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RESEARCH ARTICLE

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Vegetation Monitoring to Guide Management Decisions in Miami's Urban Pine Rockland Preserves

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ABSTRACT: We developed a monitoring program to assess the health of urban fragments of pine rockland, a globally critically imperiled, fire-dependent plant community, in order to provide feedback for adaptive land management. Our results showed negative effects of fire exclusion, including low native herb and grass cover, excessive leaf litter accumulation, and high densities of native trees in most of the twelve preserves sampled. We provide quantitative evidence of the need for instituting regular prescribed fires to Miami-Dade County's pine rockland preserves, and lend support to the idea that, in degraded urban fragments, manual hardwood reduction is sometimes a required first step toward achieving maintenance conditions. We demonstrate that simple actions like measuring litter depth or visually estimating hardwood cover can be utilized by preserve managers as a quick, inexpensive way to prioritize hardwood reduction and burn scheduling. Our results serve as a case study for other urban forest fragments with similar issues.

Index terms: fire, fragmentation, monitoring, pine rockland, wildland-urban interface

INTRODUCTION

Adaptive management is widely recognized as a critical tool in natural areas management (Walters 1986; Elzinga et al. 1998; Wilhere 2002). Although it requires dedicated funding and time, when properly executed it can ensure that sparse dollars available are used in the most effective manner possible. Adaptive management is especially important when rare species are present within rare habitats. At times, management goals for a habitat may conflict with those of a rare species, or vice versa (Meretsky et al. 2000). In such cases, the optimal management methods may not be easily apparent.

As a case study, the network of preserves in Miami-Dade County's Environmentally Endangered Lands (EEL) Program represents one of the most challenging management scenarios possible [see Alonso and Heinen (2011) for an overview]. The majority of the County's upland preserves are pine rockland, a fire-adapted, globally critically imperiled plant community (FNAI 2010). Managers of Miami-Dade's pine rocklands must address a perfect storm of issues including high endemism, fragmentation, urban interface, fire exclusion (Snyder et al. 1990; Possley et al. 2008), and non-native plant species introduced en masse through the area's booming nursery industry (Garofalo 2002). Pre-settlement extent of pine rocklands was approximately 75,000 hectares. Today, only 1500 hectares remain outside Everglades National Park. The EEL Program has acquired over 567 hectares of pine rockland, which is less than 1% of the original extent.

While it is highly unlikely that Miami-Dade's scattered forest fragments could ever be fully restored to their original, connected state, managers strive to bring each preserve from a degraded, fire-excluded status to a "maintenance" condition (Figure 1a). The specific recipe for doing so differs for each individual preserve, yet the desired end result is the same. Ideally, each pine rockland preserve will become a resilient, stable ecosystem (*sensu* Holling 1973), whereby alterations (e.g., a hurricane, weed invasion, or pest outbreak) do not permanently shift its trajectory toward either degradation or succession to a broadleaf forest (Figure 1b). Instead, natural processes such as competition, seed rain, fire, and predation would essentially allow the system to absorb change and return to a stable state.

A challenge arises for adaptive management in developing quantitative targets that indicate when "maintenance condition" has been achieved for a given fragment. Attempting to recreate historic conditions was once an end goal in restoration, but this idea has become increasingly irrelevant in a world of extreme habitat degradation (Williams and Jackson 2007; Jackson and Hobbs 2009). A pine rockland fire regime that was ideal 100 years ago (i.e., prior to fragmentation and substantial drainage) may not be relevant to the fragments that remain today. One option to address the problem of moving targets in restoration is to embrace the dynamic reference concept (Hiers et al. 2012) by comparing study plots to a reference ecosystem while measuring change over time in both. While such methodology would be ideal for our goals, we did not establish long-term

