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The effects of treatment and management history on the control of Old World climbing fern (*Lygodium microphyllum*), Brazilian pepper (*Schinus terebinthifolia*), and punktree (*Melaleuca quinquenervia*)

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Abstract

To successfully reduce overall invasive plant cover over time, an effective treatment plan must be established such that mortality exceeds new colonization and resprouting growth rates. However, few evaluations of the effects of long-term, consistent treatment at different intervals exist. We report the effects of treatment intensity on Old World climbing fern [*Lygodium microphyllum* (Cav.) R. Br.], Brazilian pepper (*Schinus terebinthifolia* Raddi), and punktree [*Melaleuca quinquenervia* (Cav.) S. F. Blake] as part of a large restoration project that has been underway for 6 yr in Telegraph Swamp at Babcock Ranch Preserve, a 27,520-hectare (68,000-acre) conservation area in Florida, USA. We found that at the end of the 6-yr period, for all three species, average live cover did not exceed 5% across all transects. In addition, dead foliar cover was higher than live cover for all three invasive plants, indicating progress toward restoration goals. We also found that percent live cover of *L. microphyllum* was significantly reduced only after four or more treatments were applied during the 6-yr period, as opposed to when three or fewer treatments were applied. Reductions in percent cover of live foliage were apparent only when the treatments were applied more often than biennially, as opposed to less often than biennially. Additionally, we found higher *L. microphyllum* cover in clear-cut and replanted cypress stands than in natural stands. Based on these findings, we conclude that treatments applied four or more times, or more often than biennially, were more effective at significantly reducing advanced invasions of *L. microphyllum*, *S. terebinthifolia*, and *M. quinquenervia*, especially where previous management activities or their effects may have increased the cover of invasive plants.

Introduction

Though monitoring and treating invasive plant species is an essential task for resource and land managers worldwide (Mack et al. 2000), empirical data on the effectiveness of long-term treatment regimens are lacking from most invasive plant control projects (Kettenring and Adams 2011). When attempting to control invasive plants, understanding the treatment regimen required to achieve mortality and prevent regrowth is key to achieving overall reductions in invasive plant cover. Having this information is especially critical in Florida, as this region has one of the most acute invasive species problems both in the United States and around the world (Corn et al. 2002; U.S. Congress 1993).

Three invasive species are of great concern in Florida: Old World climbing fern [*Lygodium microphyllum* (Cav.) R. Br.], Brazilian pepper (*Schinus terebinthifolia* Raddi), and punktree [*Melaleuca quinquenervia* (Cav.) S. F. Blake]. *Lygodium microphyllum* is an invasive twining fern found throughout the Old World tropics, including Africa, India, Sri Lanka, China, Australia, and many countries of the South Pacific (Pemberton and Ferriter 1998; Singh and Panigrahi 1984). This species is classified as a noxious weed by the U.S. Department of Agriculture (USDA-NRCS 2012) and is a Category 1 invasive plant in Florida (FISC 2019). Category 1 invasive exotic plants are defined as those that alter native plant communities by changing community structure and function or by displacing native species. *Lygodium microphyllum* is a high-priority species for management, as it shades canopy trees, envelops herbaceous marshes, entangles wildlife, and alters disturbance regimes by carrying fire into nonpyrogenic communities (Roberts 1996; Wu et al. 2006). *Schinus terebinthifolia* is an invasive, evergreen, shrub-like tree native to South America that was introduced to Florida in the

Management Implications

Our study demonstrates that to significantly reduce *Lygodium microphyllum* (Old World climbing fern) cover, treatments must be applied consistently until managers transition from reducing the overall cover of a plant to a management phase where the target species is maintained at low levels, typically < 5% cover of the management area. In addition, our results suggest that conducting only one to three treatments over 6 yr does little to bring the coverage of *L. microphyllum* to maintenance levels (i.e., <5% cover of the target species). We recommend that managers with limited resources develop a plan to work systematically through infestations of rapidly growing vines, only progressing from one unit to the next when the maintenance phase of treatment is reached and can be sustained. Based on these results, practitioners should be prepared and able to conduct a minimum of biennial retreatments for multiple years at infestation locations, regardless of the infestation size or severity, before committing resources to a treatment program. Our results support a using a "hold-the-line strategy" when attempting to reduce *L. microphyllum* cover: managers do not progress the treatment "line" and treat additional areas until the prior unit has been reduced to management levels of invasive cover. Though we determined an effective treatment regimen to be four or more treatments applied over a 6-yr period for *L. microphyllum*, these results may be less applicable to other invasive species with different life histories. However, these results do offer a rare evaluation of various treatment plans against three of the world's worst weeds in an environment where treatment is often challenging due to prolific reproduction and year-round growth in a subtropical environment. The results of this study can aid managers planning treatment projects by informing decision making on treatment intervals, number of treatments, and how to prioritize management units when the overall treatment area is large.

