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Forest structural complexity and ignition pattern influence simulated prescribed fire effects

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Abstract

Background Forest structural characteristics, the burning environment, and the choice of ignition pattern each influence prescribed fire behaviors and resulting fire effects; however, few studies examine the influences and interactions of these factors. Understanding how interactions among these drivers can influence prescribed fire behavior and effects is crucial for executing prescribed fires that can safely and effectively meet management objectives. To analyze the interactions between the fuels complex and ignition patterns, we used FIRETEC, a three-dimensional computational fluid dynamics fire behavior model, to simulate fire behavior and effects across a range of horizontal and vertical forest structural complexities. For each forest structure, we then simulated three different prescribed fires each with a unique ignition pattern: strip-head, dot, and alternating dot.

Results Forest structural complexity and ignition pattern affected the proportions of simulated crown scorch, consumption, and damage for prescribed fires in a dry, fire-prone ecosystem. Prescribed fires in forests with complex canopy structures resulted in increased crown consumption, scorch, and damage compared to less spatially complex forests. The choice of using a strip-head ignition pattern over either a dot or alternating-dot pattern increased the degree of crown foliage scorched and damaged, though did not affect the proportion of crown consumed. We found no evidence of an interaction between forest structural complexity and ignition pattern on canopy fuel consumption, scorch, or damage.

Conclusions We found that forest structure and ignition pattern, two powerful drivers of fire behavior that forest managers can readily account for or even manipulate, can be leveraged to influence fire behavior and the resultant fire effects of prescribed fire. These simulation findings have critical implications for how managers can plan and perform forest thinning and prescribed burn treatments to meet risk management or ecological objectives.

Keywords Crown damage, Fire effects, Fire modeling, Forest structure, Ignition pattern, Prescribed burning

Resumen

Antecedentes Las características estructurales de un bosque, el ambiente en que se quema, y la elección del patrón de ignición influencian cada uno el comportamiento del fuego en una quema prescripta y también sobre los efectos resultantes de esa quema; sin embargo, pocos estudios examinan las influencias e interacciones entre esos factores. El entender cómo las interacciones entre esos factores conducentes pueden influenciar el comportamiento y efectos

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del fuego en quemas prescriptas es crucial para poder ejecutar estas quemas, y que puedan ser seguras y cumplir efectivamente con los objetivos de manejo. Para analizar las interacciones entre los complejos de combustibles y los patrones de ignición, usamos FIRETEC, un modelo computacional de comportamiento del fuego tri-dimensional basado en dinámica de fluidos, para simular el comportamiento y efectos del fuego a través de un rango horizontal y vertical de estructuras forestales de distinta complejidad. Luego, para cada estructura forestal, simulamos tres quemas prescriptas diferentes, cada una con un único patrón de ignición: línea frontal, punto, y puntos alternados.

Resultados La complejidad de la estructura forestal y el patrón de ignición afectaron las proporciones de la simulación en cuanto al chamuscado de copas, el consumo, y el daño por las quemas en ecosistemas secos y proclives al fuego. Las quemas prescriptas en bosques con estructuras de doseles complejos resultaron en un incremento en el consumo de las copas, en el chamuscado y con mayores daños que en bosques con estructuras espaciadas y menos complejas. La elección del uso de la línea frontal como patrón de ignición sobre los puntos individuales o alternados incrementaron el grado de follaje chamuscado y dañado, aunque no afectó la proporción de la copa consumida. No encontramos evidencia de una interacción entre la complejidad de la estructura forestal y el patrón de ignición sobre el consumo del combustible, el chamuscado, o el daño.

Conclusiones Encontramos que la estructura forestal y el patrón de ignición, dos poderosos factores conducentes del comportamiento del fuego que los gestores de incendios pueden rápidamente tener en cuenta y aun manipular, pueden ser aprovechados para influenciar el comportamiento del fuego y los efectos resultantes de las quemas prescriptas. Estos resultados de simulación tienen implicancias críticas sobre cómo pueden los gestores planificar y llevar a cabo raleos y quemas prescriptas para alcanzar objetivos ecológicos o de reducción del riesgo.

Background

Advancing the ability to predict fire behavior and effects across a range of environmental conditions in heterogeneous fuel complexes has become increasingly critical as land managers seek to expand the frequency and extent of prescribed and managed fire. Prescribed fire is used to accomplish a variety of management objectives, such as reducing wildfire risk, enhancing biodiversity, restoring and maintaining ecological conditions and processes, mitigating climate-driven impacts, or removing invasive and unwanted species (Wade and Lundsford 1990; Fernandes and Botelho 2003; Ryan et al. 2013, Gallagher et al. 2022; Sample et al. 2022). When designing and evaluating the effectiveness of prescribed fires in meeting these objectives both safely and efficiently, it is essential for managers to anticipate how interactions between the vegetative fuels complex, fire weather (e.g., wind speed, wind direction, temperature, and relative humidity), and ignition procedures influence fire behavior and ecological effects. In this regard, particular attention has been focused on predicting prescribed fire effects in fire-dependent ecosystems with frequent, low-intensity fires for maintaining resilient forest structures, species composition, and overall ecological health (Hiers et al. 2020). However, producing accurate predictions of fire effects in these ecosystems can be challenging because of the complex fuel structures present at fine scales (Hiers et al. 2009; Loudermilk et al. 2014; Vakili et al. 2016) and a paucity of data quantifying how different ignition prescriptions interact with these complex fuel structures (Bonner et al. 2021).

In contrast to indigenous wildland fire cultural knowledge and practices (Abrams et al. 2021; Roos et al. 2021), much of the past economic, cultural, and social resources invested in wildland fire science within the U.S. have focused on understanding the behavior and resulting effects of wildfires on ecosystems (Hiers et al. 2020). As a result, land managers commonly apply tools developed for free-spreading wildland fires to predict potential prescribed fire behavior and effects (Yedinak et al. 2018; National Wildfire Coordinating Group (NWCG) 2022). However, the knowledge required to plan a prescribed fire is different from the knowledge needed to predict wildfire behavior, in part due to the differences in the burning conditions (i.e., low, or moderate vs. severe weather conditions) and fire plume interactions that emerge from various ignition patterns (Hiers et al. 2020). Because prescribed fires are frequently ignited under more moderate burning conditions than those typical of the large rapidly spreading wildfires, prescribed fire behavior is more sensitive to fine-scale variations in environmental conditions including the heterogeneous properties of the fuels complex (i.e., moisture, loading, and structural arrangement) (Atchley et al. 2021; Loudermilk et al. 2014) and local weather conditions (Linn et al. 2012).

