Analysis of Fire-Induced Circulations During the Fireflux2 Experimental Burn and Operational Rate of Spread Models

Jeremy Tyler Benik
San Jose State University

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ANALYSIS OF FIRE-INDUCED CIRCULATIONS DURING THE FIREFLUX2 EXPERIMENTAL BURN AND OPERATIONAL RATE OF SPREAD MODELS

A Thesis
Presented to
The Faculty of the Department of Meteorology and Climate Science
San José State University

In Partial Fulfillment
of the Requirement for the Degree
Master of Science

by
Jeremy Tyler Benik
May 2023
The Designated Thesis Committee Approves the Thesis Titled

ANALYSIS OF FIRE-INDUCED CIRCULATIONS DURING THE FIREFLUX2 EXPERIMENTAL
BURN AND OPERATIONAL RATE OF SPREAD MODELS

by

Jeremy Tyler Benik

APPROVED FOR THE DEPARTMENT OF METEOROLOGY AND CLIMATE SCIENCE

SAN JOSÉ STATE UNIVERSITY

May 2023

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ABSTRACT

ANALYSIS OF FIRE-INDUCED CIRCULATIONS DURING THE FIREFLUX2 EXPERIMENTAL BURN AND OPERATIONAL RATE OF SPREAD MODELS

by Jeremy Tyler Benik

In this study, the fire-induced circulations were analyzed during the FireFlux2 (FF2) experimental burn using WRF-SFIRE to directly quantify the effects of the fire on local conditions. We utilized observational data from the FF2 burn and numerical simulations to assess the impacts of fire on local micrometeorology under ~12m/s winds. Two simulations were executed. One in a two-way coupled mode and one in a one-way coupled mode. The difference between the simulations was used to quantify the fire impacts on the circulation at the head and flanks of the fire. The fire-induced horizontal winds indicated the strongest fire-induced flow at the lowest measurement levels of the head fire (as high as 3.76 m/s) decreasing to 0.3 m/s at 20m above the ground. As a result, the most noticeable impacts of the fire-induced circulation on the fire rate of spread (ROS) were at the head fire. However, there were significant differences between the simulated and observed fire progression at the flanks. To examine to what degree, the observed discrepancies can be associated with the ROS algorithm used in the coupled fire-atmosphere model, two implementations of the Rothermel model as well as the Balbi model were examined. By running experiments in varying winds, fuel moisture and topography, we found the Balbi model is generally less sensitive to changes in the local conditions than the Rothermel model, providing a lower ROS. To investigate the features of the particular Rothermel model implementation in SFIRE, we compared it to the Behave model. We identified significant differences between the models which included different calculations within the model and different data which led to varying results between the two implementations of the same Rothermel model. The implementation of the Behave-based algorithm in WRF-SFIRE enabled using the 40 Scott and Burgan (S&B) fuel classifications not available before. Multiple simulations were run to analyze the behavior of the S&B fuels compared to the Albini fuels. Although many simulations produced similar burning characteristic, some S&B fuels burned differently than their equivalents in the Albini categories and resulted in a different atmospheric effects.
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Furthermore, I would like to thanks Dr. Angel Farguell for the many hours spent coding and debugging in zoom calls. It is those experiences that made me fall in love the technicality of meteorology. I would also like to thank Dr. Aurlien Costes for introducing me to LaTeX, helping me on papers, and being a great friend. In addition, I would like to thank John Stuart for volunteering his time at WIRC and providing much needed assistance when we need it most. In particular, thank you for your contributions to the Balbi model.

Lastly, I would like to thank everyone at WIRC who made my graduate experience truly unique and my family for their constant support.
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Chapter 1
Analysis of Fire-Induced Circulations During the FireFlux2 Experimental Burn

1.1 Introduction

Fire behavior may be significantly impacted by fire-induced perturbations. As the fire releases heat and moisture from fuel combustion, it alters the local thermal structure of the lower atmospheric boundary layer which then induces buoyancy and turbulent circulation [Heilman et al., 2015]. These circulations then impact fire progression as the fire generates its own wind, controlling local ROS. To observe how the fire induces its own circulations, in-situ measurements before, during and after fire-front passage are necessary to determine how the fire changes local conditions. There have been multiple experiments conducted to observe fire-atmosphere coupling processes by sampling fire environment. Some of these experiments were intending to collect data on the fire-induced circulations, and other experiments were more focused on other aspects such as smoke transport and how fires impact the structure of the atmosphere [Heilman et al., 2015; Kochanski et al., 2013a; Clements and Seto, 2015; Clements et al., 2019, 2008]. All these experiments are crucial to better our understanding of how fire-induced circulations impact the local terrain and fire spread. To observe fire-induced circulations, prescribed burns are necessary with multiple instruments within the burn plot to sample how the weather conditions change in response to the fire front passage (FFP). The insight into the fundamental fire-atmosphere coupling processes that impact wildfire behavior is critical to improve our understanding of fire behavior in response to fire-induced winds [Costes et al., 2022; Tedim et al., 2018]. Although experimental data can provide invaluable information for the analysis of fire-induced circulations, observations alone cannot be used to systematically quantify the fire-induced circulations. On one hand, the observed winds are a result of both the ambient wind fluctuations as well as fire-induced perturbations. On another hand, the limited sampling resolution (typically just few locations within the burn plot) makes reconstructing the 3D flow near the fire and quantifying fire-induced perturbations based on observation alone, not feasible. However, with the help of coupled fire-atmosphere simulations, it is possible to overcome these limitations. Numerical experiments with and without fire-atmosphere feedback initialized to render experimental burns (both in the sense of the meteorological conditions as well as the fuel and terrain) allows us to analyze and quantify the fire impacts by subtracting variables from one-way coupled simulation from the two-way coupled ones.
The experimental burn used in this study is the FF2 experimental burn. This burn took place in Texas in 2013 in a flat, grassy field. It was conducted to better understand micrometeorological aspects of fire spread [Clements et al., 2019], and occurred during red flag warning conditions (high winds and low RH), which allowed the fire to spread much faster than in typical experimental fires. Four meteorological towers installed within the burn plot, each equipped with anemometers and thermocouples at varying heights, as well as SODAR, pressure sensors and ground thermocouples collected data on how the fire affects local atmospheric conditions. Additionally, an Infrared (IR) camera collected video footage showing the fire progression. There was also a radiosonde launched a few hours before ignition (at 15:04:08 CST) to gather information about the vertical structure of the atmosphere before the burn.

There was a similar experiment at the same location as FF2 that occurred before the FF2 burn, called the FireFlux (FF) experimental burn which provided a unique opportunity for rigorous validations of many coupled fire atmosphere models [Dupuy et al., 2014; Kochanski et al., 2013b; Costes et al., 2021; Filippi et al., 2013]. The unique character for the FF2 burn compared with FF stems from the fact that the FF2 burn was conducted under stronger winds, with more instruments, and with improved IR fire mapping. The purpose of the FF burn was to study fire-atmosphere interactions during a fast-spreading grass fire by measuring the wind, turbulence, and temperature [Kochanski et al., 2013b]. The authors found the FF burn generated turbulence around 4-5x greater than the ambient environment with turbulence kinetic energy increasing from \( \sim 2m^2/s^2 \) to \( \sim 10m^2/s^2 \) during FFP [Clements et al., 2008]. Observations also showed that turbulence induced by the FF fire could be seen downstream from the fire front from the downward transport of higher momentum [Clements et al., 2008]. The FF experimental burn provided observations critical to understanding how a fire induces turbulent flows and how that affects the conditions ahead of the fire front.

Combining these observations from the FF burn with model simulations allows for a new perspective into how fire-induced perturbations impact the fires propagation and surrounding conditions. One experiment that conducted an analysis using the FF burn occurs in [Filippi et al., 2013] where they use ForeFire/Meso-NH model in a Large Eddy Simulation (LES) configuration to determine how fire-induced perturbations impact the shape of the fire, the fire forcing on the atmospheric flow in the lowest layers, and the impacts of the fire-induced wind on the surrounding atmosphere [Filippi et al., 2013]. They found the shape of the fire front is strongly affected by the fire induced winds as the fire head becomes narrower and propagates faster, which was also recorded in the observations [Clements et al., 2008; Filippi et al., 2013]. With a similar fire shape, the heat flux injected in the atmosphere as well as
the wind perturbations in both the model and observations were consistent. The only difference between
the model and observations was a slight wind shift occurred during the burn which impacted the fire
arrival time at the fires. As the fire propagated through the towers, it produced downdrafts just before
FFP which occurred in both the simulations and observations, then a fast increase in winds when the
fire front is under the tower due to heating [Filippi et al., 2013]. Then, downdrafts occur after FFP in
both the simulation and observations [Filippi et al., 2013]. This behavior indicates how the fire-induced
updrafts and downdrafts impacted the surrounding atmosphere as it created vertical perturbations. This
can also be noted by the convective plume captured in the simulation caused by the fire heating the
atmosphere over the main tower. Strong buoyant forces lead to high vertical velocities over 10m/s at
the main tower (MT) and impacted the wind perturbations up to 170m. These similarities between
the simulation and observations acknowledge the accuracy of the model as the model captured similar
conditions to what was observed, and the model shows how fire-induced perturbations accelerated the
spread at the head fire. The model also generated strong vertical velocities and impacted conditions up
to ~170m.

Similar experiments were simulated using Australian grassfires from [Cheney and Gould, 1995] and
numerical simulations from [Mell et al., 2006] as well as with the University of Utahs Large scale Eddy
Simulation model [Sun et al., 2009]. These experiments were performed to show the variability in
fire behavior under two types of atmospheric boundary layers using a coupled fire-atmosphere model.
However, Sun et al. [2009] also analyzed how the fire-induced winds impact the ROS. The two experiments
in this study were named CBL for convective boundary layer and RBL for roll dominated boundary layer.
The setup for the CBL used a surface heat flux of 240W m$^{-2}$, a boundary layer top at 937m, and a
convective velocity at 2m/s [Sun et al., 2009]. The setup for RBL used a surface heat flux of 20 W m$^{-2}$,
a boundary layer top at 468m, and convective velocity of 0.7m/s [Sun et al., 2009]. RBL did not exhibit
as intense of fire behavior as CBL since the convective turbulence and fire-induced circulations in the
RBL case were much weaker compared to the CBL experiments. As a result, RBL was not used for the
analysis as much in the study. To analyze what was the main contributor to the ROS in the CBL burns,
they ran two simulations (one with one-way coupling and the other with two-way coupling). They found
that the fire-induced flow is mainly responsible for the differences in the ROS among all 8 of the fires in
the CBL experiments as the fire-induced winds spread spreads the fire in the downwind direction and it
significantly effects the ROS [Sun et al., 2009]. The one-way coupled fires tended to spread more along
the flanks of the fire compared to the two-way coupling cases [Sun et al., 2009], indicating the shape of
the fire is also affected by the fire-induced circulations.

Another set of numerical experiments using a coupled fire-atmosphere model occurred in Clark et al. [1996] to test how fires impact the surrounding conditions and how they create their own weather. Three different experiments were conducted under different ambient conditions and with 3 short fire lines, and 2 longer fire lines and homogeneous fuels. The different ambient conditions consisted of varying wind intensities. In the simulations with the small wind, the position of the fire front remained fairly stationary and the fireline began to break up [Clark et al., 1996]. With stronger winds, the fire front progressed much faster and took on a conical shape [Clark et al., 1996]. These shapes can be explained by the how the lower-level convergence produced by the hot convective columns tilts downstream from the fire front [Clark et al., 1996]. This effect of downstream tilting shifts the center of the convergence ahead of the fire front, and with faster ambient winds, the stronger the tilt and the farther forward the center of the convergence zone will be [Clark et al., 1996]. As a consequence of the convergence occurring ahead of the fire front, it then draws in air from behind, increasing the local winds, which increases the ROS of the fire. Under weak ambient conditions, the fire line will begin to break up and it will not generate as strong of a convective column since the fire is not burning as hot, will not spread as fast as the begin to break up, but it will not generate as strong of a convective column since the fire is not burning as hot.

To simulate and evaluate fire-induced circulations, we used WRF-SFIRE. WRF-SFIRE [Kochanski et al., 2013a; Mandel et al., 2009, 2011, 2008] is a two-way coupled fire-atmosphere model that couples the Weather Research Forecasting (WRF) model with a fire spread model (SFIRE). SFIRE is a fire spread model that incorporates the level set method [Mandel et al., 2009] using the semi-empirical Rothermel fire spread model [Rothermel, 1972]. This model has two separate meshes. One is the atmospheric mesh, and the other is a refined finer fire mesh at the surface [Kochanski et al., 2013b]. This model can simulate both real and idealized cases. It is also fast enough to be used at an operational scale. WRF-SFIRE has been used to simulate both wildfires near real-time (e.g. [Kochanski et al., 2013c; Mallia et al., 2020]) as well as experimental fires (e.g. [Clements et al., 2019; Kochanski et al., 2013b]). WRF-SFIRE numerical simulations of experimental burns were also conducted to support planning of experimental burns (e.g. [Clements et al., 2019]). Models like WRF-SFIRE have been developed to represent first-order effect of fire-atmosphere interactions at landscape-to-micrometeorological scales [Costes et al., 2022]. Coupled fire-atmosphere simulations along with observational data can therefore be used to investigate small-scale fire-atmosphere processes impacting near-fire circulations that control fire behavior.
1.2 Methods

To analyze the fire-induced circulations during the FF2 experimental burn, idealized WRF-SFIRE simulations were used. The model was configured with a 5m x 5m atmospheric mesh with 80 vertical levels reaching to 1200m. The model used a stretched vertical mesh with the first model level placed at 1.06m above the ground and the vertical resolution gradually decreasing to 27.73m at the top of the domain. At the top of the domain the simulation used a sponge layer. The domain size was 200 x 320 grid points and the timestep was 0.0025s. This simulation was run on flat ground and used fuel category 3 in the Albini categories (tall grass) with 14% fuel moisture, and fuel load set to 0.64 kg/m² according to the FF2 fuel observations. Table 1.1 contains a more detailed setup of the FF2 simulation. To initialize winds in the model, we used data from the sounding launched a few hours before ignition (as seen in Figure 1.1) along with the SODAR and tower data to create a vertical wind profile representative of the initial conditions before the burn. The towers shown in Figure 1.2 were equipped with sonic anemometers at different heights that recorded both temperature and wind, as well as thermocouples that recorded temperature. A full list of the instruments can be found in [Clements et al., 2019].

Table 1.1: WRF-SFIRE FF2 simulation setup.

<table>
<thead>
<tr>
<th>Simulation type</th>
<th>LES (Large Eddy Simulation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal domain size (E-W x N-S)</td>
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<tr>
<td>Atmospheric mesh</td>
<td>320 x 200 x 80</td>
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<tr>
<td>Horizontal resolution (atmospheric mesh)</td>
<td>5m</td>
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<tr>
<td>Model top</td>
<td>1200m</td>
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<tr>
<td>Vertical resolution</td>
<td>1.06 at the surface to 27.73m at the model top</td>
</tr>
<tr>
<td>Fire mesh</td>
<td>3200 x 2000</td>
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<tr>
<td>Horizontal resolution (fire mesh)</td>
<td>0.5m</td>
</tr>
<tr>
<td>Simulation length</td>
<td>40 minutes</td>
</tr>
<tr>
<td>Time step</td>
<td>0.0025s</td>
</tr>
<tr>
<td>Subgrid scale closure</td>
<td>1.5 TKE (Turbulence Kinetic Energy)</td>
</tr>
<tr>
<td>Lateral boundary conditions</td>
<td>Open</td>
</tr>
<tr>
<td>Surface layer physics</td>
<td>MoninObukhov similarity theory (sf.sfclay_phys = 1)</td>
</tr>
<tr>
<td>Land surface model</td>
<td>SLAB 5-layer MM5 model (sf_surface.physics = 1)</td>
</tr>
<tr>
<td>Thickness of the ignition line</td>
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</tr>
<tr>
<td>Heat extinction depth</td>
<td>6m</td>
</tr>
<tr>
<td>Fuel depth</td>
<td>1.25 m</td>
</tr>
<tr>
<td>Ground fuel moisture</td>
<td>14%</td>
</tr>
<tr>
<td>Fuel load</td>
<td>0.64 kg/m²</td>
</tr>
<tr>
<td>Fuel type of the burnt area</td>
<td>3 (Tall grass)</td>
</tr>
<tr>
<td>Inflow wind profile</td>
<td>Tower data + SODAR + Radiosonde</td>
</tr>
<tr>
<td>Inflow wind direction</td>
<td>310</td>
</tr>
</tbody>
</table>
The fire was ignited using two walking ignitions starting at 15:04:08 CST, representing the GPS-ed firefighters paths. The simulation was run for 40 minutes (14:50 - 15:30) which was sufficient to simulate the fire front passage through the locations of all meteorological towers. The initial 14 minutes were used to spin up the atmospheric model before the fire ignition. After completing the coupled simulation, another simulation was executed with the fire-induced fluxes (sensible heat flux and moisture heat flux).
turned off, referred to as a one-way coupled simulation. Then the temperature and wind from the two-way coupled simulation and the one-way coupled simulation were subtracted to obtain the fire-induced temperature and wind perturbations.

