THESIS

ADVANCING PRESCRIBED FIRE SCIENCE THROUGH NUMERICAL SIMULATION AND IMPROVED REPORTING PRACTICES

Submitted by

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ABSTRACT

ADVANCING PRESCRIBED FIRE SCIENCE THROUGH NUMERICAL SIMULATION AND IMPROVED REPORTING PRACTICES

Planning a prescribed burn that is safe and effective relies on land managers understanding how a complex suite of interactions between the burning environment (e.g., fuels, fire weather, and topography) and ignition factors influence fire behavior and effects. As the field of prescribed fire science has grown, more questions have arisen regarding how the spatial structure of forests and the ignition pattern affect the ecological outcomes of these burns. Advancing our understanding of these factors is crucial to provide managers with quality, evidence-based science that can inform prescribed fire planning.

In this two-part thesis, my objectives were: i) to evaluate reporting quality in recent prescribed fire literature and suggest minimum reporting standards for future prescribed fire experiments, and ii) to explore the potential effects of complex forest fuel structures and ignition patterns on fire behavior and the resultant ecological effects during prescribed burns.

In Chapter 1, I present results from a literature review of reporting standards from over 200 prescribed fire experiments conducted from 2016 to 2020. My results suggest substantial shortcomings in the reporting of critical data that limit the utility of prescribed fire research. Specifically, I found that specific information on burning conditions such as fuel moisture (22%), quantitative fuel loads (36%), fire weather (53%), and fire behavior (30%) were often not reported by the authors. Further, I found that only 54% of the studies provided descriptions of the ignition characteristics. Given these common deficiencies, suggested minimum reporting standards are proposed for future prescribed fire experiments which can be used to increase the quality, applicability, and reproducibility of prescribed fire science, facilitate future research syntheses, and foster actionable science.

In Chapter 2, I evaluate how forest structural complexity and ignition pattern impact crown damage during simulated prescribed fires in longleaf pine (*Pinus palustris*) dominated forests of the southeastern United States. My results show that - regardless of forest structure – using a strip-head ignition pattern consistently produced more crown damage than spot-head or alternative spot-head ignition patterns. In terms of forest structure, I found forests with greater structural complexity resulted in more crown damage than less complex forests. More specifically, I observed forests with more aggregated horizontal spatial patterns, greater vertical complexity, and moderate to high amounts of canopy cover to produce more severe fire behavior than regularly spaced, single-story forests with sparse canopy cover. These findings suggest that managers need to consider a forest's structure and their choice of ignition pattern when planning prescribed burns to ensure they meet ecological objectives.

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Chapter 1 - INVIGORATING PRESCRIBED FIRE SCIENCE THROUGH IMPROVED REPORTING PRACTICES

1.1 INTRODUCTION

Across a diversity of terrestrial ecosystems, prescribed fire is commonly used to achieve a wide variety of land management objectives, including increasing biodiversity, improving wildlife habitat, and reducing woody encroachment, invasive species, and fuel and fire hazards (Fernandes and Botelho, 2003; Ryan et al., 2013; Stephens et al., 2021). Prescribed fire and its effects are influenced by a complex suite of interactions between the burning environment (e.g., fuels, fire weather, and topography), ignition characteristics, attributes of the specific organisms and ecosystems being studied, and a host of other moderating effects, including legacies of past disturbances, climatic conditions, soils, and land management practices (O'Brien et al., 2018). Given this complexity and the time constraints faced by managers, it can be challenging to critically evaluate, interpret, and apply what often appear to be contradictory findings among scientific studies. In cases where fire science guidance is unclear, it is common for managers to rely on past experiences rather than systematic evidence in the decision-making process (Pullin et al., 2004). Although the inclusion of local knowledge and personal experience in decision-making is an important aspect of land management, fire scientists and managers increasingly recognize the vital role that sound and repeatable science plays in developing robust evidence-based policies and land management decisions related to the use of prescribed fire (Hunter et al., 2020). Fire research has historically focused its efforts more on wildfires rather than on prescribed fires, resulting in disparities in the amount of funding and volume of publications available compared to the global frequency and extent of prescribed fires (Hiers et al., 2020). Given the increased recommendations for prescribed fire use along with a paucity of prescribed fire research in many ecosystems, there is a need for research that improves our understanding of the underlying mechanisms driving the ecological effects of prescribed fires (O'Brien et al., 2018; Hiers et al., 2020).

To meet this need, investigations have increasingly utilized prescribed fire as a treatment in both controlled and natural ecological experiments using in situ space-for-time approaches and long-term monitoring. As the volume of prescribed fire research increases, there are new opportunities to advance our understanding of the broad-scale patterns, mechanisms, complex interactions, and contextual dependencies associated with prescribed fire effects through the development, refinement, and evaluation of models and the completion of systematic reviews and meta-analyses. Compared to more traditional narrative reviews and vote counting approaches (i.e., a tally of research manuscripts for or against a given hypothesis), systematic reviews and meta-analyses rely on reproducible quantitative methodologies to provide a more objective and informative synthesis of the existing literature (Cooke et al., 2017).

Although measurements and observations of prescribed fires are increasing, there are significant challenges to maximizing the utility of this information due to insufficient reporting of critical experimental details (Hillebrand and Gurevitch, 2013; Fernandes, 2018). Prescribed fire studies often use unique experimental designs and measurement protocols based on the specific response variable(s) of interest and the traditions and norms of the associated ecological subdiscipline. While variability in methodologies is expected (and in some senses required) given the breadth of subdisciplines that conduct prescribed fire experiments, this variation can lead to considerable inconsistency in how and which biotic and abiotic variables are measured during the experiment and reported in the literature. Moreover, managers conducting prescribed fire often have a specific objective, necessitating the control of timing, pattern, and pace of ignition. Inadequate reporting of methodological and contextual details such as these can hinder the readers' ability to verify and interpret the results, prevent replication of the experiment, and limit further syntheses of the data (Hillebrand and Gurevitch, 2013; Haddaway and Verhoeven, 2015).

Many ecological journals and funding agencies have recently increased author requirements to improve data archiving and availability, including requiring as a condition of publication that authors archive all data and code associated with the research in a public repository such as GitHub or Dryad (Reichman et al., 2011; Whitlock, 2011). While open data policies can vastly increase reproducibility, improve transparency, and support future repurposing of the data, they do not overcome deficiencies in reporting experimental details. A variety of other approaches can be helpful for improving the reporting of experimental details in the scientific literature. For previously published studies, searching for related studies or contacting the authors can often be a helpful approach for finding missing details (Haddaway and Verhoeven, 2015). Authors then can combine previously missing details and publish them with the original data and methods to support replication of the experiment and any future analyses. An increasingly common approach to reducing reporting deficiencies and fostering replicability is developing minimum reporting standards or guidelines (Hillebrand and Gurevitch, 2013; Vetter et al., 2016).

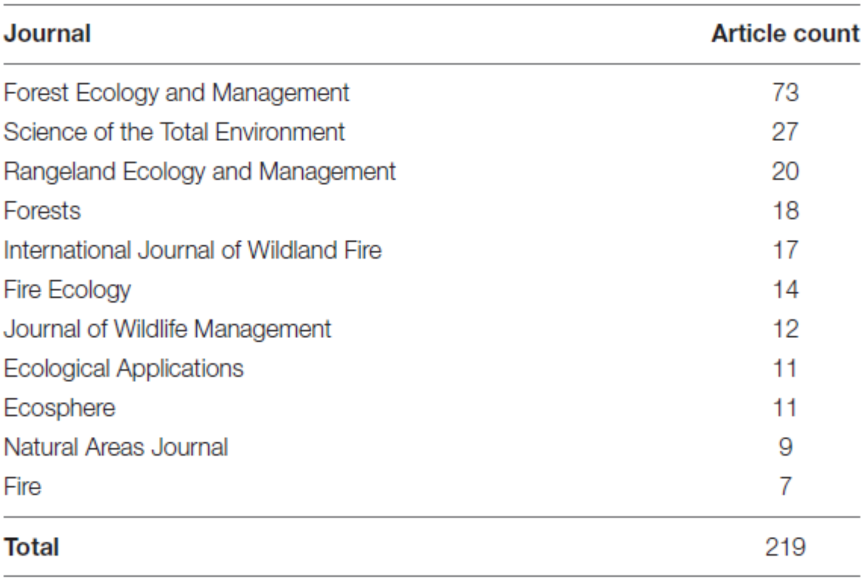
In this study, I present results from a literature review of prescribed fire experiments published in 11 ecological journals over the last 5 years to determine the degree to which experimental details are described. Based on the results of this literature review, I propose a set of minimum reporting guidelines for prescribed fire experiments in ecology and other related disciplines.

1.2 MATERIALS AND METHODS

I identified potential peer-reviewed journal articles for analysis using a Web of Science search for studies published over the 5-year period from January 2016 through December 2020. I first searched for studies that had the terms “prescribed fire” or “prescribed burn” or “controlled burn” or “controlled fire” or “hazard reduction burn” or “fuel reduction burn” or “experimental fire” in the title, keywords, or abstract. I excluded studies focused on “wildfires” or “combustion” from my search by including the “not” operator. Given that my primary interest was in the use of prescribed fire within the ecological literature, I used the “refine” function to exclude less relevant topical areas such as medicine, energy, and engineering.

Additionally, I performed an identical search within the journal “Fire” published by Multidisciplinary Digital Publishing Institute (MDPI), which only began publishing in 2018 and was not indexed by Web of Science at the time of my search. I then identified the ten journals that most frequently published ecological prescribed fire studies (Table 1.1). Articles identified from these ten journals plus the

Table 1.1. The number of published studies from 2016 through 202 that report on an ecological prescribed fire experiment for the 11 journals evaluated.



Journal	Article count
Forest Ecology and Management	73
Science of the Total Environment	27
Rangeland Ecology and Management	20
Forests	18
International Journal of Wildland Fire	17
Fire Ecology	14
Journal of Wildlife Management	12
Ecological Applications	11
Ecosphere	11
Natural Areas Journal	9
Fire	7
Total	219

journal “Fire” were used for all further analysis. I included studies that used prescribed fire as part of a controlled or natural experiment that addressed an ecological question for further analysis. I excluded studies that examined the cumulative ecological effects of repeated prescribed fires, studies performed in a laboratory, modeling experiments, and studies that primarily focused on quantifying the behavior of a free spreading fire or those focused on the ecological effects following a wildfire. At least two of the coauthors screened each study for inclusion and further analysis. In cases where coauthors disagreed about inclusion, a third co-author evaluated the article and made a final decision. The kappa test of agreement score for this screening was 0.66, indicating that substantial agreement existed among coauthors (Cohen, 1960; Landis and Koch, 1977). This process resulted in 219 studies for further analysis (Table 1.1 and Supplemental Table 1.1).

For all 219 articles, I first recorded primary data including the authors, journal, country in which the prescribed fire experiment occurred, and publication year. I then evaluated each article for information on when and where prescribed fires were conducted, the ecological context, landscape position, ignition characteristics, and burning conditions based on the highest level of precision provided by the authors.

For each study, I documented if the manuscript reported the location using specific coordinates or through a map of the burn unit. I also checked to see if authors reported on land use legacies for these locations, such as disturbance events (e.g., natural disasters, beetle infestations, disease, and drought) and historical land management practices (e.g., silvicultural treatments, livestock grazing, and farming). I classified timing based on the most precise category reported in the study (i.e., hour, day, month, season, and year) for which an exact unit was provided. For example, in a situation where a study reported a range of days in a given month, I classified the study as having reported to the month rather than to the day.

Given that fire effects are influenced by the ecological context, landscape position, and land use legacies associated with the experiment, it is imperative that this information be reported, especially for natural experiments where control of influencing factors was not possible. Although many abiotic and biotic variables can influence or moderate fire effects, I recorded how the authors described four common variables of interest: plant species composition, climate, topography, and soils for each study. I reviewed whether the plant species composition was reported using quantitative metrics (e.g., cover, tree density, and basal area), a qualitative description (i.e., plant list, plant associations, and habitat type), a cover type (e.g., Society of American Foresters; Eyre, 1980), or a physiognomic description (e.g., Faber-Langendoen et al., 2016). For climate, I noted whether studies reported along-term climate average or a climate zone for their burn units. I recorded whether studies described the burn unit topography, including aspect, elevation, and slope. Additionally, I identified if the studies provided a description or linked to a description of the underlying soils.

