



Management of a Globally Imperiled and Fire-Dependent Ecosystem in the Urban Matrix of Miami–Dade County, Florida: A Case Study of the Richmond Tract Pine Rocklands

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Abstract: Pine rockland habitat of South Florida is among the most highly threatened terrestrial ecosystems in the neo-subtropics and is among the rarest worldwide. With only 1.2% of its original extent remaining outside Everglades National Park, fewer than 780 hectares of this ecosystem remains across all of South Florida. This fire-dependent ecosystem—habitat for many rare, endemic species—has experienced substantial deforestation and defaunation due to urbanization, land use change, habitat fragmentation, fire suppression, and exotic plant invasions. Owing to the small size of remaining fragments, and the fact that most are surrounded by urbanization, adequate burning regimes are suppressed. The Richmond Tract, a complex of twelve separate parcels under multiple private and public ownership partially surrounding Zoo Miami, is the largest tract of pine rockland outside the federal protection of Everglades National Park. In this article, we take inventory of the threatened biodiversity at the Richmond Tract and focus on the policy and management landscape. We take a close look at threats to the pine rockland's persistence here and review approaches that either help maintain the health of this ecosystem or those that may need to be reconsidered. We end by discussing coordination among multiple stakeholder groups, the potential use for incentivebased conservation practices, and suggesting ways to improve management in highly urbanized South Florida.

Keywords: urban preserves; habitat management; wildland–urban interface; prescribed burning; urbanization; endangered species; critical habitat

1. Introduction

Conservation strategies vary by organization or agency and may include tax easements, land covenants, fee simple purchases, and other tools to promote conservation through both social and economic incentives [1,2]. In heavily urbanized Miami–Dade County (hereafter MDC), with a population of over 2.7 million people [3], voter-approved county-wide covenant and fee simple conservation programs have been implemented since 1979 [4] and in partnership with the State of Florida and non-governmental collaborators since the 1990s [5]. Subnational reserves generally do not correspond to globally recognized IUCN protected area categories [6], yet they serve important roles in safeguarding endangered habitats and species from threats of urban sprawl, invasive species, and land use changes that affect hydrology and fire regimes [7,8]. Small preserves within urban/suburban matrices may contain important populations of myriad plants and invertebrates [9–12] and form habitat for migratory and nesting birds [13–16]. For example, small preserves protect 205 of the 244 critically imperiled plant species native to South Florida (84%), while the region's largest protected areas, which are almost entirely wetlands, cumulatively protect only 66% of those species [17]. They can also be important for environmental



Citation: Figueroa, A.; Heinen, J.T.; Ridgley, F.N.; Whitfield, S.M.; Liu, H. Management of a Globally Imperiled and Fire-Dependent Ecosystem in the Urban Matrix of Miami–Dade County, Florida: A Case Study of the Richmond Tract Pine Rocklands. *Diversity* **2023**, *15*, 426. https:// doi.org/10.3390/d15030426

Academic Editors: Adriano Stinca and Michael Wink

Received: 11 January 2023 Revised: 10 March 2023 Accepted: 11 March 2023 Published: 14 March 2023



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education due to their proximity to communities [18–20], and their total value can thus be disproportionately large compared to their surrounding area [21].

Here, we consider a case study of MDC's efforts to conserve native habitat within a matrix of urban development. We focus on the Richmond Tract (TRT), a complex of 12 properties under multiple ownership that contains the largest remaining pine rocklands outside ENP. We report on management actions and suggestions from TRT's Management Plan [22] and make recommendations based on its ecology and socio-political background, and on current best management practices at urban–wildland interfaces.

The main purposes of this case study are to: (1) summarize the 2018 Richmond Tract Management Plan, (2) review existing knowledge on the ecology and conservation measures in effect at Richmond, and (3) make habitat management recommendations based on national and local policies, gaps within the management plan, and needs based on our experiences and that of county personnel who were consulted for the study.

2. Overview and Importance of South Florida's Pine Rockland Ecosystem

South Florida pine rocklands, which extend from North Miami to ENP and Big Pine Key (Figure 1) [23–25], have largely been replaced by urban development [26]. Like many pine forests, pine rocklands are fire-reliant and need to burn every 2 to 10 years to maintain endemic plants and prevent succession to hardwood ecosystems [27]. They are characterized by oolitic limestone bedrock and nutrient-poor calcium carbonate substrates that support a canopy of endemic South Florida slash pine (*Pinus elliottii* var. *densa* Little and Dorman), a midstory of palms, e.g., saw palmetto (*Serenoa repens* (W. Bartram) Small), sabal palm (*Sabal palmetto* (Walter) Lodd. ex Schult. & Schult. f.), and silver palm (*Coccothrinax argentata* (Jacq.) L.H. Bailey) dicot shrubs, and many rare herbaceous understory endemics [24,28]. Pine rocklands host an estimated 433 native plant species; 47 are endemic to Florida and they also support specialized mutualisms such as pollination and seed dispersal syndromes [29–32].