Fire scientists and land managers have long understood that forest structure is a key variable influencing fire behavior and effects (Rothermel 1972; Anderson 1981; Catchpole et al. 1993), although only recently has the importance of characterizing the structural complexity of the fuels been fully understood (Loudermilk et al. 2014;

Banerjee et al. 2020; Skowronski et al. 2020; Gallagher et al. 2021). While most fuel descriptions are qualitative or summarize the mean fuel loadings (Keane 2012; Vakili et al. 2016; Bonner et al. 2021), recent advancements in modeling and remote sensing technologies are allowing for a more complete depiction of the inherent complexity of wildland fuel complexes (Burt et al. 2013; Loudermilk et al. 2023; Zhou et al. 2023). Forest structural complexity is a descriptive statistic of forest attributes and their relative abundance (McElhinney et al. 2005). However, because forest structural complexity is used for a wide 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 in its calculation. For relevance to fire behavior research, forest structural complexity ideally captures the general spatial arrangement and variation of forest canopy fuels in the horizontal (i.e., the spatial distribution of individual trees within a forest [Von Gadow and Hui 2002]) and the vertical (i.e., the distribution and configuration of tree sizes across a stand dimensions, or within an aggregation of trees [Franklin and Van Pelt 2004]).

Forest structural complexity influences fire behavior directly through its effects on the amount and distribution of surface and crown fuel loadings (Loudermilk et al. 2014; O'Brien et al. 2016), and indirectly through its effects on energy transport, local wind patterns, and entrainment into the fire plume (Dupont and Brunet 2008; Boudreault et al. 2014; Parsons et al. 2017; Clark et al. 2020; Loudermilk et al. 2022). These indirect effects influence the locations, timings, and magnitudes of convective heating and cooling of fuels and determine the resulting patterns of crown consumption and scorch (Linn et al. 2013; Hoffman et al. 2015; Kiefer et al. 2016; Ritter et al. 2020; Atchley et al. 2021). Crown consumption (i.e., foliage consumed or charred during flaming combustion) and crown scorch (i.e., foliage killed but not consumed) are types of fire-induced damage to crown foliage and are linked to physiological effects such as reduced growth, weakened defenses, and greater tree mortality, as well as potential consequences to ecosystem scale processes and biogeochemical fluxes (Varner et al. 2021). Variations in forest structure occur through interacting ecological process (e.g., regeneration, mortality, growth, competition) or are created through the use of silvicultural methods to achieve specific land management objectives. Fuel treatments are a specific type of land management practice that use mechanical methods, prescribed fire, or a combination of the two to alter the amount and arrangement of the fuels complex to reduce potential fire behavior (Hoffman et al. 2018). Although it is generally recognized that forests with lower canopy fuel loads have greater convective cooling and thus are less likely to ignite and experience crown damage than dense forests (Linn and Cunningham 2005; Fulé et al. 2012; Ziegler et al. 2017; Parsons et al. 2017; Atchley et al. 2021), the arrangement of the forest canopy can influence fire behavior and effects through interactions among the fuels, wind, and fire (Atchley et al. 2021). Heterogeneous forest structures, consisting of clumps of multi-sized trees, are often assumed to have a greater potential for adverse fire effects such as crown scorch, consumption, and damage than homogeneous forest structures with evenly spaced trees. Aggregations of trees into clusters introduces unique patterns of entrainment, and convective and radiative heating and cooling that are not present when trees are evenly spread out on a landscape, resulting in localized increases in fire rate of spread, and increasing the potential for crown ignition, consumption, and scorch (Loudermilk et al. 2012; Parsons et al. 2017; Ritter 2022). Relative to the effects of fuel load and horizontal forest complexity, much less is known about the influence of vertical complexity on fire behavior and effects. In general, increased vertical complexity is associated with a reduction in the overall forest canopy base height and an increase in the potential for crown ignition and damage (Menning and Stephens 2007; Banerjee 2020). However, complex interactions exist between the horizontal and vertical arrangement which can influence crown damage (Ritter et al. 2023).

When developing prescribed fire plans, land managers must also consider how the choice of ignition pattern will influence prescribed fire effects (Fernandes and Botelho 2003). Of critical concern is how the ignition pattern—including the ignition arrangement, fire line continuity, alignment of ignition lines with the wind direction, and distance between individual ignition lines—will alter fire behavior and the resultant ecological consequences. Although it is common knowledge that land managers can alter these ignition characteristics to achieve different spread rates, fire intensities, flame heights, and residence times, and ultimately the ecological outcomes of a prescribed burn (Wade and Lundsford 1989; Fernandes and Botelho 2003; Martin and Hamman 2016; Molina et al. 2018, 2022), specific guidance on the ideal pattern to use to meet a specific objective is generally not available. Previous studies have indicated that strip-head ignitions should produce more intense fire behavior than a grid of dot ignitions (Johansen 1987; Molina et al. 2022), but this may not always be the case depending on the number of fire lines and their spacing (Molina et al. 2018; Finney and McAllister 2011; Vega et al. 2012; Canfield et al. 2014; Raposo 2016). Due to a lack of comparisons and confounding environmental conditions of field experiments, it is difficult to isolate how ignition pattern affects the behavior and ecological outcomes of any given burn unit or forest structural arrangement. Despite the importance of ignition planning, there is a lack of both experimental and modeling data on the various effects of ignition pattern on fire behavior and effects (Molina et al. 2022).

Our goal in this study was to investigate how forest structure and the choice of ignition pattern impact crown damage from prescribed fires. To meet this goal, we used HIGRAD/FIRETEC (Linn et al. 2007) to model three different ignition patterns across a range of forest structural complexities in modeled fire-dependent longleaf pine (*Pinus palustris*) forests. We derived modeled fuel complexes using data from the USDA Forest Service's Forest Inventory and Analysis (FIA) database (Forest Inventory and Analysis Database of the United States of America 2012) to generate 14 forests representative of a range of forest structures managed by forest managers, each characterized by a unique combination of canopy cover, horizontal spatial pattern, vertical complexity, and within cluster size class compositions (i.e., tree clump type) (Fig. 1). We then simulated three common ignition patterns (Fig. 1) for each of these representative forests. To distinguish between the degrees of structural complexities represented within our representative forests and enable comparisons of crown damage across all simulations, we defined a forest structural complexity index (FSCI) based on the previously defined structural metrics. For each simulation, we then assessed the proportion of crown consumption, scorch, and total crown damage.

Methods

Numerical model

HIGRAD/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. This dual model combines FIRETEC, a model that represents combustion, heat transfer, mass transfer, and aerodynamic drag of vegetation with the computational fluid dynamics (CFD) model, HIGRAD, which computes turbulence and the compressible flow in the lower atmosphere following a large eddy simulation (LES) approach (Pimont et al. 2009; Dupuy et al. 2011). These models explicitly resolve some phenomena on a numerical grid while subgrid models stochastically solve finer-scale processes. Through this process, HIGRAD/FIRETEC, hereafter in this manuscript referred to simply as 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 (such as buoyant plume formation), while maintaining conservation of mass, momentum, energy, and chemical species (Pimont et al. 2011).

