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Assessing the Ecological Need for Prescribed Fire in Michigan Using GIS-Based Multicriteria Decision Analysis: Igniting Fire Gaps

Joshua G. Cohen *, Clay M. Wilton, Helen D. Enander and Tyler J. Bassett *

Michigan Natural Feature Inventory, Michigan State University Extension, Lansing, MI 48933, USA; wiltoncl@msu.edu (C.M.W.); enander@msu.edu (H.D.E.)

*   Correspondence: cohenj@msu.edu (J.G.C.); basset17@msu.edu (T.J.B.); Tel.: +1-517-284-6161 (J.G.C.); +1-517-284-6220 (T.J.B.)

Abstract: In fire-suppressed landscapes, managers make difficult decisions about devoting limited resources for prescribed fire. Using GIS-based multicriteria decision analysis, we developed a model assessing ecological need for prescribed fire on Michigan's state-owned lands, ranging from fire-dependent prairies, savannas, barrens, and oak and pine forests to fire-intolerant mesic forests, and including a diversity of wetlands. The model integrates fine-scale field-collected and broad-scale GIS data to identify where prescribed fire needs are greatest. We describe the model's development and architecture, present results at multiple scales, introduce the concepts of "fire gaps" and "fire sink", and rate the fire needs of more than 1.8 million hectares into one of six fire needs classes. Statewide, fire needs increase with decreasing latitude. The highest and lowest needs occur in southwestern Michigan and the Upper Peninsula, respectively, but actual fire application rates for these regions are inverted. The model suggests burn rates should be increased 2.2 to 13.4 times to burn all lands with greater than high fire needs. The model identifies regional patterns; highlights specific sites; and illustrates the disparity of fire needs and fire application. The modeling framework is broadly applicable to other geographies and efforts to prioritize stewardship of biodiversity at multiple scales.

Keywords: fire; needs assessment; multicriteria decision analysis; prescribed fire; fire suppression; fire frequency; prioritization; biodiversity; Michigan; upper Midwest

1. Introduction

Fire is a key ecological process in many ecosystems worldwide that determines a wide range of ecosystem attributes, from nutrient cycling rates to vegetation structure to patterns of biodiversity at multiple scales [1]. Modern land managers use prescribed fire to restore or maintain desired ecosystem structure and species composition, particularly in grasslands, savannas, and woodlands [2,3], ecosystems that are critical habitats for a wide array of wildlife including many game species. However, the resources (time, money, and labor) available to conduct prescribed fire are limited. Where those resources are directed has profound implications for conservation and may determine the fate of many wildlife species and the ecosystems on which they depend. Using GIS-based multicriteria decision analysis, we developed a robust model for assessing the ecological need for fire at multiple spatial scales in Michigan, USA. Conceptualization and development of the model were informed by interactions with natural resource managers and fire ecology experts. The goal of developing this prescribed fire needs assessment model is to enhance the application of fire in the ecologically most important landscapes and ecosystems and thereby restore or maintain a critical ecosystem process; increase the integrity of fire-dependent systems; and improve habitat for native biodiversity, including a diverse array of both game and non-game species. While the model is focused on evaluating the ecological need for fire on state lands in Michigan, it is not a comprehensive needs assessment in that it focuses on

just one facet natural resource managers must balance while making complicated decisions about land management.

1.1. Fire Ecology, Fire Suppression, and the Need for Prescribed Fire

Globally, many landscapes and associated ecosystems evolved with fire, which has been an important ecological process at least since the appearance of terrestrial plants nearly one billion years ago [1]. In the upper Midwestern United States, fire is an integral process that influences patterning of ecosystems across the landscape and maintains species composition and vegetative structure by reducing woody species density in dry to wet tallgrass prairie, oak-dominated savannas, woodlands, and forests, and peatlands such as fens and sedge meadows [4–7]. These natural communities and many of the species associated with them are considered fire-dependent, in that their long-term persistence is contingent on regular and recurring fire. The diversity of natural communities and species within those natural communities was determined in part by the variability of fire disturbance. Fire regimes, or the occurrence and distribution of fire on the landscape, exhibit considerable spatio-temporal variation. Fire frequency, the number of times a fire occurs over a given time period, varies across space (e.g., depending on landform, vegetation type, landscape configuration, and distance and orientation to natural firebreaks) and through time (e.g., depending on climatic conditions, time since last fire, and duration of droughts) and is influenced by human population density and culture [6,8–19]. Fire frequency in the historical record is defined in terms of fire return intervals, or the average number of years between fire events for a given area. In pre-Colombian times (prior to 1500 CE), fire return intervals were generally very low in much of North America, owing in many areas to annual fires set by Native Americans [14,16]. Fire return intervals increased somewhat when diseases introduced by European colonizers in North America reduced Native American populations [20]. Juxtaposed with these broad temporal trends is the spatial variation in where fire occurred on the landscape, driven by the interaction of climatic factors, landforms, and vegetation types. Prevailing winds in the upper Midwest are westerlies. As a result, areas to the east of points of ignition would commonly burn until fire reached a topographic barrier or natural firebreak, such as a steep slope or river, or an ecological barrier such as a mesic forest interior or a poorly drained swamp [3,13,14,16]. Prairies, savannas, barrens, and forests of oak and pine developed and were maintained across the landscape in response to a combination of frequent fire, hot and dry topographic positions, and periods of hot, dry climatic conditions [16,17]. These communities, and graminoid-dominated wetlands within these fire-prone landscapes, typically had short fire return intervals, relative to communities in protected portions of the landscape [4,14,16,17]. In contrast, mesic forests developed in topographically cool and moist positions (north- and east-facing slopes and some areas of very hilly terrain), and these areas had longer fire return intervals [6,12,14,15].

Since the expansion of European colonizers across the upper Midwest, there have been drastic declines in fire-dependent ecosystems. Loss and fragmentation of habitat due to development and agriculture [11,16,21–24], declines in Native American populations, and extreme reductions in fire frequency due to widespread fire suppression [16,25], particularly over the past 100 years, have severely altered the landscape [17,19]. Biodiversity loss in response to habitat loss and fragmentation is great, particularly in the most fire-dependent ecosystems, such as prairies and savannas [26–28]. As recently as the mid-1800s in the Midwest, savanna covered 11 to 13 million hectares, and prairie covered 40 million hectares. Acreage of both ecosystems has since dwindled to just 0.02% and <0.01% of their historical extent, respectively [29,30]. In Michigan specifically, prairie, savanna, and barrens remnants occur on just 0.02% of their circa 1800 extent [31,32] (Figure 1).
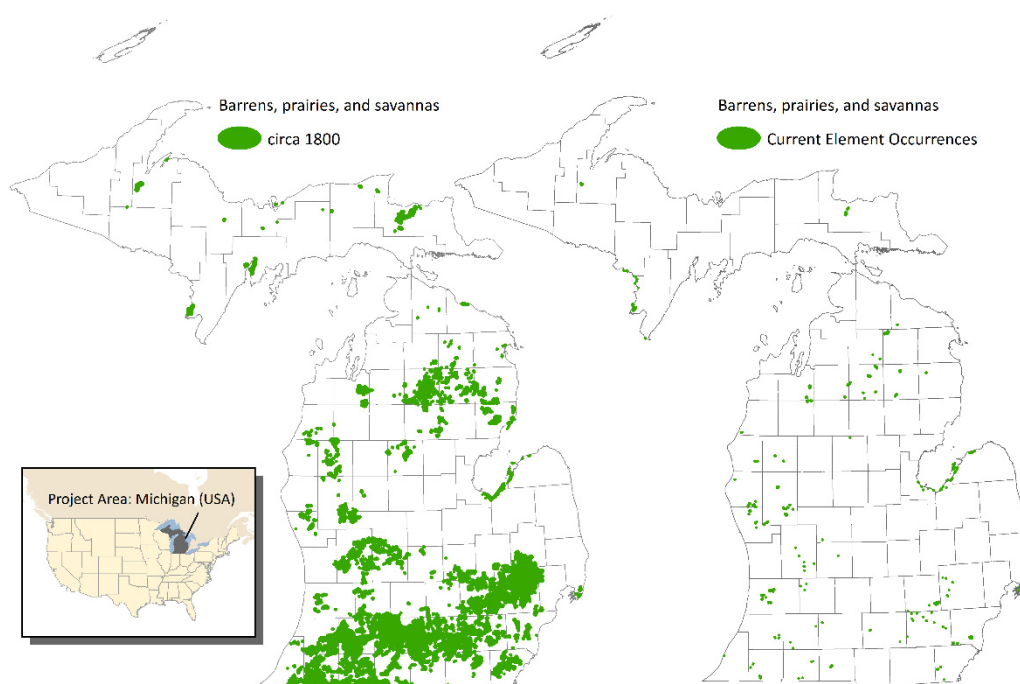
Figure 1. Comparison of circa 1800 to current extent of prairies, savannas, and barrens. In Michigan, prairie, savanna, and barrens remnants in Michigan occur on just 0.02% of their circa 1800 extent [31,32].

While the effects of fire suppression have been most immediate and dramatic in the prairie, savanna, and barrens that comprise the most fire-dependent communities, woody encroachment and other symptoms of fire suppression are widespread. For example, the process of "mesophication" has been described in fire-suppressed oak forests and woodlands, while similar processes occur in all fire-dependent ecosystems. Under mesophication, woody encroachment increases shade and moisture levels in the understory, limiting the recruitment of shade-intolerant oak species and facilitating the recruitment of fire-sensitive, shade-tolerant mesophytic tree species such as maple [17] and invasive shrubs. The result of mesophication in fire-suppressed oak ecosystems is an understory with little advanced regeneration of oak species despite the overtopping oak canopy, shifts in understory and ground cover composition, reduced herbaceous cover overall, increased leaf litter density, and ultimately decreased plant species diversity [4,33–35]. Importantly, the dense shade and leaf litter associated with mesophytic conditions depresses or eliminates graminoid species that provide fine fuels for surface fires [36]. Similar processes play out in other fire-dependent ecosystems. Woody encroachment in fire-dependent, sedge-dominated wetlands suppresses the growth of sedges and other fine fuels and facilitates the recruitment of shrubs and trees, hastening succession towards shrub swamps and forested wetlands [37,38].

Fire suppression policies instituted in the 1920s due to increasing human density and concerns for human safety in areas of wildland urban interface have limited the frequency and intensity of wildfires [25]. As the impacts of widescale fire suppression have had profound and pervasive deleterious impacts to fire-dependent ecosystems and species, prescribed fire has become a vital tool for managing fire-dependent ecosystems. The ecological benefits of prescribed fire application in fire-dependent systems are numerous. Important plant nutrients (e.g., N, P, K, Ca, and Mg) are elevated following prescribed fire [39–42]. Prescribed fire reduces litter levels, allowing sunlight to reach the soil surface and stimulate seed germination and enhance seedling establishment [40–47]. Burning has been shown to result in increased plant biomass, flowering, and seed production in a range of fire-dependent ecosystems [38,47–49]. Prescribed fire may be used to decrease the cover of invasive woody species and native fire-sensitive species (both linked to reduced plant species diversity) and increase the cover of light-demanding native grasses,

sedges, and forbs that comprise most of the floristic diversity in fire-dependent natural communities [45,46,50–56]. Frequent fire also maintains this diversity by reducing litter and providing microsites for seed germination and facilitating the expression and rejuvenation of seed banks [38,57–59].

Fire-dependent habitats are crucial for a wide array of wildlife species, and increases in habitat use by many taxa in response to prescribed fire are well-documented. Increased bee diversity and abundance [60,61], insectivorous songbird diversity and habitat use [62–65], and small mammal diversity and abundance [66] have all been observed in response to the reintroduction of fire to fire-suppressed systems. By generating a diversity of habitat patches across landscapes, large-scale fires can be beneficial to numerous wildlife game species including American woodcock (*Philohela minor*) and white-tailed deer (*Odocoileus virginianus*) [67,68]. Prescribed fires can increase the ability for fire-dependent habitats to support a variety of mammalian and avian species, including large game [69], by favoring mast-producing trees such as oaks and hickories [70] and increasing the palatability of forage for grazing ungulates [71].

1.2. Necessity of Assessing Fire Needs

The necessity of returning fire to fire-suppressed landscapes has grown apparent over recent decades, and modern land managers have used prescribed fire to respond to declining biodiversity, provide habitat for game species and other wildlife, and mitigate wildfire risk [19,22,70]. While the extent of wildfire on the North American landscape still falls well short of the land area burned prior to European colonization, the resources available to conduct prescribed fire are often insufficient in terms of the number of hectares managers want to burn and because of competing demands of wildfire management [19,72]. Evaluations are required to assess the need for fire across landscapes for managers to prioritize where limited resources should be directed. Within the upper Midwest, evaluation of the need for prescribed fire has been conducted in Michigan [73], Wisconsin [74,75], and Illinois [76]. A key outcome of these prescribed fire needs assessments is the unequivocal identification of the significant discrepancy between the need for burning in fire-dependent ecosystems and actual implementation. This is critical information for informing policy and decision making about burning and stewardship programs. These evaluation efforts were coarse-scale approaches that facilitated the identification of fire needs at broad scales useful for regional planning efforts. In Wisconsin [74,75] and Illinois [76], the base unit of the assessment was the "existing vegetation" layer from LANDFIRE [77,78]. For the Wisconsin modeling effort, this LANDFIRE layer was assigned to U.S. Geological hydrologic unit subwatersheds (HUC12s), which average just over 8000 hectares (20,000 ac) in Wisconsin. In Michigan, the focal unit of the 2008 modeling effort [73] was The Nature Conservancy's Portfolio Areas, which averaged over 32,000 hectares (80,000 ac). While these coarse-scale approaches provide important insight about where in general limited resources for fire management should be concentrated and highlight the disparity between need and application, they do not provide resource managers with the specifics about where exactly within broader landscapes prescribed fire should be implemented. In addition, they do not utilize fine-scale datasets that include site-specific factors that influence the ecological need for fire. As a result, there is a necessity for approaches that integrate fire needs at the scales at which resource managers work, such as typical burn units or forest stands (e.g., 10–100 ha or 25–250 ac), with the larger scales at which fire needs are currently understood. The factors that influence the effectiveness of and need for prescribed fire vary on at least three scales–between landscape-level and stand-level features, and among species. For a needs assessment to inform decisions regionally and within sites, it should assess factors at all three of these scales.

1.3. Landscape Factors

The factors (i.e., processes and patterns) that determine fire needs vary at the scale of landscapes and among habitat stands within landscapes, and differ by species within stands.

Throughout this paper when we refer to the "landscape scale" we mean factors that function at the scale of thousands to tens of thousands of hectares; "stand scale" refers to factors operating at the scale of tens to hundreds of hectares; and "species level" refers to factors operating within stands at the scale of one to five hectares. At the landscape scale, climatic and physiographic variation drive the patterning of vegetative cover types [4,12,31,79–84]. Under historical conditions (prior to European colonization), the interaction of these factors determined where fire occurred on the landscape. In terms of climate, landscapes characterized by warmer temperatures and less precipitation tend to be more fire prone than cooler and wetter landscapes. In terms of surficial geology, certain landforms are more prone to fire (e.g., flat, excessively drained sandy outwash plains) compared to others (e.g., poorly drained lake plain) [16,84,85]. Landforms that are characterized by soils with low water-retaining capacity (e.g., well-drained to droughty sands) are more fire prone than those with saturated to inundated organic soils (e.g., fibric to sapric peats). Landscape-level fires, set by Native Americans [16,20,70] or less commonly originating from lightning strikes, were likely more frequent and widespread in these fire-prone landscapes. The incidence and absence of fire across the landscape, in turn, reinforced the development of fire-dependent and fire-sensitive natural communities, respectively [31]. As a result, fire-dependent vegetation types are more likely to occur in these fire-prone landscapes today. Fire-prone regions in Michigan support higher concentrations of remnant fire-dependent forests, savannas, and barrens dominated by oak and pine, and to a lesser degree, treeless prairies. Fire-dependent wetlands such as fens and wet meadows also occur in higher concentrations in fire-prone portions of Michigan's landscape. Regions that are less fire-prone are characterized by more fire-sensitive natural communities such as mesic forests and swamps [32]. The current ecological need for prescribed fire is greatest in these fire-prone landscapes, especially where the departure from the past fire disturbance regime is greatest due to fragmentation and fire suppression. The necessity of returning fire to fire-suppressed landscapes has grown apparent.

1.4. Stand-Scale Factors

The type and condition of vegetative cover (i.e., natural communities), the topographical context of these communities, and their soil texture and moisture influence fire needs at the stand scale. The type of natural community will determine both the degree of fire-dependence and the fire frequency required to maintain or restore that community's ecological integrity. For example, open-canopied communities such as prairies and savannas are both highly dependent on fire and require very frequent fire to reduce woody encroachment, on the order of three to ten fires per decade [16,86–89]. In comparison, fire frequency in forested communities may range from one to three decades in oak-hickory forests to greater than 1000 years in stands dominated by northern hardwoods such as sugar maple (*Acer saccharum*) and beech (*Fagus grandifolia*) [12,17,33,90]. From the perspective of conservation practitioners, higher quality examples of natural communities [32] have greater fire needs as they are more highly valued for conservation. In predominantly forested ecosystems, the average age and dominant size-class of canopy trees correspond to successional stage and can be used to gauge a stand's need for fire. As succession proceeds in dry-mesic forests, fire is increasingly important to spur regeneration of canopy species from seedling and sapling layers, particularly in oak and pine systems. Furthermore, natural communities that occur in more fire-prone topographic settings are more likely to be aligned with positions in the landscape with a long-term fire history. Consequently, stands in either flatter topography or along west- or south-facing slopes are likely to have greater fire needs since fire has been an integral component of the processes influencing their composition, structure, and successional trajectory [13,16,91].

