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Evaluating crown scorch predictions from a computational fluid dynamics wildland fire simulator

Adam L. Atchley^{1*} , Chad M. Hoffman², Sophie R. Bonner¹, Scott M. Ritter³, Joseph O'Brien⁴ and Rodman R. Linn¹

Abstract

Background Crown scorch—the heating of live leaves, needles, and buds in the vegetative canopy to lethal temperatures without widespread combustion—is one of the most common fire effects shaping post-fire canopies. Despite the ability of computational fluid dynamic models to finely resolve fire activity and buoyant plume dynamics including heterogeneous 3D distributions of forest canopy heating, these models have had only limited use in simulating fire effects and have not been used to evaluate crown scorch. Here, we demonstrate a method of evaluating crown scorch using a computational fluid dynamics model, FIRETEC, and validate this approach by simulating the experiments that were used to develop Van Wagner's 1973 crown scorch model.

Results The average scorch height prediction from FIRETEC compares well with the empirical model derived by Van Wagner, which is the most widely used empirical model for crown scorch. We further find that the 3D buoyant plume dynamics from a steady and homogeneous idealized heat source on the ground results in a spatially heterogeneous crown scorch pattern reflecting complex heating dynamics that are best represented by percent scorch rather than height of scorch.

Conclusions The ability of the computational fluid dynamics model to capture variation in crown scorch due to 3D buoyant plume dynamics provides direct links between forest structure, fire behavior, and fire effects that can be used by forest managers and researchers to better understand how fires result in crown damage under various environmental and management scenarios.

Keywords CFD fire modeling, Crown scorch, Fire effects, Van Wagner

Resumen

Antecedentes La escaldadura de copas, que es el calentamiento de hojas, agujas y yemas vivas en el dosel vegetativo hasta temperaturas letales sin combustión generalizada, es uno de los efectos de incendio más comunes que moldean los doseles después del fuego. A pesar de la capacidad de los modelos de dinámica de fluidos computacional para resolver finamente la actividad del fuego y la dinámica de las plumas de flotación, incluyendo distribuciones heterogéneas en 3D del calentamiento del dosel forestal, estos modelos han tenido un uso limitado en la simulación de los efectos del fuego y no se han utilizado para evaluar la escaldadura de copas. Aquí, demostramos un método para evaluar la escaldadura de copas utilizando un modelo de dinámica de fluidos computacional, FIRETEC,

*Correspondence:

Adam L. Atchley
aatchley@lanl.gov

Full list of author information is available at the end of the article

y validamos este enfoque simulando los experimentos que se utilizaron para desarrollar el modelo de escaldadura de copas de Van Wagner de 1973.

Resultados La predicción promedio de la altura de escaldadura de FIRETEC se compara bien con el modelo empírico derivado por Van Wagner, que es el modelo empírico más utilizado para la escaldadura de copas. Además, encontramos que la dinámica de la pluma de flotación en 3D de una fuente de calor idealizada, constante y homogénea en el suelo, resulta en un patrón espacialmente heterogéneo de escaldadura de copas que refleja dinámicas de calentamiento complejas que se representan mejor por el porcentaje de escaldadura en lugar de la altura de escaldadura.

Conclusiones La capacidad del modelo de dinámica de fluidos computacional para capturar la variación en la escaldadura de copas debido a la dinámica de la pluma de flotación en 3D proporciona vínculos directos entre la estructura del bosque, el comportamiento del fuego y los efectos del fuego, que pueden ser utilizados por los gestores forestales e investigadores para comprender mejor cómo los incendios resultan en daños en las copas bajo diversos escenarios ambientales y de manejo.

Background

Crown scorch is one of the most visible and widely used fire effects measured to predict tree mortality and ecosystem response to wildland fire (Varner et al. 2021). Forests affected by crown scorch experience changes in biological productivity and evapotranspiration (Nolan et al. 2014; Valor et al. 2018), thereby altering landscape carbon and water balances. Crown scorch also contributes to forest response to fire, as it is a major source of post-fire litter to forest soils and determines new canopy structures and sunlight environments. Understanding forest resiliencies and susceptibilities to crown scorch is therefore necessary to predict short- and long-term ecological effects from wildland fire (Hood et al. 2018; O'Brien et al. 2018).

The most used crown scorch model in the western US relies on an empirical relationship linking Byram's fireline intensity (I [kW/m]) to crown scorch height (Ht_s [m]). This model, referred to as Van Wagner's crown scorch model, was developed from experimental data in jack pine (*Pinus banksiana*) and red pine (*Pinus resinosa*) plantations with an approximate midflame wind speed of 1 m/s (Van Wagner 1973). Byram's (1959) fireline intensity (I) is related to the observed fire rate of spread (RoS [m/s]), mass of fuel consumed (M_c [kg/m²]), and an energy release per mass of fuel (H_c [kW/kg]) by the expression:

$$I = RoS \times M_c \times H_c \quad (1)$$

or to the RoS , residence time (τ [s]), and the rate of combustion (Cr [kW/m²]) by

$$I = Cr \times RoS \times \tau \quad (2)$$

Following previous work from Taylor (1961) and Thomas (1963), Van Wagner assumed a power law relationship where the mean Ht_s increases as a function of the I raised to the two thirds. Using the empirical data, Van Wagner estimated an additional coefficient in the

model to best fit observed scorch height (Van Wagner 1973). This resulted in the equation:

$$Ht_s = 0.385 \left(I^{2/3} \right) \quad (3)$$

, which neglects the influences of variations in canopy structure, subcanopy winds, and ambient air temperature. Note, that the 0.385 has units of [m^{1/3}/kW^{2/3}] when following the International System of Units (SI) and the coefficient changes for different units. Van Wagner (1973) further surmised that wind speed influences crown scorch by changing the trajectory of the buoyant plume and thus suggesting a link between buoyant plume dynamics and crown scorch.

