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RESEARCH ARTICLE

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Evaluating a Fire Management Plan for Fire Regime Goals in a Florida Landscape

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ABSTRACT: Fire management plans (FMP) are complex documents that receive little evaluation of whether their objectives are met. We evaluate the Archbold Biological Station (ABS) FMP for goals related to the fire regime (area burned, seasonality, severity, and fire return intervals). The goals include increasing the area burned with prescribed fires, burning more areas during the May–September natural (lightning) fire season, and maintaining variation in fire severity. The ABS FMP is based on the concept of modal fire-return intervals (FRI) for each vegetation type that allow for variation in FRI in space and time. Our analysis uses detailed spatial data (5-m grid) on vegetation, fire extent, and severity. From 1967 to 2014, ABS increased area burned with prescribed fires. Over time, a greater proportion of ABS was burned with lightning-season fires. Burns had variable but mainly high severity. Fire severity varied with vegetation but was consistent over time. Vegetation slated for frequent burns tended to be behind schedule, while rosemary scrub, slated for infrequent fire, was ahead of schedule. The intermediate scrubby flatwoods, which comprise the largest part of the ABS landscape, had a FRI distribution that matched the FMP. The combination of fire mapping, FRI targets, and GIS offers a verifiable and consistent method of tracking fire regime goals in an FMP. We discuss inevitable tradeoffs in managing fire for multiple species and vegetation types over a large landscape and we provide recommendations for FMP monitoring and evaluation that may be broadly applicable to fire-adapted vegetation.

Index terms: fire return interval, fire severity, Florida scrub, geographic information system, prescribed burning

INTRODUCTION

Fire is the predominant ecological disturbance worldwide, having affected ecosystems for millennia and having profound influences on plant communities and the evolution of life histories (Bond and Keeley 2005). Fire affects ecosystems on all continents except Antarctica, and is important in grasslands, savannas, shrublands, woodlands, and forests (Bowman et al. 2009). Unlike some other disturbances (e.g., wind), fire is an ecological disturbance that can be manipulated by humans through deliberate burning or fire suppression. Pyrogenic ecosystems are often biodiversity hotspots with many species adapted to fire; one example is the North American coastal plain (Noss et al. 2015).

Despite the worldwide importance of fire (Pyne 1997), and the prevalence of fire management in many areas (Ryan et al. 2013), little has been published on the effectiveness of fire management in achieving fire regime goals such as area burned, seasonality, severity, and fire return intervals. In the southeastern United States (and especially in Florida), fire is a key ecological disturbance and management technique (Figure 1) (Robbins and Myers 1992; Platt 1999; Fowler and Konopik 2007; Noss 2013). Potential fire frequencies in the southern United States, as predicted by climate and chemistry, are quite high (Guyette et al. 2011). However, actual fire regimes are variable across Florida and the southeastern landscape, with fire frequencies and severities varying by vegetation, season, and ignition source. Historical records show that large areas were burned by lightning-ignited fires, especially in the late spring, near the end of the winter–spring dry season, which coincides with the beginning of the lightning season (Platt et al. 2015).

Prescribed fires are commonly used in the southeastern United States to reduce fuels, enhance wildlife habitat, restore ground layers (e.g., to reduce litter and duff), favor endangered and threatened species, and restore vegetation structure (Mitchell et al. 2006). In contrast to lightning fires, prescribed fires are often lit in the winter months (Platt et al. 2015). Frequent prescribed fires are used extensively in longleaf pine (*Pinus palustris* Mill.)/wiregrass (*Aristida beyrichiana* Trin. & Rupr.) ecosystems, where they are necessary to avoid degradation by increasing cover of woody plants and resulting loss of herbaceous plant diversity (Brudvig et al. 2014; Palmquist et al. 2014). Prescribed fire is also a key management choice in managing habitat for many well-known animals such as the red-cockaded woodpecker (*Picoides borealis* Vieillot; James et al. 1997), the gopher tortoise (*Gopherus polyphemus* Daudin; Mushinsky et al. 2006), the Florida scrub-jay (*Aphelocoma coerulescens* Bosc.; Woolfenden and Fitzpatrick 1984),

Figure 1. Archbold Land Manager Kevin Main ignites a headfire during a prescribed burn in scrubby flatwoods

as well as numerous rare plants (Menges 2007). Florida has had legislation since 1987 that provides some protection to prescribed burners, and many agencies and nonprofits have active fire-management programs (Brenner and Wade 2003).

Fire severities and intensities (either prescribed or lightning-ignited) vary among vegetation associations (Abrahamson et al. 1984), among fires in the same vegetation (Godwin and Kobziar 2011), and within fires (Carrington 2010; Rickey et al. 2013). Longleaf pine/wiregrass–dominated ecosystems (including sandhills and flatwoods) burn frequently with low intensity and low severity fires that are relatively complete (i.e., have few unburned patches). In general, fires in xeric Florida rosemary scrub and in seasonal wetlands can be patchier due to lower fuel loads and a high water table, respectively. Fires in saw palmetto (*Serenoa repens* [W. Bartram] Small) dominated flatwoods tend to be both intense and homogeneously complete. Typical fire-return intervals vary from every few years to many decades, depending on vegetation (Menges 2007).

Most dominant plants in the Florida landscape respond to fire by resprouting and clonal growth (Menges and Kohfeldt 1995; Maliakal et al. 2000; Maguire and Menges 2011). However, many species associated with Florida rosemary scrub are killed by fire (Menges and Kohfeldt 1995), but recover from a persistent soil seed bank (Navarra et al. 2011). Because the dominant Florida rosemary (*Ceratiola ericoides* Michx.) is a fire-sensitive species, gaps among these dominant shrubs are larger in the first years after fire (Menges and Hawkes 1998; Menges et al. 2008). These gaps are important to many herbaceous plants and subshrubs, including the endangered plants *Dicerandra frutescens* Shinners (Menges et al. 1999) and *Eryngium cuneifolium* Small (Menges and Kimmich 1996). Most endangered and threatened plants in Florida have positive responses to fire (Slapcinsky et al. 2010).

A Fire Management Plan (FMP) has been defined by the National Park Service as "a document that lays out how fire management strategies and tactics will … provide the necessary tools to meet … goals and objectives" (National Park Service 2016). Evaluation of fire management is fundamental, since the FMPs are based on our best estimates of appropriate return-fire intervals, severity, seasonality, fire sizes, and other aspects of the fire regime. Many FMPs exist, although few have been published in the open literature. Fire management and FMPs typically have myriad goals, including firefighter safety, fuel reduction, habitat restoration and management, rare species viability, and limiting of invasive species spread (Keeley 2006; Schoennagel et al. 2009; Taggart et al. 2009). FMPs often include planned fire return intervals for different vegetation types and specific burn units, which may be tracked with Geographic Information Systems (GIS) (van Wagtendonk et al. 2002). Despite the commonness of FMPs, they have received almost no evaluation in the scientific literature. More common are general assessments of fire regimes and their effects, common in Australia, South Africa, southern Europe, and the United States (e.g., Russell-Smith et al. 1997; Fernandes and Botelho 2004; Wells et al. 2004; van Wilgen et al. 2010). These often include information on fire return intervals, fire sizes, fire seasons, sources of ignitions, and weather conditions during fires. However, these analyses are rarely linked to FMPs or their goals (Burrows 2008). Assessing the effects of fire in specific areas can lead to adaptive management (e.g., van Wilgen et al. 2014), which could feed back into FMPs (Biggs and Potgieter 1999).