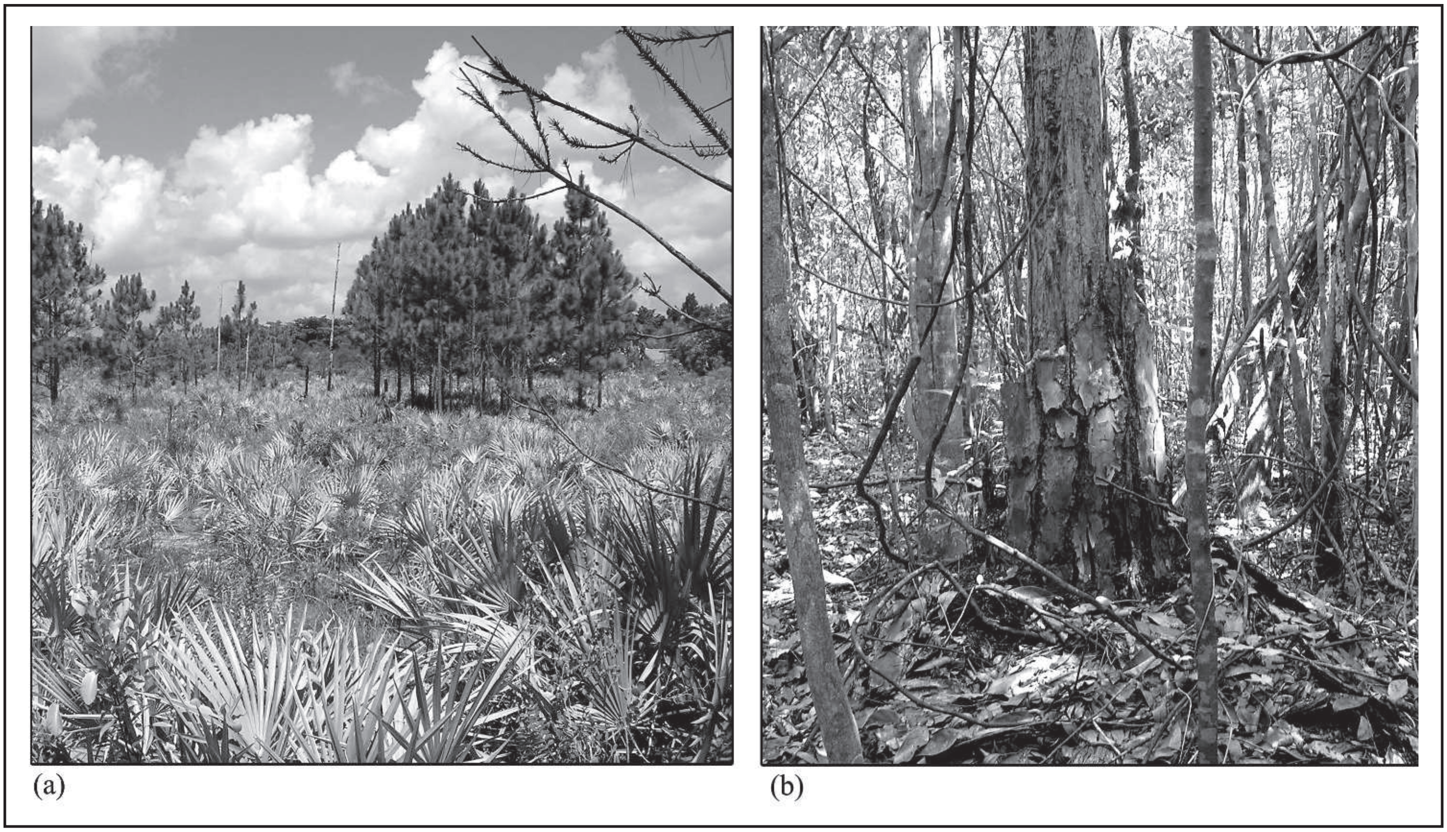

Figure 1. Different stages of succession in Miami-Dade County forest fragments. The regularly-burned pine rockland (a) has few trees and abundant grasses and open space. The fire-excluded pine rockland (b) has succeeded to hardwood hammock, with some vestiges of pineland still present like the dead pine tree shown here. Photos by Sam Wright and Jennifer Possley.

reference plots due to uncertain funding. Additionally, an appropriate reference area for Miami's pine rockland fragments may not exist. The closest non-fragmented pine rockland is Long Pine Key in Everglades National Park; however that area differs from the northern, fragmented rocklands in geology, hydrology, and soils, and, as a result, has a different suite of plant species (Snyder et al. 1990; O'Brien 1998).

In order to set quantitative targets for our system, we began with objectives suggested by historic information available for Everglades National Park and then modified or supplemented those through expert opinion. In pine rocklands within Everglades National Park, the ideal fire regime and the resultant vegetation structure have not always been well understood, but most researchers have agreed that prior to the arrival of Europeans, fire-return intervals there did not exceed 8–10 years. Historic records indicate that pre-European pine rocklands had a forest structure with a diverse understory of grasses and herbs, minimal leaf litter, a shrub layer of palms and hardwoods that remain small in stature and compose a minor component of vegetation structure, and a slash pine overstory. The structure and composition of pine rockland vegetation varies at the landscape scale in response to changes in geology, hydrology, elevation, and fire history (Wade et al. 1980; Snyder et al. 1990; O'Brien 1998).

Expert opinion was a valuable tool in developing this adaptive management program. Land managers identified three primary management concerns for pine rocklands: (1) preserving rare species, (2) promoting high native species diversity, and (3) restoring historic vegetation structure. With these concerns in mind, we identified specific monitoring questions, set quantitative target values (or a range of values) for monitoring criteria, and conducted a pilot study (with land managers present during field data collection) from which we developed and implemented a field sampling methodology. In order to set quantitative goals, we drew from the work of Maguire (1995) and considered expert input. Our primary objective was to obtain quantitative data on species of interest, species composition, vegetation structure, and litter depth in order to facilitate comparison of the restoration stage of each preserve. Additionally, we examined whether the abundance of pine trees, coverage of hardwoods, or depth of leaf litter were factors affecting the number of native herbaceous species in each transect.

METHODS

Study System

Pine rocklands have a high degree of endemism and a very narrow global range, giving them a globally critically imperiled (G1S1) conservation ranking (FNAI 2010). Outside of the United States, pine rocklands with a canopy of *Pinus caribaea* Morelet are found in eastern portions of The Bahamas and in the Caicos Islands (FNAI 2010). In the U.S., pine rocklands are only found in the three southernmost counties of Florida. Here, the canopy species is *Pinus elliottii* Engelm. var. *densa* Little & K.W. Dorman, and the number of endemic plant species is 29 (Snyder et al. 1990). The largest tracts of Florida pine rockland were historically found in Miami-Dade County, where pine rocklands once covered much of the high ground, 2–7 meters above sea level (Snyder et al. 1990). Today most of these forests have been destroyed by development. Remaining tracts of a few thousand hectares are protected in Everglades National Park and Big Cypress National Preserve. Outside of these boundaries, all that remains are widely-scattered fragments in Miami-Dade and Monroe Counties. Fire exclusion is a major threat to remnant pine rocklands. In the absence of fire, they are quickly invaded by native and/or non-native hardwoods, causing them to succeed to broadleaf forest (Wade et al. 1980; Snyder et al. 1990) known as "rockland hammock" in Miami-Dade County or "coppice" in The Bahamas. All of the pine rockland fragments we sampled for this study are protected preserves that are part of Miami-Dade County's Environmentally Endangered Lands Program (Table 1).

Field Methodology, Sampling and Analysis

During planning, land managers identified target species of interest. Reasons for species' selection included rarity, specific microhabitat requirements, and status as an invasive species or as a rare insect host plant. We restricted this list to include only species that were relatively plentiful in preserves and were present throughout the entire range of pine rocklands. We separated taxa into "positive" and "negative" ones (Table 2). Positive species of interest included three understory species that require relatively open conditions and are common in frequently burned pine rocklands: *Angadenia berteroi* (A.DC.) Miers, *Croton linearis* Jacq., and *Jacquemontia curtissii* Peter ex Hallier f. Negative species of interest included a non-native invasive tree (*Schinus terebinthifolia* Raddi), non-native invasive grasses both small (*Melinis repens* (Willd.) Zizka) and large (*Neyraudia reynaudiana* (Kunth) Keng ex Hitchc.) in stature, and the native live oak (*Quercus virginiana* Mill.), which becomes abundant with fire exclusion as the system succeeds to hardwood hammock. In addition, we counted individual *Pinus elliottii* var. *densa,* categorized into four size classes. This canopy tree is a foundation species that provides fuel as well as fuel continuity for fire in pine rocklands, shaping forest structure (Mitchell et al. 2009).

To compare forest structure between sites, we developed five categories of vegetation: hardwoods, palms, understory, bare rock or soil, and weedy natives. Targets were defined for the first four categories, based on Maguire (1995) and expert consensus (Table 3). Hardwoods included approximately 15 species of trees (excluding pines), with *Quercus pumila* Walter and *Rhus copallinum* L. being two of the most common. Palms included all three palm species native to Florida pine rocklands; *Serenoa repens* (W. Bartram) Small; *Sabal palmetto* (Walter) Lodd. Ex Schult. & Schult.f.; and *Coccothrinax argentata* (Jacq.) L.H. Bailey. Understory included all grasses and forbs, excluding vines. The category "bare rock or soil" essentially encompassed a lack of vegetation. Ground covered with leaf litter or dead plants was not included in this category. The final category, "weedy natives," included *Toxicodendron radicans* (L.) Kuntze, *Vitis rotundifolia* Michx., and *Pteridium aquilinum* (L.) Kuhn var. *caudatum* (L.) Sadeb. Because our study areas included core habitat in regularly managed preserves, it was very rare to encounter patches of non-native herbs or vines. We did not, therefore, record coverage of non-native species, which were captured in presence/absence and abundance data.