1.5. Species-Level Factors

The presence of species or suites of species within stands can provide managers with critical information about a site's fire history and potential need for fire. Plant species vary in their response to fire, ranging from being extremely dependent to extremely sensi-

tive. For example, many native species require fire for regeneration, such as warm-season prairie grasses big bluestem (*Andropogon gerardii*) and Indian grass (*Sorghastrum nutans*), leguminous savanna species wild lupine (*Lupinus perennis*) and New Jersey tea (*Ceanothus americanus*), and many oak species (*Quercus* spp.) [45,92]. In addition, many plant species, including numerous rare plants, require fire-dependent habitat. In fire-suppressed landscapes such as the upper Midwest, lack of fire is a major driver of rarity for multiple species. The reintroduction of fire is a high priority where populations of these species occur, to stimulate growth and seed production, create microsites for germination, and reduce competition [38,57–59]. The presence of fire-dependent species within remnant fire-dependent ecosystems often indicates the presence of a seed bank or underground stems and/or roots of additional fire-dependent species that can be released with the application of fire [16].

The occurrence of undesirable fire-sensitive species also increases the need for fire, especially in fire-dependent natural communities. For example, the dominance of oak ecosystems in the eastern U.S. is tightly linked to fire and the decline of oak has been attributed in part to fire suppression and the associated increase in mesophytic species such as red maple (*Acer rubrum*), which suppresses oak regeneration [17]. Similarly, there may be an increased need for fire to combat non-native invasive species if those species are sensitive to fire. Conversely, managers may wish to initially limit fire in areas with fire-dependent invasive species that increase with fire and instead favor mechanical and chemical methods for invasive species control. For example, narrow-leaved cattail (*Typha angustifolia*) invades a variety of fire-dependent wetlands and also spreads aggressively following fire, confounding efforts to use fire as a management tool [92]. In addition, numerous rare species are fire-sensitive, including forest floor herbs that depend upon high-moisture environments to prevent desiccation, as is found in close-canopied mesic forest communities. Information about the location of fire-sensitive rare and common species should also inform assessments about a site's need for fire and decisions about the application of prescribed fire.

1.6. General Introduction of the Model

There is broad interest in developing methods to assess ecological fire needs at scales that can inform planning and policy as well as on-the-ground management. However, prior efforts have focused on coarse scales of assessment [73–76]. Employing a spatial multicriteria modeling framework with fine-scale stand data as the base unit, integrated with both finer species-scale and broader landscape-scale data, we have developed a dynamic ecological fire needs assessment model that can provide useful information to inform both broad-scale planning efforts across management regions and fine-scale decisions about the application of prescribed fire in specific sites within discrete management areas. Acknowledging that multiple abiotic and biotic variables interact at different scales in determining the characteristics of a site's fire regime and its subsequent ecological need for fire, we identified thirteen input variables for our model at three spatial scales (i.e., landscape, stand, and species). Each input variable was scored and weighted to derive a cumulative fire needs score for stands within the Michigan Forest Inventory (MiFI) database [93] and thereby generate a multi-scaled prescribed fire needs assessment for state-owned lands in Michigan, USA. The resulting model provides a replicable framework for setting eco-centric management goals for the benefit of ecosystem function and native biodiversity associated with fire-dependent systems. By identifying "fire gaps", places that burn less frequently than predicted by the model, and "fire sinks", places that burn more frequently than predicted by the model, the model can help foster critical discussion about where the application of prescribed fire should be prioritized.

2. Methods
2.1. Study Area

Our modeling efforts are focused on state lands across Michigan. Michigan is characterized by a humid temperate climate that is moderated by the influence of the Great

Lakes [82,94]. Both the Upper and Lower Peninsulas of Michigan were glaciated and as a result support a diverse array of landforms. Many of these landforms (e.g., outwash plains, rolling ground moraines, and lake plains) are conducive to the development of fire-dependent ecosystems. Michigan is primarily forested, with deciduous forest and agriculture dominating the Southern Lower Peninsula and deciduous-coniferous forest abundant throughout the Northern Lower Peninsula and Upper Peninsula. Fire-dependent ecosystems are concentrated in the Southern Lower Peninsula, with savanna and barrens ecosystems dominated by oaks occurring locally and prairie ecosystems persisting infrequently as localized remnants. In the Northern Lower Peninsula and Upper Peninsula fire-dependent ecosystems include pine barrens, oak-pine barrens, and pine- and oak-dominated forests with barrens systems occurring infrequently and locally and pine- and oak-dominated forests abundant throughout [82,95].

We developed the model for state lands in Michigan administered by the Wildlife Division (WLD) and Forest Resources Division (FRD) of Michigan's Department of Natural Resources (DNR). The WLD manages lands in the Southern Lower Peninsula of Michigan for wildlife habitat and recreation (e.g., State Game Areas, State Recreation Areas, and State Wildlife Areas). The WLD and FRD jointly manage State Forests in the Northern Lower and the Upper Peninsulas for long-term forest health, forest products, recreation, and wildlife habitat. The DNR organizes management areas and resource managers tasked with their stewardship into five management regions in Michigan: Southwest (SW), Southeast (SE), Northern Lower Peninsula (NLP), Eastern Upper Peninsula (EUP), and Western Upper Peninsula (WUP) Regions. We use management areas throughout the paper to collectively refer to State Game Areas, State Wildlife Areas, and Forest Management Units. In addition, throughout the course of the paper, when we reference "state lands," we are referring to lands administered by the WLD and FRD.

It is important to note that these lands are administered by the state of Michigan DNR for multiple management goals and uses and that management is informed by the evaluation of multiple values and directed by statutory mandates. The model we present, while focused on the ecological need for fire on these lands and informed by critical interactions with DNR natural resource managers and fire ecology experts, does not attempt to include all the values that the DNR incorporates into their complicated management decisions and is not a comprehensive needs assessment. In other words, the model discussed in this paper is an ecological fire needs assessment of state lands.

2.2. Michigan Forest Inventory Database and Natural Community Crosswalk

Vegetative cover of state lands in Michigan is tracked in the Michigan Forest Inventory (MiFI) database [93]. Through aerial photographic interpretation and ground-truthing, by 2019, wall-to-wall land cover mapping generated more than 178,000 stands across Michigan, constituting 1,810,165 hectares (4,473,010 ac) with a mean stand size of 10 hectares (25 ac). The MiFI database is dynamic and is continually updated as additional stands are mapped, surveyed, and managed. These stands are classified to a cover type class (e.g., "Mixed Oak" and "Lowland Deciduous Forest") and attributed with vegetative data by strata (i.e., canopy, subcanopy, understory, and ground cover composition), canopy closure, percent cover by canopy species, and stand age. For the past decade, Michigan Natural Features Inventory (MNFI) ecologists have been conducting MiFI surveys in southern Michigan and for the past two decades DNR foresters and wildlife biologists have been conducting MiFI surveys in northern Michigan.

The foundational unit of our model are these stands that are part of the MiFI database. In 2018, there were 18,653 stands within the MiFI database for southern lower Michigan, and in 2019, there were 159,818 stands in northern Michigan. For each stand, we generated an intersection with numerous spatial data layers including datasets with information on physiographic region, landform, circa 1800 vegetation, slope, aspect, departure from historical fire regime, and occurrences of high-quality natural communities or ecosystems. We used information gleaned from this intersection as well as stand-level data to "cross-

walk" or assign a natural community type [95,96] to as many stands as possible (Table 1) (throughout this paper "natural community" and "ecosystem" are used synonymously). Anthropogenic systems (e.g., developed, cropland, plantations, roads, ruderal systems, and grassland plantings) were not crosswalked to a natural community type. Stand-level information that was useful for determining a crosswalk included canopy closure, stand age, upland/lowland classification, and percent cover by strata. In addition, many stands included an on-site classification to natural community type. Over the course of four decades, MNFI has developed a classification of natural community types in Michigan. Part of this classification includes a detailed discussion of each natural community type's vegetative composition and structure, soil texture and soil moisture, hydrology, and natural disturbance regime. The classification typically includes information on fire dependence and fire return interval gleaned from literature review and ecological inference [95,96]. Fire return interval is the time in years between two successive fires in a designated area [14] and can be used to estimate fire frequency range. We use fire frequency range throughout the paper to convey the range of time between fire events typical of a given natural community type irrespective of area. Appendix A provides fire frequency ranges by natural community type with accompanying citations when appropriate.

Table 1. Example crosswalk of Michigan Forest Inventory (MiFI) cover types to Michigan Natural Features Inventory (MNFI) natural community types with corresponding scale of fire dependence and fire frequency range.

Cover Type	Natural Community Type	Scale of Fire Dependence	Fire Frequency Range
Warm Season Grass	Dry-Mesic Prairie	Extremely Fire Dependent	1–5 Years
Oak Types	Oak-Pine Barrens	Very Fire Dependent	5–20 Years
Mixed Oak Forest	Dry-Mesic Southern Forest	Fire Dependent	10–20 Years
Fen	Prairie Fen	Fire Dependent	20–100 Years
Mixed Pine Forest	Dry-Mesic Northern Forest	Fire Dependent	100–300 Years
Lowland Shrub	Bog	Fire Sensitive	100–500 Years
Lowland Maple	Floodplain Forest	Fire Neutral	500–1000 Years
Emergent Wetland	Emergent Marsh	Fire Neutral	500–1000 Years
Lowland Cedar	Rich Conifer Swamp	Extremely Fire Sensitive	>1000 Years
Mixed Northern Hardwoods	Mesic Northern Forest	Extremely Fire Sensitive	>1000 Years
Sugar Maple Association	Mesic Southern Forest	Extremely Fire Sensitive	>1000 Years

2.3. Variable Selection and Data Preparation

Through a literature review, the evaluation of available spatial data layers, and discussion with natural resource managers and ecological experts, we identified potential variables critical for determining a site's proclivity to support a fire-dependent ecosystem or need for prescribed fire. In selecting these variables, we tried to incorporate factors that contribute to a site's past, current, and future relationship with fire. As multiple variables interact at different scales in determining the characteristics of a site's fire regime, we identified critical variables for our model at the following three spatial scales: landscape, stand, and species.

2.3.1. Landscape

Landscape-scale variables included physiographic region, surficial geology or landform, historic vegetation, and departure from historic disturbance regime. Physiographic regions are classified by large scale abiotic factors, such as climate and underlying bedrock, which, along with surficial geology, influence the patterning of ecosystems across landscapes [82,83]. We used Schaetzl et al. 2013 [83] for physiographic regions and Farrand and Bell (1982) [97,98] for surficial geology [99]. The data layer of surficial geology that we used includes descriptions of the glacial and post-glacial landforms as well as modifiers that convey information about soil texture properties of those landforms. Vegetation circa 1800 has been mapped in Michigan following interpretation of the original land surveyors'

notes. This spatial database of historic land cover provides useful information about how fire-prone and fire-sensitive ecosystems were patterned across Michigan [31]. The historical legacy of ecosystems and species influences current distribution of ecosystems and their need for fire disturbance. To incorporate departure from historic fire regime we used LANDFIRE's Vegetation Condition Class or VCC, which gauges how far removed an area is from its historic fire return interval [78,100].

2.3.2. Stand

Stand-level variables included fire frequency range, fire dependence, aspect, slope, age, size, and presence of exemplary ecosystems or natural community element occurrences. For each stand crosswalked to a natural community type we determined the scale of fire dependence (i.e., extremely fire dependent, very fire dependent, fire dependent, fire neutral, fire sensitive, very fire sensitive, and extremely fire sensitive), fire frequency (i.e., extremely frequent, very frequent, somewhat frequent, frequent, infrequent, somewhat infrequent, very infrequent, extremely infrequent), and fire frequency range (e.g., 1–5 years, 10–20 years, 200–500 years, and >1000 years). We also assigned a level of certainty for the fire frequency range (i.e., low, medium, and high). Fire frequency ranges were derived from the literature, but in cases where there was no reference for a natural community type, we relied on expert inference and evaluated similar natural community types to assign a fire frequency range (Appendix A). For natural community types with broad fire frequency ranges, such as wetland ecosystems, we modified the fire frequency range depending on the landscape context of the natural community. For example, prairie fens occurring in a fire-prone landscape were assigned a lower fire frequency range (e.g., 10–100 years) than prairie fens nested in less combustible landscapes (e.g., 100–200 years) [14]. In terms of aspect, westerly and southerly aspects are more prone to fire than easterly and northern aspects [16]. We used 30-m digital elevation model (DEM) data to incorporate slope and aspect into the model [101]. In terms of slope, flatter areas are more fire prone than areas of rugged topography. The MiFI database was used to derive the age and size variables [93]. For forested systems, stand age and size-class can be used as predictors of need for fire, since certain forest types such as oak and pine forests depend on fire disturbance to foster regeneration. Within fire-dependent forested systems in the upper Midwest, there is a greater need for fire in mature systems compared to regenerating ones. For the size-class variable, we assumed there is a greater need for fire in fire-dependent forested stands categorized in MiFI as "log" (i.e., stands characterized by a canopy cohort greater than 10 inches diameter at breast height or DBH) compared to "pole" and "sapling" stands (i.e., stands characterized by a canopy cohort greater than 5 inches and less than 10 inches DBH and stands dominated by tree species that are less than 5 inches DBH, respectively). Finally, stands that have higher ecological integrity have a higher need for fire from a conservation perspective and were therefore integrated into the model using documented examples of high-quality natural communities from MNFI's Natural Heritage Database (i.e., natural community element occurrences) [32].

2.3.3. Species

Species-level or within-stand variables included presence of fire-tolerant and fire-dependent species. Our model incorporates plant species occurrence data from the MiFI database [93] and also rare animal and plant species element occurrence data from MNFI's Natural Heritage Database [32]. Within MiFI there are currently 411 plant species that can be entered via a pull-down menu. We conducted a literature search on the fire tolerance and fire dependence of each species [92,102].

For each species, we assigned a classification for fire tolerance (i.e., tolerant or sensitive) and for fire dependence (i.e., dependent or not dependent). We then grouped species into five categories: (1) fire-sensitive, desirable natives; (2) fire-tolerant invasives; (3) fire-sensitive invasive or undesirable native species; (4) somewhat fire-sensitive invasive species

that may require multiple fires to be controlled; and (5) fire-tolerant and/or fire dependent native species.

We ran an intersection of MiFI stands with MNFI's rare species element occurrences and generated a list of known rare species occurrences that intersect with stands. For each of these species we researched whether or not the species is fire tolerant or fire dependent, and if the habitat the species depends on is fire dependent. We evaluated a total of 461 rare animal and plant species [103].

2.4. Variable Scoring

The input variables included both categorical and numerical data. For example, classes within the surficial geology layer include "end moraines of fine-textured till" and "ice-contact outwash sand and gravel," and classes attributed to the aspect variable include "south," "southwest," and "west." The variables that have numerical data are attributed with different numbering systems with different ranges. For example, for the slope variable, the data is broken into mean slope classes (e.g., ≥ 0 and ≤ 6; ≥ 7 and ≤ 9; ≥ 21 and ≤ 30), and the fire frequency range variable included 14 different classes (e.g., 1–5 years; 5–20 years; 50–100 years; 500–100 years; >1000 years). To combine the input variables into the same analysis, we reclassified each variable to the same relative evaluation scale to allow for comparison across variables. Scores for most variables were scaled equally within 6 integers and ranged between 0 and 5, in order of increasing ecological need for prescribed fire (i.e., 0 = No Fire Needs or None, 1 = Low, 2 = Moderate, 3 = High, 4 = Very High, 5 = Highest). Presence of fire-sensitive rare species and/or fire-sensitive desirable native species resulted in negative scores for the species input variable on the inverse of the 0 to 5 scale.

We developed detailed scoring rules for each input variable specific to Michigan. For example, for natural community types with a fire frequency range of 1 to 5 years, we developed the following rule: "IF Fire Frequency Range = 1–5 Years, THEN + 5." Additional examples of rules include: "IF Surficial Geology = Ice-contact outwash sand and gravel, THEN + 5"; "IF Aspect = West, THEN + 5"; and "IF stand is classified as 'fire dependent' and Mean Slope ≥ 0 AND ≤ 6, THEN + 5" (Table 2). In addition, we also developed scoring rules for rare species from the MNFI database and species from the MiFI database. For rare species, we assigned a score to each species depending on the species' fire tolerance, fire dependence, and dependence on fire-dependent habitat (Table 3). For a subset of the species noted within MiFI stand data, we developed different scoring rules based on the five categories of species (i.e., fire-sensitive, desirable natives; fire-tolerant invasives; fire-sensitive invasive or undesirable native species; somewhat fire-sensitive invasive species; and fire-tolerant and/or fire-dependent native species) (Table 4). Examples of species rules include the following: "IF Canopy (majority %) OR Subcanopy (presence only) = Yellow Birch; THEN -5"; and "IF Canopy (majority %) OR Subcanopy (presence only) = Bur Oak; THEN + 5."

Table 2. Example scoring rules for Fire Frequency Range.

Fire Frequency Range	Fire Needs Score	Rule
>1000 Years	0	If Fire Frequency Range $\geq$ 1000 Years, THEN + 0
Not Applicable	0	If Fire Frequency Range = Not Applicable, THEN + 0
80–300 Years	1	If Fire Frequency Range = 80–300 Years, THEN + 1
50–100 Years	2	If Fire Frequency Range = 50–100 Years, THEN + 2
20–100 Years	3	If Fire Frequency Range = 20–100 Years, THEN + 3
10–80 Years	4	If Fire Frequency Range = 10–80 Years, THEN + 4
1–20 Years	5	If Fire Frequency Range = 1–20 Years, THEN + 5

Table 3. Example fire needs scores for rare species from the Michigan Natural Features Inventory (MNFI) Natural Heritage Database [32]. * Stands with fire-sensitive rare species that would benefit from fire refugia are flagged.

Scientific Name	Common Name	Fire Tolerant	Fire Dependent	Fire-Dependent Habitat	Fire Needs Score
Ambystoma opacum	Marbled salamander	No	No	No	−5
Ammodramus savannarum	Grasshopper sparrow	Yes	No	Yes	3
Amorpha canescens	Leadplant	No	No	Yes	5
Asclepia sullivantii	Sullivant's milkweed	No	No	Yes	3
Atrytonopsis hianna	Dusted skipper	No	No	Yes	5 *
Botaurus lentiginosus	American bittern	Yes	No	No	0

Table 4. Example fire needs scores for plant species from the Michigan Forest Inventory (MiFI) database [93]. * Note that the negative scoring for red maple is only triggered in stands classified as an upland where mesophication is occurring.