FIRETEC models thermally-thin wildland fuels as a three-dimensional porous media described by their bulk properties such as surface area to volume ratio, fuel moisture content, and bulk density. As FIRETEC allows users to independently alter and control for multiple environmental factors, it is advantageous for systematic investigations into the effects of different environmental and fuel conditions. Though model refinement of FIRETEC is ongoing, FIRETEC has been assessed for emerging fire line properties (Linn and Cunningham 2005), complex ignitions (Furman and Linn 2018), simple (Linn and Cunningham 2005) and complex wind fields determined by fuel structures (Bossert et al. 2000; Pimont et al. 2009; Linn et al. 2013; Banerjee et al. 2020), fire on topographies (Linn et al. 2007; Linn et al. 2010; Pimont et al. 2012), crown fire rate of spread (Hoffman et al. 2016), and emissions transport (Brown et al. 2019; Josephson et al. 2019). More detailed descriptions of the physical and chemical formulation of the FIRETEC model are available in Linn (1997) and Dupuy et al. (2011).

Experimental design and simulation domain configuration

Model setup

All simulations were performed in a 400 m × 400 m × 560 m computational domain with 2 m discretization in the horizontal directions and vertical cell heights increasing following a cubed polynomial with a stretch factor of 0.1, resulting in a domain height ranging from 0.7 m along the lower boundary to 19.4 m at the upper boundary (Fig. 2). Within this domain, we defined a 204 m × 200 m area of interest (AOI) located 100 m downwind from the inlet boundary and 100 m from the crosswind boundaries of the domain within which all treatments were performed and fire behavior was examined. We placed 10 m wide roads, which had 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 functioned as firebreaks surrounding the AOI from which we simulated prescribed fire ignition. Additionally, we removed surface fuels downwind of the AOI (following Furman and Linn 2018) to isolate burn block fire effects from interactions with potential escape.

To evaluate potential interactions between ignition pattern and forest structure, we simulated three different ignition patterns across 14 representative forests for a total of 42 simulations. The three ignition patterns were strip-head, dot, and alternating dot. We 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),

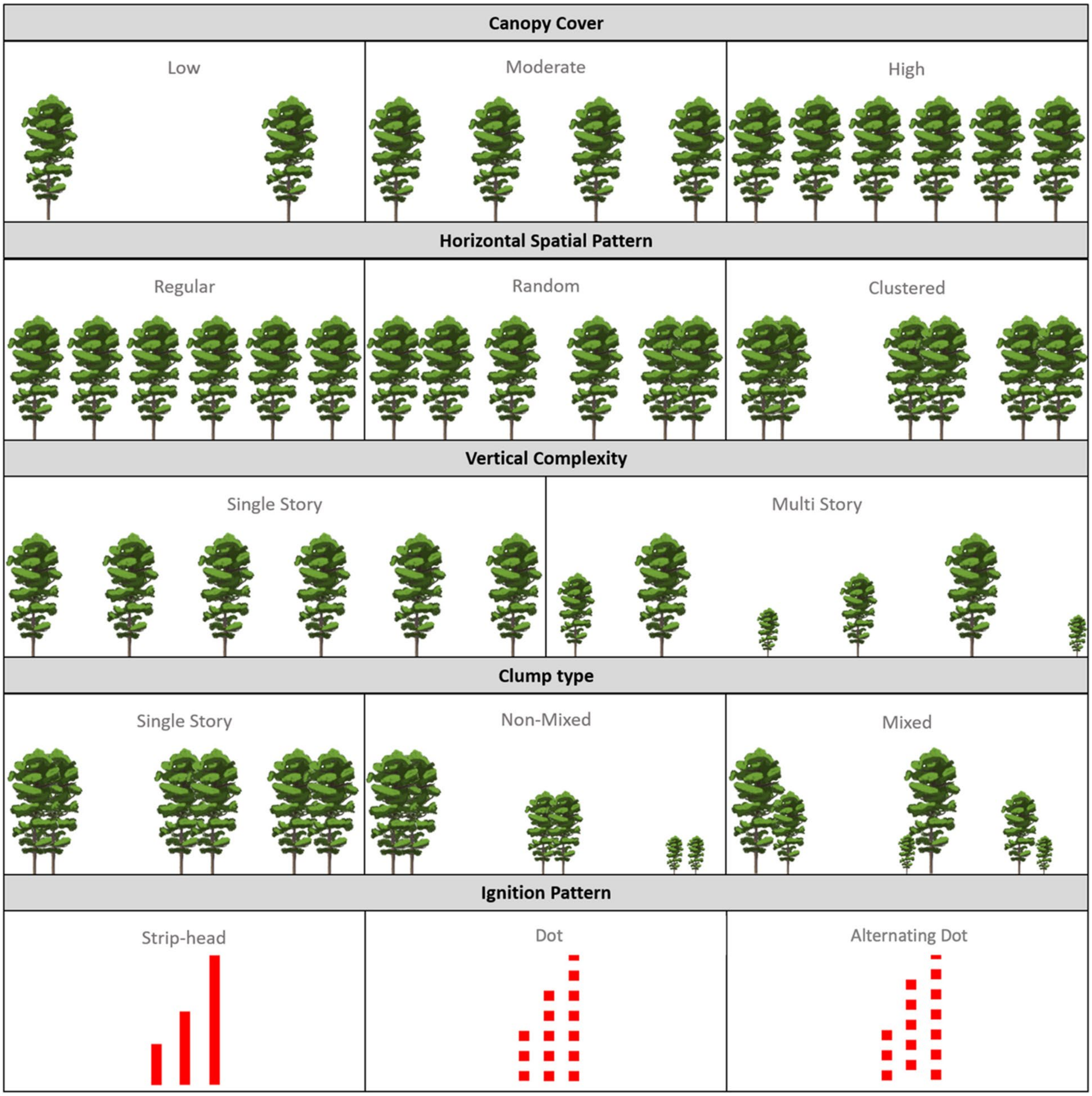

Fig. 1 Conceptual figure showing the different levels of forest structural metrics and ignition patterns used in this study. A total of 42 simulations were completed that encompassed variation in each of these conditions

and vertical complexities (i.e., single-story vs. multi-story) (Table 1). We created these representative forests using FIA data as described in the next section. For representative forests with a clustered horizontal pattern and multi-storied canopy, we developed two alternative representations: one where we allowed size classes to mix within a cluster (hereafter "Mixed"), and one where a cluster consisted of only one size class of trees ("Non-Mixed"). We chose to exclude clustered forests in context where there was high canopy cover at a landscape scale as the difference in forest structure between the clustered and random horizontal spatial patterns in high canopy cover scenarios are minor, and thus we did not expect to see a difference in fire effects (Wang et al. 2020). To isolate the effect of canopy structure and ignition pattern on prescribed fire effects, we 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

