A Windy Sabotage: Determining the Area of Jeopardy Inflicted by a Wildfire Under the Influence of Wind Through a Mathematical Approach

Raven May S. Gaso
Tanjay City Science High School, Tanjay City Division, Negros Oriental, Philippines
Princess Jane A. Landiza
Tanjay City Science High School, Tanjay City Division, Negros Oriental, Philippines
Mary Louise R. Ceniza
Tanjay City Science High School, Tanjay City Division, Negros Oriental, Philippines

Abstract

This study looks at how wind affects the spread of wildfires and creates a simple mathematical model to estimate the area that fires driven by wind can affect. Using real wildfire events from Santa Ana, Canada, the research focuses on wind speed as the main factor influencing fire spread. The model uses basic geometry and rate of spread formulas to calculate the burned area and represents fire growth as an ellipse, which helps determine how far the fire moves, which areas are affected, and how quickly it could reach nearby communities. The results show that as wind speed increases, fire spreads faster and burns a larger area, showing clearly that wind is a key factor in wildfire behavior. While the model does not include some real-world factors, such as changes in humidity, temperature, or uneven terrain, it provides a simple and practical way to estimate fire spread. This makes it useful for basic predictions, learning purposes, and raising awareness in communities. The study highlights the importance of using wind information in wildfire planning to better assess risks, prepare communities, and support emergency response. By understanding how wind influences wildfire movement, local authorities and residents can make more informed decisions about safety measures, evacuation plans, and resource allocation. Overall, this simplified approach offers a helpful starting point for understanding wildfire dynamics and shows why wind data should be included in fire preparedness strategies to reduce danger and improve response.

Keywords: Wildfire Spread, Wind-driven Fires, Rate of spread (ROS), Elliptical fire growth, Area of jeopardy

Introduction

Wildfires are most prone in areas covered in green, where extremely flammable objects can cause more than their size—jeopardizing the lives in the area. The significant spread of Wildfire incidents can be highly influenced by different factors: the number of flammable objects, temperature, humidity, and wind. These factors are considered crucial in the learnability of wildfire features for further analysis of such incidents, which are indispensable for the protection of life. This study focuses on one prominent factor in causing the spreading of wildfire: the wind, offering a model for determining the area for said disaster using wind as its main factor. Several ideas have been approved as necessary in wildfire perimeter and spread predictions, as well as for the efficiency of firefighting planning. However, a simplified model can still be a crucial step towards the actual understanding and/or predictions. In education, simplified models can illustrate core mathematical concepts and offer a meaningful understanding of the entire system.

Wildfires have repeatedly occurred in Santa Ana, Canada, and in most cases, the rapid spread of the wildfires has been caused by the wind. To effectively learn about or comprehend the spread of wildfires and the affected areas, there should be a simple and easy-to-understand mathematical model designed and capable of helping us comprehend the spread of the wildfires and the affected areas. This paper shall address the following challenges: Measurement of the wind speed and direction, and its effect on the spread of the wildfire. Estimating the distance of its spread. Identification of affected areas. Recognize the affected areas due to wind and fire patterns. This paper will address all the challenges in developing a simple and easy-to-understand model capable of calculating and helping comprehend the spread of wildfires in Santa Ana, Canada.

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Wildfires rank among the most destructive natural disasters. Wildfires impact ecosystems, society, and the economy in many parts of the world. Globally, the number of wildfire cases has risen significantly as a result of climate change, drought, and changes in land use. For instance, the 2019-2020 Australian bushfires accounted for the destruction of land in excess of 18 million hectares, as well as the massive loss of life, thus demonstrating the effect of intense wildfires in high wind conditions (Boer et al., 2020). Additionally, in the west United States, wind-borne wildfires like the 2018 Camp Fire illustrate the rapid propagation and massive impact of wildfires in high wind, which threatens lives and property (Cohen & Stratton, 2019).