The Van Wagner formulation that links fireline intensity to crown scorch height through buoyant plume theory is confirmed by empirical observations of crown scorch in prescribed and wildfire conditions e.g. (Saveland et al. 1990; Molina et al. 2022). Likewise, winds and fire weather that either drive intensity or effect buoyant plume dynamics are also noted to influence crown damage (Thompson and Spies 2009). Buoyant plume dynamics is a first-order process that determines the spatial patterns of heat transfer to the canopy that results in plant tissue damage. However, buoyant plume dynamics are influenced by canopy structure characteristics such as canopy base height and canopy gaps, which also have an observed influence on scorch height or percent scorch (Molina et al. 2022). This suggests that canopy structure, which is not accounted for in Van Wagner's empirical model, likely influences scorch height or percent canopy scorched. A more complete representation of forest structure will allow for volume or percent canopy scorch predictions, which is a more useful estimate of forest mortality as volume better estimates the percentage of effected biomass (Peterson 1985; Vega et al. 2011).

Crown scorch has been observed to vary greatly by forest type and within single burns (Burrows et al. 1989;

Finney and Martin 1993; Thompson et al. 2011). Van Wagner's model uses fireline intensities representative of fire areas that are large compared to individual trees, thus the predicted crown scorch height is meant to be representative of tree stands and not individual trees. While the basis of Van Wagner's model is buoyant plume theory, the development of the empirical model occurred at the stand scale and thus does not include spatially heterogeneous fire activity, local wind speeds, or variability in buoyant plume dynamics. In nature, the heterogeneous surface fuels, canopy structure, and subcanopy winds contribute to observed variability of crown damage from fire within single burns. The inability of the Van Wagner model to account for local variability in the fire environment or fire activity, and thus scorch variability within a stand, not to mention within a single tree, limits the ability to predict variability of tree mortality or fire effects at stand scales.

Computational fluid dynamics (CFDs) models, such as the Wildland Urban Interface Fire Dynamics Simulator (WFDS: Mell et al. 2007, 2009; Bova et al., 2016), FIRESTARD3D (Frangieh et al. 2018; Morvan et al. 2018), FIRETEC (Linn 1997; Linn et al. 2002), and a simplified CFD, QUIC-Fire (Linn et al. 2020), have been developed over the last 25 years to provide a new framework to simulate fire effects on vegetation structures by resolving buoyant plume dynamics as functions of the local fire environment and associated fire activity. These models simulate wind fields using Navier–Stokes equations and a multiphase formulation that accounts for the heterogeneous effects of vegetation structure on localized aerodynamic drag and thus the dynamic three-way feedbacks between vegetation structure, the fire, and atmospheric conditions (Linn and Cunningham 2005), which compare well with fire behavior observations in field experiments (Linn et al. 2012; Hoffman et al. 2016; Ritter et al. 2023). Although many of these models are too computationally expensive for operational fire management use, they allow for a fully 3D description of the forest, enabling them to capture how forest structure influences fire behavior (Pimont et al. 2011; Parsons et al. 2017) and subsequent fire effects of crown consumption (Hoffman et al. 2012; Sieg et al. 2017; Ritter et al. 2020). The representation of the 3D forest structures, which impart heterogeneous drag within the wind field and result in intermittent gusts and lulls (Pimont et al. 2009; Atchley et al. 2021), provides a methodology for studying where and how canopy structures heat or cool during fire, including within-tree variations of fire effects. By tracking heating and cooling of the vegetation structures, localized estimates of fire effects and associated 3D heterogeneous patterns can be made assuming biophysical responses to threshold temperatures (O'Brien et al. 2018).

Here we demonstrate a CFD approach to estimating crown scorch height. We also compute volume and percent of canopy impacted by scorch as additional metrics. We assess this approach against Van Wagner's crown scorch height observations in jack pine plantation fire experiments by simulating a rectangular heat source of specific energy intensities moving through a homogeneous plantation-like forest with similar characteristics as a jack pine plantation. We compare the CFD model estimated crown scorch heights from eight different surface fire intensities to the Van Wagner data and empirical model results. We then illustrate that even with this idealized, homogeneous heat source in the CFD model that buoyant plume interactions within the atmosphere result in complex scorching patterns.

Methods

Crown scorch tracking and temperature threshold assessment

The FIRETEC CFD model is formulated based on conservation of energy, mass, and momentum to capture the dynamic interactions occurring between fire, fuels, and the atmosphere. A multi-phase flow variation of the Navier–Stokes equations is solved to capture the complex wind dynamics that are influenced by heterogeneous drag introduced by 3D fuel structures and buoyant plume dynamics. Fuel structures in FIRETEC, which are synonymous with biomass of leaves, needles, and twigs, are represented in finite volume grid cell structures as a porous media describing fine fuel characteristics in terms of bulk or cell-averaged properties such as density, moisture content, surface area per unit volume. With this formulation, FIRETEC represents bulk momentum and heat exchange between gas and solid phases within the volume of each grid cell (Linn et al. 2005). Convective heat fluxes between the solid (fuels) and gas phases in the model are determined based on the temperature gradients between fuels and gases moving past each other. Therefore, the temperature of the fuels is a result of gradient heat fluxes from or toward that gas phase over time and given the transient nature of buoyant plume dynamics solid phase temperatures are rarely at equilibrium with the gas phase. Since FIRETEC simulates the transient and heterogeneous plume dynamics, which are compounded by the heterogeneous flow patterns resulting from wind interactions with canopy structures, it also captures the spatial and temporal variability of buoyant plume dynamics and represents dynamic heating environments in 3D space.

To represent crown scorch in the CFD model, we compare the temperatures of solid fuels in each computational cell to a user-defined scorch threshold temperature value (Fig. 1), which is the culmination of heat fluxes over time from the gas phase. Note that this value is based on

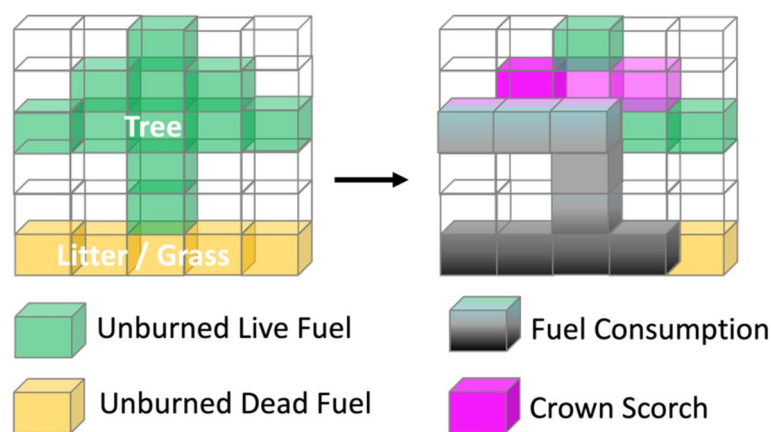


Fig. 1 Conceptualization of discretized domain representing fuel elements, fine fuels consumed by the combustion process, and resulting scorched fuel

empirical data, but questions remain regarding the lag times of measurements and the thermally thin assumption for the fine fuels in the model, which also has an equilibrium time scale associated with it. However, for the purposes of this paper, we assumed that the threshold value was 334 °K (61 °C), which is slightly more conservative compared to the generally accepted 333°K temperature above which plant tissue necrosis (i.e., crown scorch) occurs (Michaletz and Johnson 2006a, b). However, different critical threshold values could be used to capture species-specific responses for scorch (Varner et al. 2021) or the seasonal bud structures and physiological plant characteristics that moderate heat exchange between hot gasses and temperature-sensitive foliage (Michaletz and Johnson 2006a, b; Bison et al. 2022).

