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High-resolution burn prioritization models enhance fire management decisions in heterogeneous landscapes

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Abstract

Background Prescribed fire is an essential tool employed by natural resource managers to serve ecological and fuel treatment objectives of fire management. However, limited operational resources, environmental conditions, and competing goals result in a finite number of burn days, which need to be allocated toward maximizing the overall benefits attainable with fire management. Burn prioritization models must balance multiple management objectives at landscape scales, often providing coarse resolution information. We developed a decision-support framework and a burn prioritization model for wetlands and wildland-urban interfaces using high-resolution mapping in Everglades National Park (Florida, USA). The model included criteria relevant to the conservation of plant communities, the protection of endangered faunal species, the ability to safely contain fires and minimize emissions harmful to the public, the protection of cultural, archeological, and recreational resources, and the control of invasive plant species. A geographic information system was used to integrate the multiple factors affecting fire management into a single spatially and temporally explicit management model, which provided a quantitative computations-alternative to decision making that is usually based on qualitative assessments.

Results Our model outputs were 50-m resolution grid maps showing burn prioritization scores for each pixel. During the 50 years of simulated burn unit prioritization used for model evaluation, the mean burned surface corresponded to 256 ± 160 km2 y−1, which is 12% of the total area within Everglades National Park eligible for prescribed fires. Mean predicted fire return intervals (FRIs) varied among ecosystem types: marshes (9.9 ± 1.7 years), prairies (7.3 ± 1.9 years), and pine rocklands (4.0 ± 0.7 years). Mean predicted FRIs also varied among the critical habitats for species of special concern: *Ammodramus maritimus mirabilis* (7.4 ± 1.5 years), *Anaea troglodyta floridalis* and *Strymon acis bartrami* butterflies (3.9 ± 0.2 years), and *Eumops floridanus* (6.5 ± 2.9 years). While mean predicted fire return intervals accurately fit conservation objectives, baseline fire return intervals, calculated using the last 20 years of data, did not. Fire intensity and patchiness potential indices were estimated to further support fire management.

Conclusions By performing finer-scale spatial computations, our burn prioritization model can support diverse fire regimes across large wetland landscape such as Everglades National Park. Our model integrates spatial variability in ecosystem types and habitats of endangered species, while satisfying the need to contain fires and protect cultural heritage and infrastructure. Burn prioritization models can allow the achievement of target fire return intervals for higher-priority conservation objectives, while also considering finer-scale fire characteristics, such as patchiness,

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seasonality, intensity, and severity. Decision-support frameworks and higher-resolution models are needed for managing landscape-scale complexity of fires given rapid environmental changes.

Keywords Fire management, GIS, Marshes, Prairies, Pine rocklands, Critical habitats, Wildland-urban interface, Resource protection, Everglades National Park

Resumen

Antecedentes Las quemas prescriptas representan una herramienta esencial empleada por los gestores de recursos naturales para que sirvan a objetivos ecológicos y para el tratamiento de combustibles en el manejo del fuego. Sin embargo, los recursos operacionales limitados, las condiciones ambientales en que deben desarrollarse, y las diferentes metas a lograr, resultan en un número muy limitado de días en los que se puede quemar, los que deben aprovecharse para maximizar los beneficios a obtener con este manejo del fuego. Los modelos de priorización de quema deben balancear los objetivos de manejo múltiples a escala de paisaje, los que frecuentemente proveen de información bastante grosera. Desarrollamos un marco conceptual de soporte de decisión y un modelo de priorización de quemas para humedales o áreas pantanosas y áreas de interfaz urbano-rural usando mapas de alta resolución en el Parque Nacional de Everglades en Florida, EEUU. El modelo incluye criterios relevantes para la conservación de las comunidades vegetales, la protección de especies de fauna amenazadas, la habilidad de contener de manera segura a los incendios, y minimizar emisiones que puedan ser dañinas para la salud pública, la protección de recursos culturales, arqueológicos y recreacionales, y también el control de especies invasoras. Un sistema de información geográfica fue usado para integrar los múltiples factores que afectan el manejo del fuego con un solo modelo explícito de manejo espacial y temporal, que proveyó de una herramienta computacional cuantitativa alternativa al proceso de decisiones, que son tomadas generalmente basadas en de determinaciones cualitativas.

Resultados Los resultados de nuestro modelo fueron mapas con grillas de 50 m de resolución que mostraban los grados de priorización de las quemas para cada píxel. Durante los 50 años de simulación de la priorización de cada unidad de quema usada en la evaluación del modelo, la superficie media quemada correspondió a 256 ± 160 km2 por año, lo cual significa un 12% del área total del Parque Everglades que sería elegible para realizar esas quemas prescriptas. La predicción del intervalo medio de retorno del fuego (FRIs) varió entre tipos de ecosistemas: las marismas (9,9 ± 1,7 años), las praderas (7,3 ± 1,9 años) y las áreas rocosas con pinos (4,0 ± 0,7 años). El intervalo medio de retorno del fuego (FRIs) también varió entre hábitats críticos para especies consideradas especiales: *Ammodramus maritimus mirabilis* (7,4 ± 1,5 años), las mariposas *Anaea troglodyta floridalis* y *Strymon acis bartrami* (3,9 ± 0,2 años), y *Eumops floridanus* (6,5 ± 2,9 años). Aunque los FRIs se ajustaron exactamente a los objetivos de conservación, la línea de base de intervalos de retorno del fuego, usando los datos de los últimos 20 años, no lo hicieron de igual manera. La intensidad de los incendios y los índices potenciales de generación de parches de vegetación fueron estimados para apoyar el manejo del fuego.

Conclusiones Mediante computaciones a escala espacial fina, nuestro modelo de priorización de quemas puede sostener diversos regímenes de fuegos a lo largo del paisajes de humedales tales como el que presenta el Parque Nacional Everglades. Nuestro modelo integra la variabilidad espacial en tipos de ecosistemas y hábitats de especies amenazadas mientras que satisface la necesidad de contener incendios y proteger el acervo cultural y la infraestructura. Los modelos de priorización pueden permitir que se alcancen las metas de los intervalos de tiempo entre incendios para objetivos de conservación, mientras se consideran a escala más fina las características de las quemas, como el quemado en parches, estacionalidad, intensidad y severidad. Los modelos de soporte de decisiones y de alta resolución son necesarios para manejar a grandes escalas de paisajes la complejidad de los incendios dados los rápidos cambios ambientales.

Background

Fire is a fundamental driver of ecological processes that has influenced the evolution of species in fire-dependent communities, but fire regimes are changing under direct and indirect anthropogenic impacts (McLauchlan et al. 2020; Shuman et al. 2022; Turner et al. 2022). Human populations influence fire regimes worldwide, by clearing forests and shifting land use, dispersing plants, altering ignition patterns, and actively suppressing fires (Bowman et al. 2011; Parisien et al. 2016; McLauchlan et al. 2020), with important consequences for fire-adapted ecosystems and the species inhabiting them. Fire exclusion, suppression, and shifts in fire return intervals (FRIs) have caused habitat degradation (Van Lear et al. 2005), woody encroachment into grasslands (Twidwell et al. 2013) and have led to the decline and extinction of faunal populations (Woinarski et al. 2015). Model simulations have predicted that the complete exclusion of fire from Earth would result in a global transfiguration of biomes (Bond et al. 2005). Fire regimes are changing worldwide, increasing in many arid regions while also being suppressed in areas where human risks are of concern (Shuman et al. 2022).

In modern landscapes, natural resource managers often apply prescribed fire to simulate historical fire regimes that are critical for maintaining biological conservation (Frost 1998; Conedera et al. 2009). Although knowledge of historical fire regimes is important, effective fire management must also incorporate pyrodiversity (Griffiths et al. 2015; Bowman et al. 2016), or the spatial and temporal variation in fire regime. Pyrodiversity is achieved by considering the evolving feedbacks between human-altered ecosystems and fire regimes, and their influences across trophic levels, functional groups, spatial scales, and management history (Freeman et al. 2017). The concept of pyrodiversity has been increasingly considered in ecosystem ecology, forest management, and conservation biology (Martin and Sapsis 1992; Williams and Baker 2012; Kelly et al. 2012; Mason and Lashley 2021).

Management of prescribed fire is complicated by the need to consider the protection of human health and infrastructure, and the provision of ecosystem services (Bowman et al. 2013). The presence of human infrastructure, especially wildland-urban interfaces (WUIs), affects the ability of natural resource managers to achieve conservation objectives through fire management. For example, with increasing population density it becomes harder to apply the concept of pyrodiversity, as fire exclusion and suppression are prioritized over managing fire regimes (Steel et al. 2021). Moreover, land use change and fragmentation may interact with fire regimes in ways that are not totally predictable and bring the risk of causing unintended local extinctions with fire management (Driscoll et al. 2021).

Prescribed fire prioritization and spatial optimization are important tools used to balance competing needs in fire management. For example, such models can be built to use prescribed fire specifically to disrupt major fire movements and protect residential communities (Alcasena et al. 2018), to achieve ecologically beneficial fire regimes (Hiers et al. 2003), or to achieve both goals at the same time (Addington et al. 2020). Suitability analyses and burn prioritization models are similar methods that use values or scores to weigh multiple criteria used to help identify the most appropriate locations for prescribed fires (Hiers et al. 2003; Alcasena et al. 2018; Addington et al. 2020). In fire-prone Australia, a suite of metrics relating fire and biodiversity were applied to spatially nested management areas, allowing multiple agencies to guide ecological outcomes (Haslem et al. 2024).