We collected data each year from 2008 to 2012, sampling in late summer and early fall when plant growth was at a peak and blooming grasses could easily be identified. Each year we selected two to three Miami-Dade County preserves for sampling, incorporating a range of fire histories and soil types. For sites larger than 5 hectares, we chose one (or more in the case of Camp Owaissa Bauer) management unit within the site to sample. We restricted sampling areas to avoid fire breaks and weedy edges, focusing only on core habitat. Within the defined areas of interest, we installed 6 to 15 randomly placed 50-meter transects with permanently marked ends and midpoints. Prior to installation, we used ESRI ArcMap 10.0 (ESRI 2010) software to determine the dimensions of each sampling area. We used that figure to calculate the number of transects (each 100 m^2) needed to sample 5% of the area. We randomly selected endpoints of transects within the sampling area. All transects were spaced at least four meters apart.

Along each 50-meter transect, we collected four types of data. We treated the transect tape as the center of a 50-m x 2-m plot (i.e., a 100-m^2 area) and listed all species present therein. Additionally, we counted abundance of species of interest (Table 2) within the 100-m^2 plot and used the line-intercept method to estimate the percent cover of different vegetation categories (Table 3) along the transect tape. We recorded 21 litter depth measurements per transect, at 2.5-meter intervals along the line. We used Microsoft Excel (Microsoft 2002) to summarize and graph data. Because the area sampled varied by preserve, we divided area-dependent measures by the number of transects used in order to standardize results. To examine the extent to which native herb diversity was correlated with hardwood density and litter depth, we conducted linear regressions, calculating R^2 and p-values using SYSTAT 10 (SYSTAT 2002).

RESULTS

Species Composition

Three hundred and fifty vascular plant species occurred within plots in the twelve sample sites (Table 1), excluding the handful of seedlings that were unknown or identifiable only to genus. Two hundred and eighty five (81%) of the recorded species were native to Florida. Of those, 46 (13%) were listed as Florida threatened or endangered species (Coile and Garland 2003). In comparing preserves, the number of state-listed native plant species recorded per site ranged between one and three, after standardizing by number of transects sampled. Rockdale Pineland had the fewest listed species per area and Fuchs Pineland Addition had the most (data not shown).

Table 1. Preserves sampled. All sampling was conducted June-September. Dollar amounts in the last two columns indicate cost per hectare for fires or hardwood reduction. In both cases, expenditures are personnel time. An asterisk (*) in the last column indicates that pine thinning data is included with hardwood reduction data in the cost per hectare.

Preserve Name	Abbrev.	Hectares Sampled (ha of pineland)	Sample Year	Fires 2003-2012 Date(s) [Cost per hectare]	Hardwood Reduction 2003-2012 Date(s) [Cost per hectare]
Camp Owaissa Bauer (Subunits 5, 6, 9)	**COB**	2.3 (26)	2009	None	Unit 6 in 2005 [$7706] Unit 6 in 2009 [$4052] Unit 9 in 2006 [$8812]
The Deering Estate	**DEE**	1.9 (47)	2011	Nov. 2009 [$5847] Mar. 2010 [$5844] (Fires did not overlap, each burned half of sample area).	Multiple Units, 2004- [$3936 - $29,412] *
Fuchs Pineland Addition	**FAD**	1.1 (6)	2008	None	2004 [cost not available]
Ingram Pineland	**ING**	2.0 (4)	2011	None on record, but charred pines indicates a fire in the past decade.	2003-2005 [$1533]
Larry & Penny Thompson Park	**LPT**	2.9 (93)	2008	Mar. 2006 [$200] (wildfire; staff worked mop-up only)	None
Palm Drive Pineland	**PAL**	1.3 (8)	2012	None	2009 [$28,444] 2009-2010 [$9538] 2011 [$6202] 2012 [$14,207]
Pineshore Pineland	**PIN**	2.0 (3)	2012	None	None
Rockdale Pineland	**ROC**	2.0 (12)	2009	None	2003 [$10,212] 2009 [$6133]*
Sunny Palms	**SUN**	1.8 (16)	2010	Dec. 2008 [$1615]	2010 [$2560] 2012 [$2405]
Tamiami Pineland Complex Addition	**TCA**	1.8 (11)	2010	Mar. 2009. [$4622] (fire burned half of sample area)	None
Trinity Pineland	**TRI**	1.6 (4)	2010	None	2003-2005 [$16,069]
Zoo Miami	**ZOO**	2.3 (81)	2008	Jan. 2007 [$1385]	None

All floristic data recorded for this study are maintained in a database at Fairchild Tropical Botanic Garden.

Sixty-five taxa (19%) were non-native and of those, 30 were Florida invasive or potentially- invasive pest plant species (FLEPPC 2009). *Schinus terebinthifolia* was the most common non-native invasive pest plant. It was present in 51 of 117 total transects and 11 of 12 total preserves. The second most common invasive species was *Melinis repens*, which was present in 46 transects and 11 preserves. The number of invasive or potentially-invasive plant species (*sensu* Categories I and II, per FLEPPC 2009) on each study transect ranged between 0 and 2. Palm Drive and Trinity Pinelands had the most invasive plant species per area, each with 1.4 invasive species per transect (data not shown).

Table 2. Abundance of species of interest. Data shown are the number of individuals counted per site, divided by the number of transects from which we sampled. The "final score" in the last column is the result of subtracting total negative individuals from total positive individuals. Higher scores represent preserves that are closer to maintenance conditions.

