**An Analysis Between the Rothermel and Balbi Fire Spread Model**

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**Abstract.**

Accurately predicting the rate of spread (ROS) of a propagating fire in various fuels, weather, and topography poses a challenge for fire modelers as there are many factors to consider when trying to calculate the ROS. There are also small-scale processes occurring that must be taken into consideration to produce an accurate calculation for the ROS. To predict the ROS, multiple models have been created in varying environments and atmospheric conditions. These models prove invaluable to those who model wildfires as they allow modelers to run simulations and generate forecasts for wildfires. A comparison of different ROS models will allow the most accurate model to be determined and implemented to improve future forecasts and simulations. The two fire ROS models in this study are the Rothermel model and the Balbi model. These two models aim to accurately predict fire spread in various conditions, however, the way they calculate the ROS differs from one another. 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. Conceptually, the models also differ since the Rothermel model is a semi-empirical model and the Balbi model is a fully physical model. To see how each model performs, the models are converted into a MATLAB code and various tests will be run on the codes. These tests include changing parameters within the fuels, topography, fuel moisture, and weather conditions to see how each factor influences the models. Smaller scale processes within the code that lead up to the overall ROS can be analyzed to see how the individual calculations in the models weigh into the final calculations. With the smaller scale calculation at hand, that will allow the models to be compared at a much finer scale, which will allow certain processes to be studied which will contribute to the overall ROS rather than comparing just the ROS.

To see which model performs best in an operational setting, utilization of an experimental dataset will allow the comparison of the model data to observations. The data is from the Kolgerberg dataset from the Van Wilgen experiment. These tests were performed in South African fynbos and the dataset includes the observed ROS. With this dataset, the modeled ROS can be compared to the observed ROS to see which model is more accurate in an operational setting.

**Introduction.**

Providing an accurate assessment of the rate of spread (ROS) of a fire in varying environmental conditions and topography poses as a challenging task. Many small-scale processes occur both within a fire and interactions between fire and the weather/terrain. However, the formulation of an accurate model that can predict the ROS in varying fuels and weather conditions would serve as an invaluable resource for fire modelers. It can also be implemented into other fire models to allow for an accurate prediction of where a fire may spread to and how fast. With this knowledge, fire managers can use different tactics to control and extinguish fires much faster than before. There are three types of models that predict the ROS, 1. Empirical models, 2. semi-empirical models, 3. Physical models. Empirical models use statistical data and observational data to figure out the rate of spread. These models lack any physical characteristics and are usually simplified models. Semi-empirical models use both observational data and physical properties to calculate the rate of spread. Models like these have proven to be useful with calculating the rate of spread as these models simplify fire spread processes while incorporating key principles (Chatelon et al., 2022). Physical models are models that 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 rate of spread computationally challenging and time consuming. However, some models aim to simplify these principles while still producing an accurate ROS model so it can be computed much faster.

In fire models (such as WRF-SFIRE), they incorporate ROS models to help predict where the fire will spread next and how fast it will propagate. 2 models that are currently in use across an array of fire 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 that can be used by fire managers under operational conditions (Chatelon et al., 2022). It has undergone many revisions over the past 15 years and is still being worked on to this day. The other model is the Rothermel model. This is a semi-empirical model that was created by Richard C. Rothermel in 1972 and has undergone revisions by Frank A. Albini in 1976 (Andrews, n.d.). The goal of this model was to accurately calculate fire spread in different environments with only a few inputs necessary. While these models aim to calculate the same thing, the formulas and principles used to design these models differ from each other.

The Rothermel model is based on a heat balance model developed by Fransden (1971), and the data used was obtained from wind tunnel experiments in artificial fuel beds containing various fuels, and from Australian wildfire data in grasses (Andrews, n.d.). From these datasets, Rothermel was able to use observed data along with some physical properties to create his model. This model still contains a lot of assumptions and is nowhere near perfect. There are still a lot of limitations with this model, but for the purpose it was designed for it works well.

The formulation of this model is still quite complex despite it not being a fully physical model and making assumptions about some properties. In the beginning, the ROS equation was solely based on the conservation of energy equations which made the equation difficult to solve. By using observations and an understanding of how fire propagates in certain environments, simplifications to the model were made that made it easier to be solved not only by a human but a computer as well. With this model, it can then be implemented into bigger fire spread models.