Scientific Name	Common Name	Category of Species	Fire Needs Score
Fraxinus nigra	Black ash	Fire-sensitive desirable native	−5
Ailanthus altissima	Tree-of-Heaven	Fire-tolerant invasive	−1
Acer rubrum	Red maple	Undesirable native	−5 *
Ligustrum vulgare	Common privet	Fire-sensitive invasive	5
Quercus macrocarpa	Bur oak	Fire-tolerant and fire dependent native	5
Lupinus perennis	Wild lupine	Fire-dependent native	5
Elaegnus umbellata	Autumn olive	Somewhat fire-sensitive invasive	0

2.5. GIS-Based Multicriteria Decision Analysis

To synthesize the data contributed by our multiple input variables into one prescribed fire needs score, we used GIS-based multicriteria decision analysis [104,105], which combines spatially referenced data and multi-attribute criteria in a problem-solving environment. This integrated analysis allows users to apply weights to input variables and combine them into a single output. We assigned weights to variables to infer relative importance to prescribed fire needs. Weighting was determined by expert opinion and not empirical statistical analysis. Weights were derived following discussions with natural resource managers and fire ecology experts and literature review on the factors that influence fire disturbance regimes and the response of landscapes, ecosystems, and species to fire. We multiplied each reclassified score by the assigned weighting factor. Assigned variable weights include x25 for Fire Frequency Range, x20 for VCC, x20 for Fire Dependence, x15 for Physiographic Region, x10 for Surficial Geology, x10 for Aspect, x10 for Slope, x5 for Circa 1800 Vegetation, and x5 for Natural Community Element Occurrence. The remaining variables received a weight of one (x1), which is equivalent to no weight. For each stand, the prescribed fire needs score was calculated by summing the weighted scores for each variable, and then rescaling the final score to a 0 to 5 range. Once again, higher scores convey a higher level of ecological need for prescribed fire. See Figure 2 for a schematic of the model architecture and Figure 3 for how the scoring works in an example stand. To visualize the scoring, the scores were assigned colors on a blue to red color gradient with higher scores corresponding to reds and displayed within GIS.
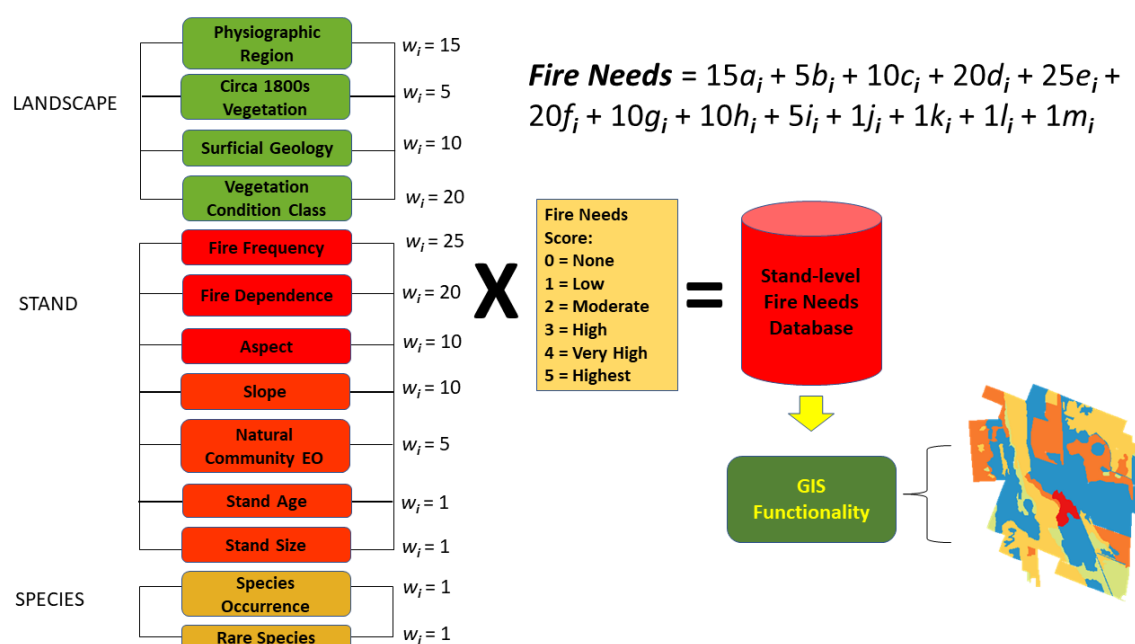
The model diagram shows:

LANDSCAPE
- Physiographic Region — $w_i = 15$
- Circa 1800s Vegetation — $w_i = 5$
- Surficial Geology — $w_i = 10$
- Vegetation Condition Class — $w_i = 20$

STAND
- Fire Frequency — $w_i = 25$
- Fire Dependence — $w_i = 20$
- Aspect — $w_i = 10$
- Slope — $w_i = 10$
- Natural Community EO — $w_i = 5$
- Stand Age — $w_i = 1$
- Stand Size — $w_i = 1$

SPECIES
- Species Occurrence — $w_i = 1$
- Rare Species — $w_i = 1$

$$\textit{Fire Needs} = 15a_i + 5b_i + 10c_i + 20d_i + 25e_i + 20f_i + 10g_i + 10h_i + 5i_i + 1j_i + 1k_i + 1l_i + 1m_i$$

Fire Needs Score:
0 = None
1 = Low
2 = Moderate
3 = High
4 = Very High
5 = Highest

X

= **Stand-level Fire Needs Database**

GIS Functionality

Figure 2. Overview of prescribed fire needs assessment model. This model gauges each stand's ecological need for prescribed fire based on an array of spatial variables and the presence of fire-dependent and fire-sensitive species. For each stand, multiple input variables at multiple scales were evaluated, scored, and weighted to generate an overall fire needs score. Each input variable was binned into one of three modules or submodels depending on the variable's scale (i.e., landscape, stand, and species).
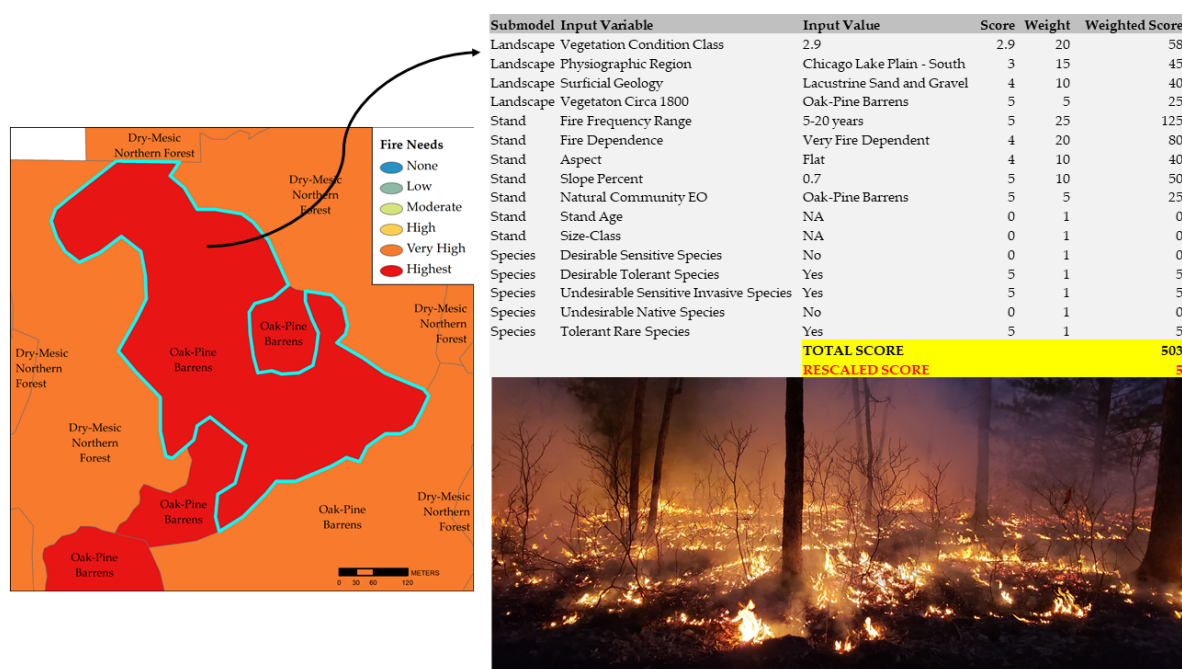

Submodel	Input Variable	Input Value	Score	Weight	Weighted Score
Landscape	Vegetation Condition Class	2.9	2.9	20	58
Landscape	Physiographic Region	Chicago Lake Plain - South	3	15	45
Landscape	Surficial Geology	Lacustrine Sand and Gravel	4	10	40
Landscape	Vegetaton Circa 1800	Oak-Pine Barrens	5	5	25
Stand	Fire Frequency Range	5-20 years	5	25	125
Stand	Fire Dependence	Very Fire Dependent	4	20	80
Stand	Aspect	Flat	4	10	40
Stand	Slope Percent	0.7	5	10	50
Stand	Natural Community EO	Oak-Pine Barrens	5	5	25
Stand	Stand Age	NA	0	1	0
Stand	Size-Class	NA	0	1	0
Species	Desirable Sensitive Species	No	0	1	0
Species	Desirable Tolerant Species	Yes	5	1	5
Species	Undesirable Sensitive Invasive Species	Yes	5	1	5
Species	Undesirable Native Species	No	0	1	0
Species	Tolerant Rare Species	Yes	5	1	5
		TOTAL SCORE			**503**
		RESCALED SCORE			**5**

Fire Needs
- None
- Low
- Moderate
- High
- Very High
- Highest

Figure 3. Example stand from the Michigan Forest Inventory (MiFI) database [93] from Allegan State Game Area (SGA). This particular stand occurs on a flat, sandy lakeplain and corresponds to a high-quality oak-pine barrens remnant that occurs in an area that was historically oak-pine barrens. Oak-pine barrens is a fire-dependent system that has a high fire frequency and supports numerous species that are dependent on fire. The stand's fire needs score is further increased by the presence of a rare animal species and an invasive understory shrub that decreases with prescribed fire. Above photo from Allegan SGA by Maria Albright (Michigan Department of Natural Resources Wildlife Division).

2.6. Incorporating Complexity

The effectiveness of prescribed fire can be complicated by numerous factors including past management history, the presence of fire-tolerant invasive species, the presence of fire-sensitive rare species, the complexity of an ecosystem's disturbance regime, and the timing and severity of fire. As this kind of nuance is not captured by the aforementioned input variables, it is not reflected in the fire needs scores. To incorporate this complexity into our model we developed several supplementary rules for highlighting stands that need to be carefully considered before the implementation of prescribed fire. Where stands include the presence of rare species that are fire sensitive but reliant on fire-dependent habitat, we have added "needs refugia" in the stand's comment field and added highlighting symbology in the stand's spatial representation. Rare species that require refugia are those that are killed by fire due to limited dispersal ability and are characterized by limited populations within remnant fire-dependent habitat. Explicit rules were developed to highlight or flag stands that contain invasive species that are fire tolerant and increase following prescribed fire or that contain invasive species that likely need multiple, intense, and/or seasonally specific fires and/or additional measures (i.e., mechanical treatment and herbicide) to be controlled. Many fire-dependent forested systems have multi-faceted disturbance regimes. For natural community types that have complex disturbance regimes that include varying fire behavior (e.g., both infrequent stand-replacing crown fire and frequent low-intensity surface fire), we have added information about the fire regime in the stand's comment field and highlighting symbology in the stand's spatial representation. Several fire-dependent ecosystems in Michigan are characterized by stand-replacing fire regimes (e.g., dry northern forests dominated by jack pine). We provided symbology for stands that have a high need for fire but are characterized by stand-replacing fire regimes so that managers can consider other management options if prescribed crown fire is not feasible. For stands in the Southern Lower Peninsula, where we found information about date of last fire, we developed a rule to identify these stands so that managers can evaluate when stands "need" fire based on their fire frequency range in relation to the latest fire event.

2.7. Quality Control

Following the initial development of the model, we engaged in several activities to quality control our model. To see how different variables influence the model, we grouped the variables into submodels or modules based on the scale of the variable (i.e., landscape, stand, and species) and examined the results of the model looking independently at those submodels (Figure 4). To further evaluate the impact of the input variables, we generated multi-panel maps illustrating the individual contribution of each variable to the total fire score, both at coarse and fine spatial scales (Figure 5). In addition, we generated histograms, pivot tables, and other chart types to visualize patterns of various fire scores and relationships between and among select variables. We generated total fire score with and without weights to assess the effect of the weighted variables.

We compiled graphics and maps into presentations that we delivered to multiple audiences at multiple scales to solicit feedback on the input variables, our weighting scheme, and our map products depicting the prescribed fire needs assessment model. We presented our model to natural resource managers from two different regions of the state (i.e., SW and NLP), fire experts (i.e., The Nature Conservancy LANDFIRE, Michigan Prescribed Fire Council, Lake States Fire Science Consortium, Sault Tribe's Natural Resources Services, and U.S. Forest Service), academics (i.e., faculty and graduate students from Michigan State University, University of Michigan, and University of Wisconsin), and regional and national conservation practitioners (i.e., we delivered presentations at the following events: the 2018 Lake States Fire Science Consortium Burning Issues Workshop; a 2018 Stewardship Network Webcast; and the 2019 NatureServe Midwest Heritage Forum). In total, the model has been presented to over 250 conservation practitioners.
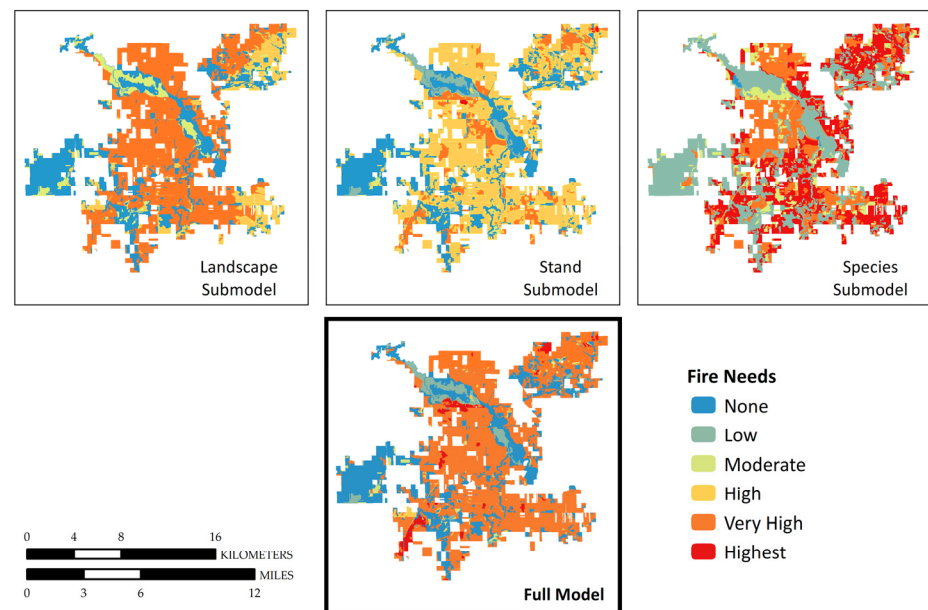
Figure 4. Fire needs score by submodels for Allegan State Game Area.

Five MNFI ecologists contributed to the development of the model and four Michigan natural resource managers and two regional fire experts provided informal input through organic discussions following presentations. We provide two examples of improvements to the model that were derived from these presentations and resulting discussions. For our physiographic regions variable, we were encouraged to switch from Albert's landscape classification (1995) [82] to Schaetzl et al.'s (2013) [83], since Schaetzl's classification incorporates more recent data on soils and climate and thereby generated more up-to-date and spatially precise physiographic regions. To increase the transparency and ease of interpretation of our model, we were encouraged to organize the input variables by submodels corresponding to our three scales of analysis (i.e., landscape, stand, and species) (Figure 4).
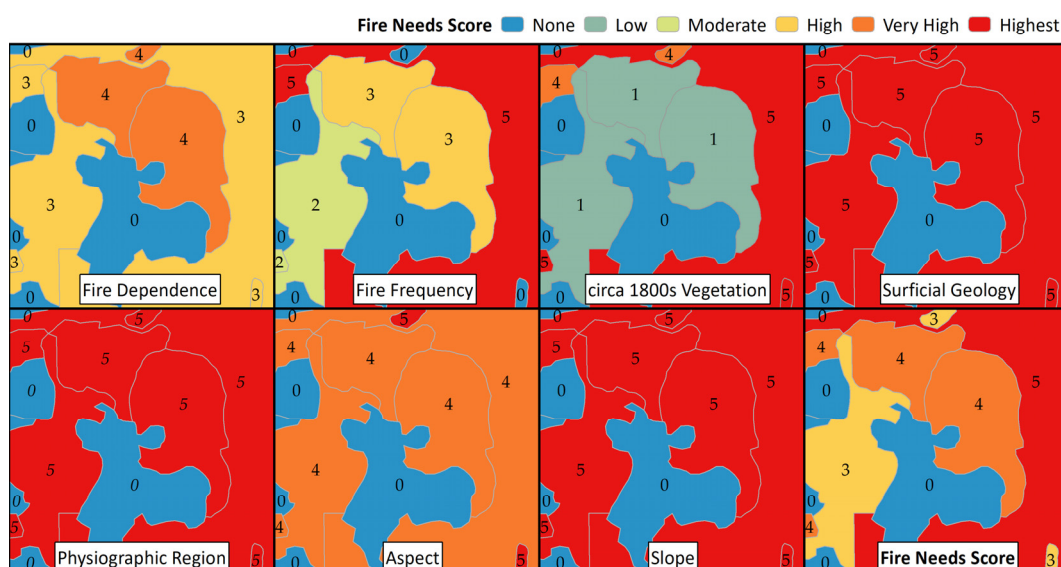
Figure 5. *Cont.*
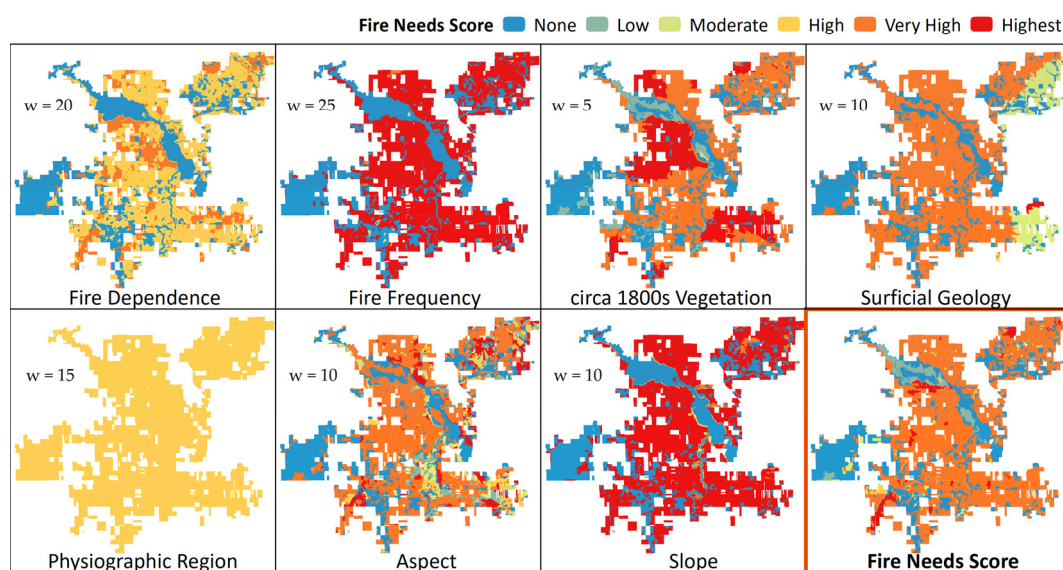
Figure 5. Multi-panel maps illustrating the individual contribution of selected input variables to the total fire needs score, both at fine-spatial (**above**) and coarse-spatial scales (**below**). The below figure depicts the fire needs scores for Allegan State Game Area for a subset of the input variables.