Many ecologically important animals occupy pine rocklands. In ENP, where the largest expanse remains, the federally endangered Florida panther (*Puma concolor coryi* Bangs, 1899), is sighted occasionally along with more common large mammals such as Florida black bear (*Ursus americanus floridanus* Merriam, 1896) and white-tailed deer (*Odocoileus virginianus* Zimmermann, 1780), the latter of which can affect successional patterns and act as seed dispersers in many forest types [33]. They are now largely absent from remnant pine rocklands throughout the region except for the population of federally endangered Key deer (*Odocoileus virginianus clavium* Barbour and Allen, 1922) on Big Pine Key [32,34].

While larger vertebrates are mostly absent outside of ENP in MDC, the gopher tortoise (*Gopherus polyphemus* Daudin, 1801)—state-listed in Florida and federally listed elsewhere—is found in some pine rocklands within MDC [35,36]. It is considered a keystone species because over 350 other species have been documented using its burrows [37–40], and it has a role in maintaining understory plant diversity via herbivory and seed dispersal of many native plants [41–45]. Historical accounts indicate that gopher tortoises have long-occupied South Florida in small but persisting populations [46–49], and it is thus important to understand the ecology of the species in remnant habitats in its southernmost range.

Pine rocklands comprise the rarest ecosystem type in the state based on the Florida Natural Areas Inventory and, with ongoing habitat fragmentation, managing small reserves is the most realistic option for conserving them [8,25,26,50]. Owing to rarity, high plant diversity [27], and the presence of imperiled animal populations, there is great interest in improving management of the TRT specifically because it is the largest single pine rockland site outside of ENP.



Figure 1. The Richmond Tract is found in Miami–Dade County, Florida, USA, within the historic extent of the pine rockland ecosystem. (a) The pine rockland ecosystem is found exclusively in southeastern peninsular Florida spanning from North Miami into Everglades National Park, with some remnants in the Florida Keys. (b) The dark green area is the historic extent of pine rocklands and the red portion is the Richmond Tract. (c) Richmond contains swaths of critical habitat (red hashed lines) and properties have varying amounts of Natural Forest Community (NFC) land, with Zoo Miami containing the most. This map was created on QGIS version 3.18.2 with layers from Google (base map), MDC (county outline and property ownership), USFWS (critical habitat), and J. Possley (historic pine rockland extent).

2.1. History of the Richmond Tract

Small, isolated habitat fragments can be difficult to manage due to edge effects and invasive species [51–53]. Yet the multiple ownership of large tracts such as TRT poses other difficulties such as policy and social constraints associated with prescribed burning near neighborhoods and conflicting goals of various owners [54]. However, if management is coordinated and successful at achieving goals set forth in the management plan; e.g., restoring ecological health, monitoring habitat integrity, communicating across boundaries, and developing best practices [22], then TRT could be a valuable network of contiguous natural area [55].

Macfie [56] covers the history of the site in detail, and we briefly summarize it here. During World War II, the Richmond Naval Air Station occupied the entire area. It was the largest naval air blimp base in the world and much native habitat was removed for infrastructure development. In 1945, the Homestead Hurricane struck the station, and a wildfire destroyed much of it. The station was then decommissioned, and losses were estimated at USD 50 million [57]. While the Navy maintained a presence, the Central Intelligence Agency established a base in 1960 and the Federal Correctional Institution of Miami and the Federal Aviation Administration moved to Richmond in 1976. After the Cold War, more than half the site was set aside for conservation, a fate shared by many former US military lands in that era [58]. Through the National Park Service Lands to Parks program, the federal government turned property over to the University of Miami and MDC under certain covenant conditions about future usage.

Today, Richmond is the location of Zoo Miami and three additional county parks, a federal prison, a Department of Defense operation, a US Coast Guard Communication Station, a National Oceanic and Atmospheric Administration (NOAA) office, University of Miami's Center for Southeastern Tropical Advanced Remote Sensing (CSTARS), the Robert Morgan magnet school/educational center, and the Coral Reef Commons; all contain pine rocklands. MDC owns 57% of the area among six county properties (Table 1), the federal government owns 30%, and private interests own the remaining 13%.

Table 1. Land ownership at the Richmond Tract (adapted from Table 1 of Possley et al. 2018). Miami– Dade County is the largest landowner at TRT with 57% of all land and 64% of all the Natural Forest Community), second is federal stakeholders with 30% total and 23% NFC ownership, and private property owners with 13% total and 15% NFC land. Meanwhile, private lands contain the highest proportion of designated NFC lands (46%) followed by Miami–Dade County (43%) and federal properties (26%).