Fire-related decision-support tools are also needed to manage wetland ecosystems that experience variation in fire regimes at large spatial scales. For example, wetlands of the Florida Everglades vary in hydrology (e.g., days of water inundation or hydroperiod, as well as flooding and drought cycles) and fire return intervals. Therefore, fire regimes in short- and long-term hydroperiod wetlands need to be managed differently (Lockwood et al. 2003). Further, the combined effects of fire and changing hydroperiod influence post-fire recovery and vegetation composition (Ruiz et al. 2013, Kominoski et al. 2022; Nocentini et al. 2024) and are therefore important for habitats structure. For example, the time window for carrying out a prescribed fire in certain areas is often constrained by the need to burn with the appropriate hydrologic conditions while also burning outside of the nesting season of endangered species. More broadly, fire management planning is a complex endeavor, as it must address a variety of competing ecological and logistical goals, as well as human risk factors (McLauchlan et al. 2020; Kupfer et al 2022; Haslem et al 2024). Although qualitative fire management plans are carefully considered and built through expert opinion based on field observations (Hiers et al. 2003), quantitative assessments that use higher-resolution spatial optimization are needed to achieve multiple conservation targets and understand scenarios (Williams et al. 2017).

Here, we present a decision-support framework (Fig. 1) and a quantitative, high-resolution burn prioritization model applied to Everglades National Park (ENP; Florida, USA). Prescribed fire has been used as an important conservation tool for fire-prone biomes of ENP since 1958 (National Park Service, 2023), and the State of Florida currently leads the USA in terms of yearly surface burned by prescribed fire (Melvin, 2021). Based on spatial variability of wetland ecosystem types and habitats of threatened species, we used finer-scale spatial computations aimed to support diverse fire regimes across the heterogeneous landscape. Our model balances ecological needs for fire with the need to contain fires in specific areas, minimizing emissions harmful to the public and protecting cultural heritage and infrastructure. Burn prioritization tools allow natural resource managers to compute FRIs, and to plan fire management in shorter- to longer-term timescales with high efficiency (Hiers et al. 2003). Fire return intervals are particularly critical as they shape vegetation structure and composition, and subsequently maintain faunal habitats (Griffiths et al. 2015). Our finer-scale model outputs will enable fire managers to estimate fire intensity and patchiness and to identify areas within

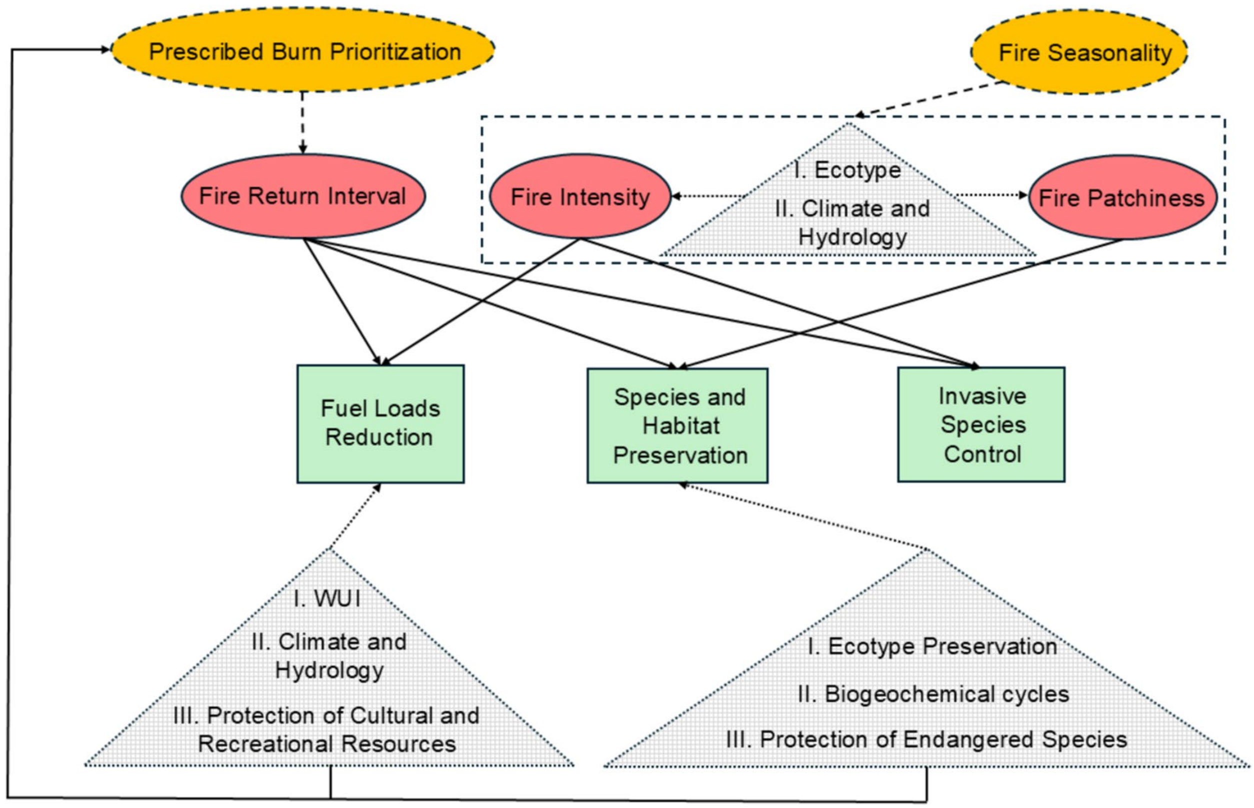

Fig. 1 Decision-support framework for burn prioritization and fire management in large, heterogeneous landscapes. Management factors that control the primary fire characteristics are in orange circles, with dashed lines and arrows. Fire characteristics that have a direct, observable effect on the landscape are within red circles. These are used as management tools to achieve the general fire management objectives, which are in green boxes. Gray triangles contain examples of parameters [e.g., wildland-urban interface (WUI), protection of endangered species] that can be used in models used to achieve fire management objectives. Fire seasonality can be managed to control fire intensity and patchiness. Fire intensity is particularly relevant when trying to reduce fuel loads or control invasive plant species. Fire patchiness is particularly relevant to support ecological niches and habitat diversity, and to create fauna corridors and refugia. Prescribed burn prioritization can be managed to control fire return intervals. Fire return intervals are extremely relevant for the preservation of ecotype communities and habitats, and also when trying to reduce fuel loads or control invasive plant species. Therefore, prescribed burn prioritization models can constitute a primary tool for fire managers

large burn units that may be treated separately, potentially increasing the efficiency in achieving biological conservation goals while reducing resource expenses.

Methods

Study region, ecosystems, and wildlife

Everglades National Park encompasses 4000 km^2 of diverse subtropical ecosystems. Ecosystem types are defined by topographic variation and associated surface water depth and inundation duration, soil types, and biogeochemistry, which collectively determine plant and animal species composition (DeAngelis and White 1994). The dominant ecosystem types within ENP are mangrove forests, freshwater marshes, marl prairies, and pine rocklands (Fig. 2). Coastal mangrove forests were not considered in this study as they are not a target of prescribed fire. Marshes, prairies, and pine rocklands make, altogether, for the whole surface eligible for prescribed fire within ENP, which corresponds to 2,166 km^2 (~54% of ENP).

Freshwater marshes are characterized by extended inundation, and by the presence of herbaceous plant species typical of both ridges (higher ground elevation and shallower surface water), such as sawgrass (*Cladium jamaicense* Crantz), and sloughs (lower ground elevation and deeper surface water), such as spikerush (*Eleocharis cellulosa* Torr.) and American white waterlily (*Nymphaea odorata* Aiton). Prairies have short inundation duration and contain herbaceous plant species, such as sawgrass and gulf hairawn muhly [*Muhlenbergia capillaris* (Lam.) Trin. Var. *filipes* (M. A. Curtis) Chapm. ex Beal]. High elevation patches of land called "tree islands," characterized by short inundation periods and high tree cover, are common. Tree islands have a mixed-species assemblage of both temperate and tropical species, ranging from swamp forests to well-drained upland tropical hardwood

