllum* in plots for all three fire and/or herbicide treatments had been reduced from 69.2% (average for all pre-treatment fire and/or herbicide plots) to 0.5% or less with no significant differences among the three treatments (Figure 1). After 22 months, mean *L. microphyllum* cover in fire and/or herbicide plots was 0.7% or less and all treatments were significantly lower than control plots. However, even with regular inspection and herbicide application, some *L. microphyllum* was present at the end of the two years in at least one plot of each treatment, although not always in a sampled area, and usually consisting of a single small frond.

Effects of treatments on non-native species other than *L. microphyllum*

Mean cover of non-native species other than *L. microphyllum* was 4.7% (SE=1.4) for all sub-plots combined in 1997 (pre-treatment), and was 3.5 (SE=1.7), 7.0 (SE=2.8), and 10.2% (SE=3.6) in control plots in 1997, 1998, and 1999, respectively (Figure 1). Cover for these species in treatment plots did not differ (P=0.15) from control plots during the course of the study. One non-native herb, *Urena lobata* L., increased with fire and/or herbicide treatments (Table 1).

Effects of treatments on all species combined

When native and non-native species cover were combined by growth form (Table 1), cover increased for grasses from the first to the final year of all three treatments, but decreased in control plots. Combined cover of herbaceous species increased in all treatments from beginning to end of the study, but with about twice the increase (114%) in fire/biannual herbicide plots, after a reduction in 1998, compared to other treatments (54%, 48%, and 58% in control, bimonthly, and biannual herbicide plots, respectively). Combined cover of ferns reflects the intentional removal of *L. microphyllum*. Combined shrub cover decreased under all treatments, but significantly more in fire/biannual herbicide plots. Changes in vine cover were not significant for either treatment or time.

Impacts to native plant community

Native species cover for all sub-plots combined averaged 51.0% (SE=3.6) at the beginning of the study, which was only 40.0% of the total cover (127.5%; SE=3.7) for all species. In 1998, native species cover was significantly lower in fire/biannual herbicide plots than in other treatments (Figure 1). By the end of the study, native species cover was significantly higher in biannual herbicide and fire/biannual herbicide plots than in bimonthly herbicide and control plots. Cover of several native species varied with time in control plots (Table 1).

Since there was only one non-native graminoid, *Sacciolepis indica* (L.) Chase, which was a very minor component, the cover of native graminoids was no different than for combined native and non-native graminoids (Table 1), with increases under all fire and/or herbicide treatments. The situation for herbaceous species was very