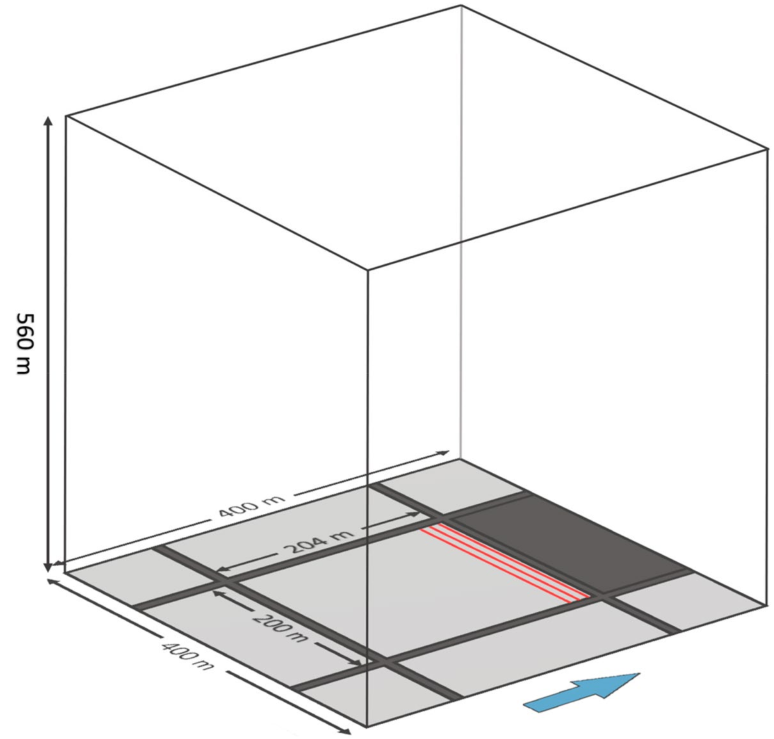

Fig. 2 Computational domain design showing areas with surface fuels (light gray), areas where surface fuels have been removed (dark gray), and the three initial fire lines (red). The arrow shows the streamwise wind direction, pointing towards the direction wind is going (blue). The area of interest (AOI) for this simulation is the light gray area (204 m × 200 m × 560 m) in the center of the domain

Table 1 Forest structural characteristics of 14 representative forests simulated in the fire simulation software, HIGRAD-FIRETEC

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	7.6	15.7	0.17
50Reg	50	Regular	Single-story	130	13.9	15.6	0.31
75Reg	75	Regular	Single-story	199	21.5	15.6	0.49
25Ran_Sing	25	Random	Single-story	67	7.4	15.7	0.17
50Ran_Sing	50	Random	Single-story	157	17.0	15.8	0.39
25Ran_Mix	25	Random	Multi-story	142	7.1	12.3	0.16
50Ran_Mix	50	Random	Multi-story	285	14.0	11.6	0.32
75Ran_Mix	75	Random	Multi-story	483	23.8	12.0	0.53
25Clu_Sing	25	Clustered	Single-story	71	7.8	16.0	0.18
50Clu_Sing	50	Clustered	Single-story	201	21.4	15.5	0.49
25Clu_Mix	25	Clustered	Multi-story	143	7.3	12.7	0.16
50Clu_Mix	50	Clustered	Multi-story	349	16.8	11.6	0.38
25Clu_NonMix	25	Clustered	Multi-story	147	7.8	12.6	0.18
50Clu_NonMix	50	Clustered	Multi-story	334	16.2	11.8	0.36

to volume ratio of 4714 m^{-1}, and fuel moisture of 9.0% (Natural Fuels Photo Series 2016).

Representative fuel complexes

We developed representative forests in FIRETEC using data collected in longleaf pine dominated forests from Florida and Georgia and spatial point pattern modeling.

We built a custom tree list using data from the United States Forest Service (USFS) Forest Inventory and Analysis (FIA) program, which produces and maintains a national inventory of forests across the United States and associated territories (Bechtold and Patterson 2005; Tinkham et al. 2018). We downloaded and combined plot, condition, and tree FIA database tables from the comma-delimited database applications webpage (Forest Inventory and Analysis Database of the United States of America 2012). We 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. We removed from consideration trees with no identified species code. This approach resulted in 12,992 unique trees, which we combined into a single custom tree list. For each tree in the tree list, we calculated crown width (CW, m) using species-specific allometric equations (Bechtold 2003) and estimated tree crown base height (CBH, m) from the FIA compacted crown ratio (CR, unitless) and tree height (HT, m). We classified trees into three size classes based on their diameter at breast height (at 1.37 m; DBH): juvenile (DBH < 10 cm), subadult (10 cm ≤ DBH < 30 cm), and adult (DBH ≥ 30 cm) (Platt and Rathbun 1993). Additionally, we classified trees as “pine” or “hardwood” depending on their FIA species group code.

We used our 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 intensity of points for each representative forest varied among simulations to ensure a specified level of canopy cover. We generated regular horizontal spatial patterns using the Simulate systematic random point pattern function (rsyst), which places evenly spaced points in a user-defined number of rows and columns within a window, resulting in a structure like what one might find in plantation forestry. We 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 interactions 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, we set the inhibition distance at 3 m (i.e., the centers of tree boles were no closer than 3 m apart). We 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, we populated the points with an inhibition distance of 1 m within a window one-third of the size of the 400 m × 400 m domain and then multiplied the x and y coordinates as well as the window by three.

We assigned each point the attributes of a tree from the FIA tree list using the Sample function from the dplyr package (Wickham et al. 2019), with sampling weights to achieve representative forest compositions of approximately 85% pine and 15% hardwood. For representative forests with single-storied canopies, we only selected from trees identified as adults. In the case of mixed clumps, we 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, we created an equal number of clumps of each size class and then sampled trees within that size class from our custom tree list using the previously mentioned pine and hardwood weights. Following Linn et al. (2002), we assigned pine trees a foliar moisture of 130%, surface area to volume ratio of 4714 m^{-1}, and a crown bulk density of 0.197 kg m^{-3} and hardwood trees a foliar moisture of 180%, surface area to volume ratio of 10,714 m^{-1}, and a crown bulk density of 0.041 kg m^{-3}. We assumed in our simulations that canopy foliar moisture was comprised solely of live fine fuels (i.e., needles, leaves, and small twigs), as FIRETEC does not account for larger 10-h, 100-h, or 1000-h canopy fuels. We simulated the three-dimensional crown 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). We then calculated the representative forest canopy cover for the AOI by creating a buffer around each point based on its assigned tree canopy radius and dividing by the 40,800 m^2 within the AOI. The resulting representative forest was then compared to the target canopy cover and either retained or simulated again using an increased intensity value.

Wind simulations

To simulate wind conditions characteristic of an interior forest, we precomputed turbulent wind fields for each representative forest before ignition following the methodology described in Pimont et al. (2020). We aimed for mean streamwise velocities of ~1 m s^{-1} at 2 m AGL within the AOI within all simulations to represent the conditions commonly experienced during a prescribed fire in longleaf pine forests. 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, we initialized each wind simulation as a log profile with a 40 m AGL wind speed between 2.6 and 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, we switched to noncyclic boundary conditions and recorded the winds for an additional ~20 min as inlet conditions for the fire simulations.