	Positive Species			Negative Species				Score		
Taxon	*Angadenia berteroi*	*Croton linearis*	*Jacquemontia curtissii*	*Neyraudia reynaudiana*	*Melinis repens*	*Quercus virginiana*	*Schinus terebinthifolia*			
Rationale	Florida threatened species	Host plant of rare butterfly	Florida threatened species	Major weed targeted by management crews	Potential range expansion	Indicates fire exclusion	Major weed targeted by management crews	Total positives	Total negatives	Final score
COB	14.1	0.3	0	0.3	1.1	7.7	0.6	14.4	9.6	4.8
DEE	20	1.8	1.4	0	0.3	12.2	0	23.2	12.5	10.7
FAD	1	0	0.2	0.2	11	16	3.3	1.2	30.5	-29.3
ING	31.6	1.4	2	0.2	10.5	0.6	1.2	35	12.5	22.5
LPT	15.7	4.2	4.4	0	2.4	0.1	0.1	24.3	2.6	21.7
PAL	3.8	2.5	1.2	0	3.8	2	2.7	7.5	8.5	-1
PIN	8	2.4	0.8	0.3	5.3	3.4	0.4	11.2	9.6	1.7
ROC	12.7	2.8	1.7	0	5.5	1.8	0.5	17.2	7.8	9.4
SUN	26.4	4.1	0.2	0.4	9.1	0.4	6.1	30.8	16.1	14.7
TCA	16.7	1.2	0	3.6	0.1	0.2	5.7	17.9	9.6	8.3
TRI	13	1.9	0.1	0.8	0	12.5	0.3	15	13.5	1.5
ZOO	47.8	18.5	6.7	1.1	0.1	0	1.3	73	2.4	70.6

Species of Interest

A comparison of the abundance of species of interest illustrates the variety of management stages among Miami-Dade County preserves (Table 2). We used the presence of "positive" and "negative" (that is, desirable and undesirable) species of interest as a rudimentary scoring mechanism, whereas the final score of each preserve (Table 2) is the result of subtracting total abundance of negative individuals from total positives. Higher scores represent preserves that are closer to maintenance conditions. Preserves with the highest scores included Zoo Miami, Ingram Pineland, and Larry & Penny Thompson Park. These preserves had abundant positive species of interest and few negative ones. On the other hand, Fuchs Pineland Addition, Palm Drive Pineland, Trinity Pineland, and Pineshore Pineland, which had the fewest positive and the most negative species, were the furthest from being in the desired "maintenance phase" of management by this measure.

Regarding pine abundance, most preserves we sampled had 2 or fewer mature pine trees per transect (≤ 200 trees per hectare), with the maximum being 2.4 mature pine trees per transect at Trinity Pineland (Figure 2). However, data for other size classes revealed extremely high densities of immature pines in two preserves (Figure 2). At Rockdale Pineland, the mean abundance of non-reproductive pine trees greater than 2-m tall was 8.3 per transect. At Trinity Pineland, the abundance of pines in the middle two classes (i.e., those above grass stage but not yet reproductive) was 25.8 per transect. Pine abundance was not significantly associated with native herbaceous species diversity ($R^2 = 0.01$, $P = 0.18$).

Vegetative Cover

Vegetative cover (native herbaceous understory, bare soil or rock, hardwoods, and palms) varied widely between preserves (Figure 3). For each of these categories, our goal was 25% cover. In general, most preserves fell short of that target for native understory and for bare soil or rock; however, Larry & Penny Thompson Park, Sunny Palms, and Zoo Miami were at or

Table 3. Quantitative biotic and abiotic target levels for pine rockland vegetation. Goals were developed using the work of Maguire (1995) and by expert consensus.

Category	Target	Comment
Palms	25% cover	Major component of shrub layer
Hardwoods	5-25% cover	Component of shrub layer, indicative of fire exclusion
Native understory	25% cover	Grasses and herbs are major source of species richness, lost with fire exclusion
Bare rock or soil	25% cover	Promotes high species richness but lost with fire exclusion
Litter depth	<3 cm deep	Indicative of fire exclusion

near the 25% target for both of those categories. The Deering Estate far exceeded the target for bare soil or rock, but that reflects a prescribed fire that passed through half of the transects just 17 months before we sampled. For palms, Fuchs Pineland Addition and Ingram Pineland were slightly below the 25% target, while palm density at Pineshore Pineland, Rockdale Pineland, Tamiami Pineland Complex Addition, and Trinity Pineland was nearly twice the target value.

Density of hardwoods was within or nearly within the target range (5% – 25%) in the majority of preserves (Figure 4). However, percent cover of hardwoods in Camp Owaissa Bauer was more than twice the upper range limit. The high figures for hardwood density at this preserve were due to very high densities in management unit 5 (not shown separately), which had mean density of 56% hardwood cover. The other two units we sampled at Camp Owaissa Bauer were within the optimum range for hardwood cover (16% and 21%). Three preserves exceeded the 25% upper-limit for hardwood densities (Figure 4), but no preserve had hardwood densities below the lower limit of 5%. Hardwood cover significantly explained 14% of the variation in native herbaceous species diversity ($R^2 = 0.14$, $P < 0.001$, Figure 5a).

While we did not choose a target density for "weedy native species," overall density was relatively low. *Toxicodendron radicans, Vitis rotundifolia,* and *Pteridium aquilinum* var. *caudatum* cover was very low at Larry & Penny Thompson Park, Zoo Miami, and Rockdale Pineland. At other sites, weedy