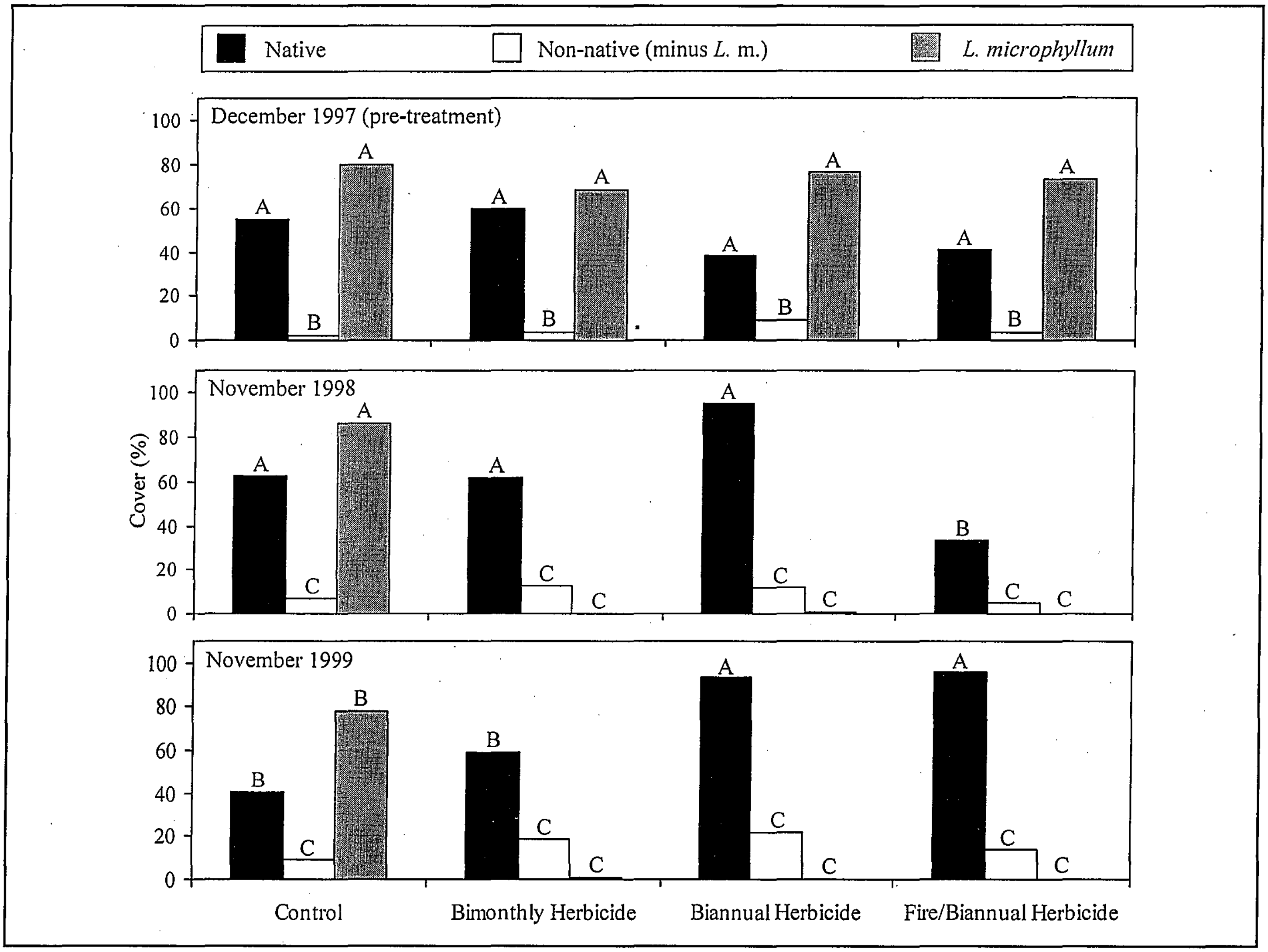

Figure 1. The effect of removing *Lygodium microphyllum* with fire and/or herbicide (triclopyr ester) on mean cover for native species, non-native species (*Lygodium microphyllum* removed), and *L. microphyllum* in a Florida pine flatwoods understory treated in 1997. Within each year, means sharing the same letter are not significantly different (P<0.05) using Fisher's Protected Least Significant Difference test.

different, with the fire and/or herbicide treatments having no effect on herb cover. Native ferns (*Blechnum serrulatum* Rich. and *Osmunda regalis* L. var. *spectabilis* [Willd.] A. Gray) decreased in control as well as fire and/or herbicide treatment plots during the study, with no significant effect of treatment. Native shrubs were unequally distributed throughout the treatments at the start of the study, with greater cover in control plots than in the other treatments. Change over time was not significant, however, nor was there a significant interaction between treatment and time. Treatment and time were not significant effects on native vine cover.

Species Richness

A total of 101 species was recorded during the study: 32 graminoids, 52 herbs, 3 ferns (including *L. microphyllum*), 9 shrubs, and 5 vines. Of these, nine were non-native species, including one graminoid (*Sacciolepis indica*), four herbs (*Cuphea carthagenensis* (Jacq.) J. F. Macbr., *Emilia fosbergii* Nicolson, *Phyllanthus urinaria* L., and *Urena lobata*), one fern (*Lygodium microphyllum*), and three shrubs (*Ludwigia peruviana* (L.) H. Hara, *Psidium cattleianum* Sabine, and *Schinus terebinthifolius* Raddi). Initial species richness (1997; Table 2) for all species combined varied nonsignificantly from a low of 4.8 (biannual herbicide) to a high of 5.4 (bimonthly herbicide). Species richness dropped in all treatment plots, with significant differences among the treatments, one year after treatments were initiated (reductions of 7.8, 27.8, 26.8, and 38.8%, for control, bimonthly, biannual, and fire/biannual herbicide plots, respectively), and recovered the following year to pre-treatment levels.

Native species richness also dropped during the second year (Table 2) and then returned to pre-treatment levels by the end of the study, but only for the fire/biannual herbicide treatment. Other treatments were not significantly different than control plots. For non-native species other than *L. microphyllum,* neither time nor treatments were significant effects.

Table 1. The effect of removing *Lygodium microphyllum* with fire and/or triclopyr ester herbicide on Florida pine flatwoods understory species cover, for life-form groups, and the twenty taxa with the largest summed cover for years and treatments combined. Data collected in December 1997, and November 1998 and 1999. Non-native species bolded. P values are for Wilks' Lambda statistic in the repeated measures ANOVA. The first P value (within each set of parentheses) is for treatment effects; the second is for time (sampling year to sampling year) effects. There were no non-native vines.