Various factors control the spread of wildfires, and these include, but are not limited to, wind speed and direction, availability of fuels, topography, temperature, and humidity. Wind is an essential factor in determining the nature of wildfires because, in addition to supplying oxygen, it can spread fire into new fuels and even lead to an explosion in spots as embers move ahead of the actual fire front (Sullivan, 2009). Globally, wind-driven fire simulation models have been developed to better predict fire spread and control in such landscapes that may be prone to wildfires (Finney, 2004).

Within the Philippines, the prevalence of fire-related hazards has also gained attention. While large-scale wildfires are less frequent compared to those that have ravaged countries like Australia or the United States, fires do pose significant risks in the country, especially during the dry season and where shifts in land use and recurring droughts prevail. Indeed, during 2016 and 2019, there were numerous forest and grassland fires that took place in Mindanao and the Visayas regions, including Negros Island, which strongly affected local communities and agricultural areas (PAGASA 2021). These localized incidents reveal that wind patterns, including the northeastern monsoon and localized gust events, can be a contributing factor to the rapid spread of fires. Because of this, most prior studies focused on wildfire modeling through computation are lacking within the Philippine context.

The study will center on one of the major contributing effects of wildland fires, particularly the dynamics of wind, identifying how disparities between wind speed or direction affect wildland fires' development and spread. Through creating a simplified computational model that would determine wildland fire propagation depending on wind variability, this study aims not only to contribute towards a deeper understanding of the complex dynamic effects between wildland fires and wind, but it could be useful for regional wildland fire management, especially for a place like Negros Oriental, which could be susceptible to wind-driven wildland fires threatening not only human life but the environment as well.

Furthermore, although complex models have been developed for predicting wildland fires, simplified models have useful applications for explaining basic mathematical ideas or for aiding decision-making processes during educational settings, disaster risk reduction, or other environmental studies.

Scope and Limitations

This study goes through different stages and land types in order to build a simple model for estimating the areas in the Philippines affected by wildfire. The main goal of this study is to create a model that is simple and understandable for students and local communities, so they can better grasp the risks of wildfires in forested and grassland regions. However, this model also has its limitations. It assumes that the terrain is flat and uniform, disregarding the possibility of the formation of rugged terrains. This study also excludes other environmental factors which could strongly influence wildfire behavior, such as humidity, rainfall, and temperature changes. In the same way, this study excludes other environmental factors such as humidity, rainfall, and temperature changes that strongly influence wildfire behavior. However, the values used for the spread rate and burning time are only estimated, which may or may not differ from the actual wildfire occurrences. In addition, the ellipse is used to represent the affected area, which does not reflect how real landscapes change the direction and intensity of fire spread. Still, it serves and simpler way good starting point for students and communities to understand wildfire risks clearer.

Literature Review

Wildfires have been known to occur in complex ways that can be affected by environmental factors and wind patterns. In this scenario, wind has been recognized as one of the top factors that can sustain wildland fires and their expansion. Based on this factor, speed and direction can be affected by wind patterns. In this way, wind can influence the expansion of wildland fires and their coverage based on the landmass.

Cruz et al. (2020) also emphasized that the speed of the wind is an extremely important factor in determining the development of a forest fire, especially if grass, leaf litter, and shrubbery are abnormally dried up. The above study mentioned what is called ‘10% Rule of Thumb’ technique, in which it is recommended that the linear speed of forest fires is 10% of the speed of wind, measured 10 meters above the ground level. The above technique is more accurate if wind speed is above 2 km/h and is accurate within 35%.

Consequently, Finney et al. (2018) pointed out that the influence of the direction and speed of the winds was instrumental in determining the size and shape of the fire. According to the research, the simulations demonstrated the influence of the winds in forming elongated elliptical patterns compared to the circular patterns formed. This means that the fuel fronts are longer and the affected area is bigger.

Sullivan, Cruz, and Matthews (2018) further verified the fact that the wind can prove to be one of the major contributors to forest fires. This is because the speed of the winds can easily result in the acceleration of forest fires. An empirical compilation was done by the same researchers, and it was proven to be true that the strength of the forest fires gets multiplied as the speed of the winds gets multiplied.