Without periodic assessment, we cannot determine whether FMPs are accomplishing their goals. Most FMPs are implemented with little or no monitoring of their success, whether in terms of putting fire on the ground or evaluating ecological effects. State agencies in Florida prepare 10-year plans to assess the effectiveness of management activities, but the data collected are coarse with no measures of fire severity or mapping of fire extent, meaning that it is difficult to accurately assess the effectiveness of fire management (Hilary Swain pers. comm. based on review of more than 100 land management plans by the state's Acquisition and Restoration Council).

At Archbold Biological Station (ABS), an FMP was written two decades ago (Main and Menges 1997). The FMP was written to balance diverse goals and provide heterogeneity in prescribed fire management across the landscape. Goals were related to conservation, research, education, interaction with agencies, fuel reduction, and fireline safety. At the time it was written, the FMP showed that ABS was behind schedule in burning some, but not all, vegetation types (Main and Menges 1997). Most fires were occurring outside of the months usually considered to be the natural (lightning) fire season in Florida (May through August). Other than summary visual reviews during annual burn planning, there has been no systematic or comprehensive accounting of the success of the ABS FMP since 1997.

This paper has several overall goals. First, we introduce the use of GIS-generated grid cells for analysis of fire history in relation to vegetation. Subsequently, we assess the success of ABS in achieving several goals of the 1997 Fire Management Plan relating to the fire regime:

- Increasing the area burned, particularly by prescribed fire.
- Burning mainly during the targeted lightning fire season (May through August).
- Providing variety in fire severities.
- Creating a distribution of FRI around modal fire-return intervals for each vegetation association.

The ABS FMP focuses on natural fire regimes to illustrate its potential benefits and inherent trade-offs, and we emphasize the importance of tracking and evaluating FMP goals to meet the diverse natural resource goals of a managed natural area. Elements of our evaluation process may be broadly applicable to natural areas containing fire-adapted vegetation, both inside and outside the southeastern United States.

METHODS

Study Site

Archbold Biological Station (ABS), established in 1941, is an independent research institution located in south-central Florida, with longstanding programs in research, conservation, and education. For this paper, we focus on fire management in the natural areas of the ABS property. This 3578-ha globally significant preserve has one of the highest concentrations of threatened and endangered species in the United States (Swain 1998).

ABS is located on the southern end of the Lake Wales Ridge (Weekley et al. 2008), a relict sand dune landscape originating during the later Neogene Period (Pliocene Epoch) during a time of elevated sea levels that covered the rest of peninsular Florida (Schmidt 1997). Among the soils left by these processes are xeric sands that are excessively well drained, acidic, and nutrient poor. Summers (June–September) are hot and wet, and the remainder of the year is mild and dry (Abrahamson et al. 1984). During this wet season, lightning is the main ignition source for wildfire (Myers 1990; Duncan et al. 2011). A transition season (approximately May) often combines dry weather, seasonal drought, and lightning ignitions, creating ideal fire weather (Platt et al. 2015). Recent dendroecological research suggests that nearby landscapes had a long history of frequent fire, with many fires occurring during the transition season (Huffman and Platt. 2014. Fire history of the Avon Park Air Force Range: Evidence from tree-rings. Unpub. report)**.** The vegetation of ABS comprises a matrix of mainly pyrogenic vegetation (Abrahamson et al. 1984), including several variants of Florida scrub (e.g., scrubby flatwoods, rosemary scrub, oak (*Quercus* spp. L.) -hickory (*Carya floridana* Sarg.) scrub (Menges 2007; equivalent to southern ridge sandhill, hickory phase of Abrahamson et al. 1984)), wiregrass-dominated sandhill, and more mesic communities such as flatwoods, seasonal ponds, and bayheads (Abrahamson et al. 1984; Menges 1999, 2007). Central Florida and Florida scrub support many endemic plants (Christman and Judd 1990; Dobson et al. 1997; Estill and Cruzan 2001).

The ABS Fire-Management Plan

Fire management has been part of ABS since 1977, when the first prescribed fire was accomplished. The first major, comprehensive Fire Management Plan (FMP) was produced in the late 1990s (Main and Menges 1997). At the time the fire management plan was written, aggressive fire management had been in place for less than a decade, and ABS was considered "behind" in bringing fire to most of the landscape (Main and Menges 1997).

The goals of Archbold's FMP are broad, and include biological, programmatic, and safety-related topics (Table 1). The implementation of the FMP depends on a series of guiding principles (Table 2). The

Table 1. Goals of the Archbold Biological Station Fire Management Plan (Main and Menges 1997).

Goal	Steps Toward Accomplishing Goals
Protect Life and Property	Continue proper training Use appropriate equipment and supplies, informed decision-making, and careful planning.
Enhance Biological Diversity	Enhance native diversity (species richness, the number of species, and equitability, or distribution of species dominances), landscape diversity (patches of various communities across space, including patches with varying fire histories), and species of special interest.
Enhance Threatened and Endangered Species	Use a mix of fire-return intervals and other components of fire regime that are favorable for the most endangered species.
Mimic Natural Processes	Mimic, where possible, the natural range of variation in fire-return interval, fire severity, fire behavior, fire effects, and other characteristics of the fire regime.
Provide a Diversity of Research Opportunities	Provide patches of various fire histories (fire frequency, time since last fire, fire severity, fire patchiness, season of burn) for comparative research; as well as opportunities for studies before, during, and after single or multiple fires.
Provide Educational Opportunities	Maintain biological diversity (so representative organisms are present) in areas accessible to classes and individuals in order to maximize educational opportunities.
Facilitate Interagency Fire Management on the Station and Externally	Interact with other fire managers and their agencies in conducting prescribed burns, sharing ideas and experience, and exchanging knowledge on fire management
Reduce Fire Hazards by Managing Fuels and Fire	Use prescribed burning to reduce fuel levels and provide fire breaks near buildings, roads, and other fire- or smoke-sensitive areas.

FMP was structured around burn units that range in size from 0.3 to 97.4 ha (median 10.4 ha). The burn units are defined by bordering firelanes, roads, or trails and they generally contain multiple vegetation associations (Abrahamson et al. 1984). The FMP focuses on fire-return intervals (FRI) for each unit and aggregated to the entire property. Archbold uses modal (the most common) FRIs and variation in FRI to provide a diversity of FRI for each vegetation association (Abrahamson et al. 1984), with the modal FRI representing what scientists and land managers assumed was the best fire regime for ecosystem management. Modal fire-return intervals range from frequent (every 2–5 years for sandhill, swales, and cutthroat ponds) to less frequent (6–9 years for flatwoods and seasonal ponds), to infrequent (6–19 years for scrubby flatwoods, 10–19 years for oak-hickory scrub, 20–59 years for rosemary scrub) to very infrequent (20–100 years for sand pine (*Pinus clausa* (Chapm. Ex Engelm.) Vasey ex Sarg.) scrub, 60–100 years for bayheads) (Figure 2). Main and Menges (1997) initially assigned a FRI to each burn unit based on its predominant vegetation association. Each unit's FRIs were then adjusted with the goals of providing heterogeneity, research, and education opportunities. For example, certain areas were assigned to a frequent modal fire-return interval to provide fuel reduction around buildings, while others were assigned less frequent intervals to provide vegetation screens or to accommodate research goals. The actual desired FRI for each burn unit was then adjusted iteratively to predict reasonable distributions of FRI across the ABS landscape for each major vegetation association. Finally, we also considered conditions for key species such as the Florida scrub-jay, which prefers fires that keep shrub canopies below about 2 m in height, requiring fires about every 10–20 years on the Lake Wales Ridge (Fitzpatrick and Bowman 2015). We also considered the needs of some rare plants, such as *Dicerandra frutescens* (Menges et al. 2006) and *Eryngium cuneifolium* (Menges and Quintana-Ascencio 2004), which require burning every 5–20 years and for which ABS is a key preserve (Turner et al. 2006). Other guiding principles of the FMP refer to creating a fire regime that retains some features of the fire regime before settlement (larger burns, lightning-season ignitions). In particular, a stated goal of the FMP is to promote pyrodiversity, defined as variation in fire regimes across space and time (Menges 2007). The FMP seeks to maintain spatial and temporal variation in fire frequency, time-since-fire, and fire severity. This pyrodiversity is intended to allow species with a range of adaptations to fire to coexist in the managed landscape and is a bet-hedging approach to our incomplete knowledge of fire regimes and biological responses (Menges 2007).