	Treatment											
	Control			Bimonthlyherbicide			Biannual herbicide			Fire/Biannual herbicide		
	1997	1998	1999	1997	1998	1999	1997	1998	1999	1997	1998	1999
	% cover											
Graminoids												
All species (P=<0.001/<0.0001)	35.9	40.3	24.8	35.7	51.8	47.4	21.0	79.7	71.0	20.7	31.3	78.3
SE=	6.1	6.4	6.1	5.0	6.0	7.1	3.6	8.7	6.6	3.3	7.0	6.9
Native spp. (P=0.001/<0.001)	35.9	40.3	24.8	35.7	51.8	47.3	21.0	79.7	70.9	20.7	31.3	78.3
SE=	6.1	6.4	6.1	5.0	6.0	7.1	3.6	8.7	6.6	3.3	7.0	6.9
Amphicarpum muhlenbergianum	0.0	0.5	4.8	0.5	0.0	18.5	0.0	0.0	18.8	0.1	0.0	9.6
Andropogon glomeratus var. *glaucopsis*	0.0	2.1	4.3	0.5	0.0	0.0	0.0	0.0	25.9	0.0	0.0	35.0
Andropogon virginicus	0.0	0.0	3.3	0.0	0.0	12.7	0.0	0.0	10.9	0.0	0.5	20.0
Andropogon sp.	0.0	2.2	1.0	0.0	10.6	4.7	0.5	18.9	1.3	0.0	13.6	2.3
Dichanthelium spp.	6.8	14.3	2.4	10.6	11.0	1.5	6.0	8.7	5.8	5.3	3.6	2.8
Dichanthelium strigosum	0.0	0.0	0.0	0.1	0.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0
Eragrostis elliottii	0.0	0.0	2.3	0.0	0.0	2.1	0.0	1.3	4.7	0.0	0.0	0.0
Fuirena breviseta	7.4	0.2	0.7	2.1	0.1	0.0	1.8	0.0	0.1	4.9	0.0	0.1
Panicum spp.	0.0	5.5	0.0	0.0	9.2	0.0	0.1	16.5	0.0	0.1	6.7	0.0
Rhynchospora divergens	6.8	0.0	0.0	0.8	0.0	0.8	2.5	0.0	0.0	0.1	0.0	1.8
Rhyncospora spp.	0.0	5.4	1.3	0.6	0.6	0.5	0.5	0.6	2.7	0.1	0.5	0.5
Scleria spp.	6.8	8.8	0.0	6.7	14.1	1.7	4.3	25.0	0.0	8.3	3.3	1.0
Herbs												
All Species (P=0.03/0.006)	13.2	19.7	20.3	19.7	21.7	29.1	25.9	27.4	41.0	15.0	7.1	32.1
SE=	3.6	5.0	3.9	4.3	4.7	6.0	5.1	5.4	7.5	3.5	2.6	5.6
Native spp. (P=0.42/0.54)	12.5	17.9	12.7	19.5	10.4	11.3	22.2	15.3	18.8	14.5	2.2	17.9
SE=	3.5	5.0	2.7	4.3	2.7	2.4	4.6	4.8	4.4	3.5	0.9	3.4
Centella asiatica	0.7	0.4	0.4	3.9	0.0	0.1	2.2	0.0	0.7	5.3	0.1	0.7
Eupatorium capillifolium	3.8	0.3	0.1	2.7	0.0	0.7	2.9	0.0	0.1	0.3	0.1	1.1

continued

Table 1. Continued

	Treatment											
	Control			Bimonthlyherbicide			Biannual herbicide			Fire/Biannual herbicide		
	1997	1998	1999	1997	1998	1999	1997	1998	1999	1997	1998	1999
	% cover											
Herbs *(continued)*												
Lachnanthes caroliana	0.1	1.3	1.1	1.5	5.1	4.8	0.2	5.3	5.6	0.1	0.0	1.1
Ludwigia microcarpa	1.7	3.0	0.3	0.4	0.6	0.8	0.8	5.3	3.9	0.8	0.6	1.4
Lycopodiella appressa	0.0	0.0	0.0	0.0	0.0	0.0	1.3	2.3	0.5	10.3	0.0	0.0
Urena lobata	0.7	1.8	7.6	0.2	11.3	17.8	3.8	12.1	21.9	0.5	4.4	14.0
Ferns												
All Species (P=<0.0001/<0.0001)	81.8	86.8	79.0	71.6	0.0	0.7	71.4	0.5	0.5	76.1	0.1	0.1
SE=	5.3	3.9	5.5	5.1	0.0	0.5	7.4	0.5	0.5	5.3	0.1	0.1
Native spp. (P=0.90/0.0001)	1.9	0.5	0.7	3.7	0.0	0.0	4.9	0.0	0.5	2.9	0.0	0.1
SE=	1.3	0.5	0.5	1.8	0.0	0.0	2.1	0.0	0.5	1.5	0.0	0.1
Blechnum serrulatum	1.9	0.5	0.7	3.7	0.0	0.0	4.9	0.0	0.5	2.9	0.0	0.0
Shrubs												
All Species (P=0.003/0.03)	6.6	6.9	3.8	3.8	1.0	1.3	5.6	0.1	3.4	4.5	0.2	0.0
SE=	2.7	2.8	1.5	2.3	0.7	1.3	3.3	0.1	2.9	2.4	0.1	0.0
Native spp. (P=0.04/0.53)	3.8	1.7	1.8	0.8	0.0	0.0	0.5	0.1	3.4	1.8	0.0	0.0
SE=	2.3	1.1	0.8	0.5	0.0	0.0	0.5	0.1	2.9	1.3	0.0	0.0
Psidium cattleianum	2.3	3.1	1.9	3.1	0.0	1.3	4.6	0.0	0.0	0.5	0.1	0.0
Vines												
(P=0.14/0.48)	0.6	2.1	1.0	0.2	0.0	0.5	0.0	0.0	0.0	1.1	0.0	0.0
SE=	0.6	2.1	0.7	0.1	0.0	0.5	0.0	0.0	0.0	0.7	0.0	0.0