mid-1800s as an ornamental plant. This species is considered a Category 1 invasive plant in the state of Florida (FISC 2019). Management of this species is critical, as *S. terebinthifolia* forms monocultures with dense canopies that shade out nearly all other plant species and alter fire regimes in pyrogenic communities by retaining moisture in leaf litter and reducing fine fuels in the understory (Gordon 1998; Wade et al. 1980). *Melaleuca quinquenervia* is an invasive tree species native to the South Pacific, considered a noxious weed by the U.S. Department of Agriculture (USDA-NRCS 2012) and is a Category 1 invasive plant in Florida (FISC 2019). This species is of management concern, as it shades out other species, reducing both plant and animal diversity (Serbesoff-King 2003). Despite the ecological and economic impacts of these three invasive species, and the frequency of management actions to reduce them (FEPPC 2006; Serbesoff-King 2003; Stevens and Beckage 2009), few, if any, empirical assessments of the effects of large-scale, long-term, high-intensity treatments exist.

Our study investigated the effectiveness of various treatment regimens on the control of *L. microphyllum*, *M. quinquenervia*, and *S. terebinthifolia*, with the goal of providing managers with recommendations that can improve current treatment programs for these and other species. Due to small sample sizes, we were unable to conduct multivariate analyses for *M. quinquenervia* and *S. terebinthifolia* and therefore only assess whether significant reductions of live cover were made with treatment. However, we were able to assess the number and timing of treatment applications required to significantly reduce *L. microphyllum* cover. Further, we assessed how previous management actions and habitat might contribute to the effectiveness of different treatment regimen for *L. microphyllum*.

Materials and Methods

Study Site

Babcock Ranch Preserve (BRP) encompasses approximately 27,520 hectares (68,000 acres) of conservation land located in Charlotte County, in southwest Florida (26.854625°N, 81.659186°W). BRP was privately owned up until 2006, when it was purchased by the State of Florida as conservation land. While under private ownership the property was primarily used for timber production and cattle ranching. Currently, the property is managed by the Florida Forest Service in cooperation with the Florida Fish and Wildlife Commission. One of the primary goals of current management at the site is to restore and maintain healthy native ecosystems (FFS 2016). The restoration of BRP likely represents one of the most concerted efforts to restore cypress swamps within Florida (FFS 2016).

Due to the potential negative impacts of invasive species spread, the Florida Fish and Wildlife Conservation Commission and the Florida Forest Service have been intensively treating all invasive plant species in BRP since 2012 (FFS 2016; L King, personal communication). One area of emphasis is Telegraph Swamp, an approximately 3,237-hectare (8,000-acre) swamp in the western half of BRP. Two natural communities comprise Telegraph Swamp: Strand Swamp and Dome Swamp (FFS 2016; FNAI 2010). Strand Swamp is generally shallow, elongated, and found along depressions or troughs within a limestone plain. Strand swamps are dominated by stands of bald cypress [*Taxodium distichum* (L.) Rich.] with an understory of tropical and temperate woody species. Dome swamps are typically small, round, and located in acidic sands or marl, which in turn covers a limestone or clay lens. Peat is the typical soil covering in dome swamps and is often thicker at the center of the swamp than at the edges. Pond cypress (*Taxodium ascendens* Brogn.) is the dominant species. Both swamp communities have a mounded profile, as younger, smaller trees are more common along the edges and taller trees are found in the deeper centers of the swamps (FNAI 2010). Telegraph Swamp plays an important role in the hydrology of the landscape and much of the surface runoff in the area flows through the swamp, ultimately discharging into the Caloosahatchee River (FFS 2016). Water levels in Telegraph Swamp begin to rise in June as a result of rain and are at their lowest in the winter and spring (FFS 2016). Telegraph Swamp contains dense infestations of *L. microphyllum* with *S. terebinthifolia* and *M. quinquenervia* present along the transitional area to uplands.