Application of Fire

In accordance with the ABS FMP, land managers have applied prescribed burns and dealt with accidental and lightning-ignited fires. In planning prescribed burns, the land manager first determines whether the time-since-fire in each burn unit is overdue (having exceeded the FRI), due (within the FRI), or not due (less than the FRI)

Table 2. Guiding Principles for the Managed Fire Regime at Archbold Biological Station, Highlands County, Florida (from Main and Menges 1997).

Component	Rationale
Use **range** rather than single return interval.	Avoid regular intervals. Maintain flexibility.
Apply **entire range** of fire-return intervals to each vegetation type, including very seldom burned.	Provide research and educational opportunities. Increase landscape diversity.
Burn majority or plurality of vegetation at **modal fire-return intervals**.	Manage most of land using evolutionarily and ecologically relevant fire-return intervals.
Apply **lightning-season ignitions** to burn units when possible.	Manage land using season of natural ignitions.
Use **non–lightning-season ignitions** to reduce fuels and for research.	Effectively and safely burn areas with large fuel accumulation, promote research.
Move to **larger burns** and aggregated burns as feasible.	Increase the spatial grain of burns to favor wide range of species, burn more cost-effectively.
Tolerate **heterogeneity in fire severity** including unburned patches.	Produce burns with realistic within-burn patchiness, provide research opportunities.
Maintain **flexibility** with regard to prescribed burn planning and wildfire control.	Provide greatest opportunities for future research and management.
Balance management for biodiversity and ecological processes with consideration of research and safety needs.	Dual missions of Archbold Biological Station, opportunities in basic and management-related research.

for burning during a given year, based on the modal fire return interval and the time-since-fire. Maps are created every January summarizing these spatial data and are shared with ABS staff. In general, scientists are encouraged to design experiments and research projects to capitalize on the annual fire plan. However, they can request a delay or advance for burns for specific research or conservation reasons. From this dialogue, the land manager creates a menu of potential prescribed burns for the coming year. Not all potential areas are burned, which gives the land manager flexibility to accomplish burns under varying conditions through the year.

Fire Mapping

ABS fires since 1967 have had their boundaries mapped. Starting in the 1970s, some fires were mapped for fire severity. Since 1989, we mapped all fires based on four severity levels as outlined in the FMP (Menges and Main 1997). Unburned patches had no consumption of surface litter, dead leaves, twigs, or palmetto leaf blades. Lightly burned patches had small-scale patchiness with unburned patches, with twigs rarely consumed and palmetto leaf blades scorched. Moderate-severity patches had surface litter consumed, but leaves, twigs, and palmetto leaf blades were not fully consumed. High-severity patches exhibited consumption of litter, leaves, twigs, and palmetto leaf blades. For each fire, we mapped areas of different severities using ground and aerial surveys a few days to a few weeks after the burn. This timing allowed the four severity levels to be distinguished. The mapping utilized photographs from small airplanes as well as on-the-ground visits utilizing GPS points, lines, and polygons. Mapping accuracy improved with increasingly better GPS capabilities. The resulting digital maps have a precision of about 3 meters, with patches <20 square meters generally not mapped. Mapped severity patches often correspond to vegetation types which differ in their ability to carry fire through space (e.g., Figure 3).

GIS Grid Cell Data and Analyses

In 2010, we created a vector grid over the ABS landscape. All static mapped datasets (i.e., vegetation and burn units) as well as all annually mapped datasets (i.e., fires) were "gridded" to these 5 × 5 m cells, which number more than one million across ABS. Each grid cell carries a unique ID defined by its centroid ("northing-easting" in UTM Zone 17n NAD 1983). For purposes of analyses, we combined some vegetation types: oak scrub refers to the combination of oak-hickory scrub and sand pine scrub; we also combined cutthroat-dominated flatwoods and seasonal ponds dominated by cutthroat grass (*Panicum abscisum* Swallen).

The cells, characterized by vegetation and fire history (years, number of fires, severity), were aggregated into a Microsoft SQL