I also evaluated reporting of the ignition characteristics and burning conditions for each study. I assessed ignition characteristics based on reporting of the ignition method (e.g., drip torch and helitorch), pattern (e.g., strips, points, and dashes), technique (e.g., backing fire, flanking fire, and strip head fire), and duration of ignition (i.e., time taken to complete ignition). I assessed the reporting of fuels based on the use of a quantitative description of the fuels complex (e.g.,fuel load and bulk density), a stylized fuel model or classification (e.g., Anderson, 1982; Scott and Burgan, 2005; Ottmar et al., 2007), or a qualitative description of the plant community or cover type. I also evaluated the reporting of weather conditions during the burn, including air temperature, relative humidity, wind speed, and fuel moisture. Finally, I assessed each study to see which metrics of fire behavior (e.g., flame lengths, rate of spread, residence time) they reported.

1.3 RESULTS

My results identified 219 ecological prescribed fire experiments from the following 16 countries: United States of America (145), Spain (28), Australia (18), Canada (6), Finland (6), Sweden (3), Hungary (2), Kenya (2), Scotland (2), Brazil (1), Germany (1), Italy (1), Lebanon (1), Lithuania (1), Mexico (1), and Nepal (1).

The approach used to report spatial and temporal details varied among studies (Figure 1.1). All but one study provided information on the location of the burn unit. Approximately 12% of studies provided a name or description of the general burn unit location without further detail. One quarter (25%) of the studies provided a map of the burn locations. In most cases, however, maps lacked sufficient detail to enable future studies to precisely identify the burn unit location. The remaining 63% of studies provided coordinates for their burn units. However, only 6% provided coordinates for sampling locations within a burn unit. Approximately 7% of studies supplied no temporal data for prescribed fire: 9%

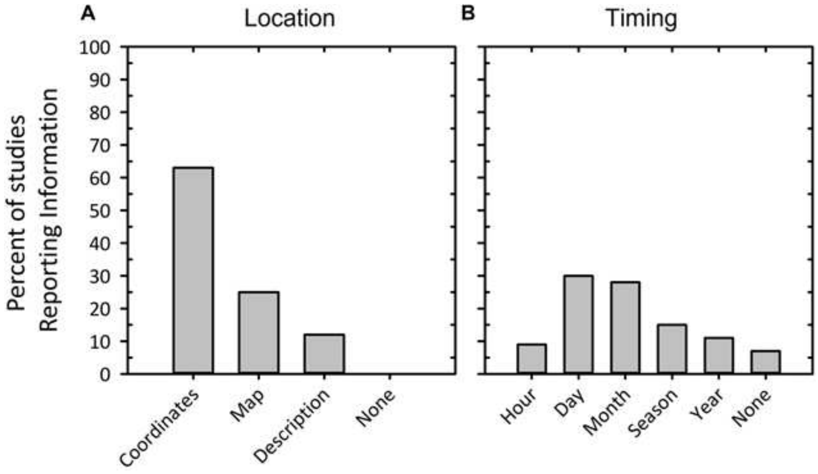


Figure 1.1. Plots showing the level of precision to which authors reported (A) the location of the burn and (B) the timing of burn in recent prescribed fire studies.

provided the hour, 30% provided the day, 28% the month, 15% the season, and 11% provided only the burn year.

Most studies provided details describing the prescribed fire's ecological context and landscape position, with only one study failing to report any details on plant species composition, climate, topography, or soils. All but one study reported plant species composition, although the reporting quality varied (Figure 1.2A). Nearly 4% of studies described plant species composition using a basic physiognomic description and 10% reported a cover type (Figure 1.2A). The remaining studies provided either a qualitative (45%) or quantitative (41%) description of the plant species composition within the burn unit (Figure 1.2A). One third (33%) of studies provided no details on the soils associated with the burn units. Most (73%) studies reported some measure of climate; 70 and 3% reported long-term climate data or climate zones, respectively (Figure 1.2B). Just 13% of studies reported post-fire climatic data. A

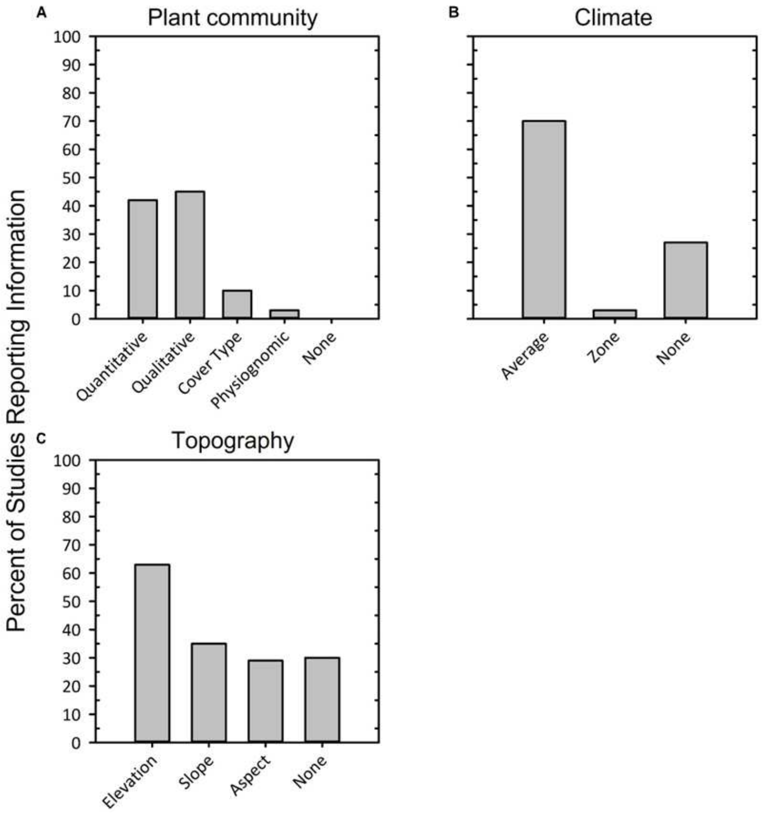


Figure 1.2. Plots showing the level of detail to which authors reported (A) plant community, (B) climate, and (C) topography in recent prescribed fire studies.

majority (70%) of studies reported at least one metric describing burn unit topography, with elevation being the most frequently reported topographic descriptor (63%), followed by slope (35%) and aspect (29%) (Figure 1.2C). Authors reported historic land use and disturbance legacies in 80% of studies. Only 54% of the prescribed fire experiments evaluated provided details on the ignition characteristics (Figure 1.3A).

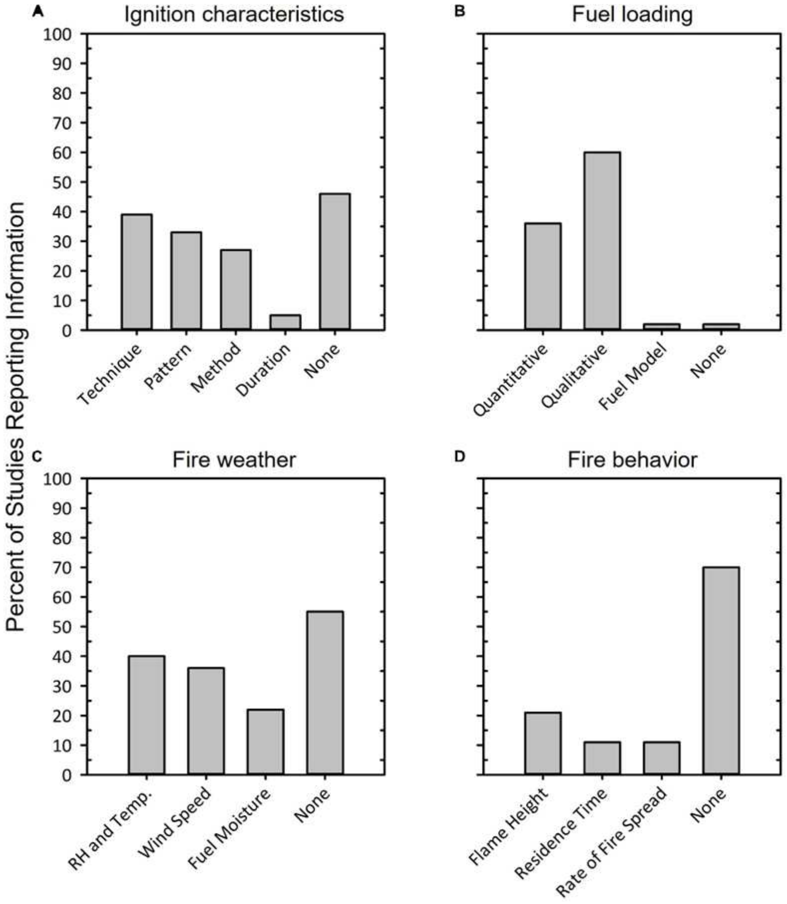


Figure 1.3. Plots showing the level of detail to which authors reported (A) ignition characteristics, (B) fuel loading, (C) fire weather, and (D) fire behavior in recent prescribed fire studies

The ignition method, ignition pattern, and ignition technique were reported in 27, 33, and 39% of studies, respectively. The duration of ignition was reported less often, with only 3% of studies providing this information.

Almost all studies (98%) provided a description of the fuel complex, with 60% relying primarily on a qualitative description of the fuels present (Figure 1.3B). Around 2% of all studies reported a standard fire behavior fuel model to describe the fuel complex, whereas 36% of studies provided a quantitative description of the fuel complex, with fuel loading being the most used metric (Figure 1.3B). Less than half (47%) of the studies reported the burning conditions, including wind speed, temperature, relative humidity, and fuel moisture during the experiments (Figure 1.3C). Less than 40% of studies reported relative humidity and air temperature, and 36% provided an estimate of the wind speed (Figure 1.3C). Fuel moisture content was infrequently described, with only 22% of studies providing data, of which 14% provided multiple fuel moisture categories and 8% provided a single estimate. Only 17% of studies included critical details on the meteorological observations, including the location of data collection or instruments used for fire weather measurements, and only 11% reported the sampling procedures (i.e., frequency of sampling or averaging procedures).

My results indicate that only 30% of studies provided a metric of fire behavior such as flame length, residence time, or rate of fire spread, and only 10% of studies provided more than one metric (Figure 1.3D). Flame length was the most reported metric (21%), followed by rate of spread (11%), and residence time (11%) (Figure 1.3D). Only 11% of all studies described the instrumentation, sampling design, or calculations used to estimate fire behavior information.