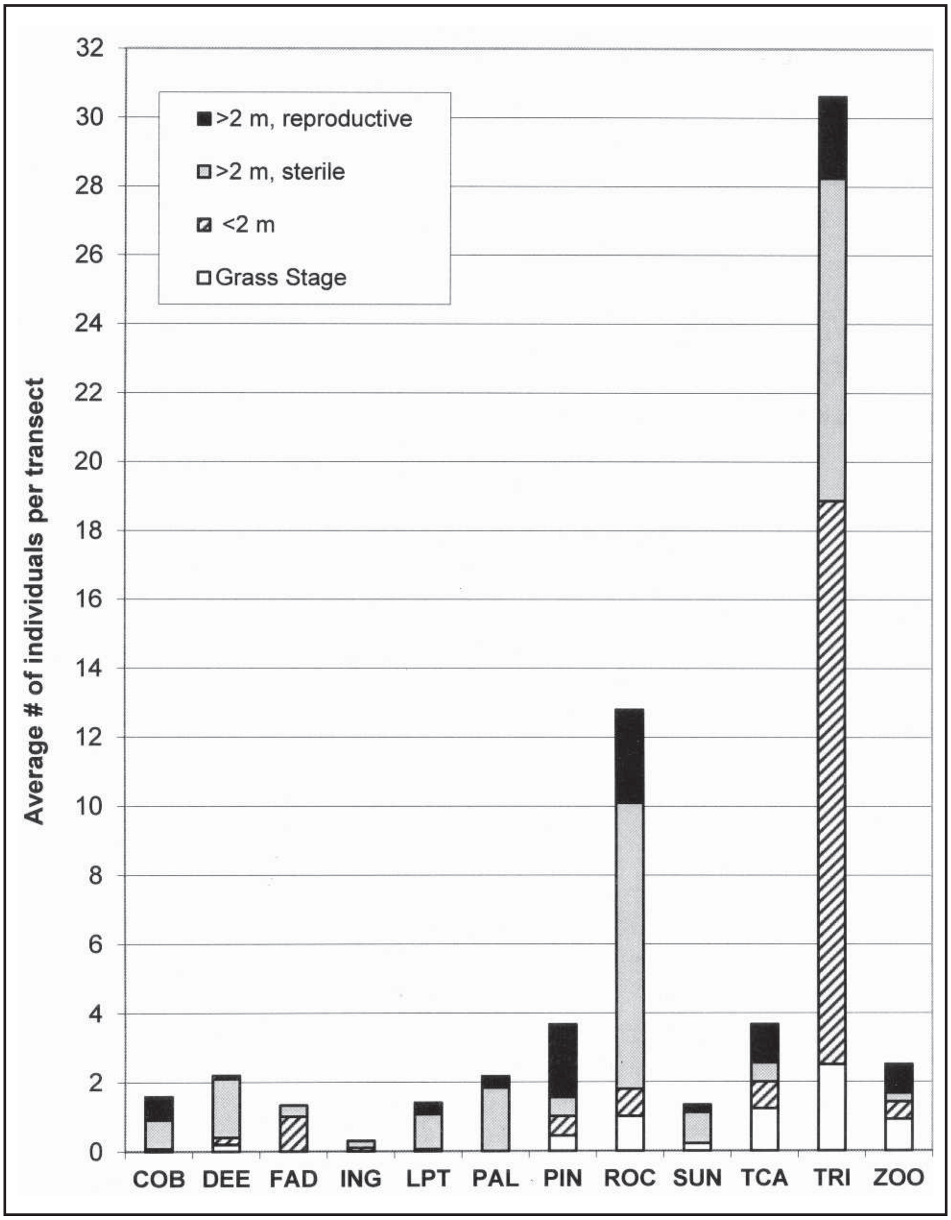

Figure 2. Abundance of slash pines per size class in 100-m^2 study transects on Miami-Dade County preserves.

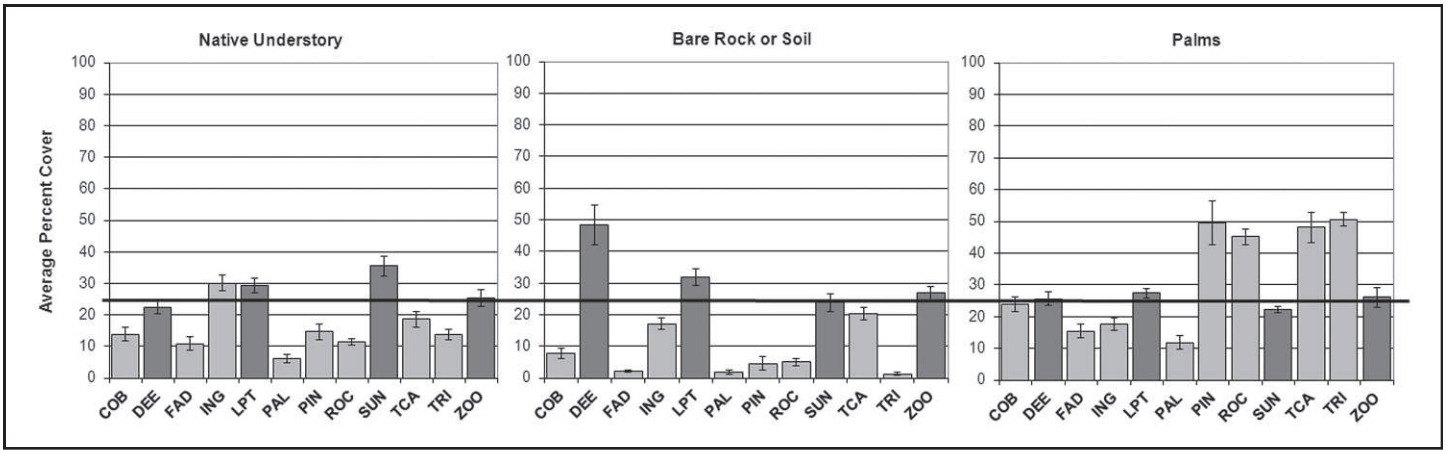

Figure 3. Percent cover of different vegetation categories across research transects. Vertical bars represent standard error of the mean. The thick horizontal line shows the target value of 25%. Preserves that experienced a fire in the entire sampling area in the three years prior to sampling are shown as a darker gray.

species cover was <10% with the exception of Fuchs Pineland Addition, where average percent cover of *V. rotundifolia* was 19%, and Palm Drive Pineland, where average percent cover of *T. radicans* was 25% and that of *V. rotundifolia* was 23%.

Leaf Litter

Only four of the 12 preserves sampled were within the maximum litter depth threshold of 3 cm (Figure 6); these are also the same preserves that experienced a fire within the entire sampling area in the three years prior to sampling. While all preserves had mean litter depths below 8 cm, some had individual measurements that were extremely high. The deepest litter measurement we made was at Trinity Pineland, at 50 cm, followed by Pineshore Pineland, which had a 41-cm reading. A linear regression comparing litter depth to understory diversity showed that litter depth significantly explained 18% of the variation in native understory species diversity in each transect ($R^2 = 0.18$, $P < 0.001$; Figure 5b).

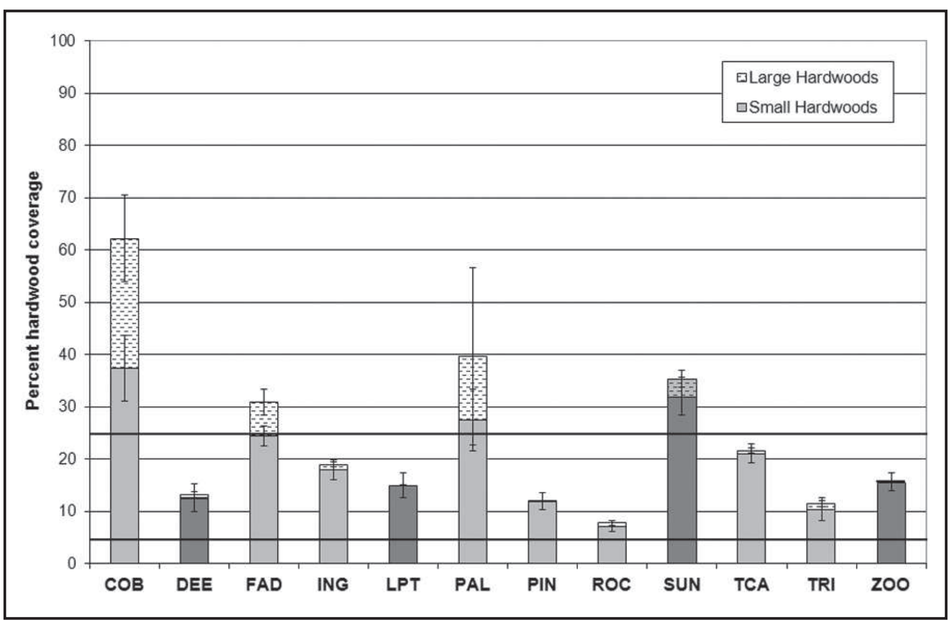

Figure 4. Percent cover of hardwood species. Vertical bars represent standard error of the mean. The thick horizontal lines show the optimum target range of 5% – 25%. Preserves that experienced a fire in the entire sampling area in the three years prior to sampling are shown as a darker gray.