Linn et al. (2019) simulated research on fire and atmosphere interaction in terms of the effect of strong wind on wildland fires using physics-based simulations. In their research, it was evident that wind affects the steepening of burning slopes, heating intensification, and pre-heating in front of the burning zone. This has significant effects on fire spread speed as well as fire-affected area size in situations where wind affects fire spread. This further confirms wind fire area expansion relevance in the case study.

The risks that might result from wind-borne wildfires were highlighted in the study that was conducted by Johnston et al. (2019). The study clearly indicated the risks that might result from the unpredictability and fast growth of the fire that might be caused by strong wind, which might be difficult to control. The model that was used in the study was important in determining the hazard zone, which was the aim of the study.

As Rothermel & Andrews (2019) further elaborated: "Current models of present wildfire behavior are based on a set of mathematical equations that describe the rate of spread of a wildfire as a function of wind speed, slope, and fuel type." The authors were able to prove that even a slight error in determining the wind speed can produce a great difference between the modeled and actual perimeter of a wildfire. The importance of accurate modeling using the wind speed is apparent in this respect too.

However, the more recent literature suggests the ongoing support for the dominant role of wind. Downslope wind-driven fires in the western United States account for a proportionately large amount of the total wildfire damage, as shown in the study carried out by Abatzoglou et al. (2023). Despite the fact that these fires account for a smaller proportion of the total number of fires and the area burned, they account for the vast majority of the total damage.

The effect of cross-winds on plume dynamics in the case of forest fires has also been observed by Barata et al. (2025), who conducted a study using Large Eddy Simulations. The result shows that even a low intensity of cross-winds has the capability of encouraging lateral transport and vorticities, specifically down-sloped, which has implications for heat and plume transport and potentially impacts the spread of wildfires.

Hayajneh et al. (2025) used simulations of fire behavior influenced by wind speed and slope using computational fluid dynamics simulations. The results of the study showed that fires moving up a slope generate higher heat compared to fires moving down a slope. The influence is strengthened by the presence of wind, implying a combination of slope and wind in determining fire intensity.

According to Flannigan et al. (2022), the impact of climate change and the risk of forest fires due to an increase in hot, dry, and windy weather was explained. The study suggested that the longer duration of the winds contributes to an increase in the burned area size and fire duration.

Furthermore, the study conducted by Sharples et al. in 2016 focused on the case of extreme events involving wildfires and identified the role of high wind in the acceleration of the development of fires as well as the transport of embers over a long range, resulting in the generation of new fires ahead of the main front. This also emphasizes the importance of wind in the simulation process.

Coen et al. (2020) used coupled fire and atmosphere models to investigate large-scale wildfires and proposed the enhancement of local wind speed near the fire front due to the feedback effects of winds and fires. Feedback effects lead to increased intensity and spread of the fire, and thus, the prediction of wind fires becomes difficult, except when using complicated models.

According to Prichard et al. (2021), having an accurate representation of wind in models is quite crucial in simulating the behavior of wildfires. The results generated in this study showed that applying simpler models in simulating wind might result in a potential underestimate of wildfire development, especially in scenarios involving strong wind speeds.

Filippi et al. (2022) examined the effect of the complexity of the terrain on the variation of the wind and the resulting fire spreading. The analysis showed that the variation of the wind direction leads to sudden changes in the fire spreading pattern, resulting in irregular fire boundaries and unpredictable fire spreading routes. This study underlines the importance of dynamic winds in fire spreading models.

Thus, a literature analysis on the different studies has made it clear that, in general, wind has a major role in determining the spread, form, intensity, or overall effect of a wildfire. Research findings over the past 5-8 years have been established to indicate the interaction between wind speed/direction, fuel, and terrain to accelerate the spread rates of fires and improve area extension. Research studies also indicate that minor variations in wind could cause significant variations in the behavior of fires because wind is a critical variable in predicting a wildfire. Research findings offer significant support in the use of mathematical models combined with wind and terrain variables in determining the area of jeopardy in a wildfire situation. Based on the understanding of the current studies on the mentioned topic, the current research study is aimed at improving the understanding of the spread of fires influenced by wind.