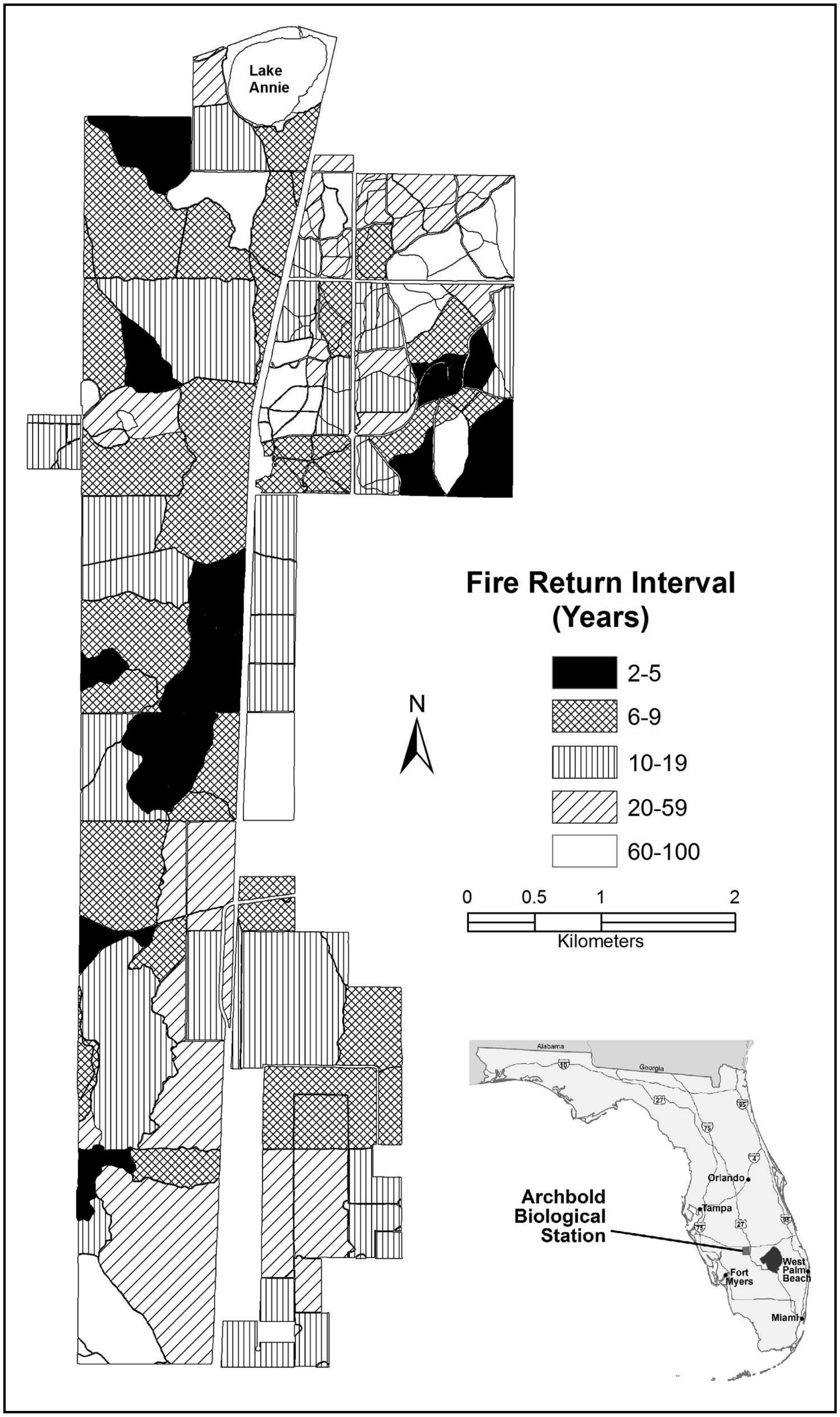


Figure 2. Fire return intervals on Archbold Biological Station, mapped over 81 burn units, specified by the ABS Fire Management Plan.

Server database for further analyses, with one table consisting of one record per grid cell, describing its static properties, and another table consisting of one record per grid cell, per fire event occurring in that cell, describing the details of each fire. The data were queried through a Microsoft Access database front-end. We then used queries to sum areas burned by combinations of calendar year, month, ignition type (prescribed vs. non-prescribed), vegetation, fire severity class, and FRI. The grid cell data were aggregated into a Microsoft Access database for further analyses.

Statistical Analyses

We assessed trends in total area burned over time by correlating annual area burned with calendar year. We used general linear models to assess the effects of fire type (prescribed, lightning, escaped, accidental (including railroad-ignited)), Keetch-Byram Drought Index (KBDI; Keetch and Byram 1968), and fire year on fire size. Pairwise differences in individual predictors were assessed using Tukey's HSD test. We also evaluated trends in the seasonality of burning using a general linear model with temporal period (pre-1990 vs. post-1990), season (May–August vs. other times of year), and their interaction. Fire severity (unburned, lightly burned, moderate severity, high severity) was evaluated in a general linear model with decade and vegetation class (bayhead, flatwoods, oak scrub, rosemary scrub, sandhill, scrubby flatwoods, wetlands; aggregated from Abrahamson et al. 1984). The distribution of fire return intervals in 2014, by vegetation class, was compared graphically to that in the FMP, using stacked bar graphs divided into the areas either overdue (time-since-fire > interval), due (time-since-fire within interval), or not due (time-since-fire < interval). For statistical tests, we used natural log transformations of areas to normalize residuals and control heteroscedasticity.

RESULTS

Area Burned

The area burned at ABS has been continually increasing over time (Figure 4). In the 1970s and early 1980s, fewer than 50 ha

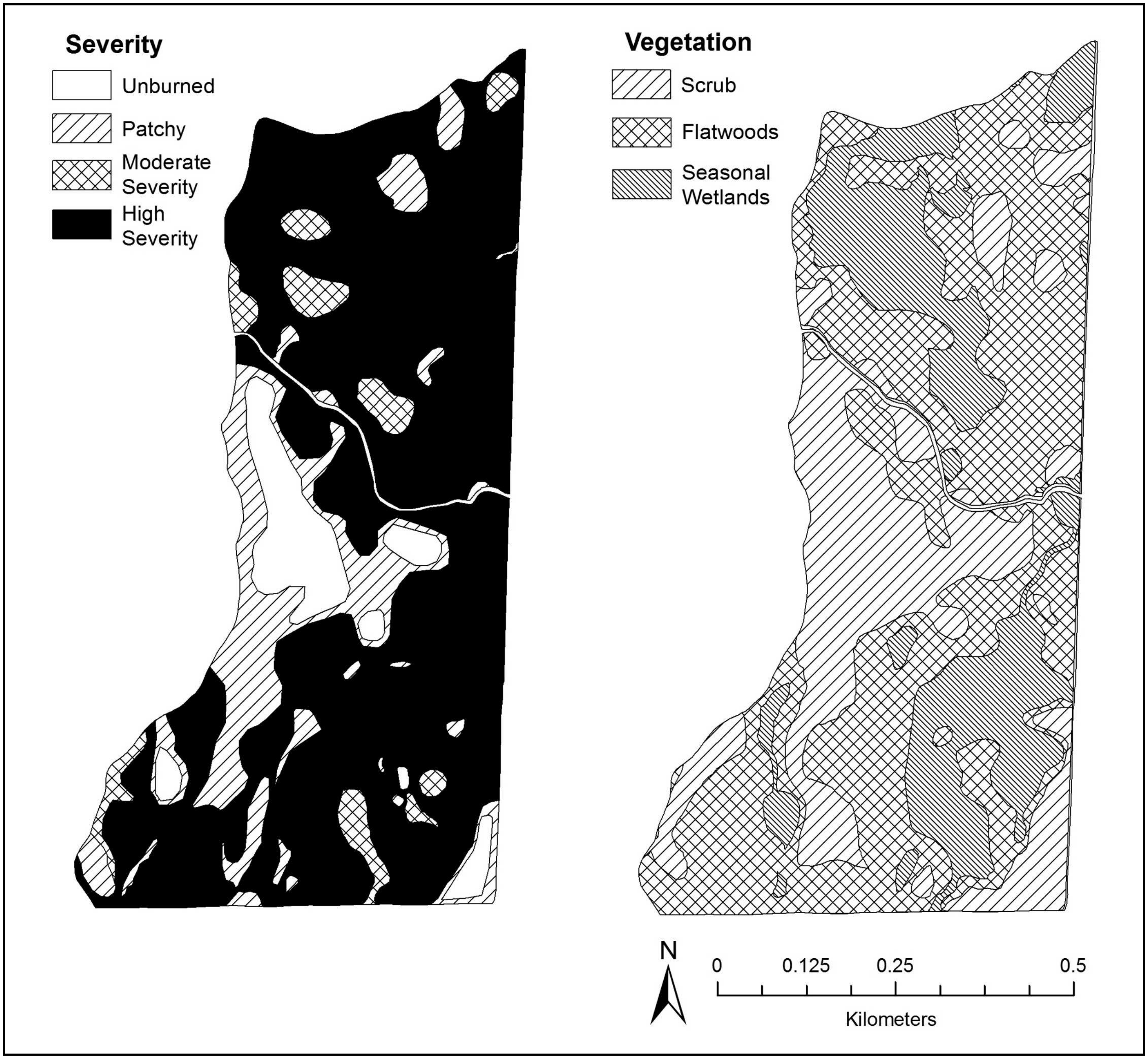


Figure 3. An example of a fire severity and vegetation map (unit 49, fire date 25 March 2010). In this case, unburned to low-severity patches occurred in scrub, while high-severity burn areas were mainly flatwoods and seasonal wetlands (see methods for details on the fire severity classification system).

per year (on average) were being burned, and much of that occurred in a few large fires. The late 1980s and early 1990s saw a large acceleration in the number of fires and areas burned. In the last decade, fires have been larger and more area has been burned. Over time, the annual area burned has increased significantly ($r = 0.397$, $n = 48$, $p = 0.005$), as has the proportion of area burned (especially due to prescribed fire) in relation to the area managed, even with increases in the size of ABS (Figure 3).