Estimating crown scorch effects to simulated trees

To map crown scorch effects to individual trees we utilize a spatial tree accounting system that tracks the fuel loading and temperatures in cells associated with each tree. The meter-scale resolution of FIRETEC results in the use of multiple grid cells to represent a single tree, and in the case of overlapping canopy's fuel elements, multiple trees can also contribute to the fuel loading in a single grid cell. In the cases where multiple trees overlap in a single cell, the masses are assumed to intermingle and are at the same temperature and the changes in mass within the grid cell are associated with individual trees in proportion to their initial mass contributions to the cell. Grid cells that experience or exceed a solid temperature greater than 334°K, and therefore experience crown scorch, are mapped onto each tree. This accounting system tracks the percent crown scorch per individual and the spatial location of that scorch, including height.

Crown scorch approach assessment

To compare our CFD crown scorch approach to the Van Wagner data and the associated empirical model, we used an idealized uniform rectangular heat source on the surface (referred to here as hotplate) to capture fire intensities of 300, 400, 550, 775, 900, 1000, 1200, and 1500 kW/m for a total of eight simulations. This hotplate application, described in detail below, provides a precise control of energy fluxes and therefore can be used to control a simulated fire intensity while strictly maintaining a consistent surface rate of spread and fire depth to relate to crown scorch height, as modeled by Van Wagner (1973). The combustion of fuels within FIRETEC was turned off while using the hotplate heat source approach to maintain specific simulated intensities.

Hotplate formulation

The hotplate specifies a specific fireline intensity (kW/m) within the designated area that can be compared directly to Van Wagner's empirical data reported as Byram's fireline intensity. Moving the hotplate along the direction of wind then mimics the RoS or τ , and assuming a constant H_C , a flexible M_c is also assumed to maintain the reported fireline intensity through Eqs. 1 and 2. The effect here is to maintain similar conditions between intensities to provide the simplest relationship between fire intensity and simulated crown scorch height. We limited the heat flux to the surface cells of the domain. The hotplate dimensions were 30 m in the crosswind and 4 m in the streamwise direction for an area of 0.012 ha for all simulations. The hotplate was initiated following the wind field spin-up starting 50 m downstream of the upwind side of the domain and centered in the middle of the domain in the lateral direction (Fig. 2). The hotplate was

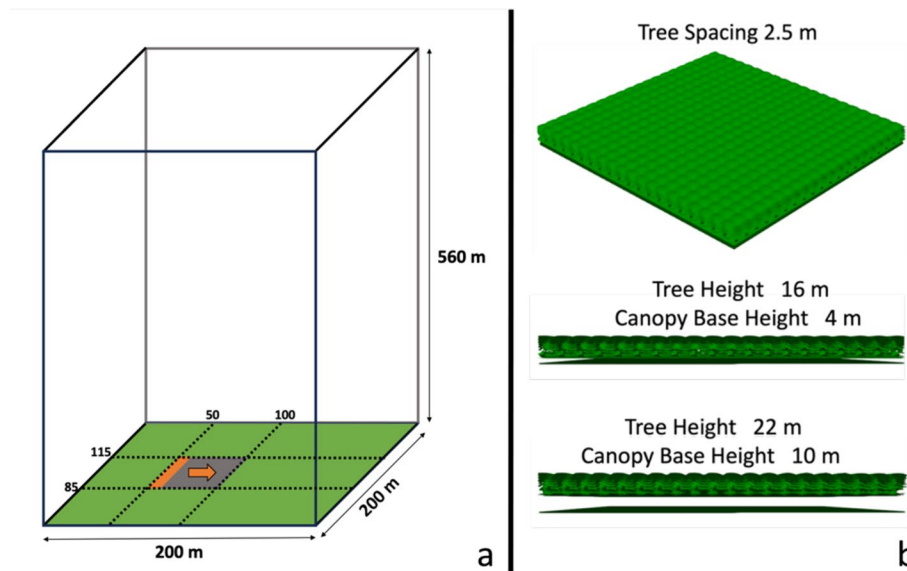


Fig. 2 Plot a is a domain map with a moving hotplate in orange, and the area the hotplate moved across is in gray, note visualizations of the forest canopy are absent. Plot b shows the trees in the domain and the two different canopy heights tested

translated in the streamwise direction at a *RoS* of 0.2 m/s. The residence time of the heat source for each simulation was held constant at 20 s, which is within the range of reported residence time and rate of spread values (Van Wagner 1977; Alexander and Cruz 2011; Cruz and Alexander 2010). With these quantities specified, the intensity becomes proportional to a mass loss rate or combustion rate. Each simulation lasted for 250 s during which the hotplate traveled a distance of 50 m.

Domain

We constructed a 200-m by 200-m domain with a 2-m $\times$ 2-m horizontal grid resolution. The computational grid is stretched vertically with cells getting larger higher in the domain to resolve both fine-scale fire dynamics near the surface and within the canopy while extending the height of the domain sufficiently to avoid the top boundary conditions influencing the near plume and canopy simulated environment. The equation for this vertical stretching is:

$$\text{Cell}_{\text{Height}} = \left[2.8699e^{-6} \times (c_n \times dz)^3 \right] + [a(C_n \times dz)] \quad (4)$$

where C_n is the cell number from the bottom of the domain, dz is the base vertical discretization set to 7, a is the stretching coefficient set at 0.1. Using these parameters, the vertical cell discretization is under a meter for the first 10 cells (to a height of 9 m) and under 2 m for the first 24 cells (to a height of 30 m). The domain is 80 cells total in the vertical and extends to 560 m in total reaching a far field top boundary condition.