Landowner	Total Hectares	NFC Hectares	Proportion Designated as NFC
County (57% total land ownership, 64% of all NFC ownership)	477.9	203.4	43%
Zoo Miami	260.8	90.2	35%
Larry and Penny Thompson Memorial Park	109.4	71.6	66%
Martinez Pineland	55.9	37.6	67%
Gold Coast Railroad Museum	22.3	1.2	5%
Former USCG "Southern Anchor" housing unit	16.6	0.8	5%
Miami–Dade County Public Schools (Robert Morgan)	13.0	1.8	14%
Federal (30% total land ownership, 23% of all NFC ownership)	255.6	66.0	26%
US Coast Guard Station	100.4	32.4	32%
Federal Correctional Institution	87.9	8.5	10%
US Army Corps of Engineers/Dept. of Defense	55.9	21.9	39%
LTC Luis E. Martinez US Army Reserve Center	7.3	0.0	0%
National Oceanic and Atmospheric Administration	4.1	3.2	80%
Private/Other (13% total land ownership, 15% of all NFC ownership)	104.9	48.2	46%
Coral Reef Commons (ownership includes Coral Reef Retail LLC, Coral Reef Resi Ph 1 LLC, RamDev LLC, and University of Miami)	55.9	20.6	37%
University of Miami CSTARS	31.6	27.5	87%
Florida Power and Light	11.7	0.0	0%
CSX (Railroad)	2.8	0.0	0%
South Florida Water Management District	2.8	0.0	0%

2.2. Ecology of the Pine Rocklands at TRT

The Miami Rock Ridge spans much of southeastern Florida and underlies the study site [24]. As a result, most of TRT comprises nutrient-poor limestone soils that support many specialized endemic plant species [27,59]. These species benefit from nutrients that leach into the soil following burns, resulting in changes to soil pH, highlighting the importance of

fire in this ecosystem [60]. The expanse of TRT contains over 300 native plant species [27]; 8 are federally listed (Table 2) and 9 others are at extreme risk of extirpation or extinction (Table 3), making TRT among the most diverse and important remnant pine rocklands. TRT also hosts many animal species, including 10 that are federally listed [61,62] (Table 4), and many of them also require regular burns to maintain optimal habitat characteristics [63]. When looking at the number of federally listed species that occur in pine rocklands, there has been a steady increase in the number of listed species from the 1970s to present (Figure 2a). Specifically, over 60% of the federal listings have taken place after 2010, highlighting the threatened nature of species that occupy this ecological community, and how rapidly listings are taking place (Figure 2b).

Table 2. List of eight federally listed plant species found in the Richmond pine rocklands (data fromthe Richmond Tract Management Plan; Possley et al. 2018).

Common Name	Scientific Name	Taxonomic Family	Federal Listing
Blogett's Wild Mercury	Argythamnia blodgettii (Torr.) Chapm.	Euphorbiaceae	Threatened
Brickell Bush	Brickellia mosieri (Small) Shinners	Asteraceae	Endangered
Carter's Flax	Linum carteri Small	Linaceae	Endangered
Crenulate Lead Plant	Amorpha herbacea var. crenulate (Rydb.) Isely	Fabaceae	Endangered
Deltoid Spurge	Euphorbia deltoidea ssp. deltoidea Engelm. ex Chapm.	Euphorbiaceae	Endangered
Everglades Bully	<i>Sideroxylon reclinatum</i> ssp. <i>austrofloridense</i> (Whetstone) Kartesz and Gandhi	Sapotaceae	Threatened
Sand Flax	Linum Arenicola (Small) H.J.P. Winkl.	Linaceae	Endangered
Tiny Polygala	Polygala smallii R.R. Sm. and Ward	Polygalaceae	Endangered

Table 3. List of nine critically imperiled plant species found in the Richmond pine rocklands, as identified by the Florida Natural Areas Inventory and Institute for Regional Conservation. Florida state listing of each plant species (if applicable) is in the rightmost column of the table (data from the Richmond Tract Management Plan; Possley et al. 2018). All abovementioned species are dependent on fire for their survival.