We examined the spatialization or spatial distribution of scoring in select state game areas and forest management units. We relied upon on-the-ground knowledge of MNFI ecologists who conducted the initial inventory of select areas and DNR wildlife biologists and foresters who are responsible for land management to see if the model made ecological sense. An example issue that was elucidated through this "ground-truthing" process was that fire-sensitive systems found on flat topography were receiving high fire needs scores. We rectified this issue by decreasing the weighting of our slope variable and modifying our script to decrease fire needs in areas of flat topography with inundated to saturated soils on poorly drained landforms.

2.8. Summary of Prescribed Fire Application on State Lands in Michigan

To provide a point of comparison for our modeling output, we compiled available data on prescribed fire application on state lands (WLD and FRD lands). Two datasets are currently available across all state lands: tabular data from 2016 to 2020 with area burned per year by management area and point data from 2007 to 2020 of prescribed fires implemented. The point data does not reliably correspond to specific stands included in each burn, and instead points correspond to access points, parking areas, ignition points, or the general vicinity of each burn. Unfortunately, there is no data layer with comprehensive spatially explicit prescribed fire data corresponding to the MiFI stand data. Additionally, due to COVID-19, no prescribed fires were implemented on state lands in Michigan in 2020. Using the tabular data of acreage burned per year, we calculated hectares burned per year by management area. Using the point data, we determined the frequency of burns by management region and area. To assess whether prescribed fires on state lands corresponded with areas with mean fire scores indicating high fire needs, we conducted two analyses. First, we tested whether mean fire needs scores were higher in management areas where at least one prescribed fire occurred during the period 2007–2020, compared to units where no fire occurred. As mean fire needs scores were not normally distributed, we conducted this test with the nonparametric Mann–Whitney statistic. Then, using only data for management areas that had received prescribed fire, we regressed the mean fire needs score for each management area by burn frequency, that is, the number of burns in the time period 2007–2020 for every thousand acres in that management area. Burn frequency values were log-transformed to conform with assumptions of normality. These analyses were conducted using R 3.5.2 [106].

3. Results

We assigned fire needs scores for thirteen attributes at three scales for 18,653 stands within the MiFI database for Southern Lower Michigan and 159,818 stands in Northern Michigan. In Southern Michigan and Northern Michigan, we crosswalked a natural community type to 77% and 78% of the stands, respectively. For the remaining 23% in Southern Michigan and 22% in Northern Michigan, we did not make an assignment to natural community type because the stand was an anthropogenic system (e.g., developed, cropland, plantations, roads, ruderal systems, and grassland plantings) or we did not have enough information to make a confident assignment. Stands classified as anthropogenic systems were assigned fire frequency and fire dependence scores of zero, and a subset of these anthropogenic systems (i.e., developed, cropland, plantations, and roads) were automatically assigned a fire needs score of zero. Stands that represent natural communities that lack fuels and never burn (e.g., water bodies and sandstone cobble shore) were also assigned a fire score of zero. Due to the prevalence of these stands with no need for fire and assigned scores of zero (just over 58% of the stands received a fire needs score of zero), our dataset of fire needs scores has a zero-inflated distribution. Throughout the results section we present summary statistics with the full dataset as well as summary statistics with the zero values excluded. In figures where we are conveying trends only among stands that were scored, we exclude the zero values.

The primary products that we have generated from this model are stand-level data files attributed with the described ecological data and a fire needs score and the spatial representation of those stand scores at multiple scales. Having this information at the stand level allows for aggregation of the information to larger scales (e.g., groups of stands, management areas, and management and physiographic regions). To demonstrate the robust capacity of our model to provide information at multiple scales we present maps and summary statistics at three scales: statewide, the DNR's five broad management regions, and smaller-scale management areas (Figure 6; Table 5; Appendices B and C). We end the results section by summarizing our efforts to incorporate complexity by supplementing stand scores with commentary and symbology.
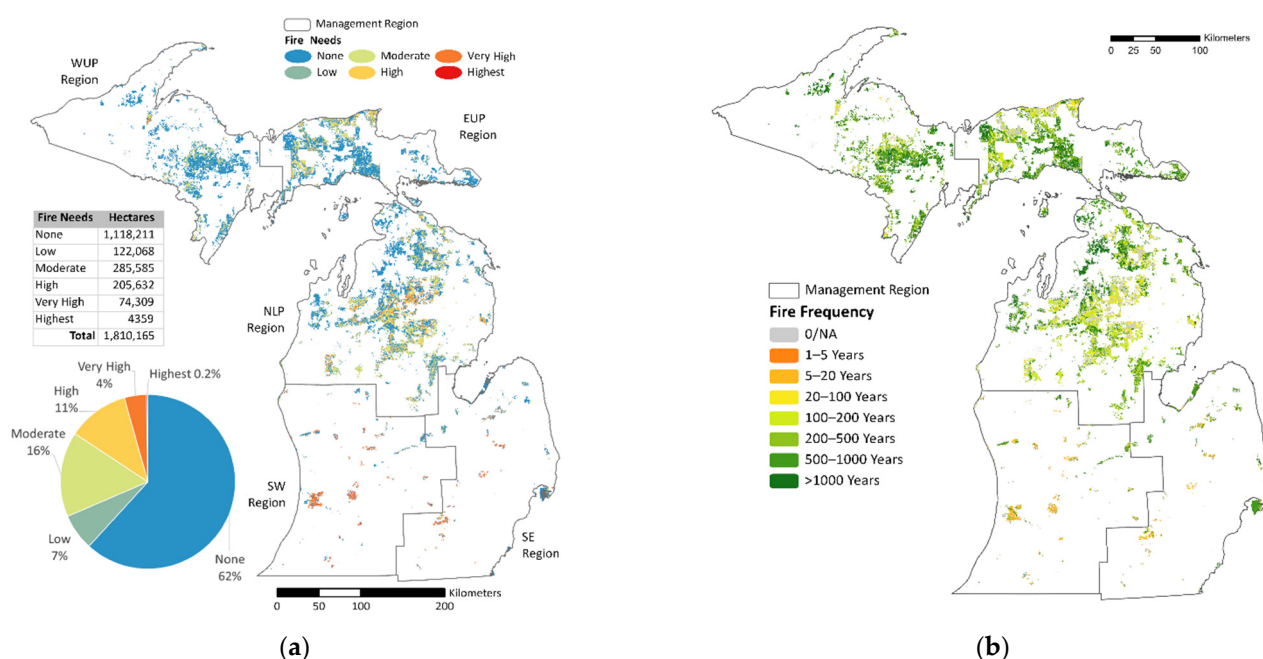

Figure 6. (**a**) Fire needs score for state lands in Michigan and proportion by fire needs class. (**b**) Fire return interval depicted using the fire frequency range mid-point assigned to each stand and aggregated into eight fire frequency classes.

Table 5. Summary statistics by state, management unit, and management area with mean fire needs score, standard deviation, sample size, number of fires from 2007 to 2020, and average area burned from 2016 to 2020.

Extent	Mean Fire Needs Score (Excluding Zero Values)	Standard Deviation (Excluding Zero Values)	Sample Size (Excluding Zero Values)	Number of Fires from 2007 to 2020	Average Area Burned from 2016 to 2020 (Excluding 2020)
Michigan	0.97 (2.32)	1.28 (0.89)	178,471 (74,743)	849	2233 ha (2791 ha)
SW Region	1.96 (3.47))	1.89 (1.06)	10,744 (6089)	248	586 ha (732 ha)
SE Region	1.64 (3.01)	1.73 (1.16)	7909 (4294)	219	579 ha (723 ha)
NLP Region	1.07 (2.25)	1.23 (0.72)	91,080 (43,340)	281	839 ha (1049 ha)
EUP Region	0.72 (2.08)	1.08 (0.74)	36,297 (12,656)	52	134 ha (168 ha)
WUP Region	0.49 (1.91)	0.91 (0.69)	32,441 (8364)	49	95 ha (118 ha)
Allegan SGA	2.79 (3.80)	1.84 (0.87)	2260 (1660)	140	204 ha (255 ha)
Port Huron SGA	1.01 (2.74)	1.47 (1.07)	346 (127)	1	5 ha (5 ha)
Gwinn FMU	0.52 (1.92)	0.93 (0.71)	11,203 (3048)	17	5 ha (5 ha)

Fire needs in Michigan are geographically variable at multiple scales. At the statewide scale, fire needs increase moving from north to south, and a large proportion of state lands have no need for prescribed fire management. Our model indicates the highest need for fire occurs in the Southern Lower Peninsula of Michigan, and the lowest need for fire occurs in the Upper Peninsula. Furthermore, the need for fire is highest in the Southwest Management Region, and among management areas within this region, the Allegan State Game Area (SGA) has the highest average fire needs score.

3.1. Statewide

We generated maps displaying the fire needs score and fire return interval for all state lands evaluated by the model (Figure 6). The mean fire needs score for all state lands in Michigan was 0.97 (SD = 1.28, N = 178,471). Among stands receiving a score (i.e., excluding zero values), the mean fire needs score was 2.32 (SD = 0.89, N = 74,743). Our model classified 0.2% (4359 ha or 10,772 ac) of these lands into the highest fire needs scoring class, 4% (74,309 ha or 183,622 ac) into the very high fire needs scoring class, and 11% (205,632 ha or 508,127 ac) into the high fire needs scoring class (Table 6). Percentage of fire needs scores statewide are depicted in Figure 7a along with a breakdown of the area in the very high needs class by fire frequency ranges. From 2007 to 2020, 849 prescribed fires occurred on state lands. On average, over the past 5 years the DNR has implemented prescribed fire on 2233 hectares (5517 ac) of state lands annually; excluding 2020, when no burning occurred due to COVID-19 restrictions, the average from 2016 to 2019 was 2791 hectares (6896 ac) per year.

Table 6. Area by fire needs class statewide and by management region.

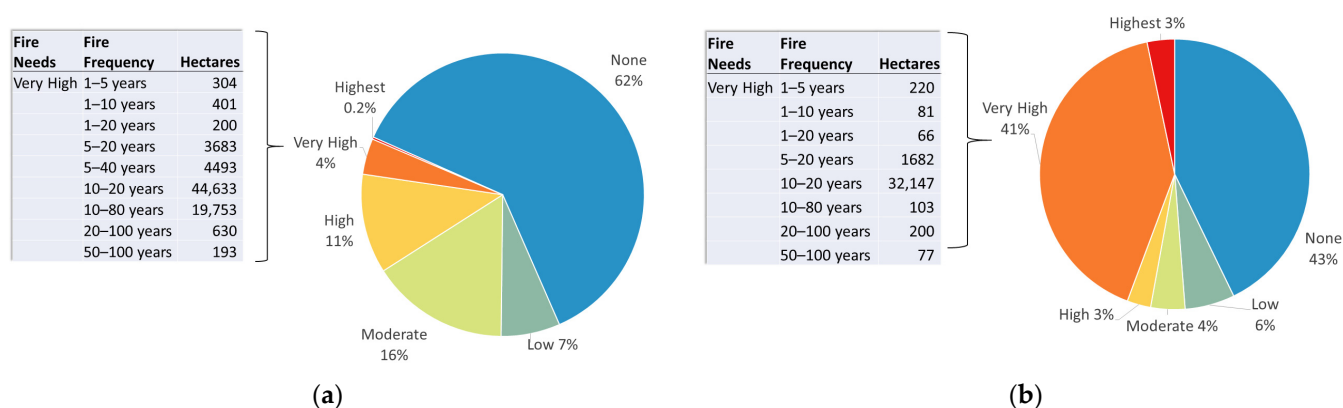| Extent	Highest	Very High	High	Moderate	Low	None
Michigan	4359 ha (0.2%)	74,309 ha (4%)	205,632 ha (11%)	285,585 ha (16%)	122,068 ha (7%)	1,118,211 ha (62%)
SW Region	2777 ha (3%)	34,582 ha (41%)	2393 ha (3%)	3457 ha (4%)	5024 ha (6%)	36,106 ha (43%)
SE Region	1493 ha (1.8%)	14,346 ha (17%)	5796 ha (7%)	4759 ha (6%)	12,050 ha (14%)	44,364 ha (54%)
NLP Region	89 ha (0.01%)	23,594 ha (2.8%)	147,180 ha (17%)	165,666 ha (20%)	48,540 ha (6%)	459,928 ha (54%)
EUP Region	0 ha (0%)	787 ha (0.18%)	38,726 ha (9%)	64,681 ha (15%)	37,705 ha (9%)	293,401 ha (67%)
WUP Region	0 ha (0%)	1000 ha (0.3%)	11,537 ha (3%)	47,022 ha (13%)	18,748 ha (5%)	284,413 ha (79%)

Fire Needs	Fire Frequency	Hectares
Very High	1–5 years	304
	1–10 years	401
	1–20 years	200
	5–20 years	3683
	5–40 years	4493
	10–20 years	44,633
	10–80 years	19,753
	20–100 years	630
	50–100 years	193

Fire Needs	Fire Frequency	Hectares
Very High	1–5 years	220
	1–10 years	81
	1–20 years	66
	5–20 years	1682
	10–20 years	32,147
	10–80 years	103
	20–100 years	200
	50–100 years	77

(a)   (b)

Figure 7. Percentage of fire needs scores statewide (**a**) and within the Southwest Mangement Unit (**b**) with a breakdown of the hectares in the very high needs class by fire frequency ranges. This breakdown can be used to calculate range of annual burn target acreage (See discussion on page 27).

3.2. Management Regions

We provide a comparison of the mean fire needs score and scoring distribution for the five management regions (Figure 8) and show the relative proportion of fire needs scores by management regions and the relative proportion of average area burned per year by management region over the past five years (Figure 9). We generated maps of the geographical distribution of fire needs scores and histograms depicting the statistical distribution of fire needs scores for the five DNR Management regions: the Southwest (SW) (Figure 10), Southeast (SE) (Appendix B, Figure A1), Northern Lower Peninsula (NLP) (Appendix B, Figure A2), Eastern Upper Peninsula (EUP) (Appendix B, Figure A3), and Western Upper Peninsula (WUP) Regions (Appendix B, Figure A4). Detailed summaries of modeling results, maps, and histograms showing density of fire needs scores are provided in Appendix B.