To reduce this main equation to what it is now, small details were implemented into the model to ensure the most accurate result. For a fire to spread, the fire must preheat the potential fuels to ignition temperature. To ignite the fuel, it depends on ignition temperature, moisture content, and the amount of fuel involved (Rothermel, 1972). The way a fire can preheat the fuels varies too. Certain components within a fire 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 paper is the reaction intensity. This is the energy released by the fire front and is produced by burning gases released from the organic matter in the fuels (Rothermel, 1972). The reaction intensity is mainly based on the fuel type but knowing the intensity can aid in developing the model. This also changes with wind and slope as the propagating heat flux exposes the fuel to additional convective and radiant heat transfer. To account for the wind and slope in the model, Rothermel adds them in as coefficients (after extensive testing with different slopes and winds) to account for these processes. With just this knowledge so far, Rothermel was able to simplify the main equation down to a bunch of variables without any need of calculus.

With the complexity of wind and slope, Rothermel began working on the model assuming no wind and slope and will add those in later to analyze the current equation he has. To test and analyze this model, 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 (Rothermel, 1972). All the load cells contained electronics that would take measurements during the burn. With this experiment, Rothermel was able to see what needs to be implemented into his model to account for no slope and no winds. The same was done for slope and winds. He constructed fuel beds with packing ratios porous enough to cause flameout and compact enough to exceed natural conditions (Rothermel, 1972). To create windy conditions, Rothermel used a wind tunnel. He also used McArthur’s dataset on the grassland fires in Australia. Rothermel came up with a correlation with the wind speed and the rate of spread, depending on the fuel type and fuel load. As for the slope coefficient, similar with other experiments, he used fuel beds and sloped the beds at 25, 50, and 75 percent and had varying packing ratios (Rothermel, 1972). After this experiment he came up with a correlation for the slope parameter.

After all these experiments, the complete set of parametric equations were developed (Rothermel, 1972), but the model still is not yet suitable for field use since it was created in lab setting. With different compositions of fuels in the environment, the model cannot properly account for these and accurately calculate the rate of spread. 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 mainly 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. While this model still has limitations, for its time it was easily the best model out there.

With more interest in fire modeling, another rate of spread model has been created that is still being worked on till this day. The Balbi model is a physical model developed by Jacques-Henri Balbi, Jean-Louis Rossi, Thierry Marcelli, and Paul-Antoine Santoni (Balbi et al., 2007). The Balbi model is proposed as a model that can run faster than real time and will be integrated into management tools (Balbi et al., 2007). The goal of this model is “to be as complete as possible with regards to the equations that govern fires and be as simple as possible to predict fire spread faster than real time” (Balbi et al., 2007). Since this model is fully physics based, there will need to be a lot of simplifying assumptions made to get this model to a point where it can be used at an operational point since the main equations governing fire spread would take too long to compute for operational use.

In the Balbi model, a major part of calculation time comes from the equations governing the flow (Balbi et al., 2007). To combat this issue, major simplifications are made such as assuming the tilting term is the main contributor to the flow. Within these simplifications, even more simplifications are made to make the model computationally fast. This occurs in the calculation of the “free stream wind and upward gas flow velocity in still air” (Balbi et al., 2007). To calculate these parameters, multiple physical processes such as thermal balance must be considered to accurately calculate these. In the Balbi model, the authors also investigate the radiant heat flux of fires on preheating fuels. This is split up into two different properties, the flame base and the embers, and the flame body. By adding these two components that should yield the resulting radiant heat flux. For the flame base radiation, this component deals more with distance from the unburnt fuel to the flame base and emissivity of the fire. As for the flame body, this 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 (Balbi et al., 2007).

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 no winds, then later slope and wind would be added into the model. Their equations incorporating slope and wind ended up producing a series of nonlinear equations, which would decrease the speed of the model. As a result, they used algorithms in Mathematica to find a solution for 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 real simulation.

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 improvied on the model and added some more constants to made calculations easier in the future. 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 this experiment, Balbi found some of the fitted parameters from the last experiment did not fit in this experiment, and there were deviations between the two experiments. Not all parameters shifted a lot though, some parameters remained relatively constant. The last experiment occurred at the “University of Coïmbra 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 model fit parameters could be tested again. With the slope and wind parameters they calculated from previous experiments, they were input into the model, and the model performed well. No statistics were given in this study, instead there were plots of the observed ROS compared to the modeled ROS. One important note is the slope factor and the wind factors are different (as predicted in the model), and these parameters fit high slope and high winds which other literature underestimates (Balbi et al., 2007). As a result of these experiments, the model has been fit for laboratory experiments.