The towers located within the burn plot provided information about the fire ROS as well as the circulations at both the flanks and the head of fire. The East Tower (ET) and Main Tower (MT) sampled the head fire, while the West Tower (WT) and South tower (ST) sampled the flank of the fire. Therefore, the towers provided not only an indication of the ROS, but also the fire-induced circulations at the head and at the flanks of the fire.

1.3 Results and Discussion

1.3.1 Rate Of Spread

The simulated fire progression generally compares well to the observed FFP at the tower locations, however there are some differences in the timing of simulated and observed FFP especially at the towers hit by the flanks of the fire. The timing of the fire front passage can be estimated by analyzing the spikes in temperature associated with the times when the fire reaches the towers set up within the burn plot. The simulation captured well the timing of the passage of the head fire through the MT (see Figure 1.3a) and the ET (Figure 1.3b). The onset of the temperature increase associated with the FFP was nearly perfectly captured by the model at the MT and within ~20s at the ET. However, more significant differences in the timing of the FFP between the simulation and observations occurred at the flanks of the fire. The temperature data suggest that the model overpredicted the ROS at the WT (Figure 1.3c) and underpredicted the ROS at the ST (Figure 1.3d). To estimate the ROS at each tower, we found the distance from the ignition point to the towers and divided that by the time where the temperature reached the maximum (in both the simulation and observations). The estimated ROS values at the tower locations can be seen in Table 1.2.

<table>
<thead>
<tr>
<th>Tower</th>
<th>Observed ROS [$m/s$]</th>
<th>Simulated ROS [$m/s$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MT</td>
<td>1.04</td>
<td>1.05</td>
</tr>
<tr>
<td>ET</td>
<td>1.33</td>
<td>1.44</td>
</tr>
<tr>
<td>WT</td>
<td>0.84</td>
<td>0.99</td>
</tr>
<tr>
<td>ST</td>
<td>1.20</td>
<td>0.92</td>
</tr>
</tbody>
</table>

The discrepancies between the simulated and observed timing of the FFP at the flank was due
Figure 1.3: Time series of the simulated temperature compared to a 10 second rolling average of the observations from the 4 towers. (a) is the MT, (b) is the ET, (c) is the WT, and (d) is the ST.

...to the later extent of the fire being different between the simulation and the observations as seen in Figure 1.4. During the FF2 burn, a slight wind shift occurred which changed the main axis of the fire propagation. This could not be captured in the idealized simulation where the winds are initialized only at the beginning of the simulation and then used for the entirety of the simulation. The wind shift made the fire propagate more in the southern direction than indicated by the simulation. This did not affect the head fire as much since the fire had already propagated through the MT and ET before this wind shift occurred.

1.3.2 Analysis of the Thermal Plume Structure

The temperature time series discussed in the previous section give a good indication of the FFP timing but are not sufficient to verify the horizontal and vertical extent of the disturbance. Therefore, to
analyze the thermal plume structure, we used the thermocouples installed on each tower. The MT had thermocouples mounted at heights from ~0.5m to 45m AGL, while the short towers had thermocouples installed between 0 and 9m AGL.

Overall, the simulation captured the thermal plume well as both the horizontal and vertical extent of the plume corresponds to what was captured during the actual burn. The fire-induced temperature perturbation at the MT (Figure 1.5a and 1.5b) extended up to 20m both in observations, and simulations. The model also realistically captured the duration of the thermal perturbation lasting ~50 seconds in both the simulation and observations. This agreement indicates the width of the convective plume column passing the tower was well represented. Looking at the ET (Figure 1.5c and 1.5d), the model resolved the temperatures above 200°C at about 5m, which is consistent with what was seen during the
Figure 1.5: Time series of the temperature from the simulation and 10 second rolling average of the temperature from the observations at the MT and ET. Simulated temperatures at the MT (a) and ET (c) and observed temperature from the thermocouples at the MT (b) and ET (d).

burn. However, duration of the thermal perturbation was overestimated. Most probably this was due to some discrepancies between the simulated and observed shape of the fire front head when it crossed the ET. As shown in Figure 1.4b, the simulated fire front was more broad than the observed one, and its tip was shifted to the south from the tower compared to the observations. This resulted in the observed discrepancies in the temperature field. Still, the overall agreement between the observed and simulated thermal structure builds confidence in the simulation and motivates the investigation of the circulations induced by pyroconvection.
1.3.3 Vertical Winds at the Main Tower

With the analysis of the heat output from the fire, the vertical winds at the MT are then assessed to determine if the model properly accounted for the heat injected into the local atmosphere, which would then cause buoyant forces and consequently, updrafts and downdrafts.

The observations in Figure 1.6b display the strongest vertical winds occurring at 20m, then 10m, and finally the weakest updrafts occurring at 5.77m AGL. The simulated values (Figure 1.6a) have the strongest updrafts occurring at 10m, then 5.77m, and finally the weakest updrafts occur at 20m. We hypothesize that in the simulation, the fire-induced circulation was not fully developed at the time it had propagated through the MT. It has to be noted that the fire front was already passing the MT while the ignition was still progressing, and the fire reached the MT very fast, roughly about one minute since the ignition start (see Figure 1.4a). The thermal plume in the observations in Figure 1.5b is significantly hotter (260°C) compared to the simulated temperatures in Figure 1.5a reaching only 200°C. We hypothesize that the underestimated buoyancy led to weaker convection produced in the simulation which manifested in undeveloped updrafts at higher elevations (i.e., 20m AGL). Instead, the vertical winds peaked at 10m and did not extend vertically as high as in the observations.

1.3.4 Fire-Induced Circulations

Since the model realistically resolved the thermal plume structure, we then focused on the horizontal wind associated with the fire front passage. This is critical due to the direct interactions between the horizontal fire-induced winds and the rate of the fire spread. Later in the text we investigate simulations at the head and the flanks to better understand the impact of fire induced circulation on fire dynamics. By analyzing the magnitude of the fire-induced winds we try to assess to what degree the fire-induced horizontal circulation could have impacted the fire behavior.

Circulation At The Fire Head

We started from the fire-induced horizontal winds at the MT. Here the winds are computed as a difference between the two-way coupled and one-way coupled simulation.

As can be seen in Figure 1.7, the fire-induced horizontal circulation is the strongest at the surface and gradually decreased with height. The strongest fire-induced winds occurred near the surface at 5.77 m AGL with winds greater than 3.5 m/s, then decreased to ~2 m/s at 10 m, and finally decreased even
Figure 1.6: Simulated vertical velocities (a) compared to the observed vertical velocities with a 10 second rolling average (b) at 20m, 10m, and 5.77m at the Main Tower.

These winds in addition to the ambient winds increased the ROS of the fire as there are now stronger surface winds behind the fire front. The peak in the fire induced winds occurred before the FFP and extended for about 100 s, indicating that the winds created by the fire affected the local conditions driving the fire front propagation. After the FFP, the winds decreased rapidly but remained elevated for a prolonged time as the fire continued to burn.

The head fire produced not only stronger winds at the surface in Figure 1.8, but also an updraft between two downdrafts. The convective column is pushed ahead of the fire front so that the inflow into the base of the column induces the cross-fire wind that accelerates its progression. Since this inflow occurs near the ground, the acceleration in the surface winds is the most intense at lowest elevations behind and at the firefront and decreases with height as previously seen in time series presented in Figure 1.7. Although the most intense horizontal winds were present near the ground, the strongest updrafts occurred ahead of the firefront between 40-60m AGL. The shape of the updraft zone presented in Figure 1.8b indicate a narrow conic shape near the ground and extending with height produced more inflow.
Figure 1.7: Time series of fire-induced winds at 20m (red), 10m (blue), and 5.77m (green) AGL at the main tower.

near the ground than higher up where the plume was wider.

The inflow into the convective column located ahead of the fire front significantly accelerated horizontal winds controlling the fire ROS. The orange wind streamlines in shown in Figure 1.8b, occur exactly over the peak heat flux represented as the blue line on the panel below. This alignment confirms that the direct dynamical coupling between the fire-induced winds and the fire behavior.

The vertical structure of the fire induced winds with the strongest winds located near the ground and decreasing with height suggest a presence of a low-level fire-induced jet that could lead to a potential local reversal of the typical logarithmic wind profile. In order to investigate whether that is the case we investigated the vertical profile at the main tower location before ignition at 15:04:08 and during the FFP. Figure 1.9 shows the wind speed vertical profile as simulated by the model and observed at the main tower. Both the simulation and observation indicate wind profile reversal associated with the FFP. This wind profile reversal results from the horizontal flow into the convective column super positioned over the ambient winds. The fire, by heating the air column, causes airmasses to rise and create a pyro-convective column. This convective column is advected downwind of the fire front (as seen in Figure 1.8b), causing the strongest fire-induced vertical wind occurring ahead of the fire front).
Figure 1.8: a) Fire front position (black line), main tower location (red icon) and the orientation of the cross section (green line). b) vertical cross-section showing winds from the two-way coupled simulation. The streamlines are color coded according to the winds speed magnitude, the shading shows the magnitude of the fire-induced vertical velocity (w).

low pressure induced as the airmass was driven up induced surface convergence ahead of the fire front as seen in Figure 1.10.

This effect is critical in controlling the shape of the fire and its ROS. It can be seen in Figure 1.11 which shows that the shape and the ROS of the fire is vastly different in the two-way coupled simulation Figure 1.11a than in the one-way coupled simulation Figure 1.11b. The lack of the convective column in the one way coupled simulation (in which no heat is released into the atmosphere) results in more uniform and weaker local winds as well as slower fire propagation. Also, the difference in the firefront shape indicates that the inflow int the pyro-convective column is responsible for the parabolic fire shape which is present only in the two-way coupled simulation. It is clear that without taking these winds into consideration, the overall fire spread will not be representative of the actual fire spread.
Figure 1.9: Vertical profile of the ambient conditions and FFP conditions at the main tower.

Figure 1.10: Surface Divergence (red) and Convergence (Blue) from the coupled FF2 simulation.
Figure 1.11: a) Two-way coupled fire spread with color coded wind vectors according to the two-way coupled horizontal wind speed. b) One-way coupled fire spread with color coded wind vectors according to the one-way coupled horizontal wind speed.

Analysis of the thermal plume structure at the flanks

After analyzing the temperature and circulations at the head fire, we then analyzed the thermal structure at the flanks to see how well the model resolved the temperature perturbations at the flanks. The thermal structure of the atmosphere over the flanks has a completely different characteristic than the one over the fire head. The fire-induced temperature perturbations remained elevated for a longer period, and the fire heated the surrounding atmosphere more because of the slower ROS. Consequently, this exposed the thermocouples on the WT to the fire for a longer time, which increased the temperature and the horizontal extent of the thermal structure in Figure 1.12b. In the simulation, the horizontal extent of the thermal perturbation did not last as long at the WT (~70 seconds in the observations in Figure 1.12a, and ~50 seconds in the simulation) in Figure 1.12b. This is likely due a larger burning zone in the observations compared to the simulation. As for the vertical extent, there were no tall towers located at the flanks of the fire in this experiment which limits the amount of data at higher heights. However, based on the lower levels of the fire, the vertical extent is also not captured well
in the simulation as the observations had temperatures \( \sim 220^\circ C \) up to 2m, but the simulation reached \( \sim 120^\circ C \) at the WT. The differences in the thermal plume affected the ROS due to an increased flame base radiation, which more effectively preheated the fuels in front of the fire and allowed it to spread faster. The difference in the plume also affected the amount of heat injected into the atmosphere, which impacted the atmospheric response as there was less heat injected in the atmosphere in the simulation compared to the observations.

![WRF-SFIRE Temperature Time Series at The WT](image)

**Figure 1.12:** Time series of the temperature from the simulation (a) and 10 second rolling average of the temperature from the observations (b) at the WT.

**Circulations at the Flanks of the Fire**

Despite discrepancies in the thermal perturbations between the observations and simulation at the WT, we still analyzed how the flanks of the fire impacted the surrounding conditions. In Figure 1.13b there are two buoyant plumes located directly over the two flanks of the fire. The left (south-western) flank burned hotter than the right flank (135°C compared to \( \sim 45^\circ C \)), and produced a more vigorous plume than the right flank. This asymmetry caused the weak flow along the cross-section plane as seen in Figure 1.13b in the right to left direction. This flow explains why the left (south western) flank burned
hotter than the right flank. This flow was pushing the left flank toward unburned fuel while the right (north-eastern) flank was pushed away from the fuel into the area that has already been burned. This decreased the temperature and the updraft over the left flank as seen in Figure 1.14b. Although the

Figure 1.13: a) Firefront position (black line) and the orientation of the cross section (green line). b) Vertical cross-section showing the temperature and winds from the two-way coupled simulation at the flanks of the fire. The size of the arrows corresponds to the intensity in wind speed.

fire flanks produced significant vertical velocities reaching over 6 m/s, they did not produce as strong cross-fire flow as was observed near the fire head. As a result, they did not experience the impact of the fire-induced circulation like the head fire. As can be seen in Figure 1.11, the flanks were represented similarly in the two-way coupled and one-way coupled simulation. This is because the main flow is in the direction roughly parallel to the flanks, so there is no mechanism to push the convective columns away from the fire, so that the inflow into the base of convective column could accelerate winds over the fire front. This can be seen in Figure 1.14b which indicates that the cores of the convective columns with strongest vertical velocities are located directly over the southern (left) flank, and there is no significant wind induced over the fire there.
The two updrafts occurring at both flanks result in the formation of counterrotating vortices as seen in Figure 1.13b, and Figure 1.14b. Here the updrafts occur over the flanks whereas at the head, the updrafts occurred ahead of the fire. This collocation results in the convergent flows occurring at the fire front instead of ahead of it, as observed near the head (see Figure 1.10).

Figure 1.14: a) Fire front position (black line) and the orientation of the cross section (green line). b) vertical cross-section showing winds from the two-way coupled simulation. The streamlines are color coded according to the wind speed magnitude, the shading shows the magnitude of the fire-induced vertical velocity (w).

1.4 Conclusion

In this study we used FF2 observations as well as numerical simulations performed with WRF-SFIRE to investigate the fire-induced perturbations in winds and temperature at the fire head and at the flanks. To determine the fire-induced circulations, two idealized simulations were used. The fully coupled one where the fire heat and moisture fluxes were fed into the atmosphere and the one-way coupled, in which atmospheric winds were used to drive the fire propagation fire fluxes were not injected into the atmosphere. The differences between these simulations allowed us to quantify the fire effects in the local meteorology near the fire front.
The comparison between the simulated and observed fire progression indicate that the model realistically captured the timing of the FFP through the main tower and the initial ROS matched nearly perfectly with the observations (1.04 m/s vs 1.05 m/s). The rate of fire head progression towards the ET was overestimated by about 8% (1.44 m/s vs 1.33 m/s). However, the timing of the flank passages through the west and south towers were simulated with smaller accuracy. The vertical structures of the plume at the MT and ET were captured realistically in terms of the temperature range, as well as vertical and horizontal plume extent, however.

This simulation overpredicted the ROS at the ET and WT, and underpredicted the ROS at the MT. This was due to differences in the shape of the fire between the simulation and observations as a wind shift occurred during the burn that the model cannot pick up when initialized with a static wind profile not changing in time.

Despite discrepancies between the simulated lateral fire extent and observations, the simulation still accurately predicted the structure of the thermal plume with temperatures profiles similar to the observed temperatures at the head fire. The widths of the thermal plume were similar between the observations and simulation at the head of the fire. Consequently, this led to similar atmospheric feedback between the simulation and observations with similar vertical updrafts. With this verification between the simulation and observations, this model output was used for further analysis for the fire-induced wind perturbations at the head and flanks of the fire.