Field Methods

To assess the effectiveness of treatment on invasive species at BRP, we estimated the extent of living and dead fern across Telegraph Swamp. Surveys were conducted in late January and late March of 2020. We employed a space-for-time experimental design to retroactively examine the effects of treatment on invasive cover, because a monitoring program was not initiated at the start of the project. We stratified transects across treatment groups (i.e., one, two, three, four, or five treatments) and then randomly selected 20 transects from each group to survey. We abandoned transects that were inaccessible due to deep water or impassible roads or were otherwise deemed unsafe. In total, 83 (40-m)

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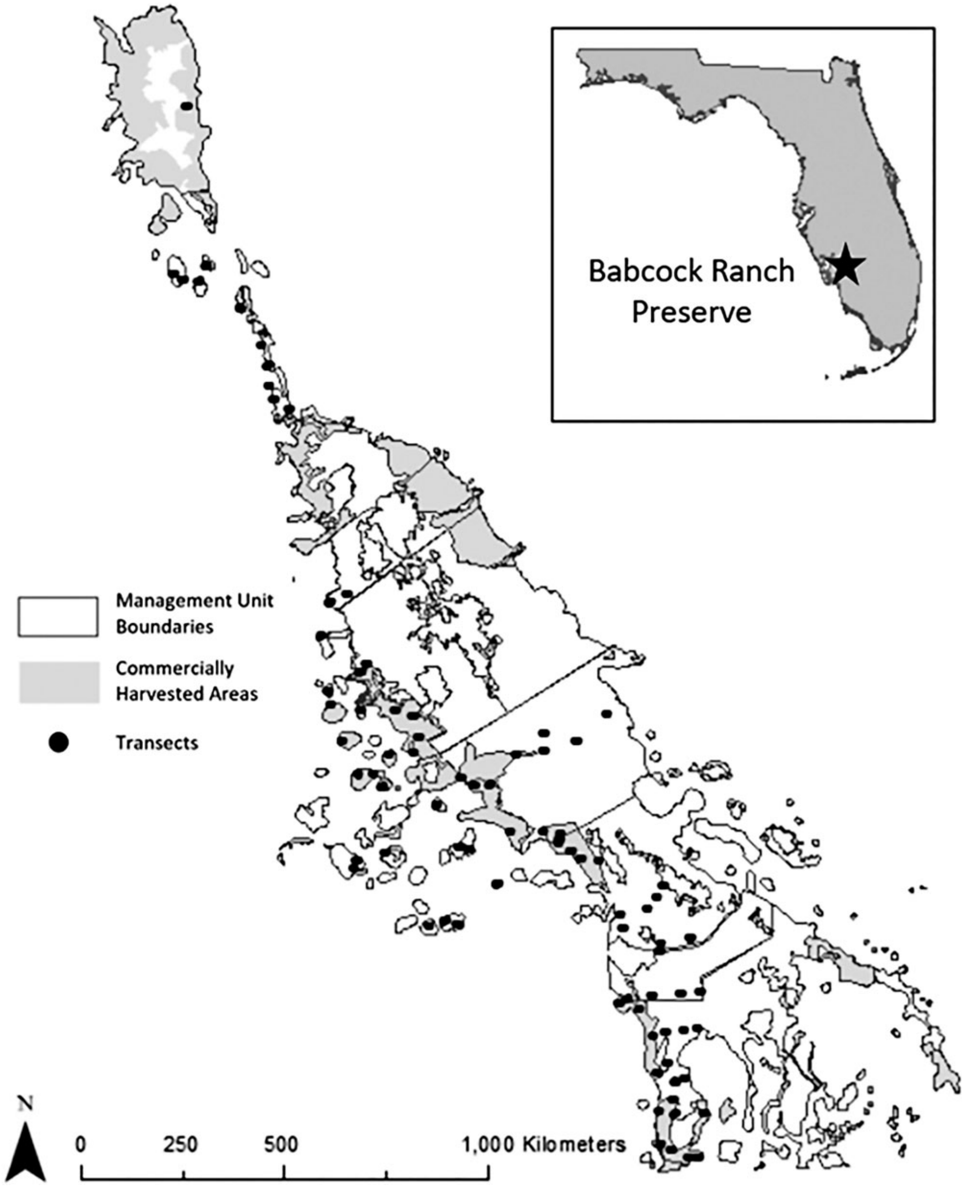

Figure 1. Babcock Ranch Preserve management unit boundaries. Areas that were clear-cut and replanted. All other areas were classified as natural stands. Transects are shown as black dots. The inset image shows the preserve's location in Florida, USA.

transects were surveyed throughout 11 of the 13 management units that comprise Telegraph Swamp (Figure 1).