The majority of fires at ABS have been prescribed. Two-thirds of fires were prescribed (67%) and about one-fourth caused by lightning (24%); 12 were escaped (5%) and nine were accidental (3%). Fire size was not correlated with the year of the fire, the fire month, or the KBDI. However, fires were larger and more variable in size for accidental (mean 36 ha, SD 77) and escaped (35, 48) fires than those that were prescribed (18, 28) or ignited by lightning (8, 26). Only fire type ($F = 27.1$, df = 3, $p < 0.001$) affected fire size; neither drought nor fire year had significant effects. Lightning-ignited fires were significantly smaller than the other three fire types ($p < 0.05$ using Tukey's HSD test).

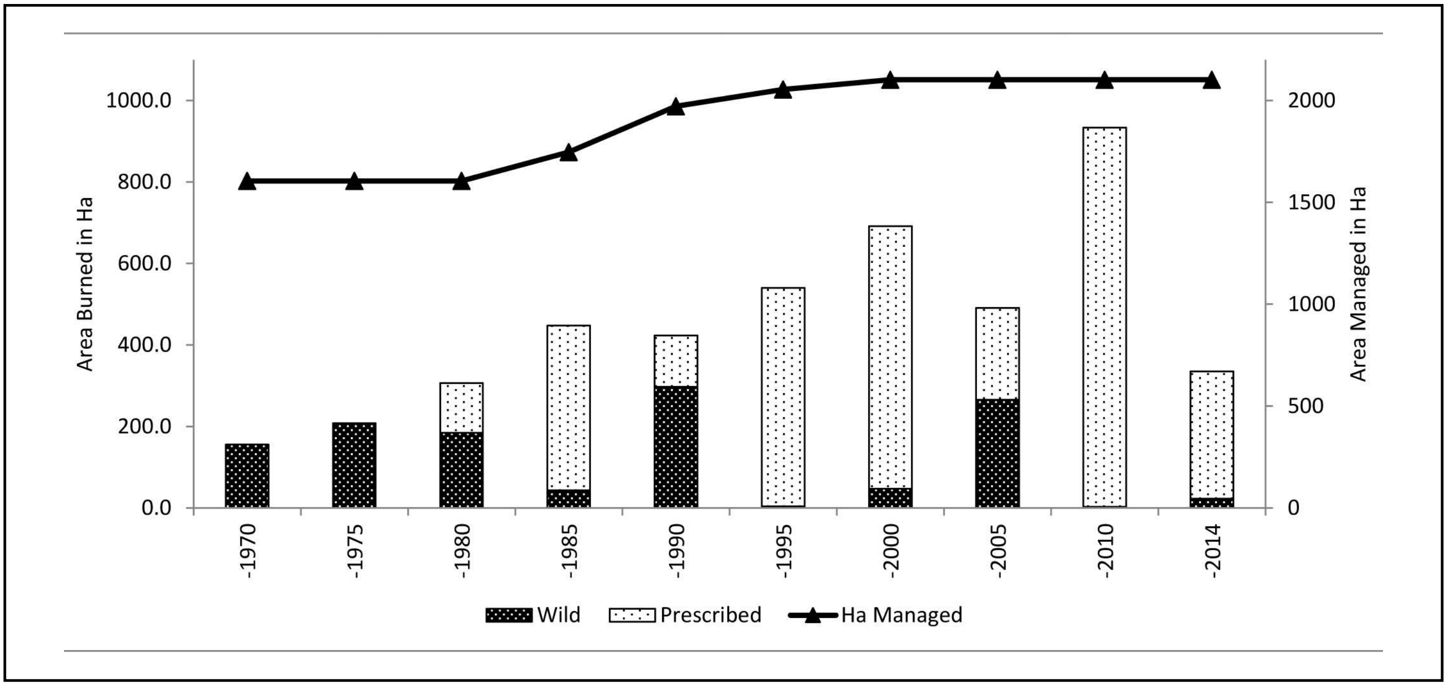


Figure 4. Area (in hectares, as bars) burned at ABS in prescribed and wildfires, binned into five-year intervals (ending with year shown; the final interval covers four years). Also shown is the area of managed land at ABS (line), which has increased due to land acquisition.

Seasonality

During the years leading up to 1990, burning took place throughout most of the year (Figure 5a), with peaks both outside (January, March) and within (May, September) the lightning-fire season (which is May through September). Overall, only 37% of total burning occurred during the lightning season. In the succeeding two decades, burning shifted to these late spring and summer months, with 67% of area burned between May through September (Figure 5b). The total area burned per year was affected by both the temporal period (pre-1990 vs. post-1989; $F = 4.19$, df = 1, $p = 0.044$) and the interaction between temporal period and season ($F = 5.57$, df = 1, $p = 0.020$), but not by season ($F = 0.78$, df = 1, $p = 0.381$), showing the shift from non-lightning to lightning season burning (Figure 5).

Fire Severity

Most fires in the Archbold landscape, whether ignited by humans or lightning, burned at high severity, consuming nearly all aboveground vegetation. Patterns of fire severity varied little among the four decades with data (interaction of severity class with decade, $F = 0.25$, df = 12, $p = 0.995$ in general linear model; Figure 6a), but they have varied by vegetation class. Xeric vegetation such as sandhill, rosemary scrub, and oak-hickory scrub had relatively less area burned at higher severities than more mesic or hydric vegetation (Figure 6b); the differences among vegetation types were significant ($t = 2.44$, df = 19, $p = 0.025$). Fire severity was not strongly affected by drought. The amount of area burned at high severity was unrelated with the KBDI (Spearman's rho = 0.011, $n = 178$, $p = 0.885$).

Fire-Return Intervals and Time-Since-Fire

By 2010, the accelerated pace of burning translated to actual time-since-fire (TSF) distributions that were approaching those suggested by the modal FRI for most vegetation types (Figure 7). ABS was ahead of schedule in burned areas in the 60–100 year and 10–19-year FRI intervals, but behind schedule in other fire intervals. For example, although over half of the landscape area in the 6–9-year FRI had a TSF of 6–9 years in 2010, most of the remaining area supported TSFs that were longer than the target FRI (i.e., the burning still lags the FMP). For the 10–19-year FRI, less than 10% of the area has a longer TSF than 19 years (i.e., the burning is mostly up-to-date or ahead of the FMP).

Planned and actual burning (through 2014) varied among vegetation types (Figure 7). Flatwoods (Figure 7a) and wetlands (seasonal ponds, swales, cutthroat flatwoods; Figure 7b) were most often slated for burning every 6–9 years, and a substantial portion was overdue in 2014 (Figures 7a and 7b). Rosemary scrub was most often slated for burning every 20–59 years, and recent prescribed burns left very little area due or overdue for burning (Figure 7c). Scrubby flatwoods was generally slated to burn either every 6–9 years or 10–19 years; most was not overdue in 2014 (Figure 7d). Oak-hickory scrub and sand pine scrub was most often slated to burn at 10–19 year intervals and most area was not overdue (Figure 7e).