(a)   (b)
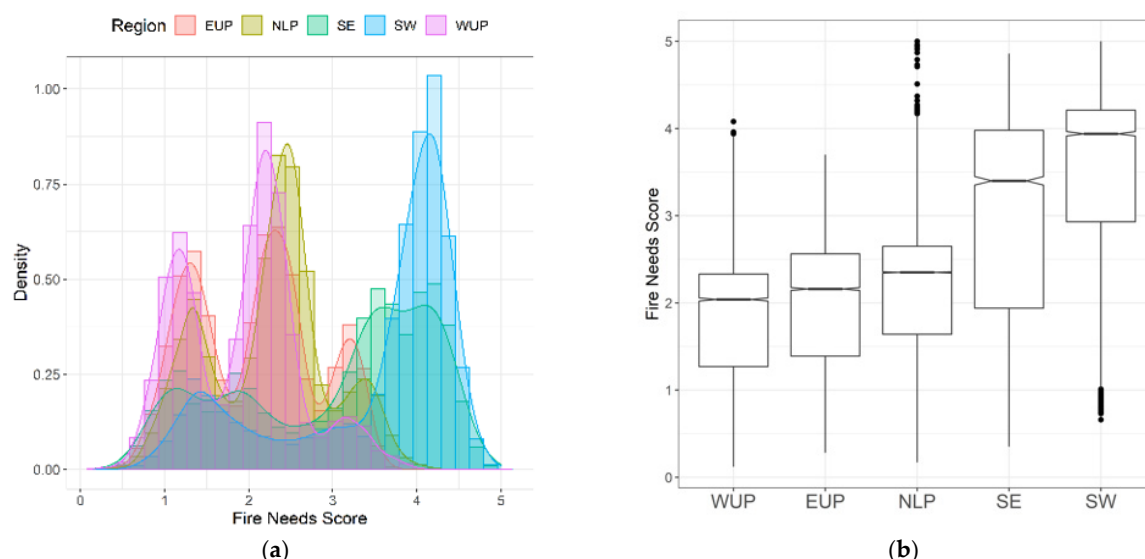
Figure 8. Comparison of fire needs scores by management region: (**a**) Histogram showing distribution of fire needs scores for all stands receiving a score with the scoring distribution color-coded by management region; (**b**) Box and whisker plots by management region showing fire needs score median and distribution characteristics for all stands receiving a score, sorted by median from lowest to highest. Black dots indicate outlier values. The notches denote the 95% confidence intervals for the medians and they do not overlap among the regions suggesting the median fire needs score differs significantly between each region (Kruskal–Wallis test, H = 10,766, $p < 0.001$).
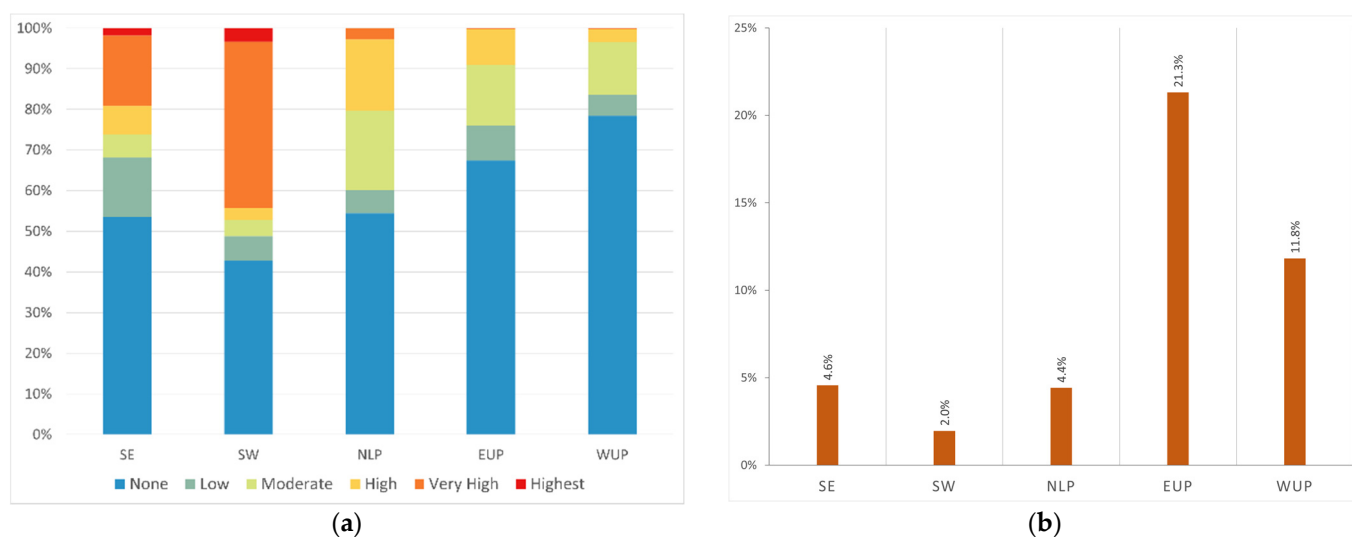
(**a**)

(**b**)

Figure 9. Comparison of fire needs and application of prescribed fire by management region: (**a**) Relative proportion of fire needs by fire needs class and management region; (**b**) Proportion of average acreage annually burned by management region relative to area identified as having very high and highest fire needs. Comparing the proportion of statewide area burned to the proportion of statewide highest and very high scores within regions, the SW burned at a rate of 0.55 of its needs, while the SE, NLP, EUP, and WUP burned at a rate of 1.29, 1.25, 6.01, and 3.33 times their needs, respectively.

(**a**)

(**b**)
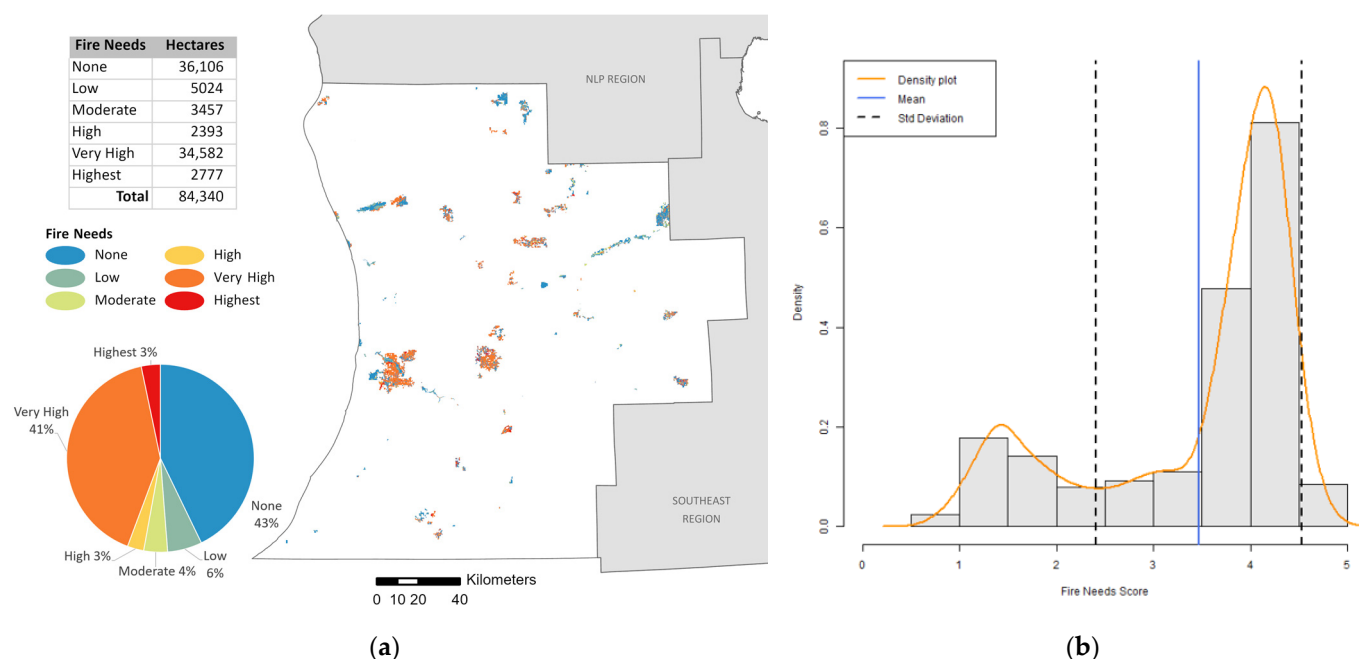
Figure 10. Prescribed fire needs score for Southwest Management Region: (**a**) Fire needs score for state lands and proportion by fire needs class; (**b**) Histogram showing density of fire needs scores for all stands receiving a score (i.e., excluding zero values). The mean fire needs score was 3.47 (SD = 1.06, N = 6089).

Stands with highest and very high fire needs scores total 37,479 ha (92,316 ac) in the SW region, which amounts to 44% of state land in the region, and 47% of all area receiving highest and very high scores statewide (Table 6 and Figures 9 and 10). By contrast, in the NLP region, 23,683 ha (58,522 ac) received highest and very high scores, or 3% of the region and 30% of statewide area receiving those scores (Table 6 and Figures 9 and A2 in Appendix B). Despite having higher fire needs on average, over the past five years, 732 ha (1810 ac) (26% of statewide total and 2% of area with highest and very high needs) burned in the SW region, while 1049 ha (2592 ac) (38% of statewide total and 4% of area

with highest and very high needs) burned in the NLP region (Table 5). Comparing the proportion of statewide area burned to the proportion of statewide highest and very high scores within regions, the SW burned at a rate of 0.55 of its needs, while the SE, NLP, EUP, and WUP burned at a rate of 1.29, 1.25, 6.01, and 3.33 times their needs, respectively (Figure 9b).

3.3. Management Areas

We evaluated average fire needs score and frequency of prescribed fire over the past fourteen years for 107 different management areas across the state. Table 7 displays summary statistics for three example areas that we discuss below and also highlights the following: areas with a mean fire needs score above 3.0; areas with a mean fire needs score above 2.5 that have not been burned from 2007 to 2020 (potential "fire gaps"); and areas with a mean fire needs score below 1.0 that have burned more than 10 times from 2007 to 2020 (potential "fire sink"). In addition to number of burns from 2007 to 2020 for each management area, we also present the proportion of prescribed burns for management area. Prescribed fire between 2007 and 2020 was not more likely to occur in management areas with high mean fire scores than in areas with low scores. Mean fire scores were not different between management areas that did and did not receive prescribed fire ($\overline{x}^{fire}$ = 2.61, $\overline{x}^{no\ fire}$ = 2.64; U = 1396.5, p = 0.86). Among management areas receiving fire between 2007 and 2020, burn frequency increased slightly with increasing mean fire needs score (ln(y) = −1.21 + 0.63x; p = 0.03), although mean fire needs score only explained 7% of the variation in prescribed fire frequency (Figure 11).

Table 7. Frequency of fires by management area. In addition to three example areas that we discuss in more detail in Appendix C (emboldened here), the table highlights: areas with a mean fire needs score above 3.0 (in red); areas with a mean fire needs score above 2.5 that have not been burned in the last decade (potential "fire gaps") (in yellow); and areas with a mean fire needs score below 1.0 that have burned more than 10 times in the last decade (potential "fire sinks") (in blue). Management areas include State Game Areas (SGA), State Wildlife Areas (SWA), and Forest Management Units (FMU). The "Number of Prescribed Fires" corresponds to the number of fires by management area from 2007–2020. The "Number of Prescribed Fires by Area" was multiplied by 1000 for scaling purposes.

| Management Area	Management Region	Number of Prescribed Fires	Number of Prescribed Fires by Area	Mean Fire Needs Score
Allegan SGA	SW	140	3.83	2.79
Brownstown Prairie SWA	SE	0	0	3.76
Davisburg SGA	SE	0	0	3.22
Escanaba FMU	WUP	18	0.48	0.56
Gagetown SGA	SE	11	16.21	0.84
Gaylord FMU	NLP	24	0.35	0.58
Goose Lake SGA	SE	0	0	2.63
Gwinn FMU	WUP	17	0.26	0.52
Haymarsh Lake SGA	SW	13	10.28	0.77
Langston SGA	SW	0	0	2.73
Newberry FMU	EUP	12	0.87	0.87
Petersburg SGA	SE	25	56.93	3.02
Pigeon River FMU	NLP	12	0.68	0.94
Port Huron SGA	SE	1	0.53	1.01
Saranac-Lowell SGA	SW	0	0	2.70
Sault Sainte Marie FMU	EUP	16	0.26	0.37
Shingleton FMU	EUP	24	0.17	0.87
Traverse City FMU	NLP	43	0.33	0.89
Verona SGA	SE	43	15.86	0.75

(**a**)   (**b**)
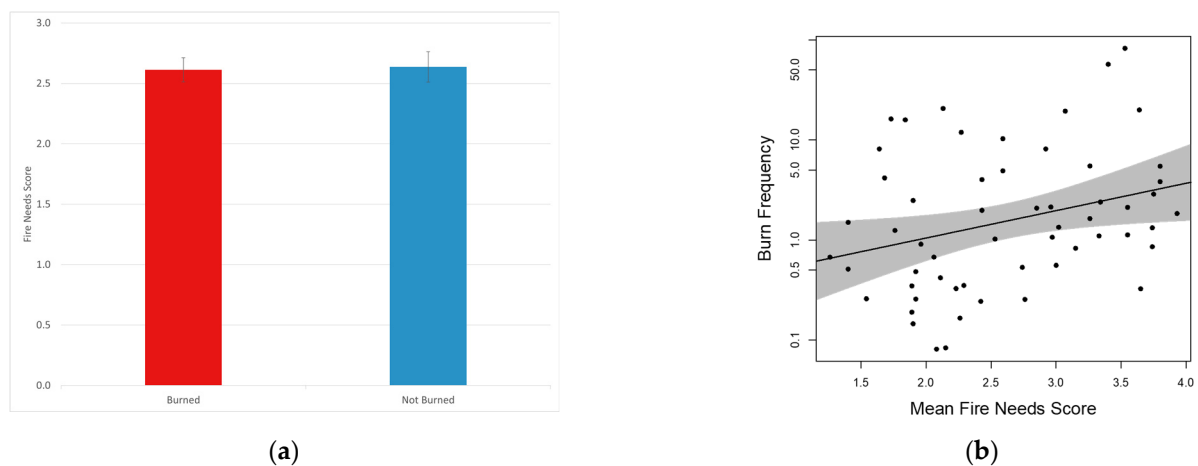
Figure 11. Mean fire needs scores by management areas, compared to occurrence of prescribed fire. (**a**) Mean ($+/-$ S.E.) of mean fire needs scores for management areas burned between 2007–2020 (2.61 $+/-$ 0.10) were not different from those that were not burned (2.64 $+/-$ 0.13) (Mann–Whitney, U = 1396.5, p = 0.86). (**b**) Among areas receiving fire between 2007–2020, areas with higher mean fire needs scores tended to burn more frequently (p = 0.03, R^2 = 0.07). Note log scale of *y*-axis, burn frequency for each management area = ln(number of burns$_{2007-2020}$/1000 acres managed).

To display the potential utility of this model in terms of helping prioritize site-specific prescribed fire implementation, we present maps and summary statistics for three distinct management areas that occur within three different DNR management regions and that vary from high to low fire needs: Allegan SGA (Figure 12), Port Huron SGA (Appendix C, Figure A5), and Gwinn Forest Management Unit (FMU) (Appendix C, Figure A6). Appendix C provides detailed summaries of modeling results, maps, and histograms showing density of fire needs scores along with a comparison of the fire needs scoring distribution for these three management areas (Figure A7,).

(**a**)   (**b**)
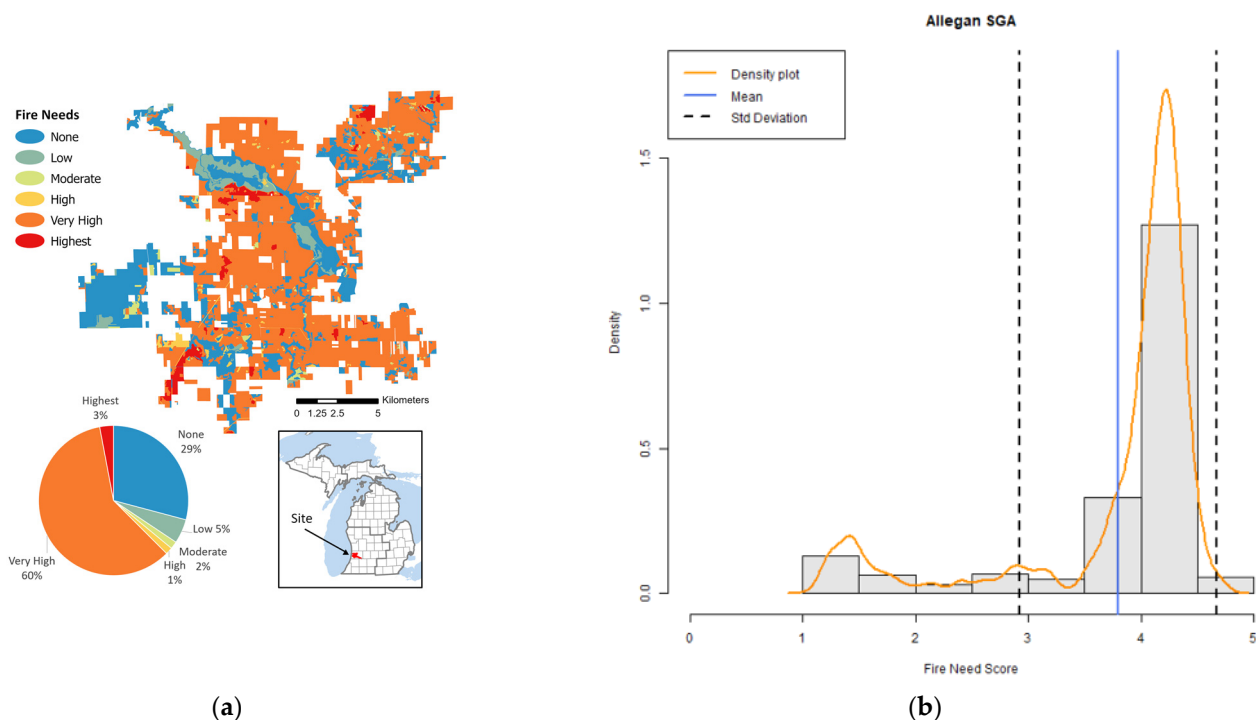
Figure 12. (**a**) Prescribed fire needs score for the Allegan State Game Area (SGA); (**b**) Histogram showing density of fire needs scores for all stands receiving a score (i.e., excluding zero values). The mean fire needs score was 3.80 (SD = 0.87, N = 1660).

3.4. Incorporating Complexity

A total of 57,113 stands were flagged with auxiliary comments to highlight the need for managers to factor in additional considerations before implementing prescribed fire: this represents just under a third of the stands evaluated. Overall, 10,513 stands (5.9%) were noted as needing fire refugia for rare wildlife species; 2055 stands (1.2%) contained invasive species that increase following fire and were marked as needing control efforts before the implementation of burning; 4963 stands (2.8%) were noted as needing multiple burns and/or additional management actions to control invasive species; and 44,987 stands (25%) were identified as having complex and/or stand-replacing fire regimes. Within the Southern Lower Peninsula, only 127 stands were attributed with the date since their last reported fire. We added this information to each stand's attribute table to facilitate decisions about when the next application is appropriate in terms of the site's fire frequency range. Figure 13 provides a graphical example of how we have incorporated complexity into the model by attributing stands with supplementary commentary and how that commentary is spatially expressed through symbology.
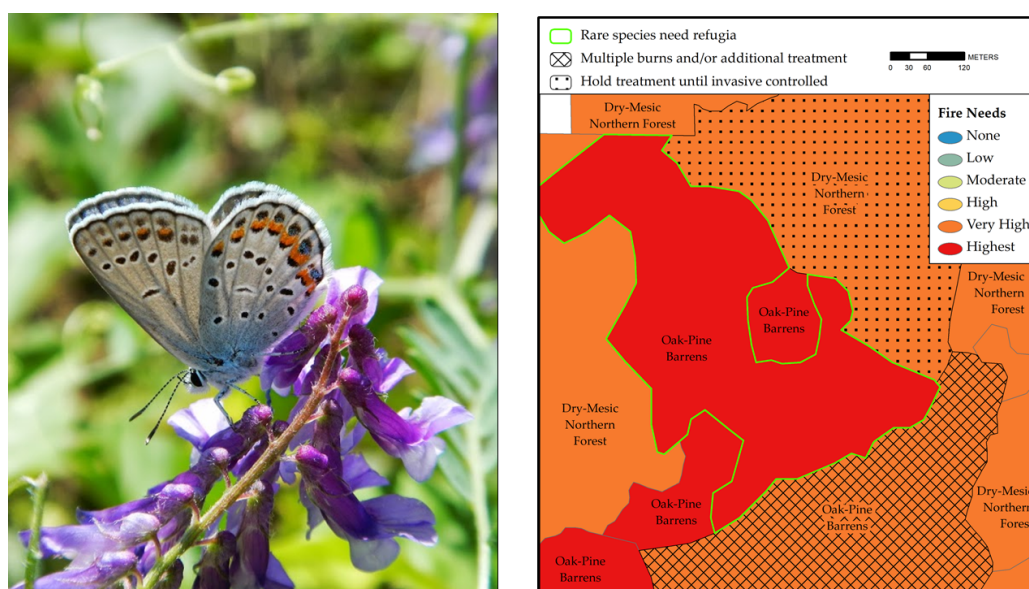
Figure 13. The stand-level data files are attributed with critical factors that resource managers should consider when evaluating a stand's ecological need for prescribed fire including, whether or not multiple burns and/or additional treatments are needed to control certain species within the stand; whether refugia should be established to protect populations of rare species, such as the Karner blue (*Lycaeides melissa samuelis*) pictured here; and whether implementation of fire should be postponed until a fire-tolerant invasive species has been controlled by other mechanisms. These details are displayed spatially with symbology that conveys the attributed information. Photo by David L. Cuthrell (Michigan Natural Features Inventory).