With this simulation, we then analyzed the fire-induced circulations at the head and flanks of the fire, and how that affected the overall spread of the fire. At the head fire, the strongest fire-induced circulations occurred near the surface and decreased with height. With the stronger winds near the surface induced by the fire, the winds near the surface became stronger than the winds aloft. As the fire heated up the surrounding atmosphere, it created hot airmasses which were driven up due to buoyant forcing. Consequently, this forcing generated updrafts ahead of the head fire. Strong surface convergence occurred as a result, which affected the winds ahead of the fire front as updrafts caused winds from ahead and behind the fire front to increase as evident at the main tower where the fire-induced winds increased before FFP. These winds affected the ROS as there was a shift in the convergence zone pushing the fire downwind, which resulted in the fire preheating the fuels more effectively allowing the fire to spread much faster. Without these winds, the fire would not spread as fast at the head fire.

The flanks of the fire did not spread as fast as the head fire since they did not generate as strong fire-induced wind as the head, and the wind direction was normal to the spread of the fire at both flanks.
As a result, the ROS between two-way coupling and one-way coupling at the flanks was similar since minimal fire-induced wind occurred at the flanks of the fire. The flanks of the fire also experienced convergent flow at the fire front instead of ahead of the fire front like the head fire. With this type of flow, the incoming winds did not push the flame body closer to the unburnt fuel. Instead, the only form of spread was the base radiative component of the flame. Consequently, the fire heated the surrounding atmosphere more at the flanks due to the slower ROS, and it generated counter-rotating vortices over the flanks. Out of the two flanks, the left flank burned hotter than the right flank as the right flank did not have fuel directly in front of it since the head fire already burned it. The fuel at the right flank is behind the fire front and against the wind, which made the right flank act more like a backfire. The differences in the heat flux at the flanks impacted the ROS at each flank as well as the temperature released and vertical winds as the left flank generated much stronger fire-induced vertical velocities and temperatures than the right flank. For future work, implementing a physical ROS model instead of the Rothermel model may help the flank ROS as currently the flank ROS is calculated as the backfire ROS, which does not yield the most accurate result. Lastly, a simulation that can accurately account for the wind shift would prove invaluable as the would help reduce the error on the shape of the fire.
Chapter 2
Analysis Between the Rothermel ROS Model and the Balbi ROS Model

2.1 Abstract

Being able to accurately predict the ROS of a propagating fire in various fuels, weather, and topography would greatly enhance the capabilities of current wildfire models. However, this is no easy task as there are multiple complex small-scale processes occurring within a fire that must be considered to produce an accurate calculation of the ROS. Accurate estimates of the ROS are critical to predict where a fire will spread and how fast. This could potentially save lives for example if eruptive fire behavior was forecasted. To predict the ROS, multiple models have been created utilizing both physical properties of fire and observational data. By comparing ROS models in similar environmental conditions, we can determine which model best calculates the ROS and implement it to improve future forecasts and simulations. The two fire ROS models in this study are the Rothermel model and the Balbi model. The goal of these models is the same, however the approach is vastly different as the Rothermel model is a semi-empirical model that was created in 1972, and the Balbi model is a physics-based model that is still being worked on to this day (with the most recent model being released in 2022). Within these models, varying assumptions are made about how each mechanism within a fire contributes to the overall ROS and how to simplify the model to reduce its complexity and computational time. To see how each model performs, the models were converted into a MATLAB code and various tests were performed on each model. These tests included changing parameters within the fuels, topography, fuel moisture, and weather conditions to see how each factor influences the ROS. Physical processes within the models were analyzed to evaluate how each calculation within the code weighs into the final calculations.

To test each ROS model, we used the 13 Albini fuels categories. This dataset is currently implemented across an array of models (such as WRF-SFIRE, WFA, and BehavePlus) as it covers a wide variety of different fuel types. Using this dataset, the ROS between each model can be accurately compared since they will be tested under the same fuel type and conditions.

2.2 Introduction

Currently, there are three types of models that are used to calculate the ROS, 1. empirical models, 2. semi-empirical models, 3. physical models. Empirical models use statistical data and observational
data to calculate the ROS. These models lack physical characteristics and are usually simplified models. Semi-empirical models use both observational data and physical properties to calculate the ROS. Models like these have proven to be useful with calculating the ROS as these models simplify fire spread processes while incorporating key principles [Chatelon et al., 2022]. Physical models are solely based on physical and chemical processes occurring within a fire. For physical models, they are based on a series of complex partial differential equations and include principles from fluid dynamics that can make solving the equations necessary for the ROS computationally challenging and time consuming. It is assumed that by simplifying these principles and making necessary assumptions, simplified models will be still able to provide an accurate calculation of the ROS in less compute time.

Larger scale fire models that predict where the fire will spread utilize ROS models to determine how fast the fire will spread in a certain environment. The two ROS models that are currently in use across an array of the larger scale models are the Balbi model and the Rothermel model. The Balbi model is a physics-based model which aims to provide computationally fast and accurate simulations of fire propagation with the idea that fire managers can use them under operational conditions [Chatelon et al., 2022]. The Balbi model has been implemented into the Meso-NH Blaze model [Costes et al., 2021] while the Rothermel model (a semi-empirical model that was created by Richard C. Rothermel in 1972 and revised by Frank A. Albini in 1976 [Anderson et al., 2010]) has been implemented in CAWFE and the original version of WRF-SFIRE [Coen, 2013; Kochanski et al., 2013b].

2.2.1 Rothermel Model

The Rothermel model is based on a heat balance model developed by Frandsen [1971] and it incorporates data obtained from wind tunnel experiments in artificial fuel beds containing various fuels and Australian wildfire data in grasses [Anderson et al., 2010]. From these datasets, Rothermel used observational data along with physical properties to create his ROS model. This model still contains many underlying simplifications and assumptions so it can be computed quickly by a human or computer. There are limitations with this model, but overall it proved useful in current wildfire models as it can provide an assessment of the ROS of a fire without taking much compute time and without a need for extensive input data.

The formulation of this model is still quite complex despite it not being a fully physical model and making assumptions about certain properties. In the beginning, the ROS equation was solely based on the conservation of energy equations which made the initial ROS equation difficult to solve. By using
observations and an understanding of how fire propagates in certain environments, simplifications were then made to the model that made the calculations much easier than before.

To reduce the initial complex equation to its final form, small details were implemented into the model to reduce the complexity but retain the accuracy. For a fire to spread, the fire must preheat the potential fuels to their ignition temperature which depends on the fuel type, moisture content, and the amount of fuel [Rothermel, 1972]. Certain components within a fire (such as how hot the base of the fire is burning or if the flame body touching unburned fuel) can preheat the fuels more than other components in different scenarios. An example of this is the horizontal propagating flux and the vertical propagating flux. In a no wind situation, the horizontal propagating flux would dominate fire spread, but when wind or a slope is introduced, the vertical propagating heat flux dominates since there is more direct flame contact and convective heat transfer to the fuels.

The next component in Rothermel's model is the reaction intensity \( (I_R) \). This is the energy released by the fire front and is produced by burning gases released from the organic matter in the fuels. The reaction intensity is mainly based on the fuel type and changes with wind and slope as the propagating heat flux exposes the fuel to additional convective and radiant heat transfer. With just this knowledge, Rothermel was able to simplify the main equation down to a handful of variables.

To finish up the model, Rothermel ran a series of experiments to gather the last few missing parameters (such as the reaction velocity, mineral damping coefficient, and moisture damping coefficient). To find these parameters, he constructed weighing platforms to support the fuel for the fuel beds and supported the beds with four load cells which had ceramic cylinders and baffles to protect it from the heat. All the load cells contained electronics that would take measurements during the burn. With this experiment, Rothermel was able to implement the missing parameters into his model without accounting for wind or slope impacts.

After all these experiments, the complete set of parametric equations were finally developed, but the model still was not yet suitable for field use since it was created in a lab setting. The model was developed with a homogeneous fuel, so it was unable to account for different compositions of fuels in the environment. To combat this, Rothermel created the concept of a fuel cell which is the smallest column of fuel within a stratum of mean depth that has sufficient fuel to be statistically representative of the fuel in the entire fuel complex” [Rothermel, 1972]. The fuel cell concept is used to weigh the input parameters and not to have specific values provided for the fuels. Instead, mean values that quantify the modeled fuel complex. By adding in these mean values and modifying the model, it can be used at
a field scale.

Once the initial model was complete, Rothermel further worked on developing the wind and slope coefficients. The wind coefficient was calculated by building multiple fuel beds in a wind tunnel and running the wind tunnel at 2, 4, 6, or 8 mph and calculating the ROS as well as comparing the model to McArthurs dataset. With these data, Rothermel developed a correlation between the wind speed and ROS. He also found that certain fuel properties affect the wind coefficient so he implemented those fuel properties into the wind coefficient. The slope coefficient was created a similar way. Multiple fuel beds were constructed at different slopes and Rothermel found a relationship between the slope of the fuel beds and the ROS. He also incorporated the packing ratio into the coefficient since that affects the ROS on sloped terrain.

2.2.2 Balbi Model

In the Balbi model, a major part of the overall calculation time comes from the equations governing the flow. To combat this issue, major simplifications are made to the model to simplify it as much as possible while retaining an accurate and fast results. The calculation of the free stream wind and upward gas flow velocity in still air is an example. To calculate these parameters, multiple physical processes such as thermal balance and radiant heat flux must be considered. To reduce this down to simple calculations, the authors split up a flame into two different sections, the flame base and the embers, and the flame body. Adding these two components, should yield the resulting radiant heat flux and thermal balance. The flame base radiation deals more with distance from the unburnt fuel to the flame base and emissivity of the fire. The flame body component takes over with a slope or windy conditions since the flames are brought closer to the unburnt fuel, resulting in more radiative heat flux impinging on the fuel.

Like with Rothermel, accounting for slope and wind speed in the model added another layer of complexity to the model. Equations were first developed with the simplifying assumption of no slope and no winds, then later slope and wind would be added into the model. In the Balbi model, the equations incorporating slope and wind ended up producing a series of nonlinear equations, which would increase the computational time of the model. As a result, algorithms in Mathematica were used to iteratively find a solution of these equations. There were still some parameters missing within the model that could only be found with testing, but for now the model could be tested and compared to observational data.

For testing the model, Balbi used 3 different sets of laboratory experimental data. The first test
occurred with both slope and windy conditions in Lisboa, Portugal. The results of this first experiment proved promising as there was a relative error of 6.54% with a correlation coefficient of 0.9836 [Balbi et al., 2007]. Some adjustments to the model had to be made, but these changes improved on the model and added some more constant values as well as a general idea of what the missing slope and wind constants should be. The next experiment was conducted in the combustion tunnel of INIA [Balbi et al., 2007]. The main goal of this experiment was to test the model with varying winds. Winds ranged from 1 to 3m/s. There were also 2 different fuel load values, and three replications per wind speed and fuel load. With these experiment, the authors were able to better fit the wind and slope constants found in the previous study and later found one of the parameters in the slope and wind equations is a function of the surface area to volume ratio (SAVR). The last experiment occurred at the University of Combra under wind or upslope conditions [Balbi et al., 2007]. The wind speeds varied between 1.5 to 4.5m/s and the fuel bed was set anywhere from 0 to 40 degrees. By testing the model in both no wind with slope, and wind with no slope conditions, the wind and slope components were tested again. Overall, they found the ROS model performed well with the new wind and slope equations and constants. No statistics were given in this study, instead there were plots of the observed ROS compared to the modeled ROS.

To get the model fit for field scales, an analysis of 29 field-scale experiments were performed for varying vegetations and winds. There was no slope present in these experiments. With a statistical study, Fernandes [2001] derived a model that fits the parameters that were causing problems in the laboratory experiments [Balbi et al., 2007]. Except this time these were for field-scales. With this analysis, the model was now claimed to be able to be used at a field scale and laboratory scale with some of the same parameters as before, and with the changing parameters being dependent on the vegetation. Overall, this model satisfied what the authors were originally looking for. It was a faster than real time model that is fully physical. This was just the beginning of the model as there have been many changes throughout the years that have led to this model getting more accurate.

With more research into how fires spread, the Balbi model has evolved significantly. One question remained unanswered in the Balbi model that needs to be addressed and that is what the dominant heat transfer mode [Balbi et al., 2020]. In this model, the authors took a closer look at how convective heat transfer impacts the ROS. To test a convective heat transfer component, they used multiple laboratory experiments. By running these experiments in a laboratory setting, the authors were able to better determine what processes are the leading cause of the fire spread. Two terms that are new in the model are convective cooling and the flame base radiation. The addition of these parameters increases the
complexity of the model, but also allows it accounts for more processes within a fire which could provide
a more accurate ROS.

After extensive testing and modifying the model based on the lab data and more than 300 exper-
imental fires, the model was found to have an error below 8% compared to the observed ROS which
proves as a satisfactory result for the authors [Balbi et al., 2020]. This model was still claimed to faster
than real time and it can be used at much larger scales. The model also has no parameter that varies
between experiments, which makes this model fully predictive [Chatelon et al., 2022].

The last modifications (and most current as of writing) occurred in 2022 where the Balbi model
was modified further to better account for field scale fires. Before, the model was built on laboratory
experiments which still proved useful as the results from the 2020 paper show, but now the model could
be better applied in the field. Some notable changes between the two models included removing certain
constants and parameters to account for field scales as well as adding in a new parameter that was used
to better fit the model to the ROS captured from observations. Sensitivity analyses were also conducted
on this model to see what parameters contributed most to the ROS. The authors found that convection
was the main heat transfer mechanism driving fire propagation [Chatelon et al., 2022].

With the introduction of convective radiation, there have been further studies to determine the
fine scale processes going on in convective heat transfer. Anderson et al. [2010] performed multiple
experiments to test how heat transfer through convection occurs. These tests were done in a wind
tunnel at the USDA Forest Service Sciences Laboratory in Missoula, Montana [Anderson et al., 2010].
In these experiments, Anderson et al. [2010] laid out various fuels and instrumentation within the burn
plot to characterize the gas temperature (air and pyrolysates) and the flow that drives convective heating
of unburnt fuels ahead of the fire [Anderson et al., 2010]. By running the experiments in both windy and
no-wind conditions, the effects of wind convective heat transfer were determined. His results indicated
that the gas temperature was greater with minimal wind. As the wind speeds increased above 1m/s
the gas temperature exponentially reached the maximum. A decrease in the gas temperature was also
noted with an increased fuel packing ratio and moisture content. After this analysis, Anderson et al.
[2010] then analyzed the surface gas velocity, which was crucial to understanding how the winds near the
surface responded to the fire. In this experiment, fuel was laid out in a way that some fuel elements were
farther away from each other. The fuels that were considered far away from other fuels (about 1.8m)
did not show much change in the surface velocity under constant wind speed. With an increase in wind
speed, the surface velocity increased as well. For fuels in the middle region (0.3-1/7m), there was a rapid
decrease in the surface wind [Anderson et al., 2010]. In fact, this would lead to a reversal in the flow
approaching the flame front [Anderson et al., 2010]. With tightly packed fuels, there was a rapid increase
in the surface wind from the minimum value to the maximum value. With the experiments performed
by Anderson et al. [2010], these provided much needed insight into how gas temperature and flow drives
convective heating. These experiments also proved that convective heating must be considered when
attempting to model the ROS of a propagating fire as it is another form of heat transfer taking place
within a fire.

2.3 Methods

To compare the two ROS models both conceptually and analytically, papers from both models as
well as MATLAB codes from both models were analyzed to better understand the underlying equations,
constants, and assumptions behind each model. By comparing the papers to the MATLAB code and
evaluating how each parameter fits in the overall ROS, we then determined which parameter within each
model contributed to the ROS.