DISCUSSION

Evaluation of the Fire Regime in a Fire Management Plan

For Fire Management Plans to be effective, they must be evaluated in relation to their

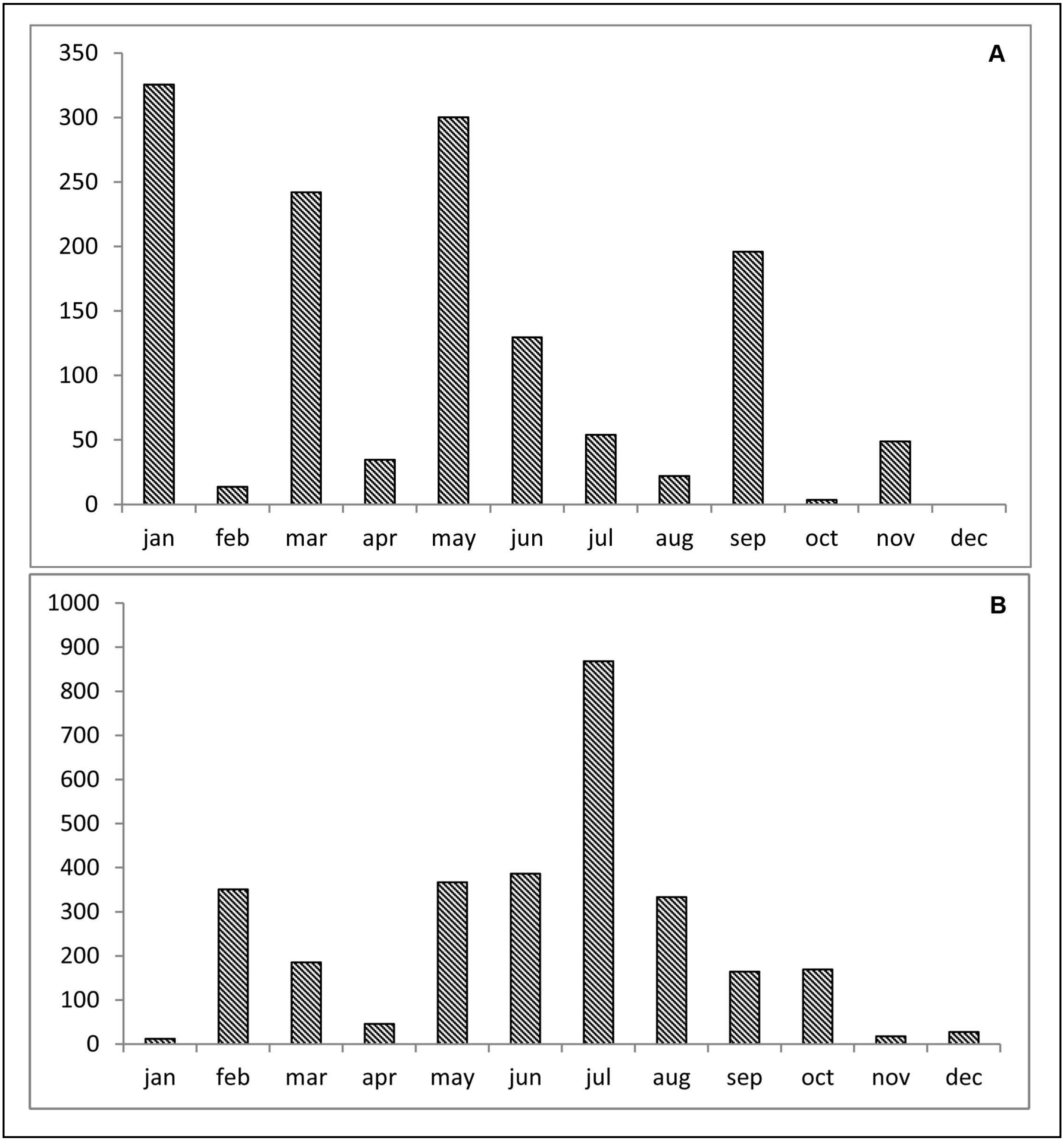


Figure 5. Area (in hectares) burned by month at ABS. Note the change in Y-axis scale.

goals and subsequent adjustments should be made to improve their performance. Yet, this evaluation process is very rarely shared with other land managers and scientists. In this study, we evaluated the goals of Archbold Biological Station's FMP that are related to the fire regime. In general, during the past two decades, burning at ABS appears to be moving closer to the expressed goals of the FMP. The proportion of the area under fire management has increased with increasing area being burned by prescribed