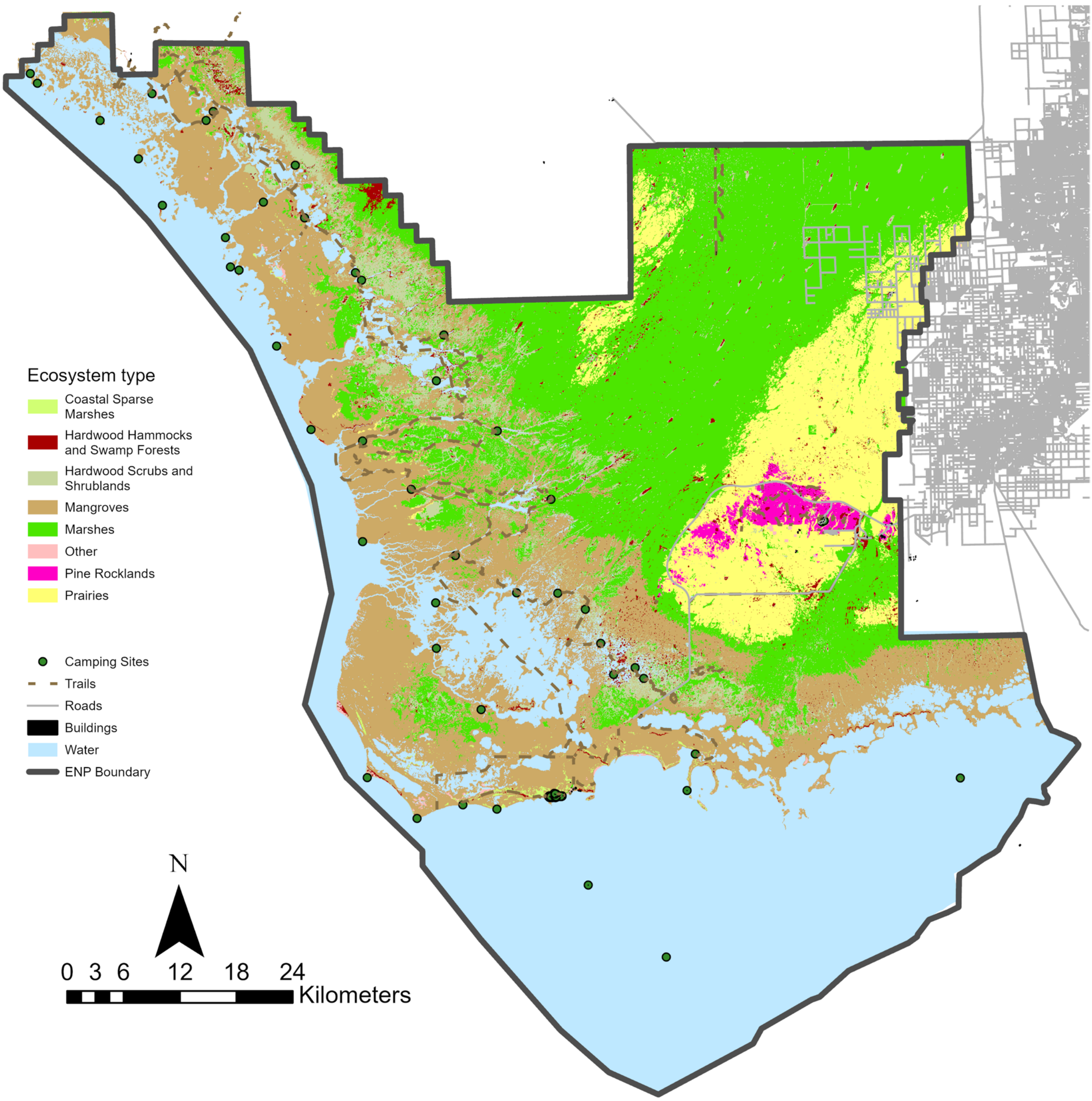

Fig. 2 Main ecosystem types, roads, buildings, trails, and camping sites within Everglades National Park (ENP) boundaries. Ecosystem types were derived from recent ENP vegetation maps (Ruiz et al. 2021). Ecosystem types that characterize the ENP's 3963 km^2 land areas include mangrove forests (34%), freshwater and saltwater marshes (40%), marl prairies (14%), hardwood scrubs and shrublands (6%), hardwood hammocks and swamp forests (2%), and pine rocklands (1%). "Other" includes dunes, barren salt flats, tidal flats, beaches, and canals and levees. These spatial data layers were used to represent criteria in the prioritization model

hammock communities (Ross et al. 2022). Pine rocklands have drier conditions and are dominated by an open canopy of South Florida slash pine (*Pinus elliottii* var. *densa*). Grasses and forbs in the subcanopy of pine rocklands have declined from long fire return intervals that facilitated encroachment by palms and shrubs (Walker and Peet 1984; Myers 1985). Tropical hardwood hammock patches are also embedded within the pine rockland fire-adapted community.

Everglades National Park hosts abundant native and non-native wildlife. A total of 23 faunal species are federally listed as threatened or endangered or are candidates for listing under the Endangered Species Act of 1973 (National Park Service 2021). Several of these species have critical habitat designation within ENP: the Cape Sable seaside sparrow (*Ammodramus maritimus mirabilis*) and the Florida leafwing butterfly (*Anaea troglodyta floridalis*), whose habitats are known to depend on certain FRIs (Possley et al. 2016; Benscoter et al. 2019; Benscoter and Romañach 2022; Henry et al. 2022). In addition, there are other endangered species with broader geographic distribution that occur within ENP, such as the Florida bonneted bat (*Eumops floridanus*) and the Bartram's scrub hairstreak butterfly (*Strymon acis bartrami*), whose habitats also depend on the application of prescribed fire (Possley et al. 2016; Braun de Torrez et al., 2018a and 2018b; Henry et al. 2022), or such as the Everglades snail kite (*Rostrhamus sociabilis plumbeus*) and eastern black rail (*Laterallus jamaicensis*), whose habitats can benefit from the application of prescribed fire (Miller et al. 1998; Lawson et al. 2022; Johnson and Lehman 2021). The presence of native and exotic invasive plant species is another factor affecting ENP fire management. Prescribed fire is employed, in some cases after herbicide applications or mechanical treatments, to remove both invasive woody plants, like coastal plain willow (*Salix caroliniana* Michx.), broad-leaved paperbark (*Melaleuca quinquenervia* Cav. S. T. Blake), and Australian pine (*Casuarina equisetifolia* L. ex J. R. & G. Forst), and herbaceous plant species like old world climbing fern (*Lygodium microphyllum* Cav. R. Br.) and cattail (*Typha* spp.)].

Wetland hydrology controls not only plant species composition but also plant aboveground biomass (Childers et al. 2006) and therefore has a strong effect on fuel loads available for wildfires. Fire further helps maintaining landscape heterogeneity (Ruiz et al. 2013), drives nutrient cycling and productivity (Carter and Foster 2004; Nocentini et al. 2022) and slows the natural successional processes which drive plant communities toward increased woody plant dominance (Robertson 1953; Duever 1984; White 1994). The composition and structure of vegetation communities maintained by fire also serve as critical habitats for the fauna (Miller et al. 1998; Benscoter et al. 2019; Henry et al. 2022). Target FRIs vary among ENP ecosystem types, based on the need to preserve the vegetation and faunal communities supported by each ecosystem type (Noss 2018).

While the southern and western boundaries of ENP adjoin Florida Bay and the Gulf of Mexico, the northern and eastern boundaries are in proximity to urban areas. The proximity of ENP to urban areas poses challenges in terms of using fire to preserve and restore, since the protection of urban and suburban communities is a priority. Prescribed fires are conducted in these areas to reduce vegetation biomass which, if left to grow, could fuel hazardous wildfires (Nocentini et al. 2021). Similarly, within ENP boundaries, there is a series of anthropogenic landscape features around which prescribed fire is applied to control fuel loads. These are cultural and archeological resources (Stutts 2014), recreational resources such as campgrounds and trails, paved roads, and buildings with various designations (e.g., management, scientific research, lodging).

Prescribe fire burn units

Everglades National Park's prescribed fire program has established burn units of varying size, which contain areas target of prescribed fire ranging from 0.03 to 413 km^2 (Fig. 3). The varying size of the units is mainly due to the varying spatial density of roads and natural barriers to fire. Small units correspond to drier areas, usually characterized by pine rockland or prairie communities, while large units correspond to wetter areas characterized by marsh communities (Table 1). Fire management in ENP adheres to the planning concept of potential operational delineations (PODs) described by Thompson et al. (2022), although in an unconventional way: PODs were envisioned to achieve conservation goals by transcending physical and jurisdictional boundaries to prescribed fire where the number of these barriers is too high, while inside ENP the number of barriers is just too low, resulting in the design of large units. However, some ecological benefits can be gained by establishing both small and large units. For example, small units allow managers to apply high frequency burns that may fully consume fuels in pine rocklands, although mosaic burns are typically the desired outcome in these units. Conversely, in large, wetter units, mostly characterized by marsh landscapes, inter-annual variability of surface water depths can produce different configuration of natural fire breaks, that can help managers in mimicking historical variability of fire regimes (Slocum et al. 2003). Because of their internal variability in fuel amounts and water depths, which result in variable flammability, large units can be leveraged to create mosaic patterns across the landscape, fostering ideal conditions for fauna refugia and corridors (Mason and Lashley 2021).

Modeling approach, criteria selection and ranking, and value scoring

To develop a spatially explicit burn prioritization model, we followed the methodology described in Hiers et al. (2003). The spatial model was built on ArcGIS Pro 3.0.3 (ESRI, California, USA). The ArcGIS Pro software was chosen because it allowed for all spatial data processing and, later, directly integrating the outputs into the built-in Model Builder (Fig. S1).