To reconstruct the jack pine plantations used in the Van Wagner crown scorch experiments we used the full stocked Jack pine plantation with a 0.8 kg/m² foliage weight and 1600 trees/ha. Trees spaced in plantation rows and columns 2.5 m apart with crown radii of 3 m, thus resulting in overlapping crowns, approximating 5 kg of foliage per tree. Following the methods outlined in Linn et al. (2005), the maximum tree crown fine fuel density (including small branches in addition to foliage) was set to 0.446 kg/m³, based on the jack pine plantation description provided in Van Wagner (1977) and is within the subsequently reported ranges (Cruz et al. 2005). Fuel moisture percent, defined as mass of water over dry biomass was set to 112.5%. Two forest canopy heights were tested depending on the heat flux intensity. A canopy height of 22 m with a canopy base height of 10 m was tested for the five simulations with intensities between 775 and 1500 kW/m, while a canopy height of 16 m and canopy base height of 4 m was tested for the three simulations with intensities below 775 kW/m.

Windspeeds for the Van Wagner experiments were measured to be less than 1 m/s. The subcanopy windspeeds for our simulations are initiated to be under 0.5 m/s and less than 1 m/s for all cells less than 15 m in height, which includes portions of the canopy. To achieve these windspeeds a 3-m/s windspeed at 25 m height with a 1/7th power law functions by height was applied as an upwind boundary condition. This resulted in a 10-m open reference wind speed of just over 3 m/s. Winds were spun up to produce low-speed turbulent

conditions below the forest canopy before implementing the moving hotplate conditions.

Crown scorch height measurement

The reported values from Van Wagner (1973) were plot-averaged crown scorch heights describing the local demarcation line in the canopy fuels where a clear distinction between dead foliage below and live foliage above was observed. To compare to Van Wagner's crown scorch observations, we found the highest scorched cell for each tree, where solid temperatures exceeded the specified threshold, 334°K. We assumed the cell center of the cell to be the height of demarcation between dead foliage below and live foliage above. We then calculated the average crown scorch height of the trees within the affected area and the standard deviation of that crown scorch height. The primary reasoning for computing the standard deviation of the simulated crown scorch height was to provide a range that could be compared to the Van Wagner reported data. However, a secondary benefit for standard deviation is it illustrates the variability of crown scorch within a stand, even with an idealized uniform heat source.

Results

Van Wagner validation

Our numerical experiments compare well to Van Wagner's observations and we demonstrate the ability of a CFD model such as FIRETEC to reproduce observational data. For comparison, the root mean squared error of the Van Wagner data compared to the Van Wagner empirical model was 1.2 and the root mean squared error of the CFD model in comparison to the Van Wagner empirical model was 2.2. Plotting the simulated average crown scorch height against the fireline intensities (Fig. 3) shows that while the simulated average crown scorch was slightly but consistently below the empirical Van Wagner model, it was within the range or reported data used to build the empirical model. More importantly, the CFD approach followed the same $I^{2/3}$ trend. We found that crown scorch was sensitive to small variations in canopy density and moisture content. Calibrating these two parameters to match experiments could yield an improved comparison to Van Wagner's model. However, because the canopy density and moisture content reported by Van Wagner varied considerably between experimental plots, for example, fuel moisture varied between 95 and 135%, we chose not to aim for a precise comparison to the empirical equation. Nevertheless, the ability of the CFD approach to capture scorch height is demonstrated based on the agreement with the data presented from the Van Wagner experiments.

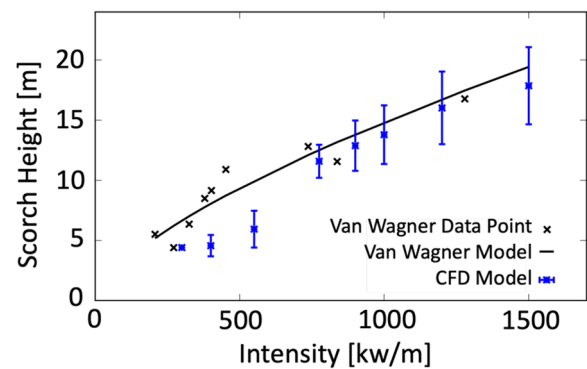


Fig. 3 Simulated average crown scorch plotted with the standard deviation of crown scorch as error bars, showing the variation of crown scorch for trees within the affected area. The black line shows scorch heights reported by Van Wagner's empirical scorch model (1973) and the black points are the digitized data reported from the Van Wagner experiments

Using two different canopy heights in the simulation resulted in a step-like function of crown scorch height at between intensities of 550 and 775 kW/m. The effect of canopy structure, particularly canopy base height, was recently identified by Molina et al. (2022) and agrees with the simulated results presented here where the lower canopy height results in lower crown scorch height. Nevertheless, the $I^{2/3}$ trend was still followed by both canopies, which suggests that while canopy characteristics may change the magnitude of scorch height, the trend between scorch height and I observed by Van Wagner holds at low windspeeds.

Discussion

An advantage to the CFD approach in simulating crown scorch is the explicit representation of the variation of height or percent crown scorch within a population of affected trees. The Van Wagner model only predicts the mean scorch height, thus ignoring within-site variations among trees. Yet the fire environment is heterogeneous and even in hyper-controlled conditions such as the hotplate-style simulations performed here, variability can be large due to buoyant plume dynamics interacting with forest structure-influenced wind fields. Such variation is likely important for predicting individual tree mortality and post-fire structure. Our simulations show that scorch height variability increases with taller canopies and increased fire intensities (Fig. 3) with a steady scorch height coefficient of variation ranging from 0.1 to 0.2 within a stand of affected trees. At lower intensities, variation is low simply because only the lowest branches of the canopies were affected. At higher intensities, a larger range of scorch height is simulated because heterogeneous plume dynamics have a larger area of canopy vegetation

to interact with. We should also note that the domain cell resolution decreases with height, which also contributes to the increasing coefficient of variation with height.