4. Discussion

In fire-suppressed landscapes such as the upper Midwest, resource managers struggle both with applying prescribed fire everywhere it is needed and with the decision-making process of where to devote limited resources. Prior fire needs assessments have provided coarse-scale analysis to help identify the need for prescribed fire at regional scales [73–76] with the research from Wisconsin representing the only published effort [75]. We developed a model to facilitate prescribed fire planning at multiple scales and thereby provide a unique and needed contribution to the fire needs assessment literature. Our model integrates both fine-scale, field-collected and broad-scale, GIS data to characterize fire needs across state lands and provides a replicable framework for application of spatial multicriteria analysis

that explicitly incorporates variables at the multiple scales (i.e., landscape, stand, species) at which prescribed fire management is planned, implemented, and monitored.

Fire needs in Michigan are geographically variable at multiple scales. Statewide, fire needs increase with decreasing latitude, and are highest in southwest Michigan. Fire-dependent ecosystems throughout Michigan have degraded due to decades of fire suppression, with critical consequences for biodiversity. The consequences may be the most dire in the southwest region. Southwest Michigan occupies the tip of the "Prairie Peninsula," an eastward extension of the tallgrass prairie region, and as such contains a high concentration of highly fire-dependent prairie and savanna remnants [107]. These ecosystems, and many species that depend upon them, are critically threatened both regionally and globally [108]. A disproportionate number of rare species depend on fire-dependent ecosystems. For example, of the 441 vascular plant species tracked as threatened, endangered, or special concern in Michigan, at least 100 are mostly or wholly limited to the prairie and savanna ecosystems that are concentrated in this region [32]. Without sufficient fire, these and other fire-dependent ecosystems will continue to degrade, and species will be lost. By determining where fire is most needed, we can better manage habitat for game species and other wildlife, and improve biodiversity management outcomes overall.

Within the subsequent discussion we explore the utility of the model framework and its output by acknowledging how understanding the model's limitations and underlying assumptions is essential for putting it into practice (Section 4.1), demonstrating how the model can inform decision making at multiple scales (Section 4.2), and illustrating broader applications of the prescribed fire needs assessment model specifically and GIS-based multicriteria decision analysis generally (Section 4.3).

4.1. Limitations: From Model to Management

The prescribed fire needs assessment model provides resource managers with information about the ecological need for prescribed fire, but it offers limited guidance on precisely how to apply that information. The model is not intended to make prescriptions but to help inform resource managers with on-the-ground expertise. While the model indicates the range of fire needs among stands across Michigan it does not provide information about the requisite seasonality and severity of prescribed fire within those stands. The model includes information about the fire frequency range for ecosystems but does not provide site-specific detail about the required frequency of prescribed fire in fire-suppressed stands in fire-suppressed landscapes. It is critical to note that for ecological systems that have been fire-suppressed for many years, simply returning fire to the system is not sufficient for the restoration of structure and biodiversity [109,110]. Application of prescribed fire in consecutive years may be required during the restoration process. In addition, burning a target acreage per year is also not enough if the fire effects are not achieving the ecological objectives of the prescribed fire. We have provided supplementary commentary to stands attributed with fire needs scores to acknowledge some of the complexity surrounding decisions about application of burning. Ultimately, decisions about severity, seasonality, and frequency remain the purview of land managers with intimate knowledge of the sites being burned.

Models are inherently limited by the quality of data that fuel them and influenced by the assumptions made to construct them. We incorporated multiple datasets of varying scales derived by varying entities. Each dataset has its own limitations and delving into these is beyond the scope of this paper. We will however touch upon the MiFI database, since it is the foundational unit of our model, as well as the fire frequency range input variable, since it received the highest weighting in our model framework. Stand data in southern Michigan and in some northern Michigan WLD lands was collected by MNFI ecologists during the growing season. In northern Michigan state forest lands, data were collected by DNR foresters and wildlife biologists, habitually during the winter months. As a result, the MiFI data gathered by MNFI ecologists typically has more detailed information about subcanopy, understory, and ground cover species for both native and

non-native species. Therefore, the stand-level species data for southern Michigan compared to northern Michigan typically contained more comprehensive data on species-level factors influencing fire needs. Another limitation of the MiFI data is the dearth and inconsistency in reporting of past fire disturbance. Date since the last prescribed fire or wildfire is frequently undocumented or reported in inconsistent notation formats within text-based comment fields. Due to the labor-intensive requirement of manually extracting this information, we did not collect this information for the 159,818 stands in northern Michigan. The need for prescribed fire in a given location should, of course, be informed by knowledge of the date since the last fire. A spatially and temporally explicit database of past prescribed burns and wildfires would help refine the output of our prescribed fire needs assessment.

We assigned weights to our input variables based on our current understanding of each variable's relative importance to prescribed fire needs. As our understanding of input variables changes, the assigned weights should be reevaluated. The greatest weight was assigned to fire frequency range, as it clearly follows that ecosystems characterized by shorter fire return intervals have greater fire needs. As we noted, this variable was derived from literature review, discussions with experts, and ecological inference. The study of fire disturbance regimes and the estimation of fire return intervals and fire frequency ranges is a relatively new and evolving science. Estimations of fire frequency ranges have been compiled from a variety of methods including historical anecdotes [16], interpretation of the circa 1800 General Land Office (GLO) surveys [15], and dendrochronological (tree-ring based) reconstructions. Each method is associated with unique advantages and disadvantages [111]. Historical anecdotes are based on observations and not derived from scientific studies. However, in many cases they offer the only documented evidence of frequent fires in prairie and savanna systems, which are too rare in the current landscape and lack sufficient tree densities to accurately assess fire history through dendrochronology. Interpretation of large-scale disturbance documented by GLO surveyors can be used to broadly map fire disturbance patches and calculate disturbance rotation intervals. An inherent bias of this method is the focus on intermediate to high-severity disturbances, which were more readily detected by the GLO surveyors, and the underestimation of low-severity fires [111]. This method, by focusing on fire extremes, tends to underestimate true fire frequency. Dendrochronological research of fire disturbance is dependent on the survival of canopy trees and the use of these fire-scarred trees facilitates precise reconstruction of site-specific fire return intervals. While this methodology is limited in its ability to predict the size or spatial complexity of past fires, it is better able to identify low-severity fire events. Recent dendrochronological reconstructions of fire in the upper Midwest have provided quantitative evidence that low-severity fire events were frequent and likely more important than once realized [111]. As the understanding of fire disturbance regimes progresses, new insights should be incorporated into the prescribed fire needs assessment model and the fire frequency ranges assigned to natural community types will need to be adjusted accordingly.

We provide explicit detail about the methods we used to derive our model to facilitate the replication of our framework. While we believe our general approach to be replicable, we acknowledge that the specific outputs of our model are unique because they are informed by expert input and several of the input variables are exclusive to Michigan. MNFI scientists who contributed to the development of the model collectively have over half a century of professional experience. Michigan natural resource managers and regional fire experts who contributed to the conceptualization of the model collectively have over a century and half a century of professional experience, respectively. As noted above, external input was provided through informal organic discussions. By not requesting formal structured responses to our presentations and not implementing facilitated discussions, we missed an opportunity to gather external input in a repeatable manner. Future efforts to model prescribed fire need that include development of expert-derived rules criteria, scoring, and weights would benefit from applying a formal conceptual framework using methods from Decision Science. The Delphi method has been applied as an effective means

to survey experts iteratively to reach consensus where no standard criteria exist [112]. The Analytic Hierarchy Process (AHP) [113,114] has been widely utilized in other fields to incorporate expert decisions within a complex hierarchy of scoring and weights, with the advantage of also evaluating consistency.

The development of this model required tens of thousands of individual decisions, including selecting input variables, crosswalking MiFI stand covertypes to natural community types, determining fire frequency ranges for each natural community type, developing a scoring system for each input variable, assigning scores for the input variables to all of the stands, and deriving a weighting system for the input variables. While these decisions were informed by a combination of literature review and expert input, our assumptions and many of our choices were certainly influenced by our inherent biases as conservation scientists and the value systems to which we ascribe. We attempted to address this limitation by transparently detailing the rationale for our decisions and soliciting input from a diverse array of parties throughout the process. We recognize that ecological need, as modeled here, is one of many values that natural resource managers evaluate when making everyday decisions about prescribed fire. The modeling framework can be easily modified to incorporate other input variables that address additional values that natural resource managers assess when making land management decisions.

4.2. Context for Informed Decision Making

The prescribed fire needs assessment model provides a framework for resource managers grappling with difficult questions critical for the restoration and management of fire-dependent ecosystems. These questions include: (1) How much land should be burned in a given year? (2) Are the ecologically most important places burning? Without spatially explicit data of prescribed burns it is difficult to retrospectively and explicitly address this last question at the stand scale, but the model can be used to proactively inform future prescriptions, and past trends can be assessed at a regional scale. In evaluating recent trends, it is clear that the application of prescribed fire is not necessarily occurring in the areas with the greatest ecological needs as indicated by the model. The greatest need for fire is in the SW region, but prescribed fire is not being applied in proportion with that need (See Figures 9 and 10). Overall, application of prescribed fire over the past five years was disproportionately higher in the NLP, SE, EUP, and WUP and lower in the SW (See Figure 9).

Management areas with higher mean fire needs scores were just as likely as not to receive fire over the period 2007–2020 (Figure 11a), suggesting that the factors driving prescribed fire on state lands in Michigan are largely unrelated to the primarily ecological considerations incorporated into the model. There was a trend suggesting that among areas receiving fire, the frequency of burning increased with mean fire needs score. However, mean fire needs score only explained 7% of the variation in burn frequency (Figure 11b). What drives the decision-making process that explains the remaining 93% of variation of when and where prescribed fire is applied on state lands in Michigan? In other words, what accounts for the incongruity between areas the model has identified as having a high fire need and places selected for prescribed burning through the current decision-making process? A possible explanation for this disparity is the prevalence of burning on state land in anthropogenic systems implemented to benefit one species or one group of species as opposed to increasing whole ecosystem integrity. Two examples of this type of prescribed burning that fall into this category include the use of fire for site preparation in plantations and repeated burning of wildlife openings and planted grasslands in forested landscapes to benefit game species. Implementation of prescribed fire as a silvicultural treatment in plantations and use of fire to maintain wildlife openings for deer, elk, and game birds are prevalent in the NLP, and burning to increase deer and game bird habitat is prevalent in the SE. While these types of fires provide benefit to the targeted species, they are occurring in stands that our model has identified as having low to no ecological need for fire. In addition, because of the operational ease of implementation and the immediate yield of beneficial

results in wildlife openings and grassland plantings, we suspect that many of these types of burns are repeated in the same stands. We refer to repeated burns in areas of low fire needs as "fire sinks" since these prescribed fires potentially divert resources away from areas with higher ecological need for fire. We raise these examples not to discourage the use of fire to meet these types of management objectives but to encourage further deliberation about whether limited resources for prescribed fire application are being expended in the places with the greatest ecological need. This also highlights the implicit bias of our model to focus on whole ecosystem needs and opportunities for ecosystem management as opposed to identifying sites for single species management. It is worth noting that many fire-dependent ecosystems developed under landscape-scale fire management by Native Americans that was explicitly focused on managing silvicultural resources (e.g., mast-producing trees) and game species [16,70]. When conducted strategically, management for silviculture and game species need not come at the expense of other ecological targets, and more explicitly integrating these goals into the fire needs assessment may be warranted.

The converse of examining why places with low fire needs are burning is considering why sites identified with the highest fire needs are not burning. What accounts for these "fire gaps"? We believe that one of the most critical questions raised by this modeling effort is why the places identified as having the highest fire needs are not burning. A more thorough multi-scaled analysis of these "fire gaps" and "fire sinks" informed by more spatially explicit prescribed fire data is merited.

The answer to the question "are we burning enough?" depends on how thresholds for sufficient burning are set, both in terms of fire needs scores and fire return intervals. Statewide, the model identified 4359 ha (10,772 ac) as having the highest fire needs (Figure 6a), yet 2233 hectares (5517 ac) on average are burned each year over the past five years, below the criteria of highest fire needs (as noted above, whether these prescribed fires are occurring in the areas of highest need is a question that cannot be answered without explicit spatial data and likely varies from region to region). However, if the criteria are expanded to include the top three fire needs classes (highest, very high, and high; 284,301 ha or 702,522 ac), then the state is well below the target suggested by the model. How far below target depends on what the appropriate fire return interval is for this acreage of highest, very high, and high fire needs, how fire-suppressed these sites are, and if fire-suppressed, how much fire they need in order to move from a restoration phase (e.g., reducing woody stem density below some threshold) to a maintenance phase (e.g., maintaining woody stem density below that same threshold).

For the sake of demonstrating the scale of disparity between the need for fire and application of fire, let us assume that these stands identified in the highest, very highest, and high fire needs classes are not fire-suppressed (i.e., they are in the maintenance phase). We can determine target acreage to burn in the highest, very high, and high classes per year by evaluating the corresponding area for each class by its corresponding fire frequency range (Figure 7). For example, if there are 100,000 hectares of a fire-dependent ecosystem that has a fire-return interval ranging between 10 and 20 years, then we can set our prescribed burn target for the extent of this ecosystem at 5000 to 10,000 hectares per year [73]. Using this same logic, we project that at a minimum 4869 to 29,924 hectares (12,031 to 73,944 ac) should be burned every year to adequately burn the areas of highest, very high, and high need on state lands in Michigan. Furthermore, as these are generally fire-suppressed ecosystems in fire-suppressed landscapes, this estimated range is conservative and should likely go up significantly since many sites on state lands, especially in the Southern Lower Peninsula, will need to burn more frequently than suggested by their assigned fire frequency range to overcome fire suppression.

Given that over the past five years 2233 hectares (5517 ac) burn annually on state lands in Michigan, this suggests that between 2.2 and 13.4 times more hectares need to burn to satisfy the fire return interval for all stands with highest, very high, and high fire needs. Applying this same reasoning, we can provide the same analysis at smaller scales. Within the SW region, just under 586 hectares (1448 ac) were burned per year from 2016 to 2020.

We project that at a minimum 1951 to 4418 hectares (4820 to 10,917 ac) should be burned annually to adequately burn the areas of highest, very high, and high need on state lands in the SW region. Our model suggests 3.3 to 7.5 times more hectares should be burned per year in the SW region. Within the Allegan SGA, 204 hectares (504 ac) were burned per year from 2016 to 2020. We project that at a minimum 652 to 1512 hectares (1611 to 3735 ac) should be burned annually to adequately burn the areas of highest, very high, and high need in Allegan SGA. Our model suggests 3.2 to 7.4 times more hectares should be burned per year in the Allegan SGA.

These types of considerations inevitably lead to additional questions. If there is a mismatch between what is being burned and what needs to be burned and if annual burning is insufficient, what accounts for this disjunction? If the current burning program in Michigan is not meeting the ecological need for prescribed fire according to our model, why is that and what can be done to remedy that situation? Barriers for application of sufficient prescribed fire noted in other fire needs assessments include budgetary constraints, insufficient personnel and equipment, inability to respond to dynamic weather conditions during a relatively short window of opportunity across a broad geography, restrictive rules and regulations, organization values and biases, and societal and safety concerns, particularly in areas where the wildland urban interface is prevalent [72–76]. Our results suggest a need (1) to evaluate what barriers are at play in Michigan and (2) for additional research focused on the social factors influencing decision making about prescribed fire and the identified gaps between the ecological need for fire and implementation. These issues could be investigated through social-ecological models that explicitly incorporate both institutional goals and ecological goals not currently addressed by those institutional goals. Policy changes may be needed to modify how prescribed fire is implemented to meet a broader suite of goals, and ultimately foster a sustainable burning program that increases the frequency, intensity, seasonal variability, and extent of prescribed fire in the ecologically most important places in Michigan.

4.3. Broader Applications

The prescribed fire needs assessment model provides a useful framework utilizing spatial multicriteria analysis to inform conservation decisions at multiple scales. While the base units of our model are stands from the MiFI database and are specific to Michigan and state lands in Michigan, our approach can be broadly applied acknowledging the limitations addressed above. By using input variables that are publicly available and universal and analogous fine-scale landcover sources, our modeling framework can be applied in different geographies and by different management agencies. Where fine-scale vegetation cover is not available, broad-scale approaches can be implemented to provide planning guidance and to help frame regional discussions [73–76]. In addition to the state lands model, we have developed a statewide prescribed fire needs assessment using 640-acre hexagons attributed with NatureServe's Ecological Systems [115] crosswalked to MNFI natural community types and intersected with a subset of the landscape-level and stand-level variables (i.e., surficial geology, physiographic region, circa 1800 vegetation, VCC, slope, aspect, and natural community element occurrences) [116]. Statewide and regionwide efforts to evaluate prescribed fire needs across jurisdictional limits and across public and private lands are critical for the conservation of native biodiversity of fire-dependent ecosystems. Fire historically was a landscape-scale disturbance that operated with no regard for artificial anthropogenic boundaries. We therefore recommend the application of prescribed fire needs assessments at even broader geographic scales (i.e., upper Midwest) to help inform conservation planning regionally.