The selection of 20 criteria essential for prioritizing burns was done by incorporating the experience of ENP

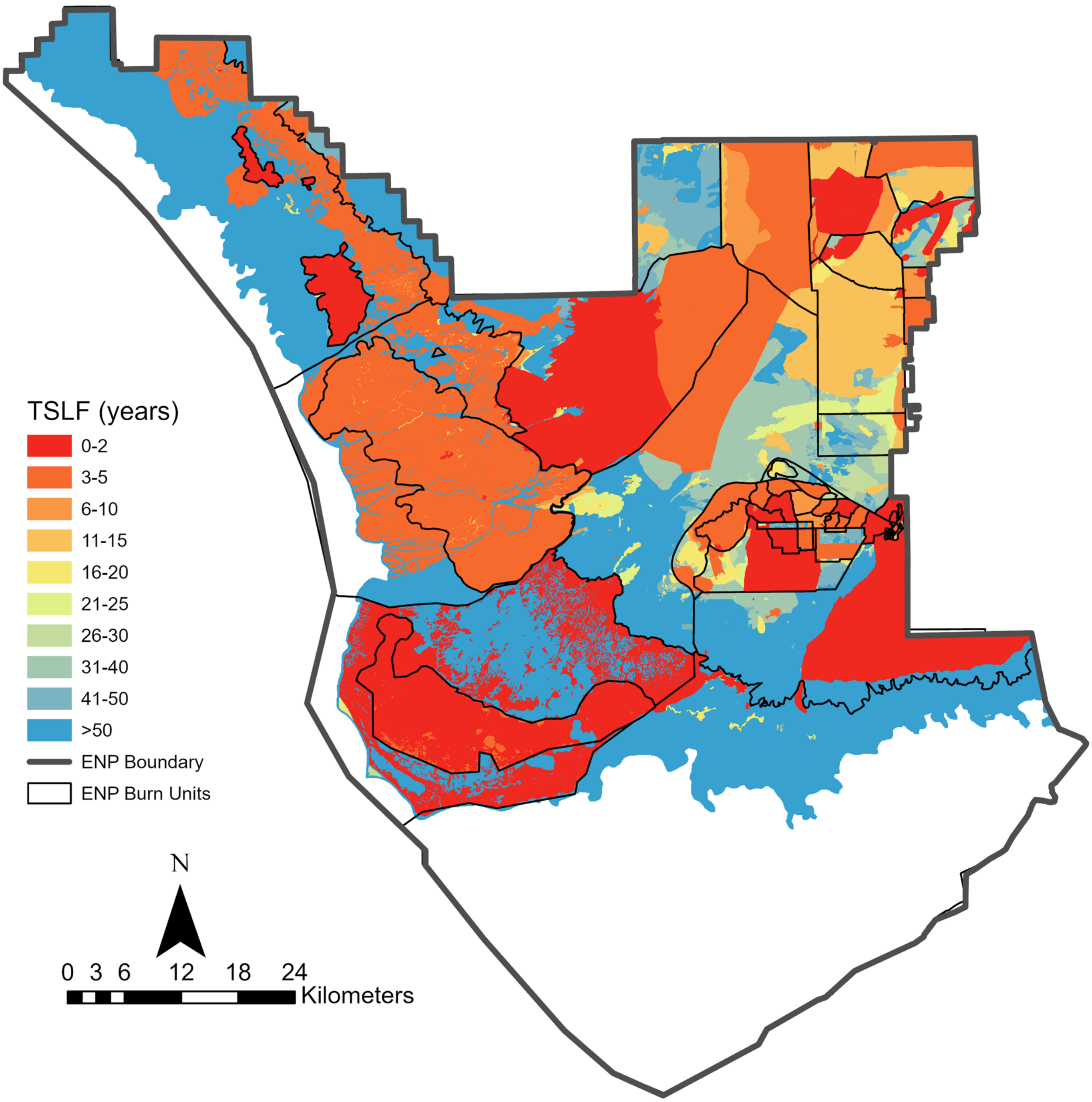

Fig. 3 Time since last fire (TSLF) at the end of calendar year 2022, calculated for each 50 × 50 m pixel within each burn unit of Everglades National Park (ENP). Fire perimeters from both wild and prescribed fires, collected from 1948 to 2022, were used in the calculation of TSLF. This is one of the spatial data layers used to inform criteria in the prioritization model

fire managers and by reviewing the ENP Fire Management Plan (National Park Service 2015). Criteria were ranked according to Fire Management Plan guidance, through discussions with ENP fire managers, and by inferring from published literature the relevance of fire toward habitat preservation. Based on the ranking, criteria were assigned a maximum potential contribution to final scores that reflected their overall importance to burn prioritization (Table 2). For example, "time since last fire" had the highest potential contribution to final scores in the model output, accounting for 30% of the total final score. Then, a value weighting factor was also used according to the specific values that each criterion could assume (Table 2). The "weight" dictated the proportion of the maximum contribution that each criterion contributed to the overall prioritization score during a single model run for a specific land unit.

Table 1 Polynomial models and determination coefficients (R^2) of the regressions between mean surface water depth (2019–2022) and surface target of prescribed fire of each burn unit, and between mean surface water depth and proportion of wildland-urban interface (WUI), marsh, prairie, and pine rockland covers within each burn unit

Predictor variable	Response variable	Polynomial model	R^2
Mean water depth (cm)	Surface target of prescribe fire (km^2)	$y=0.04x^2-0.07x-5.0$	0.29
	Proportion of WUI (%)	$y=-0.009x^2-0.34x+100.1$	0.26
	Proportion of marsh ecotype (%)	$y=0.03x^2-0.7x+0.1$	0.76
	Proportion of prairie ecotype (%)	$y=-0.02x^2+1.9x+4.1$	0.16
	Proportion of pine rockland ecotype (%)	$y=0.007x^2-1.9x+81.3$	0.44

Data sources and processing

We collected spatial data representative of each criterion from public repositories: ENP vegetation map (Ruiz et al. 2021); ENP fire perimeters (Malone 2019); faunal species critical habitats (U.S. Fish & Wildlife Service, 2023); ENP buildings, roads, trails, and campsite perimeters (Barrow and National Park Service Southeast Region Geospatial Resources, 2022); ENP cultural and archeological resources (Stutts 2014); digital elevation model (U.S. Geological Survey 2019); ENP gage surface water stages (South Florida Water Management District 2023); a total of $n=899$ data points for soil total phosphorus (TP) in ENP were compiled from multiple studies (Sah et al. 2007; Scheidt et al. 2021; Nocentini and Kominoski 2021). Due to the sensitivity of the information, the locations of some of the cultural and archeological resources within ENP are not publicly available and were directly provided to us by the National Register of Historic Places. Moreover, all tropical hardwood hammocks characterizing tree islands, identified through the ENP vegetation cover map, were considered archeological sites. This assumption derives from the fact that, potentially, any tropical hardwood hammock could have hosted indigenous people and could therefore potentially contain archeological artifacts (Fradkin 2016).

All spatial data were converted to 50-m resolution grid raster layers, which corresponded to the high-resolution LIDAR used to calculate water depths (U.S. Geological Survey 2019), together with surface water stages collected between the years 2019 and 2022 from 69 locations within and around ENP (South Florida Water Management District 2023). To allow their use together in the model, all maps were aligned by selecting the same spatial extent during conversion to raster file format.

The model outputs were 50-m resolution grid maps, showing prioritization scores only for the pixels occupied by ecotypes which are a target of prescribed fire (i.e., marshes, prairies, and pine rocklands), and maps where the prioritization scores were averaged and scaled to the burn unit polygons.

Model evaluation

Model evaluation was performed by simulating 50 years (2023 to 2072) of fire management following the priorities suggested by the burn prioritization model runs. Every year, by running the model, mean burn prioritization scores were calculated for each burn unit by averaging the pixel (50×50 m) scores. Next, based on the mean scores, units were selected to be treated with prescribed fire. Only units scoring 25 points or more were selected for burning. The 25-point prioritization score threshold was chosen because, after a sensitivity analysis where we tested different thresholds, it yielded the best fit between predicted and target FRIs. Further, no additional units could be selected once a threshold of 400 km^2 of treated land (National Park Service 2023) was passed. This annual treated surface threshold was adopted to reflect the existing operational constraints of fire management in ENP. Although fire management in ENP has gone through various phases in recent decades, it has operated at a steady level of effort since 2017, with 409 ± 165 km^2 burned every year, and this trend is expected to continue in the foreseeable future (personal communication by fire managers Michael Gue and Mayavati Tupaj). Prioritization score and treated land thresholds were therefore set during model evaluation to satisfy the conditions that ENP fire managers would not apply fire too often and achieve the desired FRIs, and that the amount of land treated every year would not exceed ENP resource capabilities. Based on the prioritization scores and the thresholds described above, we selected the units to burn for the simulated year, then we re-calculated TSLF for the following year. The model was run again with the updated TSLF values, and new prioritization scores were calculated for that year.

At the end of the model runs used for evaluation, we had simulated 50 years of prescribed fires that were used to calculate FRIs for the different ecotypes and fauna critical habitats. The predicted FRIs were then compared with the target FRIs gathered from the literature, and the goodness of fit was evaluated with Pearson's correlation.

Table 2 List of input criteria for the burn prioritization model of Everglades National Park (ENP). The "maximum contribution to final score" represents the importance of each criterion in the model and reflects how criteria were ranked. It also corresponds to the maximum score that each individual criterion can contribute to the overall prioritization score (the maximum potential overall prioritization score for a pixel equals 100). The values assumed by each criterion then dictate the proportion (i.e., weight) of the maximum potential score that is computed during a model run. TSLF = Time Since Last Fire; TP = Total Phosphorus

Input criteria	*Maximum contribution to final score*	*Value*	*Weight (%)*
TSLF in marsh ecotype (years)	30	1–2	0
		3–4	10
		5	20
		6	30
		7	40
		8	50
		9	60
		10	70
		11–12	80
		> 12	100
TSLF in prairie ecotype (years)	30	1	0
		2	10
		3	20
		4	30
		5	40
		6	50
		7	60
		8	70
		9–10	80
		> 10	100
TSLF in pine rocklands ecotype (years)	30	1	0
		2	10
		3	40
		4	60
		5	80
		6–7	90
		> 8	100
Wildland-urban interface (WUI)	10	No WUI	0
		WUI	100
Protection of cultural and archeological resources	6	No presence	0
		Presence	100
Protection of recreational resources	5	No presence	0
		Presence	100
Protection of endangered fauna species: Cape Sable seaside sparrow (*Ammodramus maritimus mirabilis*)	8	No CSSS site	0
		CSSS site with TSLF = 1	−50
		CSSS site with TSLF = 2	0
		CSSS site with TSLF = 3	20
		CSSS site with TSLF = 4	40
		CSSS site with TSLF 5–6	60
		CSSS site with TSLF 7–8	80
		CSSS site with TSLF > 8	100