Percent scorch

Similar to the volume assessment to crown scorch (Peterson 1985; Vega et al. 2011), the percent crown scorch per tree is an improved metric of evaluating the effects of crown scorch on outcomes like tree mortality because it more directly relates percent biomass affected, whereas assessing mortality from crown scorch height does not account for scorch patterns on specific canopy shapes. Plotting percent crown scorch versus intensity of the

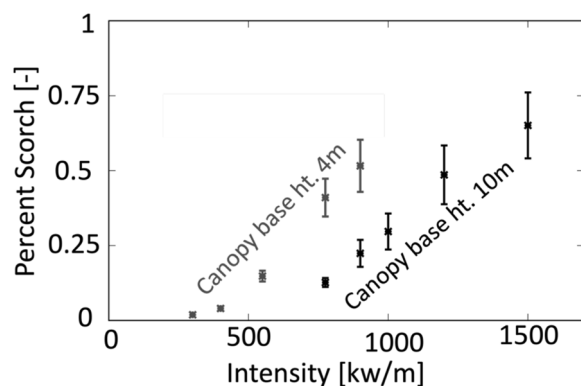


Fig. 4 Average percent biomass of each tree in a simulation is plotted against intensity. Note two additional simulations at 750 and 900 kW/m with the smaller canopy were added to demonstrate the effect of canopy base height on percent scorch

hotplate (Fig. 4) shows a greater sensitivity to I that is not captured in just evaluating crown scorch height (Fig. 3). Additionally, because the percent scorch automatically accounts for canopy height within the evaluation, we get a clearer picture of how canopy height affects percent scorch for specific intensities (Fig. 4). Here we see that percent crown scorch is much more responsive to increasing I compared to crown scorch height, which suggests that increasing intensities may trigger mortality or increased crown damage that may not be detected if evaluating crown scorch on a relationship to on height alone.

In addition to capturing crown scorch variation among a population of affected trees, CFD models can also capture variations of crown scorch within the canopy of a single tree. Figure 5 illustrates that crown scorch may not evenly affect a tree, highlighting that scorch height does not always represent the percent scorch. For example, if a larger buoyant plume structure occurs on one side of a tree, we might expect a higher or more complete crown scorch on that side. Capturing this detail in fire effects and particularly crown scorch has implications in how a tree may respond to wildland fire, where the canopy can be shaped by the fire, or how new forest sunlight environments are formed in response to partial canopy mortality. Similarly, we can also construct a heterogeneous view of crown scorch on the population of trees within an affected area of crown scorch (Fig. 5). This illustrates areas where trees with higher scorch are grouped together, possibly reflecting areas with larger buoyant plume structures that at least momentarily

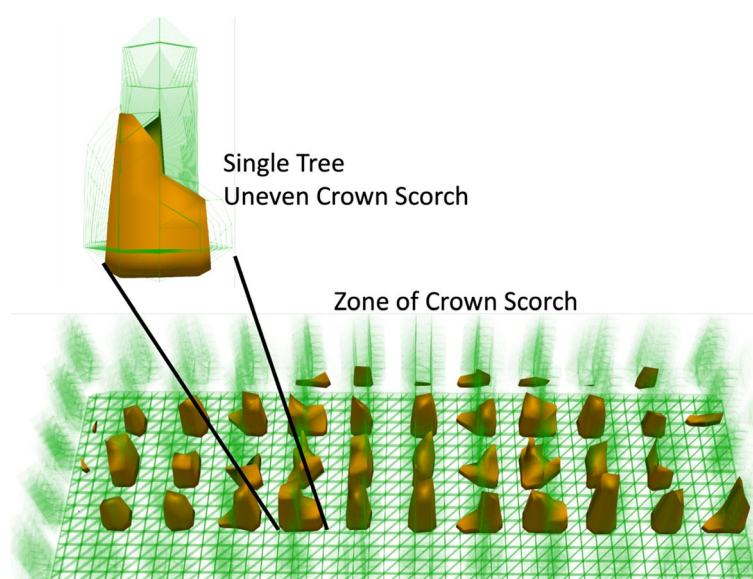


Fig. 5 Variable crown scorch on trees within the area affected by the hotplate. A single tree is viewed within the population of trees illustrating the uneven heating due to evolving plume dynamics

engulf multiple trees, as well as adjacent cooler regions where crown scorch volume is not as high. Here, we do not investigate if these structures result in a predictable pattern, but instead demonstrate a method of resolving these structures using a CFD resulting in a complex map of canopy damage.

The detailed representation of crown scorch estimated from solid fuel temperature thresholds in an individual tree could help understand how phenological characteristics and dose–response to crown heating dictate tree resiliency. The assumption of cell necrosis when plant tissue reaches 333 K, here conservatively assumed to be 334 K, is a simplified representation of a complex plant response that is unique to species traits (West et al. 2016; Varner et al. 2021; Bison et al. 2022) and likely dependent on time of exposure in addition to temperature thresholds (Wahid et al. 2007; Subasinghe Achchige et al. 2021). Representing buoyant plume dynamics provides an opportunity to isolate temperature-dependent scorch processes by capturing specific and repeated heat pulses over time that either contribute to tissue temperature surpassing thresholds or a cumulative lethal dose. Moreover, the ability to capture buoyant plume interaction with canopy structures can aid in delineating resilient forest structures or species adaptations that regulate heat transfer to foliage and buds (Michaletz & Johnson 2006b).

Buoyant plume dynamics

Buoyant plume activity is illustrated in Fig. 6 which shows an isosurface of 2 m/s vertical winds (w) is shown to have originated close to the surface and then penetrated the lower and upper bounds of the canopy. The crosswind velocity (v) is used to color the w velocity isosurface, and the u velocity or streamwise ambient wind direction is illustrated by coloring the fuel density isosurfaces that indicate the upper and lower bound of the canopy and ground surface. This figure shows that even though the heat was being emitted from a uniform rectangular source on the ground, the vertical w velocity illustrating the position of the heated plume was not homogenous. In this simulation, there were two dominant columns with reduced upward motion in between them. This is important because it further suggests that a single crown scorch number is often not going to be representative of the actual fire effects on a stand. In this case, two updrafts of hot air formed along the outer edge of the hotplate from converging winds toward the center line mapped on the contoured updrafts in Fig. 6, plot a. These updraft structures then caused increased canopy heating reflected in the two parallel zones of increased crown scorch of affected trees (Fig. 6, plot b). This pattern was consistent across all simulations and is similar