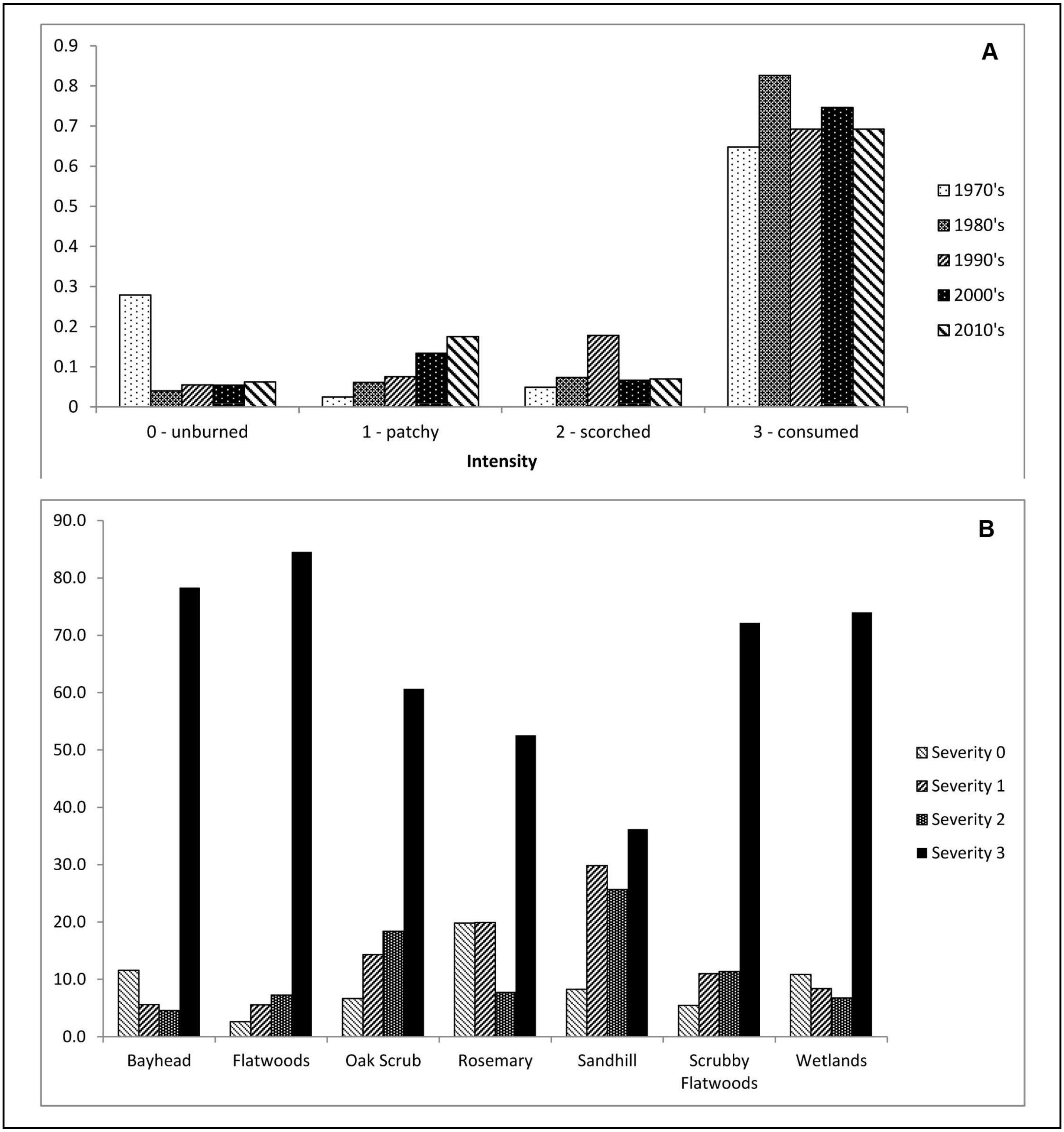
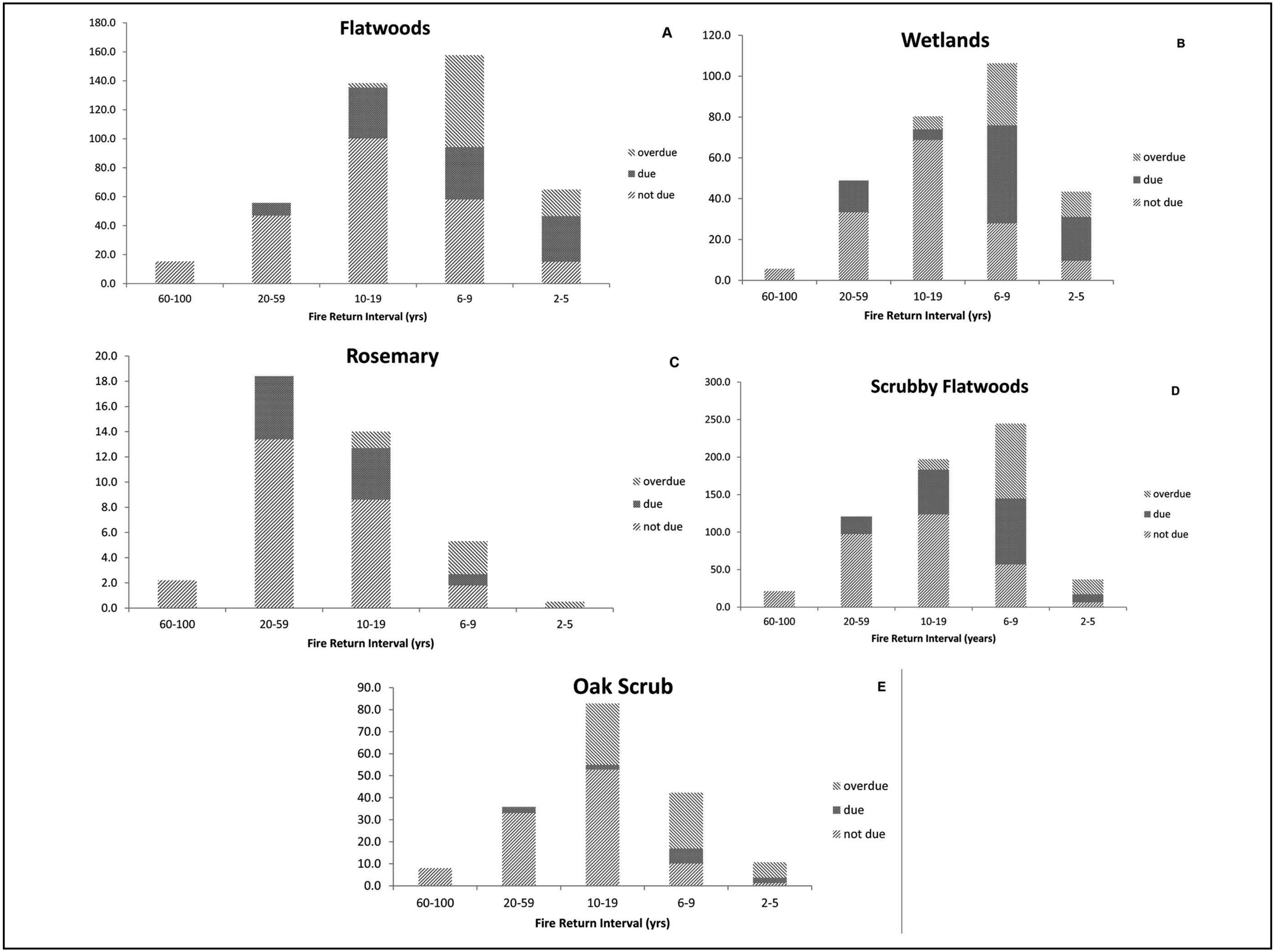


Figure 6. Area burned with different fire severity. A. Proportion burned at different severities by decade. B. Percentage burned at different severities by vegetation type.

fire rather than wildfires. Goals related to fire frequencies, seasonality, and severity have also been met to a large degree.

Management for ecological goals emphasizes burning during the historically relevant fire season, not necessarily during seasons that are convenient or ideal for resource extraction goals. In Florida, winter burns have often been used because of lower humidities, more consistent wind directions, more favorable conditions for crews, and advantages for grazing and forestry. The drier and windier conditions also make winter burns preferable for initial burns in dense, long-unburned veg-

Figure 7. Landscape area (ha) within fire-return intervals at ABS as specified by the FMP, further classified into not due, due, and overdue in 2010. We divide these by vegetation associations. Bayheads and Southern Ridge Sandhill–turkey oak phase are not included; they make up minor parts of the Archbold landscape. Vegetation follows Abrahamson et al. 1984 and Menges 1999: (A) Flatwoods; (B) Wetlands (seasonal ponds, swale, cutthroat flatwoods); (C) Rosemary Scrub; (D) Scrubby Flatwoods; (E) Oak Scrub (Sand pine scrub–oak phase and oak-hickory scrub (Menges 2007), equivalent to Southern Ridge Sandhill–hickory phase of Abrahamson et al. (1984)).



etation that holds humidity and cuts wind speeds. However, as management passes from restoration to maintenance burning, land managers are increasingly shifting to growing-season burns. At ABS, over time, a greater proportion of the prescribed fires has occurred during the summer, a major goal of the plan. Recent findings from nearby Avon Park Air Force Range suggest the historical and current ecological importance of frequent fires, especially during the transition season (centered on May) (Huffman and Platt unpub. report; Platt et al. 2015). In response, ABS will increasingly focus on burning during the month of May, which is at the end of the dry season and the start of the lightning season.

The largest portion of burned areas at ABS have burned at high fire severity and this pattern has not changed with time. The FMP has a goal of producing variation in severity, and this has been accomplished consistently over time. Fire severity varies among vegetation types, being lowest in more xeric vegetation such as sandhill and rosemary scrub. Fire severity was not higher under drier conditions (in contrast with other findings, e.g., Addington et al. 2015). While we do not have evidence of fire severity patterns before European settlement, it may be that large areas burned during drought conditions with high severity. To the extent that prescribed burning does not commonly occur during very dry conditions, prescribed burns may not provide the range of severity that once occurred in the landscape and may be necessary for some fire-specialist species (e.g., black-backed woodpeckers in Montana; Hutto 2008).

For most vegetation associations, progress is being made toward burning more areas within the fire-return intervals specified in the plan. As shown in our graphs, there is good variation in FRI in each vegetation type and most types also have a large part of their area meeting the goal for fire-return intervals. In most parts of ABS, this has involved increasing the frequency of fire. In some areas of sand pine scrub and sandhill, areas that were unburned since 1927 have been gradually burned for the first time during the last few decades. Nevertheless, there remain substantial areas outside of modal fire-return interval targets, which may actually be considered desirable under other FMP goals besides fire effects. For example, areas that have been burned quite frequently or very infrequently offer important areas for research and education, and this diversity in burning for research and education is a stated goal of the FMP. There are also some organisms that prefer long-unburned areas (e.g., black bear *Ursus americanus* Pallas, Florida perforate Cladonia, *Cladonia perforata* Evans). Also, gradually bringing areas slated for infrequent burning into regular burning will provide a diversity of age structures in the future.