Table 2 (continued)

Input criteria	*Maximum contribution to final score*	*Value*	*Weight (%)*
Protection of endangered fauna species: Florida leafwing butterfly (*Anaea troglodyta floridalis*) and Bartram's scrub-hairstreak (*Strymon acis bartrami*)	8	No butterfly site	0
		Butterfly site with TSLF = 1	−50
		Butterfly site with TSLF = 2	0
		Butterfly site with TSLF = 3	20
		Butterfly site with TSLF = 4	40
		Butterfly site with TSLF = 5	60
		Butterfly site with TSLF = 6	80
		Butterfly site with TSLF > 6	100
Protection of endangered fauna species: Florida bonneted bat (*Eumops floridanus*)	6	No bonneted bat site	0
		Bonneted bat site with TSLF 0–2	0
		Bonneted bat site with TSLF 3–4	40
		Bonneted bat site with TSLF 5–6	80
		Bonneted bat site with TSLF > 6	100
Protection of endangered fauna species: black rail (*Laterallus jamaicensis*)	2	No black rail site	0
		Black rail site with TSLF = 1	0
		Black rail site with TSLF = 2	40
		Black rail site with TSLF 3–5	80
		Black rail site with TSLF > 5	100
Protection of endangered fauna species: snail kite (*Rostrhamus sociabilis plumbeus*)	2	No snail kite site	0
		Snail kite site with TSLF = 1	0
		Snail kite site with TSLF = 2	40
		Snail kite site with TSLF 3–5	80
		Snail kite site with TSLF > 5	100
Control of invasive plant species: old world climbing fern (*Lygodium microphyllum*)	4	No presence	0
		Presence with TSLF = 1	30
		Presence with TSLF = 2	60
		Presence with TSLF > 2	100
Control of invasive plant species: willow (*Salix caroliniana*)	4	No presence	0
		Presence	100
Control of invasive plant species: paperbark tree (*Melaleuca quinquenervia*)	2	No presence	0
		Presence	100
Control of invasive plant species: australian pine (*Casuarina equisetifolia*)	2	No presence	0
		Presence	100
Control of invasive plant species: cattail (*Typha* spp.)	2	No presence	0
		Presence	100
Hydrologic conditions	4	Wet	0
		Intermediate	50
		Dry	100
Oligotrophic status	1	Soil TP ≥ 200 $\mu g\ g^{-1}$	0
		Soil TP < 200 $\mu g\ g^{-1}$	100
Size of burn unit	2	Small (< 10 km^2)	0
		Medium (10–100 km^2)	50
		Large (> 100 km^2)	100
Complexity of burn unit	2	Complex	0
		Moderate	50
		Easy	100

To assess the usefulness of the model to environmental resource managers, baseline fire return intervals were calculated as well, using data from the last 20 years (2003–2022). If predicted fire return intervals fit more accurately the target set toward conservation goals and achieved shorter fire return intervals in WUI areas, it would demonstrate the usefulness of the model to manage prescribed fire in a large, heterogeneous landscape such as ENP.

Burn unit analysis

Further analyses were conducted to show how hydrology dictates, not only ecotype and habitat differences among ENP burn units, but also their size, as more inundation translates into reduced density of natural and artificial (WUI) barriers to fire. Polynomial models and determination coefficients (R^2) were used to describe the correlations. In addition, a within-burn unit heterogeneity index was calculated, and used together with burn unit size and ecotype and habitat configurations to identify sub-units that may be managed distinctly. The heterogeneity index was calculated as the mean of the standard deviations within each burn unit, calculated each year based on the distribution of the prioritization scores at the pixel scale (50×50 m).

Fire intensity and patchiness potential indices

Fire intensity and patchiness potentials were estimated using parameters identified by previous research in ENP (Slocum et al. 2003). The authors identified both hydrologic conditions, through the progression of the wet season, and vegetation communities' characteristic of higher and lower elevations, as factors strongly influencing fire intensity and patchiness in ENP's wetlands. Although the same parameters were used to calculate the two indices, two distinct methods were applied.

For the fire intensity potential index, a score for hydrologic conditions and a score for ecotype was assigned to each 50×50 m pixel. To give the same weight to both parameters, hydrology data were grouped in the same three classes previously described: mean water depths above 50 (score of 1, wet), between 0 and 50 (score of 2, intermediate), and below 0 cm (score of 3, dry). Similarly, ecotypes were assigned a score of 1 (marshes), 2 (prairies), or 3 (pine rocklands), based on their potential for burning in high-intensity fires (Slocum et al. 2003). The fire intensity potential index was then calculated using the following equation:

$$\textit{Fire Intensity Potential} = \textit{Hydrology score} + \textit{Ecotype score} \quad (1)$$

After the calculation, the index was normalized between 0 and 1.

The fire patchiness potential index was calculated as the combined variability in ecotype and hydrologic conditions within management-relevant units. The variability of ecotype and hydrologic conditions was calculated both within burn units and within areas resulting from the intersection of burn unit and endangered species habitat boundaries. The same hydrology and ecotype classes described for the fire intensity potential index were used. The standard deviations of the hydrology and ecotype class distributions were calculated and combined to generate the index:

$$\textit{Fire Patchiness Potential} = \sigma_{ecotype} + \sigma_{hydrology} \quad (2)$$

After the calculation, the index was normalized between 0 and 1.

Results

Time since last fire (TSLF), an important parameter used in the burn prioritization model, varied across ecotypes and burn units in 2022, ranging from 1 to > 50 years (Fig. 3). Smaller and larger burn unit areas and different ecotypes shared more recent TSLF, and the longest TSLF occurred in areas dominated by mangroves (Fig. 3). The areas of ENP with the highest heterogeneity in TSLF occurred along the northern and eastern boundaries (Fig. 3), reflecting drier conditions and the occurrence of wildfires in distinct landscape patches.

Burn prioritization scores using 50×50 m pixels and scores averaged and scaled to the burn unit polygons represent nested spatial scales that can be used for selecting priority management areas (Fig. 4). Burn prioritization scores were highest in wetlands dominated by prairies along the northern and eastern boundaries of ENP, as well as within pine rocklands (Fig. 4). These prioritization scores were the outputs of the simulation to support decision-making in 2023 and varied between 0 and 71 (Fig. 4A) or between 6 and 62 (Fig. 4B).

During the 50 years (2023 to 2072) of simulated burn prioritization run for model evaluation, the mean burned surface corresponded to 256 ± 160 km^2 y^{-1}, which is 12% of the total area within ENP eligible for prescribed fires.

Based on the evaluation results, the model predicted FRIs appropriate to maintaining conservation priorities for different ecotypes and critical species habitats (Table 3). Mean predicted FRIs varied among ecotypes: marshes (9.9 ± 1.7 years), prairies (7.3 ± 1.9 years), and pine rocklands (4.0 ± 0.7 years). Mean predicted FRIs also varied among critical species habitats: *A. maritimus mirabilis* (7.4 ± 1.5 years), *A. troglodyta floridalis* and *S. acis bartrami* butterflies (3.9 ± 0.2 years), and *E.*

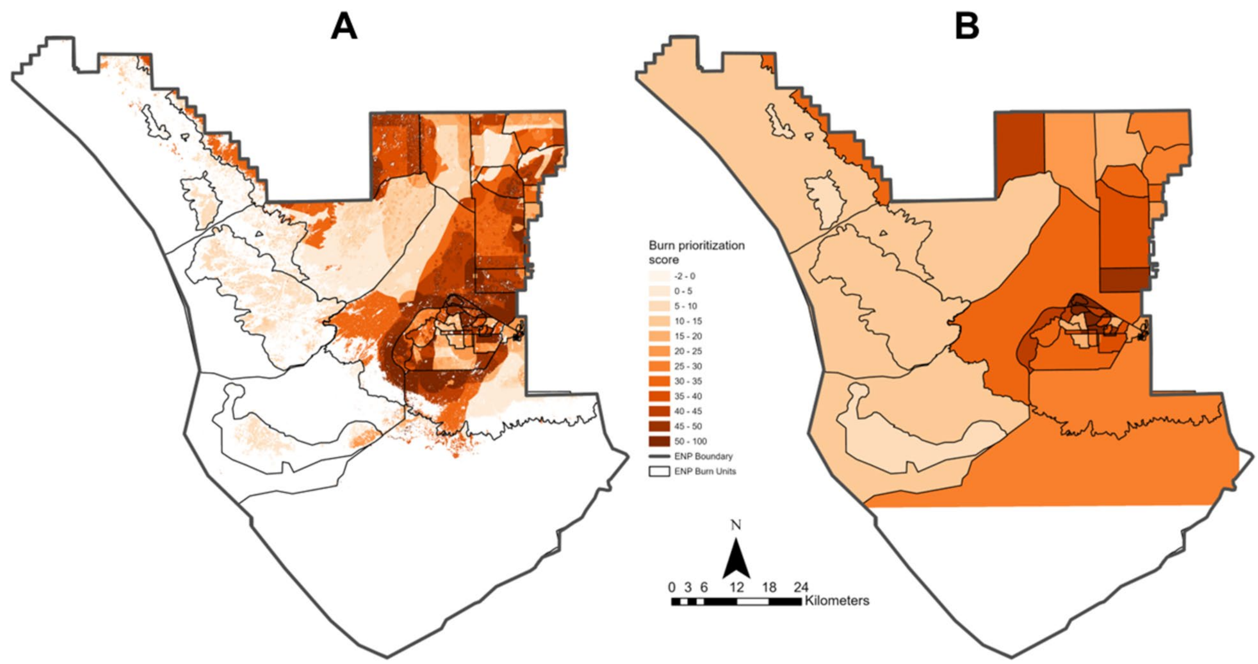

Fig. 4 Burn prioritization scores modeled for Everglades National Park (ENP) and scaled to management-relevant units: 50-m resolution grid (**A**) and burn units (**B**). High values correspond to high priority for treatment with prescribed fire. Prioritization scores were modeled only for those pixels (50 × 50 m) characterized by ecosystem types that are target of prescribed fires (i.e., marshes, prairies, and pine rocklands)