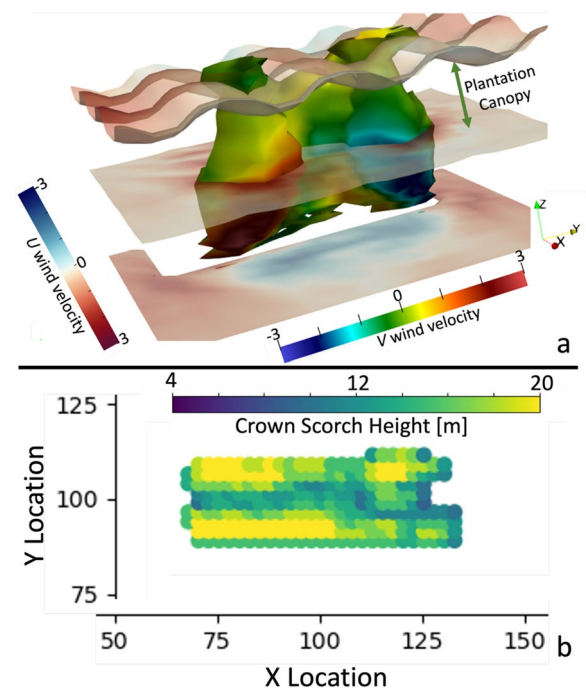


Fig. 6 View of the 1200 kW/m hotplate simulation (hotplate moving towards the camera). Visible are the 2 m/s vertical “ w ” velocity wind structures. Horizontal “ v ” velocity wind speeds are mapped to the w velocity contour showing how winds from the side converge on the hotplate. Negative v velocity values (shades of blue) equate to wind flowing right to left and positive v velocity values (shades of red) equate to wind flowing left to right. U velocity surrounding the hotplate is mapped onto a contour of fuel density (horizontal layers of surface fuel, lower canopy, and top of canopy) showing how slight ambient winds push the hot air forward along the sides and back toward the hotplate in the center. Note the illustration is tilted to better view the 3D properties of the wind structures. Plot b shows a crown scorch map of the 1200 kW/m simulation with each tree crown scorch height. Note the two parallel zones of increased crown scorch height

to the shapes and patterns shown in Linn and Cunningham (2005) for low wind cases. This pattern may change for different hotplate geometries and wind speeds. Similarly, our simplified representation of a complex heat environment creates predictable buoyant plume characteristics (Fig. 6). However, buoyant plume dynamics and subsequent crown scorch patterns observed in nature are likely to be much more heterogenous and variable due to naturally heterogenous fuel loads and combustion environments. Nevertheless, the spatial patterns arising from complex plume dynamics are likely to add to the variability in scorch height observed in nature.

Variability of crown scorch impacts the subsequent patterns of canopy bulk density, short- and long-term needle accumulation, wind and sunlight penetration, and thus future surface vegetation growth and subsequent fire potential. The 3D resolution of crown scorch

locations provided by a CFD model provides a more detailed description of the crown scorch patterns in canopies and allows for additional metrics such as correlations between scorch height and height to crown. Results from CFD wildfire models can provide individual tree and stand level quantities including the average and variability in crown scorch height, percent crown volume scorch, percent biomass scorched, and various estimates of canopy consumption. The added richness of these spatial data provides an opportunity to link fire behavior to various tree mortality models and allows the user to look beyond the immediate impacts and tree mortality towards stand-level recovery and resilience.

Conclusions

We demonstrated the ability to employ a spatially explicit CFD model, FIRETEC, to simulate crown scorch within a 3D forest canopy. In our simulations, the temperature of fine canopy fuels was used to assess if foliage reaches a threshold temperature of 334 °K and therefore experiences crown scorch. To test this application, we numerically replicated the Van Wagner experiments by approximating the forest canopy characteristics and tree density of jack pine plantations that were used to develop the empirical fire intensity to crown scorch height model. Using a hotplate formulation within the model domain, our simulations show remarkable agreement with Van Wagner's empirical model and data, thereby demonstrating the validity of using CFD models to simulate the fire effect of crown scorch within a 3D forest canopy.

In addition to demonstrating that FIRETEC can provide realistic crown scorch height predictions that agree with observations, this effort highlighted that this type of model captures spatial heterogeneity in crown scorch patterns even for a homogenized heat source. This heterogeneity is a result of the explicit representation of buoyant plume dynamics in space and time and the interaction of the fire and winds with the three-dimensional vegetation structure. To illustrate the heterogeneity, we also can examine the simulated crown scorch variation on both a population of trees and on individual trees that will occur in the highly dynamic fire environment. This enables the ability to assess variation in injuries and provide a more detailed assessment of the impacts of crown scorch on tree function or mortality. Here we showed that by representing the 3D crown scorch and accounting for uneven canopy scorch, estimates of individual tree mortality can be made based on percent crown scorch rather than just potential crown scorch height. Our comparison to Van Wagner's original work demonstrates that relying on simple fire intensity to crown scorch height estimates results in uniform predictions of fire effects, whereas simulating

buoyant plume dynamics better reflects the true heterogeneity in fire behavior and effects.

Abbreviations

CFD	Computational fluid dynamics
C_r	Rate of combustion (kW/m ²)
H_c	Energy release per mass of fuel (kW/kg)
Ht _s	Crown scorch height (m)
I	Byram's fireline intensity (kW/m)
M_c	Fuel consumed (kg/m ²)
RoS	Rate of spread (m/s)
SI	International System of Units
τ	Residence time (s)
u	Streamwise ambient wind direction (m/s)
v	Crosswind velocity (m/s)
w	Vertical wind velocity (m/s)
WFDS	Wildland Urban Interface Fire Dynamics Simulator

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Authors' contributions

A.A., C.H., and S.R. conceived and designed the experiment. A.A., C.H., and S.R. analyzed the data. A.A. wrote the manuscript. J.O. and R.L. revised the manuscript. The authors read and approved the final manuscript.

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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.

Author details

¹Los Alamos National Laboratory, Earth and Environmental Science Division, Los Alamos, NM 87545, USA. ²Department of Forest and Rangeland Stewardship, Colorado State University, 1472 Campus Delivery, Fort Collins, CO 80521, USA. ³Colorado Forest Restoration Institute, Colorado State University, 1001 Amy Van Dyken Way, Fort Collins, CO 80521, USA. ⁴USDA Forest Service, Southern Research Station, 320 E Green Street, Athens, GA 30602, USA.