Of these transects, 24 received one treatment, 25 received two treatments, 11 received three treatments, 18 received four treatments, and 5 received five treatments. Treatments of invasive species at BRP consist of ground crews systematically traversing the site while applying herbicide mix via foliar application using backpack sprayers. Crews aim to traverse the affected area in its entirety and kill 95% of the plants present. For *L. microphyllum*, a foliar application of 4% v/v glyphosate and 1% v/v nonionic surfactant via backpack sprayer was used, with a poodle cut where required. Adult *M. quinquenervia* was treated using a girdle/spray method with 15% v/v imazapyr with hand spray bottles. For adult *S. terebinthifolia*, a basal bark application of 20% v/v triclopyr 4 in 80% v/v basal oil was applied via backpack sprayer. When adult *S. terebinthifolia* occurred in areas with standing water, a cut-stump treatment of 20% v/v triclopyr 3A was used instead. However, most treatments for adult *S. terebinthifolia* were conducted via basal bark application. When *S. terebinthifolia* and *M. quinquenervia* seedlings and saplings were treated, a foliar application of 3% v/v glyphosate, 0.5% or 1% v/v imazapyr, and a 1% v/v nonionic surfactant mix was used. All glyphosate, imazapyr, triclopyr 3A, and surfactants used for treatments were aquatic labeled, due to the hydric nature of the Telegraph Swamp.

Along each transect, one 2.5-m-radius plot was placed every 10 m (5 plots per transect, 415 plots total). The minimum distance between random transects was 100 m. We confined transects to strand swamp and dome swamp plant communities. Within each plot on a transect, observers made ocular estimates of the percent cover of live plants and the percent cover of plants killed by herbicide (hereafter dead cover) by considering how much of the 2.5-m-radius plot (19.6 m^2) would have been covered with living vegetation had the dead cover been living and in leaf. Thus, the estimated dead cover of each target invasive species is an estimate of how much cover has been reduced. Live cover included plants that were untreated, were treated inadequately with herbicide, or were new growth. Ocular estimates of the percent cover of live and dead plants for each of the target invasive species were made separately using the following cover classes: <1%, 1% to 5%, 6% to 25%, 26% to 50%, 51% to 75%, 76% to 95%, and >95% (L King, personal communication). Handheld Trimble GPS units (model: Nomad) were used to navigate to transects and record data. For each transect, we recorded the corresponding management unit, the number of years since that unit had received treatment, and the first year it received treatment.

The dead foliage, rachis, boles, or stems of treated plants are believed to remain in place for several years, but the decomposition rate and the factors that would accelerate or slow decay are not known. Therefore, though we assumed that dead rachis in our study was an accurate estimation of formerly living cover, it is possible that some cover decayed in the time between initial treatment and data collection. For the purposes of this study, we assume that estimating the prior cover of each target invasive species using dead foliage is a sufficient estimation of previous infestations. To ensure the results of the most recent treatment had time to take effect, we only included management units that were not treated for a minimum of 3 mo before the survey.

BRP was used primarily for timber production before the State of Florida's acquisition of the property, but records detailing these harvests and other previous management activities are not available. Since 1914, it is very likely that all the cypress in Telegraph Swamp were harvested and replanted (FFS 2016). However, more recently, some areas have had significant alterations to their habitats by large swaths of clear-cutting and replanting (FFS 2016). Based on our field observations, areas that were recently logged using current commercial silviculture techniques were differentiated from areas that were not recently logged (Figure 2). Management history does not correspond to management unit boundaries, such that a unit could be only partially clear-cut and replanted (Figure 1). We determined management history post hoc by grouping transects into those that fell in clear-cut and replanted areas and those that were in natural stands (i.e., not recently logged). Areas with apparent prior clear-cutting included 14 transects that received one treatment, 9 transects that received two treatments, 1 transect that received three treatments, and 11 transects that received four treatments. Natural areas contained 10 transects that received one treatment, 16 transects that received two treatments, 10 transects that received three treatments, 7 transects that received four treatments, and 6 transects that received five treatments. To explore the effects of management history, we compared areas that were clear-cut and replanted to natural stands.

Figure 2. Aerial photo of cypress swamp at Babcock Ranch Preserve. Arrow A indicates swamp classified as a natural stand. Arrow B indicates areas of swamp that were classified as clear-cut and replanted based on the striated signature seen in the photo.

Analysis

We averaged the percent live and dead cover of all three target species across each transect to obtain one estimate of live cover and one estimate of dead cover per species, per transect. Using PAST (v. 4.0; Hammer et al. 2001) we conducted K-means clustering to group the total number of treatments with the goal of delineating important treatment thresholds. The total number of treatments a management unit received was binned into two clusters: management units that received one to three treatments and those that received four or five treatments over the 6-yr period.

In our analysis, all comparisons were conducted in a Bayesian framework using R (v. 3.6.1; Kruschke and Liddell 2018; R Core Team 2019). We compared both the live and dead cover of *L. microphyllum* between treatment clusters and management history using 89% high-density intervals (HDIs), which encompass the range of values in the distribution that are the 89% most probable, given the data. The HDI is also a measure of uncertainty surrounding a parameter; narrower HDIs can be interpreted with greater certainty than wider HDIs. We used a Bayesian index of effect existence, the probability of direction (pd), to assess our certainty of the observed differences between groups. The pd value reflects the certainty associated with the most probable direction of the effect given the data, either positive or negative (Kruschke and Liddell 2018; Makowski et al. 2019a). The pd values were calculated using the BAYESTESTR package (Makowski et al. 2019b).