Table 3 Summary of model evaluation results. Fire return intervals (FRIs) are shown by ecotype (marsh, prairie, and pine rockland) and critical habitat of fauna species known to benefit from certain fire regimes [i.e., "sparrow" = Cape Sable seaside sparrow (*Ammodramus maritimus mirabilis*); "butterflies" = Florida leafwing and Bartram's scrub hairstreak (*Anaea troglodyta floridalis* and *Strymon acis bartrami*); "bat" = Florida bonneted bat (*Eumops floridanus*)]. Baseline mean FRIs were calculated for the period 2003 to 2022. Predicted mean FRIs and FRI ranges were estimated with burn prioritization model runs for the period 2023–2073. Target FRIs were estimated using recommended ranges and values previously published. These targets are not necessarily the targets set by Everglades National Park (ENP) in every circumstance

Ecotype or habitat	*Baseline mean FRI (± SD)*	*Predicted mean FRI (± SD)*	*Predicted FRI range*	*Target FRI*	*Recommended FRI range*	*References*
	years					
Marsh	15.3 ± 5.8	9.9 ± 1.7	2.6–12.5	9.0	3.0–25.0; 3.0–12.0	Hendrickson (1972); Ogden et al. (2005); National Park Service (2015)
Prairie	16.6 ± 5.5	7.3 ± 1.9	2.6–12.5	7.5	5.0–10.0; 3.0–12.0; 4.0–11.0	Kushlan et al. (1982); National Park Service (2015); Benscoter and Romañach (2022)
Pine rockland	8.4 ± 4.0	4.0 ± 0.7	2.5–12.5	4.5	3.0–5.0; 3.0–7.0	Duever (2005); National Park Service (2015)
Sparrow	18.4 ± 3.9	7.4 ± 1.5	2.9–8.3	7.0	5.0–8.0; 5.0–10.0	Benscoter et al. (2019); Benscoter and Romañach (2022)
Butterflies	7.8 ± 2.8	3.9 ± 0.2	3.1–8.3	4.0	3.0–5.0	Henry et al. (2022)
Bat	10.9 ± 5.0	6.5 ± 2.9	2.5–10.0	4.0	3.0–5.0	Braun de Torrez et al. 2018b; Tallie et al. (2021)

floridanus (6.5 ± 2.9 years). There was good agreement between estimated target FRIs and predicted mean FRIs by ecotype and by fauna species critical habitat ($r^2 = 0.88$; RMSE = 1.11; $p = 0.02$; Fig. 5).

Baseline FRIs were calculated using data from the last 20 years (2003 to 2022; Table 3). The mean burned surface during the baseline period corresponded to 204 ± 186 km^2. Although mean predicted FRIs accurately fit the

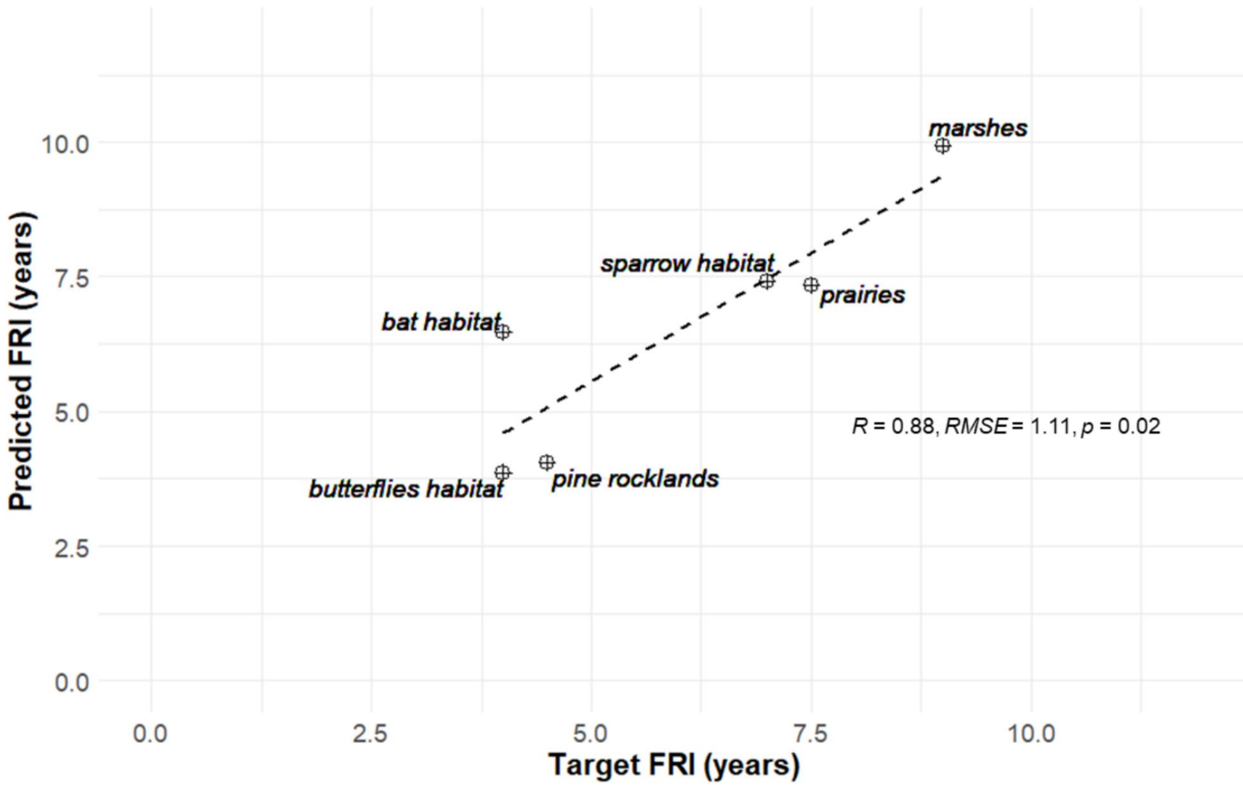

Fig. 5 Target versus predicted mean fire return intervals (FRIs). Predicted mean FRIs were calculated over a period of 50 years (2023–2072) during which, based on the simulated prioritization scores, future fire perimeters were generated every year and time since last fire was iteratively updated. Target and predicted mean FRIs were compared by ecotype (i.e., marshes, prairies, and pine rocklands), and by critical habitat of fauna species known to benefit from certain fire regimes [i.e., "sparrow" = Cape Sable seaside sparrow (*Ammodramus maritimus mirabilis*); "butterflies" = Florida leafwing and Bartram's scrub hairstreak (*Anaea troglodyta floridalis* and *Strymon acis bartrami*); "bat" = Florida bonneted bat (*Eumops floridanus*)]

estimated target FRIs toward conservation objectives, baseline FRIs did not ($r^2 = 0.82$; RMSE = 7.42; $p = 0.04$).

The mean FRI predicted for WUI areas was 7.9 ± 2.0 years, in contrast with 15.8 ± 5.7 years of the baseline period. Approximately 23% of marshes, 67% of prairies, and 95% of pine rocklands were part of the WUI areas. Therefore, the WUI criterion had a substantial impact on the predicted FRIs, especially those of pine rocklands.

The mean FRI predicted for oligotrophic wetlands (soil total phosphorus < 200 μg g^{-1}) was lower (8.1 ± 1.5 years) than the mean FRI predicted for wetlands with higher nutrient availability (9.5 ± 1.8 years).

Two burn units ("ROG E" and "ROG S") were identified that, if split into two sub-units, could increase the efficiency of ENP fire management toward conservation goals. These two were selected based on their high internal heterogeneity (> 8.0; Table S1), their large surface target of prescribed fire (> 200 km^2; Table S1), and the unique internal configuration of ecotypes and habitats (ecotype and habitat boundaries overlapped, subdividing the burn unit; Fig. S2).

Ground elevation explained differences in potential for fire intensity. The highest fire intensity potentials occurred at the highest elevation patches dominated by pine rockland vegetation, whereas fire intensity values were lowest in longer-hydroperiod marshes inundated most of the year (Fig. 6). Some of the large burn units showed high internal variability in fire intensity potential. Fire intensity is a fire characteristic that is accounted for by fire managers when targeting reduction of fuel loads or control of invasive plant species.

The potential for high fire patchiness was less predictable than the potential for high fire intensity and did not correlate with ecotype or hydrology classes (Fig. 7).