Common Name	Scientific Name	Taxonomic Family	State Listing
Bearded Skeletongrass	Gymnopogon ambiguous (Michx.) Britton, Sterns and Poggenb.	Poacaeae	N/A
Coker's Creeper	Ernodea cokeri Britton ex Coker	Rubiaceae	Endangered
Pineland Lantana	Lantana depressa var. depressa Small	Verbenaceae	Endangered
Pineland Strongback	Bourreria cassinifolia (A. Rich.) Griseb.	Boraginaceae	Endangered
Rockland Morninglory	Ipomoea tenuissima Choisy	Convolvulaceae	N/A
Sand Ticktrefoil	Desmodium lineatum DC.	Fabaceae	N/A
Shyvine	Zornia bracteate J.F. Gmel.	Fabaceae	N/A
Southern Lady's Tresses	Spiranthes torta (Thunb.) Garay and H.R. Sweet	Orchidaceae	Endangered
Yankeeweed	Eupatorium compositifolium Walter	Asteraceae	N/A

Another important consideration regarding the ecology of Richmond's pine rocklands is the presence of non-native species. Exotic species found in TRT's pine rocklands include reptiles such as brown anoles (*Anolis sagrei* Cocteau in A. M. C. Duméril and Bibron, 1837), green iguanas (*Iguana iguana* Linnaeus, 1758), and Cuban tree frogs (*Osteopilus septentrionalis* Duméril and Bibron, 1841); mammals such as feral cats (*Felis catus* Linnaeus, 1758) and black rats (*Rattus rattus* Linnaeus, 1758); and a suite of exotic plant species. Among exotic plant species, the most common are burmareed (*Neyraudia reynaudiana* (Kunth) Keng ex Hitchc.), Brazilian pepper (*Schinus terebinthifolius* Raddi), and Australian pine (*Casuarina equisetifolia* L.). There are other non-native species that have been found in the broader Richmond Tract but not often in the core of its pine rockland habitat, unlike the above-listed species. Some of these exotic species include feral dogs (*Canis lupus familiaris* Linnaeus, 1758), red-headed agamas (*Agama picticauda* Peters, 1877), and—recently—a Burmese python (*Python bivittatus* Kuhl, 1820). Natural area managers and stakeholders at TRT actively remove exotic species as they are encountered, but their mere presence in the broader complex merits consideration into how these non-native species might affect the ecological community if left unabated.

Scientific Name	Taxonomic Class	Federal Listing
Eumops floridanus G. M. Allen, 1932	Mammalia	Endangered
Polyborus plancus audubonii Cassin, 1865	Aves	Threatened
Mycteria americana Linnaeus, 1758	Aves	Threatened
Drymarchon couperi Holbrook, 1842	Reptilia	Threatened
Gopherus polyphemus Daudin, 1801	Reptilia	Threatened
Anaea troglodyta floridalis F. Johnson and W. Comstock, 1941	Insecta	Endangered
Cicindela floridana Cartwright, 1939	Insecta	Endangered
Leptotes cassius Cramer, 1775	Insecta	Threatened
Hemiargus ceraunus Fabricius, 1793	Insecta	Threatened
Strymon acis bartrami W. Comstock and Huntington, 1943	Insecta	Endangered
	Scientific NameEumops floridanus G. M. Allen, 1932Polyborus plancus audubonii Cassin, 1865Mycteria americana Linnaeus, 1758Drymarchon couperi Holbrook, 1842Gopherus polyphemus Daudin, 1801Anaea troglodyta floridalis F. Johnson and W. Comstock, 1941Cicindela floridana Cartwright, 1939Leptotes cassius Cramer, 1775Hemiargus ceraunus Fabricius, 1793Strymon acis bartrami W. Comstock and Huntington, 1943	Scientific NameTaxonomic ClassEumops floridanus G. M. Allen, 1932MammaliaPolyborus plancus audubonii Cassin, 1865AvesMycteria americana Linnaeus, 1758AvesDrymarchon couperi Holbrook, 1842ReptiliaGopherus polyphemus Daudin, 1801ReptiliaAnaea troglodyta floridalis F. Johnson and W. Comstock, 1941InsectaCicindela floridana Cartwright, 1939InsectaHemiargus ceraunus Fabricius, 1793InsectaStrymon acis bartrami W. Comstock and Huntington, 1943Insecta

Table 4. List of federally listed animals that occupy the Richmond pine rocklands.

* Gopher tortoises are only federally listed east of the Mississippi River and west of the Tombigbee River. ** Cassius and Ceraunus blue butterflies are only protected because of their resemblance to the Miami blue and are not imperiled themselves.



Figure 2. History of federal listing for pine rockland resident species. (a) Histogram illustrating the history and number of federal species listings from 1978 to present. (b) Pie chart showing the percent of pine rockland resident species listings before and after 2010. Data were extracted from the USFWS Environmental Conservation Online System.

Recently, a newly described species of trapdoor spider was discovered at TRT (*Ummidia richmond* sp. nov.) [64] and this complex of pine rocklands contains one of the largest strongholds for the Florida bonneted bat [65,66]. Additionally, the United States Fish and Wildlife Service (USFWS) proposed critical habitat designations for both the Miami tiger beetle [67] and the Florida bonneted bat [68] across the many pine rockland fragments

in MDC. In both designations, TRT is very clearly a crucial site for the persistence of both species with a vast majority of the complex's area being proposed as critical habitat (Figure 3). In total, over 130 gopher tortoise burrows have been mapped onsite [36], comprising one of three relict populations persisting in MDC. TRT is also only one of two pine rocklands where animal-mediated seed dispersal research has been conducted [42]. Onsite, tortoises disperse seeds of over 30 plant species, including those of pineland croton (*Croton linearis* Jacq.), an endemic that is the only known larval host plant for two federally endangered butterflies [69].