Table 2. The effect of removing *Lygodium microphyllum* with fire and/or triclopyr ester herbicide on species richness for a Florida pine flatwoods understory treated in 1997. Species richness is the mean number of species found in 30 sub-plots for each of four treatments on each sampling date. Data were collected in December 1997, and November 1998 and 1999. Within each column for which P<0.05, means that share the same letter are not significantly different (α<0.05) using Fisher's Protected Least Significant Difference test. The contrast variables ANOVA compared the second and third year with the first (pre-treatment) year; the asterisk indicates significant (P<0.05) difference compared to 1997.

		Species richness								
		All species			Native species			Non-native species minus *L. microphyllum*		
Treatment		1997	1998	1999	1997	1998	1999	1997	1998	1999
Control	Mean	5.1	4.7 A	4.5	3.8	3.3 A	3.1	0.3	0.4	0.5
	SE	0.5	0.4	0.3	0.5	0.4	0.3	0.1	0.1	0.1
Bimonthly herbicide	Mean	5.4	3.9 B	4.5	4.3	3.5 A	4	0.2	0.4	0.4
	SE	0.4	0.3	0.4	0.4	0.3	0.4	0.1	0.1	0.1
Biannual herbicide	Mean	4.8	3.8 B	4.7	3.8	3.4 A	3.9	0.2	0.4	0.8
	SE	0.4	0.3	0.3	0.4	0.3	0.3	0.1	0.1	0.1
Fire/Biannual herbicide	Mean	4.9	3.0 C	4.6	3.6	2.2 B	4.1	0.3	0.4	0.5
	SE	0.4	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0.1
Single year ANOVA P =		0.77	0.004	0.96	0.70	0.02	0.16	0.59	0.99	0.06
Contrast variables			*			*				

Neither time (P=0.41) nor treatment (P=0.07) were significant effects on native species evenness. Mean evenness combined across years was 0.8 for each treatment (SE=0.03 for bimonthly and biannual herbicide, and 0.04 for fire/biannual herbicide and control treatments). Treatment (P=0.82) and time (P=0.21) did not have significant effects on Shannon's *H'* for native species. Mean *H'* combined across years was 1.2 (SE=0.1) for bimonthly herbicide plots, 1.1 (SE=0.1) for biannual herbicide, and 1.0 (SE=0.1) for both fire/biannual herbicide and control treatments.

Time and herbicide requirements

The equivalent of 26 and 23 hours ha^{-1} (all comparisons are made on a calculated per ha basis) were required for initial herbicide treatment in the bimonthly and biannual herbicide treatments, respectively (Figure 2). No meaningful "application" time could be calculated for the fire portion of the fire/biannual herbicide treatment because more care and personnel were required to keep the fire contained than would be the case for an actual management burn. After relatively high time requirements for initial herbicide treatments in the bimonthly and biannual herbicide plots, and the initial herbicide application in the fire/biannual herbicide plots (30 hours ha^{-1}), time required for subsequent inspection and retreatment was much lower (Figure 2). After 12 months, little *L. microphyllum* was present in these plots, and inspection time was similar for all plots. Total time required for inspection and retreatment of the bimonthly herbicide plots was significantly greater than for the biannual herbicide treatment and the fire/biannual herbicide treatment plots.

The total amount of herbicide used for the fire/biannual herbicide treatment was about half that for the bimonthly and biannual herbicide regimes (Figure 3). This was almost completely due to differences in the initial applications.