The potential for fire intensity and fire patchiness was summarized at the sub-unit scale by intersecting the critical habitat areas with the burn unit polygons (Figs. S3, S4, and S5). Fire patchiness was more spatially complex within the habitat of *E. floridanus* (Fig. S4) than within

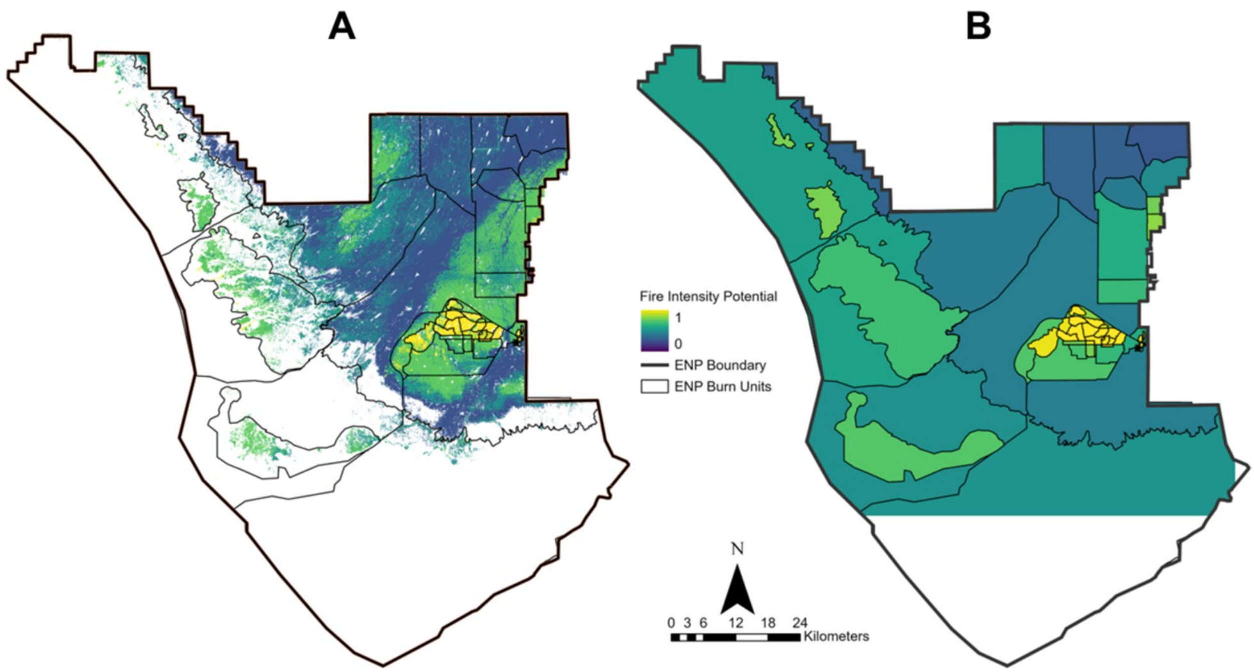

Fig. 6 Fire intensity potential index estimated for Everglades National Park (ENP) and scaled to management-relevant units: 50-m resolution grid (**A**) and burn units (**B**). High values correspond to high fire intensity potential. Fire intensity potential was estimated based on ecosystem type and hydrology information (Slocum et al. 2003), and only for those pixels (50 × 50 m) characterized by ecosystem types that are target of prescribed fires (i.e., marshes, prairies, and pine rocklands). In these ecosystem types, the application of prescribed fire is considered ecologically beneficial. Fire intensity is a fire characteristic that is accounted for by fire managers when targeting reduction of fuel loads or control of invasive plant species

either the ground-nesting *A. maritimus mirabilis* (Fig. S3) or *R. sociabilis plumbeus* (Fig. S5) habitats, reflecting the variability of ecotypes and habitat structures where *E. floridanus* can roost.

Discussion

Our decision-support framework and burn prioritization model—co-developed by fire managers, natural resource managers, and scientists—provide a transparent and objective approach needed to manage diverse fire regimes across the Everglades. Employment of the burn prioritization model presented here would allow ENP managers to achieve target FRIs or at least FRIs within the recommended range for their higher-priority conservation objectives. Our model incorporates competing management goals without being limited to single species or individual management priorities to facilitate multiple fire-driven management efforts. We predicted mean FRIs within the recommended range for different wetland ecosystems (ranging from ~ 4 to 10 years) and endangered species needs (ranging from ~ 4 to 7 years), illustrating clear targets for co-benefits. Our capacity to achieve multiple conservation goals for ENP is likely because TSLF was the dominant criterion in the model. Application of burn prioritization models to landscapes that have more than one jurisdiction (e.g., local, state, federal) are more complex to manage, making co-development of the decision-support tool even more critical. Finally, although we provide recommendations for targeting burn units, our model produces 50-m resolution grid maps that can also be used to identify and manage fire in smaller sub-units.

Fire management in Everglades National Park

Although the model predicted mean FRIs within the recommended range toward ecological goals, the predicted maximum FRIs consistently corresponded to 12.5 years across ecotypes and ranged between 8.3 and 12.5 years across habitats. This is a result of the prioritization score being averaged across large burn units, which included multiple ecotypes and parts of endangered species habitats. Unit size therefore had a large effect on predicted maximum as well as mean FRIs. Had we unrealistically applied fire during evaluation at the pixel scale, we would have observed an even better fit between the target and predicted mean FRIs. But, as a management support tool, the model needs to reflect the reality of fire management in ENP. Nonetheless, ENP fire managers will have the ability to target sub-units to achieve shorter local FRIs. One example of a sub-unit that might require such treatment are patches of prairie vegetation or of *A. maritimus mirabilis* habitat embedded within large burn units dominated by the marsh ecotype, which

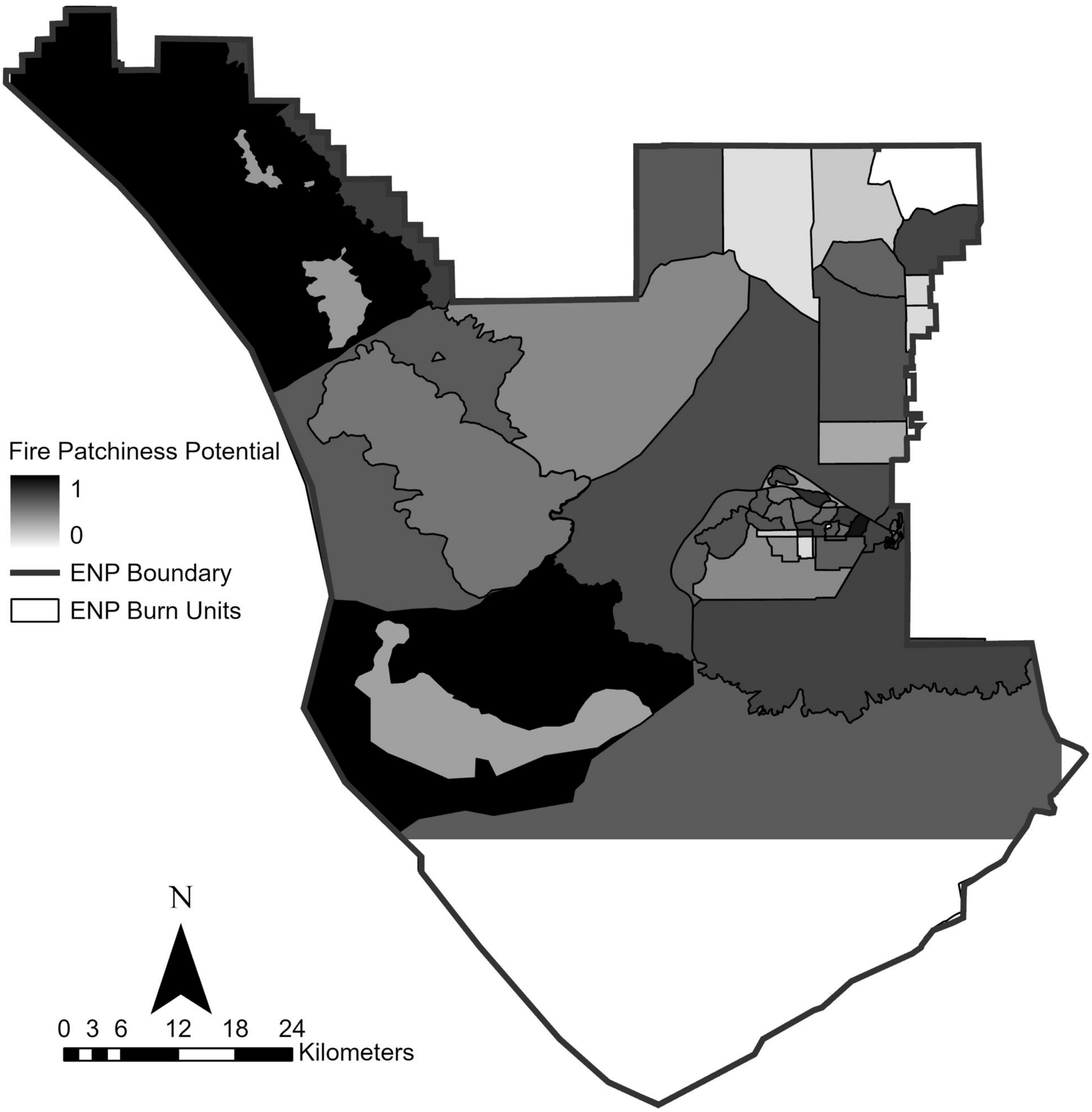

Fig. 7 Fire patchiness potential index estimated for Everglades National Park (ENP) and scaled to management-relevant units (i.e., burn units). High values correspond to high fire patchiness potential. Fire patchiness potential was estimated based on the within-unit variability (i.e., standard deviation) of ecosystem type and mean water depth. Only the pixels (50 × 50 m) occupied by ecosystem types that are target of prescribed fires (i.e., marshes, prairies, and pine rocklands) were used to calculate the standard deviations and estimate the index. In these ecosystem types, the application of prescribed fire is considered ecologically beneficial. Fire patchiness is a fire characteristic that is accounted for by fire managers when targeting preservation of ecotypes and habitats, as it helps fine-scale heterogeneity of vegetation structure

is characterized by the longest target FRI among the fire-dependent habitats identified in this study. Regardless, according to model predictions, ENP fire managers could potentially achieve FRIs $\leq$ 12.5 across the whole ENP surface target of prescribed fires. This FRI corresponds to the upper limit of the recommended range of FRIs recommended for a high proportion of ENP landscape (National Park Service 2015).