To analyze the models analytically, the two MATLAB functions were modified to accept multiple
inputs. Before the modification, the codes could only accept the fuel type, wind speed, slope, and fuel
moisture. After the modification the codes could accept another input parameter that can be assigned
to any value. We ran the codes using increasing fuel heights, fuel SAVR, fuel moisture content, slope,
and wind. The results were plotted and evaluated to determine how each parameter within the model
contributed to the overall ROS. The last change occurred in the Rothermel function. Originally, the
model caps the ROS at 6m/s, however, for this analysis this was removed to observe how the model
behaves under extreme conditions. Lastly, the fuel of choice for testing the models is tall grass (2.5ft)
since the ROS is typically very fast and any small change in the weather or terrain will likely result in
a large change in the ROS.
2.4 Results

2.4.1 Rothermel Model

Initial Rate of Spread Equation

The initial Rothermel model was based on the heat balance model developed by Frandsen [1971] and can be see in equation (2.1).

\[
\text{ROS} = \frac{I_{xig} + \int_{-\infty}^{0} (\frac{\partial I}{\partial z})_{z_c} dx}{\rho_{be} Q_{ig}}
\]  

(2.1)

Where ROS = Quasi-steady rate of spread \([\frac{ft}{min}]\)

\(I_{xig}\) = Horizontal heat flux absorbed by a unit volume of fuel at the time of ignition, \([\frac{Btu}{ft^2}]\)

\(\rho_{be}\) = Effective bulk density (the amount of fuel per unit volume of the fuel bed raised to ignition ahead of the advancing fire), \([\frac{lb}{ft^3}]\)

\(Q_{ig}\) = Heat of preignition (the heat required to bring a unit weight of fuel to ignition), \([\frac{Btu}{lb}]\)

\((\frac{\partial I}{\partial z})_{z_c}\) = The gradient of the vertical intensity evaluated at a plane at a constant depth, \(z_c\), of the fuel bed, \([\frac{Btu}{ft^3/min}]\)

With equation (2.1) being the starting equation, there was a lot of work necessary to reduce it down to the final equation. Especially when slope and wind are considered, then formulating the model becomes much more complex. To help reduce the complexity, the initial ROS equation was formulated assuming no slope and no wind conditions.

The next step within the model was to evaluate each parameter within equation (2.1) and simplify it to make the final equation able to be quickly solved without reducing accuracy.

Heat of Preignition \(Q_{ig}\)

The first equation evaluated was the heat of preignition \(Q_{ig}\). This term was "evaluated analytically for cellulosic fuels by considering the change in specific heat from ambient to ignition temperature and the latent heat of vaporization of the moisture". This resulted in equation (2.2).

\[
Q_{ig} = C_{pd} \Delta T + M_f(C_{pw} \Delta T_B + V)
\]  

(2.2)

Where:

\(C_{pd}\) = Specific heat of dry wood.
\( \Delta T_{ig} \) = Temperature range to ignition

\( M_f \) = Fuel moisture. \( \frac{[lb.\text{water}]}{[lb.\text{drywood}]} \)

\( C_{pw} \) = Specific heat of water.

\( \Delta T_B \) = Temperature range to boiling.

\( V \) = Latent heat of vaporization.

To further reduce this equation down to the final form, an assumption was made that the temperature to ignition will stay at a constant range from 20°C to 320°C and that boiling temperature will remain at 100°C, and that the fuel will remain a cellulosic fuel, the equation then became:

\[
Q_{ig} = 250 + 1116 \times M_f
\]

(2.3)

These assumptions take out the need for the temperature range to ignition, latent heat of vaporization, temperature range to boiling, and specific heat of dry wood. With less parameters necessary, the model becomes much and faster (computationally) and easier to solve. This also aids in reaching Rothermel’s goal of creating a ROS model with as few input parameters as possible.

**Effective Bulk Density (\( \varepsilon \))**

The next parameter is the effective bulk density (\( \varepsilon \)). This parameter was calculated experimentally using thermocouples laid out in a fuel bed. The effective bulk density is used in the final ROS equation with no wind and no slope (\( r_0 \)). The equation for effective bulk density can be seen in equation (2.4).

\[
\varepsilon = \exp\left(\frac{-138}{\sigma}\right)
\]

(2.4)

Where:

\( \sigma \) = Surface Area to Volume Ratio. \([\frac{1}{ft}]\)

**Reaction Intensity (\( I_R \))**

The next parameter is the reaction intensity. This is by far the hardest to calculate as it is the most complex to derive. To obtain this value, the authors used the weight loss data from the fuels to determine how intense the fire was. This parameter can be expressed as equation (2.5).

\[
I_R = -\left(\frac{dw}{dx}\right)\left(\frac{dx}{dt}\right)h
\]

(2.5)
Where:
\[
\frac{dx}{dt} = R, \text{ the quasi steady state rate of spread } \left[ \frac{ft}{min} \right]
\]
By integrating the equation with respect to the reaction zone depth D, that results in equation (2.6).

\[
IRD = Rh(W_n - W_r)
\]  \hspace{1cm} (2.6)

Where:
\( D = \text{Reaction zone depth (front to rear). [ft]} \)
\( W_n = \text{Net initial fuel loading.} \left[ \frac{lb}{ft^2} \right] \)
\( W_r = \text{Residue loading immediately after passage of the reaction zone.} \left[ \frac{lb}{ft^2} \right] \)

equation (2.6) does not account for minerals or water content so the formula was later adjusted to account for that.

**Reaction Velocity (Γ)**

The next step in creating the model was to find the reaction velocity. The reaction velocity is the ratio of the reaction zone efficiency to the reaction time and can be represented by equation (2.7).

\[
Γ ≡ \frac{η_l}{τ_R}
\]  \hspace{1cm} (2.7)

To fully utilize the reaction velocity, the fuel moisture and the mineral content must be known as that would lead to a slower reaction velocity if there is more moisture within the fuel or more noncombustibles (minerals). By incorporating both the moisture content and the mineral content as a damping coefficient, the equation then becomes:

\[
Γ = Γ' η_M η_s
\]  \hspace{1cm} (2.8)

Where:
\( Γ' = \text{Potential reaction velocity.} \left[ \frac{1}{min} \right] \)
\( η_M = \text{Moisture damping coefficient having values ranging from 1 to 0, dimensionless.} \)
\( η_s = \text{Mineral damping coefficient having values ranging from 1 to 0, dimensionless.} \)
Moisture and Mineral Damping Coefficient

The moisture and mineral damping coefficients as well as the reaction velocity could only be found through experimentation. To find the moisture damping coefficient, three fuel beds of ponderosa pine needles were tested over a wide moisture range. Rothermel [1972] found the moisture damping coefficient is dependent not only on the moisture but the fuel type as well since logging slash is much more porous and carries more moisture. To obtain the equation for the moisture damping coefficient, Rothermel [1972] created a plot (as seen in Figure 2.1) by comparing the fuel moisture of extinction (where the fire will no longer spread) to the fuel moisture. By finding an equation that fits the curve in Figure 2.1, that equation was set as the equation for the moisture damping coefficient.

![Figure 2.1: Determining the moisture damping coefficient. Figure taken from Rothermel [1972].](image)

The equation that Rothermel [1972] found that fits the curve in Figure 2.1 is represented by equation (2.9):

\[ \eta_M = 1 - 2.59 \frac{M_f}{M_x} + 5.11 \left( \frac{M_f}{M_x} \right)^2 - 3.52 \left( \frac{M_f}{M_x} \right)^3 \]  \hspace{1cm} (2.9)

Where:

- \( M_f \) is the fuel moisture.
- \( M_X \) is the fuel moisture of extinction.

\[ \text{Figure 2.1: Determining the moisture damping coefficient. Figure taken from Rothermel [1972].} \]
To find the mineral damping coefficient, Rothermel [1972] assumed the ratio of the "normalized decomposition rate would be the same as the normalized reaction intensity" [Rothermel, 1972]. Rothermel [1972] then used the maximum decomposition rate and found the mineral content was at 0.0001 which was the lowest fractional mineral content for natural fuels. By then looking into silica-free ash, Rothermel created another plot as seen in Figure 2.2. He then found the equation fitting the curve and set that as the mineral damping coefficient. To find the damping coefficient, all the user needs is to input is the effective mineral content (silica free).

Figure 2.2: Determining the mineral damping coefficient. Figure taken from Rothermel [1972].

Similar with the moisture damping coefficient, the authors fit this curve and set that as the mineral damping coefficient.

\[ \eta_S = 0.174(S_e)^{-0.19} \]  \hspace{1cm} (2.10)

Where:

- \( S_e \) is the effective mineral content (silica free).
Fuel Packing Ratio ($\beta$) and Surface Area to Volume Ratio ($\sigma$)

The last parameters are the fuel packing ratio and the SAVR. Both of these are fuel properties that need to be specified within the fuel parameter for the model to work. These parameters are necessary as they determine how intense a fire may burn. With a high packing ratio, there will be a low air-to-fuel ratio and this will make it difficult for the flame to penetrate to the top of the fuel. A more sparse fuel bed will result in a low intensity fire as there will be significant heat losses between the fuel and flame. Finding the optimal packing ratio to achieve the maximum fire intensity is a challenging task as it is likely different for each fuel. The packing ratio can be defined by equation (2.11).

$$\beta = \frac{\rho_b}{\rho_p}$$  \hspace{1cm} (2.11)

Where:
- $\beta$ = Packing ratio, dimensionless.
- $\rho_b$ = Fuel array bulk density, $[\frac{lb}{ft^3}]$
- $\rho_p$ = Fuel particle density, $[\frac{lb}{ft^3}]$

The SAVR for fuels is used to quantify the fuel particle size can be represented by equation (2.12)

$$\sigma = \frac{4}{d}$$  \hspace{1cm} (2.12)

Where
- $d$ = The diameter of the circular particles or edge length of square particles, [ft].

Fitting Missing/Unknown Parameters Through Experimentation

With the whole model setup, the next task was to find the parameters that could only be found through experimentation. This includes the parameters in the reaction velocity, and the slope and wind coefficients. To find the reaction velocity parameters, multiple fuel beds were setup on weighing platforms so the weight of the fuel could be constantly measured. With this setup, Rothermel [1972] could determine how fast the fuel was burning since there were multiple weight sensors at each part of the fuel. With this knowledge, Rothermel found that the mass loss rate related to the net initial fuel loading, reside loading, and the width of the weighing platform. Combining this with equation (2.7) yields equation (2.13).
\[
\Gamma = \frac{\dot{m}}{w_nRW\tau_R}
\]  
(2.13)

Where:

\(\dot{m}\) = Mass loss rate obtained from the weight loss data.

With this final equation, it can then be combined with equation (2.8) to get the potential reaction velocity and have it now correlated with the physical features of fuel.

\[
\Gamma' = \frac{\Gamma}{\eta_M\eta_S}
\]  
(2.14)

With all the initial equations formulated, experiments were conducted using this model and comparing it to the observed ROS. The first parameter tested within the model to observations was the reaction velocity. In particular, Rothermel [1972] wanted to find the optimum packing ratio and the optimum reaction velocity. These parameters were created by fitting curves produced from the experiments, and the results can be seen below:

\[
\beta_{op} = 3.348 \times \sigma^{-0.8189}
\]  
(2.15)

\[
\Gamma_{max}' = \sigma^{1.5}(495 + 0.0594\sigma^{1.5})
\]  
(2.16)

Where: \(\beta_{op}\) is the optimum packing ratio and \(\Gamma'\) is the maximum reaction velocity \([\frac{1}{\text{min}}]\).

After numerous experiments, Rothermel [1972] found there is an optimum fuel load for each fuel size. To incorporate this into the model, he then combined the maximum reaction velocity with the regular reaction velocity equation and an arbitrary variable \(A\) was inserted to better fit the observation. The final equation for the reaction velocity then became:

\[
\Gamma' = \Gamma_{max}' \left(\frac{\beta}{\beta_{op}}\right)^A \exp[A(1 - \frac{\beta}{\beta_{op}})]
\]  
(2.17)

Where:

\[A = \left(\frac{1}{(4.77\sigma^{-1.4777})}\right)\]

These equations were designed to fit not only the dependent variables but also the data obtained in the experimentation. These equations were specifically made for reasonable output values even when the input values may be extreme so the model should never result in a negative value.
The next parameter critical for model development was the propagating flux. To first evaluate the
equations, the analysis took place assuming no wind and no slope to make formulating these equations
much more simple. The initial equation for the propagating flux can be seen in equation (2.18).

\[(I_P)_o = R_0 \rho_b \epsilon Q_{ig}\]  

(2.18)

To relate the propagating flux to the reaction intensity, a ratio (\(\zeta\)) was computed and can be seen in
equation (2.19).

\[\zeta = \frac{(I_P)_o}{I_R}\]  

(2.19)

The values for \(\zeta\) are computed and plotted in Figure 2.3 as a function of \(\beta\) for three fuel sizes. After
finding a correlation for \(\zeta\) as a function of \(\beta\) and \(\sigma\), Rothermel found \(\zeta\) can be represented by equation
(2.20).

![Figure 2.3: Determining \(\zeta\) using three different fuel sizes. Figure taken from Rothermel [1972].](image)

\[\zeta = (192 + 0.259\sigma)^{-1} \exp[(0.792 + 0.681\sigma^{0.5})(\beta + 0.1)]\]  

(2.20)
**Initial ROS Equation**

With the missing parameters (with the exception of slope and wind) found, the ROS equation without slope and wind was finished and can be seen in equation (2.21). This equation met the initial goals as it is a simple mathematical model that can quickly and accurately calculate the ROS of a fire in no slope and no wind conditions.

\[ r_0 = \frac{I_R \zeta}{\rho_0 \varepsilon Q_{ig}} \]  

(2.21)

Where:

- \( r_0 \) is the ROS without wind or slope \( \frac{f_l}{\min} \).

**Wind and Slope Coefficients**

To first evaluate the wind and slope coefficients, he assumed the fuel type would remain constant. After performing multiple experiments with varying fuel beds at different wind speeds and using field data, he then found the wind coefficient to be a function of \( \sigma \) along with the packing ratio and many other constants to match the observed data. The wind coefficient can be seen in equation (2.22). The slope coefficient was calculated by performing experiments on fuel beds at different slopes and finding a correlation of the data collected from the experiments. This was then set as the slope factor and this can be seen in equation (2.23).

\[ \phi_W = CU^B \left( \frac{\beta}{\beta_{op}} \right)^{-E} \]  

(2.22)

\[ \phi_S = 5.275\beta^{-3}(\tan \phi)^2 \]  

(2.23)

Where:

- \( U \) = Wind Velocity \( \frac{f_l}{\min} \)
- \( C = 7.47 \exp(-0.133\sigma^{0.55}) \)
- \( B = 0.02526\sigma^{0.54} \)
- \( E = 0.715 \exp(-3.59 \times 10^{-4}\sigma) \)
- \( \phi \) = Slope of the fuel bed.
Final Rate of Spread Equation

The final ROS equation was finally complete, and it now incorporated both slope and wind components and is able to be used operationally. There was no longer any calculus needed or any complex calculations. The final equation can be seen in equation (2.24).

\[ R = \frac{I_R \zeta(1 + \phi_W + \phi_S)}{\rho_v \epsilon Q_{ig}} \]  

(2.24)

2.4.2 Balbi Model

2007 Balbi Model

With multiple versions of the Balbi model, the very first version of the model will be discussed followed by the biggest addition from the newest version to see where the model originated, and the direction it is heading. Experiments will then be performed on the 2022 Balbi model using the original 13 Albini fuel categories.

Simplified Flow and Flame Tilt Angle

The first parameter in the Balbi model is the simplified flow and the flame tilt angle. These parameters are first calculated assuming no slope and no wind conditions (like with the Rothermel model initially). Balbi et al. [2007] assume the main effect of the flow that must be accounted for is the tilting of the flames under wind and/or slope conditions. For the initial study, Balbi et al. [2007] assumes that under no wind and no slope conditions the flame tilt angle \( \gamma \) equals \( \beta_w \) which results from the buoyancy and the wind. \( \beta_w \) is given by:

\[ \tan \beta_w = \frac{\nu_w}{u_{fl}} \]  

(2.25)

Where:

\( \nu_w \) and \( u_{fl} \) represent the free stream wind speed and the upward gas flow velocity in still air at mid flame height.

With the introduction of a slope, \( \gamma \) changes as the gas velocity changes due to indrafts (\( \nu_s \)) and the slope angle (\( \alpha_0 \)). The relationship can be seen in equation (2.26) and equation (2.27).

\[ \gamma = \alpha + \beta_s \]  

(2.26)
\[
\tan \beta_s = \frac{\nu_s}{u_{fl}}
\] (2.27)

For circumstances where there are both wind and slope conditions, Balbi et al. [2007] assume the gas velocity induced from the slope factor is negligible in regards to the wind speed.