Figure 3. Miami tiger beetle and Florida bonneted bat proposed critical habitat. (**a**) Proposed critical habitat for the Miami tiger beetle at TRT and neighboring properties encompassing 589 ha of TRT. (**b**) Proposed critical habitat for the Florida bonneted bat at TRT and neighboring properties encompassing 713 ha of TRT (labeled as 9O). Panels (**a**,**b**) were aggregated from USFWS (2021) and USFWS (2022).

3. Current Management in Miami-Dade County

MDC's Environmentally Endangered Lands (EEL) Program is an example of a successful effort to conserve rare habitat in the suburban/urban landscape of South Florida [4]. EEL started with the Land Tax Covenant Ordinance of 1979 still in effect that gives private landowners a 90% property tax reduction on private native habitats [70–72], conditional upon keeping the area undeveloped for 10 years and adhering to an approved management plan. Restoration is at times necessary and could include a combination of prescribed burning and mechanical removal of debris [23,73]. EEL Covenants are subject to revision or cancellation every 10 years.

In 1990, EEL underwent a major expansion through a referendum that authorized MDC to exceed the property tax millage by USD 0.75 for every USD 1000 of value for two years [5]. County residents voted in favor, raised over USD 90 million [70], and two

trust funds were created: Acquisitions (USD 80 million) and Management (USD 10 million). Other millages were approved subsequently and, since its inception, this fee-simple program has purchased over 9400 ha of habitat [74]. While much is wetlands, many important upland tracts are included [75], totaling 650 ha of pine rocklands including portions of TRT, which contains three county-owned preserves: Larry and Penny Thompson Park, Martinez Pinelands, and Zoo Miami.

Given the patterns of land use change in South Florida, EEL has excelled by most measures. Maintaining pine rocklands can be difficult due to surrounding private uses that increase costs for prescribed burning [34,76]. Though EEL focuses on acquisition of properties larger than two ha [70–72], many are smaller and yet important for plant conservation [17,77]. In addition to EEL, MDC's 1984 Natural Forest Community (hereafter, NFC) Program limits development of upland areas containing pine rocklands and hardwood hammocks [78]. There are several properties, totaling 318 ha, that contain NFC lands at TRT, over 200 ha of which occurs on county properties, followed by federal (66 ha) and private properties (48 ha; Table 1).

3.1. Current Management at the Richmond Tract

All 318 ha of NFC in county-owned lands at Richmond are managed by one Environmental Resource Project Supervisor from MDC's Natural Areas Management Division. Regardless of ownership, landowners are legally obligated to manage NFC on their property. Any activity that results in the removal of or damage to vegetation requires a permit and all management practices must be in accordance with MDC's recommendations. Given the fire-dependence of pine rocklands, NFC areas containing this ecosystem type require prescribed burning. While mechanical thinning is common practice in fire-dependent communities where prescribed fires are not feasible to execute, it is not widely implemented in the Richmond Tract. Without mechanical thinning of vegetation, prescribed burning in overgrown tracts of pine rockland are more difficult, expensive, and hazardous to conduct [26].

According to the 2018 Richmond Tract Management Plan, there are four main goals in managing pine rocklands at TRT effectively:

- 1. Goal 1: Restore and maintain habitat structure and function to maximize native biodiversity and preserve natural resources.
- 2. Goal 2: Implement monitoring to ensure that Goal 1 objectives are met.
- 3. Goal 3: Foster communication within separate county-owned properties and with non-county properties to ensure that Goal 1 objectives are being met.
- 4. Goal 4: Develop best practices for habitats consistent with other stated goals.

Furthermore, the operational goal for pine rockland management in TRT is:

"To achieve a 'maintenance level,' whereby management treatments are conducted to sustain the conditions achieved through restoration efforts [22]".

With these goals in mind, cost-effective and feasible management activities should be coordinated across property lines at TRT, regardless of land ownership.

3.1.1. Prescribed Burning

The ecological and forest management literature is replete with examples illustrating just how important natural and prescribed burns are for the health of fire-dependent ecosystems [79–83]. There is no doubt that both natural and prescribed fires have significant effects on the structure and composition of fire-adapted forest communities. For example, in Smoky Mountains National Park, the severity of fires has been linked to reduced stand density, lower shrub cover, and higher herbaceous cover [79]. These three measures coincide with goals of the Richmond Management plan as well as habitat associations of gopher tortoises in the pine rocklands of southern Florida [22,36]. Fire also substantially reduces microbial abundance and fungal mycelia in forest systems [80]. However, these impacts to the fungal and bacterial communities are short lived as they recover quickly after a

burn [80], allowing these microbial communities to potentially facilitate colonization of the habitat by native pioneer plant species, which has been observed in southern Italy [81].

