Introduction and literature study

As a part of this assignment, you will provide an introduction to the general subject of your project and provide a short literature review outlining the current state of the knowledge (what has been already done in this subject) in relation to the proposed scope of your project.

Please adhere to the following structure:

1. Introduction - general importance of the subject

2. Current state of science or technology including literature review if applicable

3. Novel aspect of the project - description of how the proposed work will improve or advance the current state of science or technology.

(30 pts)

Notes:

* The Rothermel model was developed for the National Fire Danger Rating System
* 3 fuel sized were tested over a wide range of bulk densities, and the fuel beds were composed of uniform size particles.
* No prior knowledge of a fuel’s burning characteristic is required for this model, all that is needed are inputs describing the physical and chemical makeup of the fuel and the environmental conditions in which it is expected to burn
* First person to attempt to describe fire spread using a mathematical model was W. R. Fons
* Fon’s: Heating of the fuel ahead of the flame as it progresses is the first and most essential process of the flame propagation mechanism
* During preheating, the fuel temp exceeds the air temp which indicates the convective heating or direct flame contact does not occur until the fire front reaches the particle
* Such temperature histories indicate that basic differences exist in the mechanisms that bring fuels to ignition.
* The base equation was supplied by Fransden (1971) who applied the conservation of energy principle to a unit volume of fuel ahead of an advancing fire in a homogeneous fuel bed.
* To ignite the fuel, it depends on ignition temperature, moisture content, and the amount of fuel involved.
* Propagating flux had the units of heat per unit area per unit time and is composed of the horizontal flux and the gradient of the vertical flux
* The vertical flux is more significant during wind-driven and upslope fires due to the flame tilt over fuel increasing radiation and causing direct flame contact and convective heat transfer to the potential fuel
* The energy release rate of the fire front is produced by burning gases released from the organic matter in the fuels. (reaction intensity)
* Therefore the rate of change of this organic matter from a solid to a gas is a good approximation of the subsequent heat release rate of the fire
* This is a function of fuel parameters such as the particle size, bulk density, moisture, and chemical composition
* This is the source of the no-wind propagating flux
* With wind and slope, this changed the propagating heat flux since it exposes the potential fuel to additional convective and radiant heat
* With this knowledge, this reduced the main equation down

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Alternative Assignment #2

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METR 164

Providing an accurate assessment of the rate of spread (ROS) of a fire in varying environmental conditions and topography poses as a challenging task. However, with the formulation of an accurate model that can predict the ROS in varying fuels and weather conditions, this model will serve as an invaluable resource for fire modelers and it can 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.

During the creation of the Rothermel model, there was not much in terms of technology since it was developed in 1972. Computers were not as fast and not as much was known about fluid dynamics and other physical properties. 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. The physics being basing the model on the conservation of energy described by a heat sink (Andrews, n.d.). 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. 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 in them in as coefficients 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 to 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 operationally.

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. By looking at both conditions where there is no slope and no wind, and conditions with slope and wind, equations are made for both conditions to account for the inflow of air into the fire and how it interacts with the fire. Like with the Rothermel model, components such as radiative heat transfer and flame base heat transfer are implemented into the model. Balbi also incorporates that with a slope, the flame base is brought closer to the unburn fuels and the radiative heat flux is the main contributor to the rate of spread. To simplify this parameter, more simplifications are made to make the calculation faster.

Like with Rothermel, accounting for slope and wind speed in the model added another layer of complexity to the model. With their calculations in Balbi et al., they ended up with a series of nonlinear equations, which could decrease the speed of the model. As a result, they used algorithms in Mathematica to find a solution for these equations. With these equations in hand combined with all the other equations, the model is ready to be tested to see how accurately it can predict fire spread.

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 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 still 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 didn’t 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 experimnental 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).

By comparing the two models using different fuels and weather conditions, the most accurate model will be determined along with determining which components contribute the most to the overall ROS. With both models, they consider radiative and convective heat transfer, so by running sensitivity analysis and better understanding how each author calculated certain components, improvements can be

3. Novel aspect of the project - description of how the proposed work will improve or advance the current state of science or technology.

Andrews, P. L. (n.d.). *The Rothermel Surface Fire Spread Model and Associated Developments: A Comprehensive Explanation*.

Balbi, J. H., Chatelon, F. J., Morvan, D., Rossi, J. L., Marcelli, T., & Morandini, F. (2020). A convective-radiative propagation model for wildland fires. *International Journal of Wildland Fire*, *29*(8). https://doi.org/10.1071/WF19103

Balbi, J. H., Rossi, J. L., Marcelli, T., & Santoni, P. A. (2007). A 3D physical real-time model of surface fires across fuel beds. *Combustion Science and Technology*, *179*(12), 2511–2537. https://doi.org/10.1080/00102200701484449

Chatelon, F. J., Balbi, J. H., Cruz, M. G., Morvan, D., Rossi, J. L., Awad, C., Frangieh, N., Fayad, J., & Marcelli, T. (2022). Extension of the Balbi fire spread model to include the field scale conditions of shrubland fires. *International Journal of Wildland Fire*, *31*(2), 176–192. https://doi.org/10.1071/WF21082

Rothermel, R. C. (1972). *A mathematical model for predicting fire spread in wildland fuels*. Intermountain Forest and Range Experiment Station, Forest Service, United States Department of Agriculture.