1.4 DISCUSSION

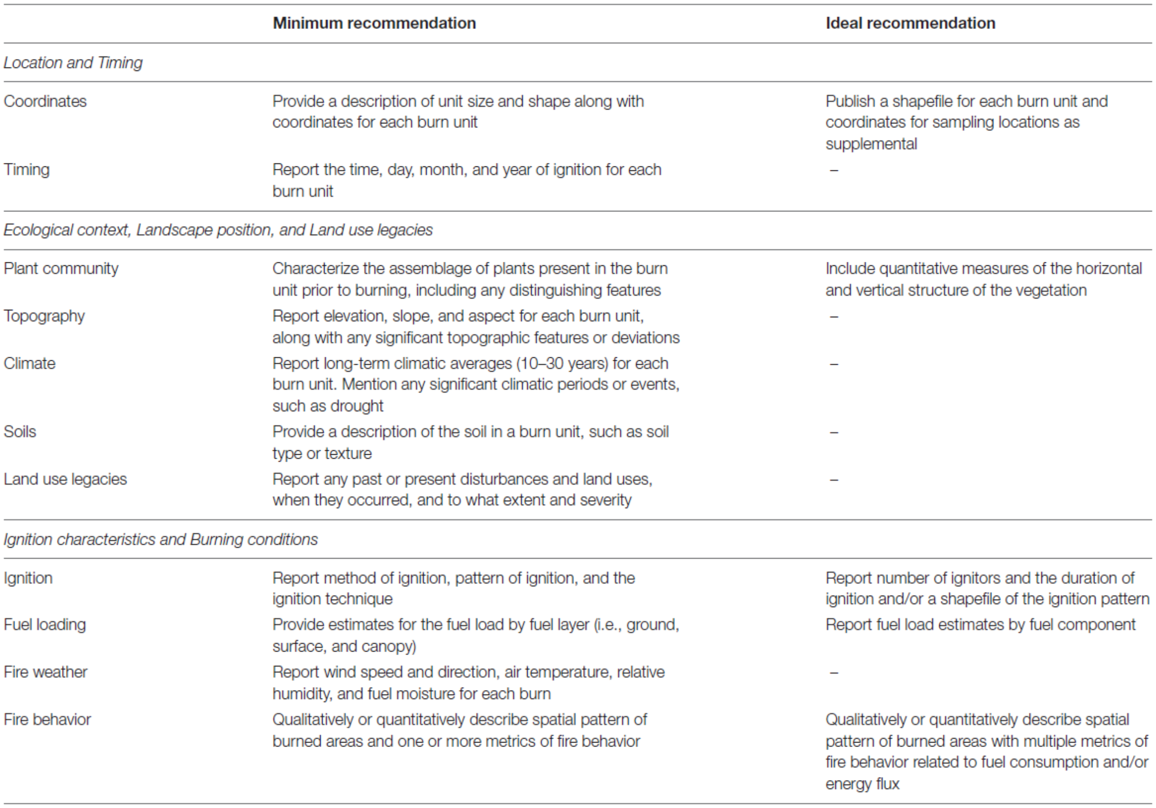
The ecological effects of prescribed fire arise through a suite of complex interactions between how the fire was ignited, the burning conditions, the fuel complex, and a host of other regulating effects such as climate and terrain (O’Brien et al., 2018; Bridges et al., 2019). Given the complexity of factors influencing prescribed fire effects, it is imperative that sufficient detail is reported. In my analysis and collective experience, there are substantial opportunities to invigorate how I describe methodology and report data for ecological research that involves prescribed fire experiments.

My review found insufficient reporting of spatial location and timing data. Published studies that did not provide precise spatial locations either presented maps with reference points or a written description of the prescribed fire location. Consistent with my findings, precise spatial locations were often not reported in landscape ecology studies (Vetter et al., 2016). Although 39% of studies reported the specific day and/or time for each prescribed fire, it was more common for temporal data to be reported with less precision. Reporting a finer temporal resolution can better account for potentially confounding temporal effects (e.g., seasonality) with other variables such as plant phenology or diel moisture dynamics (Knapp et al., 2009). Although providing less precise location and temporal data may be adequate for orienting the reader to the general area and conditions of the experiment, it may not be sufficient to allow scientists to link the results with other data sources, including vegetation and land cover, fire weather, climate, or remotely sensed data. This lack of precision thus limits the application of the information collected.

A host of biotic and abiotic factors independently and jointly influence prescribed fire effects across spatial and temporal scales. At a minimum, capturing the extent and location of burned areas is critical since fires often burn as a mosaic and whether a location received fire or not is obviously essential information. For example, the amount, extent, and pattern of post-fire recruitment in conifer forests of western North America are influenced by complex interactions among the fire severity, previous and future climatic conditions, soil characteristics, aspect, and elevation (Crotteau et al., 2013; Ziegler et al., 2017; Boucher et al., 2019; Stevens-Rumann and Morgan, 2019). My analysis found that it was common for studies to report on the long-term climatic averages, plant species composition, the underlying soil characteristics, and the land use legacies within the area burned. However, other crucial explanatory factors, including topography and quantitative measures of the plant species composition, were less frequently reported. Despite recognizing the critical role that ecological context and landscape position play in shaping ecological function and the success of land management treatments, such context is often not reported with enough detail quantitative data such as fuel loading. Fuel load estimates were commonly reported as stand scale means, which inherently average out many of the spatial and temporal characteristics of the fuel complex that explain local prescribed fire behavior and effects (O'Brien et al., 2018). Additionally, few studies reported local fire behavior, which often are the mechanisms driving fire effects.

Given these findings, I present recommendations for minimum reporting standards for prescribed fire experiments (Table 1.2). These standards are based in part on various existing manuals and procedures for documenting and reporting prescribed fire observations (e.g., Fischer, 1978). I intend for these recommendations to be a starting point that can be used by authors, reviewers, and editorial boards to increase the quality and replicability of ecological prescribed fire science. I fully acknowledge that different studies have specific needs and resources and that any added requirements will place a burden on the primary authors. However, given that many land management agencies have procedures in place that require the collection of much of these data (e.g., Alexander and Thomas, 2003; USDI National Park Service, 2003; Fernandes and Botelho, 2004; Australasian Fire and Emergency Service Authorities

Table 1.2. Suggested best practices for reporting on ecological prescribed fire experiments.



	Minimum recommendation	**Ideal recommendation**
Location and Timing		
Coordinates	Provide a description of unit size and shape along with coordinates for each burn unit	Publish a shapefile for each burn unit and coordinates for sampling locations as supplemental
Timing	Report the time, day, month, and year of ignition for each burn unit	–
Ecological context, Landscape position, and Land use legacies		
Plant community	Characterize the assemblage of plants present in the burn unit prior to burning, including any distinguishing features	Include quantitative measures of the horizontal and vertical structure of the vegetation
Topography	Report elevation, slope, and aspect for each burn unit, along with any significant topographic features or deviations	–
Climate	Report long-term climatic averages (10–30 years) for each burn unit. Mention any significant climatic periods or events, such as drought	–
Soils	Provide a description of the soil in a burn unit, such as soil type or texture	–
Land use legacies	Report any past or present disturbances and land uses, when they occurred, and to what extent and severity	–
Ignition characteristics and Burning conditions		
Ignition	Report method of ignition, pattern of ignition, and the ignition technique	Report number of ignitors and the duration of ignition and/or a shapefile of the ignition pattern
Fuel loading	Provide estimates for the fuel load by fuel layer (i.e., ground, surface, and canopy)	Report fuel load estimates by fuel component
Fire weather	Report wind speed and direction, air temperature, relative humidity, and fuel moisture for each burn	–
Fire behavior	Qualitatively or quantitatively describe spatial pattern of burned areas and one or more metrics of fire behavior	Qualitatively or quantitatively describe spatial pattern of burned areas with multiple metrics of fire behavior related to fuel consumption and/or energy flux

Council, 2016), these standards should not impede prescribed fire experimentation. My hope is that implementation of these standards will support the co-production of knowledge and ultimately foster actionable science.

I grouped my recommendations into three broad categories:(1) location and timing of prescribed fire experiments; (2) ecological context, landscape position, and land use legacies; and (3) ignition and burning characteristics.

1.4.1 LOCATION AND TIMING OF PRESCRIBED FIRE EXPERIMENTS

Given that prescribed fire effects and ecosystem response can be highly variable at fine spatial scales (Hiers et al., 2009; Mugnani et al., 2019), I suggest that authors report coordinates for each experimental burn unit with a precision of seconds or 30 m resolution (Vetter et al., 2016), along with a clear description of the unit size and shape. Ideally, supplying spatial data (such as a shapefile) for each burn unit and specific coordinates for any sampling locations within burn units is helpful and can be included as “supplementary data”. In some cases, such as those dealing with endangered species, excluding precise locations may be permissible if the authors can provide specific instructions for how others looking to replicate the experiment or use the data for synthesis can gain access (Vetter et al., 2016). Lastly, giving the exact timing for each burn unit, including the hour, day, month, and year of ignition, enhances the usefulness of the study to researchers and managers.

The inclusion of more precise data on the location and time of the prescribed fire experiment would allow researchers to extemporaneously connect the study to covariates describing the ecological context and landscape positioning, topography, climate, fuels, and weather conditions not reported in the original study. Additionally, such reporting may be useful in assessing the experiment’s overall representativeness with respect to environmental and socioeconomic context and if geographic bias in site selection occurred (Gerstner et al., 2017). The ability to link experimental burn datasets to other data through spatial and temporal information will facilitate the development of new understandings, across and between ecosystems and sets of conditions.

1.4.2 ECOLOGICAL CONTEXT, LANDSCAPE POSITION, AND LAND USE LEGACIES

Reporting data on the ecosystem burned, the landscape position of the burn unit, and any land use legacies that frame critical fire outcomes is foundational for the interpretation of study results, identifying causes of variation among studies, ensuring replicability, and furthering the potential usefulness of the study in quantitative syntheses (Haddaway and Verhoeven, 2015; Gerstner et al., 2017; Halbritter et al., 2020). I focused my suggestions on five descriptors that scientists commonly recognize as critical factors in ecological studies: the plant community; topographic characteristics such as elevation, slope, and aspect; the long term climate; soils; and land use legacies.

Plant community descriptions should characterize the assemblage of plants that occur in the study area, as well as any unique features such as invasive species. Ideally, plant community descriptions will go beyond reporting species composition and describe the horizontal and vertical structure of the vegetation with metrics such as height, diameter, density, basal area, or cover. Authors can enhance site descriptions by giving ranges in the elevation, slope, and aspect, and providing data on long-term climatic averages, soils, and land use legacies such as disturbance history. This should include a description of the disturbance history, including the type of disturbance and information on the timing, extent, and severity. In cases of chronic rather than acute disturbance, I suggest authors give estimates of extent, severity, or intensity. When reporting data from external databases, such as climate data, land cover, or soil type, I recommend that authors include citations or attributions to the source data or follow other best practice guidelines, such as Morueta-Holme et al., (2018).

I recognize that my minimum recommendations for reporting on ecological context, landscape position, and land use legacies may not be directly related to the objectives of any given study, nor are they necessarily the most important or useful contextual details. While I recommend primary authors still report on these details, ideally authors should expand on these to include information on any contextual details that help in the interpretation of the results and improve replicability of experimental findings.

Although most studies provide these details for a burn unit, it would be ideal if authors also report variations among sampling locations either in the text or as “supplementary data”.

1.4.3 IGNITION CHARACTERISTICS AND BURNING CONDITIONS

Given their relative importance, I recommend that authors include data on the methods of ignition, the pattern of ignition, and the ignition technique. Ideally, details including the number of ignitors and the rate and duration of ignition, would also be included in the “Materials and Methods” section or as a “supplementary data” file (Figure 1.4A). In addition to a description of the plant community within the burn area, I also suggest that the authors supply quantitative data describing the fuels in each layer. I suggest reporting the fuel load for both the surface and ground fuel layers, and either the canopy fuel load or bulk density, along with the canopy base height (Figure 1.4B). Authors should provide a minimum estimate of the fuel moisture content by fuel layer or dominant vegetation type. Ideally, authors would include quantitative fuel descriptions and fuel moisture contents, including some measure of variability, for each fuel component. Also, given the array of options for fuel sampling, it is critical that authors report their sampling design and methods (Keane, 2012).

Quantitative data on the fire weather observed during the active fire period is critical for authors to include in publications. Fire practitioners often measure weather data, yet authors rarely include this critical information. I suggest that authors report the mean and variability in wind velocity, air temperature, and relative humidity for each experimental prescribed fire. The type of instrument used, the location and frequency of sampling, and any averaging procedures should also be reported (Figure 1.4C). Any relevant shifts or changes in the wind conditions during the burns are also of interest. In cases where authors rely on data from a meteorological station to obtain fire weather data, they should report the station latitude, longitude, elevation, and identifier along with information on how to access the data.