Some lessons to be learned from forest management and fire ecology literature are that, in southern Europe for example, prescribed burns are used as a tool to decrease the risk of out-of-control wildfires that pose a threat to infrastructure, as is the case in TRT, and to enhance habitat quality for wildlife [82]. While the impacts of fire management can vary from being negligible to reducing plant biomass volume by over 90%, the most effective approach to reducing surface fuels is by applying prescribed burns in areas that have a closed overstory and high surface fuel load [83]. It is important to note that in cases where surface fuels are excessively high, mechanical removal should precede burning to reduce the risk of extremely hot or uncontrolled fires.

Even after considering the benefits of implementing fire as a management tool, prescribed burning remains an underused tool in many parts of the world due to policy-related and logistical barriers to its implementation [54,82]. A consideration to make regarding the use of fire at TRT is stated by Possley et al. [26], where they suggest that what was once considered an ideal fire regime prior to fragmentation and land use change may not be relevant to remaining pine rockland now. Accordingly, the recommendation for TRT is to conduct burning every two to seven years to bring the site to "management condition" [22]. Many areas at TRT are overdue for fire and could benefit from more frequent burns. When a prescribed burn is planned, landowners are notified via mailers with final notification one or two days before the fire [84]. If MDC plans the burn, its Natural Areas Management Division monitors weather conditions to forecast the best burn time. The Florida Forest Service (FFS) issues burn permits to MDC's Natural Areas Management Division and private contractors burning at CSTARS and Coral Reef Commons. However, FFS is usually not present during smaller burns that pose little risk to nearby infrastructure but typically will be present when larger burns could put infrastructure at risk.

In total, 16 individual parcels now comprise TRT and a large proportion of the land under private and county ownership is classified as NFC, i.e., 46% and 43% respectively, compared to 26% federal land (Table 1). With widespread coverage of NFC land—primarily pine rocklands—burning is a priority. The management plan suggests leveraging wildfires opportunistically in addition to prescribed fires to achieve frequent and consistent burns. To enhance management capacity, the establishment of a repository with fire management equipment is recommended in the management plan such that multiple agencies can use the equipment during burns.

3.1.2. Habitat Restoration and Management

Habitat management goals for pine rocklands involves restoring fire return intervals to between two and seven years, oligotrophic limestone substrates, and appropriate canopy and midstory cover [22,85]. To achieve these objectives, actions include prescribed burns at appropriate times, augmenting populations of rare or absent species, and removing invasive species. Concerning prescribed fires, a combination of wet and dry season burns should be implemented to mimic both natural and anthropogenic fires that historically occurred in the pine rocklands [86]. Additionally, the literature provides support for dry season burning as it lowers the extinction risk of a narrowly endemic pine rockland plant species [51].

However, prescribed fires are only feasible in habitat that is not too densely overgrown due to potential hazards of flare-ups during a burn. To achieve the appropriate density of vegetation, areas that lack the appropriate pine density between 50 and 70 mature pines per acre may require planting irregularly-spaced saplings where pines are sparse or removing excess trees where they are too dense [22]. Similarly, if there is more than 25% midstory palm cover, TRT Management Plan recommends mechanical thinning.

A common practice for restoration is to manually remove overgrown trees and vegetation. In the case of heavily disturbed and invaded pine rocklands, a more impactful action is to scrape the habitat down to the bedrock and allow both the seed bank and natural dispersal processes to repopulate the area with characteristic pine rockland flora. While this is labor-intensive and requires heavy machinery, it has been completed in parts of Zoo Miami's pine rocklands with promising results [79]. This practice has also been implemented in Long Pine Key within ENP and it is especially successful in reducing the foothold of highly invasive plant species.

Lastly, another management activity implemented at TRT includes captively rearing and reintroducing rare species, specifically butterflies and native plants [87]. Pine rocklands in South Florida host at least 40 different species of butterflies [19] and, by captively rearing, head-starting, and releasing these pollinators, many native plants are better able to persist. Zoo Miami's Conservation and Research Department has collaborated with Disney's Animal Kingdom and the Florida Museum of Natural History to release and monitor Atala hairstreak butterflies (*Eumaeus atala* Poey, 1887) at TRT. With programs such as Fairchild Tropical Garden's Connect to Protect Network and the MDC EEL program providing stepping-stone habitats [77], healthy populations of plants and pollinators can be maintained in the urban matrix with TRT as a source for many species.