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References

Alexander, M. E., and M. G. Cruz. 2011. Interdependencies between flame length and fireline intensity in predicting crown fire initiation and crown

- scorch height. *International Journal of Wildland Fire* 21 (2): 95–113. <https://doi.org/10.1071/WF11001>.
- Atchley, A. L., R. R. Linn, A. Jonko, C. M. Hoffman, J. D. Hyman, F. Pimont, C. Sieg, and R. S. Middleton. 2021. Effects of fuel spatial distribution on wildland fire behaviour. *International Journal of Wildland Fire* 30 (3): 179–89. <https://doi.org/10.1071/WF20096>.
- Bison, N. N., R. Partelli-Feltrin, and S. T. Michaletz. 2022. Trait phenology and fire seasonality co-drive seasonal variation in fire effects on tree crowns. *New Phytologist* 234 (5): 1654–63. <https://doi.org/10.1111/nph.18047>.
- Bova, A. S., W. E. Mell, and C. M. Hoffman. 2015. A comparison of level set and marker methods for the simulation of wildland fire front propagation. *International Journal of Wildland Fire* 25 (2): 229–41. <https://doi.org/10.1071/WF13178>.
- Burrows, N. D., Y. C. Woods, B. G. Ward, and A. D. Robinson. 1989. Prescribing low intensity fire to kill wildings in *Pinus radiata* plantations in Western Australia. *Australian Forestry* 52 (1): 45–52. <https://doi.org/10.1080/00049158.1989.10674535>.
- Byram, G. M. 1959. Combustion of forest fuels. In Davis KP, Ed. *Forest fire: Control and use*, (Ed. KP Davis), pp. 61–9, 554–5. New York, NY: McGraw-Hill.
- Cruz, M. G., and M. E. Alexander. 2010. Assessing crown fire potential in coniferous forests of western North America: A critique of current approaches and recent simulation studies. *International Journal of Wildland Fire* 19:377–98. <https://doi.org/10.1071/WF08132>.
- Cruz, M. G., M. E. Alexander, and R. Wakimoto. 2005. Development and testing of models for predicting crown fire rate of spread in conifer forest stands. *Canadian Journal of Forest Research* 35 (7): 1626–39.
- Finney, M. A., and R. E. Martin. 1993. Modeling effects of prescribed fire on young-growth coast redwood trees. *Canadian Journal of Forest Research* 23 (6): 1125–35. <https://doi.org/10.1139/x93-143>.
- Frangieh, N., D. Morvan, S. Meradji, G. Accary, and O. Bessonov. 2018. Numerical simulation of grassland fires behavior using an implicit physical multiphase model. *Fire Safety Journal* 102:37–47. <https://doi.org/10.1016/j.firesaf.2018.06.004>.
- Hoffman, C. M., P. Morgan, W. Mell, R. Parsons, E. K. Strand, and S. Cook. 2012. Numerical simulation of crown fire hazard immediately after bark beetle-caused mortality in lodgepole pine forests. *Forest Science* 58 (2): 178–88. <https://doi.org/10.5849/forsci.10-137>.
- Hoffman, C., J. Canfield, R. R. Linn, W. Mell, C. Sieg, F. Pimont, and J. Ziegler. 2016. Evaluating crown fire rate of spread predictions from physics-based models. *Fire Technology* 52:221–37. <https://doi.org/10.1007/S10694-015-0500-3>.
- Hood, S. M., J. M. Varner, P. Van Mantgem, and C. A. Cansler. 2018. Fire and tree death: Understanding and improving modeling of fire-induced tree mortality. *Environmental Research Letters* 13 (11): 113004. <https://doi.org/10.1088/1748-9326/aae934>.
- Linn, R. R., J. Reisner, J. J. Colman, and J. L. Winterkamp. 2002. Studying wildfire behavior using FIRETEC. *International Journal of Wildland Fire* 11 (4): 233–46. <https://doi.org/10.1071/WF02007>.
- Linn, R., J. L. Winterkamp, J. J. Colman, C. Edminster, and J. D. Bailey. 2005. Modeling interactions between fire and atmosphere in discrete element fuel beds. *International Journal of Wildland Fire* 14 (1): 37–48. <https://doi.org/10.1071/WF04043>.
- Linn, R. R., K. Anderson, J. L. Winterkamp, A. Brooks, M. Wotton, J. L. Dupuy, F. Pimont, and C. Edminster. 2012. Incorporating field wind data into FIRETEC simulations of the International Crown Fire Modeling Experiment (ICFME): preliminary lessons learned. *Canadian Journal of Forest Research* 42 (5): 879–98. <https://doi.org/10.1139/x2012-038>.
- Linn, R. R., and P. Cunningham. 2005. Numerical simulations of grass fires using a coupled atmosphere–fire model: basic fire behavior and dependence on wind speed. *Journal of Geophysical Research: Atmospheres* 110 (D13). <https://doi.org/10.1029/2004JD005597>.
- Linn R. R., S. L. Goodrick, S. Brambilla, M. J. Brown, R. S. Middleton, J. J. O'Brien, J. K. Hiers. 2020. QUIC-fire: a fast-running simulation tool for prescribed fire planning. *Environmental Modelling & Software* 125:104616. <https://doi.org/10.1016/j.envsoft.2019.104616>.
- Linn, R. R. 1997. *A transport model for prediction of wildfire behavior*. New Mexico State University. Report number: LA-13334-T (Los Alamos, NM, USA).
- Mell, W., M. A. Jenkins, J. Gould, and P. Cheney. 2007. A physics-based approach to modelling grassland fires. *International Journal of Wildland Fire* 16 (1): 1–22. <https://doi.org/10.1071/WF06002>.
- Mell, W., A. Maranghides, R. McDermott, and S. L. Manzello. 2009. Numerical simulation and experiments of burning douglas fir trees. *Combustion and Flame* 156 (10): 2023–41. <https://doi.org/10.1016/j.combustflame.2009.06.015>.
- Michaletz, S. T., and E. A. Johnson. 2006a. A heat transfer model of crown scorch in forest fires. *Canadian Journal of Forest Research* 36 (11): 2839–51. <https://doi.org/10.1139/x06-158>.
- Michaletz, S. T., and E. A. Johnson. 2006b. Foliage influences forced convection heat transfer in conifer branches and buds. *New Phytologist* 170:87–8.
- Molina, J. R., M. Ortega, and F. R. y Silva. 2022. Scorch height and volume modeling in prescribed fires: Effects of canopy gaps in *Pinus pinaster* stands in Southern Europe. *Forest Ecology and Management* 506:119979. <https://doi.org/10.1016/j.foreco.2021.119979>.
- Morvan, D., G. Accary, S. Meradji, N. Frangieh, and O. Bessonov. 2018. A 3D physical model to study the behavior of vegetation fires at laboratory scale. *Fire Safety Journal* 101:39–52. <https://doi.org/10.1016/j.firesaf.2018.08.011>.
- Nolan, R. H., P. J. Mitchell, R. A. Bradstock, and P. N. Lane. 2014. Structural adjustments in resprouting trees drive differences in post-fire transpiration. *Tree Physiology* 34 (2): 123–36. <https://doi.org/10.1093/treephys/tpt125>.
- O'Brien, J. J., J. K. Hiers, J. M. Varner, C. M. Hoffman, M. B. Dickinson, S. T. Michaletz, E. L. Loudermilk, and B. W. Butler. 2018. Advances in mechanistic approaches to quantifying biophysical fire effects. *Current Forestry Reports* 4:161–77.
- Parsons, R. A., R. R. Linn, F. Pimont, C. M. Hoffman, J. Sauer, J. L. Winterkamp, C. H. Sieg, and W. M. Jolly. 2017. Numerical investigation of aggregated fuel spatial pattern impacts on fire behavior. *Land* 6 (2): 43. <https://doi.org/10.3390/land6020043>.
- Peterson, D. L. 1985. Crown scorch volume and scorch height: estimates of postfire tree condition. *Canadian Journal of Forest Research* 15 (3): 596–8.
- Pimont, F., J. L. Dupuy, R. R. Linn, and S. Dupont. 2009. Validation of FIRETEC wind-flows over a canopy and a fuel-break. *International Journal of Wildland Fire* 18 (7): 775–90. <https://doi.org/10.1071/WF07130>.
- Pimont, F., J. L. Dupuy, R. R. Linn, and S. Dupont. 2011. Impacts of tree canopy structure on wind flows and fire propagation simulated with FIRETEC. *Annals of Forest Science* 68:523–30. <https://doi.org/10.1007/s13595-011-0061-7>.
- Ritter, S. M., C. M. Hoffman, M. A. Battaglia, C. S. Stevens-Rumann, and W. E. Mell. 2020. Fine-scale fire patterns mediate forest structure in frequent-fire ecosystems. *Ecosphere* 11 (7): e03177. <https://doi.org/10.1002/ecs2.3177>.
- Ritter, S. M., C. M. Hoffman, M. A. Battaglia, R. R. Linn, and W. E. Mell. 2023. Vertical and Horizontal Crown Fuel Continuity Influences Group-Scale Ignition and Fuel Consumption. *Fire* 6 (8): 321. <https://doi.org/10.3390/fire6080321>.
- Saveland, J. M., S. R. Bakken, and L. F. Neuenschwander. 1990. Predicting Mortality and Scorch Height from Prescribed Burning for Ponderosa Pine in Northern Idaho. *Bulletin* 53:1–9.
- Sieg, C. H., R. R. Linn, F. Pimont, C. M. Hoffman, J. D. McMillin, J. Winterkamp, and L. S. Baggett. 2017. Fires following bark beetles: Factors controlling severity and disturbance interactions in ponderosa pine. *Fire Ecology* 13:1–23. <https://doi.org/10.4996/fireecology.130300123>.
- Subasinghe Achchige, Y., L. Volkova, A. Drinnan, and C. Weston. 2021. A quantitative test for heat-induced cell necrosis in vascular cambium and secondary phloem of *Eucalyptus obliqua* stems. *Journal of Plant Ecology* 14 (1): 160–9.
- Taylor, G. I. 1961. Fire under influence of natural convection. *The Use of Models in Fire Research* 786:10–31.
- Thomas, P. H. 1963. The size of flames from natural fires. In *Symposium (International) on Combustion*, 9 (1): 844–59. Elsevier.
- Thompson, J. R., T. A. Spies, and K. A. Olsen. 2011. Canopy damage to conifer plantations within a large mixed-severity wildfire varies with stand age. *Forest Ecology and Management* 262 (3): 355–60. <https://doi.org/10.1016/j.foreco.2011.04.001>.
- Thompson, J. R., and T. A. Spies. 2009. Vegetation and weather explain variation in crown damage within a large mixed-severity wildfire. *Forest Ecology and Management* 258 (7): 1684–94. <https://doi.org/10.1016/j.foreco.2009.07.031>.
- Valor, T., P. Casals, S. Altieri, J. R. González-Olabarria, M. Piqué, and G. Battipaglia. 2018. Disentangling the effects of crown scorch and competition release on the physiological and growth response of *Pinus halepensis* Mill. using