Given the complexity of interactions that drive prescribed fire behavior and effects, it is essential to include metrics that describe the fire behavior (Figure 1.4D). I suggest that authors include a spatial description of the pattern of burned areas since mosaics of burned and unburned areas can be important for

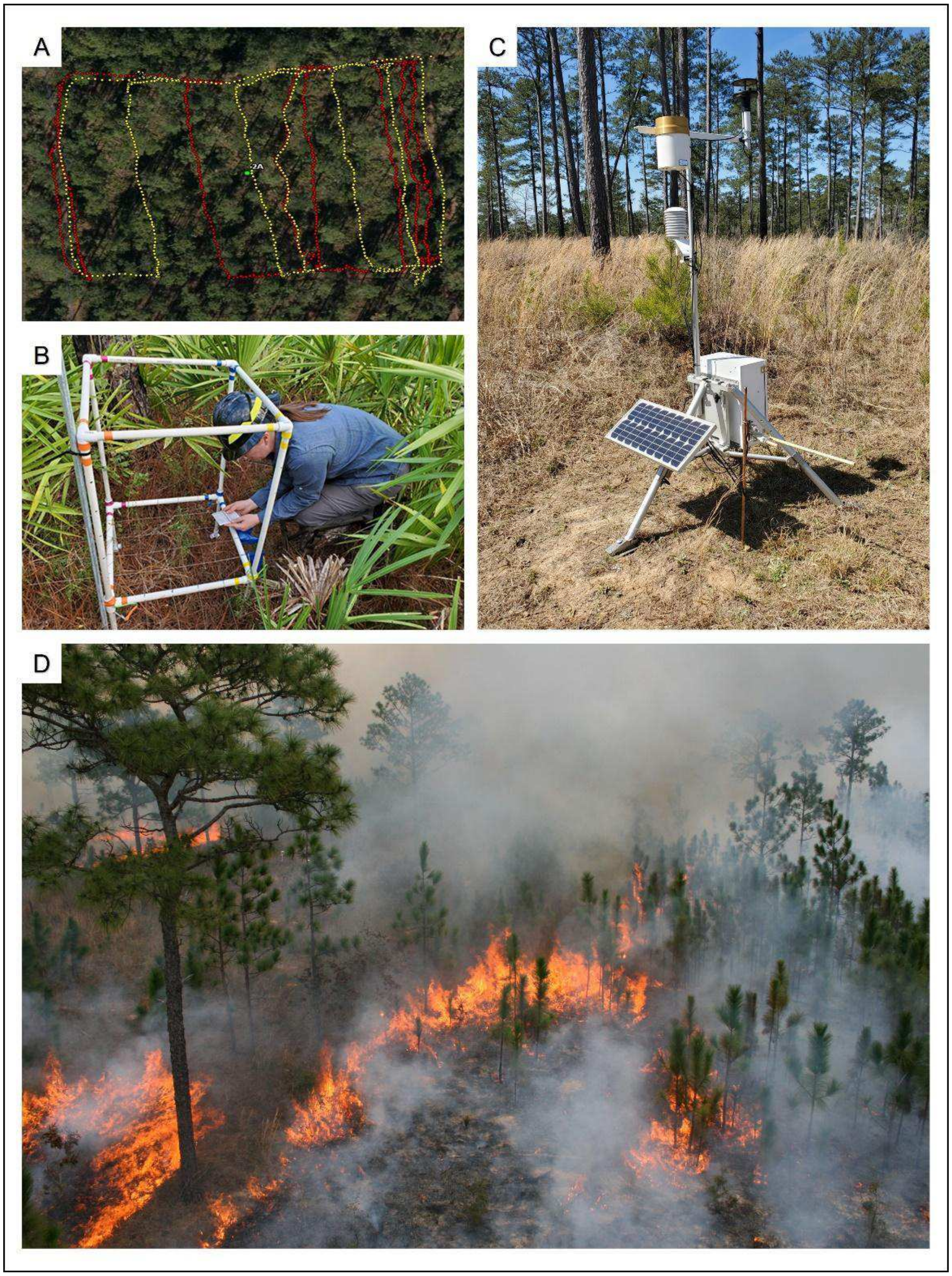


Figure 1.4. Images of (A) Ignition pattern for an experimental prescribed fire at Tall Timbers Research Station based on GPS tracking. Ignition was conducted by two individuals (red and yellow dots) with drip torches. (B) 3-Dimensional surface fuels sampling based on the methods of Hiers et al., (2021). (C) A Campbell Scientific Remote Automated Weather Station (RAWS) used to monitor and collect data on wind speed, air temperature, relative humidity, and other meteorological conditions during prescribed burns. (D) Still shot from oblique color video of interacting fire lines during a 2012 prescribed burn at Eglin Air Force Base, Florida.

understanding subsequent ecological responses (Mugnani et al., 2019). Given that even in areas that burned completely there is substantial variation in fire energy release, often at fine scales (O'Brien et al., 2016), I also recommend that authors provide qualitative (e.g., ocular estimates of flame length) or quantitative estimates of fire behavior. Quantitative estimates of fire behavior are best, given that there can be low confidence associated with qualitative estimates. Fire effects, particularly those related to plant physiology (e.g., mortality, embolism, and scorching), directly link to fire intensity (O'Brien et al., 2018; Varner et al., 2021), so fire behavior metrics should ideally focus on heat release, either measured directly or inferred post hoc from biomass consumption. Although authors often report fire temperatures, as estimated by widely used measurement techniques such as thermocouples and temperature-sensitive paints, such approaches are not particularly valuable as temperatures are not mechanistically related to fire behavior or fire effects (Bova and Dickinson, 2008). Extensive documentation on fire variable terminology, instrumentation, measurements, and data resources is available in National Wildfire Coordinating Group (2014). Reporting relevant fire behavior metrics, in conjunction with the fuels complex, fire weather, and the ecological and landscape characteristics can often provide better explanations for prescribed fire effects rather than relying solely on the pre-fire ecological and landscape conditions.

1.5 CONCLUSIONS

As fire scientists worldwide strive to develop new predictive modeling tools and acquire a deeper mechanistic and empirical understanding of prescribed fires, knowing the details of these experiments is critical. My analysis of top journals showed that insufficient reporting of critical details is pervasive within the literature. Although I was not able to identify the reasons for the lack of reporting, my collective experience is that much of the data required to meet these recommendations is often collected during prescribed fires, indicating that a lack of reporting could be because data was not transferred from managers to researchers or was simply disregarded during manuscript preparation or revision. Regardless of the reasons for underreporting, the lack of methodological detail impedes the replication of prescribed fire studies, verification and comparison of their results, and decreases the potential for insights derived from meta-analyses. To combat this, I presented a list of suggested reporting standards for ecological prescribed fire studies. I believe that these minimum standards could be a starting point for more consistent and rigorous interpretation of research results. In some cases, the additional resources of meeting these requirements may encourage scientists to develop meaningful linkages with managers conducting prescribed fires and stimulate the co-production of knowledge within prescribed fire research. It is my hope that these suggestions promote future quantitative research syntheses, increase the quality and replicability of ecological prescribed fire experiments, and ultimately foster actionable science.

Although the focus of this study was on evaluating ecological prescribed fire experiments, my recommendations could generally be useful to improve the quality and value of primary research studies within wildland fire sciences more broadly. For example, studies focused on the ecological effects of wildfires and managed wildfires would benefit from reporting the location and time of burn (and daily fire progression), ecological context, landscape position, and the burning conditions within these fires. The expansion of my suggestions to wildfires could also help foster needed synthesis across prescribed fire and wildfire literature. Similarly, studies that seek to understand the cumulative effect of multiple fires over time could benefit from understanding the characteristics of each fire rather than solely focusing on the net effect of multiple burns. Finally, more comprehensive reporting of the burning conditions, fuel complexes, and fire behavior could facilitate model development and evaluation (Hoffman et al., 2016). Improving wildland fire research via invigorated standards offers tremendous promise for moving prescribed fire applications forward and opening this expanding scientific area to more rigorous future analyses.

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Chapter 2 - IGNITION PATTERN AND FOREST STRUCTURAL COMPLEXITY INFLUENCE SIMULATED PRESCRIBED FIRE EFFECTS

2.1 INTRODUCTION

As wildland and urban ecosystems become increasingly susceptible to the negative impacts of wildfire, land managers are more commonly employing proactive management techniques such as prescribed fire to mitigate the adverse effects and restore ecosystem functionality. Prescribed fire is broadly defined as the purposeful ignition of fire under a discrete range of environmental conditions to accomplish well-defined management objectives (Wade et al., 1990), such as improving biodiversity and wildlife habitat, stimulating pyrogenic species, removing invasive species, or fuel hazard reduction (Fernandes and Botelho, 2003; Ryan et al., 2013; Hiers et al., 2020). To safely and efficiently meet these objectives, land managers must consider how the variable environmental features of their burn unit (i.e., fuels, topography), weather conditions, and the proposed ignition prescription will interact to determine fire behavior and the resulting effects. Although there is a wide body of literature suggesting that prescribed fire can be used as an effective and efficient tool to meet various land management objectives, there is a notable lack of understanding regarding exactly how different ignition prescriptions react to those environmental features and affect the resulting ecological outcomes (Hiers et al., 2020; Bonner et al., 2021).

When planning prescribed fire prescriptions, land managers rely on their understanding of the drivers of fire behavior (i.e., the fire behavior triangle - fuels, weather, and topography) and the ecology of their burn unit to predict potential fire behavior and effects. Often this understanding is based on a manager's past experiences with wildfire (Pullin et al., 2004), however, the knowledge required to plan a prescribed fire is fundamentally different from the knowledge needed to predict wildfire behavior (Hiers et al., 2020). Whereas wildfires are spontaneous events, prescribed fires are entirely planned, thus their behavior is further influenced by an additional anthropogenic factor characterized by the ignition prescription. Additionally, because prescribed fires are frequently ignited under more moderate burning conditions than those typical of wildfires, prescribed fire behavior is often more sensitive to fine-scale variations in environmental conditions including the properties of the fuels complex (i.e., moistures, loading, and structural arrangement) (Atchley et al., 2021), local weather conditions (Parsons et al., 2017), and ignition patterns (Molina et al., 2022). Yet, there is a paucity of prescribed fire scientific literature that considers both the ignition pattern and the heterogeneity of the canopy fuels complex.

Understanding how the structural arrangement of canopy fuels (i.e., forest structural complexity) influences fire behavior is essential for land managers planning prescribed fires in forested environments. Forest structural complexity is a descriptive statistic of forest structural attributes and their relative abundance (McElhinney et al., 2005). However, because forest structural complexity has been used for an assortment of ecological applications (e.g., linking structure to habitat quality, biodiversity, fire effects and successional stages), there is no universally accepted set of structural metrics or formulas used to calculate it. For the purposes of fire research, forest structural complexity can be described through measures of horizontal spatial pattern, vertical complexity, and the proportion of canopy cover (Ziegler et al. 2017). Horizontal spatial pattern (i.e., regular, random, and clustered) describes the spatial relationships and distribution of individual trees within a forest (Gadow, 2002). A common metric used to measure horizontal spatial pattern is the Clark-Evans statistic (Clark and Evans, 1954; Donnelly, 1978), which compares a forest's nearest neighbor distances between trees against a random horizontal spatial pattern to determine if the forest is regularly spaced (>1), randomly spaced (~1) or clustered (<1). Additionally, trees per hectare (TPH) is a useful metric for measuring horizontal spatial pattern as it not only describes the density of trees in a forest, but also can be used to distinguish successional forest stages related to horizontal spatial patterns (McElhinny et al., 2005). Vertical complexity of a forest refers to the distribution and configuration of tree sizes across a stand or within an aggregation of trees (Franklin and Van Pelt, 2004). Past studies have shown relationships between the vertical structure of forests and tree height, which indicates on average how elevated fuels are, as well as the standard deviation of tree height which is a proven measure for describing the vertical layering of canopy fuels (Zenner, 2000). Lastly, canopy cover refers to the proportion of stand surface area covered by the canopy overstory and has been used to determine the successional stage of the forest and to describe canopy fuel density and canopy closure.

Forest structural complexity can influence fire behavior both directly through its effects on surface and crown fuel loadings and locations, and indirectly through its effects on local wind patterns, entrainment of cooler air into fire lines, and energy transport (Finney, 2001; Dupont and Brunet, 2007; Boudreault et al., 2014; Parsons et al., 2017; Atchley et al., 2021). Spatially complex forest structures can introduce discontinuities in the canopy, resulting in localized areas of turbulence, sweeps, and ejections which affect how air mixes, enters, and exits a canopy, and alter the magnitude of convective heating and cooling, which is critical for determining whether fuels will ignite (Linn et al., 2013; Hoffman et al., 2015; Kiefer et al., 2016; Atchley et al., 2021). Horizontal clustering of trees creates gaps in the canopy where winds can accelerate and develop more severe fire behavior and effects (Loudermilk et al., 2012; Parsons et al., 2017). Vertical complexity is commonly assumed to be positively associated with greater crown damage due to increased fuel continuity, however this concept has not been well studied under the low to moderate weather conditions characteristic of prescribed fires. Under these less intense burning conditions, we might expect vertical complexity to have a relatively greater effect on the proportion of crown damage due to the decreased influence of weather on fire behavior. The positive relationship between the proportion of canopy cover and fire severity has been observed within past studies (Fulé et al., 2012; Ziegler et al., 2017; Parsons et al., 2017; Atchley et al., 2021), though not in combination with all of these other measures of forest structural complexity.