5. Conclusions

Native biodiversity is jeopardized by an alarming rate of ecosystem degradation from continued landscape fragmentation, climate change, invasive species infestation, and fire suppression [19,117–120]. Conservation practitioners need to employ tools that can

match the pace and scale of this unprecedented change and facilitate the prioritization of biodiversity stewardship in the most ecologically important areas. Spatial multicriteria models offer one means of enhancing our ability to efficiently and effectively inform critical conservation decisions at multiple scales and promote restoration of biodiversity.

Using a spatial multicriteria modeling framework, we have developed a model that facilitates assessment of the ecological need for prescribed fire on state lands in Michigan. The model was developed not to provide definitive answers or replace on-the-ground expertise but instead to spark informed discussion at multiple scales, guide difficult decisions about allocation of finite resources, and ultimately enhance the restoration of native biodiversity of fire-dependent ecosystems. By identifying regional patterns of fire needs, the model can advance broad-scale planning efforts. By highlighting specific sites in need of fire management, the model can help direct on-the-ground implementation of prescribed fire. By illustrating the disparity of the ecological need for fire and the actual application of fire and identifying "fire sinks" and "fire gaps," the model can enlighten policy makers tasked with funding and structuring burning programs.

Appendix A Fire Frequency Ranges by Natural Community Types

Table A1. Fire frequency ranges by natural community type.

Natural Community Type	Fire Frequency	Fire Frequency Range	Confidence	Reference
Alvar	Infrequent	>200 years	Low	Reschke et al. 1999 [121], Jones and Reschke 2005 [122], Catling and Brownell 1998 [123]
Bog	Infrequent	100–>200 years	Low	Camill et al. 2009 [124], Wieder et al. 2009 [125]
Boreal Forest	Very Infrequent	>200–500 years	Medium	Bergeron et al. 2004 [126]
Bur Oak Plains	Very Frequent	1–10 years	Low	Leitner et al. 1991 [13], Chapman and Brewer 2008 [16]
Cave	NA	NA	High	-
Clay Bluff	NA	NA	High	-
Coastal Fen	Very Infrequent	>500 years	Medium	-
Coastal Plain Marsh	Infrequent	70–200 years	Low	-
Dry Northern Forest (low-severity)	Frequent	10–40 years	High	Simard and Blank 1982 [127], Drobyshev et al. 2008 [128], Meunier et al. 2019 [129], Meunier and Shea 2020 [109]
Dry Northern Forest (high-severity)	Frequent	60–300 years	High	Heinselman 1973 [8], Whitney 1986 [12], Drobyshev et al. 2008 [128]
Dry Sand Prairie	Very Frequent	1–10 years	High	Chapman 1984 [11], Chapman and Brewer 2008 [16]
Dry Southern Forest	Frequent	10–35 years	Medium	Nowacki and Abrams 2008 [17]
Dry-Mesic Northern Forest	Infrequent	120–300 years	High	Heinselman 1973 [8], Heinselman 1981 [10], Whitney 1986 [12]
Dry-Mesic Prairie	Very Frequent	1–5 years	High	Cottam 1949 [33], Chapman 1984 [11], Chapman and Brewer 2008 [16]
Dry-Mesic Southern Forest	Infrequent	10–35 years	Medium	Schmidt et al. 2002 [90], Nowacki and Abrams 2008 [17]
Emergent Marsh	Very Infrequent	>500 years	High	-
Floodplain Forest	Infrequent	>500 years	Low	-
Granite Bedrock Glade	Infrequent	20–100 years	Low	-
Granite Bedrock Lakeshore	NA	NA	High	-
Granite Cliff	Very Infrequent	>1000 years	Medium	-
Granite Lakeshore Cliff	NA	NA	High	-
Great Lakes Barrens	Infrequent	80–300 years	Low	-
Great Lakes Marsh	Very Infrequent	>500 years	High	-
Hardwood-Conifer Swamp	Infrequent	120–>500 years	Medium	Whitney 1986 [12], Zhang et al. 1999 [130]
Hillside Prairie	Frequent	5–20 years	Medium	Chapman and Brewer 2008 [16]
Inland Salt Marsh	Infrequent	70–300 years	Low	Chapman et al. 1985 [131]
Intermittent Wetland	Infrequent	50–200 years	Low	-
Inundated Shrub Swamp	Very Infrequent	>500 years	High	Snyder 1991 [132]
Lakeplain Oak Openings	Frequent	5–20 years	High	Dorney 1981 [5], Wolf 2004 [133]
Lakeplain Wet Prairie	Frequent	5–20 years	Medium	Chapman and Brewer 2008 [16]
Lakeplain Wet-Mesic Prairie	Frequent	1–10 years	High	Chapman and Brewer 2008 [16]
Limestone Bedrock Glade	Infrequent	>200 years	Low	Jones and Reschke 2005 [122], Catling and Brownell 1998 [123]
Limestone Bedrock Lakeshore	NA	NA	High	-
Limestone Cliff	NA	NA	High	-
Limestone Cobble Shore	NA	NA	High	-

Table A1. *Cont.*

Natural Community Type	Fire Frequency	Fire Frequency Range	Confidence	Reference
Limestone Lakeshore Cliff	NA	NA	High	-
Mesic Northern Forest	Extremely Infrequent	>1000 years	High	Whitney 1986 [12], Frelich and Lorimer 1991 [134]
Mesic Prairie	Very Frequent	1–2 years	High	Cottam 1949 [33], Chapman 1984 [11], Chapman and Brewer 2008 [16]
Mesic Sand Prairie	Very Frequent	1–5 years	High	Chapman 1984 [11], Chapman and Brewer 2008 [16]
Mesic Southern Forest	Very Infrequent	>1000 years	High	Curtis 1959 [4], Grimm 1984 [6]
Muskeg	Infrequent	100–>500 years	Medium	Heinselman 1981 [10], Camill et al. 2009 [124], Wieder et al. 2009 [125]
Northern Bald	Infrequent	>200 years	Low	-
Northern Fen	Infrequent	100–> 200 years	Low	-
Northern Hardwood Swamp	Very Infrequent	>500 years	High	MN DNR 2003 [135]
Northern Shrub Thicket	Very Infrequent	>500 years	Low	-
Northern Wet Meadow	Infrequent	100–>200 years	Low	Curtis 1959 [4], Davis 1979 [136]
Oak Barrens	Frequent	5–20 years	High	Dorney 1981 [5], Wolf 2004 [133], Nowacki and Adams 2008 [17]
Oak Openings	Very Frequent	1–10 years	Low	Cottam 1949 [33], Chapman 1984 [11], Chapman and Brewer 2008 [16]
Oak-Pine Barrens	Frequent	5–20 years	Low	Dorney 1981 [5], Faber-Langendoen and Davis 1995 [137], Wolf 2004 [133], Nowacki and Adams 2008 [17]
Open Dunes	NA	NA	High	-
Patterned Fen	Infrequent	100–>200 years	Low	Camill et al. 2009 [124], Wieder et al. 2009 [125], Drobyshev et al. 2008 [128]
Pine Barrens	Frequent	5–40 years	High	Curtis 1959 [4], Simard and Blank 1982 [127], Whitney 1986 [12]
Poor Conifer Swamp	Infrequent	100–>200 years	High	Heinselman 1981 [10], Whitney 1986 [12]
Prairie Fen	Frequent to Infrequent	20–>100 years	Low	Kost and Hyde 2009 [138]
Rich Conifer Swamp	Extremely Infrequent	>1500	High	Whitney 1986 [12], Zhang et al. 1999 [130]
Rich Tamarack Swamp	Infrequent	100–>200 years	Low	Zhang et al. 2000 [139]
Sand and Gravel Beach	NA	NA	High	-
Sandstone Bedrock Lakeshore	NA	NA	High	-
Sandstone Cliff	NA	NA	High	-
Sandstone Cobble Shore	NA	NA	High	-
Sandstone Lakeshore Cliff	NA	NA	High	-
Sinkhole	NA	NA	High	-
Southern Hardwood Swamp	Very Infrequent	>500 years	High	-
Southern Shrub-Carr	Very Infrequent	>500 years	Low	-
Southern Wet Meadow	Frequent to Infrequent	50–100 years	Medium	Curtis 1959 [4], Davis 1979 [136]
Submergent Marsh	NA	NA	High	-
Volcanic Bedrock Glade	Frequent	20–100 years	Low	-
Volcanic Bedrock Lakeshore	NA	NA	High	-
Volcanic Cliff	NA	NA	High	-
Volcanic Cobble Shore	NA	NA	High	-
Volcanic Lakeshore Cliff	NA	NA	High	-

Table A1. *Cont.*

Natural Community Type	Fire Frequency	Fire Frequency Range	Confidence	Reference
Wet Prairie	Very Frequent	5–20 years	High	Chapman 1984 [11], Chapman and Brewer 2008 [16]
Wet-Mesic Flatwoods	Very Infrequent	>500 years	High	-
Wet-Mesic Prairie	Frequent	1–10 years	High	Chapman 1984 [11], Chapman and Brewer 2008 [16]
Wet-Mesic Sand Prairie	Very Frequent	1–10 years	High	Chapman 1984 [11], Chapman and Brewer 2008 [16]
Wooded Dune and Swale Complex	Frequent to Very Infrequent	50–>500 years	Low	-

Appendix B Detailed Summaries of Modeling Results, Maps, and Histograms by Management Region

Appendix B.1 Southwest Region

The mean fire needs score for state lands in the SW was 1.96 (SD = 1.89, N = 10,744). Among stands receiving a score (i.e., excluding zero values), the mean fire needs score in the SW was 3.47 (SD = 1.06, N = 6089) (Figure 10b). Our model classified 3% (2777 ha or 6862 ac) of these lands into the highest fire needs scoring class and 41% (34,582 ha or 85,454 ac) into the very high fire needs scoring class (Figure 10a). Percentage of fire needs scores within the SW are depicted in Figure 7b along with a breakdown of the area in the very high needs class by fire frequency ranges. From 2007 to 2020, the DNR implemented 248 burns on state lands in the SW, 29% of the burns statewide. On average, over the past 5 years the DNR has implemented prescribed fire on 586 hectares (1448 ac) of state lands in the SW annually; excluding 2020, when no burning occurred due to COVID-19 restrictions, the average from 2016 to 2019 was 732 hectares (1810 ac) per year. This constitutes 26% of the total area of state land burned during that timeframe.

Appendix B.2 Southeast Region

The mean fire needs score for state lands in the SE was 1.64 (SD = 1.73, N = 7909). Among stands receiving a score (i.e., excluding zero values), the mean fire needs score in the SE was 3.01 (SD = 1.16, N = 4294) (Figure A1b). Our model classified 1.8% (1493 ha or 3690 ac) of these lands into the highest fire needs scoring class and 17% (14,346 ha or 35,450 ac) into the very high fire needs scoring class (Figure A1a). From 2007 to 2020, the DNR implemented 219 burns on state lands in the SE, 26% of the burns statewide. On average, over the past 5 years the DNR has implemented prescribed fire on 579 hectares (1430 ac) of state lands in the SE annually; excluding 2020, when no burning occurred due to COVID-19 restrictions, the average from 2016 to 2019 was 723 hectares (1787 ac) per year. This constitutes 26% of the total area of state land burned during that timeframe.
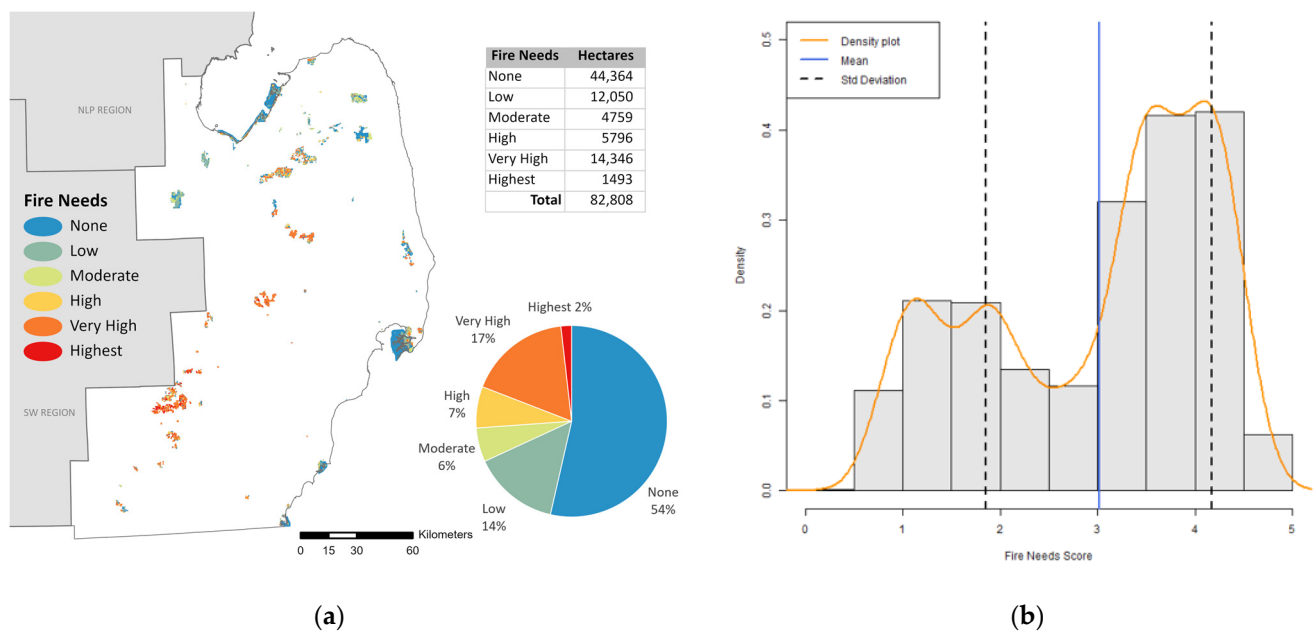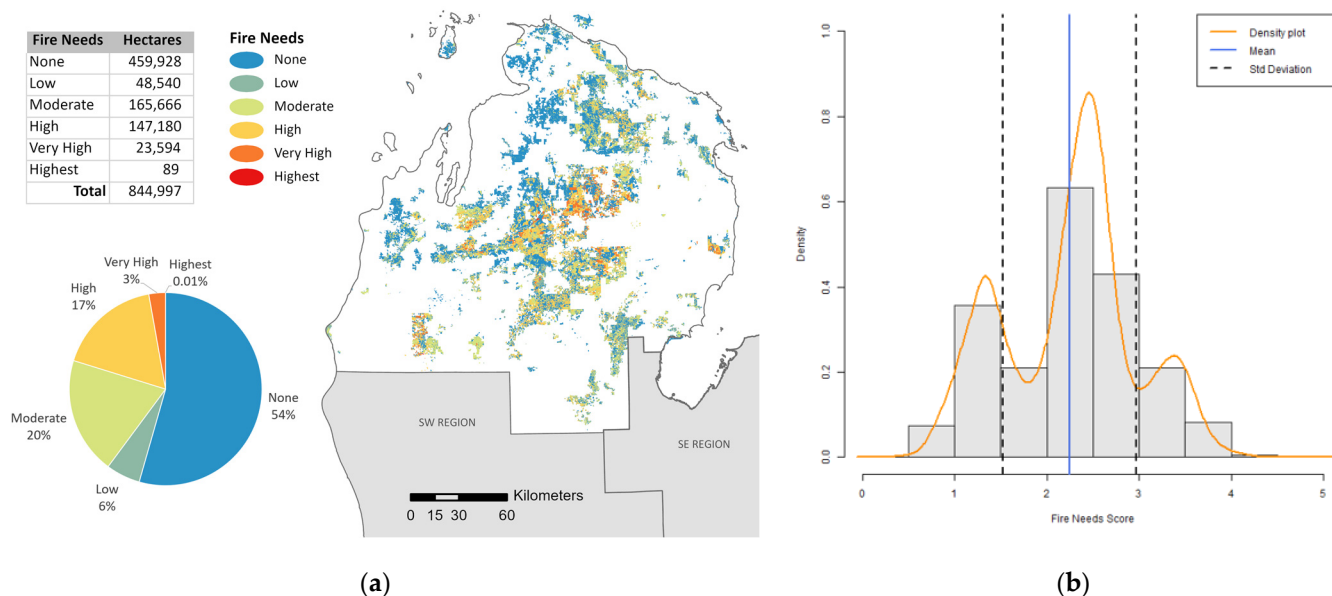
(**a**)   (**b**)

Figure A1. Prescribed fire needs score for Southeast Management Region: (**a**) Fire needs score for state lands and proportion by fire needs class; (**b**) Histogram showing density of fire needs scores for all stands receiving a score (i.e., excluding zero values). The mean fire needs score was 3.01 (SD = 1.16, N = 4294).

Appendix B.3 Northern Lower Peninsula Region

The mean fire needs score for state lands in the NLP was 1.07 (SD = 1.23, N = 91,080). Among stands receiving a score (i.e., excluding zero values), the mean fire needs score in the NLP was 2.25 (SD = 0.72, N = 43,340) (Figure A2b). Our model classified 0.01% (89 ha or 220 ac) of these lands into the highest fire needs scoring class and 2.8% (23,594 ha or 58,302 ac) into the very high fire needs scoring class (Figure A2a). From 2007 to 2020, the DNR implemented 281 burns on state lands in the NLP, 33% of the burns statewide. On average, over the past 5 years the DNR has implemented prescribed fire on 839 hectares (2073 ac) of state lands in the NLP annually; excluding 2020, when no burning occurred due to COVID-19 restrictions, the average from 2016 to 2019 was 1049 hectares (2592 ac) per year. This constitutes 37% of the total area of state land burned during that timeframe.

Fire Needs	Hectares
None	459,928
Low	48,540
Moderate	165,666
High	147,180
Very High	23,594
Highest	89
Total	**844,997**

(a)   (b)

Figure A2. Prescribed fire needs score for the Northern Lower Peninsula Management Region: (**a**) Fire needs score for state lands and proportion by fire needs class; (**b**) Histogram showing density of fire needs scores for all stands receiving a score (i.e., excluding zero values). The mean fire needs score was 2.25 (SD = 0.72, N = 43,340).