DISCUSSION

1. Restoring pine rockland fragments with frequent fire

Overwhelmingly, our data show the need for more frequent fires in Miami-Dade County's pine rockland preserves. Sites with at least one fire in the past three years have clearly reaped the benefits of fire, meeting our target objectives for percent cover of bare ground and hardwoods and depth of leaf litter (Figures 3, 4, 6). This work also underscores the importance of fire by demonstrating negative relationships between native herbaceous diversity and two factors that increase in the absence of fire: hardwood density (Figure 5a) and leaf litter depth (Figure 5b).

Reintroducing frequent fires to pine rockland fragments is by far the most effective means to achieve monitoring targets and meet goals of preserving rare species and maintaining high native plant diversity. By conducting fires every 3–8 years, Miami-Dade County's land managers can shift the trajectory of pine rockland fragments away from hardwood hammock and toward that of a pine rockland with patchy distribution of pines and palms and a grass-dominated understory. Such a structure has three major management advantages. First, it meets primary management goals for promoting rare plants and native species richness. Second, future prescribed fires in

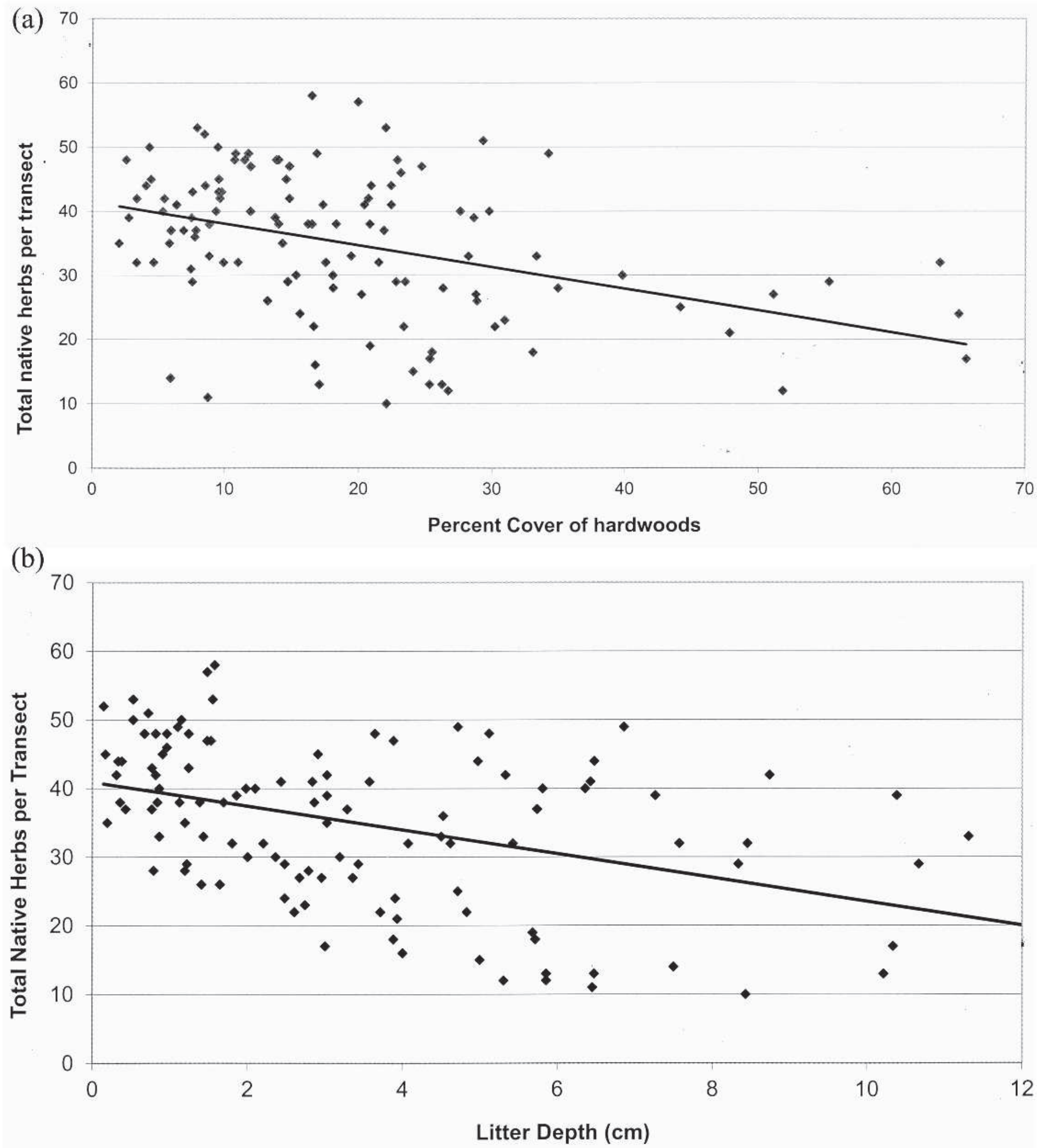

Figure 5. Linear regression showed two factors had negative effects on native herb diversity in study plots: (a) percent cover of hardwoods (R^2 = 0.14, P < 0.001), and (b) litter depth (R^2 = 0.19, P < 0.001).

frequently burned habitat are much easier and, therefore, much less expensive to conduct. Because fuel accumulation over 3–8 years is relatively low, smoldering is rare and little mop-up would be required; this process of suppressing smoke can be the most costly part of prescribed fires, exceeding $30,000 per hectare in long-unburned preserves (Miami-Dade County Natural Areas Management, unpubl. data). Third, fires in frequently burned pine rocklands are likely to be less noticeable and, therefore, more acceptable to the public. In such cases, fine fuels such as grasses, pine needles and pine straw are present but not yet accumulated to the point where they remain constantly moist. This facilitates fire and minimizes smoke, an important consideration for urban prescribed fires (Maguire 1995).