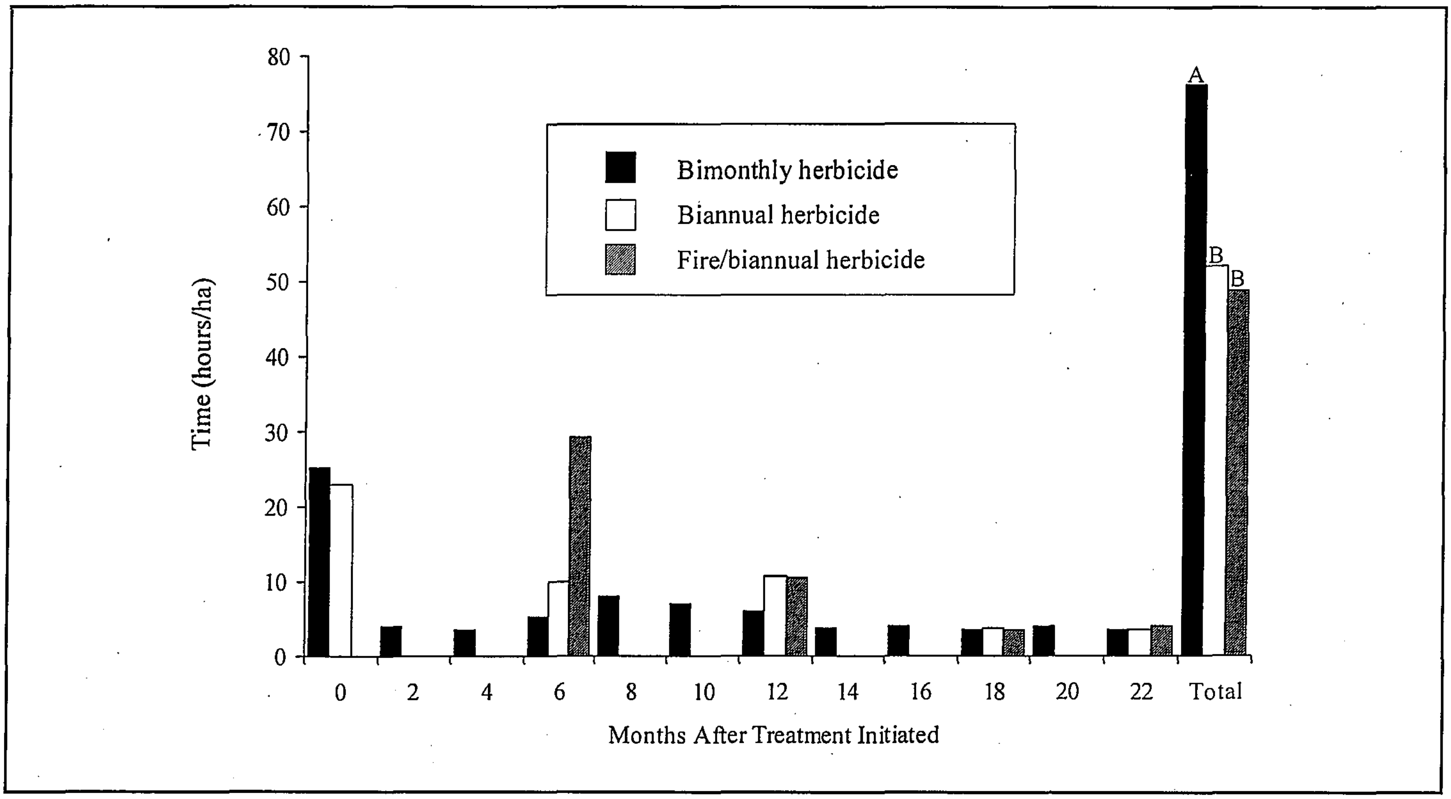

Figure 2. Time required to inspect and apply herbicide (triclopyr ester) to *Lygodium microphyllum* regrowth in Palm Beach County, Florida. Means in the Total column that do not share the same letter are significantly different (P<0.05) using Fisher's Protected Least Significant Difference test.