Fire simulations

We simulated each representative forest with three different prescribed fire ignition patterns (strip-head, dot, and alternating dot; Fig. 1). Strip-head ignitions were 2 m in width and extended 200 m in length. Dot ignitions were individual 2 m × 2 m dots of fire set at 10 m intervals along 200 m strips. Alternating dot ignitions were an offset pattern of the dot ignitions, with every other fire line shifted to center on the gaps from the previous head fire (Fig. 1).

The head fires were successively ignited 10 m apart at a production 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. We ignited the head fires in sets of 3, with each successive set alternating direction. We 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, we included a 20 s 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 dot and alternating dot ignitions. The time from start of ignition to when all fire ceased was ~20 min.

Statistical analyses

Outputs

To quantify prescribed fire effects on forest canopies, we estimated the proportion of crown fuel consumed, damaged, and scorched for each tree within the AOI. We tracked the mass of fuels and the solid fuel temperature (T_{Cell}) in each constituent cell for every tree over the course of the simulated prescribed burn. The proportion of crown fuels consumed for each tree was estimated by subtracting the post-burn crown fuel mass from the pre-burn crown fuel mass and dividing by the pre-burn crown fuel mass. We calculated the proportion of crown fuel damaged for each timestep (1 s simulation time) by comparing solid fuel temperatures in each cell to a set scorch temperature of 334 K (60 °C) (Methven 1971; Van Wagner 1973) and used linear interpolation to estimate damage to fuels in the given cell (*Cell*) and the cell above (*Upcell*). First, we calculated a scorch height vector (HT_{vect}) using Eq. 1 and the cell temperatures.

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

Using this value, we determined the vertical interpolation equation we would use. If $HT_{vect} < 0$ or $HT_{vect} > 0.5$, then we used Eq. 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 Eq. 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, we calculated the proportion of crown fuel scorched for each tree by subtracting the proportion of crown fuel consumed from the proportion of crown fuel damaged for each tree. We used the mass proportion rather than the original van Wagner (1973) scorch height metric to assess overall crown scorch, as crown scorch volume has been suggested to be a better indicator of tree mortality (Hood et al. 2018), and scorch height can greatly differ depending on canopy gap size (Molina et al. 2022). We then calculated the stand level 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.

Data analysis

We estimated forest structural complexity using a custom index, 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 complexity (i.e., tree height (HT) and the standard deviation of tree height (HTsd)), and canopy cover (Eq. 4). The Clark-Evans statistic (Clark and Evans 1954) compares a forest's nearest neighbor distances between trees against a random horizontal spatial pattern estimate if the forest is regularly spaced (>1), randomly spaced (~1), or clustered (<1). As a result, we weighted the Clark-Evans term to put it on the same scale as the other metrics. TPH 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). 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 (Zenner 2000). Canopy cover refers to the percent of stand surface area covered by the canopy overstory and has been used both to determine the successional stage of the forest and describe canopy fuel density and closure.

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

Following this schema, forests that have aggregated horizontal spatial patterns, 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.

To investigate how forest canopy structure and ignition pattern influence prescribed fire effects, we ran three generalized linear mixed models (GLMM; Brooks et al. 2017) with a beta family distribution and logit link function. Within this model, we 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, we used this GLMM in a two-way analysis of variance (ANOVA; Fox and Weisberg 2018). Finally, we used Tukey's post hoc test for pairwise comparisons (Lenth 2019) between the different ignition patterns (*alpha* < 0.05).

Results

Our model results show that both ignition pattern and FSCI were important factors for determining crown scorch and damage, whereas only FSCI was significantly associated with crown consumption (Table 2). We did not find a significant interaction between FSCI and ignition pattern on crown consumption ($\chi^2 = 0.30$, $p = 0.86$; Supp. Table 1), scorch ($\chi^2 = 0.34$, $p = 0.85$; Supp. Table 1), or damage ($\chi^2 = 0.17$, $p = 0.92$; Supp. Table 1).

GLMM results indicate a positive linear association between the three metrics of crown damage (consumption, scorch, and total crown damage) and the FSCI (Figs. 3 and 4). A one unit increase in FSCI (ranging here from 25 to 110) resulted in a relative increase in the proportion of crown damage by 0.6%, crown scorch by 0.8%, and overall crown damage by 0.9% ($p < 0.05$; Table 2; Fig. 4a, b, and c; Supp. Table 1). These results indicate that dense forests or those with greater aggregation of trees or multiple vertical layers will experience greater crown consumption, scorch, and damage than forests with less clumping, a single-storied canopy, and a sparse overstory.

Changes in ignition pattern were not associated with changes in crown consumption ($\chi^2 = 4.28$, $p = 0.12$; Supp. Table 1), but were associated with alterations in the

Table 2 Model results of crown consumption, scorch, and overall damage experienced by 14 structurally-unique simulated forests in three prescribed fire simulation experiments. The intercept is built on the strip-head ignition pattern and its interaction with our forest structural complexity index (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
	Dot	−0.171	0.09	−1.88	0.06
	Alternating dot	−0.145	0.09	−1.62	0.11
	FSCI: dot	0.000	0.00	0.14	0.89
	FSCI: alternating dot	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
	Dot	−0.238	0.08	−3.01	0.00
	Alternating dot	−0.184	0.08	−2.34	0.02
	FSCI: dot	0.001	0.00	0.56	0.58
	FSCI: alternating dot	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
	Dot	−0.245	0.09	−2.83	0.00
	Alternating dot	−0.192	0.09	−2.22	0.03
	FSCI: dot	0.001	0.00	0.36	0.72
	FSCI: alternating dot	0.000	0.00	0.34	0.73