2. Restoring pine rockland fragments without fire

Despite the clear need for frequent fire to maintain healthy urban pine rockland fragments, a significant increase in the implementation of prescription fires may be out of reach for Miami-Dade County in the near future. The current logistics of staffing and prescribing fires in Miami are difficult. As a result, the majority of the County's pine rockland preserves are beginning to transition to hardwood hammock, a process which managers combat by alternative means when fire is not an option or when fuels have changed to the

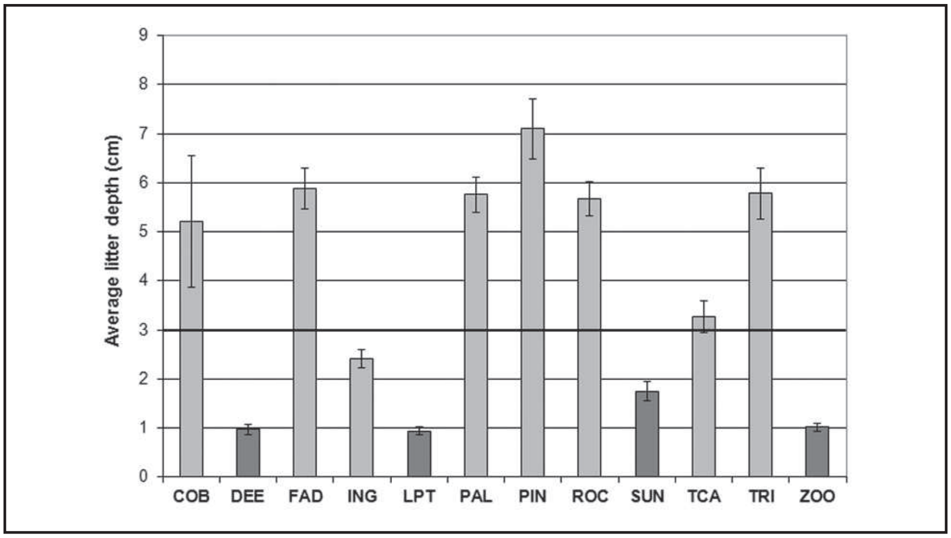

Figure 6. Range of litter depths present in study transects in Miami-Dade County preserves, 2008–2012. Error bars represent the standard error of the mean. The thick horizontal line shows the maximum target threshold of 3 cm. Preserves that experienced a fire in the entire sampling area in the three years prior to sampling are shown as a darker gray.

point where fire will not carry through a pine rockland fragment.

In lieu of applying fire, Miami-Dade County land managers have used manual hardwood and pine reduction, which strives to both recapture the proper vegetation structure and to prepare the site to better carry fire at a future date. Though this practice is not a long-term solution and cannot replicate the effects of fire (Mast 2003; Menges and Gordon 2010), it can temporarily shift the ecosystem closer to the desired maintenance state. Hardwood reduction is often seen as a costly-yet-necessary step in the pine rockland restoration process in urban Miami. There are, however, significant downsides to the process. First, mechanical treatments can actually stimulate the growth of hardwoods as well as weedy invasives. Our data from Palm Drive Pineland supports this premise as it had the most intensive hardwood reduction (Table 1) and corresponding high density of hardwoods (Figure 4) and weedy native vines. Second, mechanical treatments may cause significant disturbance and/or compaction of the substrate (Menges and Gordon 2010) and accumulation of woody debris (Possley et al., unpubl. data). Finally, mechanical treatments can be quite costly (Maschinski et al. 2005). If hardwood reduction is not followed by a fire within the next year, the investment may have been fruitless, as has been shown to be the case for Florida scrub habitat (Weekley et al. 2011).

3. Costs and benefits of management alternatives in Miami and beyond

Perhaps the most important question for managers of fire-excluded forests is whether there is an ecological threshold for one or more controlling variables beyond which the ecosystem trajectory is irreversibly shifted away from that of a healthy, pyrogenic community. In other words: how do we know when a fire-excluded ecosystem is approaching the ecological point-of-no-return? Studies of ecosystem dynamics in other forest types have shown that significant abiotic changes can occur when plant communities transition between stable states (Vituosek and Reiners 1975; Berendse 1998; Read and Lawrence 2003). These changes to soil nutrient and moisture levels can, in turn, alter biotic factors including microbes (De Deyn et al. 2003; Jia et al. 2005; Fierer et al. 2010) and flora (Olff et al. 1993; Berendse 1998). In our study system, it is possible that once significant abiotic and microbial changes have occurred, restoring pine rockland vegetation, along with frequent fires, may be prohibitively complex or not even possible.

The ecological point-of-no-return for pine rocklands and other pyrogenic forests corresponds with the loss of flammability (Figure 7). Pine rockland fragments may withstand 3–8 years (Wade et al. 1980) without fire and still maintain their flammable properties; fine fuels like pine needles, grasses, and dead palm fronds are key. But when litter depth and tree density reach a threshold, flammability is lost and managers must intervene to bring the system back to the point where it could carry a fire. Eventually, when the flammable species are no longer part of the system, it has effectively transitioned to an alternative stable state of a hardwood forest, and restoration to pineland simply by reintroducing fire is impractical and may, in fact, be impossible.

Ideally, we would prefer to identify early warning signals that foretell an impending critical state change, so that transition from pineland to hammock could be avoided (see Scheffer et al. 2009). Our study cannot definitively provide early warning signals, but it suggests which preserves are closest to the tipping point. We hope that this dataset might serve as a baseline for a long-term study that could capture such ecological warning signals.

While the ecological barriers to restoring fire-excluded pine rocklands can be difficult to quantify, the financial barriers are clear. For extremely closed-canopy pine rocklands, the cost to remove thick moist litter and hardwoods in order to return the community to a pyrogenic state would certainly be prohibitive (Maschinski et al. 2005). Additionally, any such costly large-scale actions attempting to re-create a pyrogenic community are likely to create so much disturbance that they would introduce invasive species, hindering the original restoration goals. In our case study, economics alone are just cause for instituting regular prescribed burns. In 2010, the average cost of prescribed fire was $5883 per hectare for preserves in various stages of fire exclusion (Miami-Dade County Natural Areas Management, unpubl. data). Once the preserve loses flammability, hardwood reduction must be conducted. Then costs increase exponentially, at $2500 per hectare for mildly fire-excluded areas (8–12