4. Discussion

In many ways, the longstanding federal ownership and military presence safeguarded TRT from land conversion, especially considering the ever-increasing development pressures in the region. There are obstacles to overcome if TRT is to remain ecologically functional and the lack of large vertebrates and other integral fauna and flora, coupled with infrequent burns and uncoordinated management, threaten its health. In the past decade, swaths of pine rockland in Coral Reef Commons were converted to shops and apartments and, during summer 2020, a waterpark and hotel were approved for lease and construction in what is now proposed as Florida bonneted bat critical habitat. While the NFC ordinance provides some protection for pine rocklands, county regulations allow for the development of up to 20% of existing upland habitats in project sites. A limitation to the NFC designation is that the Board of County Commissioners could vote to forgo the 20% rule if they choose to do so [78]. Thus, even more than 20% of globally imperiled pine rocklands at TRT could potentially be developed by circumventing the NFC ordinance, a loophole we suggest should be closed.

Ongoing development exacerbates challenges such as habitat loss to edge effects and invasive species, and more development translates to increased difficulty in conducting burns [34,88,89]. As the largest continuous pine rockland outside ENP, and subdivided into multiparty ownership, coordinating management efforts across property lines at TRT remains difficult. One major shortcoming is the lack of firefighting equipment onsite that would allow for more effective fire management [22]. Allowing MDC's Natural Areas Management Division to become more autonomous from the FFS in conducting burns could address the relative lack of burns at TRT and other county sites. In remnant pine rocklands, the major issue is fire suppression, which makes addressing other issues more difficult. Longer fire intervals correlate with growth and accumulation of excess vegetation [86], leading to more costly management and posing threats to public health and safety when burns do occur [26]. By maintaining appropriate fire regimes, other management costs and local community conflicts would likely decrease thus allowing managers to prioritize other threats.

Inadequate management of patchy preserves is exacerbated by dwindling EEL Program funds. More than 30 years after the referendum was first approved, funds are no longer sufficient to manage sites under the Natural Areas Management Division's jurisdiction, including EEL properties in TRT. The Division is currently understaffed and underfunded, with the EEL Program managing approximately 87 preserves. In the proposed budget for the 2022–2023 fiscal year, MDC allocated USD 3 million for habitat management as part of the EEL program [90], while the estimated amount needed to bring all parcels into "management" status is about USD 10 million per year [79]. Although the proposed budget for 2022–2023 includes a total of USD 68.975 million in grant support from various sources for the EEL program, the large managerial shortfall remains.

There is a clear need to generate revenue for habitat management. Considering the extent to which EEL preserves are dense with South Florida slash pine and overrun by saw palmetto, an alternative approach to both manage habitat and generate revenue could be the implementation of Sustainable Forest Management practices [91]. This approach should not be confused with prioritizing extractive uses while considering benefits to biodiversity as an afterthought. Rather, in Sustainable Forest Management, biodiversity indicators and desirable landscape-level features are first considered with the feasibility of generating revenue being explored secondarily [91]. For example, in the case of the state-threatened gopher tortoise and its habitat associations in pine rocklands, burrow presence is strongly predicted by low levels of canopy cover, leaf litter cover, and midstory vegetation [36]. Mechanically thinning the midstory and canopy could both meet indicators for this species' persistence and achieve other desirable landscape-level features according to the Richmond Tract Management Plan [22].

Another example is in the high density of saw palmetto in EEL preserves. In addition to crowding out rare herbaceous species, these thickets likely interfere with the ability of gopher tortoises to disperse seeds in natural areas [43]. While thinning saw palmetto thickets would reduce its spatial extent and open the mid- and understory, allowing saw palmetto fruit harvesting can reduce the flow of propagules and subsequent recruitment of this dominant palm. Saw palmetto harvesting could be allowed via an existing permitting system through the Florida Department of Agriculture and Consumer Services (FDACS). Individuals holding a valid harvest permit can apply to a lottery-type system for the opportunity to harvest saw palmetto fruits, a form of incentive-based conservation [92,93]. Such a program could require interested parties to purchase lottery tickets for the right to harvest fruits, thereby generating revenue simply through ticket purchases. Subsequently, a percentage of profits generated through harvesting this resource could be taxed so that additional funds are secured for habitat management. An approach such as this which draws from Sustainable Forest Management principles to first meet the needs of biodiversity and subsequently generate funds for other management actions would indirectly demonstrate the extractive use value of urban preserves to the public as well as policymakers, generating public buy-in to preserve these natural areas because of how these parcels would contribute to the common good of the community [94].