Appendix B.4 Eastern Upper Peninsula Region

The mean fire needs score for state lands in the EUP was 0.72 (SD = 1.08, N = 36,297). Among stands receiving a score (i.e., excluding zero values), the mean fire needs score in the EUP was 2.08 (SD = 0.74, N = 12,656) (Figure A3b). Our model classified 0% of these lands into the highest fire needs scoring class and 0.18% (787 ha or 1944 ac) into the very high fire needs scoring class (Figure A3a). From 2007 to 2020, the DNR implemented 52 burns on state lands in the EUP, 6% of the burns statewide. On average, over the past 5 years the DNR has implemented prescribed fire on 134 hectares (332 ac) of state lands in the EUP annually; excluding 2020, when no burning occurred due to COVID-19 restrictions, the average from 2016 to 2019 was 168 hectares (414 ac) per year. This constitutes 6% of the total area of state land burned during that timeframe.

Appendix B.5 Western Upper Peninsula Region

The mean fire needs score for state lands in the WUP was 0.49 (SD = 0.91, N = 32,441). Among stands receiving a score (i.e., excluding zero values), the mean fire needs score in the WUP Region was 1.91 (SD = 0.69, N = 8364) (Figure A4b). Our model classified 0% of these lands into the highest fire needs scoring class and 0.3% (1000 ha or 2472 ac) into the very high fire needs scoring class (Figure A4a). From 2007 to 2020, the DNR implemented 49 burns on state lands in the WUP, 6% of the burns statewide. On average, over the past 5 years the DNR has implemented prescribed fire on 95 hectares (234 ac) of state lands in the WUP annually; excluding 2020, when no burning occurred due to COVID-19 restrictions, the average from 2016 to 2019 was 118 hectares (292 ac) per year. This constitutes 4% of the total area of state land burned during that timeframe.
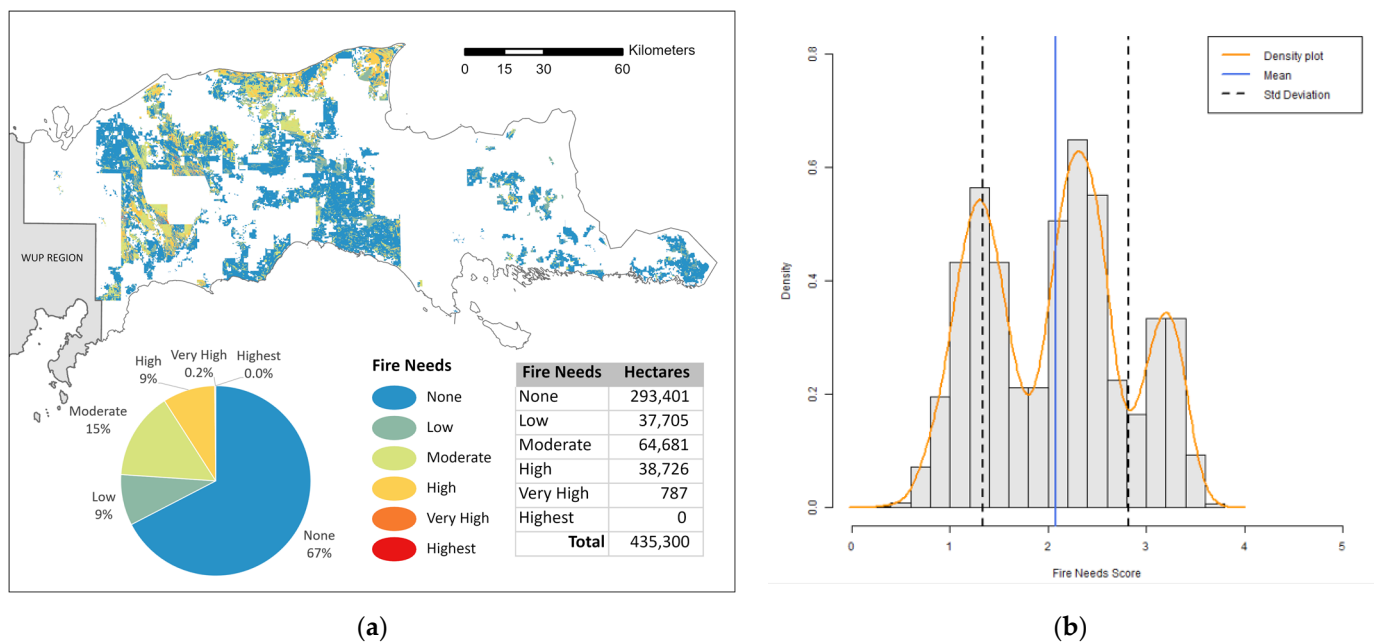
(**a**)   (**b**)

Figure A3. Prescribed fire needs score for the Eastern Upper Peninsula Management Region: (**a**) Fire needs score for state lands and proportion by fire needs class; (**b**) Histogram showing density of fire needs scores for all stands receiving a score (i.e., excluding zero values). The mean fire needs score was 2.08 (SD = 0.74, N = 12,656).
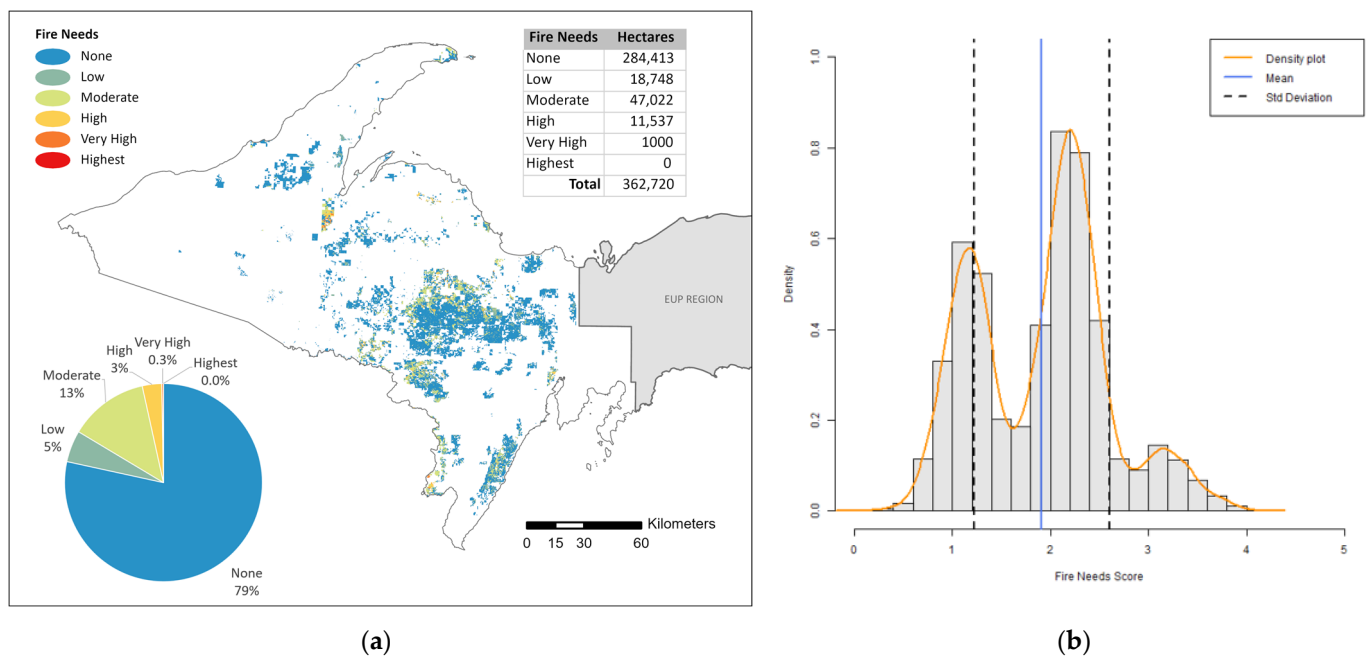

(**a**)   (**b**)

Figure A4. Prescribed fire needs score for the Western Upper Peninsula Management Region: (**a**) Fire needs score for state lands and proportion by fire needs class; (**b**) Histogram showing density of fire needs scores for all stands receiving a score (i.e., excluding zero values). The mean fire needs score was 1.91 (SD = 0.69, N = 8364).

Appendix C Detailed Summaries of Modeling Results, Maps, and Histograms for Three Example Management Areas

Appendix C.1 Allegan State Game Area

Allegan State Game Area (SGA) occurs within the SW and is characterized by high to very high fire needs (Figure 12a) with the highest mean fire needs score in the SW and the

fifth highest fire needs score in the state. The mean fire needs score for Allegan SGA was 2.79 (SD = 1.84, N = 2260). Among stands receiving a score (i.e., excluding zero values), the mean fire needs score for Allegan SGA was 3.80 (SD = 0.87, N = 1660) (Figure 12b). From 2007 to 2020, the DNR implemented 140 burns in Allegan SGA, 16% of the burns statewide, 30% of the burns in the SLP, and 56% of the burns in the SW. From 2016 to 2020, 1019 hectares (2518 ac) were burned in Allegan SGA. On average, over the past 5 years the DNR has implemented prescribed fire on 204 hectares (504 ac) of the game area annually; excluding 2020, when no burning occurred due to COVID-19 restrictions, the average from 2016 to 2019 was 255 hectares (630 ac) burned per year with an average burn size of 23 hectares (57 ac).

Appendix C.2 Port Huron State Game Area

Port Huron State Game Area (SGA) occurs within the SE and is characterized by low to moderate fire needs (Figure A5a). The mean fire needs score for Port Huron SGA was 1.01 (SD = 1.47, N = 346). Among stands receiving a score (i.e., excluding zero values), the mean fire needs score for Port Huron SGA was 2.74 (SD = 1.07, N = 127) (Figure A5b). From 2007 to 2020, the DNR implemented 1 burn in Port Huron SGA, 0.11% of the burns statewide, 0.21% of the burns in the SLP, and 0.45% of the burns in the SE. This burn was 26 hectares (65 ac) in size.
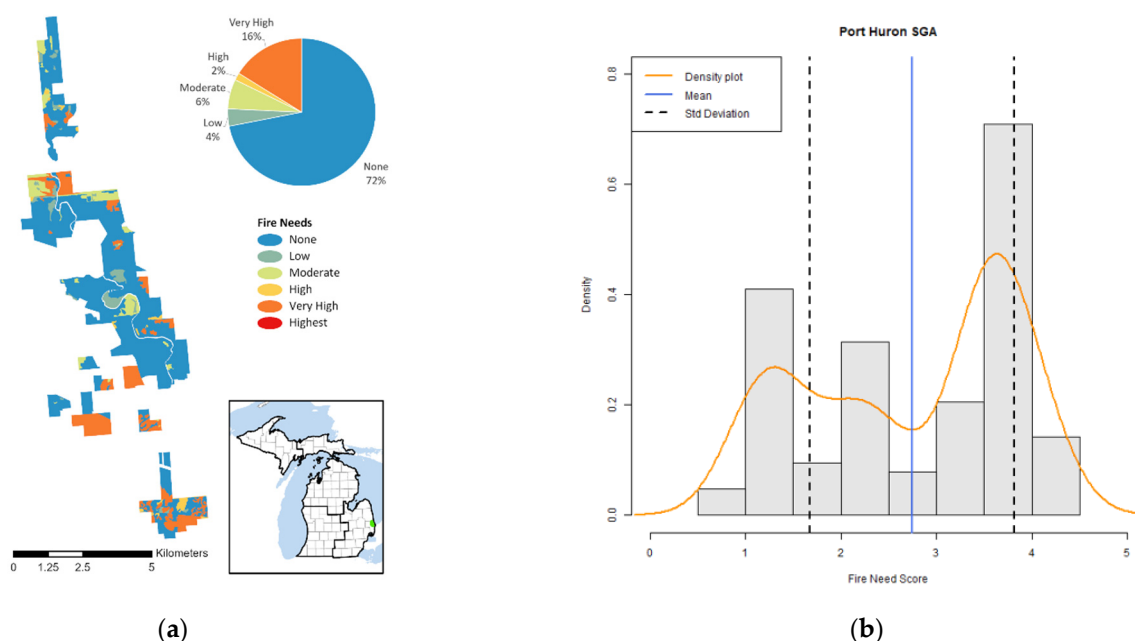

| (**a**) | (**b**) |

Figure A5. (**a**) Prescribed fire needs score for the Port Huron State Game Area (SGA); (**b**) Histogram showing density of fire needs scores for all stands receiving a score (i.e., excluding zero values). The mean fire needs score was 2.74 (SD = 1.07, N = 127).

Appendix C.3 Gwinn Forest Management Unit

Gwinn Forest Management Unit (FMU) occurs within the WUP and is characterized by low fire needs (Figure A6a). The mean fire needs score for Gwinn FMU was 0.52 (SD = 0.93, N = 11,203). Among stands receiving a score (i.e., excluding zero values), the mean fire needs score for Gwinn FMU was 1.92 (SD = 0.71, N = 3048) (Figure A6b). From 2007 to 2020, the DNR implemented 17 burns in the Gwinn FMU, 2% of the burns statewide, 17% of the burns in the UP, and 35% of the burns in the WUP. Over the past five years, one burn of 25 hectares (62 ac) was implemented in the Gwinn FMU.
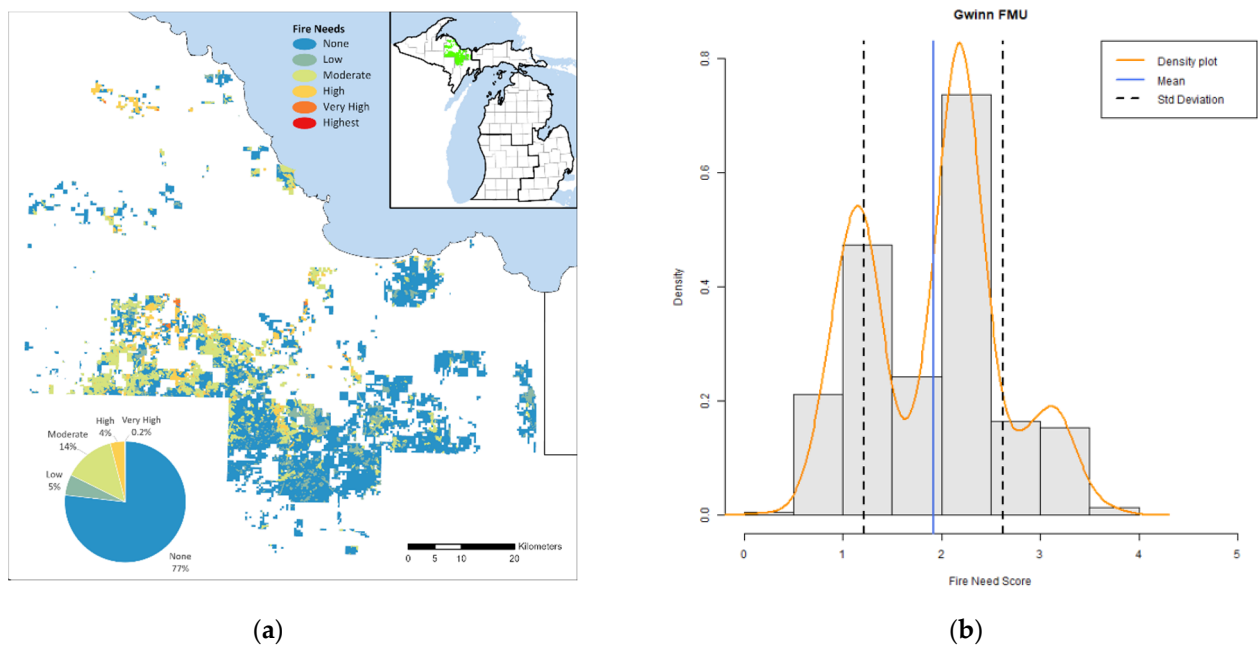
(**a**)   (**b**)

Figure A6. (**a**) Prescribed fire needs score for the Gwinn Forest Management Unit (FMU); (**b**) Histogram showing density of fire needs scores for all stands receiving a score (i.e., excluding zero values). The mean fire needs score was 1.92 (SD = 0.7a, N = 3048).
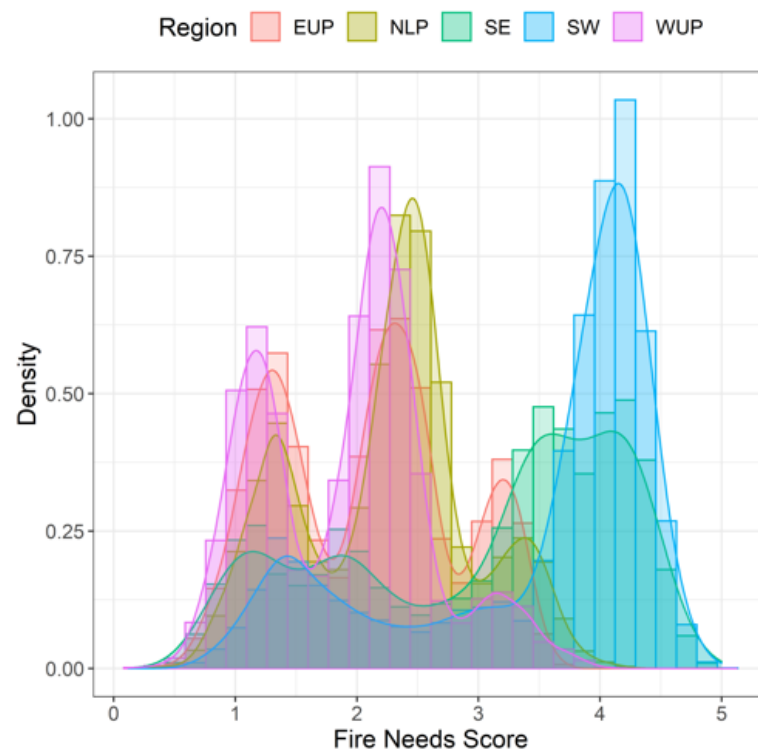

Figure A7. Histogram showing density of fire needs scores by management area for all stands receiving a score (i.e., excluding zero values) for Allegan State Game Area (red), Gwinn Forest Management Unit (green), and Port Huron State Game Area (blue).

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