Methodology

In describing the structure of the provided formula, it is important to clearly identify the variables used. Wind speed is the independent variable because it is a dominant driver of wildfire behavior and directly influences the rate of fire spread (Rothermel, 1972). The area of wildfire and affected area is the dependent variable, representing the resulting extent of fire spread over time under specific environmental conditions (Finney, 2004; Sullivan, 2009). Wind direction, slope and terrain (fixed), fuel type and moisture, and rate of spread (ROS) are treated as controlled variables: they are either held constant or recalculated under controlled conditions using the same fire behavior model (Rothermel, 1972; Weise & Biging, 1997). The materials used include Google Maps (for mapping), data analysis of recent wildfire events in Santa Ana, Canada, and wildfire statistics. The procedure involves acquiring wildfire hazard maps covering the area of interest, gathering reliable wildfire activity data, and then applying the formula that combines Rothermel’s rate of spread with an elliptical area approximation to estimate the burned area.

This study utilizes mathematics to analyze wildfire intensity and spread formulas derived from scientific studies to estimate the possible range and impact of wildfire in various areas, such as Santa Ana in Canada and wooded areas of the Philippines. Furthermore, the researchers will determine the approximate areas of wildfire danger by tracking environmental and climatic activity such as temperature, wind speed, and humidity. This study undergoes three phases to achieve its objective: a. input; b. process; and c. output.

This research uses a quantitative-descriptive design with a computational model in mathematics to analyze and compute the estimates for the spread of fire under wind-driven situations. A quantitative-descriptive design is appropriate for this research since its aim is to explain and describe how wind speed values impact the rate of spread and the affected area of wild fires using mathematical equations and computations. Instead of conducting a hypothesis test using experimentation or survey research, a quantitative approach models fire spread using equations for fire spread and geometric equations.

The computational mathematical model employed for this analysis combines the rate of spread of fire formulation proposed by Rothermel with an ellipse representation of the geometric process of fire growth. The advantage of the integrated mathematical approach adopted in this study is that it enables the researchers to calculate the distance of fire spread and burned area over time corresponding to different wind conditions. The burned area representation using the ellipse has been justified by the research on empirical wildfires that have confirmed that fires spread in an anisotropic process along the direction of the prevailing wind.

The starting phase, known as the input, includes independent, dependent, and controlled variables. One example of the Independent Variable includes wind speed and terrain slope. These elements affect the speed and the direction in which the wildfire spreads. At the same time, the spread of fire the distance traveled, and the total affected area are the Dependent Variables. These act as the correlation coefficients that can be expressed mathematically to show the relationships among the variables. The approach consists of using a quantitative method where mathematics was directly applied to represent and examine the interaction of wildfire behavior.

Results

$$\square(\square) = \frac{\square(\square \cdot \square)^{2}}{4(\square : \square)}$$

Wildfire spread was studied by combining a rate-of-spread (ROS) model with an elliptical fire growth geometry to estimate the burned area over time. Recent wildfire research shows that fires do not spread evenly in all directions. When wind is present, the fire spreads fastest at front (head fire) and more slowly on the sides, creating a shape similar to an ellipse or oval (Finney et al., 2018; Sullivan, 2019).
The forward rate of spread $\square$ was calculated based on basic fuel characteristics, such as the type and condition of vegetation, and then adjusted account for environmental factors like wind and slope. This approach is based on updated versions of the Rothermel fire spread model:

$$\square = \square_{0} \cdot \square_{\square} \cdot \square_{\square},$$

Here, $\square_{0}$represents the fires spread rate when there is no wind and no slope spread rate, $\phi_{\square}$ represents the effect of wind, and $\phi_{\square}$ represents the effect of slope on how fast the fire spreads. Studies from the past decade show that wind and slope are still the main factors that cause fires to spread faster in the forward direction, especially during intense fire conditions. (Cruz et al., 2020; Sullivan et al., 2021).

The shortcut formula for calculating the burned area in this study is based on the idea that Wind-driven wildlifes usually spread in an oval or elliptical shape, with the longest part of the fire moving in the same direction as the wind. This way of representing fire spread is supported by many years of real-world observations and fire behavior models. Is it especially accurate for fires that burn freely in similar types of vegetation and on mostly flat land (Finney et al., 2018; Sullivan, 2019).