Profitable forest resources could be sold through a market-based conservation program [95]. Such a market-based conservation incentive program—where profitable natural resources are extracted primarily to benefit the biodiversity in these preserves and secondarily generate revenue—could be used as a management strategy to generate funds that would support further management actions (e.g., installing fencing, planting rare species, etc.) [6]. We believe that combining habitat management for biodiversity with selective harvesting of forest resources will lead to both greater income generation for habitat management by the EEL program while providing greater benefits to biodiversity conservation than continuing with the status quo.

5. Conclusions

Preventing further loss of pine rocklands in South Florida is a high conservation priority, as is managing the natural integrity of existing tracts. One essential step is to close loopholes in legislation that allow up to one-fifth of sites containing NFC lands to be developed. MDC's lack of staffing and fiscal resources for pine rockland management could be addressed by introducing another EEL referendum via another temporary millage on property taxes. If necessary, an ad valorem tax could also be considered to generate funds for habitat management; with extra resources, it would be feasible for MDC to acquire necessary firefighting equipment to establish an onsite fire cache at TRT and plan more frequent burns.

As suggested in the management plan, habitat management would improve if landowners coordinated burns times so that fires are conducted heterogeneously, thus imitating natural burn regimes [96]. Given that shade tolerance varies among understory plants [97], and litter can be important habitat for many animals [98], management strategies that maintain multiple seral stages tend to optimize native species diversity. Habitat evaluation techniques can be applied cheaply to assess these effects. For example, aerial photographs alone or in combination with field transects can be used to assess or plan for changes in vegetation and litter density, ground cover, shading, etc. Such techniques could be used for species-specific habitat assessments and/or for exploring associations between physical variables and important habitat features [36,99]. This information could be used to inform managers about the spatial scale and the timing of prescribed burns that may be needed [100]. Unified management spanning property lines could include burning as well as the treatment and eradication of invasive species, therefore restoring the diversity of seral stages and preventing further degradation.

Constraints that hinder prescribed burning typically consist of negative public opinion, concerns over liability, and limited funding and personnel [54]. Public outreach should be a core component to enhance education and local support for fire management. Establishing a Richmond Tract Management Council could allocate resources where needed (i.e., to purchase equipment or contract restoration specialists) and coordinate with the appropriate personnel for management activities and public outreach, as suggested in the TRT Management Plan [22]. A unified effort by land managers in neighboring properties would be necessary to preserve pine rocklands optimally, but there is no formal network among the owners. The closest to achieving a coordinated effort was through the development of the TRT Management Plan. This could be rectified through the establishment of a council comprising county, state and federal officials, and private owners, which could meet concurrently with the Pine Rockland Working Group Conference in which pine rockland experts meet annually. Coordinated activities such as prescribed burns, plant monitoring, removing invasive species, and reintroducing extirpated species could be mutually discussed and planned in such a space, with much expertise present.

In summary, TRT is arguably the most important tract of pine rocklands in South Florida given its size, location, elevation, biodiversity, and populations of rare species [19,25,27,32,36,51,62,64,65,87]. While governments at several levels, especially MDC, have strong policies in support of conserving remnant habitats in rapidly urbanizing areas, we contend that plans for managing TRT need more actionable steps to achieve unified, cross-boundary collaboration. Primary among them is the need for consistent, agreed-upon burn policies and better coordination between county and non-county stakeholders.

We end by recommending:

- 1. Introducing another EEL referendum to the MDC electorate to raise funds for habitat management across the county.
- 2. Closing loopholes in county regulations that allow for further destruction of pine rockland habitats.
- 3. Establishing an onsite fire cache and dedicated MDC Natural Areas Management Fire Crew that would work independently to conduct burns at TRT and elsewhere.
- 4. Developing TRT Management Coordination Council to meet at the Pine Rockland Working Group's annual conferences for target setting and coordinating activities.
- 5. Undertaking a public education campaign to inform the local community about pine rockland habitat management through prescribed burning.

If consistent meetings are held and management activities executed in a cohesive fashion as suggested in this case study, TRT could become a foremost example of successful pyrogenic habitat management at the urban–wildland interface.

Author Contributions: Conceptualization, A.F. and J.T.H.; methodology, A.F.; investigation, A.F.; data curation, A.F.; writing—original draft preparation, A.F.; writing—review and editing, A.F., J.T.H., S.M.W., F.N.R. and H.L.; visualization, A.F.; supervision, J.T.H.; project administration, A.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in references [22,67,68] as well as in the USFWS Environmental Conservation Online System.

Acknowledgments: The authors would like to tremendously thank J. Possley and J. Klein for their valuable input in the drafting and early development of this manuscript, given their crucial roles in the development of TRT Management Plan and insight in pine rockland plant conservation on the ground. We would also like to thank S. Munguia for assisting in editing the manuscript and providing helpful feedback on the content of this case study.

Conflicts of Interest: The authors declare no conflict of interest.

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