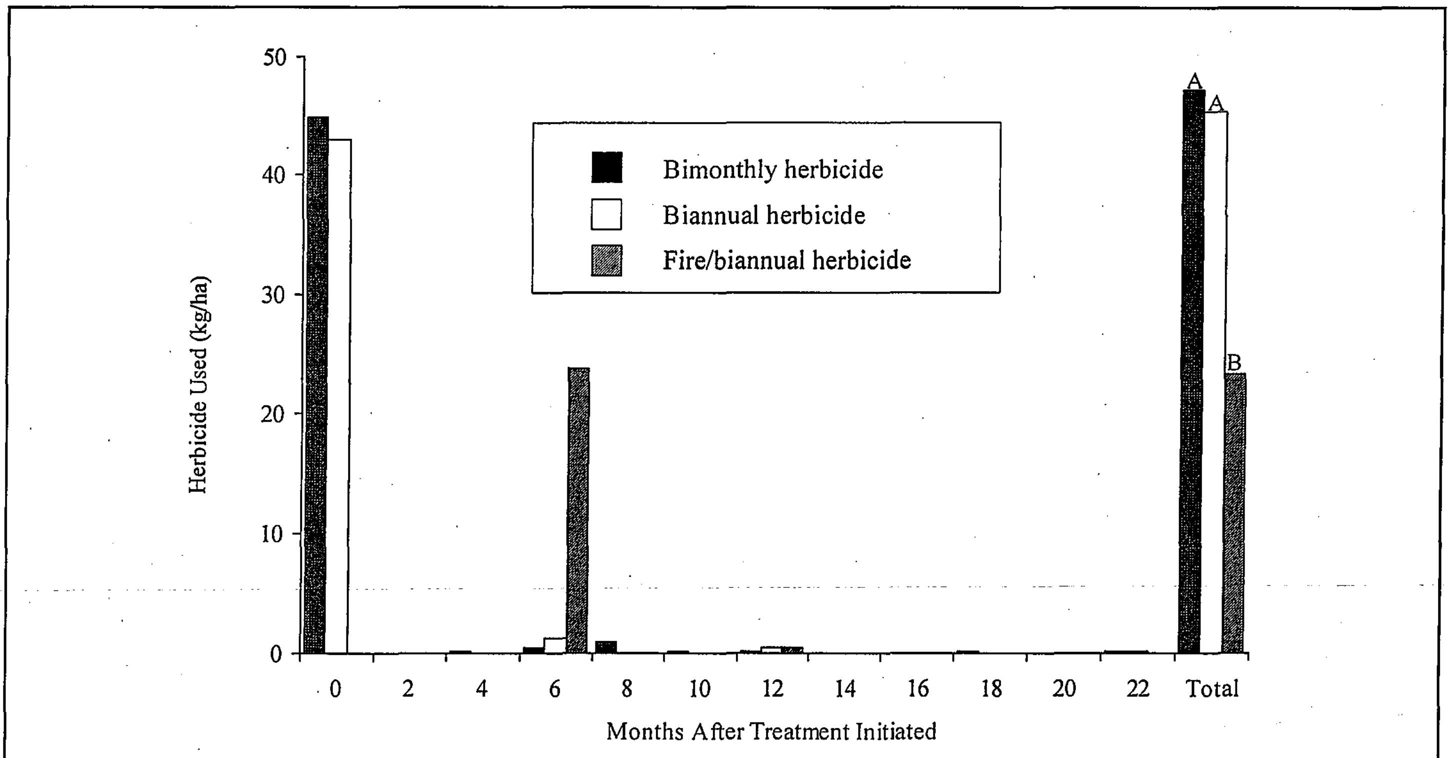

Figure 3. Amount of herbicide (triclopyr ester) required to treat *Lygodium microphyllum* growth and regrowth in Palm Beach County, Florida. Means in the Total column that do not share the same letter are significantly different (P<0.05) using Fisher's Protected Least Significant Difference test.

DISCUSSION

Both fire followed by herbicide, and herbicide-alone treatments were effective in removing almost all *L. microphyllum* from the pine flatwoods community – and without lasting negative effects on the native species cover, richness, evenness, nor diversity. The use of fire, however, resulted in some very different patterns than the herbicide-alone treatments. Regrowth of *L. microphyllum* in fire/biannual herbicide plots was vigorous following the prescribed fire treatment, and the first herbicide application visit (six months after the prescribed fire) alone required the equivalent of 30 hours ha^{-1} of inspection and treatment time. The prescribed fire did reduce standing biomass of *L. microphyllum*, but the subsequent new growth of many other species made finding regrowth of *L. microphyllum* in the understory very difficult.

Regrowth of *L. microphyllum* in burned plots was much less synchronous than in herbicide-only plots. Following initial herbicide application in herbicide-only plots, almost all regrowth emerged within two months. Regrowth in burned plots started within two months, but new growth emerged in several bursts over the next year. Herbicide application may kill *L. microphyllum* fronds back to healthy rhizomes more uniformly than fire, resulting in less sporadic re-emergence. The asynchronous regrowth in fire/biannual herbicide plots, however, did not negate the approximately 50% reduction in herbicide used compared to the herbicide-only treatments, and the total time required to inspect and retreat fire/biannual herbicide plots was the same as biannual herbicide plots without fire.

Under typical conditions, a crew of five can burn about 120 ha of *L. microphyllum*-infested pinelands in a single 10-hour day (S. Smith, research scientist, South Florida Water Management District, pers. comm.), which equates to approximately 0.08 hours ha^{-1} for five people, or about 0.4 hours ha^{-1} $person^{-1}$. Because the per ha time for burning areas larger than the small study plots would be expected to be minimal compared to time requirements for ground-based herbicide applications, no estimated value for time required to burn was included in Figure 2. Prescribed burn logistical difficulties and costs would be an important consideration in an actual management program.