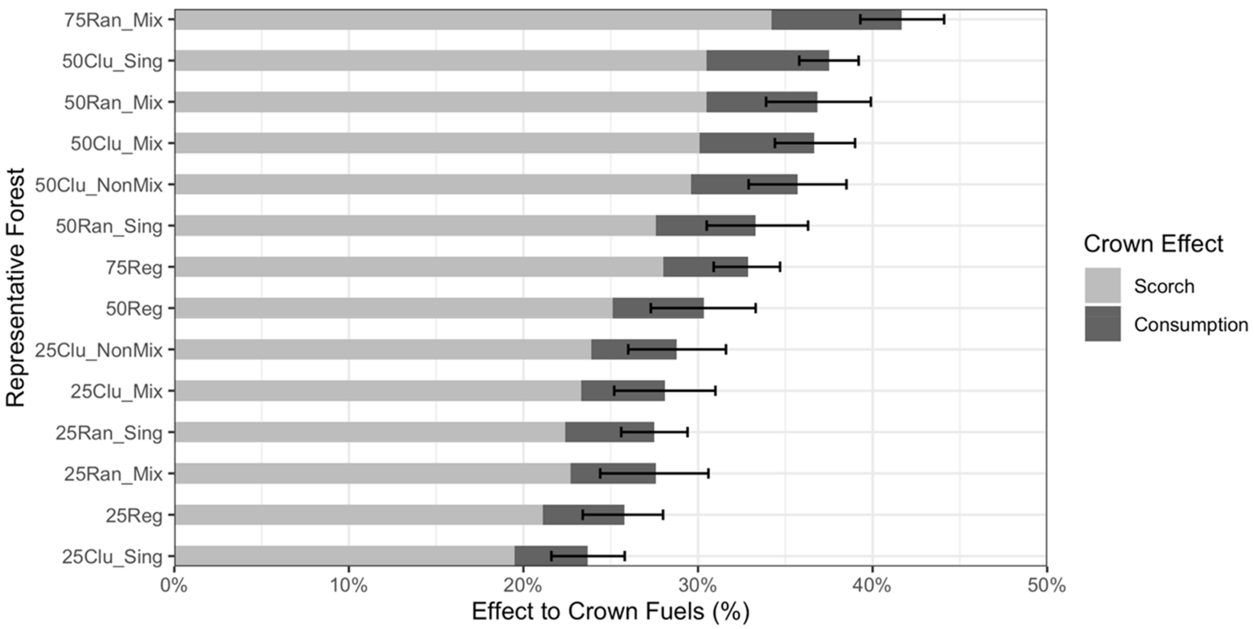

Fig. 3 Histogram showing the means of crown scorch and consumption for prescribed fire simulations in 14 representative forests. Standard deviations for overall crown damage (i.e., the sum of crown scorch and consumption) are shown

proportion of crown scorch ($\chi^2 = 10.12$, $p < 0.05$; Supp. Table 1) and damage ($\chi^2 = 8.95$, $p < 0.05$; Supp. Table 1). Tukey pairwise comparisons of the ignition patterns showed that the proportions of crown scorch and total crown damage were greater for a strip-head ignition pattern than a dot pattern (odds ratio = 1.22, $p < 0.05$; odds ratio = 1.24, $p < 0.05$) or alternating dot pattern (odds ratio = 1.17, $p < 0.05$; odds ratio = 1.18, $p < 0.05$). There was no evidence of a difference in crown scorch or damage between the two dot type ignition patterns (odds ratio = 1.04, $p = 0.40$; odds ratio = 1.05, $p = 0.34$) (Supp. Table 2).

Discussion

Our results indicate that both forest structural complexity and choice of ignition pattern influence crown damage during prescribed fires. These findings support the long-held assumption of land managers and the scientific community that both forest structure (Anderson et al. 2015; Parsons et al. 2017; and Ritter 2022) and ignition pattern (Molina et al. 2018; Molina et al. 2022) have critical roles in determining fire behavior and effects. As land managers can use silvicultural techniques to manipulate forest structure and have full control over choice of ignition pattern, these findings also emphasize the importance of the human decision factor leading to prescribed fire behavior.

Our model results provide evidence of a linkage between structural diversity and fire effects during prescribed fires under low to moderate burning conditions. More specifically, we found that as both canopy cover—a surrogate for fuel loadings—and the horizontal or vertical complexity increased, forest stands generally experienced more crown fuel damage. Studies exploring the effect of forest structure on free spreading wildfires under more extreme burning conditions have similarly observed positive relationships between canopy cover (Pimont et al. 2011; Parsons et al. 2017), horizontal (Hoffman et al. 2015; Pimont et al. 2011) and vertical complexity (Johnson and Kennedy 2019; Ritter 2022) and fire behavior metrics such as rate of spread, crown ignition, and consumption. Structural diversity primarily influences fire behavior and effects by altering the spatial and temporal distribution of heat released, plume entrainment, and convective and radiative heat transfer (Weatherspoon et al. 1989; Linn et al. 2013; Atchley et al. 2021). Our simulations were characterized by relatively little consumption of canopy foliage, suggesting that the primary effect of structural heterogeneity on canopy damage during prescribed fire was through effects on plume entrainment and convective and radiative heat transfer rather than alterations to the pattern of canopy combustion and local energy release. Although there is growing evidence that structural diversity influences fire behavior and effects for both wildfires and prescribed fires, our results suggest that the mechanisms driving these relationships may depend on the burning conditions.