Given a specific fuels complex, managers need also consider how and when to ignite when planning a prescribed fire. For prescribed fires to be effective, practitioners must understand how the resources and techniques they employ during the ignition phase interact to affect fire outcomes (Fernandes and Botelho, 2003). Of critical concern is how the ignition pattern – including the overall ignition arrangement, head fire line geometry, burn direction relative to wind, and distance between individual ignition head fires and spots - will alter fire behavior and the resultant ecological consequences. Land managers can alter these ignition characteristics to achieve different spread rates, fire intensities, flame heights, and residence times, which alter the ecological outcome of the burn (Fernandes and Botelho, 2003; Martin and Hamman, 2016; Molina et al., 2018, 2022). Developing a full understanding of how these ignition characteristics interact in different combinations and under different canopy arrangements is necessary to optimize burn plans to meet management outcomes. For example, a set of ignition lines (strip-head fires) are generally considered to produce more intense fire behavior than a line of point ignitions (spot-head fires) (Johansen, 1987; Molina et al., 2022), but this may not always be the case. Spot-head fires can become more intense than strip-head fires under the same environmental conditions depending on spacing between individual spot ignitions (Molina et al., 2018; Finney and McAllister, 2011; Vega et al., 2012; Canfield et al., 2014; Raposo, 2016). However, due to a lack of comparisons, it is difficult to answer what this “correct” ignition pattern would be for any given burn unit or forest structural arrangement. Despite the apparent importance of ignition planning, there is a lack of experimental and modeling data on the various effects of ignition pattern on fire behavior and effects (Molina et al., 2022) and an additional need for studies that investigate how ignition patterns and forest structure potentially interact.

Through improved understanding of how different environmental conditions and ignition prescriptions influence potential fire behavior, land managers can better predict the ecological outcomes of their burn. The degree of success of a prescribed fire in meeting management objectives is often determined by measuring the magnitude of one or more effects on relevant ecological factors. For example, when attempting to assess the success of a fuel hazard reduction burn, managers may be interested in both the proportion of surface fuels burned and the effects on crown fuels such as scorch (portion of the tree’s foliage that is killed but not consumed), consumption (portion of tree’s foliage consumed), and damage (overall sum of scorch and consumption). Quantifying such effects to tree crowns not only acts as a useful predictor for the post-fire health and mortality of trees, but also offers a simple way to assess overall fire severity (Eidenshink et al., 2007) and determine larger effects on the ecosystem such as impacts to resilience and changes to carbon, nutrient, and hydrologic flows (Hood et al., 2018; O'Brien et al., 2018; Varner et al., 2021).

The aim of this study was to investigate how forest structural complexity and ignition patterns impact simulated crown damage from prescribed fires in longleaf pine forests. To meet my objective, I used data from the Forest Inventory and Analysis (FIA) database to develop 14 forests representative of a range of forest structures. I used longleaf pine (*Pinus palustris*) dominated forest data to generate these representative forests because these systems are representative of many forest ecosystems with frequent low intensity fire regimes and there is substantial use of prescribed fire in these systems. I simulated crown damage from prescribed fires across forests with different levels of structural heterogeneity including canopy cover, horizontal spatial pattern, vertical complexity, and within cluster size class compositions (i.e., clump type) and three common ignition patterns (Figure 2.1) using a coupled atmospheric transport/wildfire behavior model, HIGRAD/FIRETEC (Linn, 1997). To evaluate the effects of the various forest structural metrics and ignition patterns on simulated crown damage, I created a forest structural complexity index (FSCI) based on the structural metrics of horizontal spatial pattern, vertical complexity, and canopy cover, and used this index and the ignition patterns within a Generalized linear mixed model (GLMM) and Analysis of Variance (ANOVA).

2.2 MATERIALS AND METHODS

2.2.1 NUMERICAL MODEL

FIRETEC is a physics-based, three-dimensional wildland fire behavior model (Linn, 1997; Linn et al., 2002) that captures the ever-evolving, interactive relationship between wildland fire and its environment by combining models that represent thermal degradation, combustion, and heat transfer with the computational fluid dynamics (CFD) model, HIGRAD, which computes turbulence and the compressible convective flow in the lower atmosphere following a large eddy simulation (LES) approach

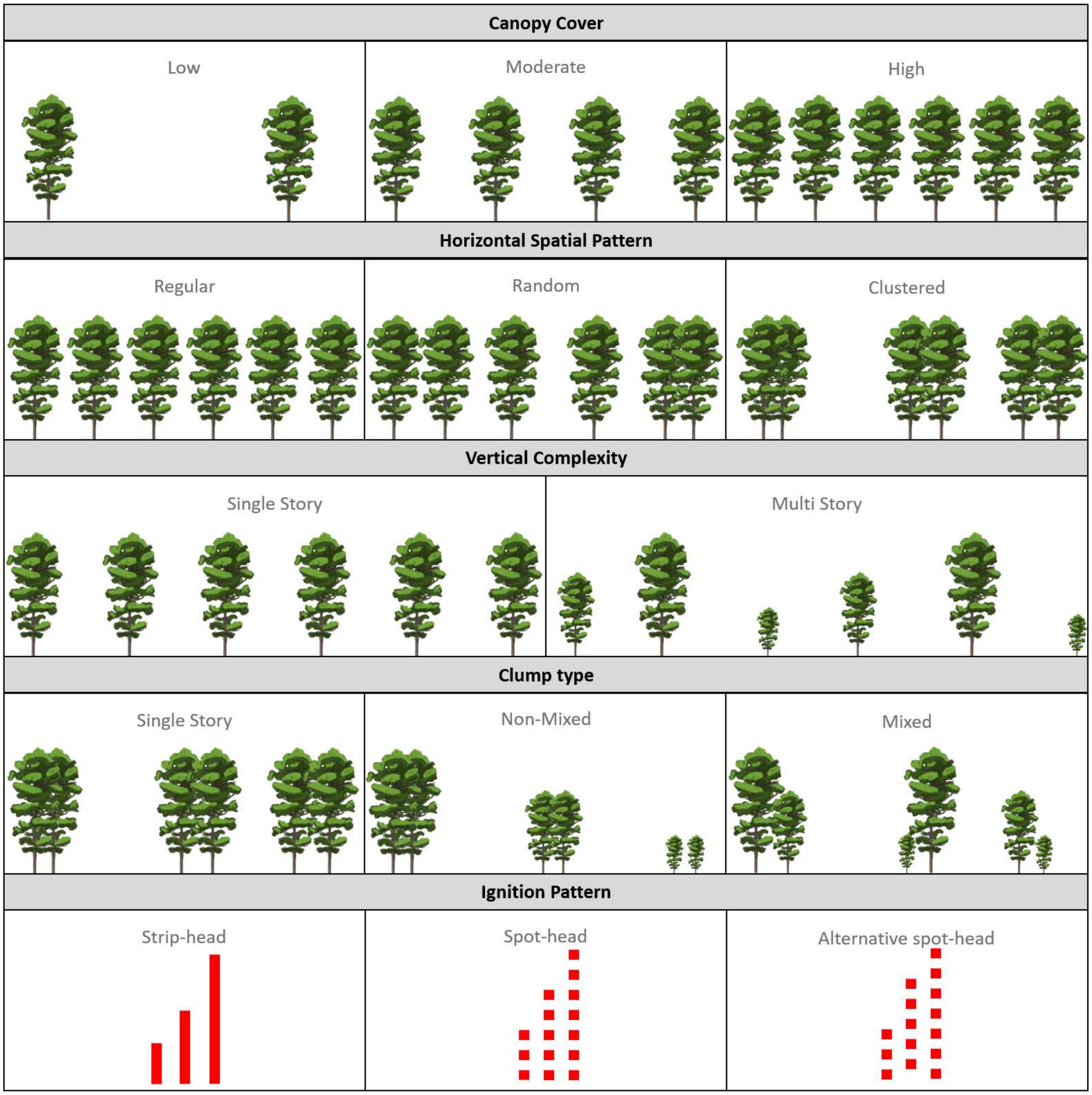

Figure 2.1. Conceptual figure showing the different levels of forest structural metrics, including canopy vegetative structures and respond to the dynamic interactions between the fire and winds (Pimont et al., 2011).

(Pimont et al., 2009; Dupuy et al., 2011). These models are explicitly resolved on a numerical grid while finer-scale processes are stochastically solved by sub grid models. Through this process, FIRETEC develops wind fields that capture the variability in flow velocities and turbulence introduced by complex vegetative structures and respond to the dynamic interactions between the fire and winds, while maintaining conservation of mass, momentum, energy, and chemical species (Pimont et al., 2011).

FIRETEC models wildland thermally-thin fuels as a three dimensional porous media described by their bulk properties such as the surface area per unit volume, fuel moisture content, and bulk density. Because fine fuels are the main driver of fire spread (Rothermel, 1983), only thermally thin fuels, such as grass, litter, and leaves, are represented in the model. FIRETEC can control for multiple environmental factors and thus is advantageous for systematic investigation into the effects of different environmental conditions and treatment combinations. Though evaluations of FIRETEC are still ongoing, it has been compared against experimental studies and demonstrated its ability to produce similar fire behavior, wind flows through complex canopies, surface and crown fire spread, and emissions transport (Bossert et al., 2000; Linn and Cunningham, 2005; Linn et al., 2005, 2012; Pimont et al., 2009; Hoffman et al., 2016; Brown et al., 2019; Josephson et al., 2019). More detailed descriptions of the physical and chemical formulation of the model are available in Linn (1997) and Dupuy et al. (2011).

2.2.2 EXPERIMENTAL DESIGN AND SIMULATION DOMAIN CONFIGURATION

2.2.2.1 MODEL SETUP

All simulations were performed in a 400 m x 400 m x 560 m computational domain with 2 m discretization in the horizontal directions with vertical cell heights ranging from 0.7 m along the lower boundary to 19.4 m at the upper boundary (Figure 2.2). I designated the inlet boundary (i.e., where wind enters the domain) as x = 0 m and the downstream outlet boundary (i.e., where the wind exits the domain) as x = 400 m. The y-dimension, stretching from y = 0 to y = 400, represented the crosswind boundaries. Within this domain, I defined a 204 m x 200 m area of interest (AOI) located 100 m downwind from the inlet boundary and 100 m from the cross-wind boundary of the domain within which all treatments and computations were performed. I placed 10 m wide roads, which contained no canopy or surface fuels, in a grid around the AOI, with each road stretching the entire length or width of the domain. These roads acted as firebreaks surrounding the AOI from which we simulated prescribed fire ignition. Additionally, I

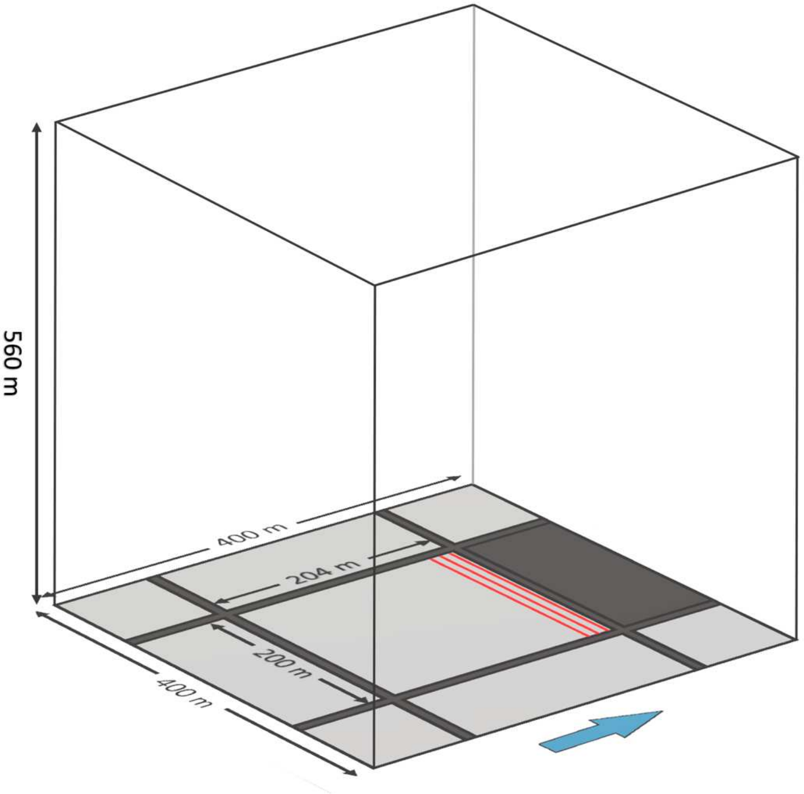

Figure 2.2. Computational domain design showing areas with surface fuels (light gray), the three initial fire lines (red), and the streamwise wind direction (blue).

removed surface fuels downwind of the AOI prior to my ignitions to better contain the fire to the AOI as is often a concern in experimental prescribed fire experiments.