**Simplified Flame Sub-Model**

**Flame height**

To be able to calculate \( \nu_w \) and \( u_{fl} \) and keep the model computationally fast, many simplifying assumptions are made to generate a simple model. The authors split the flame into two different categories, the flame base and the flame body. The flame base will be attached to the fuel bed, and \( D \) will be the depth of the fuel bed and \( h \) is the height. The flame body is the fire plume and \( l \) will represent the depth and \( H \) is the flame body height. Balbi et al. [2007] then split the calculation up into 6 sections: Flame height, State Equation, Vertical Momentum Equation, Mass Balance, Stoichiometric Ratio, and Thermal Balance to make formulating the model easier. The first calculation is the flame height. To calculate the flame height, the authors used a previous relationship by Sun et al. [2009] for vegetation fires:

\[
H = H^*Q^{\frac{2}{3}} = H^*(\Delta h_{fu}\sigma_{fu}c)^{\frac{2}{3}}
\] (2.28)

Where:

- \( H \) is the flame height [m].
- \( Q \) is the rate of heat release per unit length of fire front \([kW/m]\)
- \( H^* \) is a parameter to fit.
- \( \Delta h_{fu} \) is the heat of combustion of the vegetative fuel \([kJ/kg]\)
- \( \sigma_{fu} \) is the surface mass \([kg/m^2]\)
- \( c \) is the rate of fire spread \([m/s]\)

For a visualization, refer to Figure 2.4.

**State Equation**

For the state equation, the authors ”consider the gas state equation for the quasi-isobaric diffusion flame” [Balbi et al., 2007]. This equation can be seen in equation (2.29).
\[ \rho_g T_g = \rho_a T_a \]  \hspace{1cm} (2.29)

Where:
\( \rho_g \) is the density of the gas \( \frac{[kg]}{[m^3]} \).
\( T_g \) is the temperature of the gas [K].
\( \rho_a \) is the density of the air \( \frac{[kg]}{[m^3]} \).
\( T_a \) is the temperature of the air [K].

**Vertical Momentum Equation**

As seen in Figure 2.4, there is a vertical component to the flame. To calculate this component, Balbi et al. [2007] first neglect the shear stresses in the gas and instead use buoyancy as the main mechanism involved in the vertical momentum. This is given by:

\[ \rho_g \frac{\partial u}{\partial t} = (\rho_a - \rho_g)g \]  \hspace{1cm} (2.30)

Where \( g \) is gravitational force \( \frac{[m/s^2]}{[s^2]} \)

To solve for this equation, simple integration along the flame length results in the gas velocity at mid flame, \( u_{fl} \)

\[ u_{fl} = Q^\frac{1}{2} \sqrt{\left( \frac{T_{fl}}{T_a} - 1 \right) g H^*} \]  \hspace{1cm} (2.31)
Mass Balance

Mass balance is kept simple for the whole flame structure based on the geometry of the flame. In slope and wind conditions, the rate of air entrainment is considered negligible in mass balance. With this assumption, the continuity equation per unit length of the fire can be used and is given by:

$$\rho_g u_f l = \rho_{ga} h \nu_u + D \dot{\sigma}_f a$$  \hspace{1cm} (2.32)

Where the left hand side of the equation is the rate of mass loss from the flame body, $\rho_{ga} h \nu_u$ is the rate of air entrainment upward in the flame, and $D \dot{\sigma}_f a$ is the rate of mass increase due to the thermal degradation of the vegetation.

Stoichiometric Ratio

The stoichiometric ratio involves the rate of air entrainment upward in the flame and how that is proportional to the rate of mass incoming from thermal degradation, $\nu$ being the stoichiometric ratio [Balbi et al., 2007].

$$\rho_a h \nu_u = \nu D \dot{\sigma}_f a$$  \hspace{1cm} (2.33)

Thermal Balance

The last parameter in the flame sub model is the thermal balance. The thermal balance calculates the temperature of the flame and has the same assumptions as the continuity equations. After simplifications and rearranging the initial equation, as well as assuming the specific heat is held constant in the flame, fuel gases, and that the fuel gases are emitted near the ambient temperature, the equation for the flame temperature becomes:

$$T_f = T_a + \frac{(1 - \chi)Q}{(v + 1)D \dot{\sigma}_f a c_{pg}} = T_a + \frac{(1 - \chi)\Delta h_f u}{(v + 1)c_{pg}}$$  \hspace{1cm} (2.34)

Where: $T_f l$ is the flame temperature [K]
$\chi$ is the law for fraction radiation
$c_{pg}$ is the specific heat of gas mixture [$\frac{J}{K\cdot m^3}$]
D is the width of the flame base [m]
**Simplified radiation Sub-Model**

When a fire front spreads, there is a radiant heat flux impinging on the unburnt fuels ahead of the flame front [Balbi et al., 2007]. This component is split up into two different components. The radiative component from the flame base, and the flame body radiation. For the flame base radiation, Balbi et al. [2007] assume the emissivity of the flame base is equal to unity [Balbi et al., 2007], which results in:

\[ R_b = \sigma T_b^4 d (\delta - x) \]  \hspace{1cm} (2.35)

Where: \( R_b \) is the flame base radiation
\( \delta = 4/\alpha_f \zeta_f \) is the mean penetration distance of radiation within the fuel bed [m]
\( x \) is the coordinate in space normal to the fire front [m]
\( d \) represents the fuel depth [m]

When flames are on a slope or under windy conditions, the flame is brought closer to the unburnt fuel, which preheats the fuels more than if the flame were vertical. The base radiation would stay the same under any conditions. The amount of radiation is a complex calculation since the amount of radiation reaching the unburnt fuel from the flame body must be integrated from the length of the flame as well as using an inverse square law to find the distance \( r \) between the two areas [Balbi et al., 2007]. To reduce this equation to be used in a simplified model that is faster than real time, an assumption that the fire front is a flame panel with height \( H \) and infinite width from a surface fuel element [Balbi et al., 2007]. The equation then becomes:

\[ R_{fl} = \epsilon_f \sigma \frac{T_b^4}{2} (1 - \cos \theta) \]  \hspace{1cm} (2.36)

Where:

\( R_{fl} \) is the flame body radiation
\( \theta \) is the angle between the base of the flame panel and the element of surface fuel.

**Preheating Sub-Model**

This is the last submodel in the 2007 Balbi model. In this submodel, the authors introduce the relationship for the ROS under low speed regimes, relationship for the ROS under high speed regimes, and a simplified model of fire spread under high speed regimes. The major assumption here is the radiation is denoted as the prevailing form of heat transfer in fire spread. Like with the Rothermel
model, calculations are first made with no wind no slope conditions to simplify calculations and those parameters are added in later. With no wind no slope conditions, the fire propagation will remain relatively constant for a given fuel. Whereas with wind or a slope, that will introduce a flame tilt and thus preheat the fuels ahead of the fire much more effectively. The base equation for the preheating sub model (which also represents the thermal balance for the unburned fuel ahead of the fire front) is as follows:

\[ \sigma_{fu}c_{pfu} \frac{dT_{fu}}{dt} = R_b + R_{fl} - \Delta h_w \frac{d\sigma_w}{dt} \]  

(2.37)

Under a low speed regime, \( \gamma \) will likely remain close to 90° as there is no slope or little to no wind pushing the flame closer to the unburnt fuel. As a result, \( R_{fl} \) can be neglected in this case and equation (2.37) can be solved with neglecting the flame body radiation. After substitutions and some manipulation of equation (2.37), the resulting equation is:

\[ c_1 = \frac{\sigma T_{fl}^4 d \delta^2}{2\sigma_{fu} c_{pfu} (T_{ig} - T_a) + \Delta h_w \eta} \]  

(2.38)

Where:

- \( c_1 \) = constant ROS \([\frac{m}{s}]\)
- \( dx = c_1 dt \)
- \( \eta \) = moisture content defined by \( \eta = \frac{\sigma_w}{\sigma_{fu}} \)
- \( \Delta h_w \) is the heat of latent evaporation \([kJ/kg]\)

On the other hand, with a high speed regime, the flame body radiation is assumed to be the main form of heat transfer to the unburned fuels. As a result, \( R_b \) is negligible and can be omitted in these calculations. By assuming that the ROS is constant over the space interval from 0 to \( H \sin \gamma \), equation (2.37) can be integrated and solved as:

\[ c_h = c_t + \frac{\epsilon_{fl} \sigma T_{fl}^4 H}{2\sigma_{fu} (c_{pfu} (T_{ig} - T_a) + \Delta h_w \eta)} (1 + \sin \gamma - \cos \gamma) \]  

(2.39)

Where:

- \( \epsilon_{fl} \) is the flame emissivity

Sine \( c_t \) is negligible as the flame body is the main contributor to the ROS, it can be removed from equation (2.39).
The final parameter is the simplified model of fire spread under high-speed regimes. First the authors define how much heat is actually transferred from the flame to the unburnt fuel. This is given by:

\[ \varepsilon_d \sigma T_d^4 = \chi Q / H \]  

(2.40)

To further reduce this model to reach the final form, the fraction of radiation decreases with flame width according to a parameter q that must be fitted in experimentation later on [Balbi et al., 2007].

By combining all the above equations together, both no slope no wind and conditions with slope and wind, it resulted in a large series of simplified nonlinear equations. Since there is no longer a need for calculus or solving partial differential equations, this model has succeeded in becoming simple enough for a computer to solve quickly. To test the speed of the model, the authors simulated a fire front shape, and found the ROS at specific points along the fire front. Usually, a grid would be constructed to help in solving this, but the authors utilized Mathematica to represent the fire front shape on a three dimensional domain. By using this technique, Balbi et al. [2007] found the computational time was lower than real time [Balbi et al., 2007]. Now all that is left for the model was validating it using lab and experimental burns and fitting parameters. Some of the parameters Balbi et al. [2007] found remained relatively constant throughout the different burns (ex: \( q = 3 \)), but the other parameters varied with different fuels characteristics.

**Wind and Slope**

To calculate the wind and slope parameters, the authors initially used multiple high speed regimes to calculate how slope and wind would impact the fire spread (these calculations can be seen in equation (2.41) and equation (2.42)). Balbi et al. [2007] then used multiple laboratory and field experiments in different slopes and wind speeds to observe how the flame behaves in different conditions and verify their calculations. In slopes and windy conditions, the authors realized with a greater slope or greater wind speed, that would change the flame tilt angle and the flame height which would bring the flame closer to the unburnt fuel. After comparing the model to numerous datasets, the authors kept getting different values for the wind and slope coefficients (which was expected). Balbi et al. [2007] found these parameters vary with different fuel properties. With a greater fuel height, fuel load, and SAVR, then there would be more fuel to burn and the flame body radiation can reach the fuel much more effectively.
With a greater FMC, then the flame would take more energy to dry out the fuel, slowing down the ROS.

\[
\begin{align*}
\frac{c_h}{c_l} &= A(1 + \sin \gamma - \cos \gamma)^q \\
\gamma &= \alpha + \beta_s \\
\tan \beta_s &= b_s c_h^{3/5} \\
\end{align*}
\]

Where:

\[b_s = \frac{\tau}{0.08(\Delta h_{fu} \sigma_{fu})^{2/5}}\]

\[
\begin{align*}
\frac{c_h}{c_l} &= A(1 + \sin \gamma - \cos \gamma)^q \\
\gamma &= \alpha + \beta_w \\
\tan \beta_w &= b_w \nu_c c_h^{-1/5} \\
\end{align*}
\]

Where:

\[b_w = \frac{1}{0.2 \sqrt{\left(\frac{T_f}{T_m} - 1\right) g(\Delta h_{fu} \sigma_{fu})^{1/5}}}\]

\[A = \left(\frac{0.15 \Delta h_{fu}}{C_p fu (T_{ig} - T_u) + \Delta h_{w} \eta}\right)\]

2.4.3 2022 Balbi Model

With many other revisions to this model (such as the 2009 paper and 2020 paper), this model has undergone a lot of change evident in the 2022 Balbi paper. The most notable difference is a convective radiative component was added to the model and there are now just 3 components in the final ROS equation. In the 2022 paper they are all represented as the equations below for simplifying the terms to a scaling factor (a), the ignition energy (q), and the dead fuel load (σ).

\[
R_b = a_b \frac{\phi_b}{\sigma \ast q} \\
R_c = a_c \frac{\phi_c}{\sigma \ast q} \\
R_e = a_b \frac{\phi_r}{\sigma \ast q}
\]
Convective Radiation

Before, the model only considered the flame base radiation and the flame body radiation, but now there is a convective radiative component that helps spread the fire in a similar location as the base radiation according to Figure 2.5. Convective radiation is based on the inflow of hot gases from the lower part of the flame base. The convective component was originally introduced in the 2020 Balbi model that was created in a laboratory setting and was advertised as able to be used in a field setting. After extensive testing, the developers created another model (the 2022 model) that included removing constants, updating other constants, and model parameters (such as the ignition line width \( W_0 \) was removed). They also updated the convective radiative component and that was initially modeled as:

\[
\phi_c = \frac{\Delta H}{2\tau_0} \sigma_s \min(h, \delta) \tan \gamma_c
\]  

(2.46)

Where:

\( \Delta H \) and \( \tau_0 \) are the heat of combustion of pyrolysis gases and the flame residence time parameter [Chatelon et al., 2022].

The angle \( \gamma_c \) is defined as:

\[
\tan \gamma_c = \tan \alpha + \frac{U(L)}{u_c}
\]  

(2.47)

Where \( U(L) \), \( u_c \), and \( \alpha \) are horizontal wind speeds at point B [Chatelon et al., 2022]. \( U(L) \) is further expressed as a function of the wind velocity at mid flame and accounts for drag forces. After some
simplifications and substitutions, the authors found the final equation for the convective component \( R_c \):

\[
R_c = a_M \min\left( \frac{W_0}{50}, 1 \right) \frac{\Delta H \rho_a T_a s \sqrt{h}}{2 q (s_t + 1) \rho_c T_m} \min \left( S, \frac{2 \pi S}{S_t} \tan \alpha + U \exp\left( -\frac{\beta_t}{\min\left( \frac{W_0}{50}, 1 \right)} R \right) \right) \tag{2.48}
\]

Where:

\( R_c \) = Contribution of convection to the ROS \([\frac{m}{s}]\).

\( a_M \) = Fitted model parameter.

\( W_0 \) = Ignition line width [m].

\( \Delta H \) = Heat of combustion of the pyrolysis gases \([\frac{J}{kg}]\).

\( \rho_a \) = Air Density \([\frac{kg}{m^3}]\)

\( T_a \) = Air Temperature [K]

\( h \) = Fuel bed depth [m]

\( q \) = Ignition Energy \([\frac{J}{kg}]\)

\( s_t \) = Air pyrolysis gases mass ratio in the flame body.

\( \rho_c \) = Fuel Density \([\frac{kg}{m^3}]\)

\( T \) = Mean flame temperature [K]

\( \tau_0 \) = Flame residence time parameter \([\frac{s}{m}]\)]

\( S \) = Leaf area by square meter \([\frac{m^2}{m^2}]\)

\( \alpha \) = Terrain slope angle [degrees]

\( U \) = Sum of normal component (to the fire front) of the natural wind velocity and fire generated inflow coming from the burnt area \([\frac{m}{s}]\)).

\( \beta_t \) = Total packing ratio.

\( R \) = Rate of Spread \([\frac{m}{s}]\).

Base Radiation

This version of the model uses a different base radiative calculation. In this version, the temperature of the burning fuel particle is assumed to be equal to the temperature of the flame [Balbi et al., 2020]. Next, the fuel is assumed to be a black radiant panel, which allows for the radiative flux to be expressed using Stefan-Boltzmann modeling [Balbi et al., 2020]:

\[
\phi_b = B T^4 h \tag{2.49}
\]
Where:

\[ B = \text{Stefan-Boltzmann constant} \left[ \frac{w}{m^2 k^4} \right] \]
\[ T = \text{mean flame temp} \ [K] \]
\[ h = \text{fuel height} \ [m] \]

To find the scaling factor \( a_b \), they found the energy losses from the top of the preheating zone are proportional to the extinction depth (\( \delta \)), and this is all inversely proportional to the height of the radiant panel (\( h \)) [Balbi et al., 2020] which resulted in:

\[ a_b = \min\left(2 \frac{h}{\delta}, 1\right) \]  \( (2.50) \)

Where \( \delta \) is equal to \( \frac{2\pi}{s\beta_h} \)

In 2022, the authors adjusted equation (2.50) by removing the factor 2 because at field scales, the soil will absorb part of the flame base radiative flux, and the extinction depth was changed to \( \delta = 2\pi/(s\beta_h) \) where \( s \) is the SAVR and \( \beta_h \) is the total packing ratio [Chatelon et al., 2022]. This changed the equation to be:

\[ a_b = \min\left(\frac{S_t}{2\pi}, 1\right) \]  \( (2.51) \)

Where \( S_t \) is the total leaf area by square meter (which is equal to double the leaf area index).