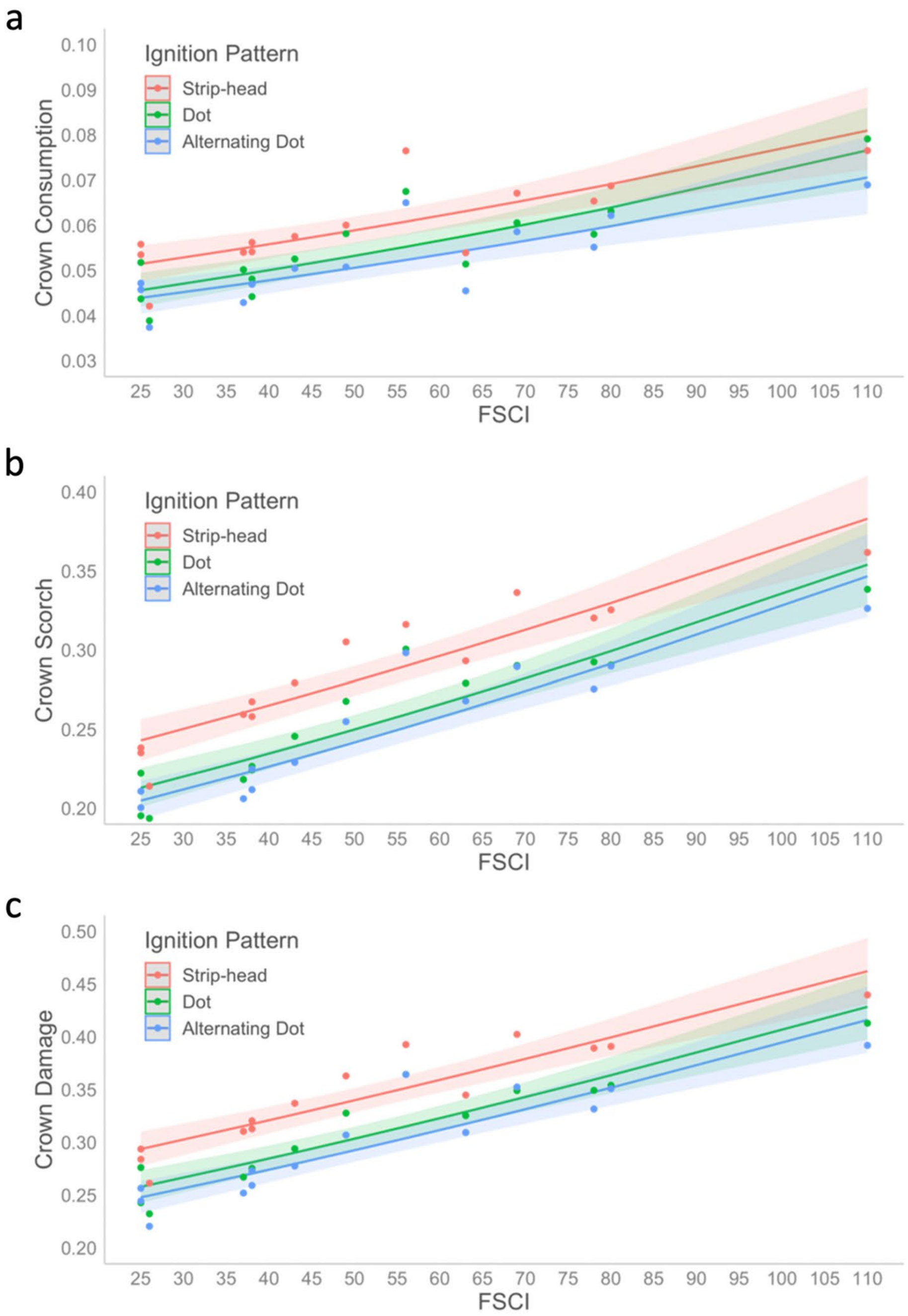

Fig. 4 The forest structural complexity index (FSCI) plotted against the proportion of **a** crown consumption, **b** crown scorch, and **c** crown damage observed within each simulation. The three linear regression lines show linear fits for simulations ignited with strip-head (red), dot (green), and alternating dot (blue) ignition patterns. The points show the simulation results

Under different burning conditions than those represented in this study, canopy damage may become dominated by crown consumption rather than crown scorch, indicating that plume entrainment and convective and radiative heat transfer are no longer the dominant mechanisms driving the pattern of crown damage in forest canopies. Consequently, it may be expected that the distribution of tree injuries and mortality will vary under different burning conditions even given the same forest structure. Further work that investigates the relative roles of plume entrainment, local combustion, and heat release and heat transfer across a range of environmental conditions is needed.

Further evaluation of our FSCI provides additional insight into the specific aspects of the fuels complex and how they may influence fire effects. Our results indicate that canopy cover and crown damage are positively related. As canopy cover increases, the number of moderate to small size gaps in the forest canopy decreases. These gaps play an important role in limiting crown damage by fostering cool air entrainment into the canopy which convectively cools fuels and funnels buoyant hot gasses out of the forest canopy (Kiefer et al. 2018). In the absence of these gaps, these hot gasses become trapped within the canopy where they scorch and consume forest fuels (Schwilk 2003; Kiefer et al. 2018; Ritter et al. 2020).

Like the effects of canopy cover, increased horizontal heterogeneity alters the amount, size, and distribution of canopy gaps, which in turn affects the heat transfer mechanisms driving fire effects. The horizontal aggregation of fuels describes a canopy with diversely sized and spaced gaps and clumps of crown fuel wherein wind will accelerate or decelerate, and heat will disperse or accumulate depending on the absence or presence of drag-inducing foliage (Patton 1997; Parsons et al. 2017). We found forests characterized with clumps tended to experience greater crown damage than other forest structures due to these heat dispersion mechanisms. Although we did not explore clump size effects, these mechanisms are likely also present within clumps, though varying in degree of effect by clump size (Ritter et al. 2020) due to differential heating and cooling associated with entrainment. In large clumps, this could result in greater crown damage due to tree proximity limiting the convective cooling of fuels within the clump and easing the propagation of fire between tree crowns (Parsons, Mell, and McCauley 2011; Hoffman et al. 2012).

Our results also indicate that crown damage was positively related to increased vertical complexity. In our study, increased vertical complexity is associated with the addition of smaller, juvenile and subadult trees and a decrease in the canopy base height. Given this, our findings are supported by a long-held understanding of the links between forest structure, fire behavior, and fire effects (Van Wagner 1973 and 1977). As the vertical density of foliage increases, the vertical movement of air that drives convective cooling weakens and temperatures within canopy fuels and downstream of fires increase due to the dampening effect of the foliage (Kiefer et al. 2018). This influence over vertical motion emphasizes that the presence of canopy fuels in the space between the surface fuels and the top of the canopy can reduce the magnitude of convective cooling and may cause the fire plume to become more horizontal (Pimont et al. 2011), resulting in more heat energy being transferred to crown and surface fuels (resulting in greater amounts of crown scorch) rather than to the atmosphere. The strength of this effect was sufficient to overwhelm the protection offered by the layers of canopy fuels that would otherwise reduce the amount of scorch inflicted on upper-canopy fuels. For example, whereas the *50Ran_Mix* strip-head and *50Ran_Sing* strip-head simulations had a similar horizontal spatial pattern (Table 1), the *50Ran_Mix* simulation (which included 3 size classes) experienced more overall crown damage than the *50Ran_Sing* simulation (which included only adult sized trees) (Fig. 3). Adult trees in both sets of simulations experienced the same proportion of crown damage (37%) regardless of the vertical complexity. However, the juvenile and subadult trees of *50Ran_Mix* simulation experienced 47% crown damage, resulting in an overall crown damage value of 40% for the *50Ran_Mix* simulation (Fig. 5). The 17% difference in the proportion of crown damage between the adult tree and juvenile and subadult biomass loadings demonstrates how low crown base heights promote crown scorch and consumption (Ray and Landau 2019).

Additionally, the increased vertical complexity led to greater vertical continuity (i.e., ladder fuels) of canopy fuels, resulting in increased opportunity for the vertical ascension of fire and increased consumption of upper-level canopy fuels (Ziegler et al. 2017; Atchley et al. 2021). The only case in which this positive trend did not hold was for *50Clu_Sing*, which experienced the second greatest amount of crown damage of all our representative forests. This was likely due to the increased canopy fuel loading introduced due to the amount of large and dense adult trees represented in our single storied representative forests (Table 2).