We compared 16 candidate linear models to test hypotheses about which factors were most important in explaining the live cover of *L. microphyllum*. We made too few observations of *S. terebinthifolia* and *M. quinquenervia* to test multivariate relationships between those species and factors that could have influenced treatment effectiveness. For this reason, we compare live and dead cover of *S. terebinthifolia* and *M. quinquenervia* on transects, as opposed to using models to assess overall treatment progress. Models were run with a zero inflated beta distribution using the BRMS package (Bürkner 2017). Model assumptions and performance were assessed using the PERFORMANCE package (Lüdecke et al. 2020). We used the YARRR package to visualize the data (Phillips 2017).

To understand whether treating an infestation for a long time was the best explanation of treatment progress, we included a model with only the year a transect was first treated as a single predictor. We also included a model containing the year a transect was last treated as a single predictor to understand whether recent treatments were more effective at reducing live cover of *L. microphyllum*. Another model contained both years since first treatment and years since last treatment to determine whether a combination of these effects predicted *L. microphyllum* cover. To determine whether the number of treatments an area received best predicted *L. microphyllum* cover, we included a fourth model containing only treatment cluster. We included another model that contained treatment cluster, years since an area was first treated, and years since an area was last treated to understand whether there was an effect of a combination of these factors. To understand whether factors relating to history or swamp type were important in predicting *L. microphyllum* cover, we also included a model with the three aforementioned parameters and history, and an additional model with the three parameters and swamp type. To test whether prior land management history was an important predictor of *L. microphyllum* cover, we included a model containing the interaction of the treatment cluster and history. Two additional models were included in which history and swamp types were single predictors to assess each variable's relative strength as a single predictor. To understand whether areas that were more heavily invaded had a higher cover of *L. microphyllum*, we included a model that contained the total cover of invasive species (excluding *L. microphyllum*), the treatment cluster, years since first treatment, and years since last treatment. Finally, to test whether treatment cluster represented an important threshold for controlling *L. microphyllum*, we also included a model containing the interaction between the total number of treatments (one, two, three, four, or five) and history and a model containing total number of treatments as a single predictor.

Models were compared using the Bayes factor (BF), which was calculated using the BAYESTESTR package. The BF is a relative index of support for one model over another that is determined by comparing the marginal likelihoods of the models. We first compared all our candidate models to the null model using the BF to determine which model had the most support over the null model. To check our assertion that the model with the most support over the null model was the top model, we made a second comparison of all the candidate models relative to the top model. A BF > 3 indicates evidence for the alternative hypothesis (Makowski et al. 2019a).

Results and Discussion

Assessment of Current Invasive Cover

Across all transects, 81% had a live or dead invasive plant (*L. microphyllum*, *S. terebinthifolia*, or *M. quinquenervia*). Live cover of at least one invasive plant was found in 63% of transects. Live cover of *L. microphyllum* was found on 68% of transects, live *S. terebinthifolia* was found on 19% of transects, and live *M. quinquenervia* was found on 6% of transects. Despite the frequent occurrence of live plants on transects, we found the average live percent cover of each of the three focal species along a transect was less than 35% (Figure 3). Dead cover of *L. microphyllum* was found on 74% of transects, dead *S. terebinthifolia* cover was found on 31% of transects, and dead *M. quinquenervia* was found on 19% of transects.

Effects of Management Actions on *L. microphyllum*

Treatment cluster was related to the average live and dead cover of *L. microphyllum* along a transect. On transects that were treated one to three times, average live cover of *L. microphyllum* was 3.4% (1.9% to 4.5%), and on transects treated four or five times, average live cover was 0.4% (0.1% to 0.6%). Based on the pd, there was a 92% chance of a negative effect of more treatments on live *L. microphyllum* cover. Along transects that were treated one to three times, dead *L. microphyllum* cover was 13.3% (9.3% to 16.7%), and on transects treated four or five times, average dead cover was 4.2% (2.0% to 5.8%). Based on the pd, there was a 95.4% chance that transects treated four or five times had less dead cover than transects treated one to three times. Across transects, those that received four or five treatments were likely to have less total cover (live cover and less dead cover) than those transects treated one to three times.