To get the model fit for field scales, an analysis of 29 field-scales was performed for varying vegetation and winds. There was no slope in these experiments. With a statistical study, Martins Fernandes (author of the paper) derived a model that fits the parameters that were causing problems in the laboratory experiments (Balbi et al., 2007). Except this time these are for field-scales. With this analysis, the model is 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 satisfies what the authors were originally looking for. It is a faster than real time model that is fully physical. This however is 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 fire spread models, the Balbi model has evolved quite a bit. One question remains unanswered in this model that needs to be addressed and that is what the dominant heat transfer mode is (Balbi et al., 2020). Some models began removing certain parameters since they did not think they contributed to the ROS. In this model, the authors take a closer look at how convective heat transfer impacts the rate of spread and to do that, they use multiple laboratory experiments. They still want to keep the model faster than real time so it can be used operationally so there is still some restriction to how complex the model can get. By running these experiments in a laboratory setting, the authors were able to better determine what processes are the leading cause of the rate of spread along with finding finer details about each process that contribute to the ROS. Two terms that are new in the model is the convective cooling and the flame base radiation. With the addition of these two parameters, it adds another layer of complexity to the model, but overall, it accounts for more processes within a fire which could provide a more accurate ROS.

After extensive testing and modifying the model with their lab setting and more than 300 experimental 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 is still claimed to faster than real time and it can be used at much larger scales. This model also does not need the Rothermel model to calculate the ROS. Before, the Rothermel model was implemented into the Balbi model to get a first guess for the ROS so it can go through the iterative process to find the ROS, but now it uses the flame base radiation. This means the model is independent now. The model also has no parameter that varies between experiments, which makes this model fully predictive (Chatelon et al., 2022). With the other versions of the model, some constants and parameters needed to be modified, but not this version of the model.

The last modifications (and most current as of writing) occurred this year in 2022. This year, the Balbi model was modified further to better account for field scale fires. Before, the model was built off laboratory experiments which still proved useful as the results from the 2020 paper show, but now the model can be better applied in the field. Some notable changes between the two models include removing certain parameters to account for field scales and setting some values constant. This model also better considers convective and radiative heat transfer as heat transfer mechanisms and can be used under operational conditions (Chatelon et al., 2022). One parameter of interest in this study was the fitted model parameter. The goal of this was to provide a coefficient that would allow this model to be used at an operational setting. After running thew model on various field experiments the authors were able to come up with a parameter that better calculates the ROS. Sensitivity analyses were also done 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 a convective component, 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 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, they could determine how much wind affects convective heat transfer. They found that the gas temperature was greater with minimal wind. As the wind speeds increased above 1m/s there was an exponential maximum gas temperature. A decrease in the gas temperature was also noted with an increased fuel packing ratio and moisture content. Next is the surface gas velocity. In this experiment, they laid out fuel in a way that some fuel elements were farther away from each other than 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 however, 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.

By comparing the two models using different fuels and weather conditions, each component within the model can be evaluated to see what contributes the most to the ROS. With this knowledge, certain components within a fire can be better evaluated and calculated in future models to better calculate the ROS. With a more accurate ROS model, this will improve bigger fire models such as WRF-SFIRE. With a more accurate model, that can help fire managers better decide where the fire will spread and how fast it will spread to a certain area. This in turn will help scientists better understand fine scales processes such as fire-induced circulations since the models are more accurate. Also, with improvements in technology, these models can be further improved, and more complex processes could be added into the model in the future to make them even more accurate since there are not as many simplifications. These improvements will likely be with modern models (such as the Balbi model) and not older models, but overall, any improvements could help fire managers better control fire spread.

**Methods**

To compare the two rates of spread models both conceptually and analytically, papers from both models as well as MATLAB codes from both models were used 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 rate of spread, it was much easier to understand how each parameter contributes to the ROS. This also goes for each assumption since these models had to make a lot of assumptions to make them computationally fast as in each paper there were a series of complex equations that would usually take computers much longer than “real time” (Balbi et al., 2007).

To analyze the models analytically, the two MATLAB functions (link to them is in Appendix A) were modified to accept more input parameters as well as accept multiple values as an input. 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 (named input in the code), that can be assigned to any value, and it accepts an array of numbers. Originally the code cannot accept an array, but with modifying the equations to accept an array and output the rate of spread components as an array (specifically in the Balbi model), the results can then be plotted and evaluated to determine how that parameter impacts the overall ROS.

**Results**

**Discussion**

Comparison between the semi-empirical Rothermel fire spread model and 1D physical Balbi fire spread model. This project will include the analysis of the fundamental concepts and assumptions behind these models and analysis of the results under various fuel and weather conditions.

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