In the year following the prescribed burn, native species cover was significantly lower in fire/biannual herbicide plots than in other treatments, probably due to the less selective effects of a fire versus spot herbicide treatment than to any negative response by native species to fire in this fire-maintained plant community. It is possible that the timing (winter) of the burn could have affected native plant response. A comprehensive review of fire in southern Florida ecosystems (Wade et al.) points out that it is frequently assumed that pre-European influence fires in Florida were predominantly wet season (summer) fires. While lightning in Florida is much more common during the wet summer months, and lightning-initiated fires peak at this time (Snyder et al. 1990), little is known about the frequency of dry-season fires set by Native Americans (Wade et al. 2000). Indirect evidence for anthropogenic dry-season fire (Myers and Peroni 1983; Snyder 1991; Robbins and Myers 1992; Kjellmark 1995, 1996) does suggest that Florida's fire-dependent plant communities, such as the pine flatwoods in this study, were subject to fire at any time of year for many centuries, and thus the winter fire conducted for this study may not have presented an atypical disturbance.

The more important factor related to this prescribed burn was probably its slow rate of travel through the plot and the associated higher temperatures of the slow-moving fire. Larger-scale management burns would have moved much faster through a pine flatwoods because of air movement generated by a larger fire and because the fire prescription would have called for appropriate wind strength and direction to manage the dispersal of smoke. Very low wind speed was a required condition for the prescribed burns in this study to reduce the chances of fire damaging adjacent non-burn plots.

Cover of non-native species other than *L. microphyllum* increased during the study, but the increase also occurred in control plots and was not related to fire and/or herbicide treatment effects. It is not known why native species cover was lower at the end of the study in bimonthly herbicide plots than the biannual herbicide and fire/biannual herbicide treatments. Even though care was taken to avoid damaging plants, it is possible that the more frequent traffic in the bimonthly herbicide plots resulted in the lower native vegetation cover. Bimonthly herbicide plots used the same about of herbicide as the biannual herbicide plots, so the effects were not due to differences in amount of herbicide applied.

The bimonthly herbicide schedule obviously required more frequent visits, contributing to greater total time, although each visit was of very short duration. Since the final biomass of *L. microphyllum* was the same in both bimonthly and biannually inspected/treated plots, there was no benefit from the more frequent visits. It is likely that a longer interval than biannually would be more cost effective, although observations suggest that nearly complete regeneration of *L. microphyllum* biomass following fire or partially effective herbicide application can occur within two years.

It is important to note that even after inspection and retreatment for 22 months, some, albeit small, amounts of *L. microphyllum* remained in the treatment plots. This was new growth connected to existing rhizomes, not new plants. This suggests that periodic inspection and retreatment may be necessary for quite some time after operational management programs begin. While the regrowth in this study could be shown to come from existing rhizomes, the possibility of establishment of new plants is always present. It is not known how far *L. microphyllum* spores travel, and under what conditions they are able to germinate, but they are very small and can be expected to be wind-borne for considerable distances. *Lygodium microphyllum* is able to reproduce by intragametophytic selfing, which means that only one gametophyte, from one spore, is required, an obvious advantage in long-distance dispersal (Lott et al. 2003). Regional approaches to *L. microphyllum* management will no doubt be necessary to reduce the possibility of reinfestation of previously cleared areas.

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LITERATURE CITED

Beckner, J. 1968. *Lygodium microphyllum*, another fern escaped in Florida. American Fern Journal 58:93-94.

Daubenmire, R. 1959. A canopy-coverage method of vegetational analysis. Northwest Science 33:43-64.

Ferriter, A., and T. Pernas. 2006. An explosion in slow motion: tracking the spread of *Lygodium microphyllum* in Florida. Wildland Weeds 9:7-9.

Goolsby, J.A. 2004. Potential distribution of the invasive Old World climbing fern, *Lygodium microphyllum* in North and South America. Natural Areas Journal 24:351-353.

Goolsby, J.A., A.D. Wright, and R.W. Pemberton. 2003. Exploratory surveys in Australia and Asia for natural enemies of Old World Climbing Fern, *Lygodium microphyllum*; Lygodiaceae. Biological Control 28:33-46.

Kjellmark, E. 1995. The effects of late Holocene climate change and human disturbance on the vegetation and fire history of Andros Island, Bahamas. Ph.D. diss., Duke University, Durham, N.C.

Kjellmark, E. 1996. Late Holocene climate change and human disturbance on Andros Island, Bahamas. Journal of Paleolimnology 15:133-145.

Langeland, K., and J. Hutchinson. 2006. Fire. Pp. 44-46 *in* J. Hutchinson, A. Ferriter, K. Serbesoff-King, K. Langeland, and L. Rodgers, eds., Old World climbing fern (*Lygodium microphyllum*) management plan for Florida. Florida Exotic Pest Plant Council, Lygodium Task Force, 2nd ed. Available online <http://www.fleppc.org/publications.htm>

Lott, M.S, J.C. Volin, R.W. Pemberton, and D.E. Austin. 2003. The reproductive biology of the invasive ferns *Lygodium microphyllum* and *L. japonicum* (Schizaeaceae): implications for invasive potential. American Journal of Botany 90:1144-1152.