As the heat released affects the live fuel, and assuming the spread of the ignition interface is dependent on the catalytic effect of the dead fuels, the leaf area ratios (both dead and alive) are added into the final equation for \( a_b \) [Chatelon et al., 2022].

\[ a_b = \min\left(\frac{S_t}{2\pi}, 1\right)\left(\frac{S}{S_t}\right)^2 \]  \( (2.52) \)

Where \( S = \text{Leaf area by square meter} \left[ \frac{m^2}{m^2} \right] \)

**Flame Radiative Heat Flux**

The next component is the flame radiative heat flux. The flame is assumed to be a grey radiant panel with emissivity \( \varepsilon \) [Balbi et al., 2020] and can be represented by:

\[ \phi_r = \varepsilon BT^4 \int_D B \left(\frac{1}{\pi} \int_{AB} \frac{\cos \theta_1 \cos \theta_2}{d^2} d \sum \right) dx \]  \( (2.53) \)

Where: \( d \) is the distance between a point \( M \) belonging to the segment \([BD]\) and point \( P \) from the fire
front panel in Figure 2.5. 

\( \vartheta_1 \) and \( \vartheta_2 \) are the angels between the straight line (MP) and the normals to the fire front [Balbi et al., 2020].

After some calculations (calculations can be found in Balbi et al. [2020]), they were able to simplify \( R_r \) down to:

\[
R_r = AR \left( 1 + \frac{\sin \gamma - \cos \gamma}{1 + \frac{R \cos \gamma}{\sigma r_{02}}} \right)
\] (2.54)

Where: \( R_r \) is the flame body radiation \\
\( r_{02} \) is a model coefficient \\
A is a radiative factor defined by:

\[
A = a_r \frac{\chi_0 \Delta H}{4q}
\] (2.55)

Where \( \Delta H \) and \( \chi_0 \) are the heat of combustion of the pyrolysis gases and a radiative factor [Balbi et al., 2020]

Finally, the scaling factor \( a_r \) is set to 1 if the extinction depth is smaller than the fuel thickness, which also depends on the leaf area [Balbi et al., 2020]. This can be seen by:

\[
a_r = \min \left( \frac{S}{2\pi}, 1 \right)
\] (2.56)

In the 2022 paper, this term was later updated to include the same changes as the base radiative component and to include the absorption of the heat flux which resulted in:

\[
a_r = \min \left( \frac{S}{2\pi}, \frac{S}{S_t} \right)
\] (2.57)

**Balbi Final Rate of Spread Equation**

The final ROS equation is computed by adding up all the components in the fire (the flame body radiation, base radiation, and convective component) and this can be found in equation (2.58).

\[
R = R_c + R_b + R_f
\] (2.58)
2.4.4 Comparison of the Two Models

To directly compare these two models, we used fuel category 3 (tall grass) from the 13 Albini fuel categories and the same environmental conditions as input parameters. The base testing occurred in 1.5m/s winds and a slope of 3 degrees. We used the 2020 version of the Balbi model for the analysis as it had been verified with the Kolgerberg experimental dataset from the Van Wilgen experiment. Some assumptions in these experiments were the air temperature remained constant and the ignition line width remained constant at 50m (this was later removed in the 2022 paper). Another assumption made for testing the Balbi model in this experiment was the dead fuel load and the total fuel load are the same. With these conditions, the models were properly compared.

Wind Speed

Figure 2.6 presents the ROS as a function of the midflame wind speed. The Rothermel model produced a non-linear, exponential increase in the ROS as the wind speed increased. The Rothermel model ROS accelerated with an increase in the wind speed as initially (0-2m/s), the ROS increased by 0.24 m/s. As the winds increased, so does the ROS with winds between 8m/s and 10m/s, the ROS increased by 0.51 m/s. For the Balbi model, it also produced a non-linear increase in the ROS. Under low wind conditions (0-2m/s), the Balbi model provided a higher ROS than the Rothermel model. Once the winds increased past 2m/s, then the Rothermel model produced greater ROS values.

![Graph showing the ROS as a function of wind speed](image)

Figure 2.6: Comparison of the Balbi model and Rothermel model under increasing midflame winds.
The nonlinear, exponential Rothermel curve came from the wind coefficient. Since the base model was built on a no wind and no slope assumption, the only factor affected was the wind coefficient \( \phi_w \). As the wind speed \( U \) increased, it is raised to a constant value that was found through experimentation (B), which produced an exponential growth in the ROS. This can be seen in the truncated equation (2.59) for \( \phi_w \) that focuses on the exponential growth aspect of the wind coefficient.

\[
\phi_W = CU^R
\]

This behavior in the Balbi model was due to \( R_f \) and \( R_c \). In \( R_f \), the wind speeds affected the flame tilt. With a stronger wind speed, the closer the flame is brought to the unburnt fuel which preheats it more effectively. As the flame was pushed closer, the angle between the flame and the fuel decreased, which led to a nonlinear increase in the ROS in equations (2.60). \( R_c \) produced a linear increase to the ROS as this component is solely based on the heat transfer due to convection. With a higher wind speed, more heat was transferred convectively which helps preheat the fuels. Under low wind conditions (0-2m/s), \( R_c \) contributed more to the ROS. Under high winds, \( R_f \) overtook \( R_c \) and was the main contributor to the ROS. \( R_c \) was still relevant under high winds as the heat transfer mechanism is still present.

\[
\Gamma = \arctan\left(\tan(\alpha) + \frac{U}{u_0}\right)
\]
\[
R_f = 1 + R \ast \cos(\Gamma)
\]
\[
R_c = U \ast \exp(-K_{drag} \ast R)
\]

**Slope**

Figure 2.7 shows the progression of the ROS as a function of the slope on a log scale. The Rothermel model produced a non-linear, exponential growth in the ROS as a function of slope. The ROS accelerated rapidly when the slope approaches 60°, indicating the Rothermel model is very sensitive to steep terrains. Usually the model would cap the ROS at 6m/s, but that was removed for this analysis. With slopes less than 10°, the model remains stable with no large increases in the ROS. The Bali model also exhibited similar behavior as the Rothermel with a nonlinear increase in the ROS, however this curve was not exponential like the Rothermel model. The Balbi model ROS accelerated when the slope approached 70°, but it remained stable with no acceleration in the ROS until that point. Under small slope conditions,
the Balbi model yielded a higher ROS, but as soon as the slope reaches 15°, the Rothermel model quickly accelerated and yielded a higher ROS.

Figure 2.7: Comparison of the Balbi model and Rothermel model under increasing slope.

The exponential, non-linear behavior in the Rothermel model is solely based on the slope component in the model ($\phi_s$). An increase in the slope exposes the unburnt fuel to additional radiant heat Rothermel [1972], which preheats it and allows the fire to spread faster. Since this parameter was made to fit an exponential curve in the correlation parameter for the slope coefficient (Figure 22 in [Rothermel, 1972]), the resulting equation for slope uses an exponential increase where the slope is raised to the power of 2. This can be seen in the modified, truncated equation for $\phi_s$ in equation (2.61). The full equation is equation (2.23).

$$\phi_s = \tan \phi i^2$$  \hspace{1cm} (2.61)

The Balbi model also produced a non-linear result. This is due to the angle of the flame decreasing, and approaching the surface (similar to Rothermel), which allows $R_f$ to preheat the fuels ahead of the fire. This also impacts the $R_c$ as with a greater slope, the flame tilts closer to the fuel, which allows for the convective heat transfer to more effectively reach the fuel and ignite them. With slopes above 70°, the ROS accelerated as the flame body tilt angle to the surface was so small that the fire was essentially on top of the unburnt fuels at those steep slopes.

52
Fuel Moisture

Figure 2.8 shows the evolution of the ROS as a function of increasing fuel moisture without wind or slope as those produced the same behavior in the model only the ROS is slightly higher. The Rothermel model produced a decreasing non-linear, non-monotonic, 3rd order polynomial curve as a function of the ROS. From 0% to ~8%, the ROS decelerated until ~10% when the ROS began to accelerate slightly, which resulted in the ROS not decreasing as quickly. When the FMC reaches ~17%, the ROS decelerated again, dropping to 0 m/s for the ROS. The ROS goes down to 0 as 25% is the fuel moisture of extinction for this fuel type. The Balbi model also produced a decreasing non-linear curve as a function of increasing FMC. Since the Balbi model does not have a fuel moisture of extinction, the ROS will never fully reach 0, instead it will only approach 0 under very wet conditions. The Balbi model yielded higher ROS values than the Rothermel model. With an increase in the FMC, a decrease is expected in the ROS as it takes more energy for the fire to dry out the fuel and then begin the combustion process. With more energy required to ignite the fire, it will slow down the fire’s propagation as it has to remove all moisture.

![Comparison of the Balbi model and Rothermel model under increasing FMC with no slope and no wind.](image)

This behavior in the Rothermel model is due to the third order polynomial that is used for the calculation of the moisture damping coefficient, which is then used in the calculation for the reaction intensity. The FMC is used in other places, but those all would produce a linear result. A truncated list of equations can be found in equation (2.62) while the full equation is equation (2.9).
\[ rtemp1 = \frac{FMc}{fuelmce} \]

\[ etam = -3.52 \times rtemp1^3 \]

\[ ir = etam \]

The Balbi model on the other hand follows this trend due to the decrease in \( R_b \). Since there is no slope or wind, there is no contribution from \( R_e \) and \( R_f \). FMC is used in the calculation of the activation energy, which is then used in the calculation of \( R_b \). Since the activation energy is used in the denominator, with an increase in the activation energy, the ROS will decrease. In this sense, \( R_b \) becomes equation (2.63).

\[ R_b = \frac{1}{q} \]  

(2.63)

**Fuel Height**

Figure 2.9 shows the ROS progression as a function of the fuel height (fueldepthm in the models). The Rothermel model yielded a linear increase with an increase in the fuel height. The Balbi model produced a non-linear increase with an increase in fuel height. With fuel heights less than 1m, the Balbi model yielded the faster ROS. When fuel heights got above 1m, the Rothermel model then provided the faster ROS.

![Figure 2.9: Comparison of the Balbi model and Rothermel model under increasing fuel height.](image-url)
The linear behavior in the Rothermel model is due to the fuel height being used linearly within the model, which produced a linear ROS as a function of the fuel height. The fuel height is used to calculate the packing ratio and the ovendry bulk density. All of which are linear equations.

As for the behavior in the Balbi model, this occurred due to $R_e$ and $R_f$ as $R_b$ remained linear with the increase in fuel height. Since wind and slope are present in this study, that drove $R_e$ and $R_f$ which ultimately made the curve nonlinear with an increasing fuel height. If there was no wind and no slope, the driving factor for the ROS would be $R_b$ which increased linearly in the model. With an increase in the fuel height, there is more area for the fire to heat up for all components, which then preheats the fuels and allows the fire to spread faster.

**SAVR Comparison**

Figure 2.10 presents the evolution of the ROS as a function of the SAVR. The Rothermel model produced a non-linear and non-monotonic behavior that can be divided into three parts. For SAVR lower than 500 ft$^{-1}$, the model showed a rapid increase in the ROS. Then, for a SAVR between 500 ft$^{-1}$ and 2000 ft$^{-1}$, the ROS decreased to about 20% of the maximum values reached for $\sigma = 500$ ft$^{-1}$. Above 2000 ft$^{-1}$, the ROS increased non-linearly with the SAVR. On the other hand, Balbi’s model provided a strictly increasing behavior that can be described by two linear sections. For SAVR lower than 1400 ft$^{-1}$, the slope is $1.61 \times 10^{-4}$, for SAVR above this threshold, the slope is $5.86 \times 10^{-5}$.

![Figure 2.10: Comparison of the Balbi model and Rothermel model under increasing fuel SAVR.](image-url)
This threshold also corresponds to the moment where the two models intersect. For SAVR lower than 1400 ft\(^{-1}\), the Rothermel model provides a greater ROS value, and for SAVR above this threshold, the Balbi model gives greater ROS values.

The nonlinear Rothermel ROS curve comes from the use of SAVR in the Rothermel model. SAVR is used in multiple nonlinear equations in the model (such as equation (2.20), (2.4), (2.15), (2.16)), producing a nonlinear result in the ROS. In the Balbi model, the ROS

This behavior in the Balbi model is due to \( R_f \) and \( R_b \). In those equations, there is a minimum function (examples can be seen in the truncated equations (2.64)) that limits how high the SAVR can get before it takes a constant parameter. As the SAVR increases, there are contributions from all three parameters (\( R_c, R_f \) and \( R_b \)), which was why the fastest acceleration occurs with smaller SAVR’s. Once the limit is reached, the contributions from \( R_f \) and \( R_b \) to the ROS stop as they became constant, and \( R_c \) was the only parameter contributing to the ROS. This slowed down the acceleration of the ROS as \( R_c \) was the only parameter contributing to the ROS, but it still linearly increased with an increase in SAVR.

\[
R_f = \min \left( \frac{S_I}{2\pi}, 1 \right) \\
R_b = \min \left( \frac{S_I}{2\pi}, 1 \right)
\]  

(2.64)

Where \( S_I \) is linked to the SAVR with the fuel height and total packing ratio.

2.5 Discussion

Both the Balbi model and Rothermel model have proven to be useful and reliable in certain environments despite the differences between them. By using observational and statistical data, and physical properties, the Rothermel model is limited on the conditions it can be used in. One major feature of the Rothermel model is the fuel moisture of extinction, which limits how a fire can spread under moist conditions. The Balbi model only relying on physical properties puts it at an advantage since it can account for more extreme weather and fuel conditions and not have issues converging to a solution with respect to these experiments. Both models had similar assumptions in the beginning by assuming no slope no wind conditions, but they quickly diverged from each other. The Rothermel model was developed based on the heat balance model and made several assumptions based on observations and physical proper-
ties. The Balbi model uses equations based on various heat transfers and forms equations based on that concept instead of relying on just one principle and simplifying that down. The Rothermel model also considers different properties of heat transfer than the Balbi model. In the Rothermel model, processes such as the reaction intensity, heat of preignition, and reaction velocity are used to calculate the ROS. In the Balbi model, the authors utilize similar concepts such as the preheating sub model, but it mostly relies on how much heat is transferred to unburnt fuels and what processes are causing that to occur (such as the base radiative component and flame body radiation).

In terms of the wind and slope coefficients, these were approached similarly in the models by using experimental data to better fit the parameters that were already developed. These parameters were then related to fuel and weather conditions as they vary under different conditions. The overall equations for them vary since the models were built with different approaches. With no flame body radiation in the Rothermel model, the slope and wind parameters can quickly become the main contributors to the ROS with wind and slope. Whereas with the Balbi model, most parameters change with the exception of the base radiation. With a greater wind and slope, there are more in drafts into the fire, increasing the convective and flame body heat transfer.

2.6 Conclusion

Both models handled extreme cases with the exception for slope in the Rothermel model. When it comes to extreme conditions, the Balbi model performed much better than the Rothermel model. With extreme wind speeds and extreme slope angles the Rothermel model resulted in ROS above 10m/s whereas the Balbi model provided a much more reasonable ROS under 5m/s. With the FMC, the Rothermel model produced zero ROS when the fuel reaches the fuel moisture of extinction. This was not the case in the Balbi model as the Balbi model accounts for high FMC in the fuel and calculates how much heat it would take to dry out the fuel and ignite it. That is where some of the main differences between these models come in. By using purely physical properties to create a model rather than using physics and observations, the physical model will likely yield a much closer approximation to the ROS since finer scale details are being accounted for and implemented into the model. The Balbi model is constantly being improved as well with another version soon to come that will remove the iterative process from the current model. The Rothermel model has had a few updates throughout the years, but not nearly as many. Running some small base tests on the model this is easily seen as the model seems to overpredict the ROS (at least in this dataset it exceeded the observed ROS and the Balbi model).
Rothermel model is still a useful model that can be and is currently implemented into larger fire models. For future work, running the Balbi model in a larger wildfire model (like WRF-SFIRE) on experimental datasets where the ROS is known can validate the accuracy of the model.
Chapter 3
Comparison of Rothermel Rate of Spread Model in BehavePlus and WRF-SFIRE

3.1 Introduction

WRF-SFIRE and BehavePlus both utilize the Rothermel ROS model to calculate how fast a fire will propagate under various terrains and weather conditions. However, their implementations differ from one another which yields different ROS results given the same fuel class and weather. WRF-SFIRE uses the Rothermel model implementation from the original CAWFE code [Coen, 2013] and BehavePlus uses an updated Rothermel model that incorporates different fuel parameters that can represent more fuel properties under various conditions [Andrews, 2013]. To investigate the Rothermel implementation in BehavePlus, we utilized Andrews [2018] paper as it provides a detailed discussion on the data flow in the ROS calculation in BehavePlus.