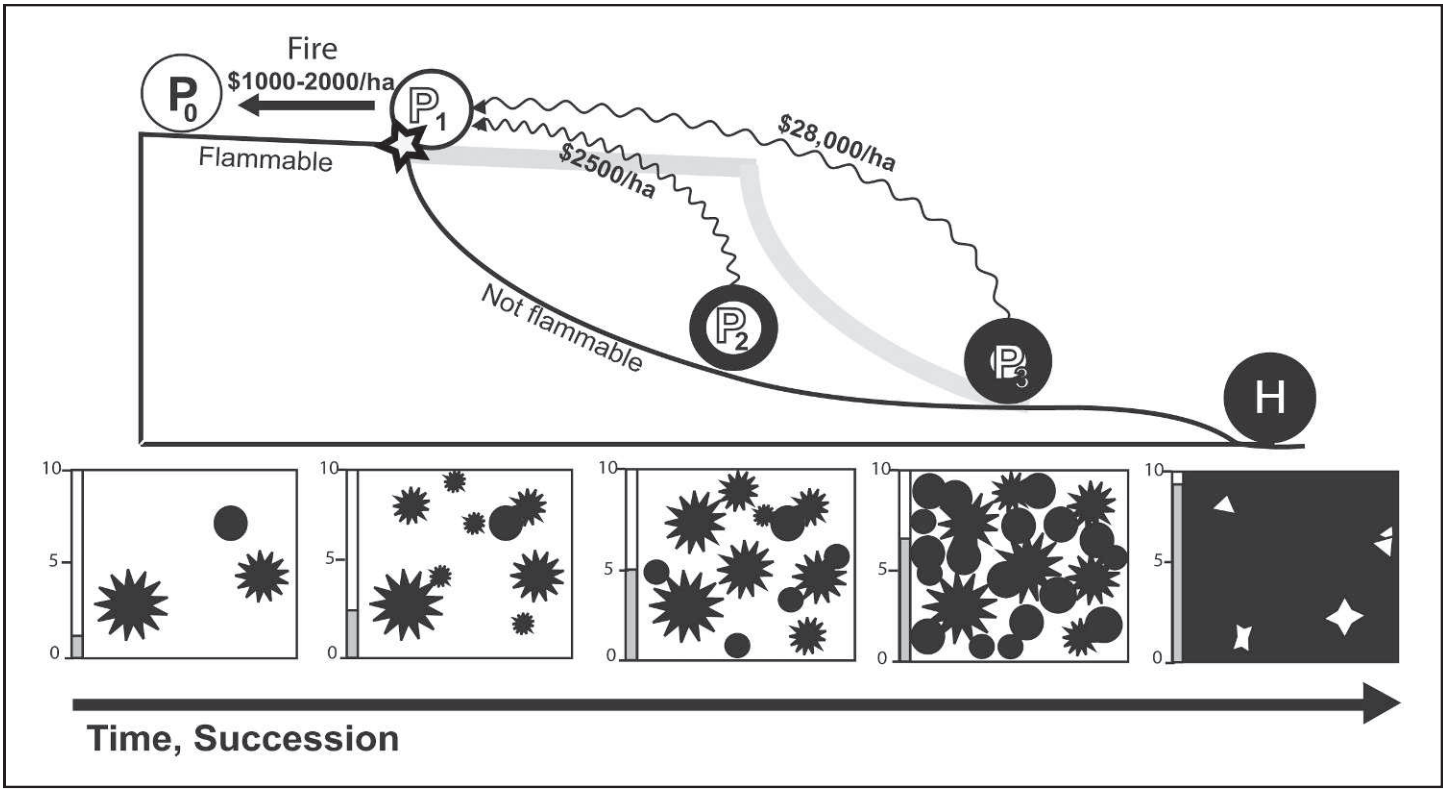

Figure 7. Simplified schematic of the trajectory of an urban pine rockland fragment (represented by a circle). The graphic directly below each stage represents average litter depth (gray bars, in centimeters) and density of shrubs and trees (in black). Depending on the overall health of the system, the point (hollow star) where flammability is lost may shift left (more vulnerable) or right (more resilient). The trajectory shown in gray represents a more resilient, contiguous pine rockland.

- **P_0 – Maintenance conditions. The ideal pine rockland preserve, needing very little management other than prescribed fire every 3–8 years.**
- **P_1 – Fire exclusion Phase – I. Over time, the preserve nears a threshold where it will no longer carry a fire. Without fire the ecosystem will transition to a state (P_2) with increased hardwood density and more closed canopy. If a prescribed fire is conducted, the cost to return to maintenance conditions (P_0) will be relatively low.**
- **P_2 – Fire exclusion Phase – II. The preserve is on a trajectory toward becoming a hammock and will not burn without vegetation management. Inflammable species are present in the understory, and the shrub and canopy layers have become dense with hardwoods. Hardwood reduction at a cost of a few thousand dollars per hectare will allow the system to burn. Then, fire every 2–3 years for a period of 6–9 years followed by fire every 3–8 years (Wade et al. 1980) will return it to maintenance conditions.**
- **P_3 – Fire exclusion Phase – III. Fire exclusion is severe but fine fuels are still present. It is feasible to restore it to a pine rockland by removing hardwoods at high cost and possibly pines, palms, and accumulated organic matter prior to reinstating fire.**
- **H – Hammock. The pine rockland has succeeded to a hammock. Whether or not it is even possible to return it to a pine rockland, the cost to do so would be so high that it is not logistically possible. Costs to maintain the system as a healthy hammock are comparatively very low.**

years) to $28,000 per hectare for more severe fire exclusion (> 12 years) (Table 1). The earlier fire can be reinstated, the greater the savings will be. Maintenance of regularly-burned fragments will continue to be necessary, but costs-per-hectare will continue to decrease until a regular fire rotation is achieved. It is only after a regular fire regime has been reinstated to an urban pine rockland fragment that vegetation management can provide the ultimate step to achieving a maintenance state.

4. Practical applications for managers

In addition to making site-specific recommendations and re-emphasizing the importance of fire as a management tool, this monitoring program has produced several useful products. First, the summary charts and tables we generated have been beneficial to visually compare the restoration stage of different Miami-Dade County preserves during discussion and planning. Second, because we make a direct link between our data and herbaceous diversity, we demonstrate that simple actions like measuring litter depth, or even visually estimating percent hardwood cover, can be applied by managers of pine rocklands as a very quick, inexpensive, and easy way to prioritize hardwood reduction and burn scheduling. A “flammability scorecard” where managers estimate the cover of grasses, hardwood, and palms, and measure depth of leaf litter could help to prioritize fire and hardwood reduction in preserves. Finally, we have generated clear, quantitative data justifying the use of fire in Miami’s pine rockland fragments, even though the process is, at times, unpopular or difficult. We hope this brings Miami-Dade County one step closer to having greater public and municipal support for prescribed fire in the wildland urban interface.

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