Given a specific fuels complex, the choice of ignition pattern is one of the key factors under land manager control that influences fire behavior and effects. Our results show that simulated strip-head ignition patterns consistently produced more severe crown damage than either dot ignition pattern, which is consistent with past ignition studies (Johansen 1987; Molina et al. 2022). This highlights the tremendous impact of convective cooling on crown damage, as fragmented fire lines created by dot patterns increase the entrainment of cooler air at all heights, whereas the strip-head ignition pattern added more energy into the system and reduced opportunities for convective cooling. Although our simulation results show clear evidence of interactions between fire lines (i.e., alterations to inflow, spread rate, and burning rates), as suggested in Johansen (1987), Finney and McAllister (2011), and Canfield et al., (2014), the effect of interactions between the fire lines or dots on crown damage did not depend upon the FSCI and thus we had no

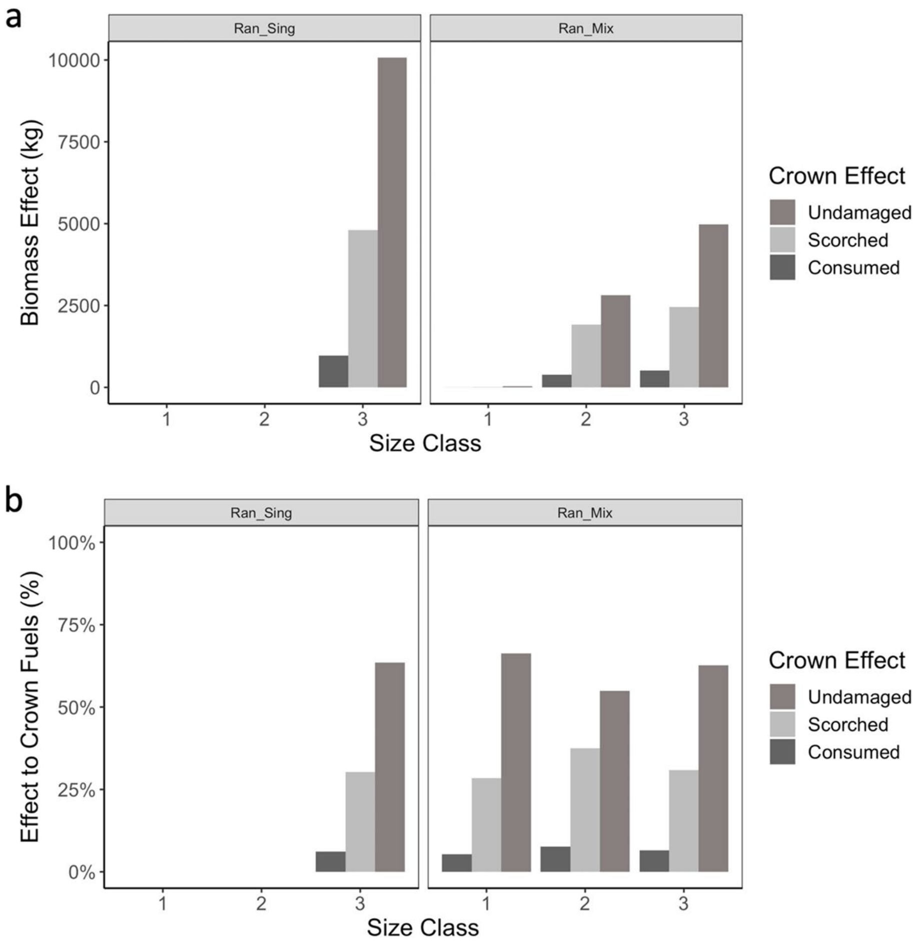

Fig. 5 Comparison of crown fire effects by **a** biomass and **b** percent of crown fuel on different tree size classes (1: juvenile, 2: subadult, and 3: adult) in two similar forests (50% canopy cover and random horizontal spacing: Random Single Story and Random Multi-Story) differing by vertical complexity

interaction term in the model as previously inferred by Rothermel (1985) and Finney et al. (2011). Rather, these two factors were additive in their effects to crown damage, which simplifies management applications. Considerations of which ignition pattern and techniques to use can be tailored to the fire behavior wanted with respect to the fire behavior predicted from the forest structure and burning conditions at the time of burn.

Our assumption of homogeneous surface fuels allowed us to simplify the numerical experiments and focus on the direct effects of forest canopy complexity; yet this assumption also limited our ability to understand the influences of surface fuel complexity on fire behavior and effects. We simulated surface fuel loading and moisture based on plot averaged data from real longleaf pine forests (Natural Fuels Photo Series 2016); however, we did not attempt to simulate any spatial aspects of these surface fuels. Real-world forest surface fuel distributions and moistures are formed from the arrangement of overstory canopy and local wind patterns, which direct litter-fall, affect grass growth and decay, and influence moisture contents (McDanold et al. 2023). The understory can represent a diversity of species and vegetative structures with fuel heterogeneity changing across multiple spatial scales. The heterogeneous spatial arrangement and loadings of surface fuels can be a major driver of variability in fine-scale fire behavior, which can have important ecological implications for the maintenance and restoration of fire tolerant forests (O'Brien et al. 2016; Babl et al. 2020; Whelan et al. 2021). As surface and understory fuels are a common focus of land managers, further research into understanding temporal and spatial variations in surface fuels and the linkage between these changes and fire behavior and effects is needed to continue to improve prescribed fire planning.

We explored three common ignition line patterns used by land managers to perform prescribed fire; however, ignition patterns can be incredibly diverse and specific to a landscape, burning conditions, and the fuels present. Ignition scenario factors, such as ignition line length, variable dash and gap lengths, ignition timings and intensities, pace of ignition, line orientation relative to topography, and combinations of techniques such as backing, flanking, and heading fires will need to be further investigated to see how ignition patterns influence fire-atmosphere-fuel feedbacks and the resulting fire behavior and effects. Understanding these intricacies of ignition patterns will be key in assisting land managers in planning prescribed fires that effectively meet their objectives and potentially widen the acceptable burning period window.

Conclusions

Our simulation results suggest that complex forest fuel structures, such as those with high canopy cover, spatial aggregation, and vertical complexity, enhance the consumption, scorch, and overall damage of crown fuels in dry fire prone ecosystems. Additionally, we found the choice of simulated ignition pattern to positively influence crown damage. Our study both demonstrates the importance of characterizing forest structural complexity and ignition pattern for understanding fire behavior and effects, and further provides some scientific backing for managers using silvicultural treatments and prescribed fire patterns to alter fire behavior. It is our hope that future research will be designed to continue to explore the interaction of prescribed burning parameters and forest structure attributes on fire effects under increasingly complex circumstances.

Abbreviations

AOI	Area of interest
ANOVA	Analysis of variance
CBH	Crown base height
CFD	Computational fluid dynamics
CR	Crown ratio
CW	Crown width
DBH	Diameter at breast height
FIA	Forest Inventory and Analysis
FSCI	Forest structural complexity index
GLLM	Generalized linear mixed model
HT	Height
HTsd	Standard deviation of tree height
HIGRAD/FIRETEC	FIRETEC
LES	Large eddy simulation
TPH	Trees per hectare
U.S.	United States of America
USDA	United States Department of Agriculture
USFS	United States Forest Service

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-024-00314-7.

Additional file 1: Supplemental Table 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. Supplemental Table 2 Tukey pairwise comparisons for the three ignition patterns across the forest structural complexity index.

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Authors' contributions

SB, CH, RL, RP, and JKH conceived the original idea. SB and CH designed the experiment and analyzed the data. RL, WT, AA, JMV, JO'B, and JKH provided technical and forestry advice. All authors contributed to writing and editing the article.

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Availability of data and materials

The data generated and analyzed during this study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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