Management history (i.e., clear-cut vs. natural) was correlated with average live *L. microphyllum* cover along a transect (Figure 4). Transects in clear-cut and replanted areas had an average live *L. microphyllum* cover of 3.7% (0.7% to 2.4%), and those in natural stands had an average live *L. microphyllum* cover of 1.7% (0.7% to 2.4%). Based on the pd, there was a 92% chance that clear-cutting

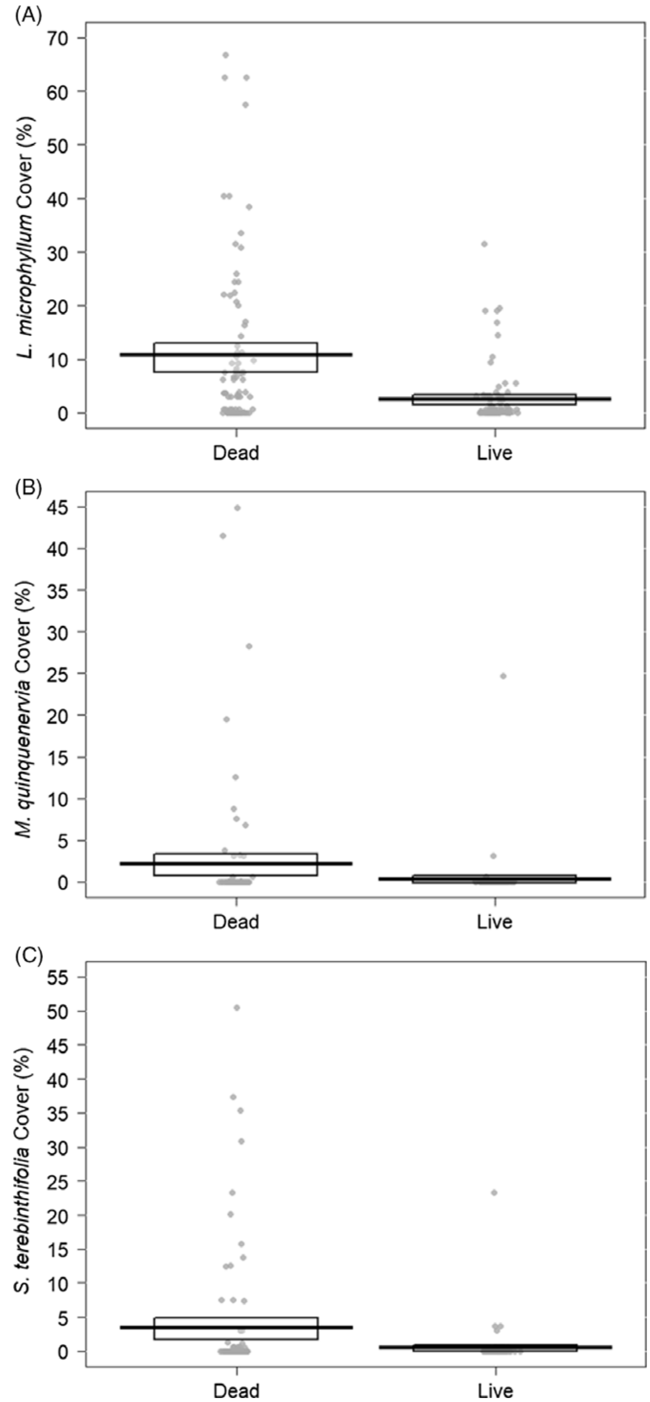

Figure 3. Comparisons of live and dead percent cover of each of the three target invasive species across all transects at Babcock Ranch Preserve. (A) Live and dead cover of *Lygodium microphyllum*. (B) Live and dead cover of *Melaleuca quinquenervia*. (C) Live and dead cover of *Schinus terebinthifolia*. The black line represents the mean cover, and the boxes represent the 89% high-density interval around the mean. Raw percent cover values for each transect are shown as gray dots.

and replanting resulted in higher cover of *L. microphyllum*. Dead *L. microphyllum* cover averaged 14.8% (2.0, 5.8%) along transects in clear-cut areas and 7.8% (4.1, 10.6%) in natural stands. Based on the pd, there was a 91% chance that dead *L. microphyllum* cover was lower in clear-cut and replanted areas than in natural stands.