There seems to be wide consensus on the beneficial FRI ranges for the prairie and pine rockland ecotypes (Kushlan et al. 1982; Duever 2005; National Park Service 2015; Benscoter and Romañach 2022). Further confirmation of this is that, for example, the target FRI used here for marl prairies, which we estimated from the literature, corresponded to 7.5 years, which almost coincided with the 8-year FRI indicated in ENP fire management plan for prairies outside of the WUI zone (National Park Service 2015); 8 years is also the time needed by prairie vegetation to fully recover (Sah et al. 2007). In contrast, almost no information is available on beneficial FRIs for the marsh ecotype. Therefore, it seems that the marsh ecotype, although it benefits from the application of fire (Ogden et al. 2005), depends on FRIs less than the other ENP ecotypes analyzed in this study.

In wetland landscapes, prudent fire management needs to be complemented by prudent wetland hydrologic management (Lockwood et al. 2003). Although our predicted mean FRI within the *A. maritimus mirabilis*'s habitat is toward the high end of the recommended FRI range reported by some authors (Benscoter et al. 2019), it would be still short enough for maintaining habitat structure (La Puma 2010). Achievement of recommended FRIs, complemented by the right amounts and timing of water deliveries, would constitute a solid foundation for the prosperity of *A. maritimus mirabilis* (Haider et al. 2021; Benscoter and Romañach 2022). The mean predicted FRI for *A. troglodyta floridalis* and *S. acis bartrami*'s habitat was extremely close to the target FRI recommended by Henry et al. (2022). In the case of *E. floridanus*'s habitat, the predicted mean FRI is higher than the recommended target FRI, and even higher than the recommended range. However, differently from habitats inside ENP for which there's agreement in the scientific literature on their dependance on certain FRIs (i.e., *A. maritimus mirabilis*'s, *A. troglodyta floridalis*, and *S. acis bartrami*'s habitats), it seems that the effect of fire management on *E. floridanus*'s activity is confounded by other important factors such as vegetation type and conditions (Tallie et al. 2021). For this reason, the maximum score that the protection of *E. floridanus*'s habitat contributes during model simulations (6 points) is slightly lower than the maximum score attainable for the protection of *A. maritimus mirabilis*'s, *A. troglodyta floridalis*, and *S. acis bartrami*'s habitats (8 points). Moreover, a high portion of the *E. floridanus*'s habitat within ENP surface target of prescribed fire is characterized by the marsh ecotype (42%; 65.7 km^2), which is the ecotype with the highest target FRI. Overall, the variability simulated in fire regimes by our model among landscape patches within the *E. floridanus*'s habitat may reflect an acceptable fire management toward this ecological goal (Tallie et al. 2021).

Enhancing adaptive fire management and pyrodiversity

Decision-support tools and burn prioritization models can use scenarios to understand tradeoffs that allow for adaptive fire management. For example, a decision-support tool in Queensland, Australia, compared prioritization of biological conservation versus human property protection. Burn heterogeneity (i.e., pyrodiversity) at multiple spatial scales was greater with a conservation-focused approach that also reduced TSLF fire among forest patches (Williams et al. 2017). Increasing human development into WUIs will make it more difficult to manage for pyrodiversity, as fire exclusion and suppression are prioritized over managing ecological needs for fire (Steel et al. 2021). Increases in public concerns about fire risk, resource constraints, and increasing need to prioritize managing for catastrophic fire may reduce the capacity of prescribe fire management (Kupfer et al. 2022). In the Everglades, fire intensity and patchiness estimates vary spatially based on ecosystem type and hydrology, and our modeled outputs of fire intensity were greatest in higher elevation, drier areas that overlapped with endangered species habitats. These same areas also contain the highest density of human infrastructure in the ENP. However, given the relatively small spatial extent of burn units with WUIs, ENP fire managers will likely be able to maintain prescribed burns. The capacity to balance competing objectives in landscapes with larger WUIs and multiple landowners is more challenging, requiring the co-development of both decision support tools and higher-resolution burn prioritization model outputs.

Fire management and global environmental challenges

Fire management is complex and becoming increasingly challenging given rapid global environmental changes (Shuman et al. 2022). Managing fire for species, habitat, and humans poses many challenging interactions and tradeoffs. Recent research identified that burning in WUIs, despite the additional benefits gained through the reduction in damages, is not the most economically efficient strategy (Florec et al. 2020). Prioritizing ecosystem preservation over WUI management, which was the most influential criterion after TSLF in our model, is not always possible especially for arid regions prone to wildfires. However, our decision-support tool and burn prioritization model offer flexibility and can be easily adapted to different criteria and weighting by fire scientists and natural resource managers. This dynamism fits the adaptive management approach adopted by ENP and other collaborating agencies in the context of Everglades restoration (Gunderson and Light 2006). As management priorities or landscape conditions may change, new spatial layers may be added, or existing spatial layers may be replaced with current conditions. Similarly, if new information becomes available through scientific literature or technical reports, model parameters may be re-calibrated. Another advantage of our spatially explicit model is that it can be understood and employed by a variety of professionals within and among agencies that manage prescribed fires in similar habitats. For example, natural areas outside of ENP are also characterized by similar environmental conditions and by the same endangered species to protect and invasive species to control (Ogden et al. 2005; Duever 2005). Further, applications involving finer-spatial scale fire management (e.g., avoiding endangered species or preserving cultural resources), higher-resolution grid maps, like we generated for the ENP, provide information about the complexity needed to manage heterogeneous landscapes.

Wildfire frequency, intensity, and severity are accelerating with increasing landscape aridity and human develop in WUIs (Shuman et al. 2022; Turner et al. 2022), making it essential to apply prescribed fire management at landscape scales. Wildland and urban planning around fire must balance landscape heterogeneity and finer-scale fire characteristics. For example, fire patchiness, seasonality, intensity, and severity, are important controls of ecosystem processes that need to be addressed during planning and when applying prescribed fires (Noss 2018). Once FRIs have been planned through the simulation of burn priorities, fire patchiness, intensity, and severity can be controlled, to a certain extent, through fire seasonality; this is particularly true in the Florida Everglades (Slocum et al. 2003). Although variability of surface water expression can be an impediment to the design of burn prioritization in wetlands, it can make the logistics of prescribed fires more challenging, and may even create prohibitive conditions for carrying out a prescribed fire, spatiotemporal variation in environmental factors also offer opportunities for achieving the desired fire patchiness and intensity to maintain FRI targets for diverse vegetation communities (Slocum et al. 2003). Using some of the results published by Slocum et al. (2003), we estimated the potential for fire intensity and fire patchiness within ENP. Fire managers can use the fire intensity and patchiness potential maps as an additional support tool for deciding the seasonality of the prescribed fires recommended by the burn prioritization model.

Conclusions

Prescribed fire is an essential tool of natural resource and urban managers in many regions worldwide. Applying spatial, numerical models built for prescribed fire prioritization can support efficient decision making and resource allocation toward biological conservation, built infrastructure and human health concerns, especially in large, heterogeneous landscapes. Our burn prioritization model for the Everglades integrates spatial variability in ecosystem types and habitats of endangered species, while satisfying the need to contain fires and protect cultural heritage and infrastructure. Burn prioritization models can allow the achievement of target fire return intervals for higher-priority conservation objectives, while also considering finer-scale fire characteristics, such as patchiness, seasonality, intensity, and severity. Decision-support frameworks and higher-resolution models are needed for managing landscape-scale complexity of fires given rapid environmental changes. Although prescribed fire is essential to maintaining fire-adapted species and native habitats, changes in both climate and fire regimes are likely changing the role of fire as a driver of ecosystem structure and function (Lockwood et al. 2003; Johnstone et al. 2016; Shuman et al. 2022). Increases in global temperatures and shifts in precipitation patterns with climate change are transforming the frequency, severity, and intensity of fires worldwide (Shuman et al. 2022), with important consequences for vegetation structure and productivity (Wardle et al., 2004; Krawchuk et al., 2009; Turner et al. 2022). It is critical to better understand how both altered climate and hydrology and subsequent changes in wildfires will influence fire management needs among ecosystems, especially in WUIs. Our decision-support framework and burn prioritization model are broadly applicable to ecosystems that range in habitat types and hydrology, where FRIs need to be forecast and managed to achieve enhanced pyrodiversity (Griffiths et al. 2015; Bowman et al. 2016).

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

Supplementary Material 3.

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Authors' contributions

AN, PR, JO'B, and MR conceived the study. AN and JK designed the general decision-support framework for burn prioritization. AN, MG, PR, and MT selected criteria, assigned overall model influences, and value scoring. AN, TM, CA, and PR collected and processed the spatial data, and built the model. AN and TM performed model evaluation. All authors contributed to manuscript preparation.

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Data availability

All data used in the study are already published and publicly available from a variety of sources, which are cited in the main text and reported in the reference list (Ruiz et al. 2021; Malone 2019; U.S. Fish & Wildlife Service, 2023; Barrow and National Park Service Southeast Region Geospatial Resources, 2022; Stutts 2014; U.S. Geological Survey 2019; South Florida Water Management District 2023).

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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