To evaluate potential interactions between ignition pattern and forest structure, I simulated three different ignition patterns through 14 representative forests for a total of 42 simulations. The three ignition patterns were strip-head, spot-head, and alternate spot-head. I generated 14 representative forests that span a range of canopy covers (i.e., low = 25%, moderate = 50%, and high = 75%), horizontal spatial patterns (i.e., regular, random, clustered), and vertical complexities (i.e., single-story vs. multi-story) (Table 2.1). I created these representative forests using Forest Inventory and Analysis data as described in the next section. For representative forests with a clustered horizontal pattern and multi-storied canopy, I developed two different alternatives; one where I allowed size classes to mix within a cluster, and one where a cluster consisted of only one size class of trees. I refer to these two scenarios as Mixed or

Table 2.1. Representative forests for FIRETEC simulations.

Representative Forest Name	Canopy cover (%)	Horizontal spatial pattern	Vertical complexity	Trees per hectare	Basal area (m^2 / ha)	Crown base height (m)	Canopy fuel loading (kg/m^2)
25Reg	25	Regular	Single-Story	71	7.61	15.67	0.17
50Reg	50	Regular	Single-Story	130	13.90	15.58	0.31
75Reg	75	Regular	Single-Story	199	21.51	15.56	0.49
25Ran_Sing	25	Random	Single-Story	67	7.39	15.69	0.17
50Ran_Sing	50	Random	Single-Story	157	17.00	15.79	0.39
25Ran_Mix	25	Random	Multi-Story	142	7.13	12.3	0.16
50Ran_Mix	50	Random	Multi-Story	285	14.01	11.64	0.32
75Ran_Mix	75	Random	Multi-Story	483	23.81	11.99	0.53
25Clu_Sing	25	Clustered	Single Story	71	7.75	15.99	0.18
50Clu_Sing	50	Clustered	Single Story	201	21.40	15.51	0.49
25Clu_Mix	25	Clustered	Multi-Story	143	7.30	12.26	0.16
50Clu_Mix	50	Clustered	Multi-Story	349	16.75	11.61	0.38
25Clu_NonMix	25	Clustered	Multi-Story	147	7.79	12.59	0.18
50Clu_NonMix	50	Clustered	Multi-Story	334	16.17	11.83	0.36

Non-Mixed. I chose to exclude clustered forests with high canopy cover as the difference in forest structure between the clustered and random horizontal spatial patterns were relatively minor and thus I did not expect to see a difference in fire effects (Wang et al., 2020). To isolate the effect of canopy structure on prescribed fire effects, I simulated a consistent homogeneous grass-litter surface fuel complex that was 28 cm deep, with a fuel load of 0.4 kg m^{-2}, a surface area to volume ratio of 47.1 cm^{-1}, and fuel moisture of 9.0% (Ottmar et al., 2000).

2.2.2.2 REPRESENTATIVE FUEL COMPLEXES

I developed representative forests in FIRETEC using data collected in longleaf pine dominated forests from Florida and Georgia and spatial point pattern modeling. I built a custom tree list using tree data from the United States Forest Service (USFS) Forest Inventory and Analysis (FIA) program, which produces and maintains annual inventories of forests across the United States and associated territories (Bechtold and Patterson, 2005; Tinkham et al., 2018). I downloaded and combined plot, condition, and tree FIA database tables from the comma-delimited database applications webpage (USDA Forest Service FIA Datamart webpage (https://apps.fs.usda.gov/fia/datamart/CSV/datamart_csv.html). I filtered the dataset in R (R Core Team, 2021) to select for living trees located in mesic longleaf pine plots, based on the FIA site species index code (SISP) within the condition dataset. I removed from consideration trees with no identified species code. This approach resulted in 12,992 unique trees, which I combined into a single custom tree list. For each tree in the treelist I calculated crown width (CW) using species-specific allometric equations (Bechtold, 2003) and estimated tree crown base height (CBH) from the FIA compacted crown ratio (CR) and tree height (HT). I classified trees into three size classes based on their bole diameter (DBH): juvenile (DBH < 10 cm), subadult (10 cm ≤ DBH < 30 cm), and adult (DBH ≥ 30 cm) (Platt and Rathbun, 1993). Additionally, I classified trees as “pine” or “hardwood” depending on their FIA species group code.

I used my custom tree list and functionalities within the *Spatstat* package (Baddeley et al., 2015) in R to generate the horizontal spatial pattern of each representative forest. The initial intensity of point placements for each representative forest were chosen to achieve the required level of canopy cover when combined with my custom treelist. I generated regular horizontal spatial patterns using the Simulate systematic random point pattern function (rsyst), which simulates evenly-spaced points in a user-defined number of rows and columns within a window, resulting in an evenly-spaced forest similar to what one might find in plantation forestry. I generated random horizontal spatial patterns using the Simulate Simple Sequential Inhibition function (rSSI), which randomly generates points within a window with a user-defined inhibition distance. The random horizontal spatial pattern is common among many forests and generally forms from combinations of randomness in disturbance events, seed dispersal, competition, herbivorous activity, and both large- and small-scale environmental heterogeneities (Wolf, 2005; Getzin et al., 2008). To prevent unrealistic tree spacing and reduce crown overlap, I set the inhibition distance at 3 m, which helped ensure that the overall loading and density of crown fuels in the representative forest were similar to real longleaf forests. I generated clustered forest patterns using the Simulate Matern Cluster Process function (rMatClust) with a 10 m cluster radius around parent points and a mean of 7 points per cluster. To impose a 3 m distance between points for the clustered forests, I populated the points within a window a third of the size of the 400 m x 400 m domain and then multiplied the x and y coordinates as well as the window by three.

I assigned each point the attributes of a tree from the FIA tree list using the Sample function from the *dplyr* package (Wickham et al., 2021) with sampling weights to achieve representative forest compositions of approximately 85% pine and 15% hardwood. For representative forests with single-storied canopies, I only selected from trees identified as adults. In the case of mixed-clumps, I controlled the distribution of tree sizes within clumps by weighting tree assignment within each clump to be consistent to the size class weighting present throughout the other multi-story representative forests. To generate non-mixed clumps, I created an equal number of clumps of each size class and then sampled trees within that size class from my custom treelist using the aforementioned pine and hardwood weights. Following Linn et al. (2002), I assigned pine trees a fuel moisture of 130%, surface area to volume ratio of 4714 m^{-1}, and bulk density of 0.197 kg m^{-3} and hardwood tree cells a fuel moisture of 180%, surface area to volume ratio of 10714 m^{-1}, and bulk density of 0.041 kg m^{-3}. I simulated the three-dimensional canopy shape for each tree as an ellipsoid with a horizontal axis equal to the crown radius and a vertical axis equal to half the crown depth ([HT – CBH] / 2). I then calculated the representative forest canopy cover by creating a buffer around each point based on its assigned tree canopy radius and dividing by the 400 m x 400 m forest area. The resulting representative forest was then evaluated for canopy cover and was either retained or regenerated using an increased intensity value.

2.2.2.3 WIND SIMULATIONS

I aimed to attain mean streamwise velocities of ~ 1 m s^{-1} at 2 m AGL within the AOI for each representative forest. To simulate wind conditions characteristic of an interior forest, I precomputed turbulent wind fields for each representative forest prior to ignition following methodology described in Pimont et al. (2020). The Pimont et al. (2020) methodology uses a large-scale pressure gradient force and cyclic boundary conditions to create an effectively infinitely looping domain where winds cycle from the domain outlet back to the domain inlet, enabling the turbulence to develop over a much smaller area. Using these cyclic boundary conditions, I initialized each wind simulation as a simple log profile with a customized 40 m AGL wind speed (2.6 – 4.4 m s-1) and ran them for 800 s, which allowed enough time for the winds to cycle through the domain twice and develop sufficient turbulent structures. After this period, I switched to noncyclic boundary conditions and recorded the winds for an additional ~1200 s as inlet conditions for the fire simulations.

2.2.2.4 FIRE SIMULATIONS

I simulated each representative forest using the same wind field but with three different ignition patterns (strip-head, spot-head, and alternative spot-head; Figure 2.1). Strip-head ignitions were 2 m wide and 200 m long fires. Spot-head ignitions were 2 m x 2 m spots of fire set at 10 m intervals along 200 m strips. Alternative spot-head ignitions were like spot-head ignitions, except every other head fire line was shifted to center on the gaps from the previous head fire.

The head fires were successively ignited 10 m apart at a rate of 1.5 m s^{-1}, starting with the line located adjacent to the downwind edge of the AOI and ending at the upwind edge of the AOI after 21 lines had been ignited. I ignited the head fires in sets of 3, with each successive set alternating direction. I included a stagger distance of 5 m between the start of each head fire within a set to mimic realistic safety precautions for ignitors. Further, I included a 20 second period where no fire was ignited between ignition sets to simulate the time it would take ignitors to travel between lines. Ignition time ranged between ~ 1045 s for strip-head ignitions to 1060 s for spot-head and Alternative spot-head ignitions. The time from start of ignition to when all fire ceases was ~ 1200 s.

2.2.3 STATISTICAL ANALYSES

2.2.3.1 OUTPUTS

To quantify prescribed fire effects on tree canopies, I estimated the proportion of crown fuel consumed, damaged, and scorched for each tree within the AOI. I tracked the mass of fuels and the solid fuel temperature (T_{Cell}) in each constituent cell for every tree over the course of the prescribed burn. I calculated the proportion of canopy fuels consumed for each tree by subtracting the post-burn canopy fuel mass from the pre-burn canopy fuel mass and dividing by the pre-burn canopy fuel mass. I calculated the proportion of canopy fuel damaged by comparing cell solid fuel temperatures to a set scorch temperature of 334 K (60°C) (Van Wagner, 1973) and used linear interpolation to estimate damage to fuels in the given cell (Cell) and the cell above (Upcell). First, I calculated a scorch height vector (HT_{vect}) using equation 1 and the cell temperatures.

$$HT_{vect} = \frac{(334\,K - T_{Cell})}{(T_{Upcell} - T_{Cell})} \tag{1}$$

Using this value, I determined the vertical interpolation equation I would use. If $HT_{vect} < 0$ or $HT_{vect} > 0.5$, then I used equation 2 to determine the proportion of damage within the cells.

$$p_{Cell} = 1;\ p_{Upcell} = HT_{vect} - 0.5 \tag{2}$$

Otherwise, if $Ht_{vect} > 0$ and $Ht_{vect} < 0.5$, then the proportion of crown fuel damage for the cells are as shown in equation 3.

$$p_{Cell} = HT_{vect} + 0.5;\ p_{Upcell} = 0 \tag{3}$$

However, if the solid fuel temperature of a given cell was less than the scorch temperature then both p_{Cell} and p_{Upcell} would be set to 0. Based on this, I calculated the proportion of crown fuel scorched for each tree by subtracting the proportion of canopy fuel consumed from the proportion of canopy fuel damaged for each tree. I then calculated the proportions of canopy fuel consumed, scorched, and damaged by dividing the sum of all crown biomass consumed, scorched or damaged by the sum of the initial biomass for that simulation.