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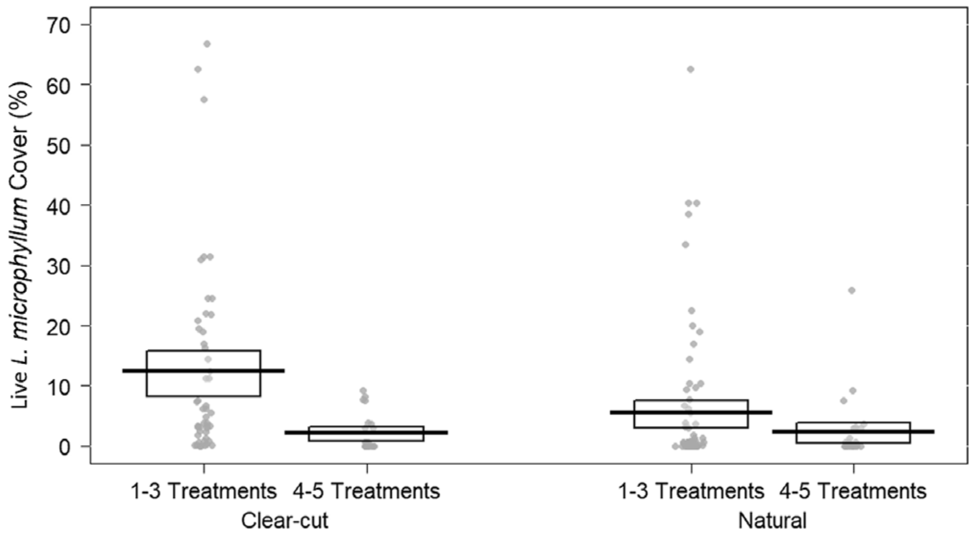

Figure 4. Comparisons of live cover of Old World climbing fern (*Lygodium microphyllum*) along transects in clear-cut and replanted areas (Clear-cut) and natural stands (Natural). Each management history group is further delineated into transects that were treated one to three times and those treated four or five times. The black line represents the mean percent cover, and the boxes represent the 89% high density interval around the mean. Mean percent cover values for each transect are shown as gray dots.

The best model to explain the cover of live *L. microphyllum* along transects was an interaction between treatment cluster and history (Table 1; Figure 4). The top model received more support than the null model (BF: 7.46; Table 1). To affirm that this model was the top model, we compared it with the other models in our data set and found that all other models had a BF < 1, indicating that no model received more support than the top model (Table 1). For this reason, we rejected models that included time since first treatment, time since last treatment, swamp type, cover by other invasives, and total number of treatments. Models containing the treatment cluster performed better than those that contained the number of treatments (Table 1). This indicates that the difference between treatment clusters was a meaningful threshold for significantly reducing *L. microphyllum*, as compared with a reduction in cover from each additional treatment.

Recommendations for Managers

This brief case study offers a rare look at the results of consistent, repeated efforts undertaken for many years in a natural area that can be considered a near worst case scenario for invasive species infestation. While this study would have ideally been initiated before any treatments took place, we were still able to detect meaningful patterns using a space-for-time experimental design. We found that significant gains can be made, even with dense and long-established *L. microphyllum* colonies, with consistent treatment over long periods. As one might expect, we observed declines in *L. microphyllum* cover when more treatments were applied. However, the relationship between treatment number and *L. microphyllum* cover was not linear. Instead, significant reductions in *L. microphyllum* cover only seemed to occur after four treatments were applied.

A major assumption of our study was that dead rachis mat represented live *L. microphyllum* cover before any treatments. Using this method, it is more likely that the observer would underestimate dead cover than overestimate it, resulting in a smaller reduction in overall cover than likely occurred. In addition, we have observed *L. microphyllum* rachis persisting in the field for long durations, though the exact decay rate and conditions that affect decay are not known. It is likely that at BRP these plant materials are protected from intense wind, rain, and ultraviolet light beneath the cypress dome canopy for a longer period relative to other exposed areas. If *L. microphyllum* rachis does decay at a faster rate than we assume, our estimations of prior cover would be lower than the true cover of dead rachis. Therefore, the reductions in cover we documented would likely be larger than we described. For these reasons, we believe using dead *L. microphyllum* rachis as a proxy for prior live cover is an appropriate assumption. However, it is possible that dead rachis does not accurately reflect the live cover at the start of the experiment and the results should be interpreted with caution.

We observed lower dead rachis cover on transects treated four or five times than on transects treated one to three times. One potential explanation for this pattern is that rachis treated earlier in the study (i.e., at the beginning of the 6-yr period) had more time to decay than rachis treated at the end of the study. A second potential explanation is that transects treated more times likely had less opportunity for new growth in between treatments, therefore reducing the potential for high cover of dead rachis. Determining the decay rates of this and other invasive species after treatment could help improve our comparisons of different treatment regimens and comparisons made by future studies.

Because our study took place over a finite duration, units that received more treatments were inherently treated more often than units treated fewer times. In this case, units in the one to three treatment group were treated less than biennially, and units in the four or five treatment cluster were treated more frequently than biennially. Therefore, we conclude that treatments applied less often than every other year were not effective at significantly reducing *L. microphyllum* cover. We were able to identify that biennial treatment is a critical threshold for outpacing growth and new colonization of *L. microphyllum*. A study by Hutchinson and Langeland (2012) determined that treating annually for 3 yr was effective for significantly reducing live cover. Our results suggest that treating at a slightly longer interval (less than biennially) is still effective at controlling *L. microphyllum* if four or more treatments are applied. This threshold may be beneficial to managers who lack the resources to treat on an annual schedule.