Maithani, G.P., V.K. Bahuguna, and P. Lal. 1986. Effect of forest fires on the ground vegetation of the moist deciduous sal forest. India Forester 112:646-667.

McCune, B., and M.J. Mefford. 1999. PC-ORD. Multivariate Analysis of Ecological Data, Version 4. MjM Software Design, Gleneden Beach, Ore.

Myers, R L., and P.A. Peroni. 1983. Approaches to determining aboriginal fire and its impact on vegetation: a commentary. Bulletin of the Ecological Society of America 64:217-218.

Nauman, C.E., and D.F. Austin. 1978. Spread of the exotic fern *Lygodium microphyllum* in Florida. American Fern Journal 68:65-66.

Pemberton, R.W. 1998. The potential of biological control to manage Old World climbing fern (*Lygodium microphyllum*), an invasive weed in Florida. American Fern Journal 88:176-182.

Pemberton, R.W., and A.P. Ferriter. 1998. Old World climbing fern (*Lygodium microphyllum*), a dangerous invasive weed in Florida. American Fern Journal 88:165-175.

Pemberton, R., J. Goolsby, and T. Wright. 2006. Biological control. Pp. 26-33 *in* J. Hutchinson, A. Ferriter, K. Serbesoff-King, K. Langeland, and L. Rodgers, eds., Old World climbing fern (*Lygodium microphyllum*) management plan for Florida. Florida Exotic Pest Plant Council, Lygodium Task Force, 2nd ed. Available online <http://www.fleppc.org/publications.htm>.

Pielou, E.C. 1969. An Introduction to Mathematical Ecology. J. Wiley, New York.

Roberts, R.E. 1996. Climbing fern wreaks wetland havoc. Florida Department of Environmental Protection Resource Management Notes 8:13.

Robbins, L.E., and R.L. Myers. 1992. Seasonal effects of prescribed burning in Florida: a review. Miscellaneous Publication No. 8, Tall Timbers Research Station, Tallahassee, Fla.

SAS Institute. 1982. SAS® User's Guide. SAS, Cary, N.C.

SAS Institute. 1985. SAS® User's Guide: Statistics, Version 5 Edition. SAS, Cary, N.C.

Shannon, C.E. 1948. A mathematical theory of communication. The Bell System Technical Journal 27:379-423.

Singh, S., and G. Panigrahi. 1984. Systematics of genus *Lygodium* Sw. (Lygodiaceae) in India. Proceedings of the Indian Academy of Science 93:119-133.

Snyder, J.R. 1991. Fire regimes in subtropical Florida. Proceedings. Tall Timbers Fire Ecology Conference 17:303-319.

Snyder, J.R., A. Herndon, and W.B. Robertson. 1990. South Florida Rockland. Pp. 230-277 *in* R.L. Myers, and J.J. Ewel, eds., Ecosystems of Florida, University of Central Florida Press, Orlando.

Stocker, R.K., A. Ferriter, D. Thayer, M. Rock, S. Smith, and G. Jubinsky. 1997. Old World climbing fern hitting south Florida below the belt. Wildland Weeds 1:6-10.

Tagawa, M., and K. Iwatsuki. 1979. Flora of Thailand. Thailand Institute of Scientific and Technological Research, Bangkok, Thailand.

Volin, J.C., M.S. Lott, J.D. Muss, and D. Owen. 2004. Predicting rapid invasion of the Florida Everglades by Old World Climbing Fern (*Lygodium microphyllum*). Diversity and

Distributions 10:439-446.

Wade, D.D., B.L. Brock, P.H. Brose, J.B. Grace, G.A. Hoch, and W.A. Patterson, III. 2000. Chapter 4: Fire in eastern ecosystems. Pp. 53-96 *in* J.K. Brown, and J.K. Smith, eds., Wildland fire in ecosystems, effects of fire on flora. General Technical Report RMRS-GTR-42-Volume 2, Rocky Mountain Research Station, Ft. Collins, Colo.

Wu, Y., K. Rutchey, N. Wang, and J. Godin. 2006. The spatial pattern and dispersion of *Lygodium microphyllum* in the Everglades wetland ecosystem. Biological Invasions 8:1483-1493.

Wunderlin, R. P. and B. F. Hansen. 2004. Atlas of Florida Vascular Plants <http://www.plantatlas.usf.edu/>. [S. M. Landry and K. N. Campbell (application development), Florida Center for Community Design and Research.] Institute for Systematic Botany, University of South Florida, Tampa.

Yen, S-H., M.A. Solis, and J.A. Goolsby. 2004. *Austromusotima*, a new Musotimine genus (Lepidoptera: Crambidae) feeding on Old World climbing fern, *Lygodium microphyllum* (Schizaeaceae). Annals of the Entomological Society of America 97:397-410.