2.2.3.2 STATISTICAL TESTS

To simplify the concept of forest structural complexity, I first created an index of forest structural complexity (FSCI). This index was meant to describe the degree of structural complexity represented within a forest and was based on an average of several forest attributes suggested by McElhinny et al., (2005), including measures of horizontal spatial pattern (i.e., the Clark-Evans statistic (ClarkEvans) and trees per hectare (TPH)), vertical structure (i.e., tree height (HT) and the standard deviation of tree height (HTsd), and canopy cover (Equation 4). The Clark-Evans term was weighted to put it on the same scale as the other metrics.

$$FSCI = \frac{\left(\frac{10 * (2 - ClarkEvans) + TPH}{2}\right) + \left(\frac{HT + HTsd}{2}\right) + Canopy\ Cover}{3} \tag{4}$$

Following this schema, forests that have aggregated horizontal spatial pattern, multiple vertical layers, or have dense canopies will have a greater index value than forests with regular horizontal spatial patterns, a single-storied canopy, or sparse canopy cover. Using these forest spatial statistics, I calculated a FSCI value for each of my 14 representative forests.

To investigate how forest canopy structure and ignition pattern influence prescribed fire effects, I ran three generalized linear mixed models (GLMM; Brooks et al., 2017) with a beta family distribution and logit link function. Within this model, I included FSCI and ignition pattern as interactive terms and the three different metrics of crown consumption, scorch, and damage as the response variables. To explore a potential interaction between forest structural complexity and ignition pattern, I used this GLMM in a two-way analysis of variance (ANOVA; Fox and Weisberg, 2019). Finally, I used Tukey's post hoc test for pairwise comparisons (Lenth, 2022) to compare between the different ignition patterns (*alpha* < 0.05).

2.3 RESULTS

2.3.1 MODEL DATA

FSCI values for the 14 representative forests ranged between 24 – 111 with a mean of 52. All representative forests at the lower end of this index (index value: 24 - 38) consisted of forests with low canopy cover, while the upper end (index value: 44 - 111) consisted of forests with moderate to high canopy cover. Vertical complexity further sub-divided these index value ranges, as representative forests with single story canopies (low vertical complexity) had lower index values than representative forests with multi-story canopies (high vertical complexity).

Overall mean canopy consumption for the representative forests was 6% with a standard deviation of 1%. Mean canopy scorch was 26% with a standard deviation of 5%. Overall canopy damage was 32% with a standard deviation of 6%. Mean crown scorch and consumption values for each representative forest averaged across the three ignition patterns are shown in figure 2.3.

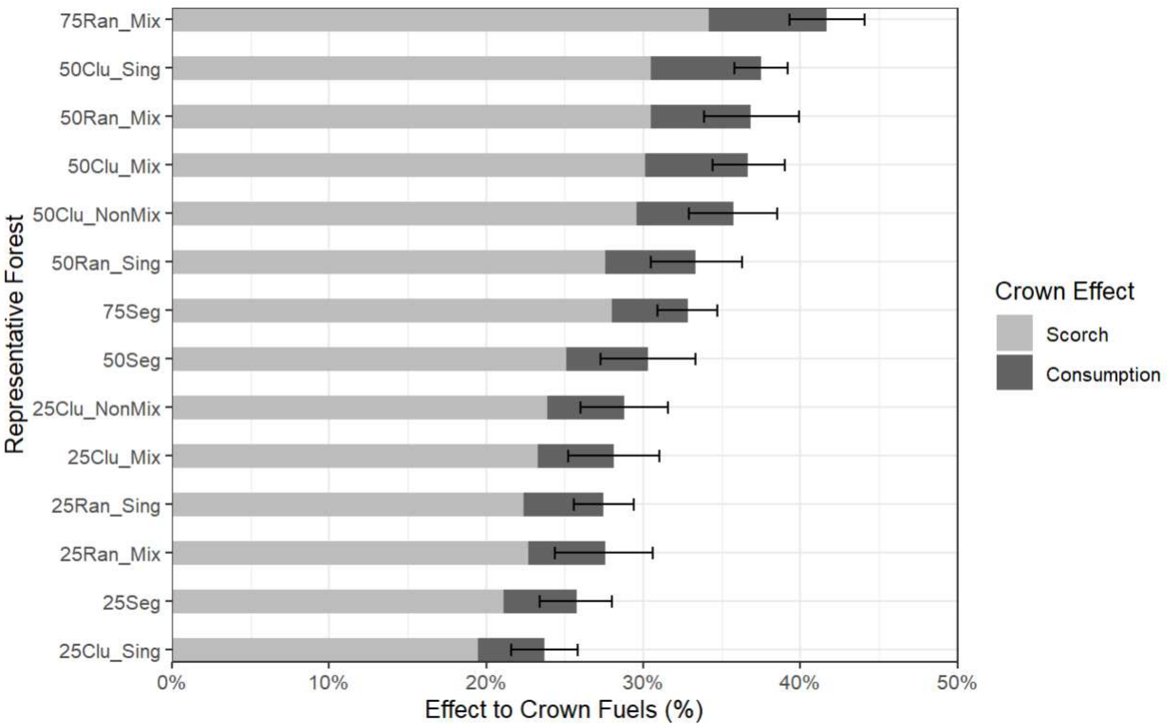

Figure 2.3. Histogram showing the means of crown scorch and consumption for prescribed fire simulations in 14 representative forests. Standard deviations for overall crown damage (i.e., the sum of crown scorch and consumption) are shown.

2.3.2 GLMMS, ANALYSIS OF VARIANCES (ANOVAS), AND POST-HOC PAIRWISE COMPARISONS

The three GLMMs showed that an increase of 1 unit in FSCI was associated with relative increases of 0.6%, 0.8%, and 0.9% in the proportions of crown consumption, scorch, and damage, respectively (Table 2.2; Figure 2.4 a, b, and c). Crown consumption had the lowest intercept estimate at -3.057, followed by scorch at -1.330, and then damage at -1.091 (Table 2.2). Spot-head and Alternative Spot-head ignition patterns showed negative estimates for their intercepts, indicating that the y-intercept of their regression lines were less than the referenced y-intercept of the Strip-head ignition pattern regression line (Table 2.2). There appears to be no interaction between FSCI and ignition pattern as evidenced by the large p-values of the interaction coefficients in Table 2.2. This is corroborated by results from the two-way ANOVAs, which revealed no evidence of a statistically significant interaction between the effects of forest structural complexity and ignition pattern on crown consumption ($\chi2 = 0.30$, $p = 0.86$;

Table 2.2. Summary table showing model coefficient estimates, error, z-values, and p-values for the generalized linear mixed models with family = beta and logit link function. The intercept is built on the strip-head ignition pattern and its interaction with FSCI.

Response	Coefficient	Estimate	Std error	z-value	p-value
Consumption	Intercept	-3.057	0.06	-49.26	<2.00E-16
	FSCI	0.006	0.00	5.61	2.01E-08
	Spot-head	-0.171	0.09	-1.88	0.06
	Alternative Spot-head	-0.145	0.09	-1.62	0.11
	FSCI: Spot-head	0.000	0.00	0.14	0.89
	FSCI : Alternative Spot-head	0.001	0.00	0.53	0.60
Scorch	Intercept	-1.330	0.05	-24.41	<2.00E-16
	FSCI	0.008	0.00	8.50	<2.00E-17
	Spot-head	-0.238	0.08	-3.01	0.00
	Alternative Spot-head	-0.184	0.08	-2.34	0.02
	FSCI: Spot-head	0.001	0.00	0.56	0.58
	FSCI : Alternative Spot-head	0.001	0.00	0.41	0.68
Damage	Intercept	-1.091	0.06	-18.14	<2.00E-16
	FSCI	0.009	0.00	8.40	<2.00E-17
	Spot-head	-0.245	0.09	-2.83	0.00
	Alternative Spot-head	-0.192	0.09	-2.22	0.03
	FSCI: Spot-head	0.001	0.00	0.36	0.72
	FSCI : Alternative Spot-head	0.000	0.00	0.34	0.73

Supp. Table 2.1), scorch ($\chi2 = 0.34$, p = 0.85; Supp. Table 2.1), or damage ($\chi2 = 0.17$, p = 0.92; Supp. Table 2.1). However, there was evidence that the main effect of FSCI produced differences in the proportions of crown consumption ($\chi2 = 32.26$, p = 0.00; Supp. Table 2.1), scorch ($\chi2 = 72.62$, p = 0.00; Supp. Table 2.1), and damage ($\chi2 = 70.49$, p = 0.00; Supp. Table 2.1). Ignition pattern showed no evidence of causing a difference in the proportion of crown consumption ($\chi2 = 4.28$, p = 0.12; Supp. Table 2.1), but there was evidence that the choice of ignition pattern was statistically significant for the proportion of crown scorch ($\chi2 = 10.12$, p = 0.01; Supp. Table 2.1) and damage ($\chi2 = 8.95$, p = 0.01; Supp. Table 2.1).

Tukey-pairwise comparisons of the ignition patterns showed that the proportions of crown scorch produced in a prescribed fire was greater when ignited in a Strip-head ignition pattern than in a Spot-head

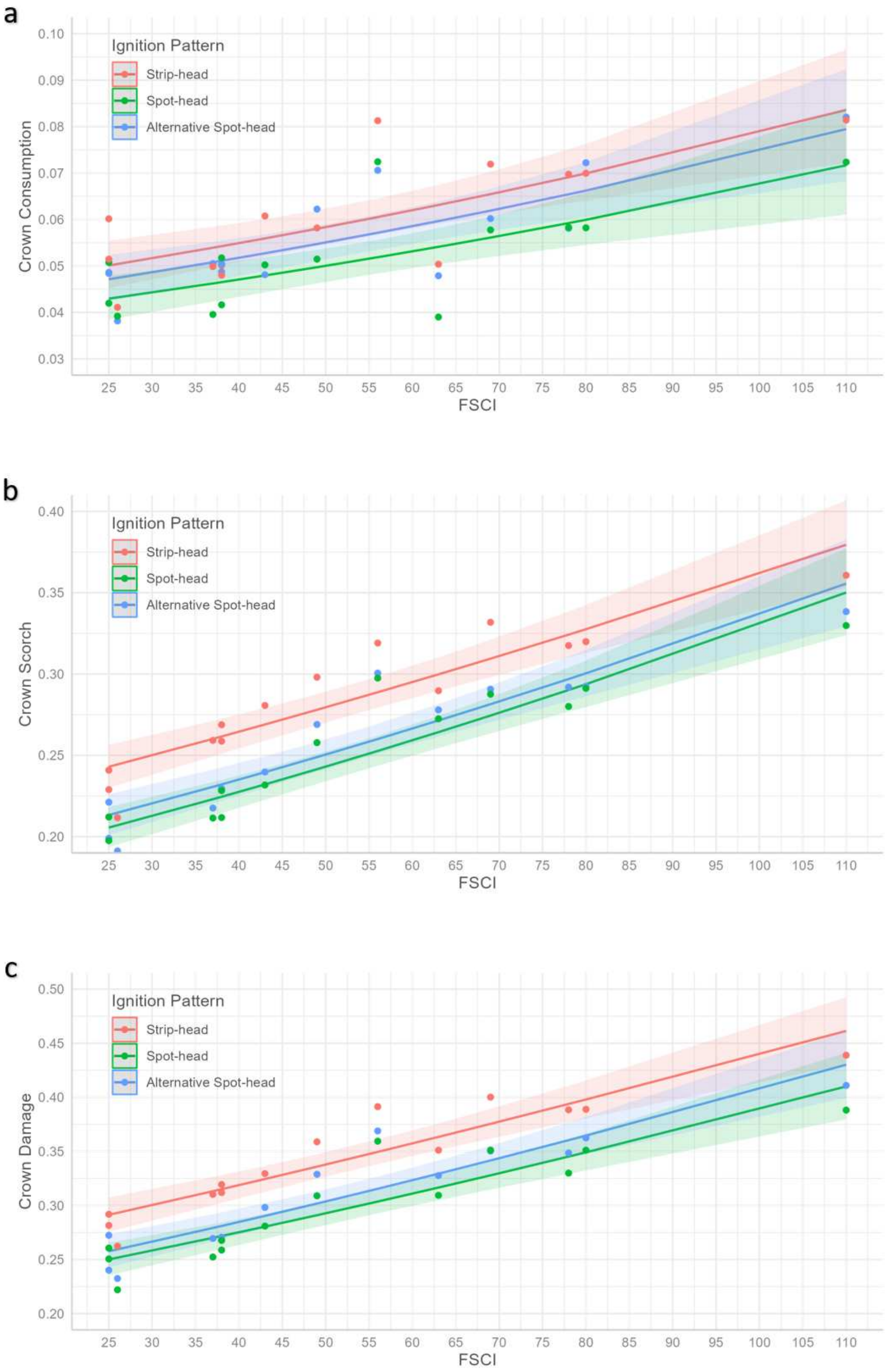

Figure 2.4. The Forest Structural Complexity Index (FSCI) plotted against the proportion of a) crown consumption, b) crown scorch, and c) crown damage observed within each simulation. The three linear regression lines show linear fits for simulations ignited with strip-head (red), spot-head (green), and alternative spot-head (blue) ignition patterns. The points show the simulation results.

pattern (odds ratio = 1.22, p = 0.00) or Alternative Spot-head pattern (odds ratio = 1.17, p = 0.00). Similarly, the Tukey-pairwise comparisons of the ignition patterns showed that the proportions of crown damage were greater when ignited in a Strip-head ignition pattern than in a Spot-head pattern (odds ratio = 1.24, p = 0.00) or Alternative Spot-head pattern (odds ratio = 1.18, p = 0.00). There was no evidence of a difference in crown scorch or damage between the Spot-head and the Alternative Spot-head ignition patterns (Supp. Table 2.2).