For this analysis, the final ROS equations from both models were compared, and each component with major differences was further discussed and analyzed. The first section (3.2) analyzes the no slope and no wind component, and the second section (3.6) focuses on the analysis of the effect of slope and wind on the ROS. For the analysis these models, we used the same vector of input parameters corresponding to fuel type 1 (short grass), 3% FMC, no wind, and no slope.

3.2 Rothermel Model From BehavePlus and WRF-SFIRE

To analyze the models, we first investigated the final form of the two Rothermel models. This is important as any discrepancies between the base computation would result in a different output. Since wind and slope are represented by coefficients ($\phi_w$ and $\phi_s$), we excluded those initially and analyzed them later. We then examined the coefficients within the model (such as the reaction intensity), that produced a different result between the two models.

3.2.1 BehavePlus

$$r_0 = \frac{ir \times xif r}{heat\_sink\_dead + heat\_sink\_live} \times 0.00508,$$

$$0.0297 = \frac{939.3928 \times 0.0578}{(0.0340 \times 0.9613 \times 283.4800) + 0} \times 0.00508,$$  

(3.1)
Where:

\( r_0 \) is the rate of spread under no slope and no wind conditions \( \left[ \frac{m}{s} \right] \)

\( ir \) is the reaction intensity \( \left[ \frac{ft^2}{min} \right] \)

\( xifr \) represents the propagating flux ratio

heat\_sink\_dead is the heat sink of the dead fuel

heat\_sink\_live represents the heat sink of the live fuel

### 3.2.2 WRF-SFIRE

\[
\begin{align*}
  r_0 &= \frac{ir \times xifr}{\rho_b \times \varepsilon \times Q_{tg}} \times 0.00508, \\
  0.0265 &= \frac{812.8685 \times 0.0577}{0.0330 \times 0.9613 \times 283.4800} \times 0.00508,
\end{align*}
\]

Where:

\( r_0 \) is the rate of spread under no slope and no wind conditions \( \left[ \frac{m}{s} \right] \)

\( ir \) is the reaction intensity \( \left[ \frac{ft^2}{min} \right] \)

\( xifr \) represents the propagating flux ratio

\( \rho_b \) is the oven dry bulk density \( \left[ \frac{lb}{ft^3} \right] \)

\( \varepsilon \) represents the effective heating number

\( Q_{tg} \) is the heat of preignition \( \left[ \frac{lbm}{lb} \right] \)

Comparing the 2 Rothermel models, the structure of the two final equations differ between the models. Equation (3.1) has heat\_sink\_dead and heat\_sink\_alive in the denominator whereas equation (3.2) uses \( \rho_b \), \( \varepsilon \), and \( Q_{tg} \) from the dead fuels in the denominator. Despite the same input conditions, the output differed between each model. To find these differences, we went through each component of equation (3.1) and equation (3.2) to find which component caused the difference in the final calculation.

### 3.3 Heat Sink Dead and Heat Sink Live

The first difference between the models lies in the final equation for the ROS. BehavePlus equation (3.1) uses the heat sink for both the dead and live categories in the denominator whereas WRF-SFIRE equation (3.2) uses the heat sink for just the dead categories \( \left( \rho_b \right. \), \( \varepsilon \), and \( Q_{tg} \)). This is because WRF-SFIRE does not explicitly resolve live fuel components. The heat sink parameters for dead and live fuels
contain the same general equations as in the WRF-SFIRE ROS denominator. However, they include additional parameters such as both dead and live weighting factors, effective heating number of each size class within each category, and the heat of preignition of each size class within each category. In this case, heat sink dead contains the same calculations as the denominator of equation (3.2). To show how the heat sinks are calculated, the equations for heat sink dead and heat sink live are presented in Table 3.1.

Table 3.1: Evaluating the heat sink parameters from BehavePlus and WRF-SFIRE. \( S_d \) is the heat sink for the dead fuel \( \frac{BTU}{ft^2} \), \( S_l \) is the heat sink for live fuel \( \frac{BTU}{ft^2} \), \( \rho_b \) is the ovendry bulk density \( \frac{lb}{ft^3} \), \( f \) is the weighting factor, \( q_{ig} \) is the heat of preignition \( \frac{BTU}{lb} \), the subscript \( d \) represents dead fuel, \( l \) represents live fuels, \( w \) represents woody fuels, and \( h \) represents herbaceous fuels.

<table>
<thead>
<tr>
<th>BehavePlus</th>
<th>WRF-SFIRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_d = \rho_b f_d \left( \sum_{i=1,10,100} f_i \varepsilon_{q_{ig,i}} + f_h,d \varepsilon_{h,d,q_{ig,d}} \right) )</td>
<td>( \rho_b \varepsilon q_{ig} )</td>
</tr>
<tr>
<td>9.29 = 0.0340 * 1 * (1 * 0.9613 * 283.4800) + 0</td>
<td>8.99 = 0.0330 * 0.9613 * 283.4800</td>
</tr>
<tr>
<td>( S_l = \rho_b f_l (f_h \varepsilon_h q_{ig,h} + f_w \varepsilon_w q_{ig,w}) )</td>
<td></td>
</tr>
</tbody>
</table>

In this analysis, the fuel type used contained no 10hr, 100hr, or live component and the weighting factor \( f_{1,1} \) and \( f_{dead} \) were equal to 1. This was done to make the analysis easier and provide a more direct comparison between the models. It has to be noted that with different fuel types and different fuel moistures, the BehavePlus equations in Table 3.1 would no longer be like the denominator in equation (3.2).

### 3.4 Reaction Intensity

Another difference between the models was the calculation of the reaction intensity (ir). In equation (3.1), the value for ir (939.39 \( \frac{BTU}{ft^2 \cdot min} \)) was much greater than in equation (3.2) where ir was 812.86 \( \frac{BTU}{ft^2 \cdot min} \). Below (in Table 3.2) is the calculation for ir for both models.

These two parameters differed from each other by 14.4%. The biggest difference between the two equations were the values for \( \Gamma' \) and the \( h \). The \( h \) is an input parameter from the fuels file and it varies between these two models. In BehavePlus, \( h \) is set to 8000 BTU/lb and \( h \) in WRF-SFIRE is 7496.2 BTU/lb. By modifying the \( h \) in BehavePlus to have the same value as WRF-SFIRE, we obtained an ir \( [btu/ft^2 \cdot \text{-min}] \) of 880.2345 which is still significantly larger that the calculation in WRF-SFIRE. To
Table 3.2: Comparison of the calculations for \( \text{ir} \) from BehavePlus and WRF-SFIRE. \( \text{ir} \) is the reaction velocity \( \frac{\text{ir}}{\text{m}_{\text{min}}} \), \( \Gamma' \) is the optimum reaction velocity \( \frac{1}{\text{m}_{\text{min}}} \), \( \eta_m \) is the moisture damping coefficient, \( \eta_s \) is the mineral damping coefficient, \( W_n \) is the net fuel loading \( \frac{\text{Lb}}{\text{h}} \), \( h \) is the fuel heat \( \frac{\text{BTU}}{\text{h}} \), the subscript \( d \) is for dead fuels, and \( l \) is for live fuels.

<table>
<thead>
<tr>
<th>BehavePlus</th>
<th>WRF-SFIRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{ir} = \Gamma'(W_n, d \eta_m, d \eta_s, a + W_n, l \eta_m, l \eta_s, l) )</td>
<td>( \text{ir} = \Gamma' W_n, h \eta_m, \eta_s )</td>
</tr>
<tr>
<td>939.3928 = 14.2014 * (0.0321 * 8000 * 0.6169 * 0.4174 + 0 + 0)</td>
<td>812.8685 = 13.4642 * 0.0313 * (7.4962 \times 10^3) * 0.6169 * 0.4147</td>
</tr>
</tbody>
</table>

To better understand what led to these differences, we went through the calculations for \( \Gamma' \) to find what caused these differences in the calculation. These calculations can be seen in Table 3.3.

### 3.4.1 Optimum Reaction Velocity (\( \Gamma \))

Table 3.3: Comparison of the calculations for \( \Gamma \) from BehavePlus and WRF-SFIRE. \( \beta_{fl} \) is the packing ratio, \( \beta_{op} \) is the optimum packing ratio, \( a \) is the optimum reaction velocity, \( \sigma \) is the SAVR, \( \Gamma_x \) is the maximum reaction velocity \( \frac{1}{\text{m}_{\text{min}}} \).

<table>
<thead>
<tr>
<th>BehavePlus</th>
<th>WRF-SFIRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma' = \Gamma_x \left( \frac{\beta_{fl}}{\beta_{op}} \right)^n \exp(a(1 - \frac{\beta_{fl}}{\beta_{op}})) )</td>
<td>( \Gamma' = \Gamma_x \left( \frac{\beta_{fl}}{\beta_{op}} \right)^n \exp(a(1 - \frac{\beta_{fl}}{\beta_{op}})) )</td>
</tr>
<tr>
<td>14.2014 = 16.1837 * 0.2534^0.2087 * \exp^{0.2087(1 - 0.2534)}</td>
<td>13.4642 = 16.1837 * (0.24590.2836) * \exp^{0.2836(1 - 0.2459)}</td>
</tr>
<tr>
<td>( \Gamma_x = \sigma^{1.5} / (495. + 0.0594*\sigma^{1.5}) )</td>
<td>( \Gamma_x = \sigma^{1.5} / (495. + 0.0594*\sigma^{1.5}) )</td>
</tr>
<tr>
<td>16.1837 = 2.0706 \times 10^5 (495 + 0.0594* 2.0706 \times 10^5)</td>
<td>16.1837 = 2.0706 \times 10^5 (495 + 0.0594* 2.0706 \times 10^5)</td>
</tr>
<tr>
<td>( \frac{\beta_{fl}}{\beta_{op}} = \beta_{fl} / \beta_{op} )</td>
<td>( \frac{\beta_{fl}}{\beta_{op}} = \beta_{fl} / \beta_{op} )</td>
</tr>
<tr>
<td>0.2534 = 0.0011 / 0.0042</td>
<td>0.2459 = 0.0010 / 0.0042</td>
</tr>
<tr>
<td>( \beta_{fl} = \text{fuelload} / (\text{fueldepth} \times \text{fueldens}) )</td>
<td>( \beta_{fl} = \text{fuelload} / (\text{fueldepth} \times \text{fueldens}) )</td>
</tr>
<tr>
<td>0.0011 = 0.0340 / (1 * 32)</td>
<td>0.0010 = 0.0330 / (1.0007 * 32)</td>
</tr>
<tr>
<td>( a = 133 \sigma^{-0.7913} )</td>
<td>( a = 133 \sigma^{-0.7913} )</td>
</tr>
<tr>
<td>0.2807 = 133 * 3500^{-0.7913}</td>
<td>0.2836 = 133 * 3500^{-0.7913}</td>
</tr>
</tbody>
</table>

The major differences between the calculations for the optimum reaction velocity were the calculations of the coefficient for optimum reaction velocity (\( a \)). WRF-SFIRE uses the equation from the original Rothermel paper, but BehavePlus uses a different equation taken from Andrews [2018], which yielded a different value. By modifying the BehavePlus model and forcing \( a \) to equal 0.2836, the resulting ROS was the same as the WRF-SFIRE calculation, indicating this parameter greatly influenced the final ROS.
3.5 Different Fuel Classes

Another difference among the models is that BehavePlus incorporates different fuel classes (such as 1hr FMC, 10hr FMC, 1hr fuel load, 10hr fuel load, etc.) into the model whereas WRF-SFIRE only uses one value per class to represent the fuel. There are many places where BehavePlus uses the different classes for the calculation of the ROS, and they impact the model significantly.

3.5.1 Fuel Load

One of the fundamental fuel properties is fuel load. BehavePlus adds all the fuel loads together but this total fuel load is only used in the calculation of \( \rho_b \) and \( \beta_{fl} \) (packing ratio). However, different fuel loads are used in computations of the mean total surface area per unit fuel cell, weighting factors of each size class within each category, net fuel loading of each size class within each category, and the live fuel moisture of extinction. The mean total surface area per unit fuel cell is then used to calculate weighting factors for each fuel type. These weighting factors are based on a concept that a singular characteristic parameter can be found by weighting the variations in the parameter across the heterogeneous mixture [Andrews, 2018]. Weighting the fuels this way results in the highest sensitivity of the ROS to the fine fuel parameters [Andrews, 2018].

For example, comparing the two models, the total fuel load for fuel category 7 (Southern Rough) in BehavePlus is 0.2240 lb/ft\(^2\), but the fuel load in WRF-SFIRE for the same fuel type is 0.2172 ft\(^2\). With bigger fuels, there are more classes for that fuel category compared to finer fuels. With more classes of fuels, this will add an extra weighting parameter to the final calculation.

3.5.2 Surface Area to Volume Ratio

Another fundamental fuel property is the SAVR. In BehavePlus, the different SAVR classes are used extensively throughout the model and some examples can be seen in equation (3.3). WRF-SFIRE only uses one value for SAVR for every fuel type. Like with the fuel load, the larger fuels have more classes for the SAVR compared to the finer fuels which typically have one or two classes in the BehavePlus model. When BehavePlus only uses one SAVR (calculated from all SAVR classes and weighting parameters), the output is the same as in WRF-SFIRE. For example, the SAVR in BehavePlus for fuel type 11 (light logging slash) is 1182 ft\(^{-1}\), and in WRF-SFIRE it is 1182 ft\(^{-1}\). However, by incorporating more classes
of SAVR in BehavePlus, that would yield a different result under similar conditions.

\[ \sum_{i=1,10,100,hd,hl,w} A_i = \sigma_i * w_{0,i}/\rho_p \]

\[ A_{\text{dead}} = \sum_{i=1,10,100,hd} A_i \]

\[ A_{\text{live}} = \sum_{i=hl,w} A_i \]

\[ AT = A_{\text{dead}} + A_{\text{live}} \]

\[ \sigma_{\text{dead}} = \sum_{i=1,10,100,hd} f_i * \sigma_i \]

\[ \sigma_{\text{live}} = \sum_{i=hl,w} f_i * \sigma_i \]

\[ \sum_{i=1,10,100,hd,hl,w} \exp_i = w_{0,i} * \exp\left(\frac{-138}{\sigma_i}\right) \]

\[ \sum_{i=1,10,100,hd,hl,w} \varepsilon_i = \exp\left(\frac{-138}{\sigma_i}\right) \]

Where: \( \sigma = \text{SAVR} \left[ \frac{1}{ft^2} \right] \)

\( \rho_p = \text{fuel density} \left[ \frac{lb}{ft^3} \right] \)

\( A = \text{mean total surface area per unit fuel cell of each size class within each category} \)

\( AT = \text{mean total surface area of the fuel} \)

\( \sigma_{\text{dead}} \) and \( \sigma_{\text{live}} \) are the fuel particle surface-to-volume ratio of the dead and live categories

\( \exp = \text{part of the live fuel moisture of extinction calculation} \)

\( \varepsilon \) is the effective heating number of each size class within each category

The subscripts 1, 10, 100 stand for 1hr, 10hr, and 100hr fuels.

The subscripts \(hd, hl, w\) stand for herbaceous dead, herbaceous live, and woody fuels.

### 3.5.3 Fuel Moisture Content

The last parameter with multiple classes is the fuel moisture. This is an input parameter for both of the models since the FMC controls the heat of pre-ignition and the overall ROS. BehavePlus uses the multiple FMC values in their calculations of the: live fuel moisture of extinction, fuel moisture content of the dead and live categories, and the heat of pre-ignition of each size class within each category. WRF-SFIRE only uses one FMC value for each fuel.
3.6 Wind and Slope

The equations to calculate the wind and slope parameters differ slightly between both models as well. BehavePlus incorporates both the total SAVR and fuel load in their calculation, whereas WRF-SFIRE just uses a single value. The other major difference between the models is how the wind speed is input into the model. In BehavePlus, there is a limit to how strong the winds can get before the model caps it off. This cap is based off the reaction intensity. If the reaction intensity multiplied by a coefficient in the model is less than the input wind speed, then the model will use the reaction intensity multiplied by the coefficient. This can be seen in the truncated wind coefficient equation (3.4). WRF-SFIRE has a set cap at 30 m/s (as can be seen in the truncated wind coefficient equation (3.5)).

\[ \phi_w = \min(\max(0, U * 196.850), 0.9 * ir) \]  
\[ \phi_w = \min(U, 30) \]  

This difference in thresholds will affect the ROS in under super high winds as some fuels ROS will be capped off below 1 m/s in the BehavePlus model in Figure 3.1a, indicating this model is much less sensitive to changes in wind. In WRF-SFIRE, the same fuel type under the same conditions results in the ROS above 5 m/s in Figure 3.1b. This artificial limit on the wind was developed to avoid over-prediction of fires burning in sparse fuels under high winds, and it also plays a role in low intensity fires resulting from high moisture content [Andrews, 2018]. These artificial caps reduce the sensitivity of the model to high winds as the ROS cannot exceed a certain threshold in both models, which can reduce overprediction in the fire spread. However, a less sensitive model may result in underprediction of the ROS, which can affect fire fighting tactics as the fire may begin to exhibit extreme behavior and the model cannot pick it up due to the artificial cap set on the ROS and the winds.