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Table 1. The 16 candidate models that explained live *Lygodium microphyllum* cover.

Model[a]	Bayes factor[b] Compared with null model	Compared with top model
Intercept-only model	*	0.13
trt clust	1.94	0.26
yr first trt	0.17	0.02
yr last trt	0.74	0.10
yr last trt + yr first trt	0.32	0.04
yr last trt + yr first trt + trt clust	0.52	0.07
yr last trt + yr first trt + trt clust + history	0.82	0.11
yr last trt + yr first trt + trt clust + swamp	0.78	0.11
trt clust + history	2.60	0.35
trt clust * history	**7.46**	*
history	1.65	0.22
swamp	0.87	0.12
num of trt * history	0.35	0.05
num of trt	0.27	0.04
yr last trt + yr first trt + trt clust + inv cov	0.01	0.002
inv cov	0.02	0.003

[a]Model parameters shown are treatment cluster (trt clust), management history (history), swamp type (swamp), number of years since first treatment (yr first trt), number of years since last treatment (yr last trt), the number of treatments an area received (num of trt), and sum of all invasive cover except *L. microphyllum* (inv cov).
[b]Models were compared using the Bayes factor, for which values >3 indicate separation of that model from the comparison. The top model was separated from the null model and contained an interaction of treatment cluster and history (bolded). To confirm that no other models were better predictors of live *L. microphyllum* cover, we also compared the top model with the other candidate hypotheses. No other models better explained live *L. microphyllum* cover than the top model. Asterisks are used as placeholders to denote the model against which all other models are being compared.

Though low samples sizes prevented us from drawing conclusions about a minimum number of necessary treatments to reduce *S. terebinthifolia* and *M. quinquenervia* cover, we still observed declines in live cover as the result of treatment. This suggests that consistent treatments of *S. terebinthifolia* and *M. quinquenervia* over multiple years will reduce live cover and help control invasions. Based on the treatment threshold required to reduce live *L. microphyllum* cover, we suggest that managers treating *S. terebinthifolia* or *M. quinquenervia* invasions make frequent treatments, less than 2 yr apart, for at least four consecutive treatments. However, as these recommendations are based on our findings for *L. microphyllum*, we suggest managers regularly reevaluate their progress using this treatment regimen. Once invasive plants are reduced to less than 5% live cover (maintenance levels), managers should reevaluate the treatment intervals necessary to maintain progress.

Some research suggests that spending time, money, and resources on treating smaller, younger, or more rapidly growing infestations is cost-effective for reducing infested acres and money spent per hectare and protecting biodiversity (Higgins et al. 2000; Moody and Mack 1988). All three of the focal species in this study are believed to have detrimental effects on biodiversity (Gordon 1998; Turner et al. 1998). Though we did not assess the overall effects of treatment on biodiversity in our study, biodiversity may increase if the live and dead covers of the target invasive species were significantly reduced. Hutchinson and Langeland (2010) found that while richness and diversity did increase after significant reductions in *L. microphyllum* cover were made, many of those gains resulted from increases in nonnative graminoids and forbs. However, this study was conducted in areas that were already disturbed from weather events such as hurricanes and heavily invaded by exotics other than *L. microphyllum*. It is possible that in other areas that are less disturbed and have fewer invasive species, biodiversity gains after *L. microphyllum* treatment would be due to native species recruitment. The lack of information about how both native and nonnative species respond after large-scale and long-term *L. microphyllum* treatments indicate managers must continue to monitor communities even after large invasions have been treated. Additional research in these areas to understand how communities respond after treatment of *L. microphyllum* is necessary to improve posttreatment management plans.

In addition to considering the resources available to conduct treatments, previous history of disturbance, management activities, and habitat type at potential treatment sites should be considered when creating a treatment plan for *L. microphyllum*. We found evidence that swamps recently logged using commercial silviculture techniques may be more vulnerable to invasion by *L. microphyllum* than those that were naturally regenerated. It is well known that disturbed areas have a higher probability of being invaded by exotic species, which may result from physical disruption of soils and increased resource levels (D'Antonio and Meyerson 2002). However, the reasons for increased *L. microphyllum* cover in commercially harvested areas over naturally regenerated areas at BRP remain unknown and require further investigation. Our finding that invasive cover was high in more disturbed areas of the site may also help conservation agencies estimate the management needs of potential acquisitions when management history is known.

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