2.4 DISCUSSION AND CONCLUSIONS

Land managers across a diversity of ecosystems are increasingly using prescribed fire to meet their various management objectives. Thus, it is important, especially in complex ecosystems such as forests, to understand the relationship between fire effects, behavior, and vegetative structure and how the ignition pattern influences those relationships. The influence of forest structure on fire behavior and effects has been investigated in past studies, however, most of these studies target only one or two structural factors in isolation. My work incorporates numerous structural factors that describe both the horizontal and vertical complexity of forests to create a more comprehensive understanding of how overall structural complexity affects the ecological outcome of a prescribed fire. Further, I included three different ignition patterns into my study, which is an underrepresented factor of prescribed fire behavior and effects within the fire literature (Johansen 1987; Molina et al., 2022).

2.4.1 FOREST STRUCTURAL COMPLEXITY

Across 42 fire simulations in 14 structurally unique representative forests, I found that both the structural complexity of forests and the ignition pattern influenced the proportions of crown consumption, scorch, and damage during prescribed fires. As crown consumption, scorch, and damage all followed the same trend, I focus on discussing crown damage for simplicity. Crown damage was positively correlated with FSCI. This result supports the concept that greater structural complexity fosters more severe fire effects during prescribed fires. Further, the structural factors composing FSCI each contributed to the proportion of resulting crown damage, and visual inspection of the data and findings from past studies help describe the relationship between these structural factors.

I found crown damage tended to increase as the complexity of the horizontal spatial pattern of my representative forests increased from regular to random to clustered. This increase in crown damage likely resulted due to the effects that forest horizontal spatial patterns have on local wind movements. Gaps of varying sizes, characterized as areas with few to no trees, often appear between clumps of trees in locations where environmental conditions are less favorable to vegetative survival and growth. The spatial arrangement of gaps and clumps of trees increases the variability of wind movements within the forest as the winds react to the absence or presence of drag-inducing foliage (Patton, 1997; Parsons et al., 2017). As the clustered horizontal spatial pattern is defined by the structural arrangement of clumps and gaps, forests with this pattern experience greater variability in their wind fields (Pimont et al., 2011) which could result in greater variability in fire behavior and effects. Wind facilitates the convective cooling and heating of fuels, and the presence of gaps eases the vertical transport of buoyant winds produced from surface fires to the canopy fuels, increasing the convective heating of canopy fuels and the resulting amount of fuel consumption, scorch, and overall damage that may occur (Kiefer et al. 2018). Further, the clumping of trees has been found to ease the propagation of fire between tree crowns and cause greater damage to crown fuels (Parsons et al., 2011; Hoffman et al., 2012), however, the effect of clumping may not always result in significant differences in crown damage from other spatial patterns (Ritter et al., 2022). Against my expectations, I found no difference in the proportion of crown damage between the Mixed and Non-Mixed clustered horizontal spatial patterns. However, past research into forest horizontal spatial patterns has shown that clump size is the primary determining factor driving differences in fire behavior in clustered forests (Pimont et al., 2011; Ritter et al., 2020).

I found a positive relationship between the degree of vertical complexity in my representative forests and the proportion of crown damage. The vertical structure of a forest plays a role in how well a wind can penetrate the canopy fuels and the effect that plays on vertical wind movements and heat energy transference. The vertical movement of air driving convective cooling is weaker and temperatures within canopy fuels and downstream of fires are greater in multi-storied forest canopies (i.e., understory dominated) than in single-story forest canopies due to the dampening effect of the foliage (Kiefer et al., 2018). This emphasizes that the presence of canopy fuels in the space between the surface fuels and the top of the canopy reduces the magnitude of convective cooling that can occur and may cause the fire plume to become more horizontal. Further the increased vertical complexity can lead to improved vertical continuity of canopy fuels, resulting in increased opportunity for the vertical ascension of the fires and increased effects to canopy fuels (Ziegler et al., 2017; Atchley et al., 2021).

As the proportion of canopy cover increased, the proportion of crown damage also increased. Within my index, representative forests with moderate to high amounts of canopy cover were considered more complex and resulted in a greater proportion of crown damage than forests with low canopy cover. Pimont et al. (2011), who used identical levels of canopy cover (i.e., 25%, 50%, and 75% canopy cover), similarly observed decreased fire behavior and effects under low canopy covers. The presence of increased canopy cover within a forest reduces the number of gaps, which hinders vertical convective cooling of the fire and fire plume and traps heat within the canopy, resulting in an increased effect to canopy fuels (Schwilk, 2003; Kiefer et al., 2018; Ritter et al., 2020).

2.4.2 IGNITION PATTERN

Given a specific fuels complex and weather conditions, the choice of ignition pattern is one of the few factors that land managers can control to influence fire behavior and effects. My results show that - regardless of forest structure – using a strip-head ignition pattern consistently produced more severe crown damage than spot-head or alternative spot-head ignition patterns, which was also found by Johansen (1987) and Molina et al. (2022). The use of strip-head ignition patterns in prescribed fire could be considered for use in forest ecosystems where managers seek to achieve greater damage to crown fuels or more severe fire behavior in general. Otherwise, a less intense ignition pattern, such as spot-head or alternative spot-head may be enough to achieve the desired fire behavior and effects to crown fuels.

Further fine-tuning of fire behavior and effects can be achieved through alterations to the spacing between individual head-fires and between spots of fire (Molina et al., 2022) or alterations to the timing of number of fire lines, though further research may be required to determine the optimal pattern for a given ecosystem and objectives. Lastly, though generally not of extensive concern, using one of the spot-head ignition pattern instead of a strip-head pattern can reduce the amount of fuel and time required to ignite the fires.

2.4.3 INTERACTIONS

I found no evidence of an interaction between FSCI and the three ignition patterns. Despite this, managers should still account for the additive effect of the degree of structural complexity and the ignition pattern, as certain combinations may produce unfavorable results. For example, using a strip-head ignition pattern in forests with a high FSCI value may produce more severe fire behavior and ecological effects than tolerable for managers or safe for ignitors. Conversely, using a spot-head or alternative spot-head ignition pattern in a forest with a low FSCI value may not produce the fire behavior needed to meet objectives.

The absence of an interaction between the FSCI and ignition pattern could be due to there simply not being an interaction, or the set of environmental conditions I ignited under, or a product of the surface fuel structure. Different ignition patterns and methods can be used to achieve different fire behaviors and effects (Molina et al., 2022) and it may be that while the particular ignition patterns and details I used were not conducive to an interaction, that other ignition patterns (e.g., Ring or Aerial) or methods (e.g., flanking fire or backing fire) would interact with forest structural complexity (Johansen, 1987). Ignition line length may have also played a role in the lack of interaction. Pimont et al. (2011) and Canfield et al. (2014) observed that long fire lines (e.g., 300 m) were not affected by heterogeneity in canopy fuels as long lines of fire prevent lateral indrafts from cooling the fuels in front of the fire. Shorter lines of head-fires may see more of an interaction as lateral indrafts become more prevalent. The environmental conditions I ignited my simulations under were within the range of acceptable burning conditions for longleaf pine forests, however, changing the fuel moisture or wind speeds of these simulations would likely change fire behavior. Under drier initial conditions or faster wind speeds, the fire would be predicted to exhibit more severe fire behavior (Rothermel, 1972) and the proportion of crown damage produced by each of the three ignition patterns may converge as the crown damage maxima is reached. The spatial arrangement and loadings of surface fuels is a major driver of variability in fire behavior and the ecological outcomes of prescribed fires (O'Brien et al., 2016; Babl et al., 2020; Whelan et al., 2021). Locations and loadings of surface fuels such as litter and grass are influenced by the nearby canopy fuels, as the canopy fuels drop to become litter and shading and soil nutrient leeching discourages grass growth near tree boles (Keane et al., 2012; Keane 2015; Vakili et al., 2016). Because I used a homogenized grass-litter layer to isolate the effects of canopy structure, my ignitions only responded to variations in the wind field and not the surface fuels. It may be that an interaction would be seen in simulations with heterogeneous surface fuel structures built on the properties of the overstory fuels.

2.4.4 MERITS OF MODELING

Although field experiments are crucial for gathering data on real life environmental and ecological factors, developing our collective understanding of fire behavior and effects, building empirical models, and setting realistic expectations for experimental results, they lack the absolute control that is featured in detailed physics-based models (Hoffman et al., 2016). Models such as FIRETEC grant users full command over the ignitions, environmental factors, and weather conditions of the burn unit (Linn et al., 2002) without the constraints and tribulations of field experiments and further facilitates experimental replication. The sheer quantity and diversity of relevant data collected at each time step and the freedom for users to run and build calculations on these data based on their needs allows users to gain unique insights into fire and the associated environmental factors beyond those from experimentation. As detailed physics-based models such as FIRETEC are developed and improved, our ability to explore and understand the mechanisms and processes that drive fire behavior and effects will also improve. It is likely that future investigations of prescribed fire behavior and effects will rely heavily on the quality of the science behind these models and the computational power available to researchers.

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APPENDIX

APPENDIX A

Supplemental Table 1.1. Supplementary Data 1

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APPENDIX B

Supplemental Table 2.1. Results of the ANOVA testing for interactions between the forest structural complexity index (FSCI) and clump type in relation to the proportion of canopy consumption, scorch, and damage amassed during prescribed fire simulations.

Response	Parameter	Wald ($\chi 2$)	df	p-value
Consumption	(Intercept)	2474.29	1	<2.20E-16
	FSCI	32.26	1	1.35E-08
	Ignition Pattern	4.28	2	0.12
	FSCI : Ignition Pattern	0.30	2	0.86
Scorch	(Intercept)	595.60	1	<2.20E-16
	FSCI	72.22	1	<2.20E-16
	Ignition Pattern	10.12	2	0.01
	FSCI : Ignition Pattern	0.34	2	0.85
Damage	(Intercept)	328.93	1	<2.20E-16
	FSCI	70.49	1	<2.20E-16
	Ignition Pattern	8.95	2	0.01
	FSCI : Ignition Pattern	0.17	2	0.92

Supplemental Table 2.2. Tukey pairwise comparisons for the three ignition patterns across the Forest Structural Complexity Index

Response	Contrast		Odds Ratio	Std Error	df	t Ratio	p - value
Scorch	Strip-head	Spot-head	1.22	0.04	35	6.05	0
	Strip-head	Alternative Spot-head	1.17	0.04	35	4.76	0
	Spot-head	Alternative Spot-head	0.96	0.04	35	-1.43	0.40
Damage	Strip-head	Spot-head	1.24	0.05	35	6.05	0
	Strip-head	Alternative Spot-head	1.18	0.04	35	4.62	0
	Spot-head	Alternative Spot-head	0.95	0.04	35	-1.43	0.34