In basic wildfire spread theory, the burned area at a given time *t* is estimated by treating the fire's shape as an ellipse and calculating the area of that ellipse:

$$\square = \square\square\square,$$

Here, $\square$ represents the semi-major axis, which is half of the fire's total length, and *b* represents the semi-minor axis, or half of the fire's width. Fire behavior studies show the distance the fire moves forward at the head is directly related to the rate of spread (ROS) multiplied by the time the fire has been burning.

$$\square = \square \cdot \square$$

For a fire that spreads in an elliptical shape, the semi-major axis is half of the total fire length, which is the same as half of the distance the head fire has traveled:

$$\square = \frac{\square}{2} = \frac{\square \cdot \square}{2}$$

The semi-minor axis depends on the length-to-breadth ratio (L:B), which is a value taken from real fire data that shows how stretched the fire becomes because of wind and slope. The ratio describes how the fire's width compares to it's length, and it is used to determine the relationship between the two axes of the ellipse:

$$\square = \frac{\square}{\square : \square}$$

Length-to-breadth ratios are commonly used in operational and research fire spread models, with typical values ranging from 1.5 to over 6 depending on wind strength and fuel type (Anderson et al., 2020; Finney et al., 2018).

Substituting the expressions for $\square$and $\square$into the ellipse area equation yields:

$$\square = \square\left(\frac{\square \cdot \square}{2}\right)\left(\frac{\square \cdot \square}{2(\square : \square)}\right)$$

After multiplying the terms together, the equation becomes simpler and gives the final expression for the burned area:

$$\square = \frac{\square(\square \cdot \square)^2}{4(\square : \square)}.$$

This equation shows the complete solution for estimating the burned area of an idealized wildfire that spreads in an elliptical shape, using the rate of spread, time, and fire shape. Since the formula already combines fire behavior and geometry into one equation, it can be calculated quickly and easily without needing to separately find the fire's length and width at each moment.

The final expression,

$$\square(\square) = \frac{\square(\square \cdot \square)^2}{4(\square : \square)}$$

The equation is called a shortcut formula because it combines several steps into one direct calculation. Instead of first figuring out the fire's length and width and then calculating the area, this formula let's you quickly estimates the burned area using just three key factors: the rate of spread, time, and the length-to-breadth ratio.

Simpler formulas like this are commonly used in wildfire research to run simulations faster, test different scenarios, check how sensitive results are to changes, and do preliminary risk assessments, especially when detailed, physics-based models would take too much computing time (Sullivan, 2017; Johnston et al., 2022).

Where:

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A = Area Affected by the Wildfire L = Length of Wildfire t = Time of Spread
R = Rate of Spread of Wildfire B = Width/Breadth of Wildfire

Assume a wildfire starts at a point 1,200 m from the town of Santa Ana, Canada. The fire spreads at a steady rate of 1,127 m/h and the fire shape is approximated by an ellipse with a length-to-breadth ratio L: B = 3.0 (wind-elongated). Using the combined ellipse formula for burned area, what is the burned area (in m² and hectares) at the moment the fire's head reaches Santa Ana?

With the given speed and distance from ignition to Santa Ana, the researchers can use this to calculate for the time (denoted by t), then proceed to calculatin for the total area (denoted by A) using the given formula.

Distance = 1,200 m. Rate of Spread (R) = 1,127 m/h. Length: Breadth (L: B) = 3.0.

The researchers will calculate the time (t) for the fire to reach Santa Ana.

$$t = \frac{\square}{\square} \rightarrow t = \frac{\square}{\square} \qquad t = \frac{1{,}200\ \square}{1{,}127\ \square/h} = 1.06477\ \text{h}$$

With the calculated time, the researchers can now calculate for the burned area caused by the wildfire.

$$A = \frac{\Pi(\square \times \square)}{4\ (\square : \square)'} \qquad A = \frac{3.14(1{,}127 \times 1.06477)}{4\ (3.0)'} \qquad A = \frac{3.14(1{,}125.94)}{12} \qquad A = \frac{3535.45}{12} \qquad A = 249.62\ \text{m}$$

The unit will be converted to hectares for better accuracy.