Of course, vegetation does not segregate by burn unit and most burn units have many interdigitating vegetation associations. At first glance, this implies unavoidable tradeoffs inherent with burning entire units. For example, fire-return interval targets in the flatwoods portion of a unit may imply burns every few years while the rosemary scrub portions may imply burns every few decades. To some degree, the ability of each vegetation type to carry fire helps the land manager deal with these apparent tradeoffs. Vegetation types that are thought to burn more often actually are more likely to be burned, while more xeric, less frequently burned vegetation types have a higher probability of remaining unburned (ABS, unpub. data). Therefore, the land manager can introduce fire more frequently into a unit with mixed vegetation, knowing that certain vegetation types will not burn every time. Vegetation patterns in the landscape provide feedbacks to fire patterns that the astute burn manager can use to his or her advantage.

One challenge is making sure that lighting patterns are supporting these vegetation differences. For example, in areas that are critical for rosemary scrub species like *Eryngium cuneifolium* (Menges and Quintana-Ascencio 2004), fire frequencies may need to be less than ideal for flatwoods species that benefit from frequent fire (Maliakal et al. 2000). In some units with competing species with high conservation value, portions of the burn unit have been protected from fire with mown or wet lines that allowed fire to affect one species (e.g., *Dicerandra frutescens*) and not another (e.g., Florida scrub-jay).

Fire management plans, if closely evaluated, can provide important information to guide future management. Such evaluations can also help to assess critiques made on the basis of alternative data. In the case of Archbold, our evaluation of the FMP provides some response to concerns voiced by Abrahamson et al. (2010), after their analysis of vegetation data along permanent transects. They suggested that fire-return intervals were too narrow and that a wider range of FRIs should be applied to the landscape. Our analysis shows a fairly wide range of FRIs being applied for each vegetation type. In addition, vegetation data collected by Abrahamson et al. (2010) indicated a decline in Florida rosemary cover. This species is killed by fire and must regenerate from a soil seed bank (Johnson and Abrahamson 1990). Vegetation mapping also shows a decline in rosemary scrub coverage (Gehring and Menges, unpub. data) and the evaluation of the FMP confirms that rosemary scrub has been burned ahead of schedule. Current plans are to limit burning of rosemary scrub in many areas, and many stands are recovering well due to abundant Florida rosemary seedling recruitment. At the same time, the relatively frequent burning of rosemary scrub in some places is expected to favor populations of the endangered *Eryngium cuneifolium*, which is specialized for recently burned rosemary scrub (Menges and Quintana-Ascencio 2004). Many other specialists for rosemary scrub appear to have their metapopulations benefit from fire (Miller et al. 2012; Menges et al. in preparation).

Similarly, Abrahamson et al. (2010) worried about declines in bayhead vegetation due to frequent wildfires that convert this forested vegetation into a shrubby stand. Fires during wetter summer months (May through September) would reduce the probability that bayheads would burn, since they often support standing water at this time. On the other hand, frequent fires can help restore unique vegetation dominated by cutthroat grass (Bridges and Orzell 1999), which has been reduced by fire suppression and drainage (Yahr et al. 2000). With fire suppression, bayhead invasion has occurred into nearby seasonal ponds (Landman and Menges 1999) and flatwoods (Peroni and Abrahamson 1986).

This emphasizes that fire regimes can alter vegetation, often causing alternate stable states (Staver et al. 2011; Hoffman et al. 2012). In these cases, it is necessary to outline the vegetation goals for burning. At Archbold, this may involve decisions on the proposed extent of forested bayheads vs. herbaceous wetlands. Currently, both types of vegetation still occur over large areas, although they have been reduced by drainage and development on lands adjacent to ABS. To some extent, patchy fires can help land managers balance the needs of species that have differing responses to frequent or infrequent fires. Fortunately, patchy fires are not uncommon, especially in rosemary scrub and in wetlands during the summer and fall months.

Our analysis of the FMP for Archbold Biological Station has been useful in that it has lead us to plan an update of the Plan, scheduled to be completed in 2017. We also plan to subsequently reanalyze fire management and update the Plan at 10-year intervals.

RECOMMENDATIONS

Tracking the fire regime goals of an FMP, as we have shown in this paper, is an important first step in evaluating whether changes need to be made in fire management. This tracking should include mapping actual areas burned (not merely burn units ignited). The increasing availability of remote-sensing data and the potential use of unmanned aerial vehicles (drones) may make this mapping easier. Mapping fire and other forms of land management is a crucial part of evaluating prescribed burn programs and creates a powerful source of data for fire research and management (Morgan et al. 2001). At a local scale, maintaining accurate spatial records of exactly which units are burned, with all associated metadata, and a coarse estimate of fire severity, will provide information on the effectiveness of land management. At larger scales, geospatial tools and remote sensing can provide key information. For example, LANDFIRE is a shared program among federal agencies that develops and shares geospatial data related to fire and fuels. Databases include Landsat satellite imagery and ground-based assessments of vegetation condition that could be used to evaluate fire management effects (LANDFIRE 2016). Remote-sensing data can be analyzed to prioritize areas for fire management; for example, fire return interval departure analyses (FRID) quantify differences between presettlement and current fire frequencies (Safford and Van de Water 2014). Areas with either fire suppression or increased fire frequency may need management to avoid extreme, threshold responses (Safford and Van de Water 2014). Fire mapping over large spatial scales using remote sensing algorithms is occurring in the United States (MTBS 2016) and worldwide (Roy et al. 2005).

Population responses to fire management may also be important in evaluating whether an FMP is achieving broader management goals. In the case of ABS, independent research projects on key species such as the Florida scrub-jay, gopher tortoise, *Dicerandra frutescens,* and *Eryngium cuneifolium* provide continual feedback on whether fires are too frequent, too intense, etc. The Florida scrub-jay population, although varying locally, has been stable over time, suggesting the FMP as implemented is appropriate for this species (Fitzpatrick and Bowman 2015). Surveys of gopher tortoise burrows suggest that the reintroduction of prescribed burns to fire-suppressed areas has been beneficial to gopher tortoises (Ashton et al. 2008). Frequent fires are also crucial to several rare plant species, particularly *Eryngium cuneifolium* (Menges and Quintana-Ascencio 2004) and *Dicerandra frutescens* (Menges et al. 2006). These species have fluctuating populations that have generally declined in fire-suppressed areas, but have often increased under ABS fire management.

Combining fire mapping data with other geographic data (e.g., vegetation, hydrology) will help fire managers understand the feedbacks between vegetation and fire, and between hydrology and fire, and may help fine-tune fire planning and practice. Vegetation dynamics in response to fires may also provide important feedback to fire management. In the case of ABS, we do not have an overall program to track vegetation responses to fire, but were able to use a research project (Abrahamson et al. 2010) to provide important feedback that has influenced our fire planning going forward. ABS also uses photo-monitoring to track gross structural changes with fire or lack of fire.

We recommend that fire management plans and their evaluations be made accessible to others in the fire management community, so we may learn from successes and failures and improve our use of fire to meet management goals.

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