- $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotopes. *Forest Ecology and Management* 424:276–87. <https://doi.org/10.1016/j.foreco.2018.04.056>.
- Van Wagner, C. E. 1973. Height of crown scorch in forest fires. *Canadian Journal of Forest Research* 3 (3): 373–8.
- Van Wagner, C. E. 1977. Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research* 7 (1): 23–34.
- Varner, J. M., S. M. Hood, D. P. Aubrey, K. Yedinak, J. K. Hiers, W. M. Jolly, T. M. Shearman, J. K. McDaniel, J. J. O'Brien, and E. M. Rowell. 2021. Tree crown injury from wildland fires: Causes, measurement and ecological and physiological consequences. *New Phytologist* 231 (5): 1676–85. <https://doi.org/10.1111/nph.17539>.
- Vega, J., E. Jimenez, D. Vega, L. Ortiz, and J. R. Pérez. 2011. Pinus pinaster Ait. tree mortality following wildfire in Spain. *Forest Ecology and Management* 261 (12): 2232–42. <https://doi.org/10.1016/j.foreco.2010.10.019>.
- Wahid, A., S. Gelani, M. Ashraf, and M. Foolad. 2007. Heat tolerance in plants: An overview. *Environmental and Experimental Botany* 61 (3): 199–223.
- West, A., J. Nel, W. Bond, and J. Midgley. 2016. Experimental evidence for heat plume-induced cavitation and xylem deformation as a mechanism of rapid post-fire tree mortality. *New Phytologist* 211:828–38.

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