A = 0.025 ha

Discussion

The implications of this analysis serve to support and confirm the long-recognized role of wind as a driving force in fire growth and area expansion during wildfires. The model used in this analysis incorporates wind speed in a rate of spread and elliptical model of fire growth to illustrate how even a small increase in wind speed has a disproportionately greater effect on fire area size. The implications of this analysis support other studies in illustrating how a fire propagates quickly in the direction of the winds in a given area (Cruz et al., 2020; Finney et al., 2018; Sullivan et al., 2018).

The main strength of this model is its simplicity. The model is easy to understand, unlike other complicated models used to simulate fire, which consume huge computational power. The main aim of this model is to provide an easy-to-understand representation of fire spread influenced by wind. The model will help students, disaster preparedness teams, and planners to understand fire spread influenced by wind. The zones that will be most vulnerable to fire spread influenced by wind will also be determined using this model.

It is particularly significant to discuss the issue of the variability of the direction and speed of the wind. Despite the fact that the simulation assumes the constant direction of the wind and the uniform terrain, the actual wildfires are affected by the changing nature of the winds, which can suddenly change the course of the wildfires. Even the slightest change in the direction of the winds can cause the head fire to move into the undamaged regions.

Although the model has proven very useful, there are some obvious shortcomings. The model does not take into consideration fuel moisture variation, transport of embers, spot fire behavior, fire suppression, or interaction with complex terrain. These phenomena may enhance or diminish the growth of fire in practical situations. This model may, therefore, overestimate or underestimate the extent of fire in some situations. However, in its proper domain as a simplified model emphasizing the effect of wind, the model gives fairly good estimates.

On the whole, it is clear that the role of wind should never be considered as a secondary factor in studying wildfires. Wind plays such an important role in the rate of spread and fire shape that it becomes an important determinant of the area of endangerment. Although more research and more environmental factors would make it more precise, it is evident that this model is successful at showing how simplifying math concepts can close the gap between scientific knowledge and application. In any case, it is evident that the wind effect regarding wildfires can by no means be viewed as a secondary element, whereas any further development and introduction of additional factors of nature can only improve the validity of the achieved results. Nevertheless, the method presently used within the equations has proved to a large extent that a simplified or mathematical method of scientific and practical development and applications can certainly lead to a positive result and fill the gap between scientific success and applicability.

Conclusion

The importance of wind in controlling both the rate and area of the spread of wild fires is succinctly illustrated in this study where even slight variations in wind velocity affect the area affected. This research simplifies the already complex equations associated with the behavior of wind and the spread of fire and hence contributes to easier understanding of the dynamics of wildfires by not only academically inclined people but by all stakeholders in the management of such disasters, such as students and those involved in the management of such potential hazards on the ground. In agreement with past research, the findings of this research validate the notion that wind-borne wildfires have the ability of spreading faster and over a broader perimeter and hence posing hazards to adjacent settlements (Cruz et al., 2020; Finney et al., 2018; Sullivan et al., 2018). In showing graphical maps of areas at possible fire risk, it increases wildfire danger awareness and preparedness within a community.

Moreover, the research also highlights the relevance of preparedness and planning in the region to reduce the effects of wildfires. These types of forest fires spread very quickly, and the unpredictability and rapid nature of the spread, driven by the wind, result in extensive damage (Abatzoglou et al., 2023). The proposed model is helpful for the regions as well as the emergency response teams through zoning identification for danger zones, evacuation routes, and emergency response during a fire outbreak. Although it is not a substitute for more complex fire simulation software, the model provides a useful preliminary indicator for risk analysis and preparedness in the event of disasters. Based on the results obtained from this research, it is recommended that there be greater emphasis placed upon the analysis of wind observations, particularly during the Dry Seasons, together with taking into account the aspect of winds in risk analysis for fire disasters in land use management. This study therefore, links scientific knowledge with people's demands by presenting in a straightforward manner wildfires simulation.

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