An example of how this influences the models can be seen in Figure 3.1. Panel a) shows the ROS in higher winds insensitive to the wind speed, whereas panel b) shows the SFIRE representation in which wind speed still influences the ROS up to 15 m/s. The cap in the original WRF-SFIRE implementation would cap the resulting ROS for all categories at 6 m/s which generally wouldn’t happened under winds up to 15 m/s.

The slope parameter is calculated the same way between the models with the exception of BehavePlus including the total fuel load for all size classes compared to WRF-SFIRE which uses one bulk value for
Figure 3.1: a) BehavePlus ROS comparison for fuel types 5-9 with an increasing midflame wind speed. b) WRF-SFIRE ROS comparison for fuel types 5-9 with an increasing midflame wind speed.

the fuel load.

3.7 Conclusion

The two implementations of the Rothermel model in BehavePlus and WRF-SFIRE produced different results even under similar conditions using the same fuel. BehavePlus incorporates both live and dead components into the model which allows the model to account for the impact of live fuels on the ROS. WRF-SFIRE always assumes the vegetation is dead and it only accounts for the dead fuel components, which may not be fully representative of the fuel conditions. Besides accounting for the live and dead fuels, BehavePlus uses slightly different equations to calculate the reaction intensity which deviates the ROS from the WRF-SFIRE model even under conditions where 100% of the fuel can be classified as dead. This difference comes from the calculation of the optimum reaction velocity. BehavePlus uses an updated calculation whereas WRF-SFIRE uses the original calculation from the CAWFE model. Besides the differences in calculations, the initial model approach differs between WRF- SFIRE and BehavePlus. BehavePlus accounts for varying fuel parameters such as the fuel load (with BehavePlus accounting for 1hr, 10hr, 100hr, etc.), SAVR (1hr, 10hr, 100hr, etc.), and FMC (1hr, 10hr, etc.), whereas WRF- SFIRE uses one bulk fuel parameters per fuel type without the specification into classes (1h, 10h, 100h, etc.) contributing to a given fuel type. In BehavePlus these components are then used to calculate a weighting factor used in the final calculation of the ROS depending on the fuel type. Lastly, BehavePlus has a dynamic cap on the input wind speed, while WRF-SFIRE has an artificial cap on the input wind speed.
(30 m/s) and the final ROS (6 m/s). For future work examining fire propagation at high wind conditions would be needed to assess if these caps are realistic and needed.
4.1 Abstract

The original implementation of the Rothermel ROS model in WRF-SFIRE used only 11 fuel categories with a single value for parameters such as fuel load, fuel moisture, and SAVR. Later, 2 more fuels were added to the 11 fuels to create the 13 categories ([Albini, 1976]). This classification presents an issue as these 13 fuels may not fully represent the variability of fuel properties in the western United States. Being able to have exact fuel properties everywhere would not only be nearly impossible as the dataset would be too large, but mapping that constantly would prove too difficult. To combat this, a larger set of fuel models that represent multiple fuel classes (timber, grass, shrubs, etc.) and contain more parameters that allow differences in spatial distributions per fuel type and fuel class would increase the accuracy of the Rothermel ROS model as it accounts for more fuels. These fuels can then represent the entirety of the western United States while incorporating weather and seasonal changes as the fuels cure. In order to address the limitation of the 13 categories and increase granularity of the fuel description the 40 Scott and Burgan (S&B) fuel categories have been implemented. With 40 fuels categories, more complex fuel characteristics can be represented to increase the diversity of possible fire spreads. For instance, instead of representing all shrub as one and setting them to a common value, now there is a larger diversity that can represent different types of shrubs each with different set of parameters introduced with the intention to improve ROS calculations.

4.2 Introduction

When Rothermel created the fire spread model, he originally had 11 fuels for his model. These fuels were developed for the National Fire-Danger Rating System (NFDRS), and they were representative of a large portion of the forests, brush fields, and grasslands found in the temperate climates of North America [Rothermel, 1972]. To then get to the 13 categories that are currently implemented in models, Frank A. Albini added 2 more fuel classes, and he made a few changes to the model. One of the changes includes changing the dead fuel moisture of extinction from a constant 30% to various values, as it was set to 30% in the original Rothermel model [Andrews, 2018]. These fuel models then came to be the original 13 Albini categories that WRF-SFIRE, WRF-FIRE, Wild Fire Analyst, BehavePlus, and other
The 13 fuel models are used to establish the current fire danger when coupled with the weather. The NFDRS depends upon the weather conditions along with the fuel models to represent the day-to-day and seasonal trends in fire danger [Anderson, 1982]. The fuels can also be modified to better fit the current conditions (based on the live/dead ratios, moisture content, fuel loads, drought influences), which allow these models to be fine-tuned to better estimate fire behavior during the peak of fire season [Anderson, 1982]. These 13 fuels cannot match some of the real-world fuel scenarios. Especially when it comes to wildland fire use, prescribed burns or burns setups for experimental purposes (such as the FireFlux2 experimental burn). They are not able to properly account for the surrounding conditions in cases where there is not a high fire danger as they were designed for the purpose of being used during the peak of fire season. This includes setting the grass models as fully cured so they can represent the severe part of the fire season, but can lead to overprediction in grasslands that are not fully cured [Scott and Burgan, 2005]. There is also a lack of fuel categories in high humidity environments, which would greatly change the fuel parameters. Therefore, Scott and Burgan [2005] developed a new set of fuel models that can characterize additional fuels and provide input into the Rothermel model. These new fuels follow the similar fueled assumptions of homogeneity and continuity as in the original fuel categories [Rothermel, 1972; Scott and Burgan, 2005].

To develop these new fuel models, S&B compiled a series of fuel detailed information from the Natural Fuels Photo Series (and some other sources) and found a range of different fuel models that were needed based on the range of fuel complex characteristics [Scott and Burgan, 2005]. They then assigned to each fire-carrying fuel type the dead fuel moisture of extinction to each fuel complex and grouped each fuel by fine fuel, fuel type, and extinction moisture [Scott and Burgan, 2005]. From these groups, they created one fuel model and ended up with about 60 different groups. They assigned the SAVR, live herbaceous, live woody, and fuelbed depth for each class and set the heat content to 8000BTU/lb for all fuels except for one (GR6 at 9000 BTU/lb) and then simulated fire behavior over a range of midflame wind speeds and several fuel moisture scenarios [Scott and Burgan, 2005]. Several of the models were found to have similar flame lengths and ROS so those models were scrapped, and they added a few stylized fuel models to simulate specific fire behavior not simulated by any of the initial 60 draft models [Scott and Burgan, 2005]. After adjusting the remaining fuels, the new draft models were sent to fire managers and researchers for further review [Scott and Burgan, 2005]. Their comments were taken into consideration and incorporated into the fuel models.
With this new set of fuel models, many fire modelers began implementing them into their models such as BehavePlus. These new fuel models expand the capabilities of these models to better account for different fuel characteristic. It has to be noted that the original 13 fuel models are kept in these fire models since there is no overlap between the S&B 40 and the 13 Albini categories [Andrews, 2018]. This results in 53 different fuel models available to choose from within these models.

4.3 Methods

To test the 40 S&B fuels in WRF-SFIRE, the existing file in WRF-SFIRE (namelist.fire) that contains the 13 Albini fuels has been modified to account for the 40 fuel categories. Next the updated BehavePlus ROS has been implemented into WRF-SFIRE to be able to leverage these new parameters (such as 1hr fuel load, 10hr fuel load, 1hr SAVR, etc.). With these new fuels, we then compared the new fuels to the Albini fuels to see which fuel out of the 40 S&B fuels matches the closest in terms of ROS the original Albini fuels. These categories are shown in Table 4.1.

<table>
<thead>
<tr>
<th>Albini fuel category</th>
<th>Fuel category from the 40 S&amp;B fuels that closely relates in terms of ROS</th>
<th>Description of how the ROS compares</th>
<th>Flame length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Short grass (1ft)</td>
<td>GR7</td>
<td>Comparable</td>
<td>Significantly higher</td>
</tr>
<tr>
<td>2: Timber (grass and understory)</td>
<td>GR2</td>
<td>Comparable</td>
<td>Slightly lower</td>
</tr>
<tr>
<td>3: Tall grass (2.5 ft)</td>
<td>GR8</td>
<td>Comparable</td>
<td>Higher</td>
</tr>
<tr>
<td>4: Chaparral (6ft)</td>
<td>SH5</td>
<td>Slightly lower</td>
<td>Slightly lower</td>
</tr>
<tr>
<td>5: Brush (2ft)</td>
<td>SH7</td>
<td>Slightly higher</td>
<td>Higher</td>
</tr>
<tr>
<td>6: Dormant brush, hardwood slash</td>
<td>SH4</td>
<td>Slightly lower</td>
<td>Comparable</td>
</tr>
<tr>
<td>7: Southern rough</td>
<td>SH4</td>
<td>Comparable</td>
<td>Comparable</td>
</tr>
<tr>
<td>8: Closed timber litter</td>
<td>TL3</td>
<td>Comparable</td>
<td>Comparable</td>
</tr>
<tr>
<td>9: Hardwood litter</td>
<td>TL9</td>
<td>Comparable</td>
<td>Higher</td>
</tr>
<tr>
<td>10: Timber (litter and understory)</td>
<td>TU5</td>
<td>Comparable</td>
<td>Slightly higher</td>
</tr>
<tr>
<td>11: Light logging slash</td>
<td>SB1</td>
<td>Comparable</td>
<td>Comparable</td>
</tr>
<tr>
<td>12: Medium logging slash</td>
<td>SB2</td>
<td>Comparable</td>
<td>Slightly lower</td>
</tr>
<tr>
<td>13: Heavy logging slash</td>
<td>SB2</td>
<td>Comparable</td>
<td>Slightly lower</td>
</tr>
</tbody>
</table>

With these fuels, we then ran 13 small simulations and compared the shapes of the fires and the fire
heat flux to determine if the 40 S&B fuels were properly implemented and if they can work in WRF-SFIRE. Some of the spread rates are slightly lower or slightly higher in the table, but these were the best we could find to compare the Albini fuels ROS to the new S&B fuels ROS.

The simulation used for testing was a modified hill simulation that can be found in the WRF-SFIRE repository. This idealized WRF-SFIRE simulation used a 60m x 60m resolution atmospheric mesh with 41 vertical levels up to 1500m. The domain size was 42 x 42 grid points and the simulated timestep was 0.25 seconds. This simulation was run for 15 minutes, and ignition occurs 2 seconds after the simulation begins with a walking ignition line normal to the ambient winds. The fuel moisture was set at 40% for all simulation.

4.4 Results

The implementation of the 40 S&B fuels into WRF-SFIRE was successful as the model completed all 13 simulations with these new fuels. Not all S&B fuels from Table 4.1 output similar results to the original 13 fuels, but that is to be expected as the 40 S&B fuels were not designed to replace the Albini fuels, but instead be used alongside the Albini fuels. To compare the simulations, we analyzed a case where the Albini fuel category burned more area than the S&B category (greater than 1 in Figure 4.1), S&B burning more than the Albini category (less than 1 in Figure 4.1), and similar burned area (close to 1 in Figure 4.1). With these three cases, we then compared the shape of the fire, fire ground heat flux, and the distribution of the horizontal winds within the burn plot to determine the differences among the two fuels as well as see how well the model accounted for the new fuels and how they compare to the existing Albini categories.

4.4.1 Fuel Type 5 (Brush (2 ft)) and SH7

These two fuels produced the most similar results between all other fuel comparisons with a 2% difference between the fire areas. The shapes of the fire in Figure 4.2a are similar between the two fuel categories. The heat flux produced by the S&B fuel is greater than the Albini fuel. In the S&B fuels, the heat flux is concentrated at the head of the fire. As noted in Table 4.1, fuel category 5 is only similar in the ROS but the flame height is higher in the S&B fuels. The increased flame height produced a stronger heat flux. Consequently, the heat flux will created stronger fire-induced winds, which increased the local wind speed in Figure 4.2b.
Figure 4.1: Scale of the total fire area burnt from the Albini categories and S&B categories. The total fire area from the Albini category was divided by the total fire area from the S&B category to obtain the difference in area burnt. Fuels were based on Table 4.1.

4.4.2 Fuel Type 9 (Hardwood Litter) and TL9

In these simulations, the Albini fuel burned more area than the S&B fuels (20% more in the Albini category). The shape of the fire in the Albini category in Figure 4.3a is much more conical whereas the S&B fuel is more rounded. Like with section 4.4.1, the flame height produced from the S&B fuels is higher than the Albini fuels, which increased the heat flux and the mean wind speed due to stronger fire-induced circulations in Figure 4.3b.
Figure 4.2: a) Comparison of the fire shape for Albini fuel category 5 (Brush 2ft) (top left) and S&B fuel category SH7 (bottom left) with horizontal wind vectors at ~45m AGL color coded based on the horizontal wind speeds. Also in a) is the fire ground heat flux from the Albini fuel (top right), and S&B fire ground heat flux (bottom right) in kW/m². b) Box and whisker plot showing the mean distribution of the horizontal winds from the Albini fuel (Orange) and S&B fuel (Blue). These fire shapes, horizontal wind vectors, fire ground heat fluxes, and horizontal winds were taken from the last timestamp from the simulation.

4.4.3 Fuel Type 6 (Dormant Brush, Hardwood Slash) and SH4

In these simulations, the S&B fuel burned more area than the Albini fuel (with nearly double the amount of fire spread) in Figure 4.4a. The S&B fire burned much wider and produced a conical shape whereas the Albini fire was thinner and less conical. However, contrary to section 4.4.1 and section 4.4.2, the heat flux is greater in the Albini fuel category, which led to a faster mean wind distribution than the S&B fuels.
Figure 4.3: a) Comparison of the fire shape for Albini fuel category 9 (Hardwood litter) (top left) and S&B fuel category TL9 (bottom left) with horizontal wind vectors at ~45m AGL color coded based on the horizontal wind speeds. Also in a) is the fire ground heat flux from the Albini fuel (top right), and S&B fire ground heat flux (bottom right) in kW/m². b) Box and whisker plot showing the mean distribution of the horizontal winds from the Albini fuel (Orange) and S&B fuel (Blue). These fire shapes, horizontal wind vectors, fire ground heat fluxes, and horizontal winds were taken from the last timestamp from the simulation.

4.5 Conclusion

The 40 S&B fuels were successfully implemented into WRF-SFIRE and future simulations using these fuels can now be performed. This allows for a more accurate simulation since there is a wider array of fuels to choose from. There is still a need to keep both the Albini categories as well as the S&B categories as there are no two fuels that are alike between these models. Between the ROS, fire ground heat flux, winds, and fire area burned, the fuel models produced different results under the same ambient conditions that need to be taken into consideration. These results differed from the crosswalk table presented in Scott and Burgan [2005] outlining the similarities between the S&B fuels and the Albini fuels. With both models, that will mean there are now 53 different fuels for use in larger wildfire models such as WRF-SFIRE. These fuels also do not take more computation time compared to the 13 fuels since the Rothermel model used to calculate the ROS is the same as before.
Figure 4.4: a) Comparison of the fire shape for Albini fuel category 6 (Dormant brush, hardwood slash) (top left) and S&B fuel category SH4 (bottom left) with horizontal wind vectors at ~45m AGL color coded based on the horizontal wind speeds. Also in a) is the fire ground heat flux from the Albini fuel (top right), and S&B fire ground heat flux (bottom right) in kW/m². b) Box and whisker plot showing the mean distribution of the horizontal winds from the Albini fuel (Orange) and S&B fuel (Blue). These fire shapes, horizontal wind vectors, fire ground heat fluxes, and horizontal winds were taken from the last timestamp from the simulation.
REFERENCES


